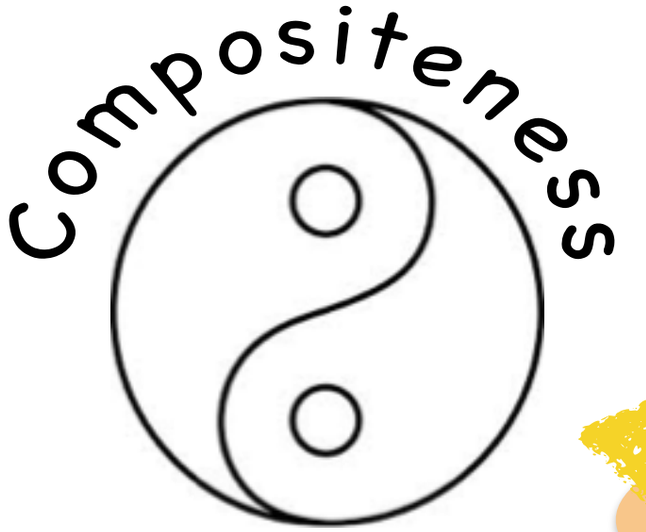




Energizing Higgs Phenomenology at the LHC

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IPPP, Durham University



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

Measurements

Leptons

mass

MET

width

boost

Photons

Jets

interference

Due to absence of signs of new physics

HEP has 'Big Mac' blues,

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



Commercial Reality

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



New Physics has got to be out there:

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

Higgs interpretation and resonance searches promising avenues

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	EFT	Simplified Models	Full (UV) Model
▸ NP models simple rescaling of couplings ▸ No new Lorentz -structures or kinematics	▸ SM degrees of freedom and symmetries ▸ New kinematics/ Lorentz structures	▸ New low-energy degrees of freedom ▸ Subset of states of full models, reflective at scale of measurement	▸ Very complex and often high-dimensional parameter space ▸ Allows to correlate high-scale and low-scale physics



Complexity/Flexibility

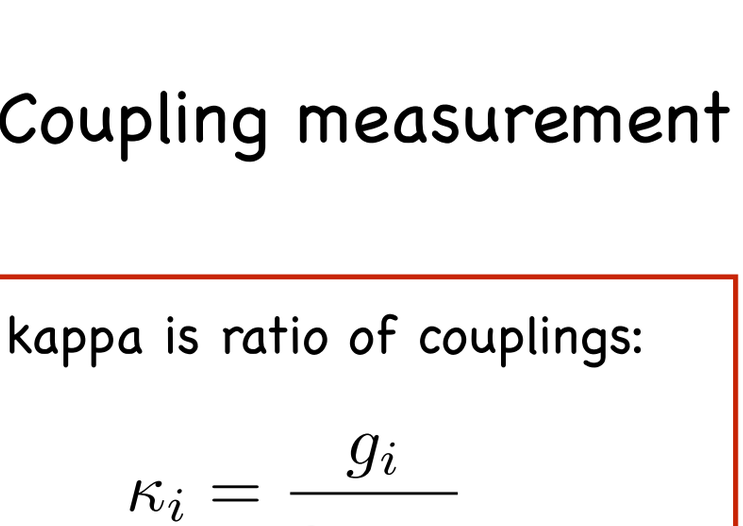
Coupling measurement during Run 1 using kappa-framework:

kappa is ratio of couplings:

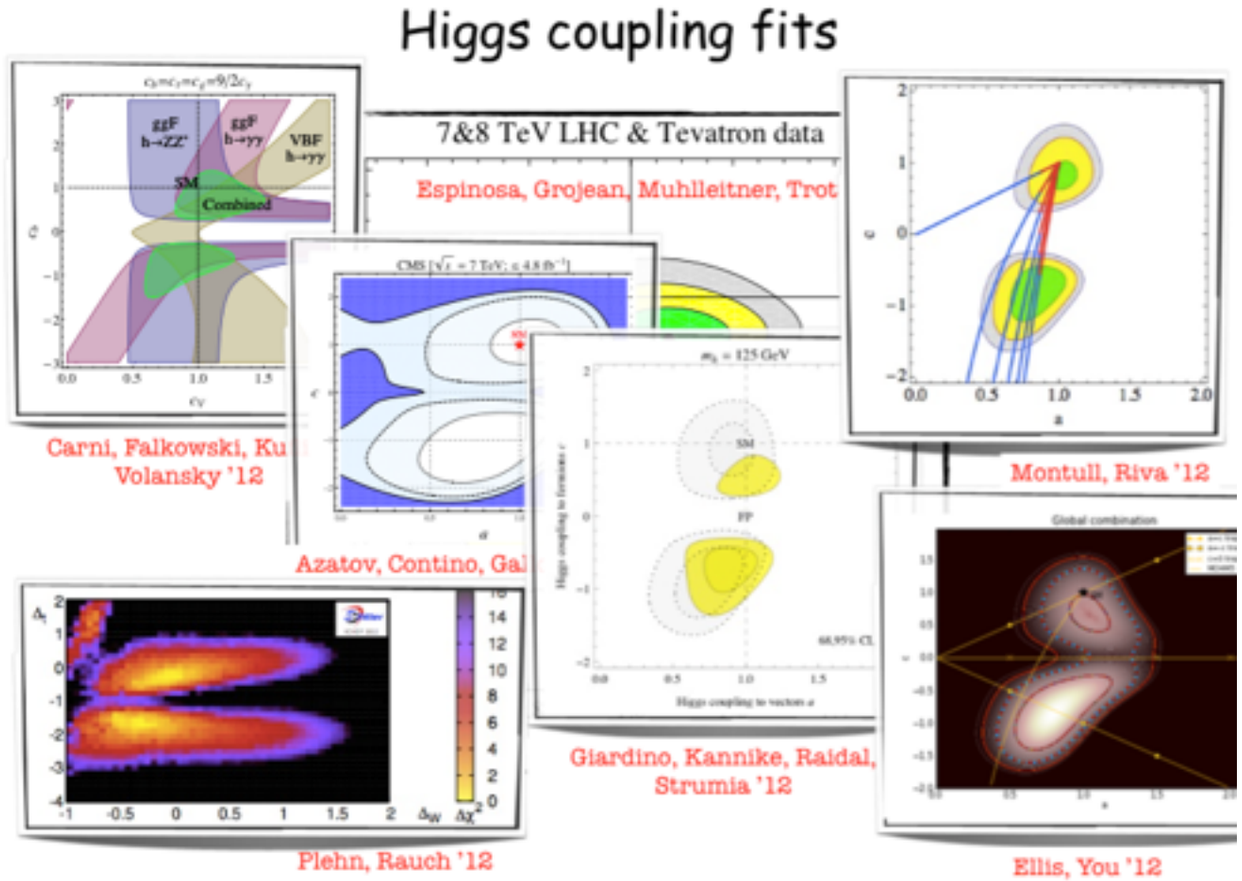
$$\kappa_i = \frac{g_i}{g_{i,SM}}$$

so-called

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



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)

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$ $\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D_\mu} H\right)^2$ $\mathcal{O}_6 = \lambda \lvert H\rvert^6$		
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$		
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$ $\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$ $\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2$		
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$		
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$ $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$		
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu}$ $\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{ABC} G^{A\,\nu}_{\mu} G^{B}_{\nu\rho} G^{C\,\rho\mu}$		

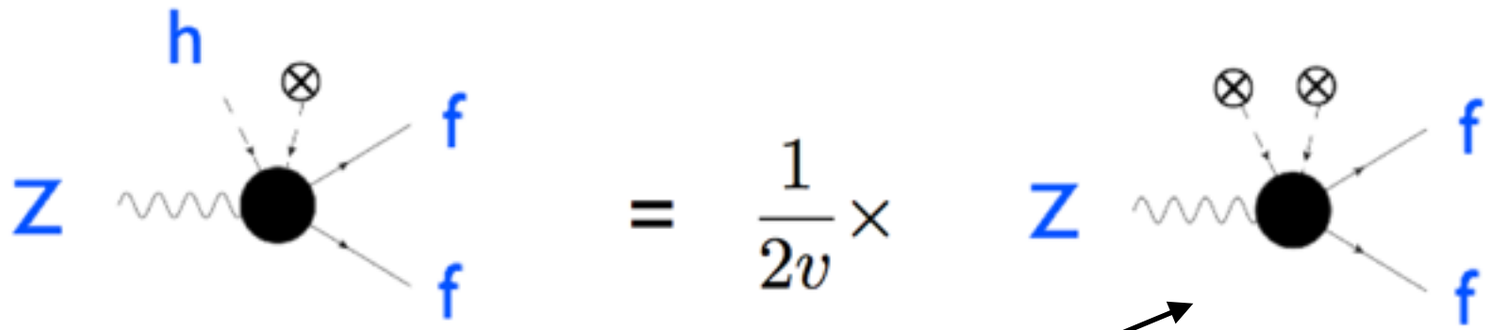
$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D_\mu} H)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D_\mu} H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D_\mu} H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D_\mu} H)(\bar{Q}_L \gamma^\mu Q_L)$		$\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D_\mu} H)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D_\mu} H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$		$\mathcal{O}^{(3)\,l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D_\mu} H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}^u_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^{(8)\,u}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{u}_R \gamma^\mu T^A u_R)$	$\mathcal{O}^{(8)\,d}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{d}_R \gamma^\mu T^A d_R)$	
$\mathcal{O}^u_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_{RR} = (\bar{e}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^q_{LL} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L)$		$\mathcal{O}^l_{LL} = (\bar{L}_L \gamma^\mu L_L)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}^{(8)\,q}_{LL} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{Q}_L \gamma^\mu T^A Q_L)$		
$\mathcal{O}^{ql}_{LL} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{L}_L \gamma^\mu L_L)$		
$\mathcal{O}^{(3)\,ql}_{LL} = (\bar{Q}_L \gamma^\mu \sigma^a Q_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$		
$\mathcal{O}^{qe}_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{e}_R \gamma^\mu e_R)$		
$\mathcal{O}^{lu}_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^{ld}_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{d}_R \gamma^\mu d_R)$	
$\mathcal{O}^{ud}_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{d}_R \gamma^\mu d_R)$		
$\mathcal{O}^{(8)\,ud}_{RR} = (\bar{u}_R \gamma^\mu T^A u_R)(\bar{d}_R \gamma^\mu T^A d_R)$		
$\mathcal{O}^{ue}_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{e}_R \gamma^\mu e_R)$	$\mathcal{O}^{de}_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{e}_R \gamma^\mu e_R)$	
$\mathcal{O}^{ud}_R = y_u^\dagger y_d (i\tilde{H}^\dagger \overleftrightarrow{D_\mu} H)(\bar{u}_R \gamma^\mu d_R)$		
$\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{Q}^s_L d_R)$		
$\mathcal{O}^{(8)}_{y_u y_d} = y_u y_d (\bar{Q}^r_L T^A u_R)\epsilon_{rs}(\bar{Q}^s_L T^A d_R)$		
$\mathcal{O}_{y_u y_e} = y_u y_e (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{L}^s_L e_R)$		
$\mathcal{O}'_{y_u y_e} = y_u y_e (\bar{Q}^{r\,a}_L e_R)\epsilon_{rs}(\bar{L}^s_L u^a_R)$		
$\mathcal{O}_{y_e y_d} = y_e y_d^\dagger (\bar{L}_L e_R)(\bar{d}_R Q_L)$		
$\mathcal{O}^u_{DB} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \tilde{H} g' B_{\mu\nu}$	$\mathcal{O}^d_{DB} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$	$\mathcal{O}^e_{DB} = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$
$\mathcal{O}^u_{DW} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \tilde{H} g W^a_{\mu\nu}$	$\mathcal{O}^d_{DW} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$	$\mathcal{O}^e_{DW} = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$
$\mathcal{O}^u_{DG} = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \tilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}^d_{DG} = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	

Practicality

- Focus on operators with Higgs involvement (new kid on the block)

Observation:

Many Higgs operator indirectly constrained by EWP measurements



constrained by LEP at permille level

- Focus on operators that are probed predominantly at LHC

→ In the end ~8 operators including Higgs of interest

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]

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

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

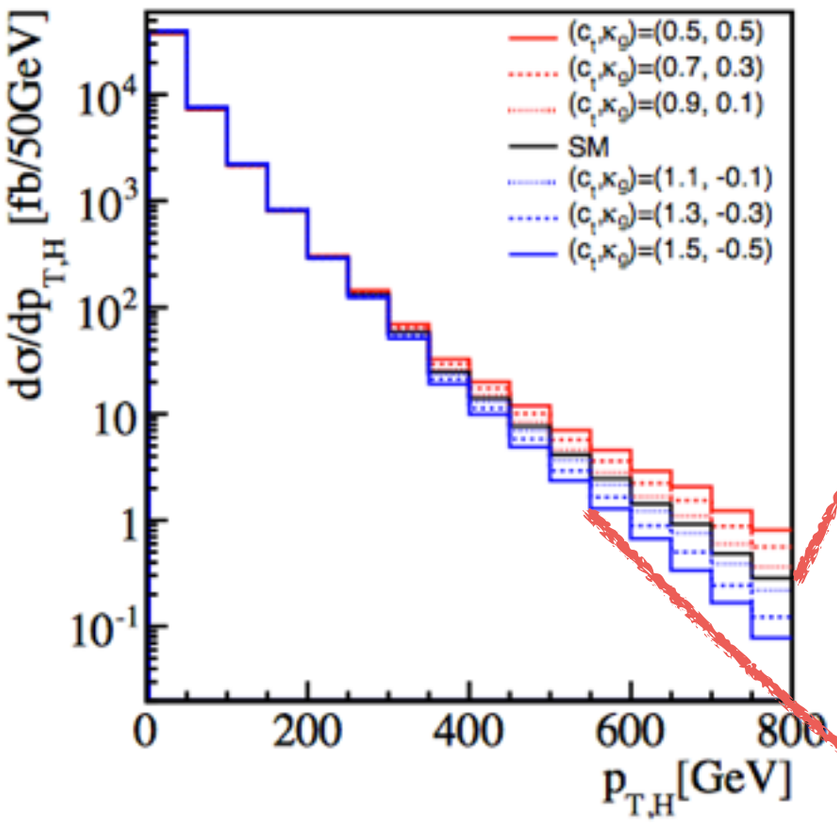
$pp \to HV$ $pp \to ttH$

Validity and Relevance of EFT

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

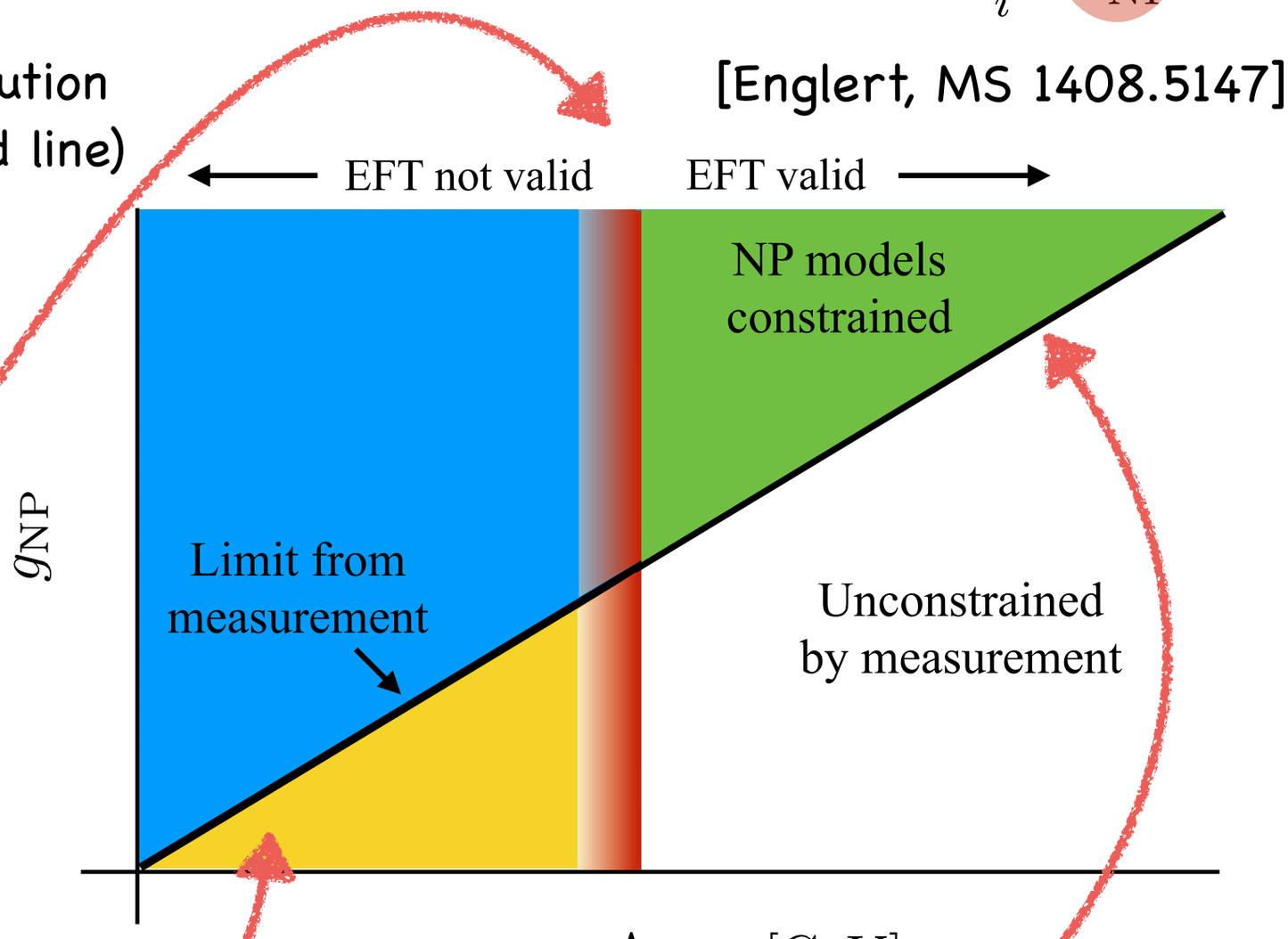
Lagrangian dim-6: $\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{g_i^2}{\Lambda_{\rm NP}^2}\mathcal{O}_i$

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



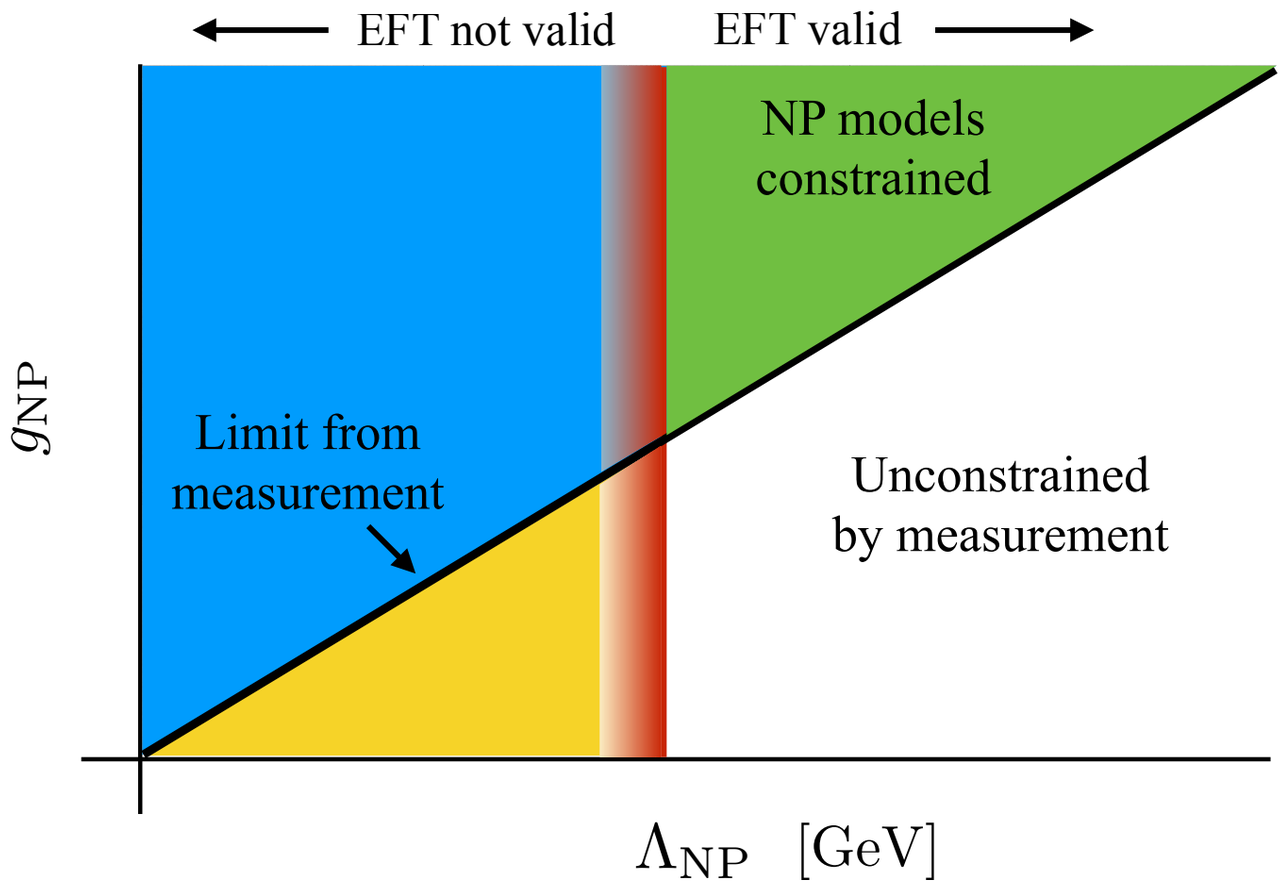
shape sets limit on Wilson coefficient (black line)

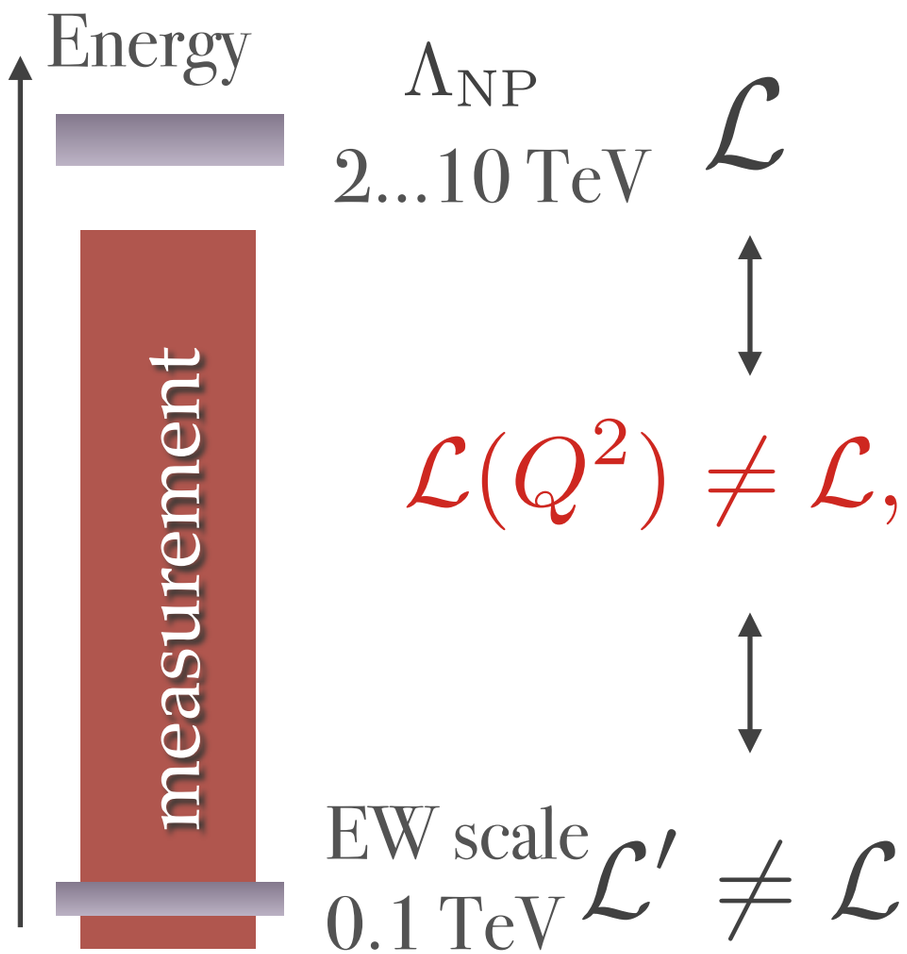
[Englert, MS 1408.5147]



Any UV (weakly coupled) models left?

Validity and Relevance of EFT



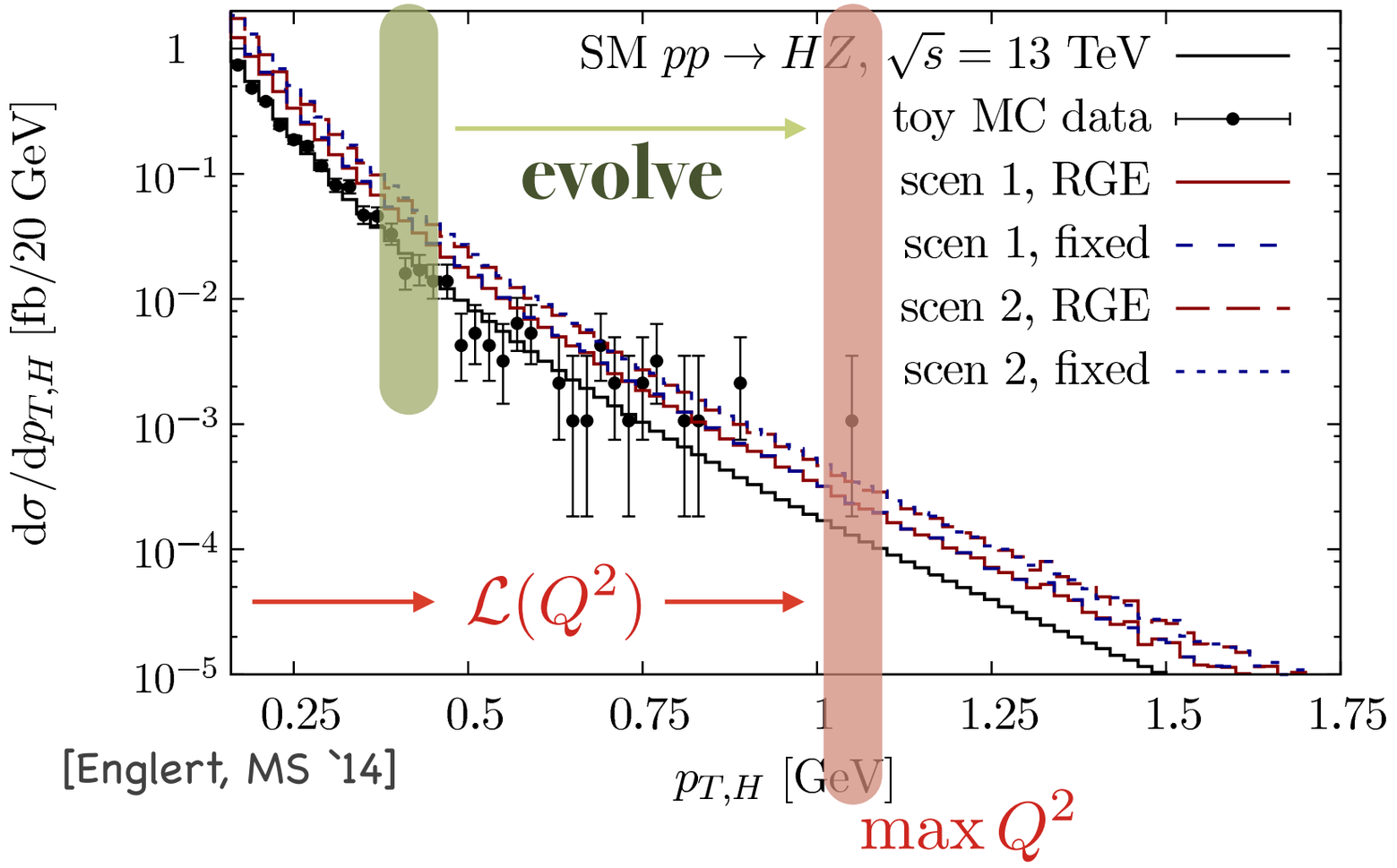


Lagrangian dim-6: $\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{g_i^2}{\Lambda_{\rm NP}^2} \mathcal{O}_i$

- 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]

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

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

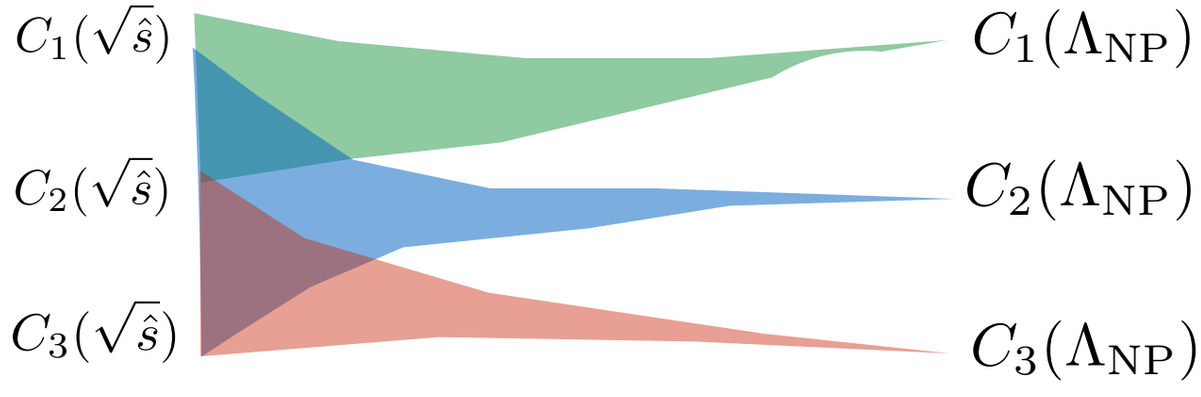
$$\hat{O}_{WB} = \frac{gg'}{\Lambda^2_{\rm NP}} \hat{H}^\dagger t^a \hat{H} \hat{W}^a_{\mu\nu} \hat{B}^{\mu\nu} \,,$$

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

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

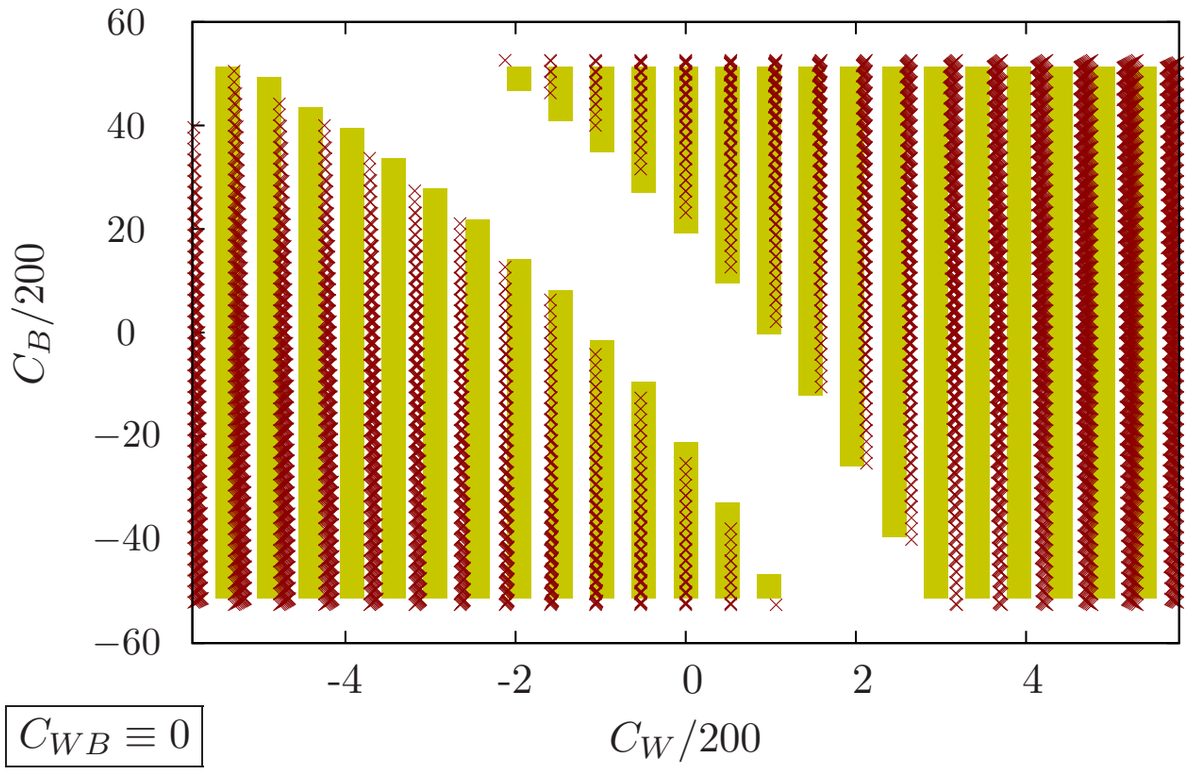
As a result, each measured **event** probes a different combination of operators

measurement at characteristic scale of event

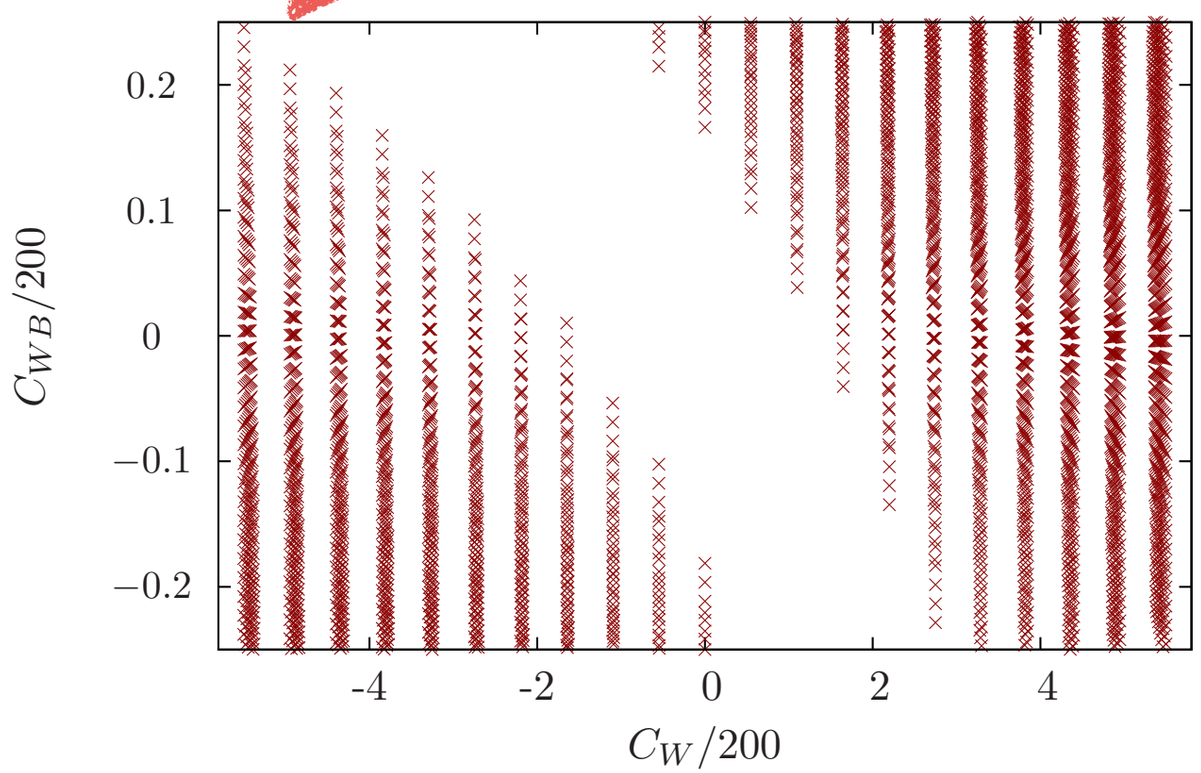


Coefficients of operators at New Physics scale

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



$C_{WB} \equiv 0$



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

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:

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \mathcal{M}_{d=6}$$

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

Included production and decay modes:

(incl.theory uncertainties)

production process		decay process	
$pp \to H$	14.7	$H \to bb$	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:

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

Each channel has own prod. and decay efficiencies:

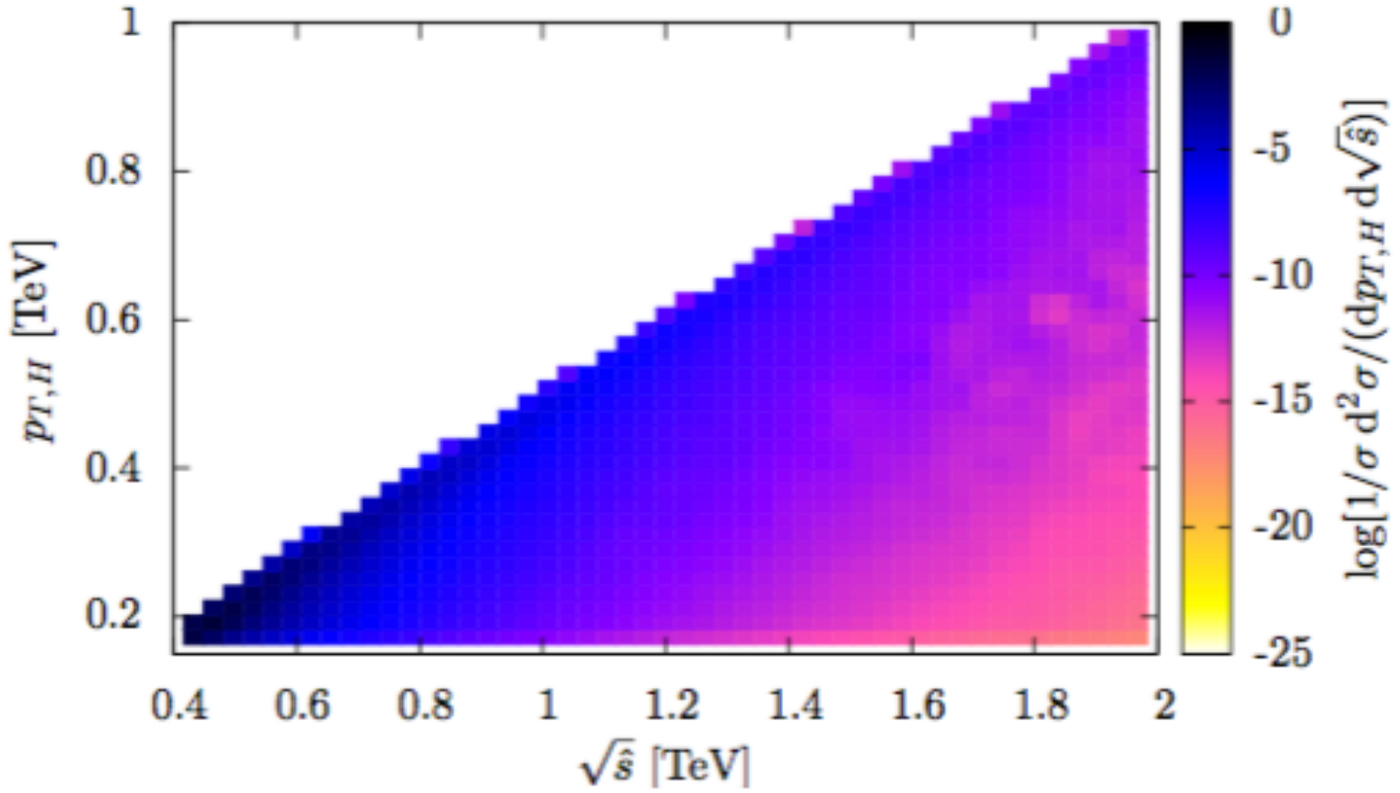
$$N_{\rm ev} = \epsilon_p \epsilon_d N_{\rm th}$$

Parametrisation of cross sections with Professor and fit using Gfitter

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

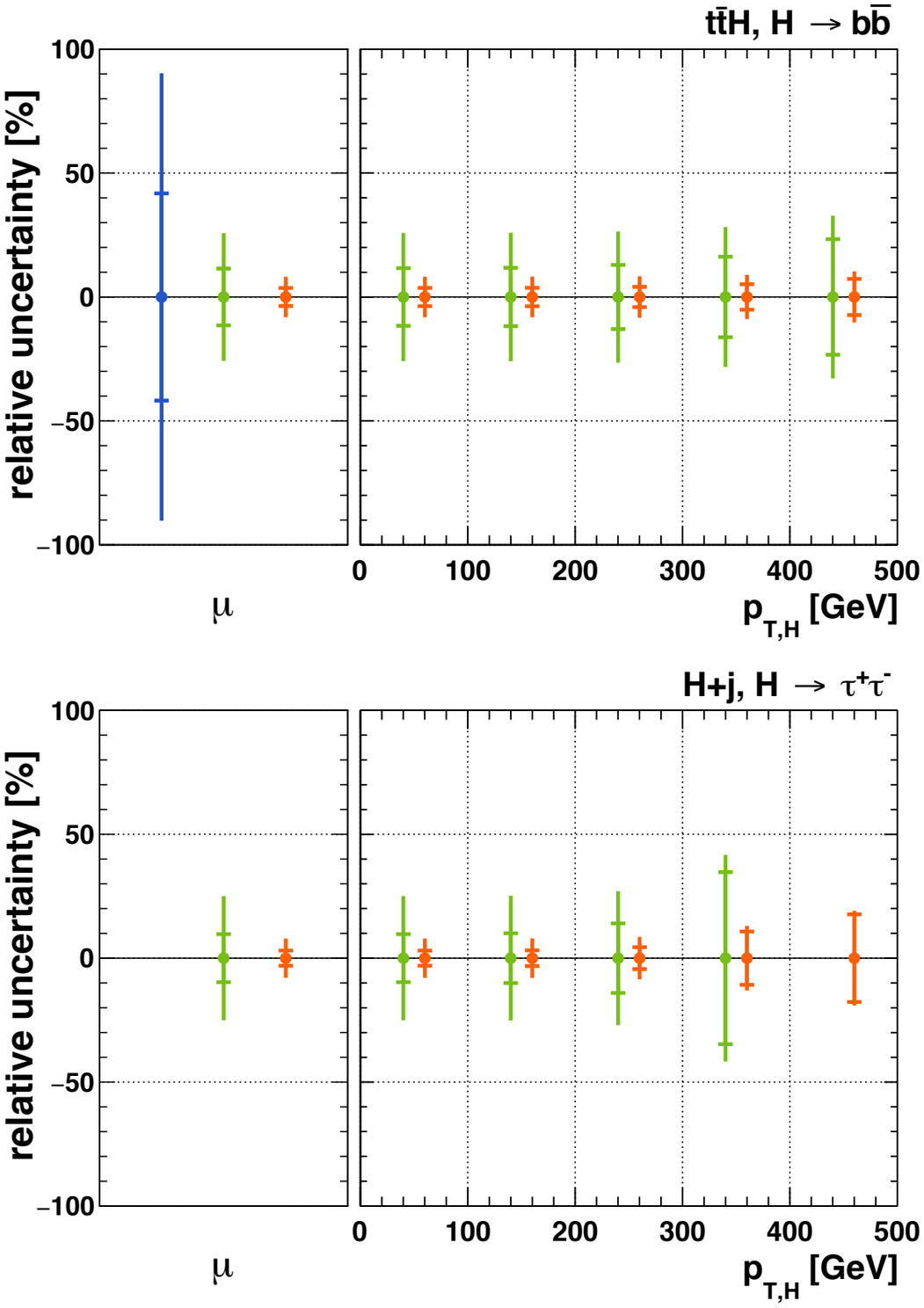
high correlation

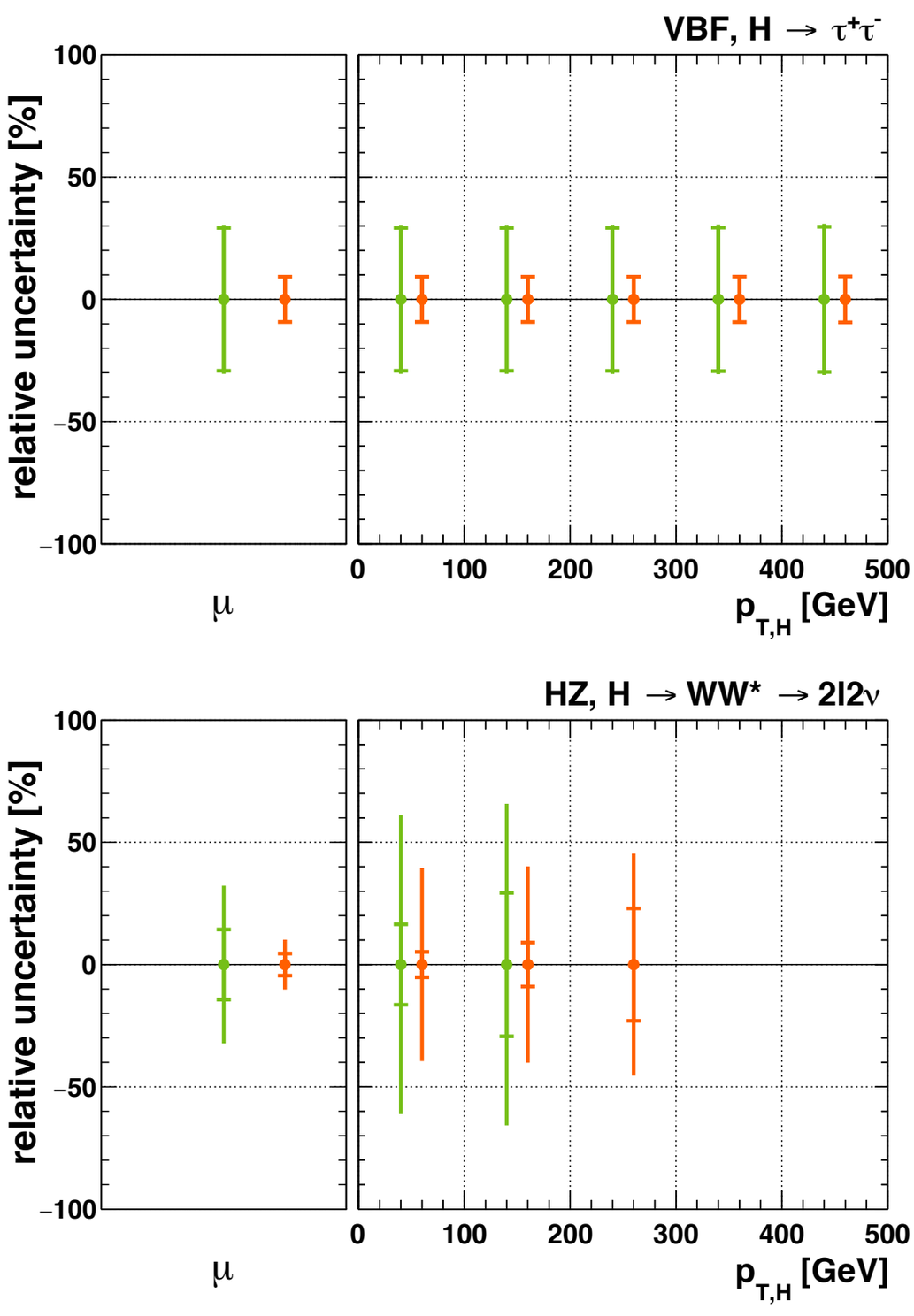
$$\sqrt{\hat{s}} \sim m_H + p_{T,H}$$

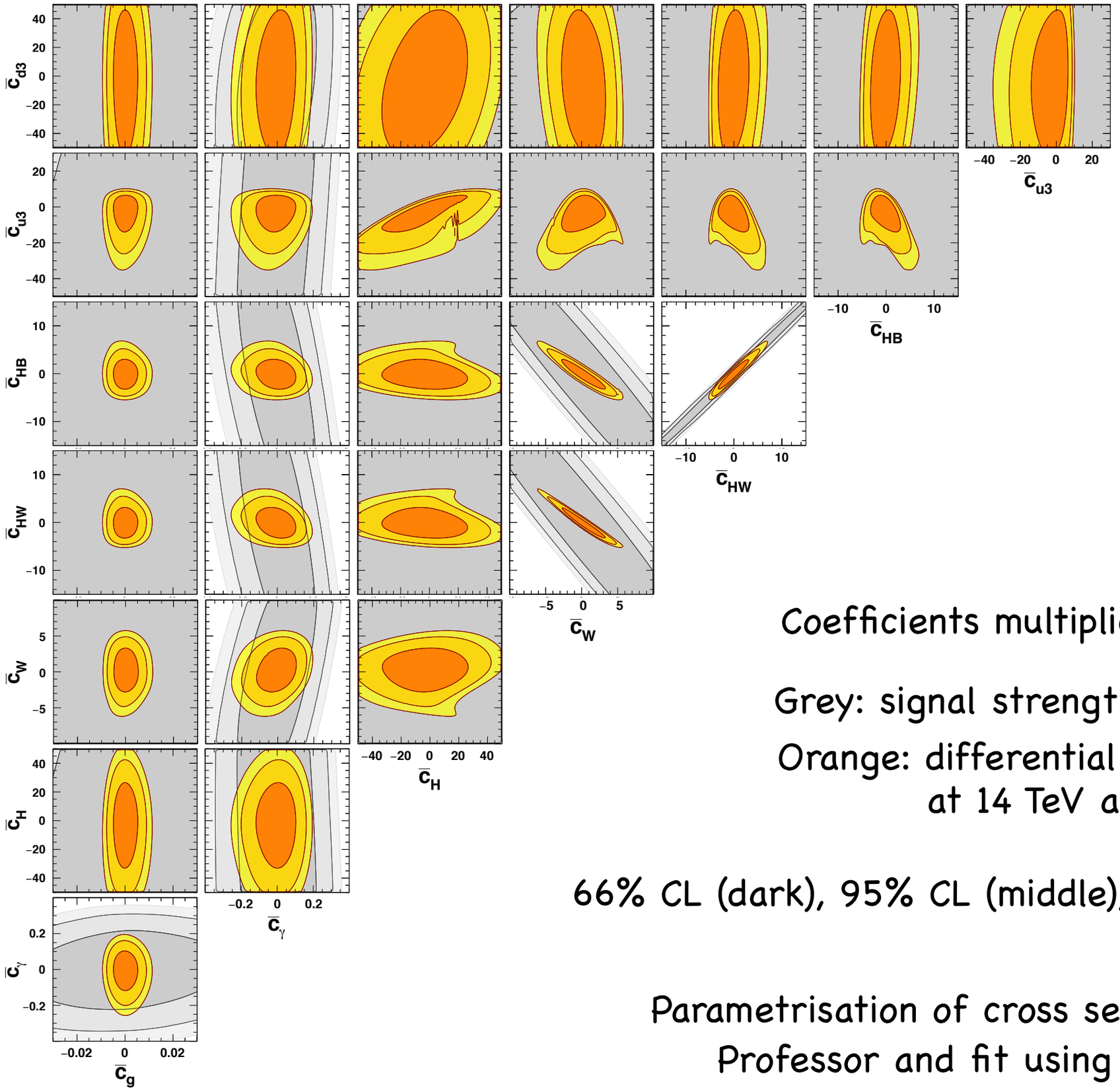


Systematic uncertainties obtained for 7/8 TeV are scaled to 14 TeV with 300 and 3000 ifb respectively by $\sqrt{\mathcal{L}_8/\mathcal{L}_{14}}$

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)

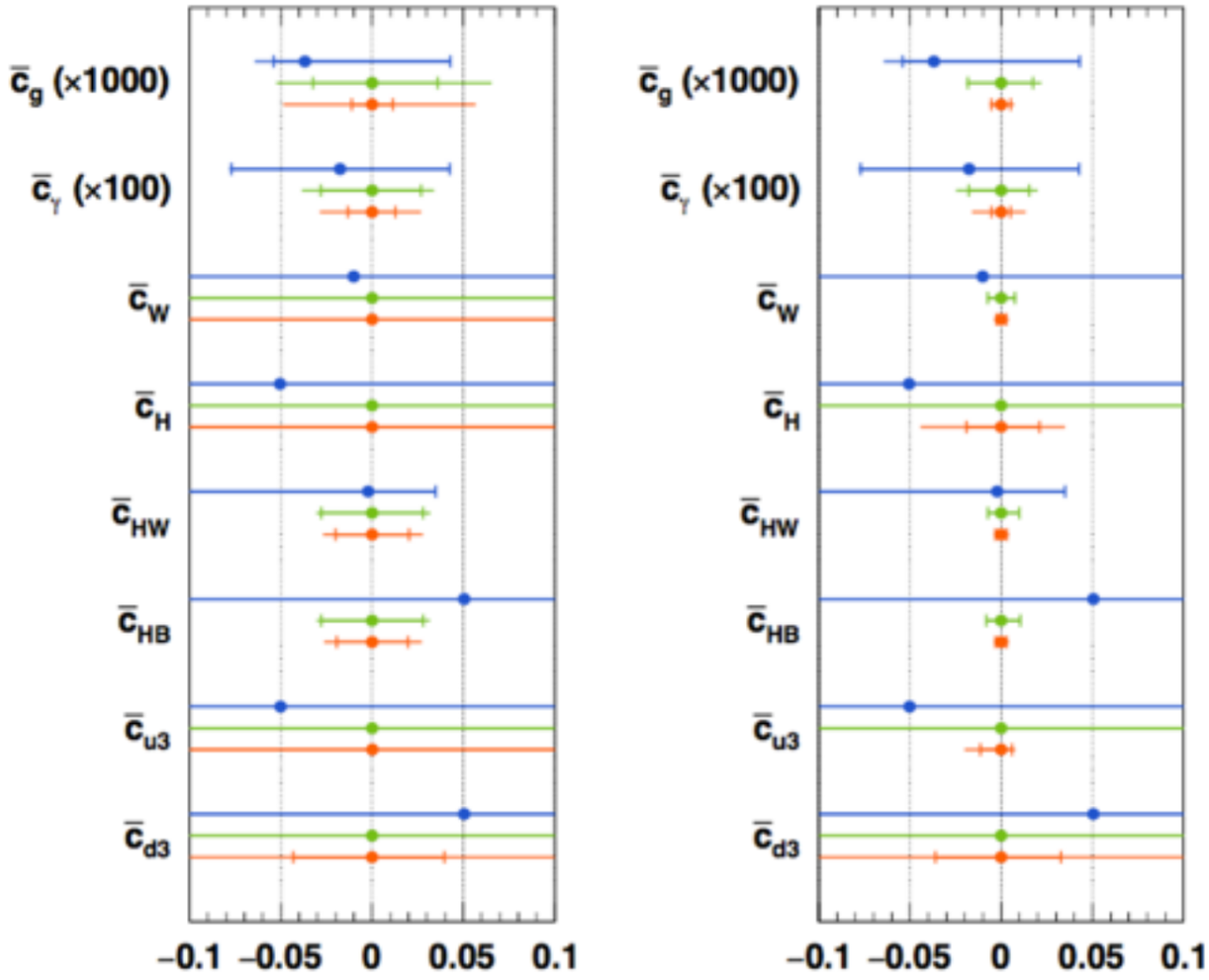
Parametrisation of cross sections with Professor and fit using Gfitter

7/8 TeV (blue)

14 TeV, 300 ifb (green)

14 TeV, 3000 ifb (orange)

Signal strength only **differential distributions**



Setup allows to address most fundamental question for high-energy physics:

- Which theory calculations most important?
- Which systematic uncertainties most limiting?
- Where can we improve knowledge most?

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:

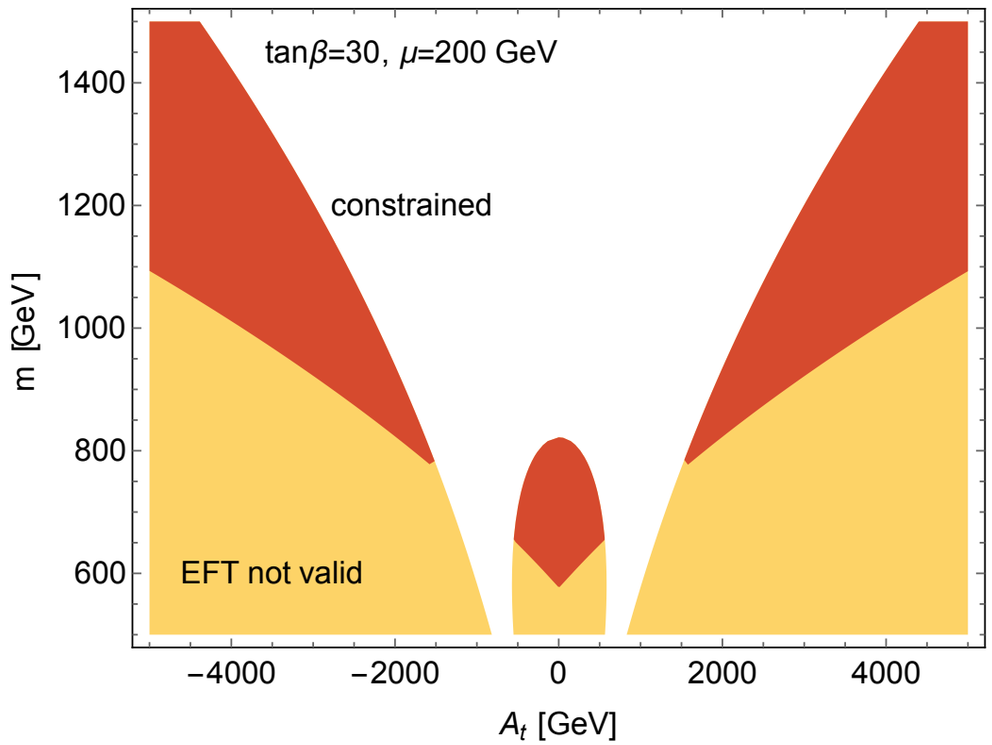
$$\bar{c}_g = \frac{m_W^2}{(4\pi)^2}\frac{1}{24}\left(\frac{h_t^2 - g_1^2 c_{2\beta}/6}{m_{\tilde{Q}}^2} + \frac{h_t^2 + g_1^2 c_{2\beta}/3}{m_{\tilde{t}_R}^2} - \frac{h_t^2 X_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2}\right)$$

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

$\tan\beta = 30$

$\mu = 200$ GeV

→ large At can be constrained

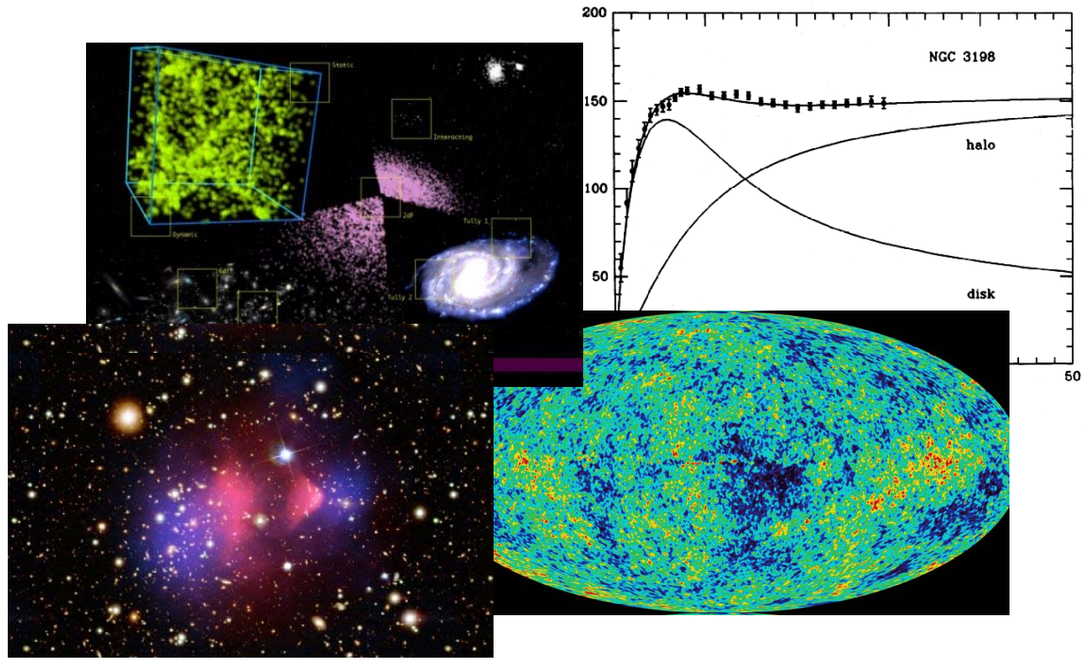


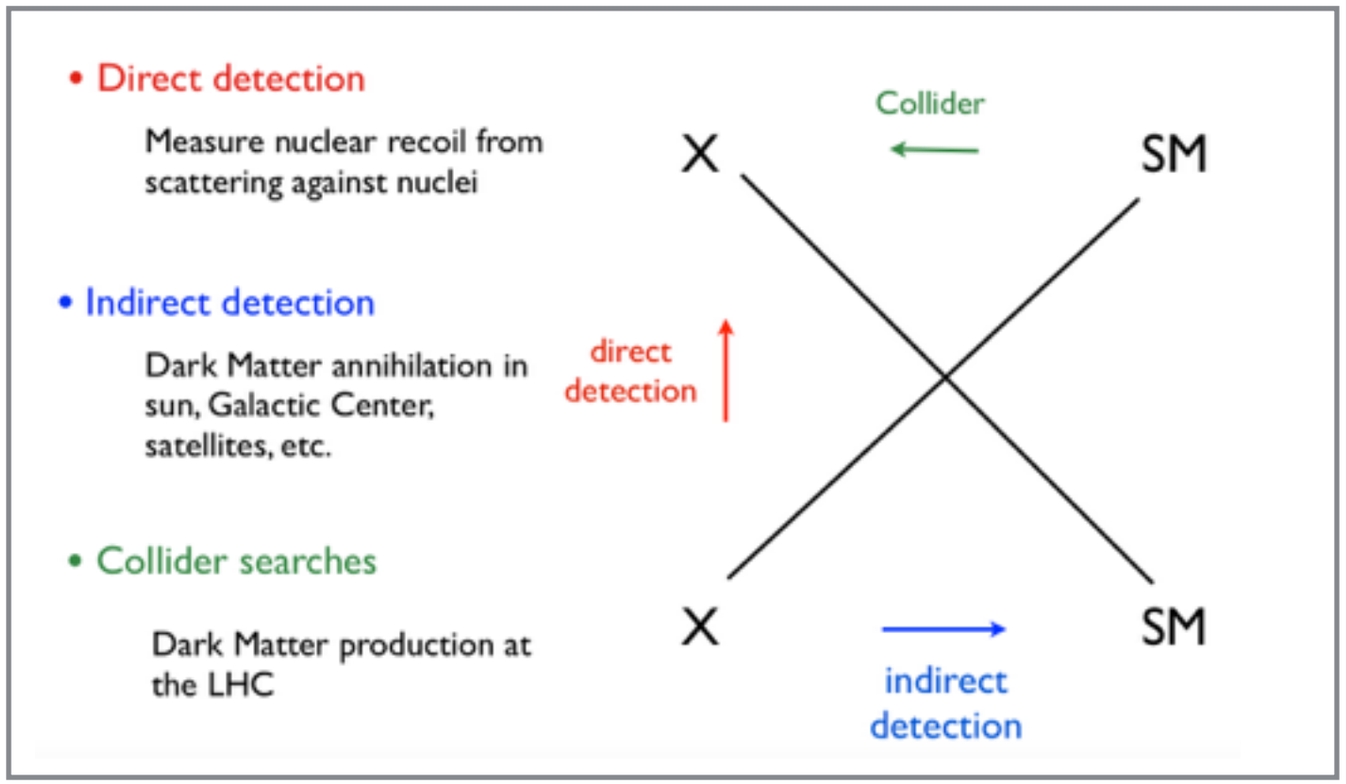
EFT language potentially inapt:

Evidence for Dark Matter overwhelming:

- Spiral Galaxy rotation curves
- Gravitational lensing
- Acoustic peaks

Higgs/Scalars and their Dark Matter relation





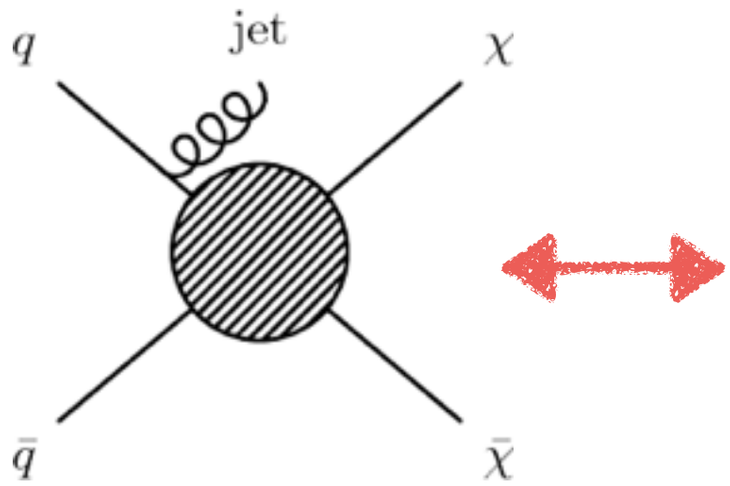
Several ways to look for Dark Matter

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

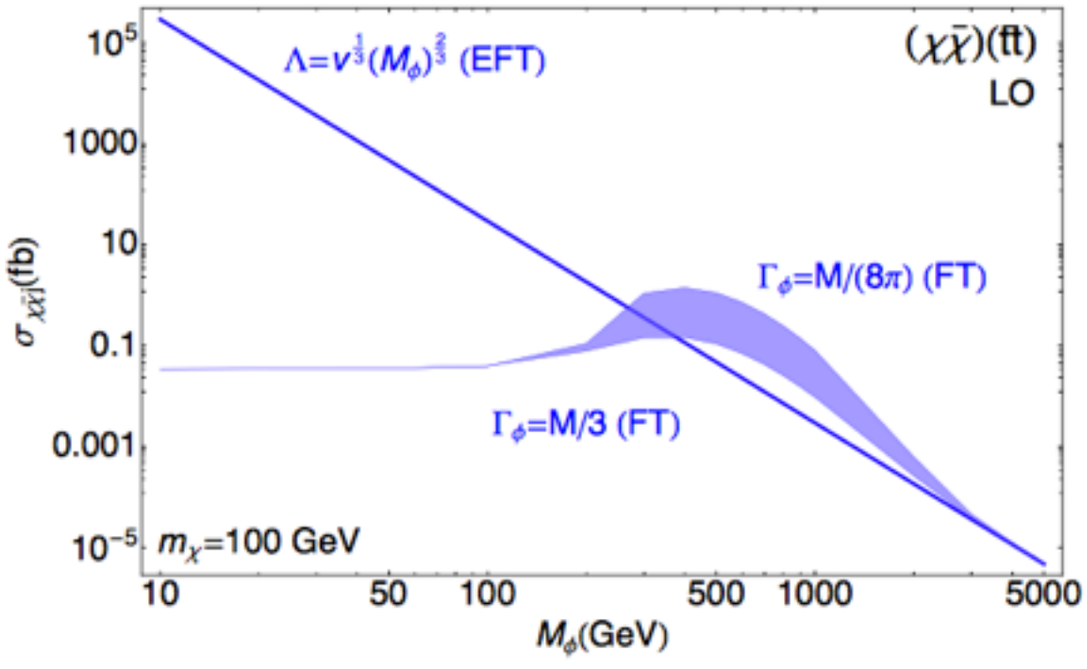
- However, only valid if interaction not resolved

Going beyond:

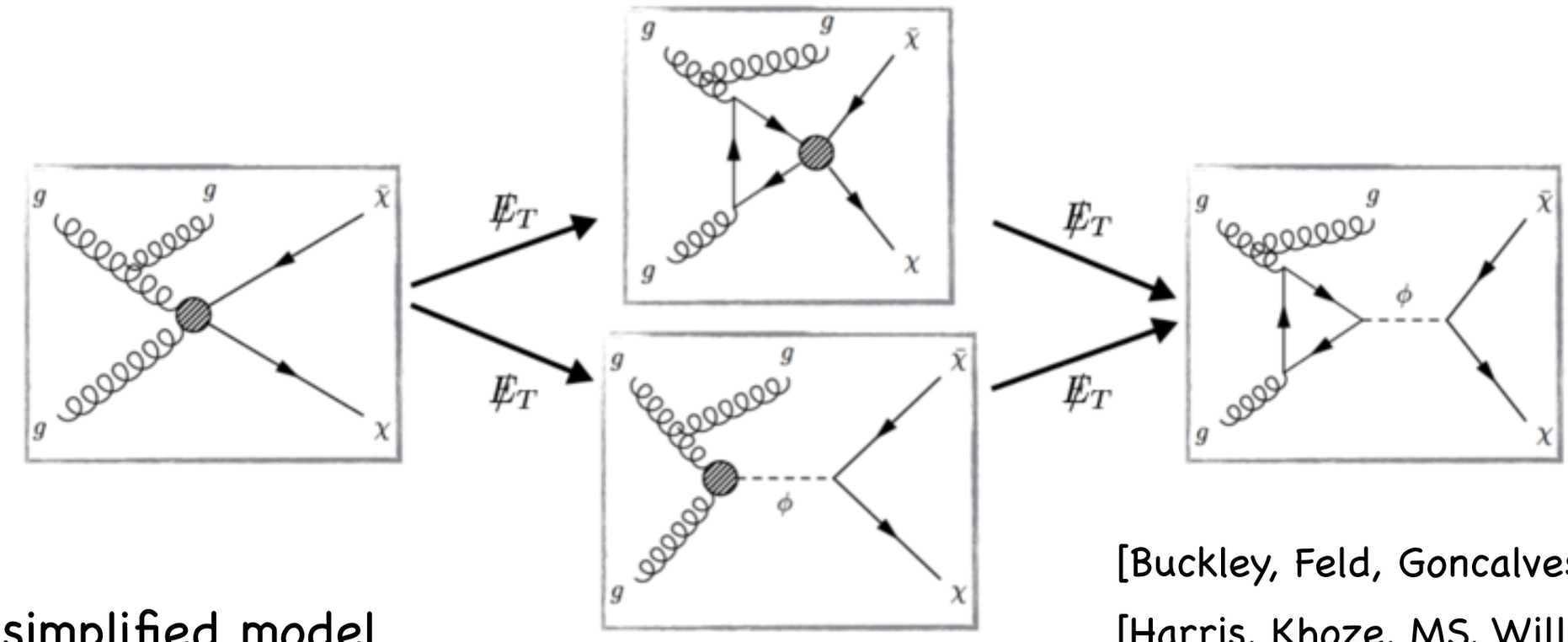
- At colliders momentum transfer too large for EFT approach

→ Need simplified models

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



Searching scalar DM-mediators in mono-jets



[Buckley, Feld, Goncalves '14]

[Harris, Khoze, MS, Williams '14]

simplified model

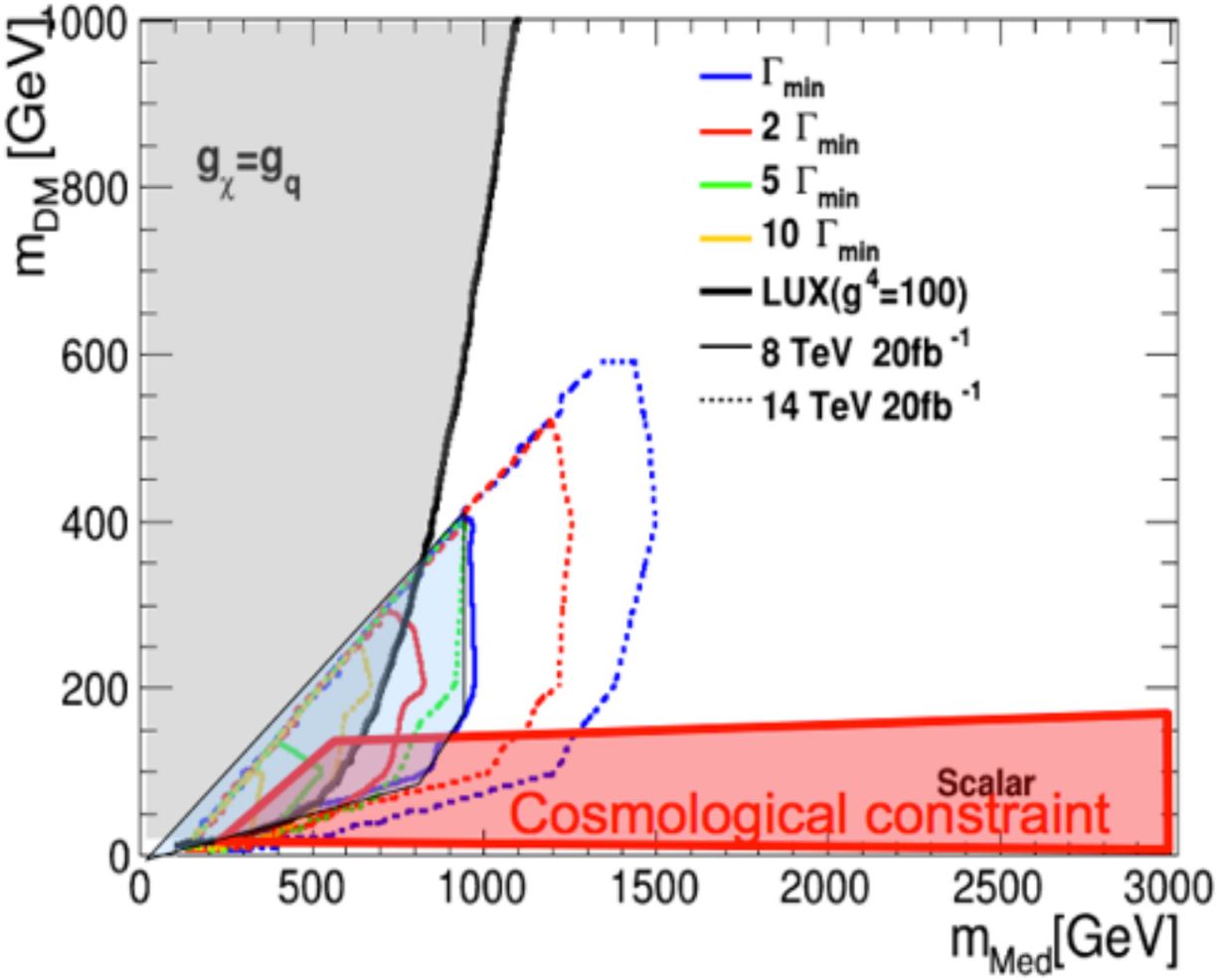
$$\mathcal{L}_{\text{pseudo-scalar}} \supset -\frac{1}{2}m_{\text{MED}}^2 P^2 - g_{\text{DM}} P\, \bar{\chi}\gamma^5\chi - g_{SM}^t P\, \bar{t}\gamma^5 t - g_{SM}^b P\, \bar{b}\gamma^5 b$$

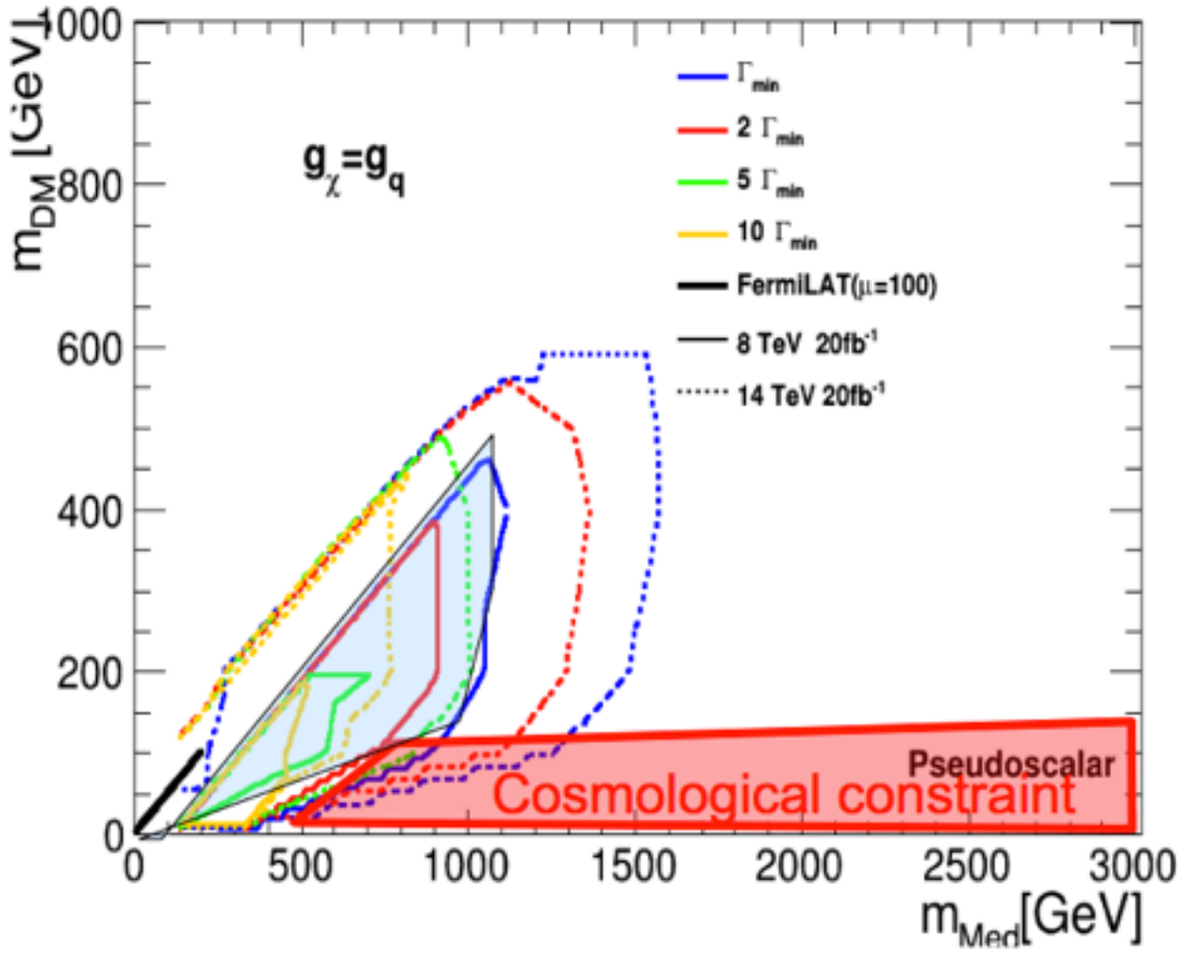
$$\mathcal{L}_{\text{scalar}} \supset -\frac{1}{2}m_{\text{MED}}^2 S^2 - g_{\text{DM}} S\, \bar{\chi}\chi - g_{SM}^t S\, \bar{t}t - g_{SM}^b S\, \bar{b}b$$

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]



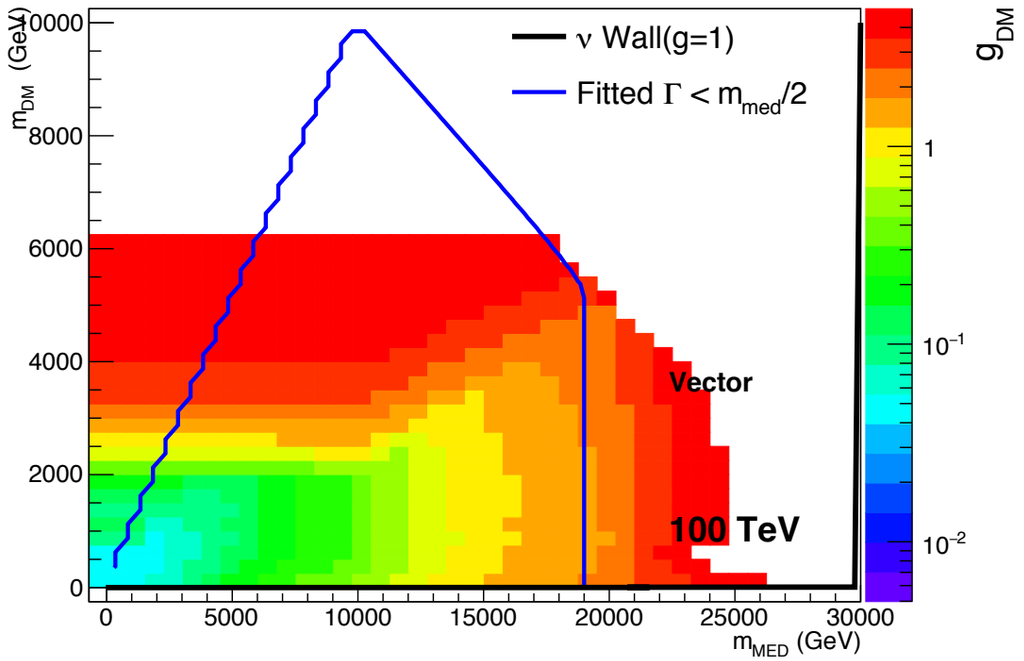


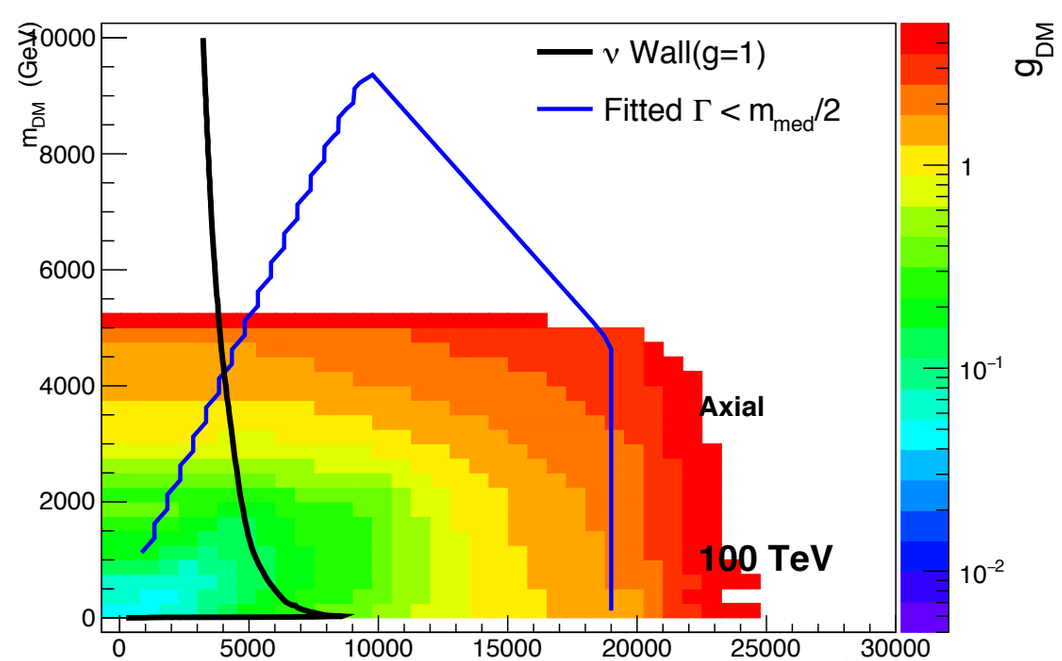
- For light Dark Matter and heavy mediators the LHC can provide complementary information to DD and ID experiments
- A joint effort of all possible ways to look for (coy) Dark Matter is needed to maximize our chances to find it

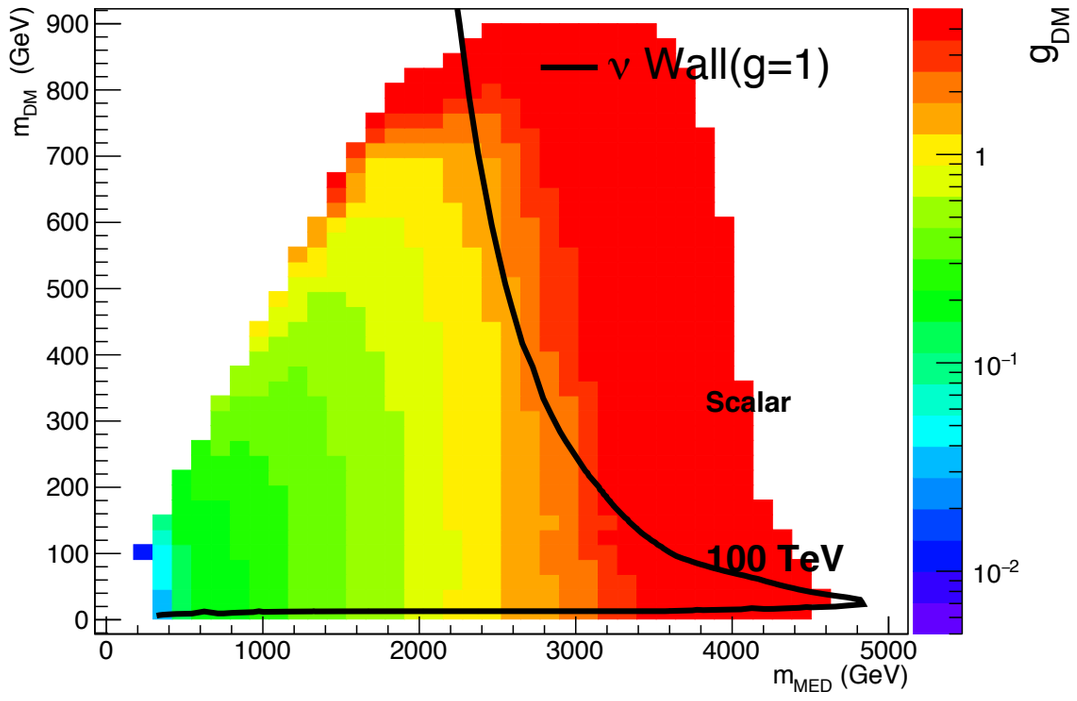
[Boehm, Dolan, McCabe, MS, Wallace '14]

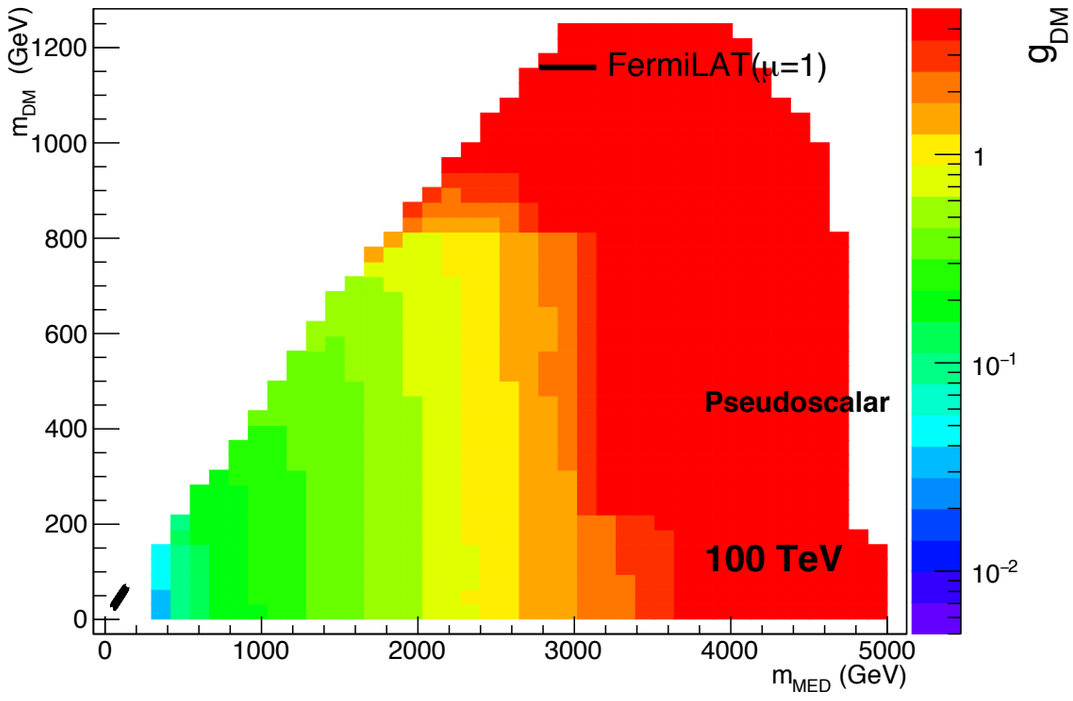
Expectations at 100 TeV pp

[Harris, Khoze, MS, Williams '15]

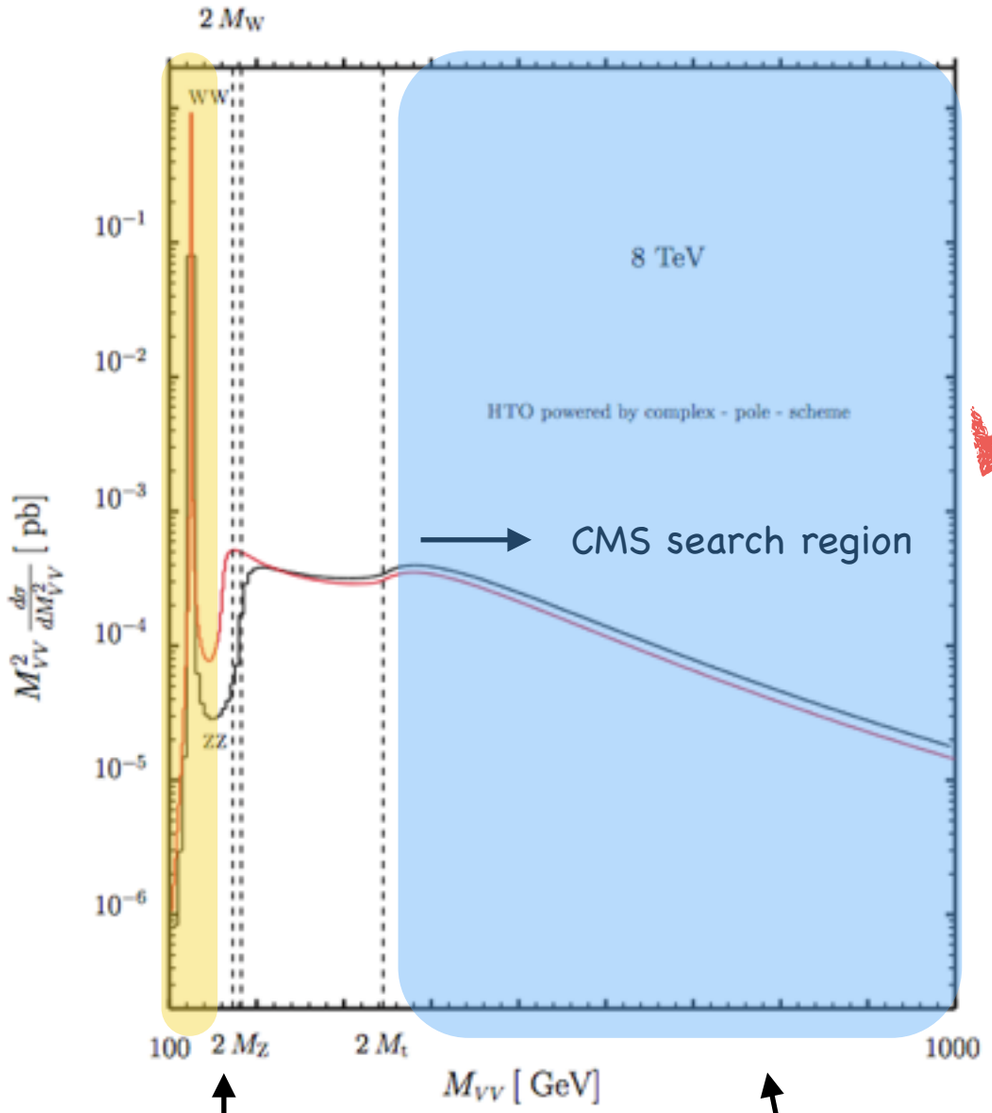


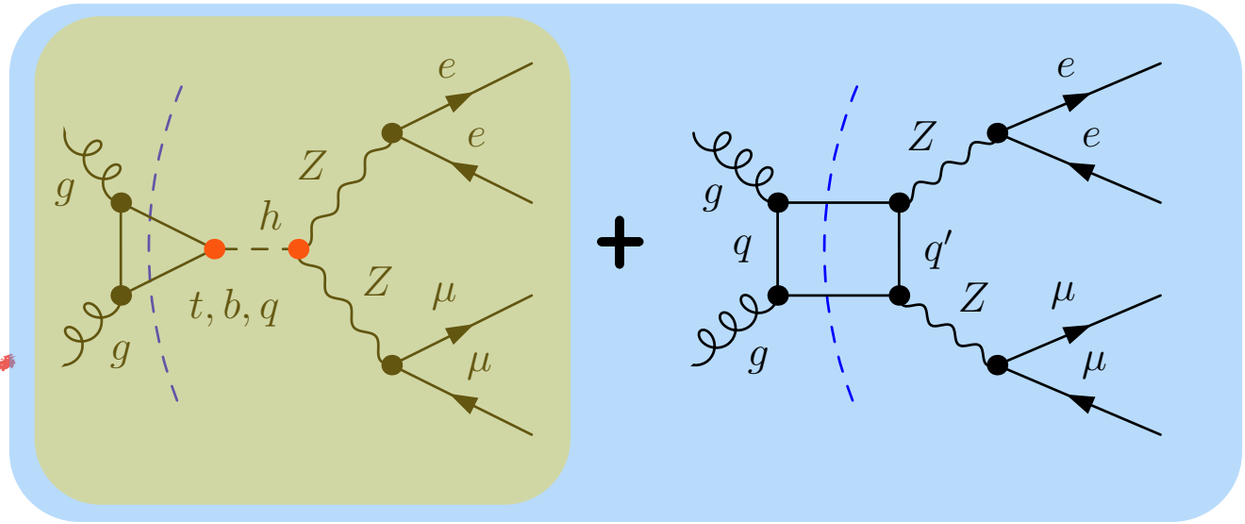






Chosen language affects answer: CMS 'width' Measurement





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

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

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

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

$\Gamma_H < 4.2(8.5)\ \Gamma_H^{SM}$

$\Gamma_H < 17.4\ (35.3)$ MeV

[Kauer, Passarino 2011]

[Caola, Melnikov 2013]

Example 'width-measurement'

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

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

Kappa Framework

- Assuming global coupling rescaling

EFT

- Assuming valid and no flat directions

Coupling assumptions strong
LEP limits stronger than LHC

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

[Englert, McCullough, MS '15]

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

- Uninteresting width not a free parameter of the theory

  width derived and fully determined

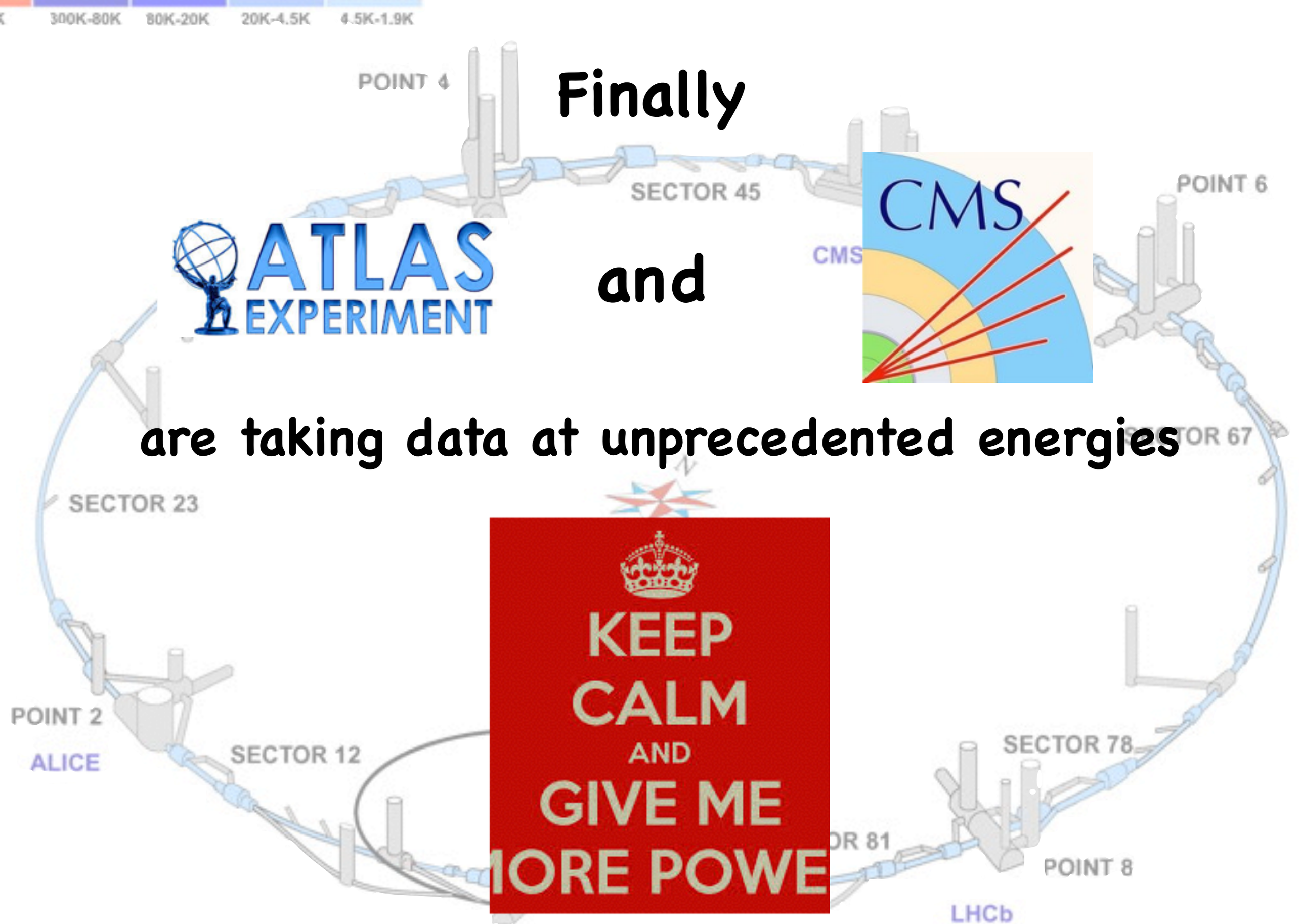
Finally

ATLAS EXPERIMENT

and

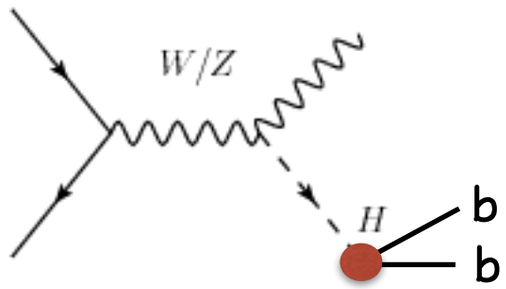
CMS

are taking data at unprecedented energies



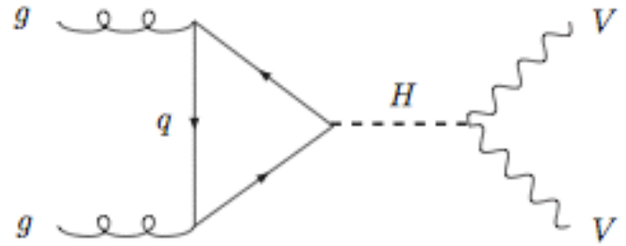
Energetic final states not only important for effective couplings

Higgs-bottom coupling



[Butterworth, Davison, Rubin, Salam '08]

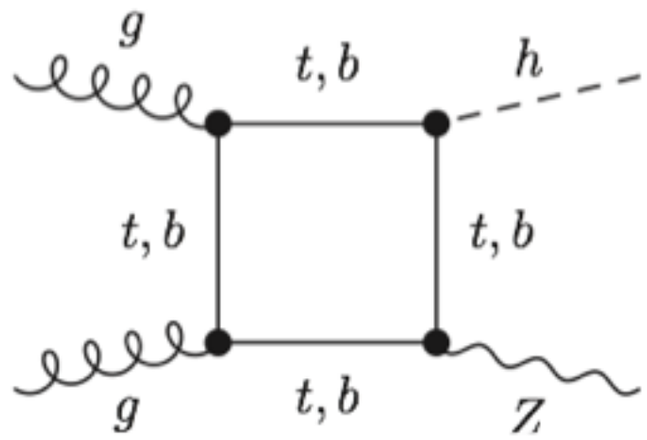
Off-shell Higgs (Width)



[Kauer, Passarino '12]

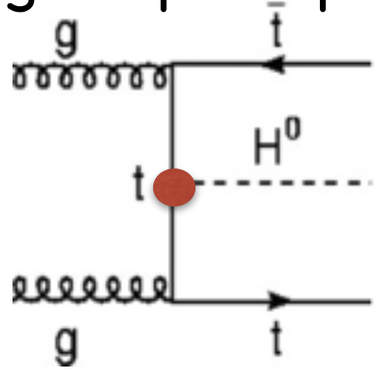
[Caola, Melnikov '14]

HZ final state



[Englert, McCullough, MS '13]

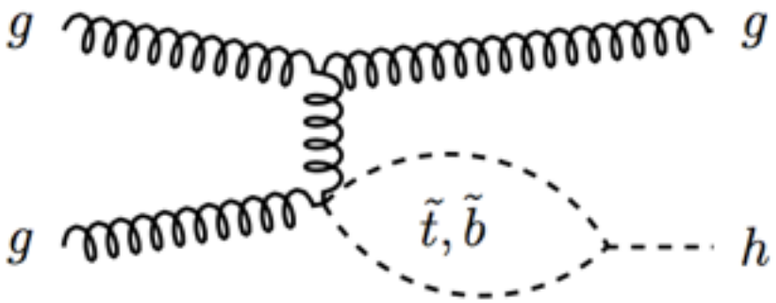
Higgs-top coupling



[Plehn, Salam, MS '09]

[Moretti, Petrov, Pozzorini, MS '15]

Boosted Higgs in H+jet

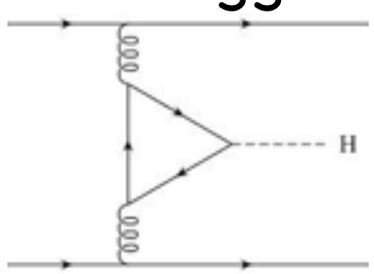


[Harlander, Neumann '13]

[Banfi, Martin, Sanz '13]

[Grojean, Salvioni, Schlaffer Weiler '14]

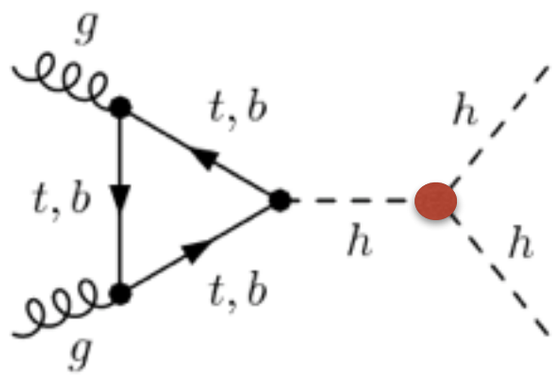
CP Higgs



[Plehn, Rainwater, Zeppenfeld '01]

[Klamke, Zeppenfeld '07]

Higgs selfcoupling



[Baur, Plehn, Rainwater '02 '03]

[Dolan, Englert, MS '12 '12]

[Baglio et al '13]

Observations:

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

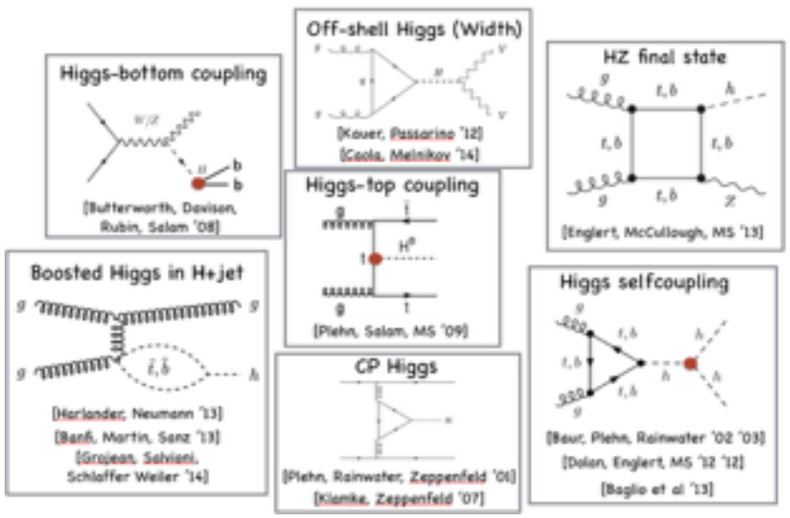
- The information extracted depends on the 'picture', i.e. hypothesis, we compare with nature

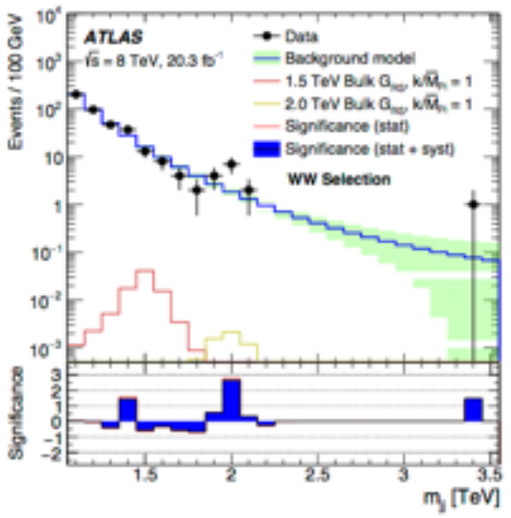
- The more precise the picture is we have in mind, the more precise will be the answer on the question of interest



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]

The matrix element method in a nutshell:

Given a theoretical assumption α, attach a weight $P(\mathbf{x}, \alpha)$ to each experimental event **x** quantifying the validity of the theoretical assumption for this event.

$$P(\mathbf{x}, \alpha) = \frac{1}{\sigma} \int d\phi(\mathbf{y}) |M_\alpha|^2(\mathbf{y}) W(\mathbf{x}, \mathbf{y})$$

$|M_\alpha|^2$ is squared matrix element

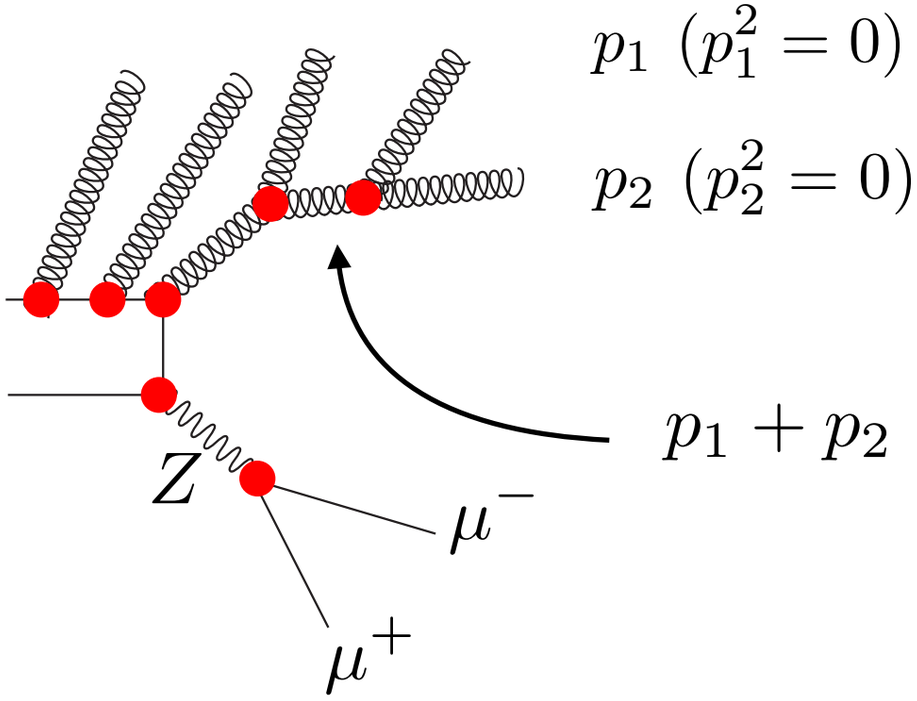
$W(\mathbf{x}, \mathbf{y})$ is the resolution or transfer function

$d\phi(\mathbf{y})$ is the parton-level phase-space measure

The value of the weight $P(\mathbf{x}, \alpha)$ is the probability to observe the experimental event **x** in the theoretical frame α

Parton shower in a nutshell

The parton shower bridges the gap from the hard interaction scale down to the hadronization scale O(1) GeV



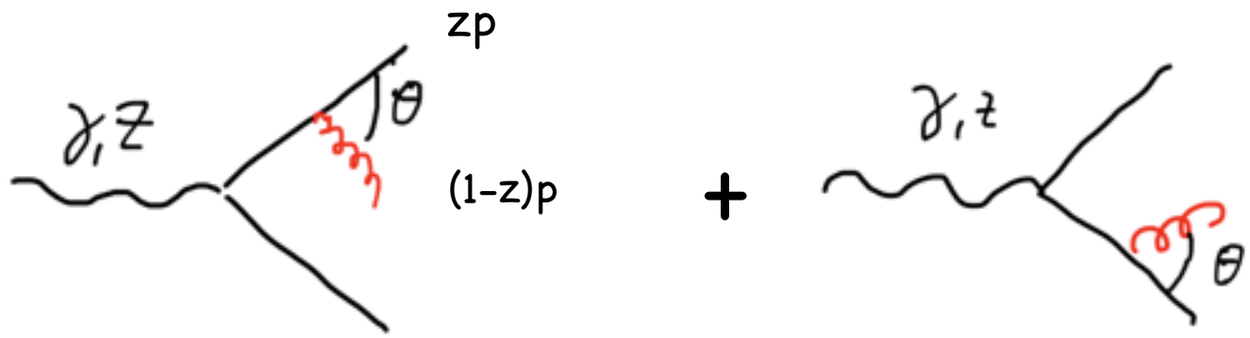
partons from the hard interaction emit other partons (gluons and quarks)

These emissions are enhanced if they are collinear and/or soft with respect to the emitting parton

Probability enhanced in soft and collinear region due to ~ $1/(p_1 + p_2)^2$

- If $p_1 \to 0$, then $1/(p_1 + p_2)^2 \to \infty$
- If $p_2 \to 0$, then $1/(p_1 + p_2)^2 \to \infty$
- If $p_2 \to \lambda p_1$, then $1/(p_1 + p_2)^2 \to \infty$

Shower approximation



Collinear limit:

$$d\sigma_{ee\to 3j} \approx \sigma_{ee\to 2j} \sum_{j\in\{q,\bar{q}\}} \frac{\alpha_s}{2\pi} \frac{d\theta_{jg}^2}{\theta_{jg}^2} P(z)$$

$$P_{q\to qg} = C_F \frac{1+z^2}{1-z} \qquad P_{g\to gg} = C_A \frac{(1-z(1-z))^2}{z(1-z)} \qquad P_{g\to q\bar{q}} = T_R n_f (z^2+(1-z)^2)$$

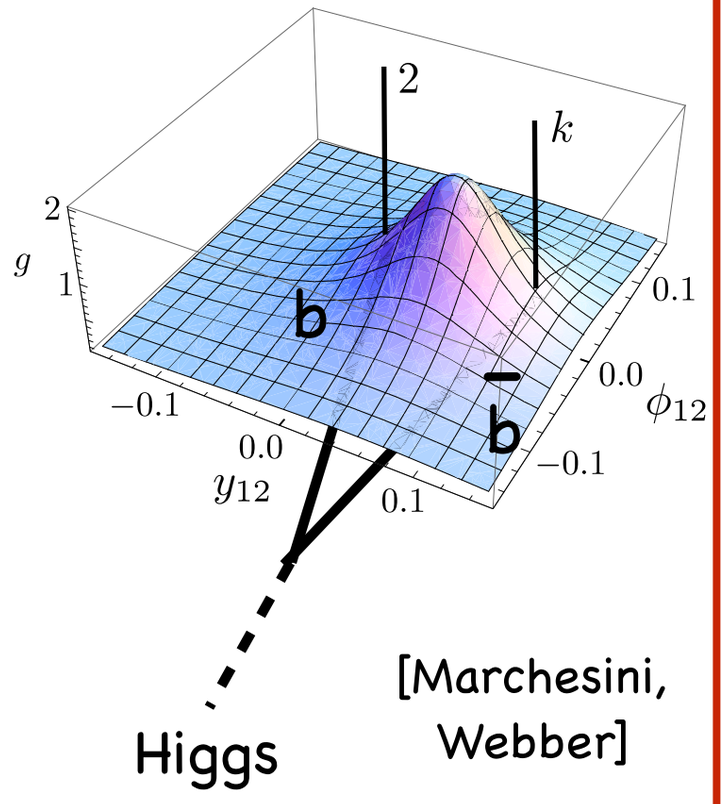
Soft limit: $E_g \to 0$ $\quad k^\mu \ll p_i^\mu$ the matrix element for

$e^+e^- \to \bar{q}qg$ factorizes (Eikonal Current)

↓ dipole

$$|\mathcal{M}_{q\bar{q}g}|^2 = |\mathcal{M}_{q\bar{q}}|^2 g_s^2 C_F \frac{2p_1\cdot p_2}{p_1\cdot k\ p_2\cdot k}$$

In the large Nc limit most radiation occurs in a cone between colour partners

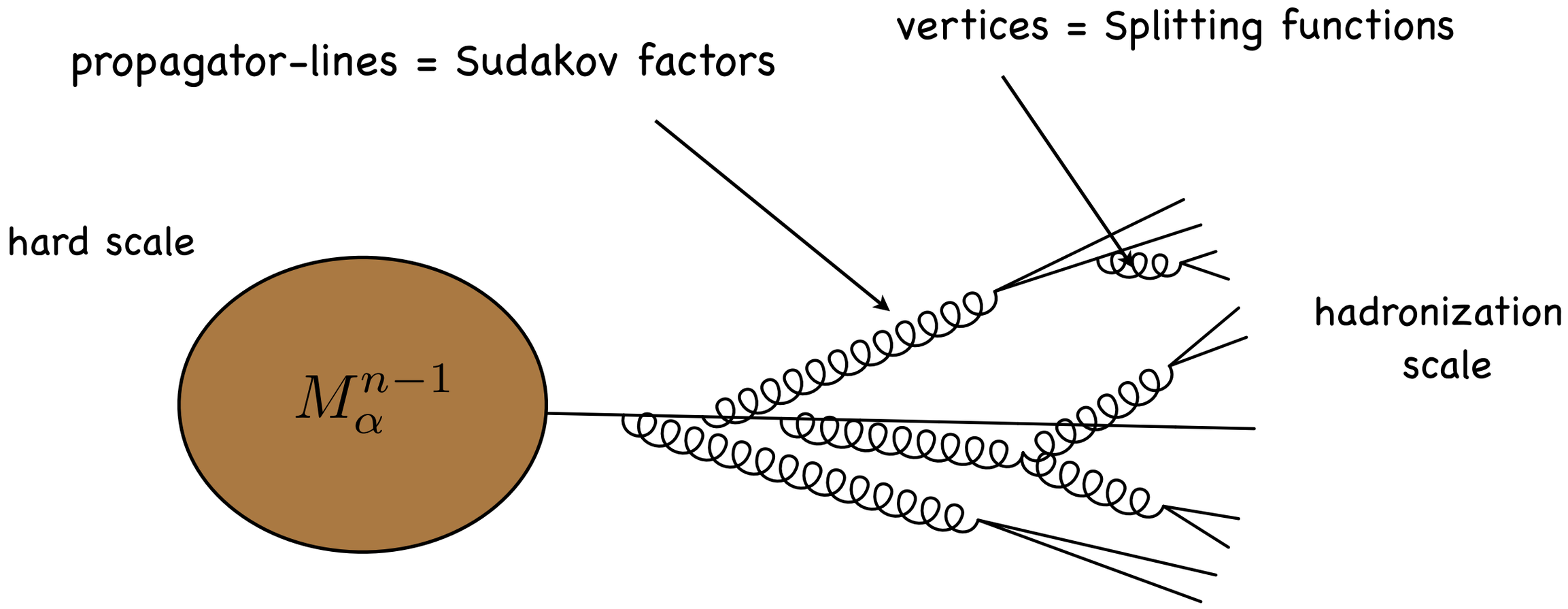


[Marchesini, Webber]

In summary:

Perform resummation calculation to discriminate between signal and background

The probability weights in the evolution from the hard interaction scale to the hadronization scale are given by Sudakov factors and splitting functions.



Tagging = Identify Object

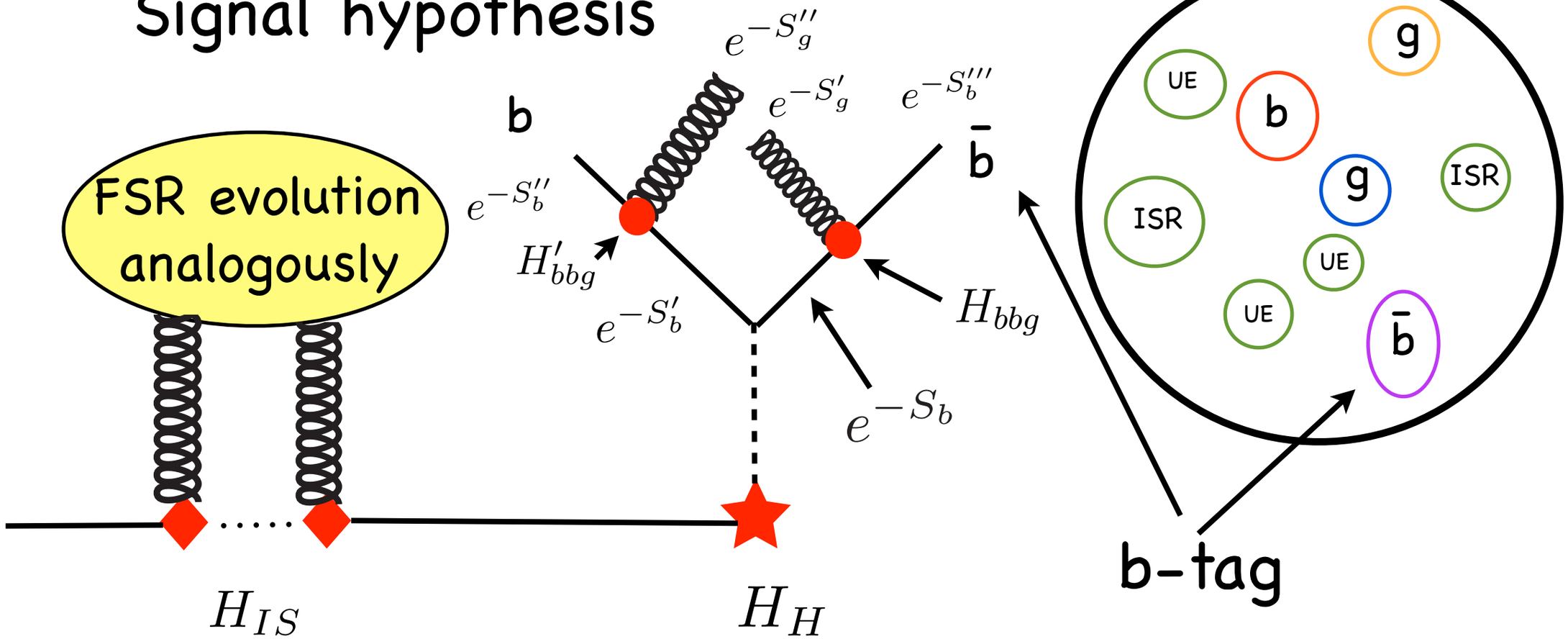
Identification exploits fact that quantum numbers of signal resonance different than backgrounds

Quantum numbers are: mass, colour, spin, couplings (width)

-> we need to construct observables which indicate different QN

Higgs: (125 GeV, 0, 0, 4 MeV) → Simplest! Success of BDRS
W/Z: (80-90 GeV, 0, 1, ~2 GeV) → Spin correlations
top: (170 GeV, 1/3, 1/2, ~2 GeV) → Only EW scale colored object

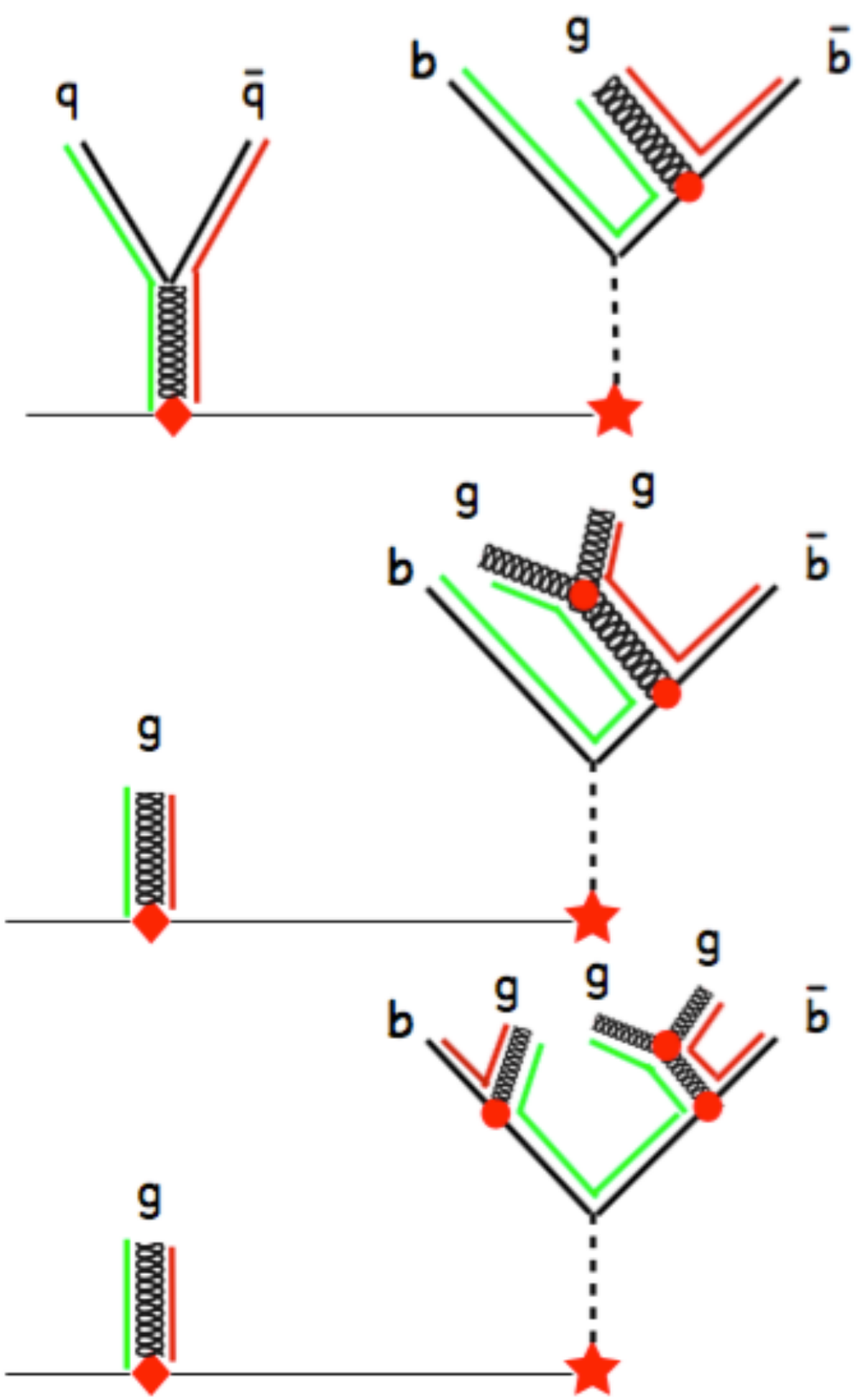
Signal hypothesis

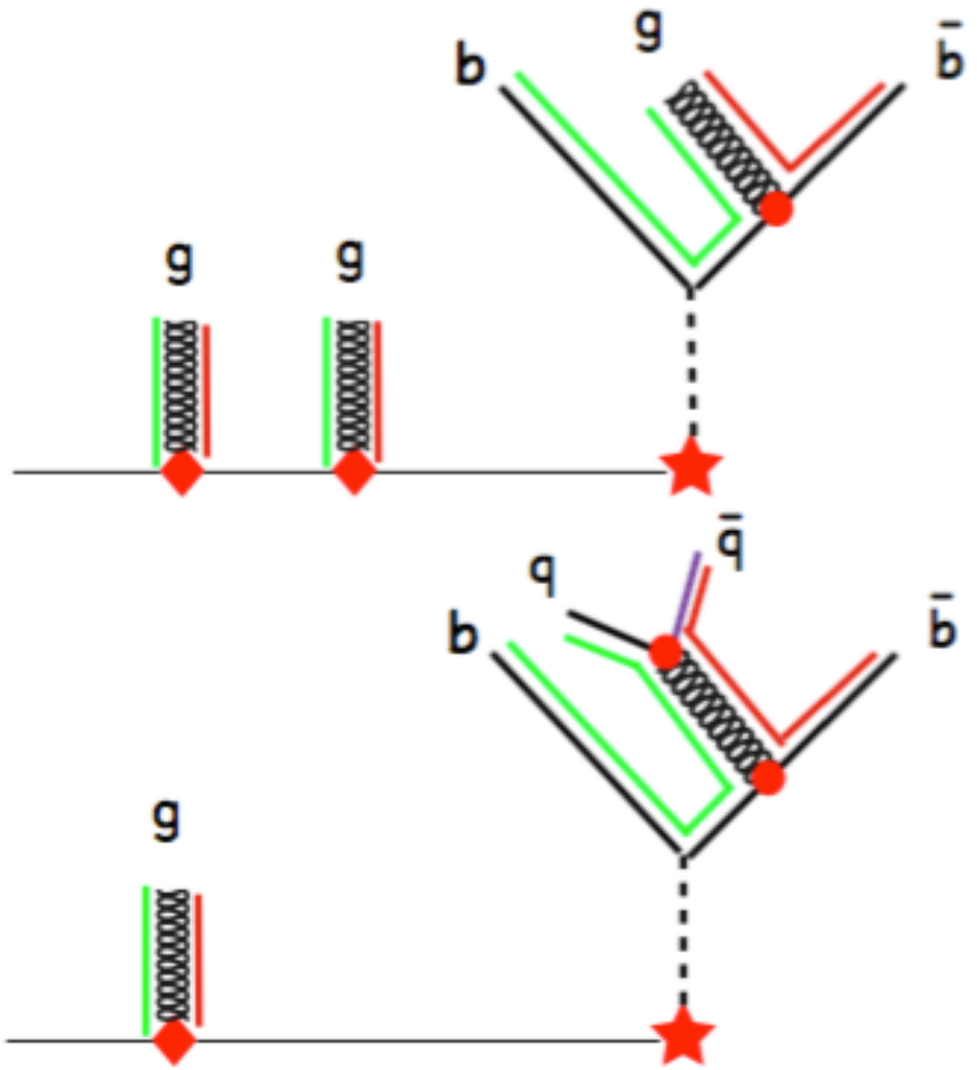


Wrapping up all factors gives weight for shower history

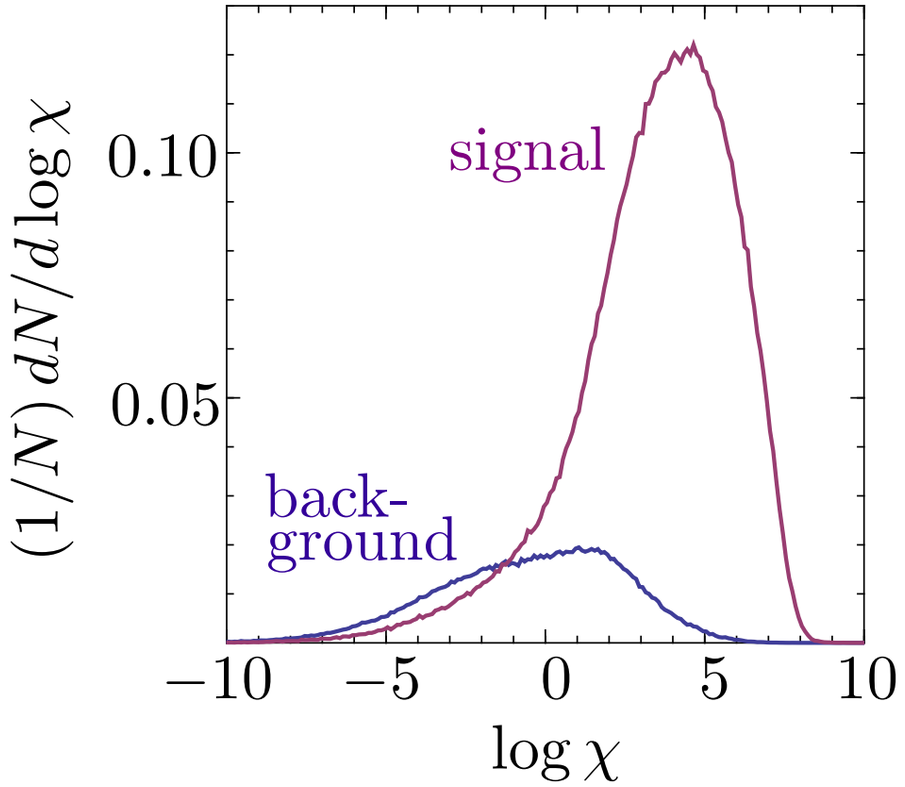
$$\chi = \frac{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_\mathrm{j} \mathrm{Signal_j}\right)}{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_\mathrm{j} \mathrm{Backg_j}\right)}$$

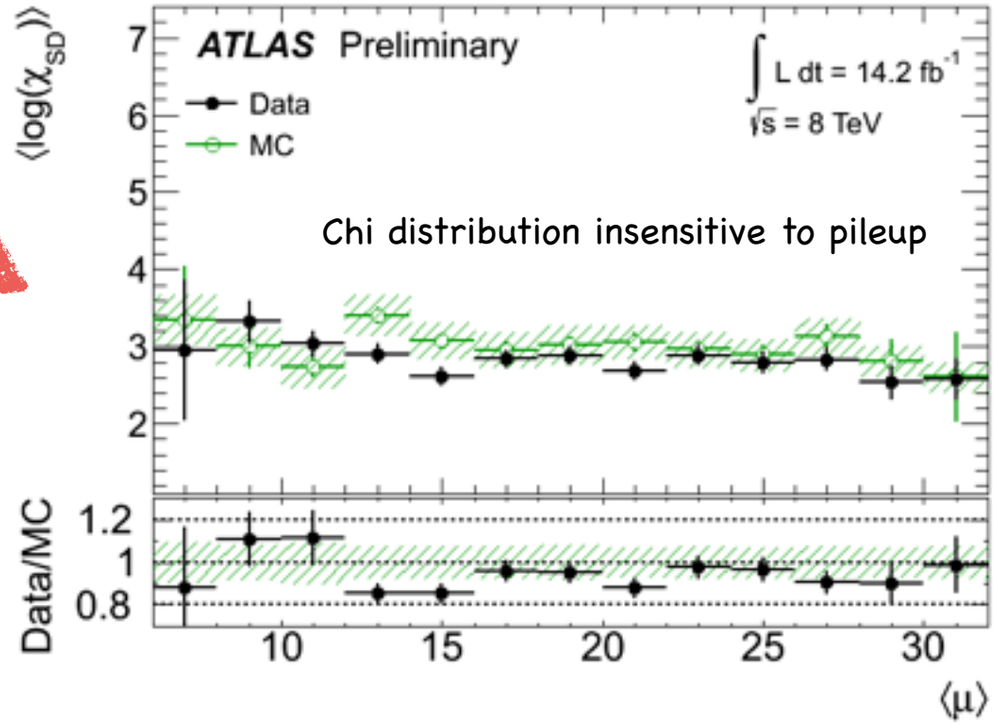
Here $\mathrm{Signal_1} = \mathrm{H_H H_{split} e^{-S_{split}} H_{bbg} e^{-S'_b} e^{-S'''_b} e^{-S'_g} H'_{bbg} e^{-S''_b} e^{-S_b} e^{-S''_g}}$



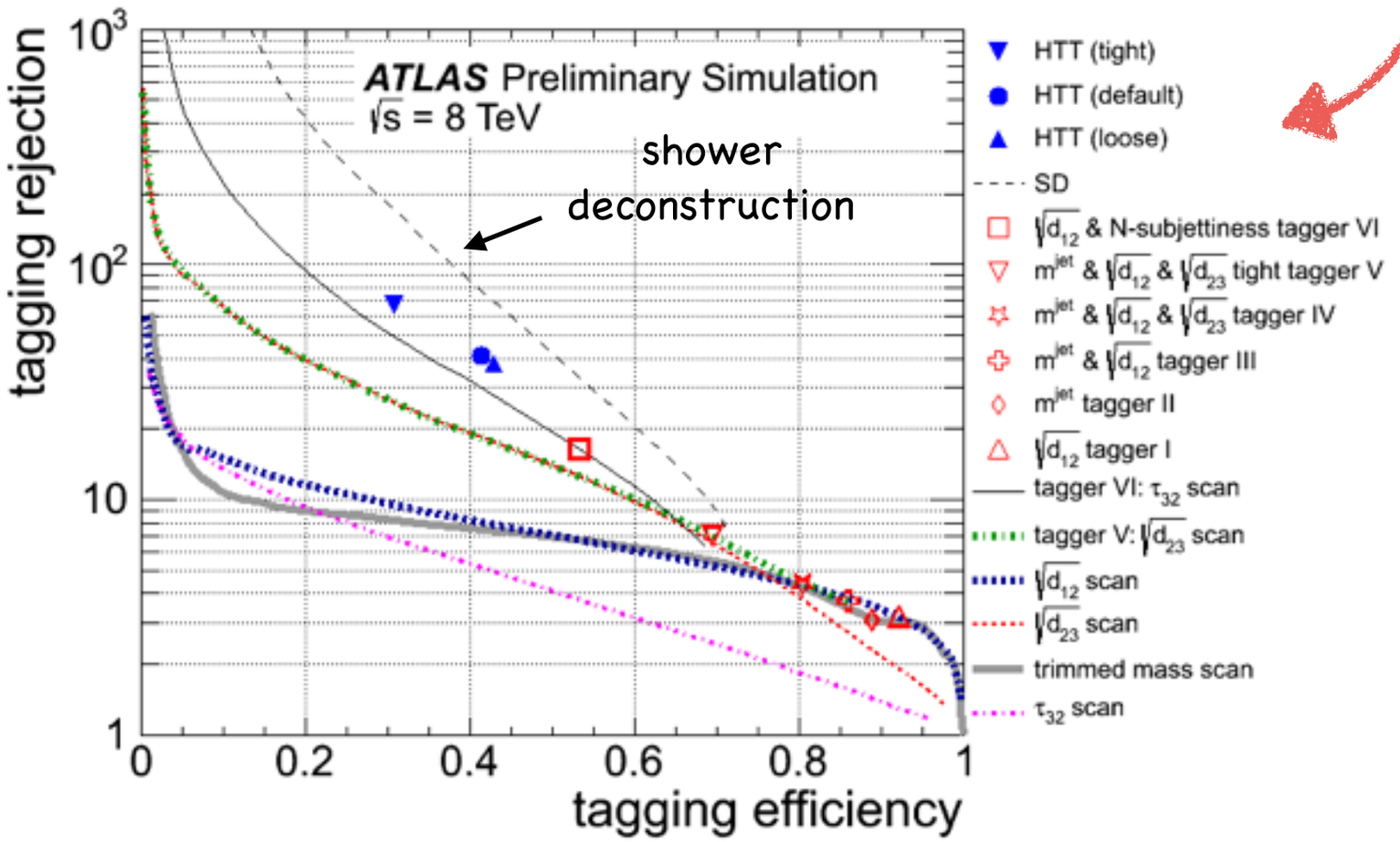


- And many more...
- And for all backgrounds...

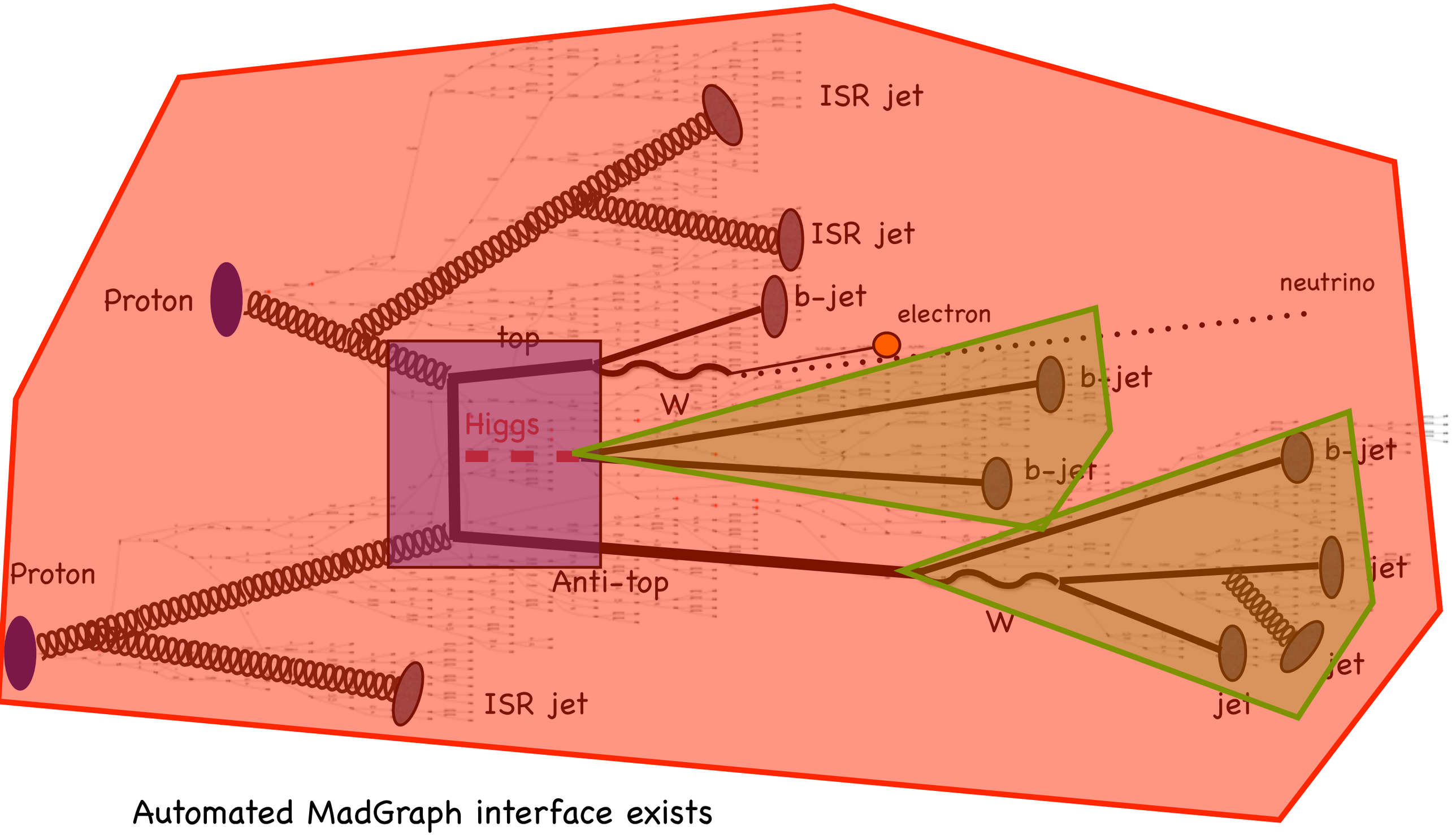




Shower deconstruction improves on best taggers by factor 2-4 in S/B



Event Deconstruction = Matrix. Method + Shower Deconstruction



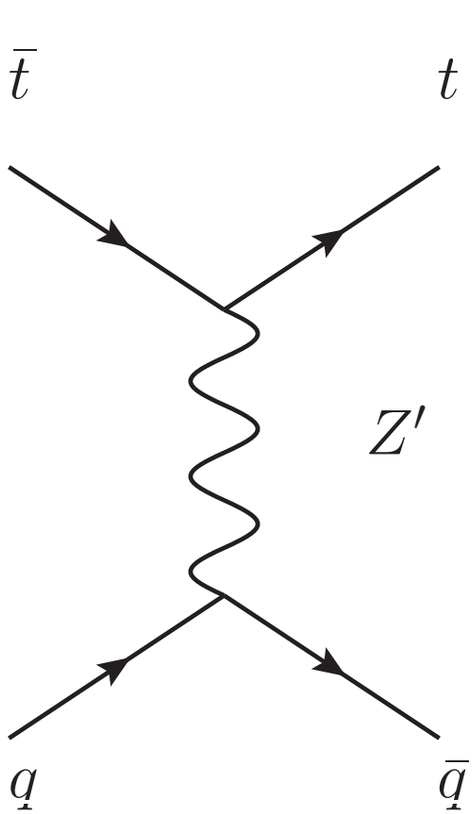
Automated MadGraph interface exists

First application of Event Deconstruction

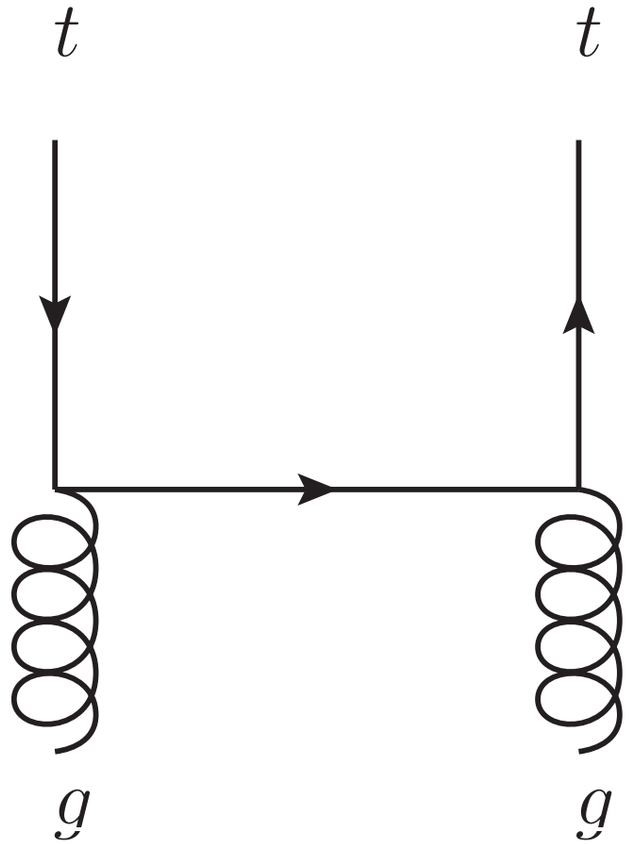
[Soper, MS '14]

fully hadronic Z' -> tt

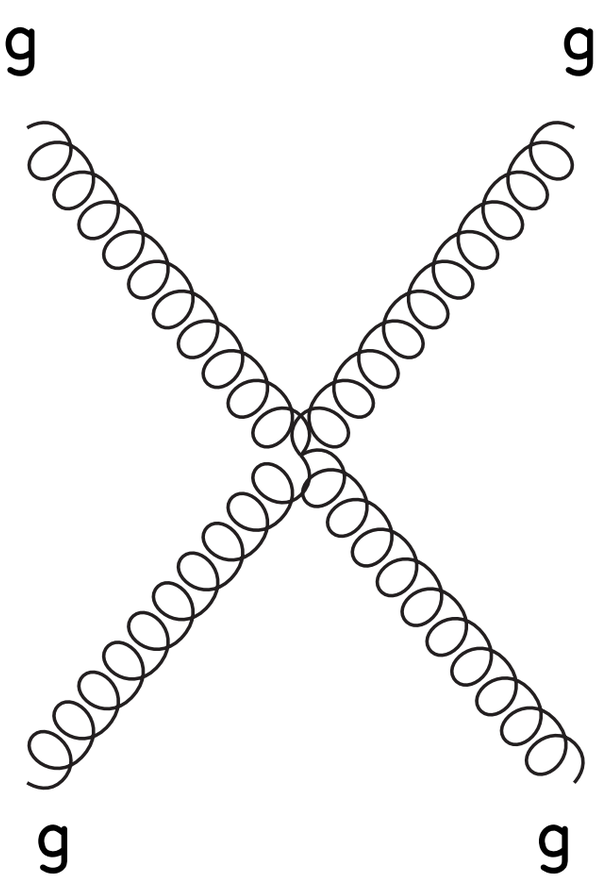
Signal



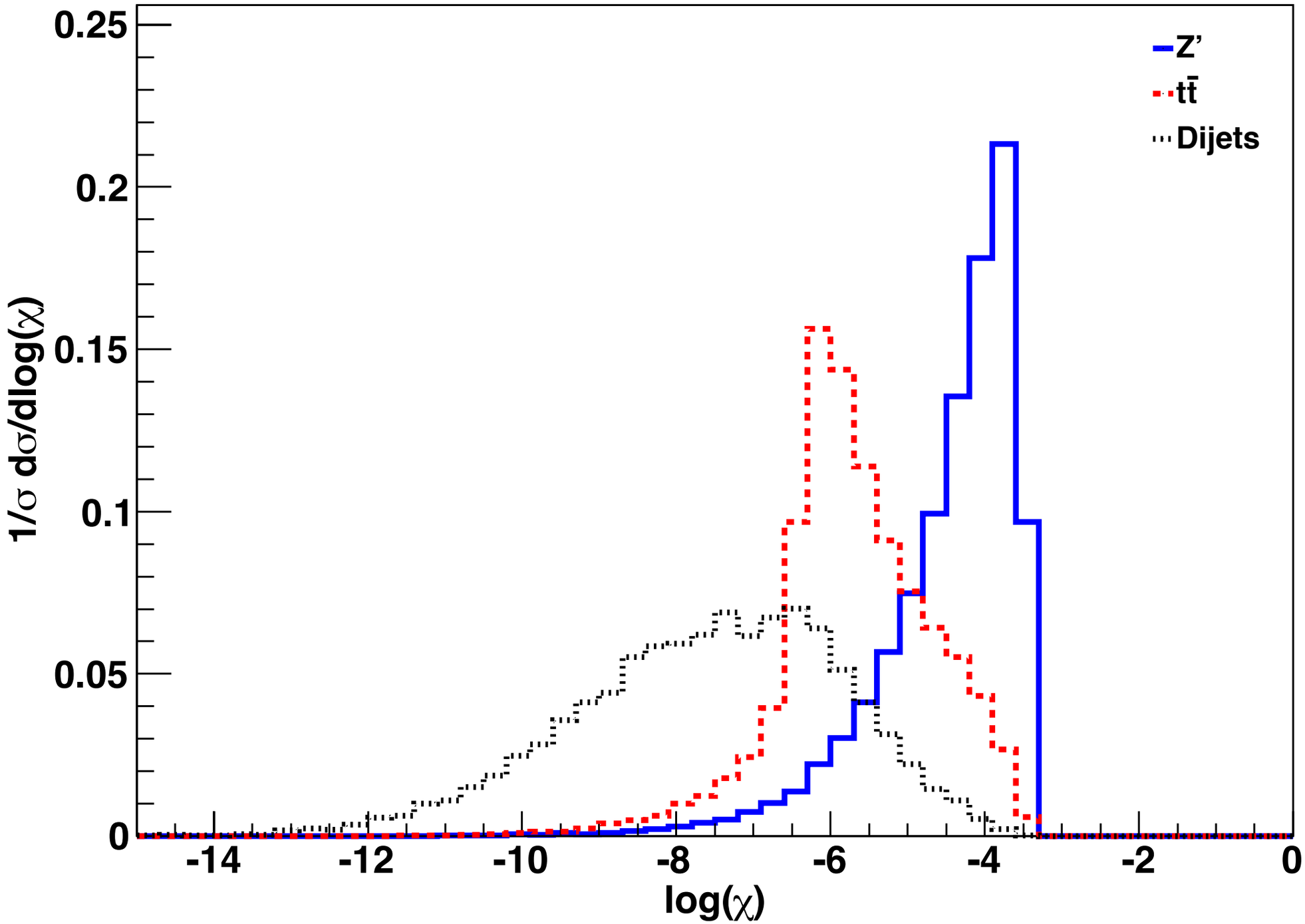
$t\bar{t}$

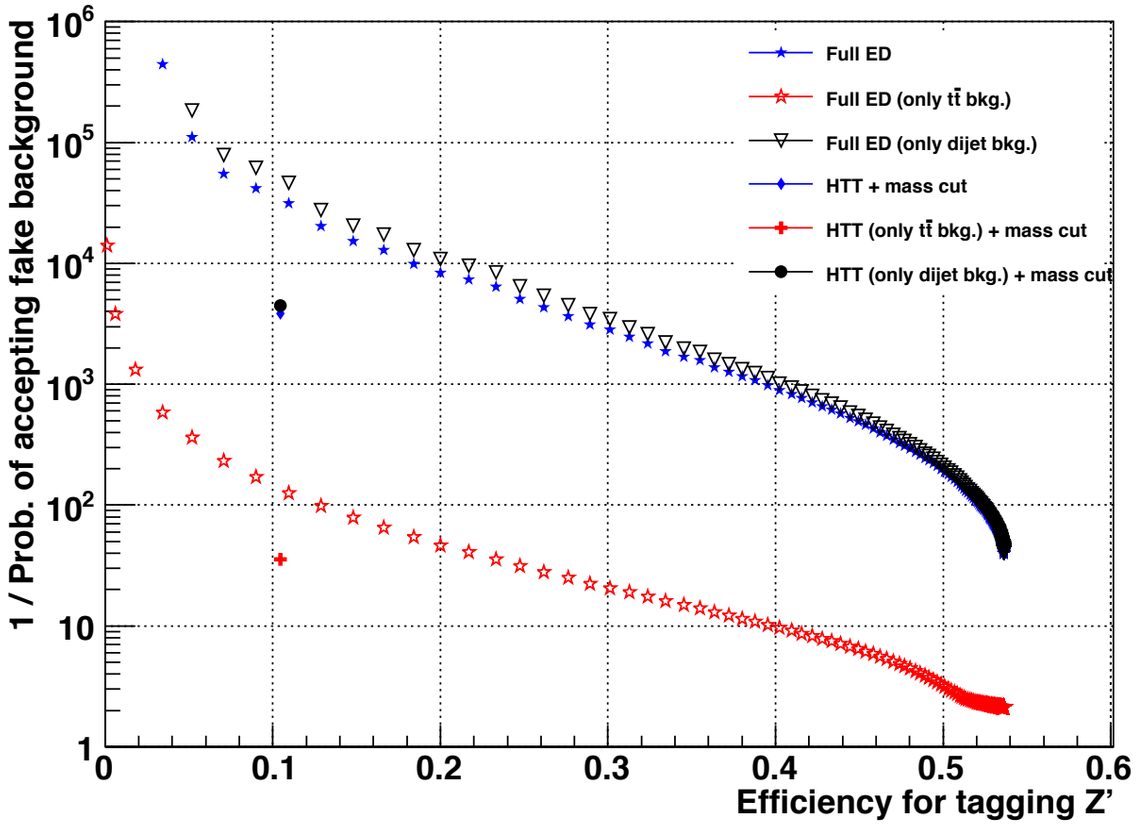


dijets

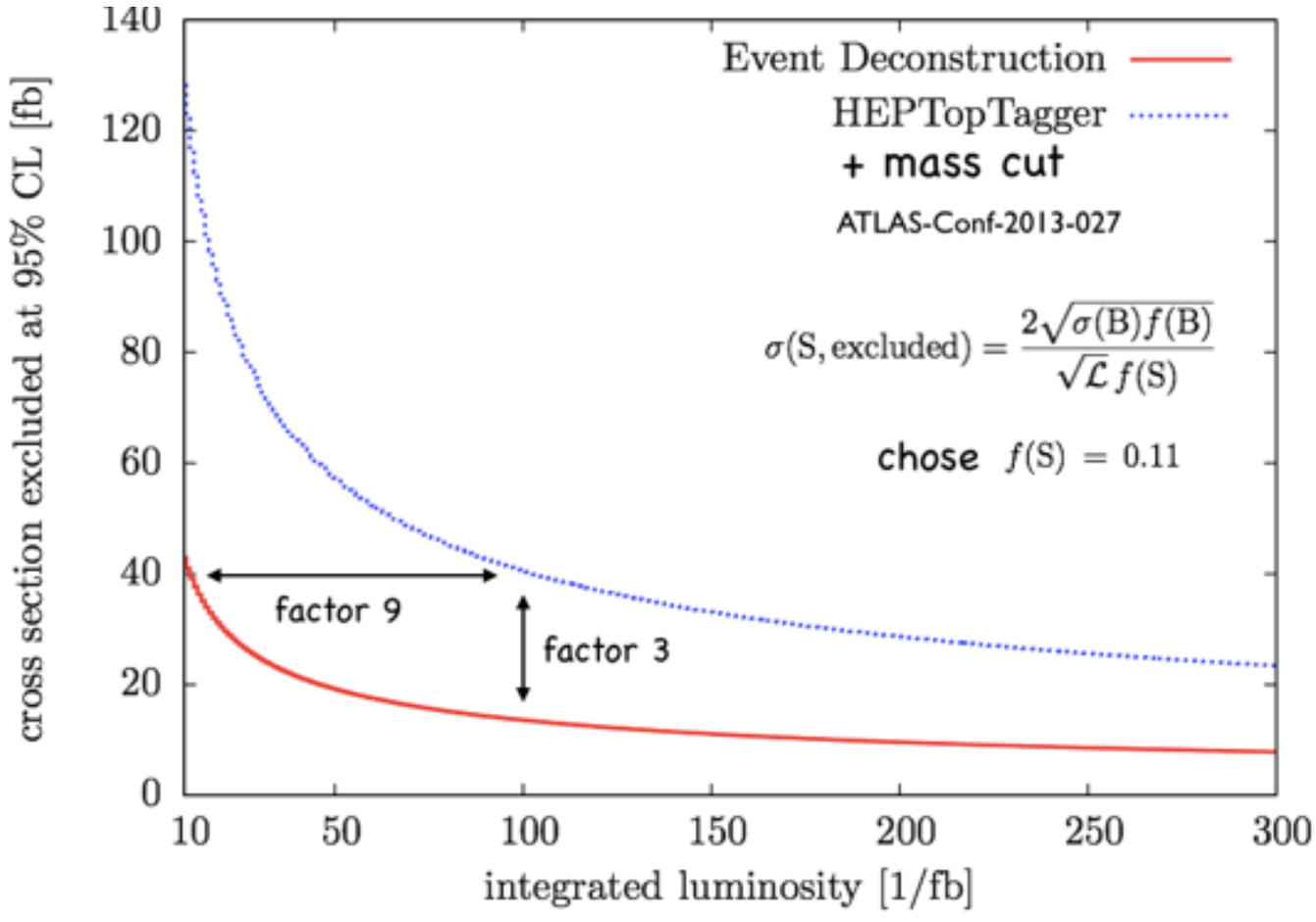


$$\chi = \frac{P(X|Z')}{P(X|t\bar{t} + \text{dijets})}$$



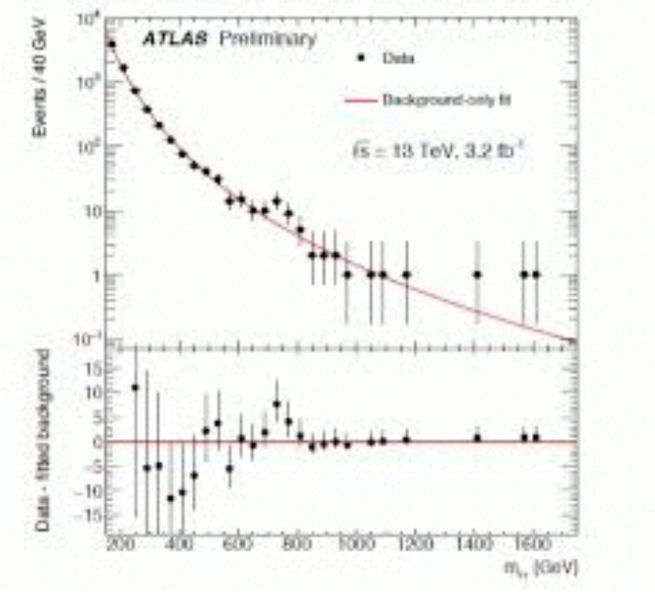


Discovery 9 times faster or for
3 times smaller cross section



Event Dec: eff : 0.109538
fkr : 3.20063e-05
1/fkr : 31243.8

HTT: eff: 0.104659
fkr: 0.000259946
1/fkr: 3846.95



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!