  

Matrix Element Methods
for
Higgs phenomenology

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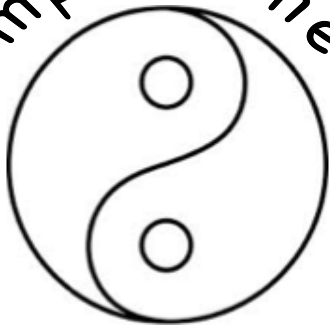
Compositeness



Effective Theory

$\mathcal{L}_{\mathrm{eff}} = \sum C_i \mathcal{O}_i$

Symmetry

SUSY, CW, ...

Naturalness

fermionic

top partners

simplified models

scalar

top partners

simplified models

Jets

Measurements

Leptons

width

interference

MET

mass

boost

Photons

Due to absence of signs of new physics

HEP has 'Big Mac' blues,

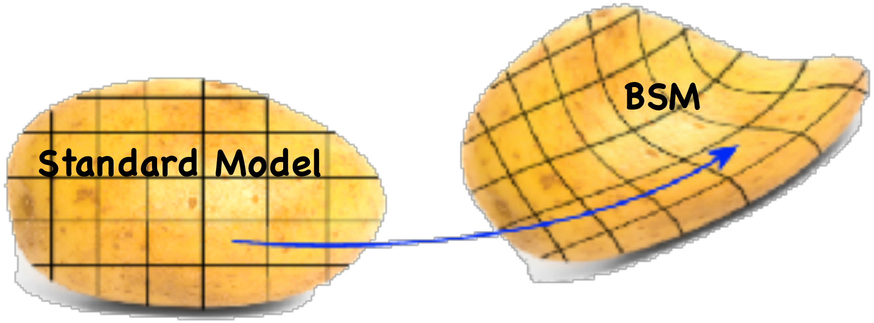
i.e. why nature not like (as natural as) advertised?

Commercial Reality

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

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

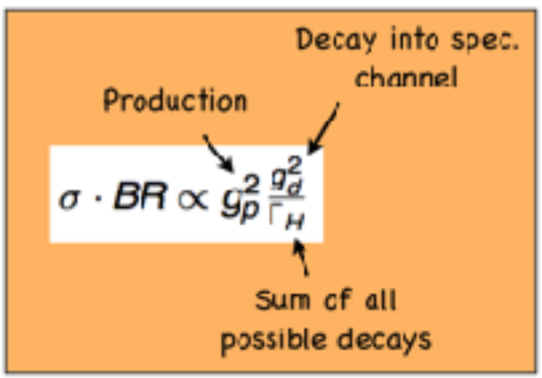
Coupling measurement during Run 1 using kappa-framework:

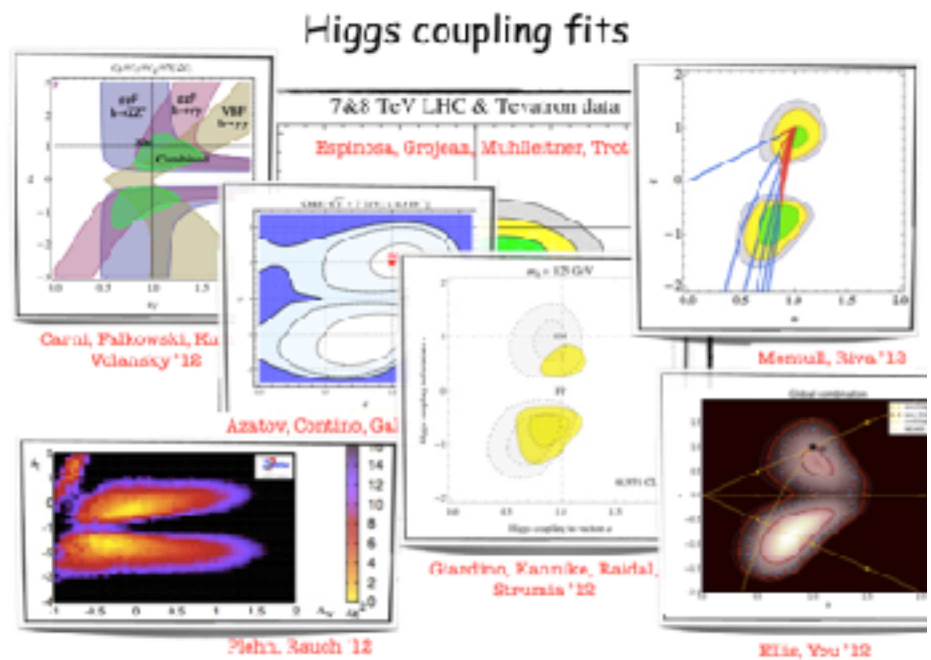
kappa is ratio of couplings:

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

so-called

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





- 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

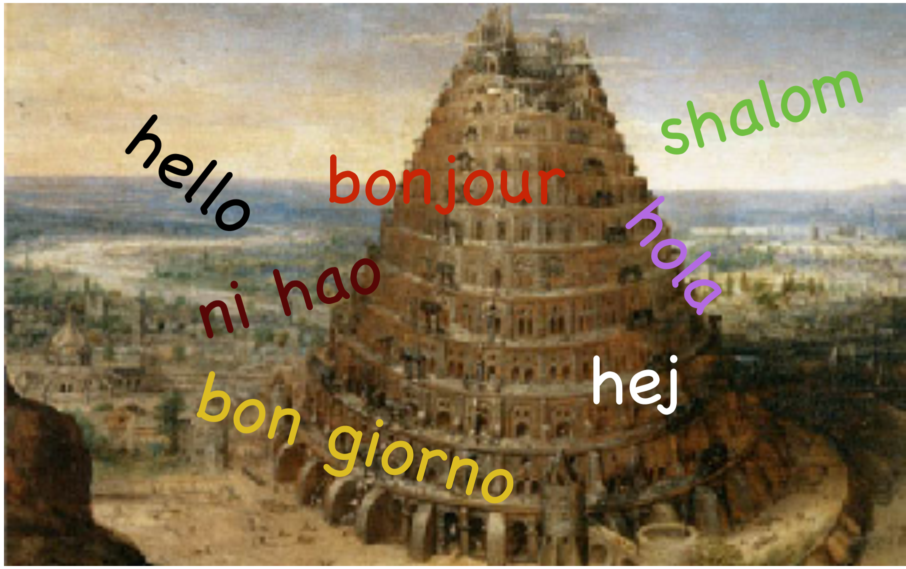
Struggle for a unified language (basis) for Higgs EFT

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

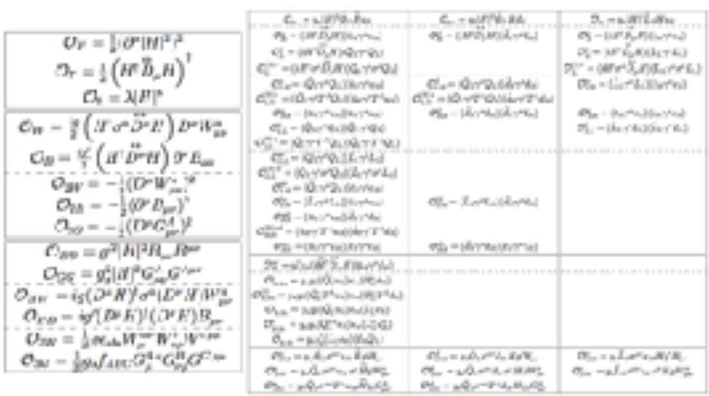
Basis and choice of operators to consider

Agnostic operator basis highly complex:

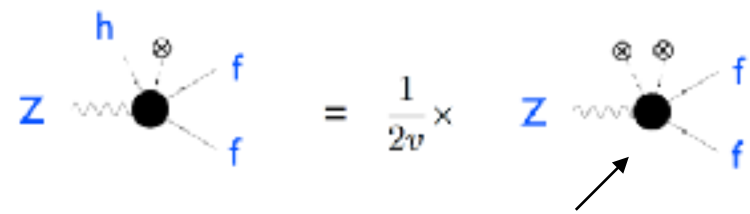
2499 non-redundant parameters at dim-6

Flavor diagonal still complex:

59 operators



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



constrained by LEP at permille level

- Focus on operators that are probed predominantly at LHC

Choose SILH basis:

$$\mathcal{L}_{\rm SILH} = \frac{\bar c_H}{2v^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar c_T}{2v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar c_6\lambda}{v^2}\left(H^\dagger H\right)^3$$
$$+\left(\frac{\bar c_{u,i} y_{u,i}}{v^2} H^\dagger H \bar u_L^{(i)} H^c u_R^{(i)} + \text{h.c.}\right) + \left(\frac{\bar c_{d,i} y_{d,i}}{v^2} H^\dagger H \bar d_L^{(i)} H d_R^{(i)} + \text{h.c.}\right)$$
$$+\frac{i\bar c_W g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar c_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(\partial^\nu B_{\mu\nu}\right)$$
$$+\frac{i\bar c_{HW} g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar c_{HB} g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+\frac{\bar c_\gamma g'^2}{m_W^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar c_g g_S^2}{m_W^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}.$$

[Giudice, Grojean, Pomarol, Rattazzi '07]

here $c_T \sim T$ and

$c_B + c_W \sim S$

[Peskin, Takeuchi '91]

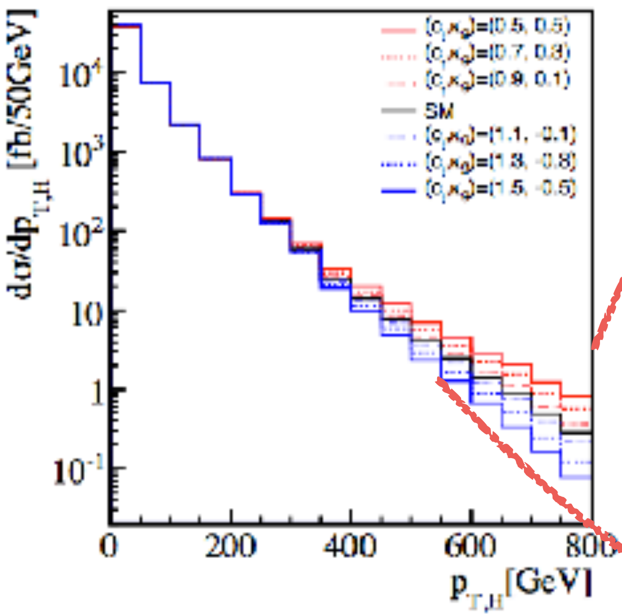
Validity and Relevance of EFT

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

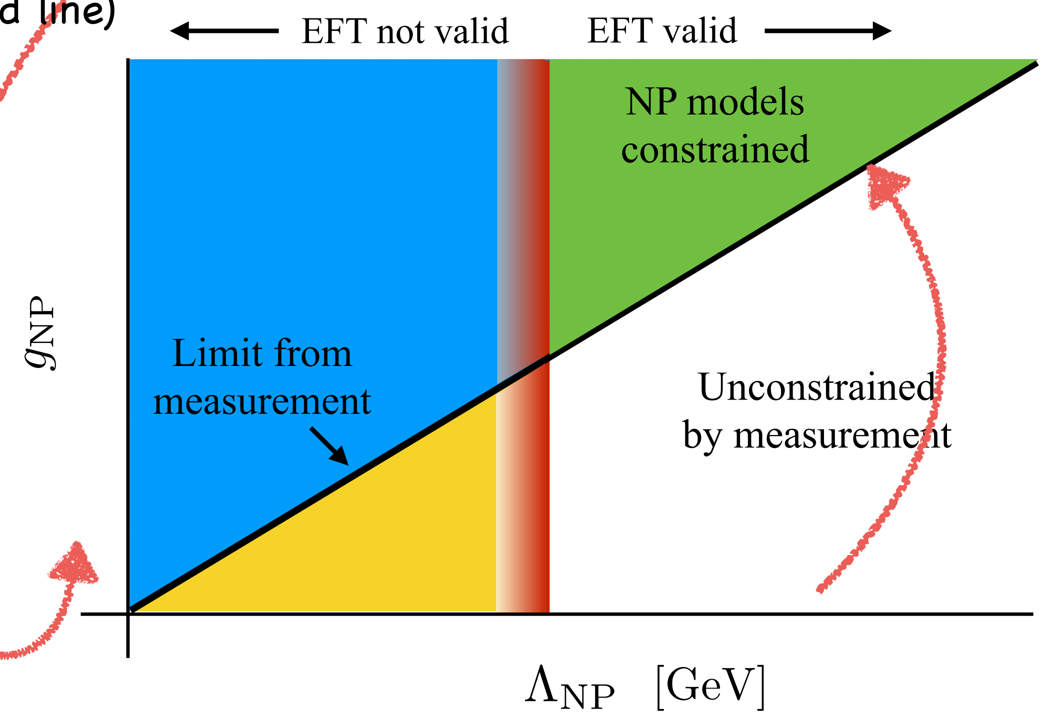
Lagrangian dim-6: $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{g_i^2}{\Lambda_{\mathrm{NP}}^2} \mathcal{O}_i$

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

[Englert, MS 1408.5147]



shape sets limit on Wilson coefficient (black line)



Any UV (weakly coupled) models left?

Results for linearised LO EFT approach

[Englert, Kogler, Schulz, MS 1511.05170]

Focus on linear contribution of EFT for theory prediction:

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

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

Number of predicted events:

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

We assume that production and decay factorise to good approximation

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

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

signal strength:

36 indep. meas. (300 ifb)

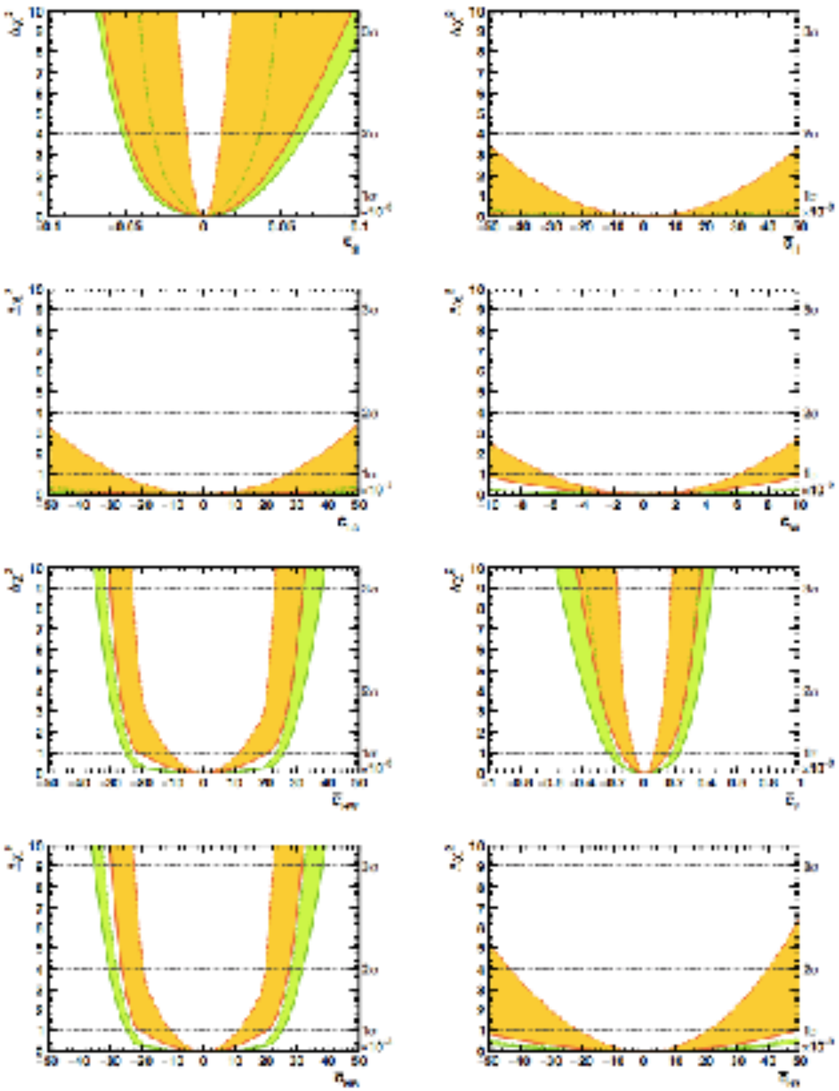
46 indep. meas. (3000 ifb)

differential:

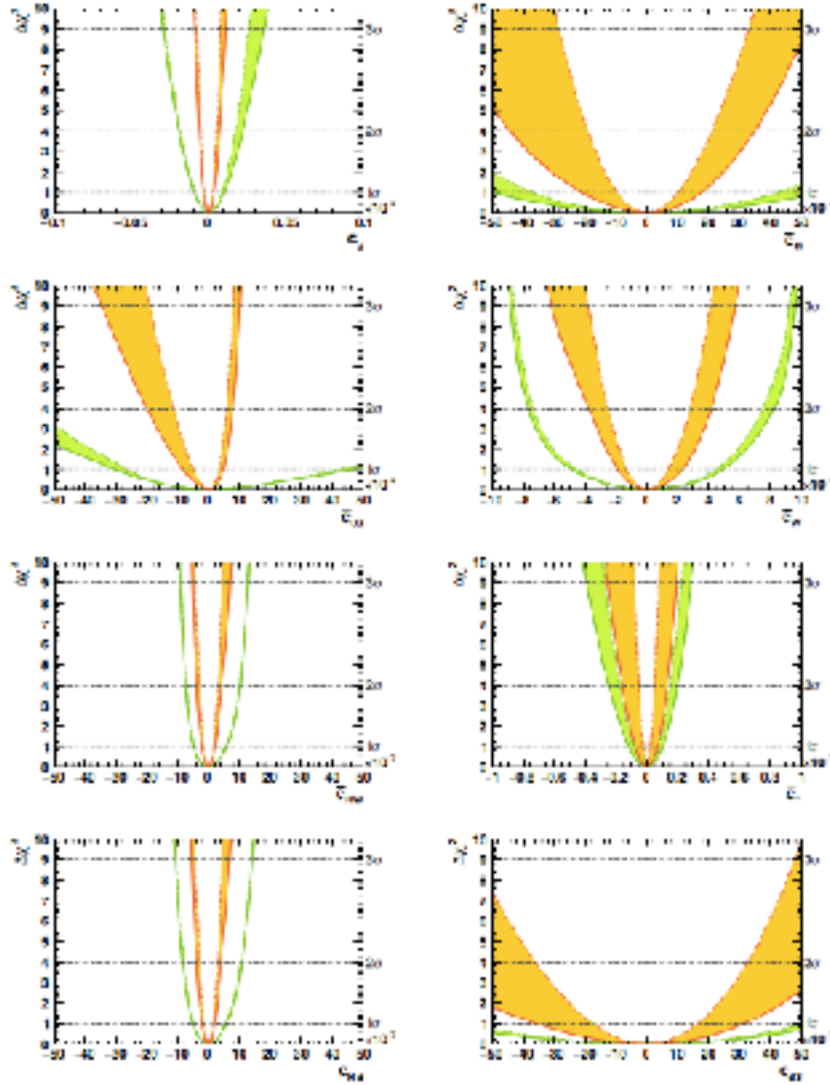
88 indep. meas. (300 ifb)

123 indep. meas. (3000 ifb)

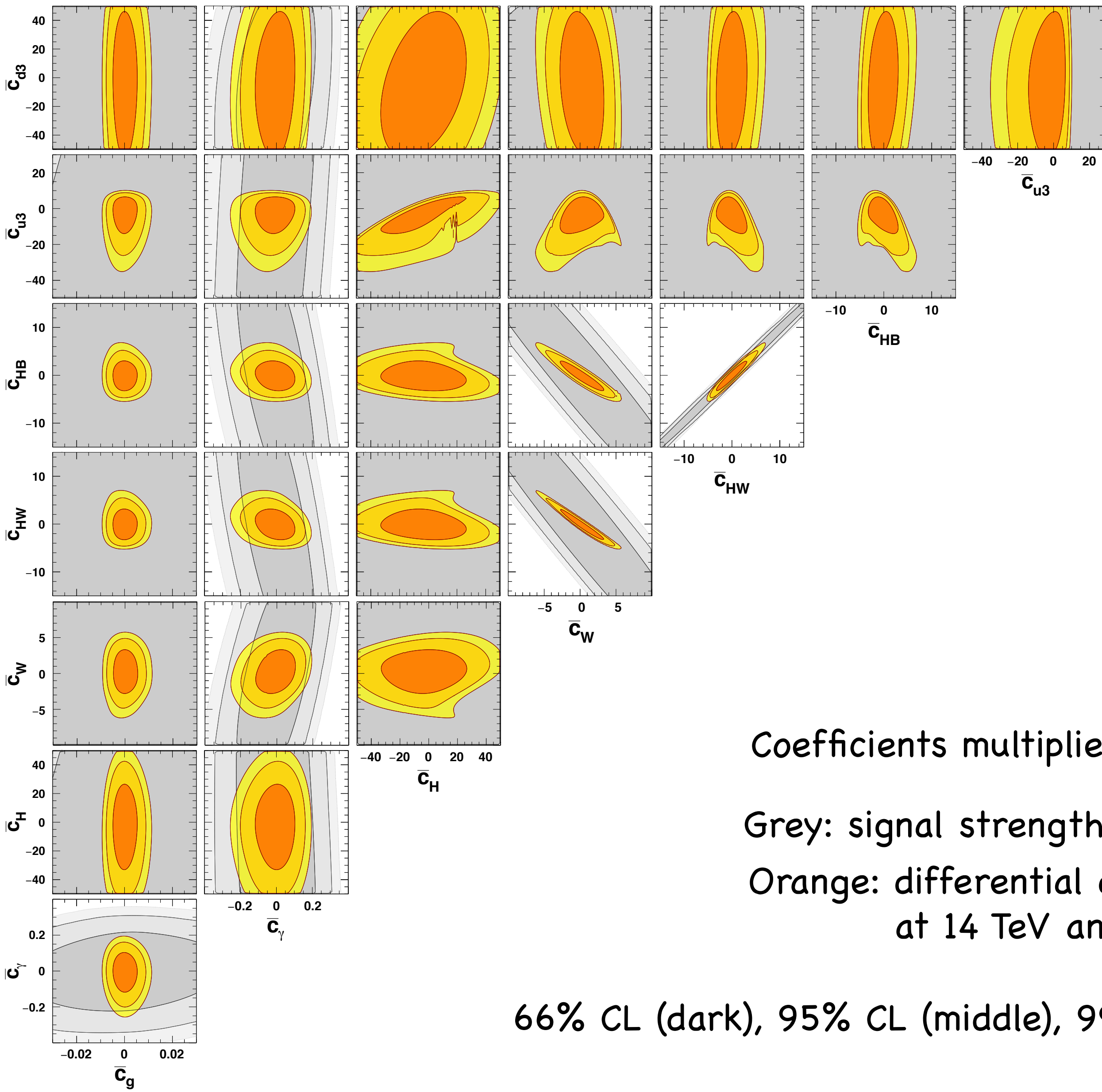
signal strength measurement



differential measurement



green = 300 ifb   orange = 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)

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

→ indirect probe of new physics scenario using Higgs observables only

MSSM:

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

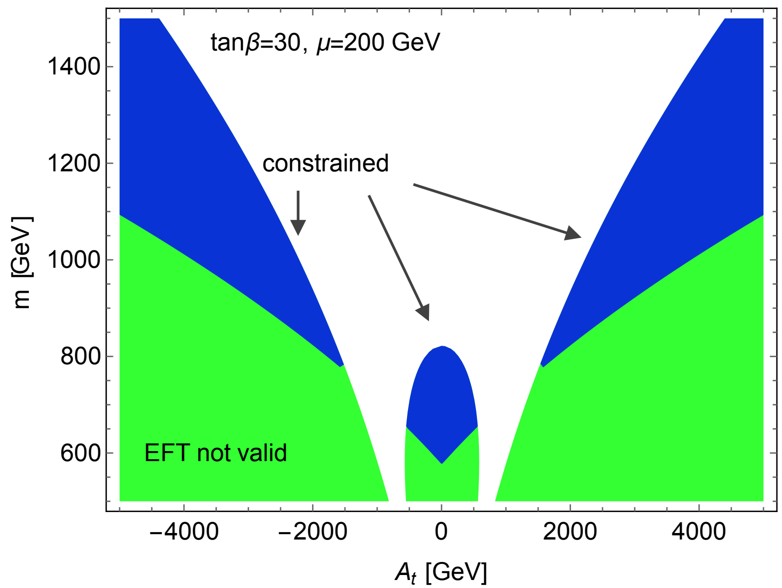
$$m_{\tilde{Q}} = m_{\tilde{t}} = m$$

$$\tan\beta = 30$$

$$\mu = 200 \text{ GeV}$$

$$h_t \equiv y_t s_\beta$$

→ large At can be constrained



Global Fit 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?

[Englert, Kogler, Schulz, MS 1708.06355]

Theoretical uncertainties:

$$\delta(p_T^H) = \delta_0[a + b f(p_T^H)]$$

flat band

pT normalisation

$$f(p_T^H) = \frac{p_T^H}{m_H}$$

$$f(p_T^H) = \log\left(1 + \frac{p_T^H}{m_H}\right)$$

pT uncertainty shape

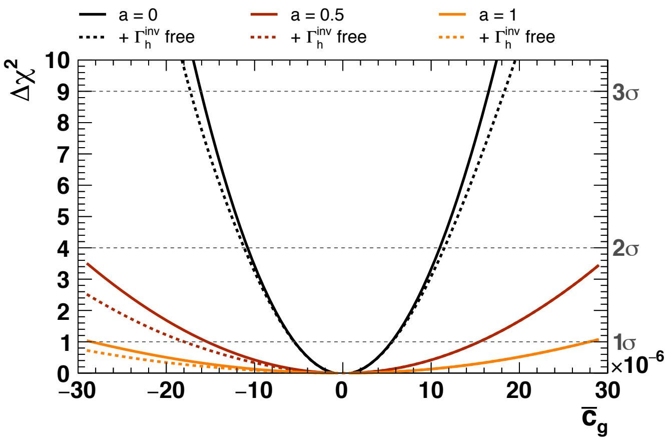
Additional weakly-coupled light degree of freedom:

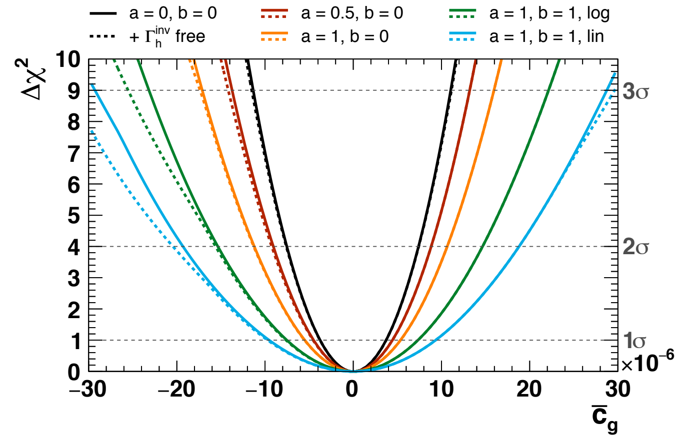
Affects only decay

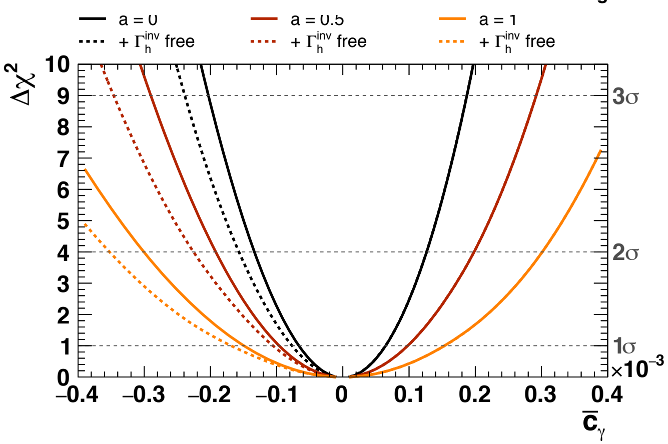
$$\Gamma_h = \Gamma_h^{\mathrm{SM}} + \Gamma_h^{\mathrm{D6}} + \Gamma_h^{\mathrm{inv}}$$

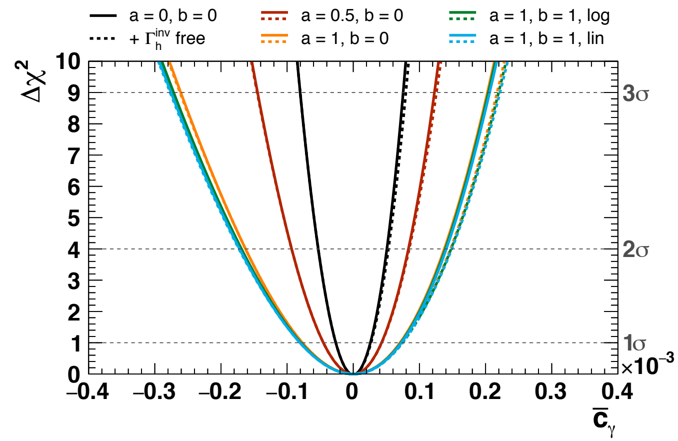
signal strength measurement

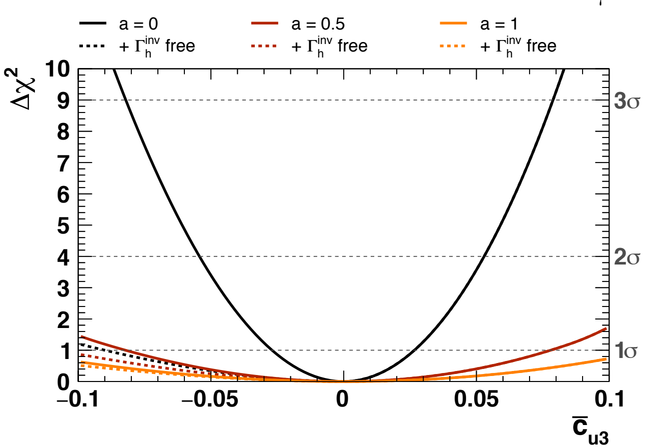
differential measurement

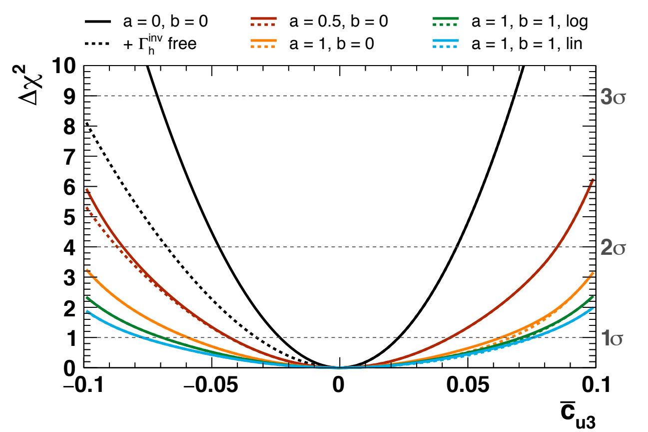










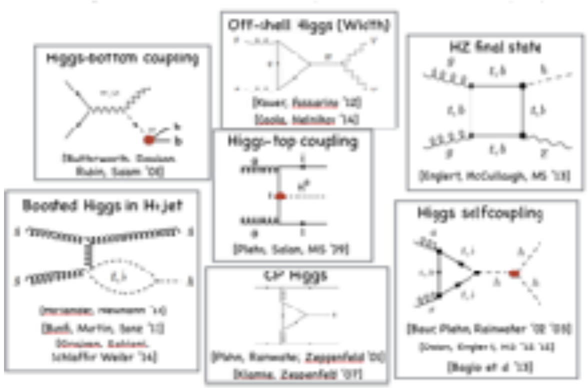


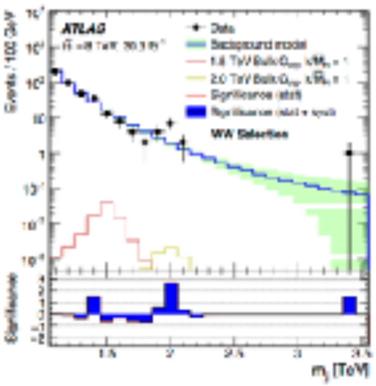
Observations:

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





- EFT measurements
- direct searches for new physics

Matrixelement method for jet- and met-rich final states

- In Matrix Element our physics understanding encoded
- MEM can improve S/B and S/sqrt(B)

- The more precise our physics picture, the better the discrimination
- MEM can improve S/B and S/sqrt(B)
- MEM provides direct connection between Lagrangian and Data
- Matrix Element Method does not need MC samples as opposed to BDT, NN, …

Nature:
Symmetries, Forces, Particles

Theory assumption:
Symmetries, Forces, Particles

Result in measurable objects, e.g.
Jets, stable leptons, photons

Encoded in Lagrangian Density

$$\mathcal{L} = \mathcal{L}_{\mathrm{EW}} + \mathcal{L}_{\mathrm{QCD}} + \mathcal{L}_{\mathrm{Higgs}}$$

Experiments measure radiation

Event Generators predict radiation

Comparison

Phenomenology

Nature:
Symmetries, Forces, Particles

Theory assumption:
Symmetries, Forces, Particles

Result in measurable objects

Encoded in Lagrangian Density

$$\mathcal{L} = \mathcal{L}_{\mathrm{EW}} + \mathcal{L}_{\mathrm{QCD}} + \mathcal{L}_{\mathrm{Higgs}}$$

Matrix Element Method

Machine Learning MVAs

Experiments measure radiation

Event Generators predict radiation

Comparison

Phenomenology

“The strange death of theory”

Frankfurter Allgemeine Zeitung

23.01.2017

or is it?

Matrix Element Method vs Multi-variate Analysis

(= pQCD = QFT)

- MVA well motivated to extract correlations without existing theory, i.e. **stock trading or PDF fitting ;-)**
- In particle physics we established gauge theories, thus, we have existing theory to predict connection of 'input with output'
- Current pheno approach:

We take first-principle QFT: $\mathcal{L} = \mathcal{L}_{\mathrm{EW}} + \mathcal{L}_{\mathrm{QCD}} + \mathcal{L}_{\mathrm{Higgs}}$

Put it into an event generator to generate pseudo-data

Then a smart physicist or MVA comes up with way to access the Lagrangian we put in in the first place

$\longrightarrow$ Seems like an unnecessary detour…

Training MVAs on Monte Carlo

- MVAs will optimise for - according to MC - most sensitive exclusive phase space regions

$\longrightarrow$ theory uncertainties difficult to control

- Full event generators are mashup of different parts that are partly tuned, i.e. hard interaction, UE, ISR, hadronisation, ...

- Highly computationally intensive. If you want to template correlations of say 7 particles:
  - Time estimate:

    7 microjets, each 4-momentum components divided into only 10 bins

    -> $10^{28}/7! \sim 10^{24}$ configurations

    If MC takes 1 ms per event -> 10^{13} years to have 1 hit per config.

Training MVAs on data only

- Less plagued by systematics

- But only possible if objects to reconstruct or events to measure already in data.
  -> oxymoron for discovery of anything new,
  e.g. gluino-tag, axion-tag, pp->HH->4b,...

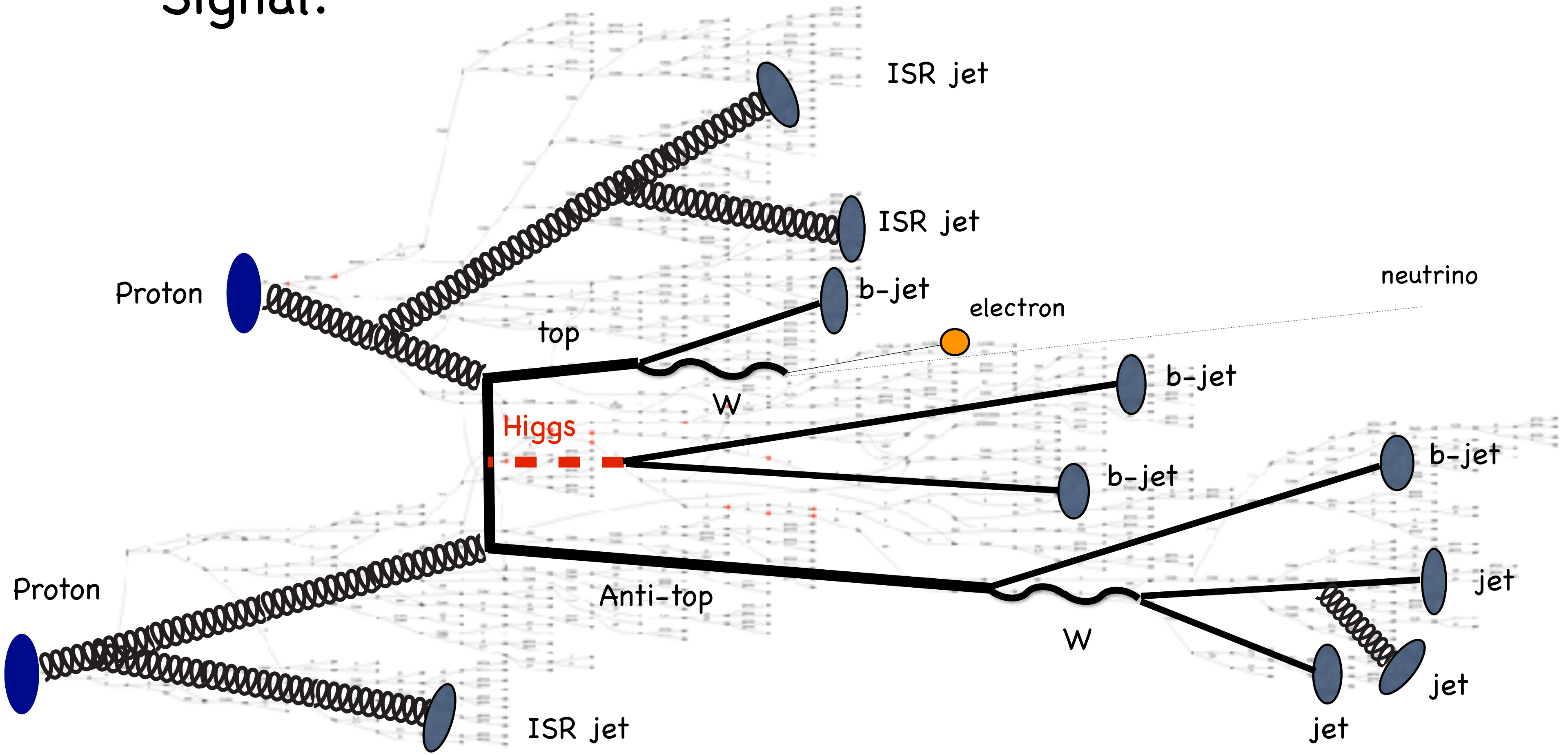
- Everything done purely on data without theory cross-check has 0 safety margins...

➡2 TeV excess in ATLAS and CMS might be an example (though I am not saying that anything was done wrongly)

see [Goncalves, Krauss, MS '15]

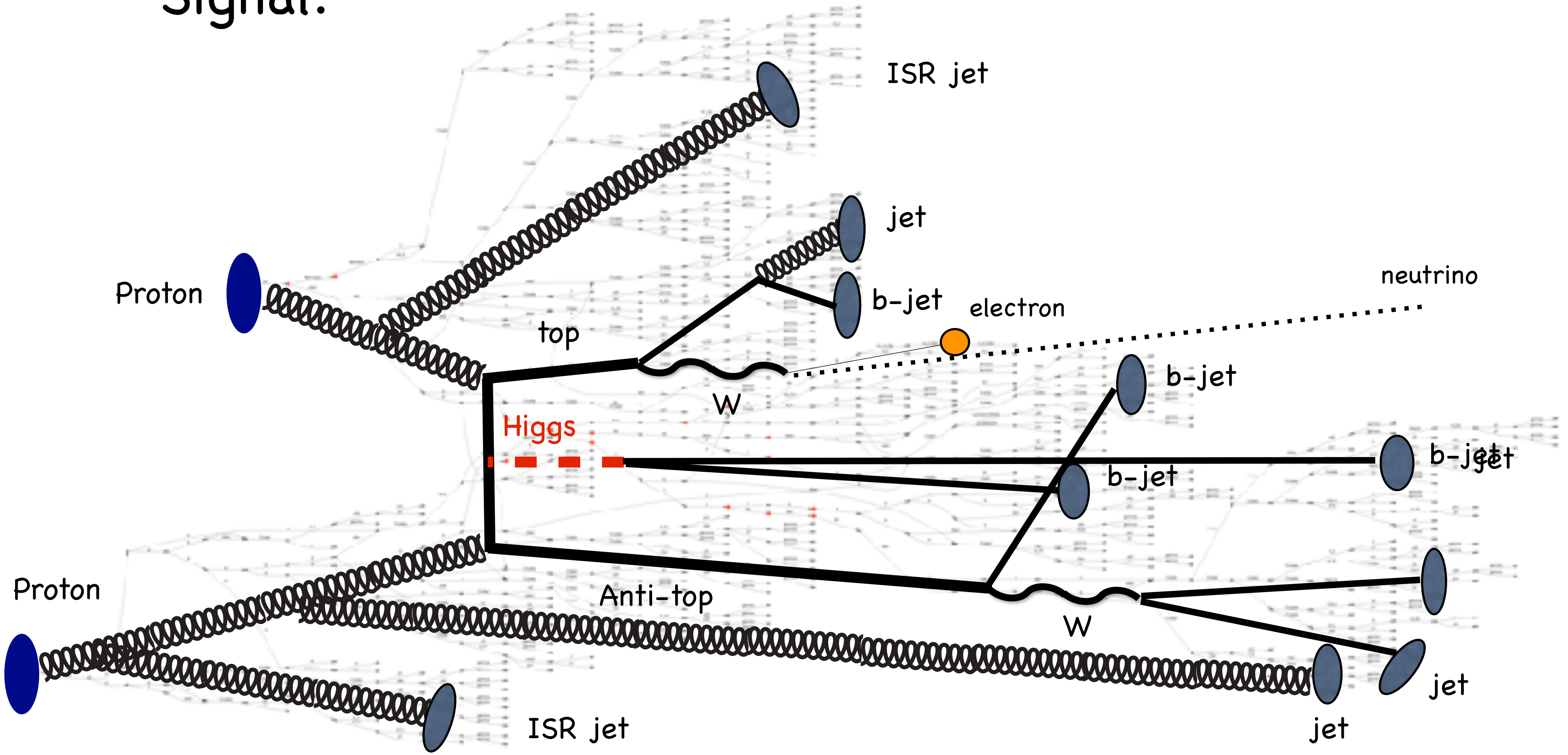
Give final state radiation distinctive meaning in terms of hypothesis

Signal:



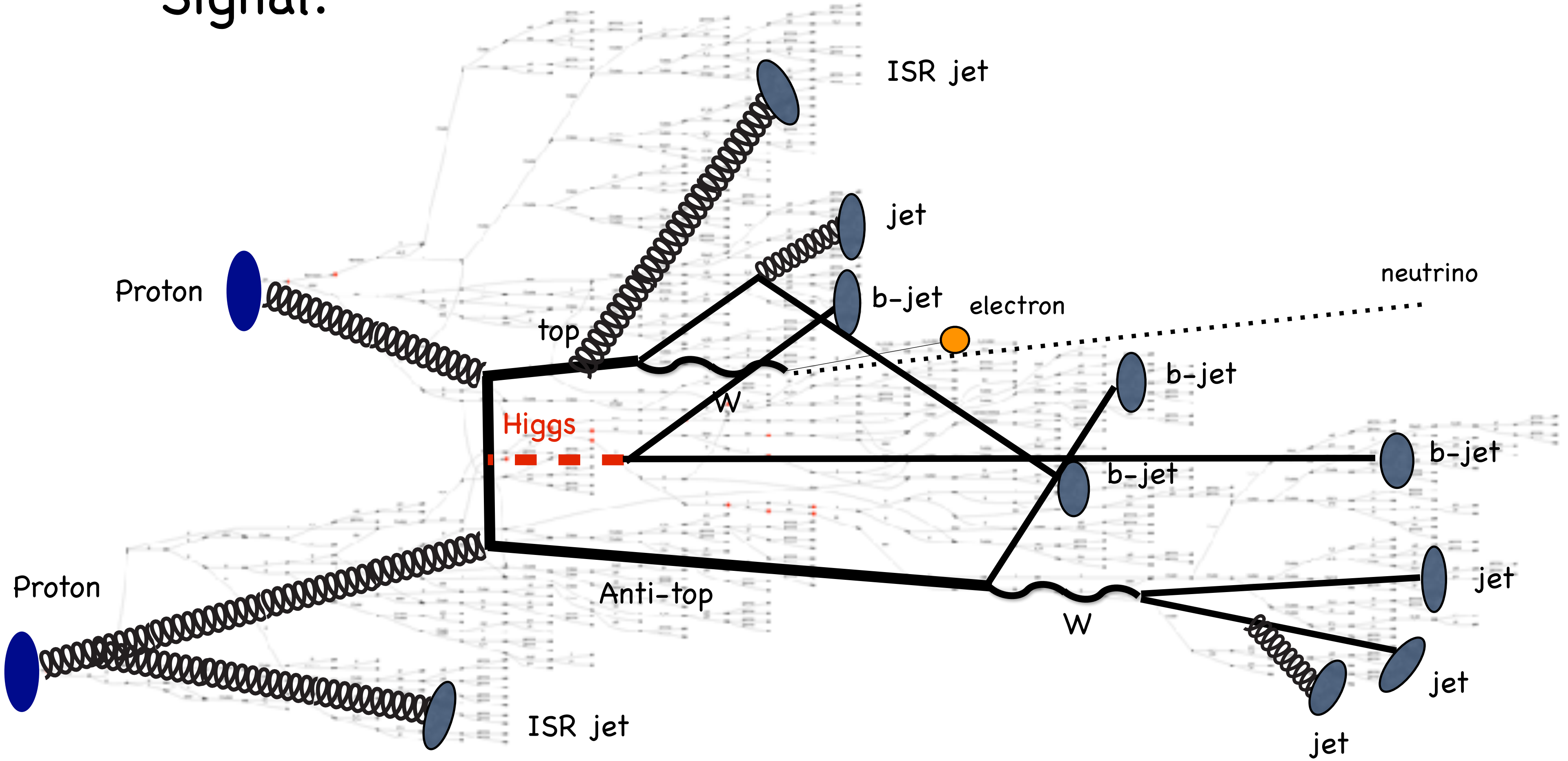
Give final state radiation distinctive meaning in terms of hypothesis

Signal:



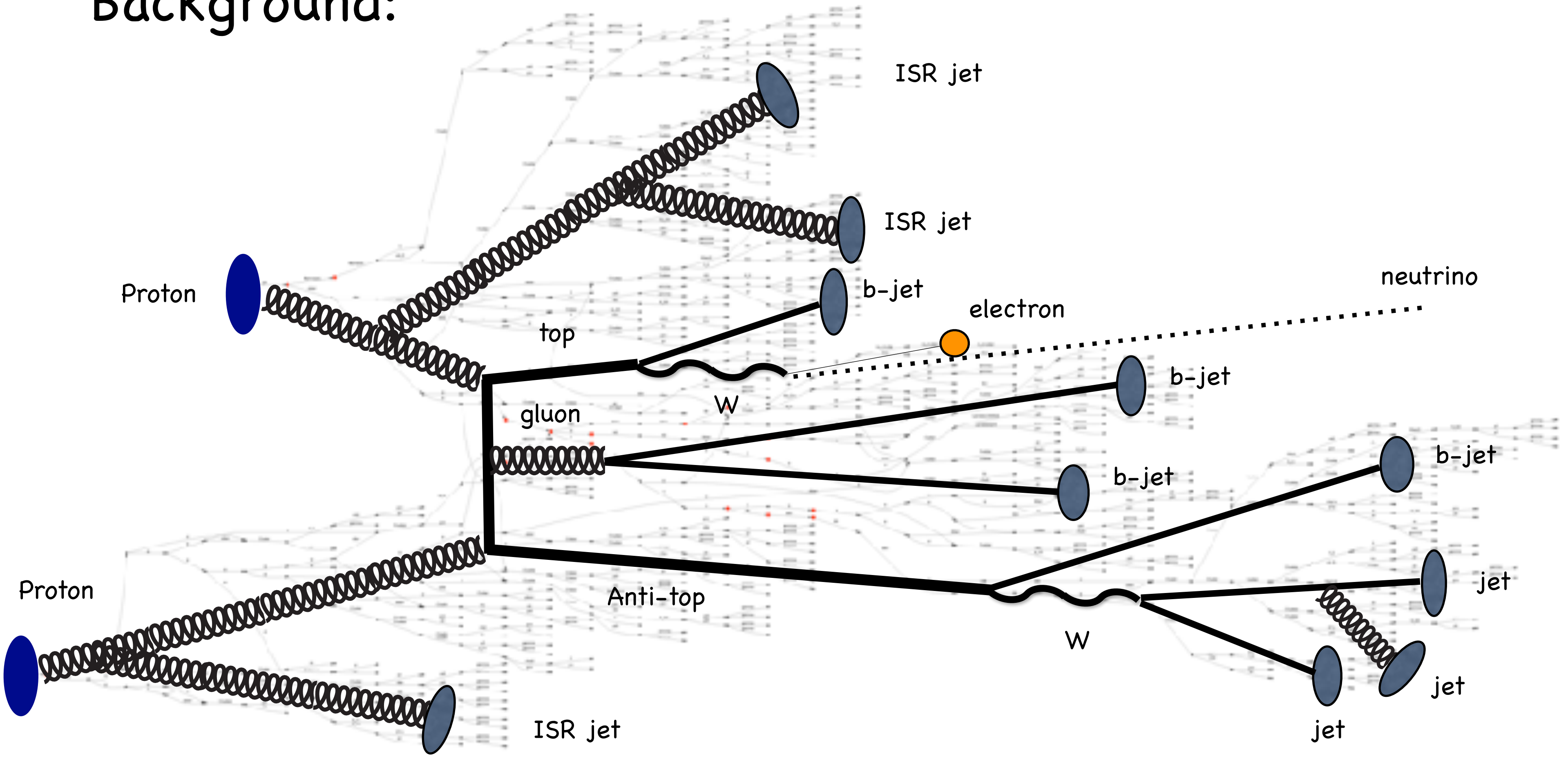
Give final state radiation distinctive meaning in terms of hypothesis

Signal:

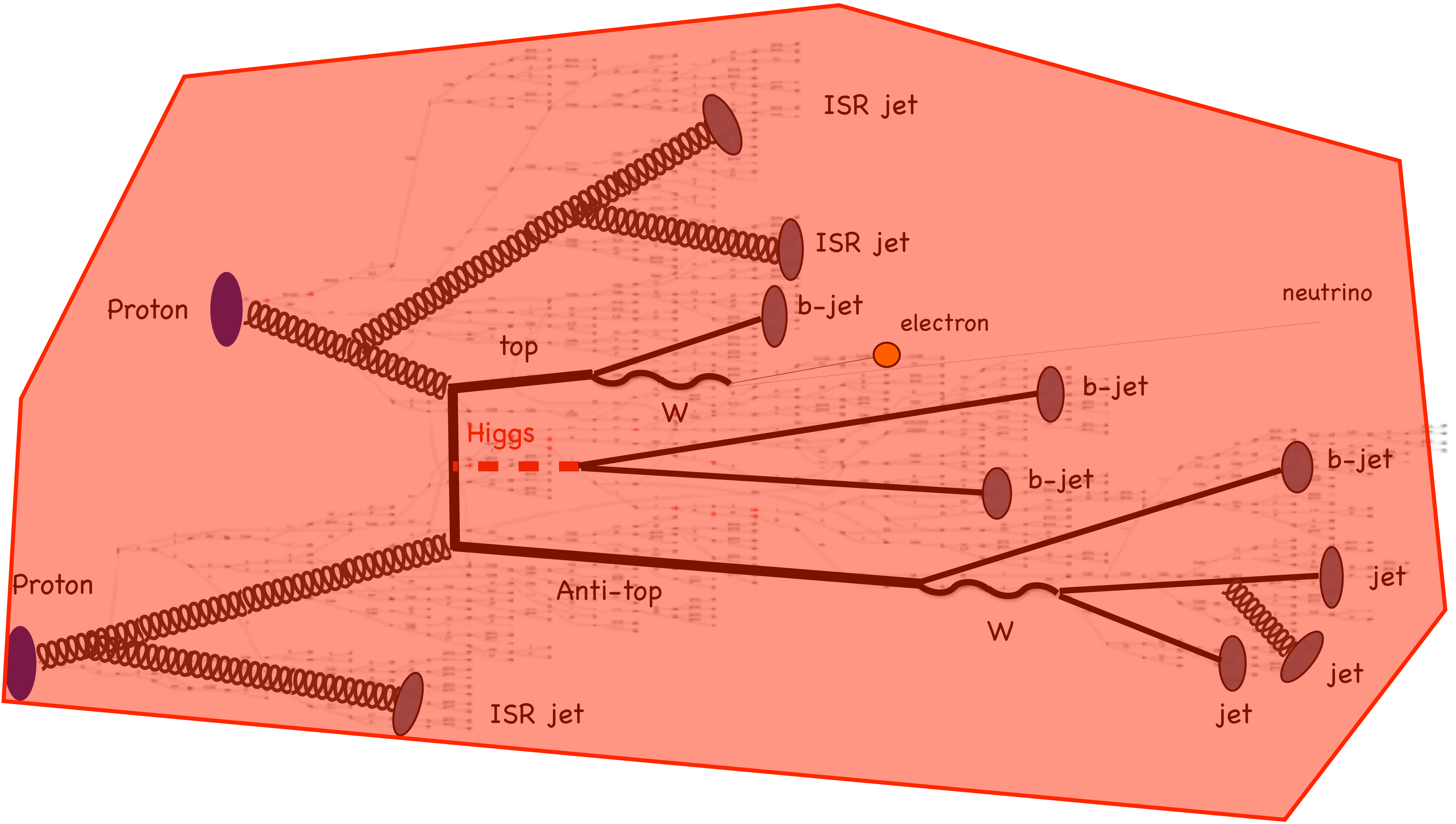


Give final state radiation distinctive meaning in terms of hypothesis

Background:



Ideally one would like to use all radiation related to hard process to discriminate signal from background



Applications of Matrix Element Method:

1988	Rec. of events with MET	[Kondo, J.Phys.Soc.Jap. (1988)]
1998	Anomalous gauge couplings	[Diehl, Nachtmann Eur. Phys. J. C1 (1998)]
2005	top quark physics	[Abazov et al., Nature (2004), D0 Collab.] [Abulencia et al., PRD 73 (2005), CDF Collab.] [Abazov et al., PLB 617 (2005), D0 Collab.]
2010	Automated implementation in MadWeight	[Artoisenet et al, JHEP 1012 (2010)]

Plenty of recent applications in Higgs physics:

$H \to \mu^+ \mu^-$ [Cranmer, Plehn EPJC 51 (2007)]

$H \to b\bar{b}$ [Soper, MS PRD 84 (2011)]

$H \to \gamma\gamma$ [Andersen, Englert, MS PRD 84 (2013)]

$pp \to t\bar{t}H$ [Artoisenet et al. PRL 111 (2013)]

$H \to ZZ^*/WW^*/Z\gamma$ [Campbell et al JHEP 1211 (2012)]
[Freitas et al PRD 88 (2013)] [Campbell et al PRD 87 (2013)]

Spin/Parity [Avery, et al. PRD 87 (2013)] [Gao et al. PRD 81 (2010)]

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.

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

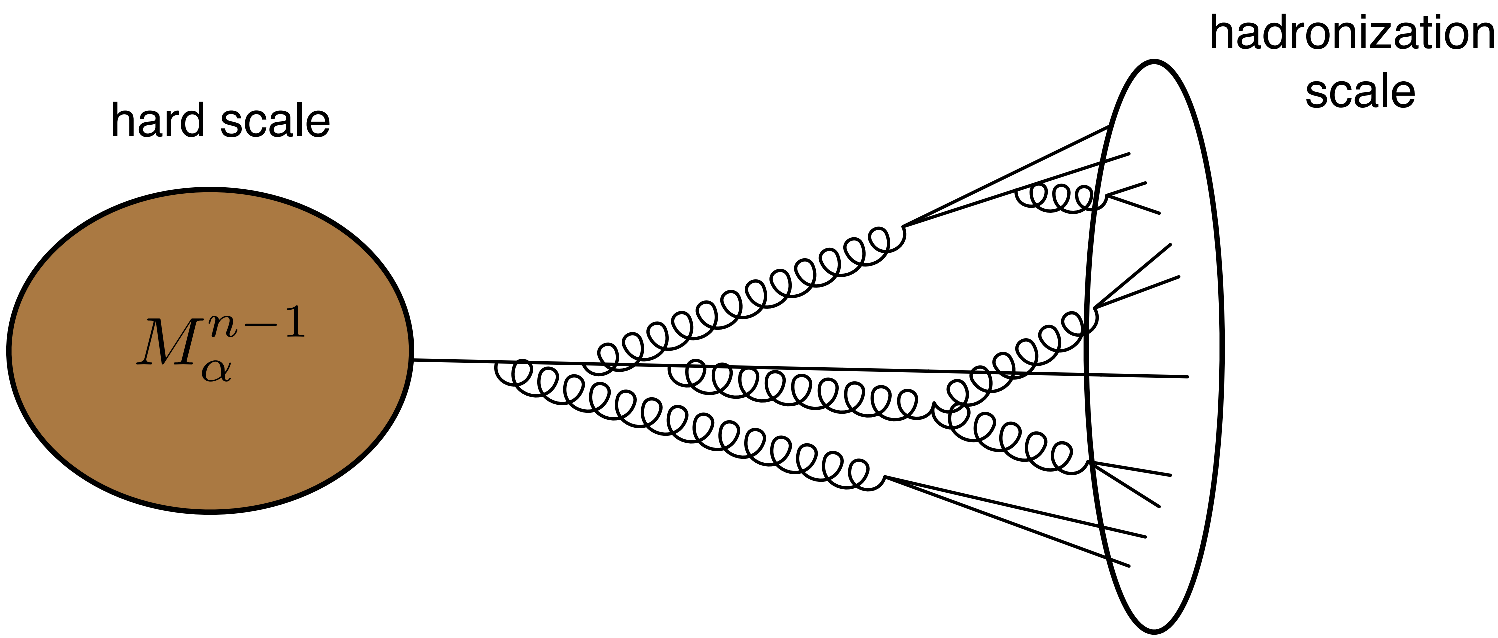
$|M_\alpha|^2$ is squared matrix element

$W(\mathbf{x}, \mathbf{y})$ 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

Purpose of the transfer function is to match jets to partons



Probability density function: $\int d\mathbf{y}\; W(\mathbf{x},\mathbf{y}) = 1$

The form of the transfer function:

resolution in

$$W(\mathbf{x},\mathbf{y}) \approx \Pi_i \frac{1}{\sqrt{2\pi}\sigma_{E,i}} e^{-\frac{(E_i^{rec}-E_i^{gen})^2}{2\sigma_{E,i}^2}}$$

Energy

$$\times \quad \frac{1}{\sqrt{2\pi}\sigma_{\phi,i}} e^{-\frac{(\phi_i^{rec}-\phi_i^{gen})^2}{2\sigma_{\phi,i}^2}}$$

azimuthal angle

$$\times \quad \frac{1}{\sqrt{2\pi}\sigma_{y,i}} e^{-\frac{(y_i^{rec}-y_i^{gen})^2}{2\sigma_{y,i}^2}}$$

rapidity

Complex, high-dimensional gaussian distribution!

Transfer function introduces new peaks on top of propagators

Subtleties of the convolution $|M(y)|^2 \times W(y,x)$

1) $|M(y)|^2$

- Can be calculated at different order in pert. series (LO, NLO)
- Final state multiplicity fixed (exclusive process)
- Some kinematic configurations induce large logs (need resummation)

2) $W(y,x)$

- Number of final state objects limited to exclusive process
- Integration very time consuming -> limits final state multiplicity
- Transfer function fit dependent (input from experiment)

Two objects that prove to be challenging for MEM (mapping to matrix element)

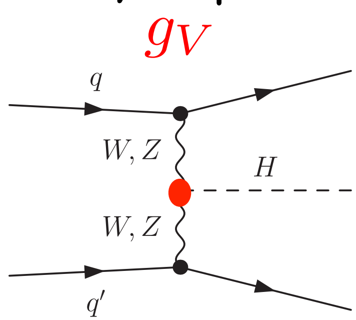
- Jet-rich final state
  - ➡ jet -> parton mapping difficult, i.e. depends on jet definition, detector response
  - ➡ many sources of jets at hadron colliders, i.e. particle multiplicity of hard process, not jet multiplicity of event
- MET-rich final state
  - ➡ MET -> particle mapping difficult, i.e. only indirect information about particle

We want to study more objects in final state -> Transfer function limits us. Do we always need it?

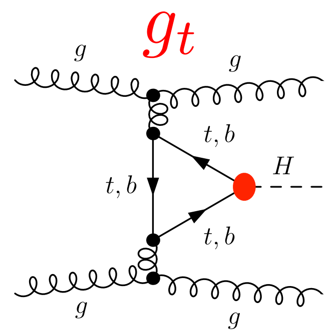
Transfer functions only important if matrix element varies quickly:

Example

[Andersen, Englert, MS PRD 84 (2013)]

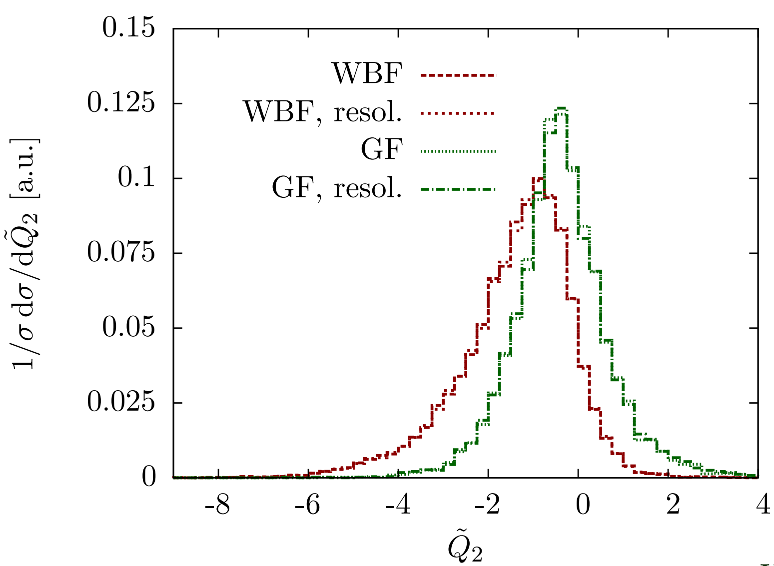


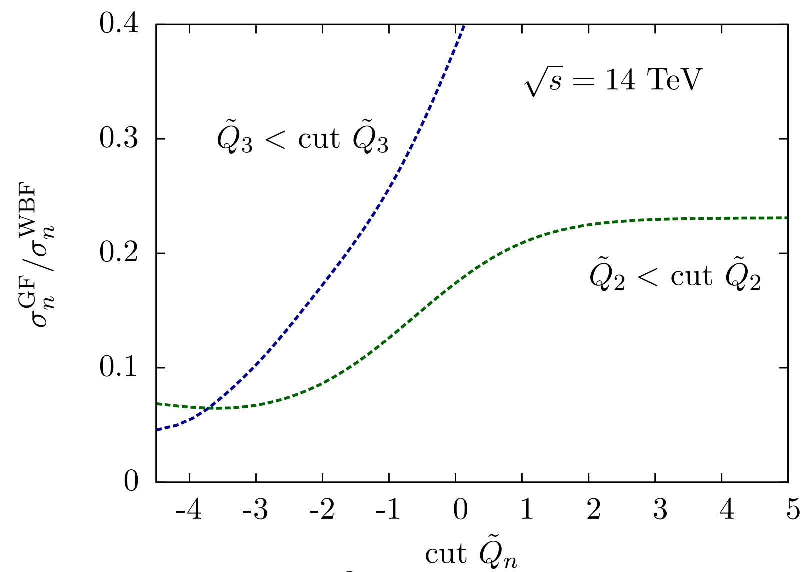
vs



in $H \to \gamma\gamma$

Higgs reconstructed, but no transfer function for jets:





$$\tilde{Q}_n = -\log\left[\frac{|\mathcal{M}^{\mathrm{WBF}}(pp \to (h \to \gamma\gamma)j^n)|^2}{|\mathcal{M}^{\mathrm{GF}}(pp \to (h \to \gamma\gamma)j^n)|^2}\right]$$

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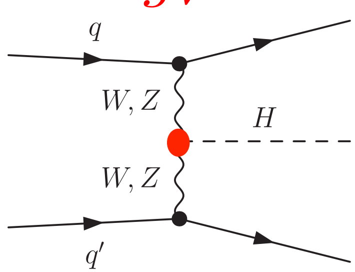
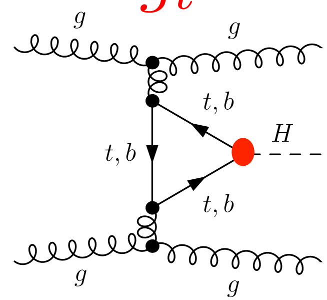
Example g_V

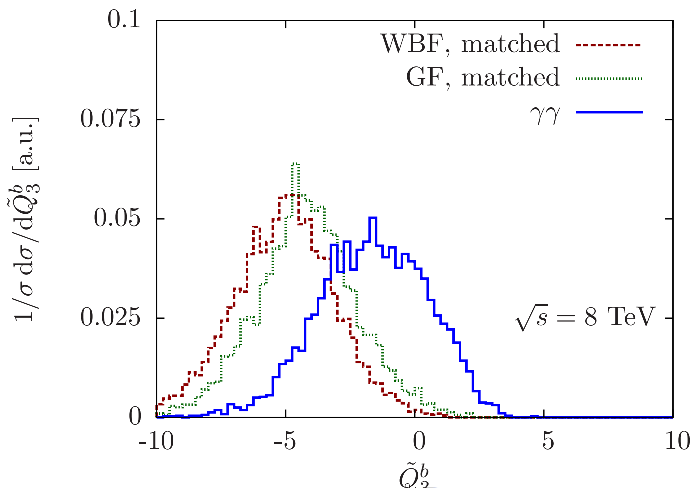


vs g_t



in $H \to \gamma\gamma$

Higgs reconstructed, but no transfer function for jets:



$S/B \nearrow 100\%$

compared to ATLAS selection

$$\tilde{Q}_n^b(p_1^\gamma, p_2^\gamma, \{p_n^j\}) = -\log\left[\frac{\{|\mathcal{M}^{\rm WBF}(pp \to (h \to \gamma\gamma)j^n)|^2 + |\mathcal{M}^{\rm GF}(pp \to (h \to \gamma\gamma)j^n)|^2\}}{|\mathcal{M}^{2\gamma}(pp \to \gamma\gamma j^n)|^2}\right]$$

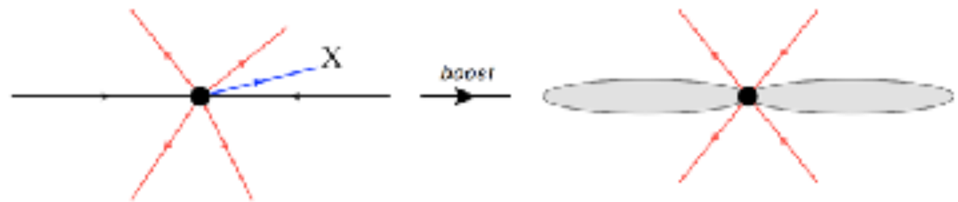
After removing transfer function we can improve on precision of matrix element $|M(y)|^2$

Matrix element method at NLO:

[Campbell, Giele, Williams JHEP 1211 (2012)]

[Martini, Uwer '15 '17] [Gritsanen et al '16]

Boost along transverse and longitudinal direction such that LO final state multiplicity momenta balance



Born phase space, but long. boost not unique, need longitud. integration

$$\mathcal{P}^{MEM}_{NLO}(\{Q_n\}) = \frac{1}{\sigma_{NLO}} \int_{x_{min}}^{x_{max}} dx_1 \mathcal{P}_{NLO}(\Phi_B)$$

Calculate virtual for born topology

real for jet function

$$\eta^{lab,i} = \frac{1}{2}\log\left(\frac{x_a^2 s}{s_{ab}}\frac{s_{ib}}{s_{ai}}\right)$$

Application to H->4l (boost easier to identify)

sensitivity LO vs NLO improvement ~ 10%

Remove limitation of final state objects on $|M(y)|^2$

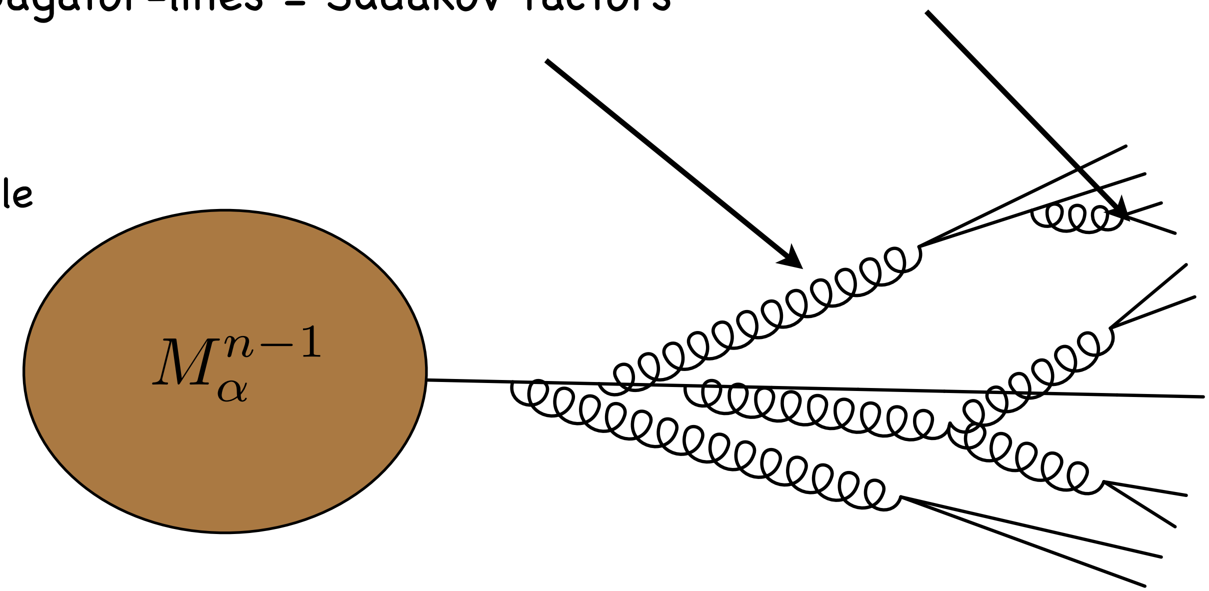
Factorization of emissions in soft/collinear limit [Soper, MS PRD 84 (2011)]

and Sudakov factors allow semiclassical approximation of quantum process:

vertices = Splitting functions

propagator-lines = Sudakov factors

hard scale



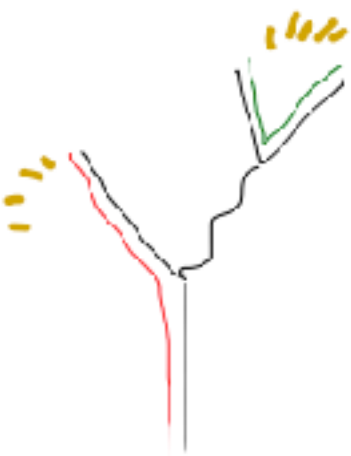
hadronization scale

- Can calculate weight for shower history iteratively
- Can use smaller objects and more objects (more information)

Can improve reconstruction for tops and Higgs

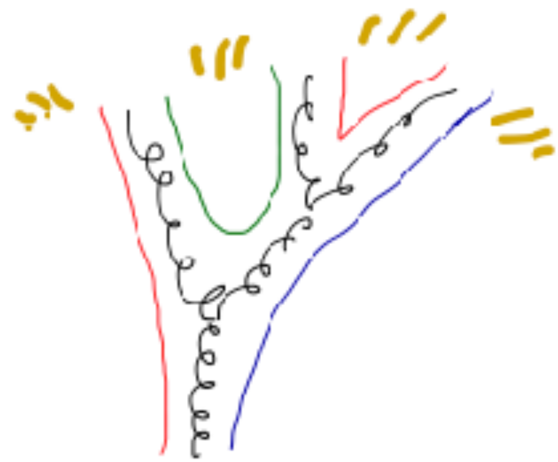
make use of many properties of the top for reconstruction (top mass, W mass, EW structure of decay)

However, QCD radiation pattern are left mostly aside.



top

QCD

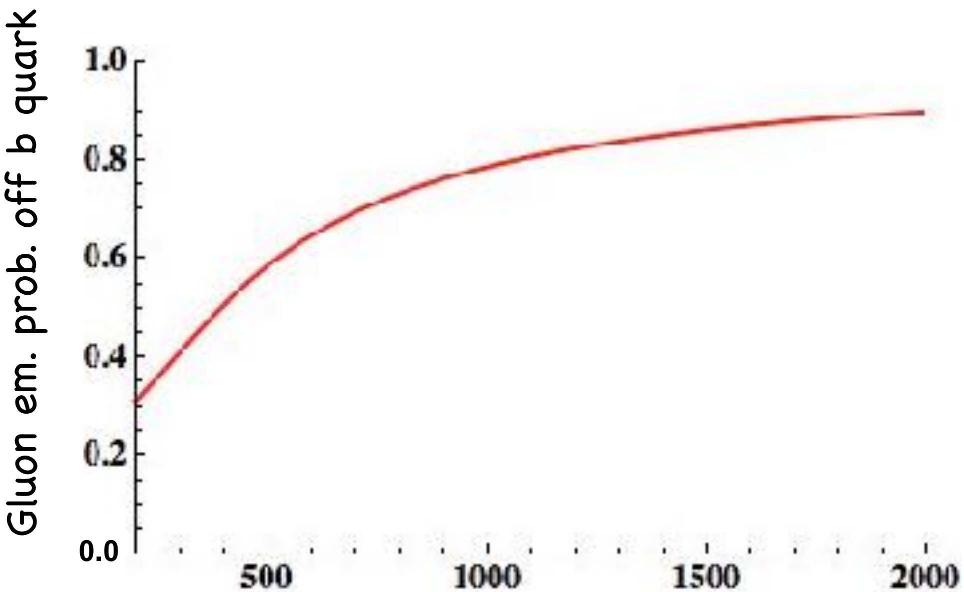


QCD

Radiation off bottom quark down to hadronization scale

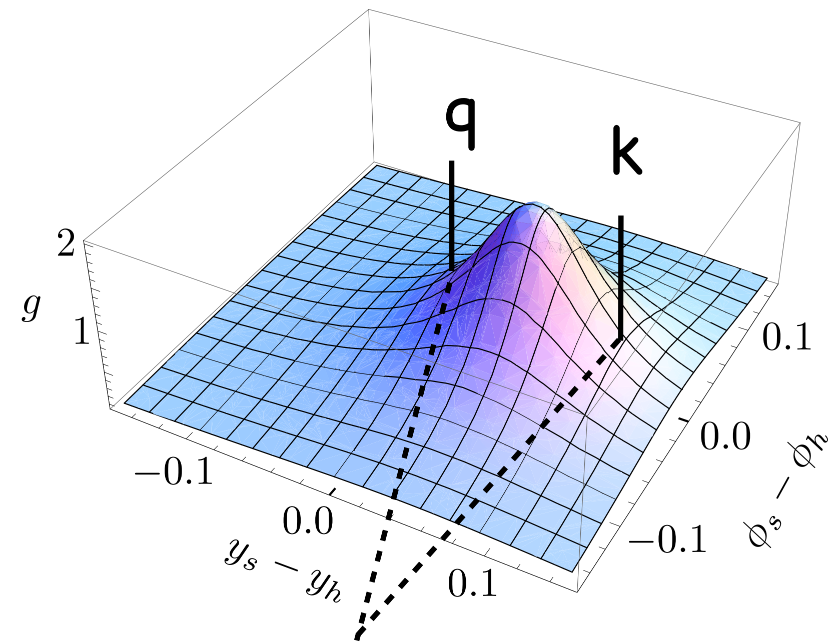
angular distribution for radiation off H/W decay products

$$\mathcal{P} = 1 - e^{-S_{bbg}}$$



pT top quark [GeV]

pT bottom = pT top / 3

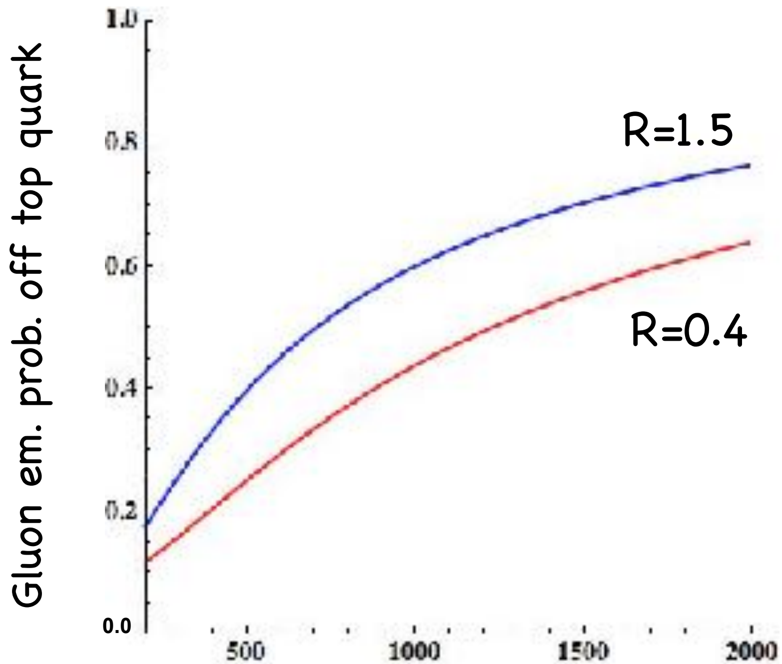


H/W decay products

One can be more quantitative...

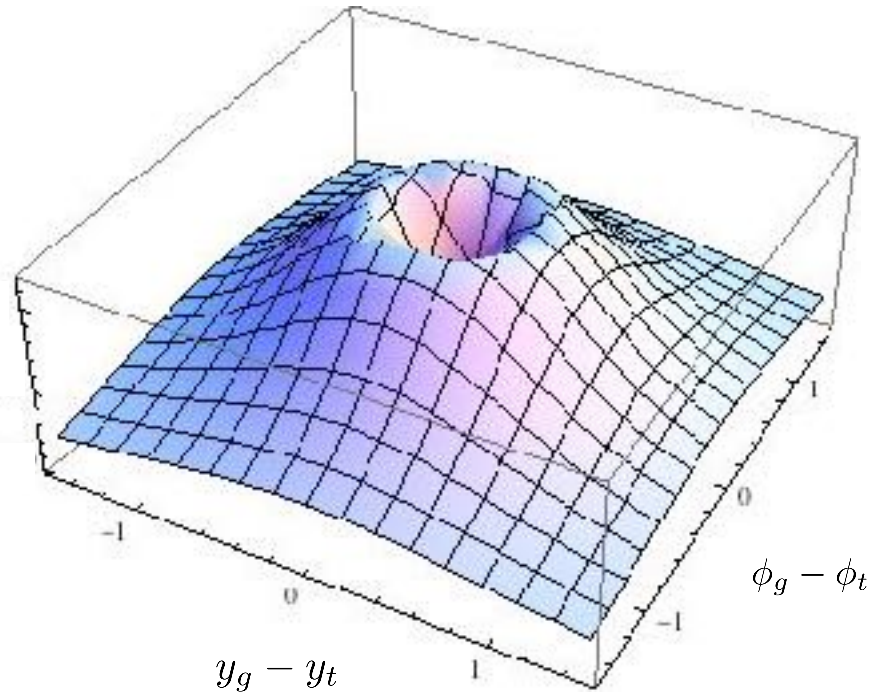
use emission prob. from [Soper, MS PRD 87]

$$\mathcal{P} = 1 - e^{-S_{ttg}}$$



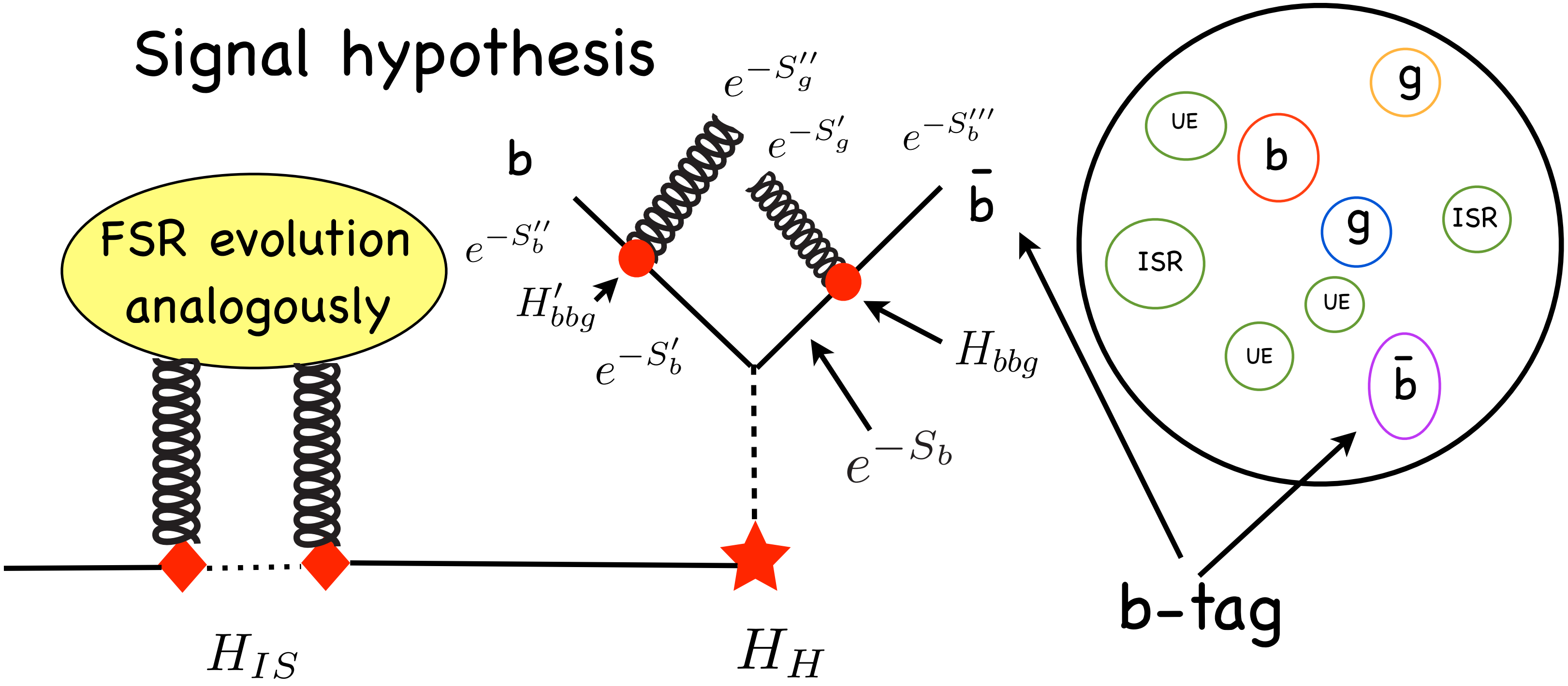
pT top quark [GeV]

Dead cone region around top



pT top 500 GeV, pT gluon 20 GeV

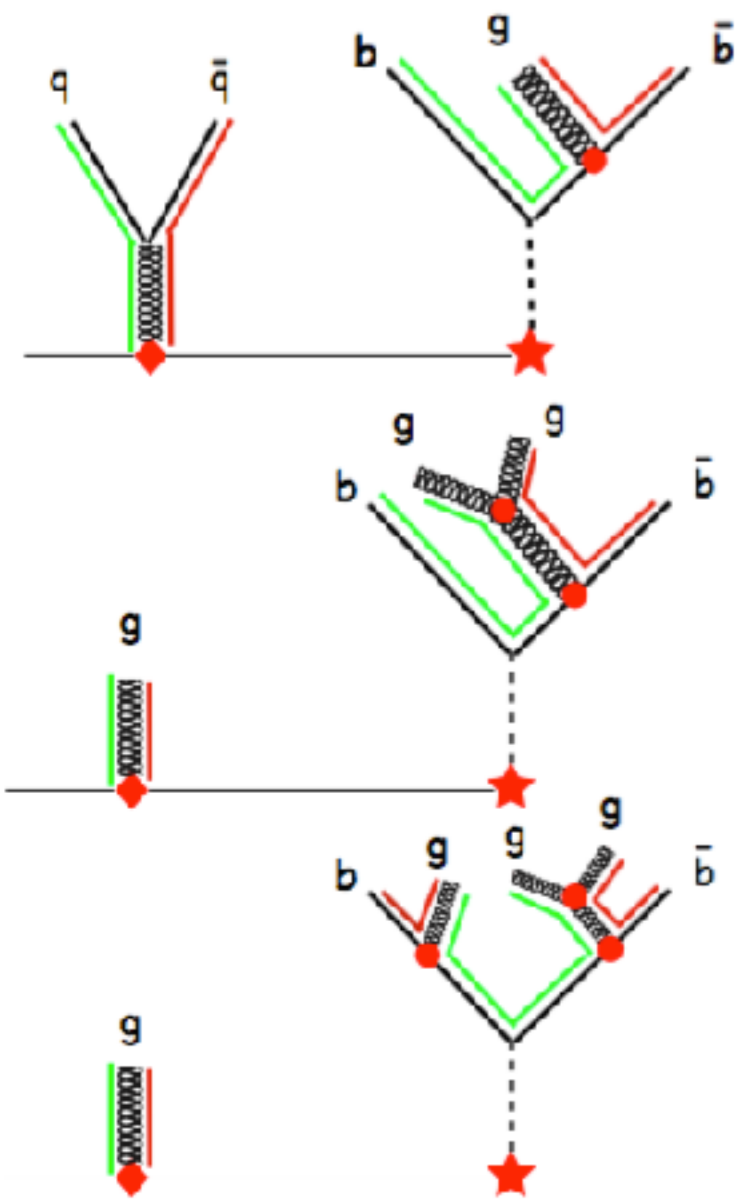
Signal hypothesis

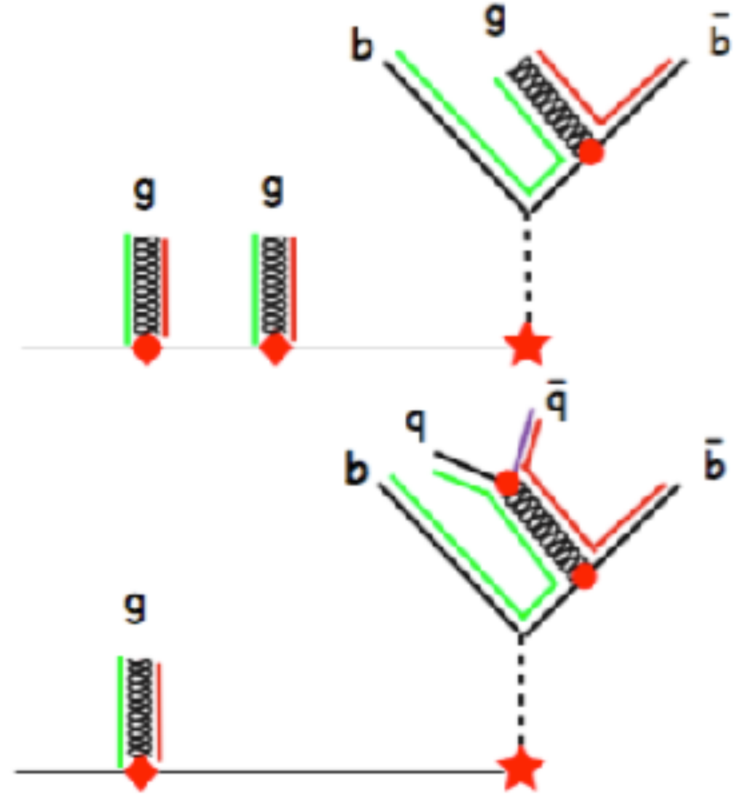


Wrapping up all factors gives weight for shower history

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

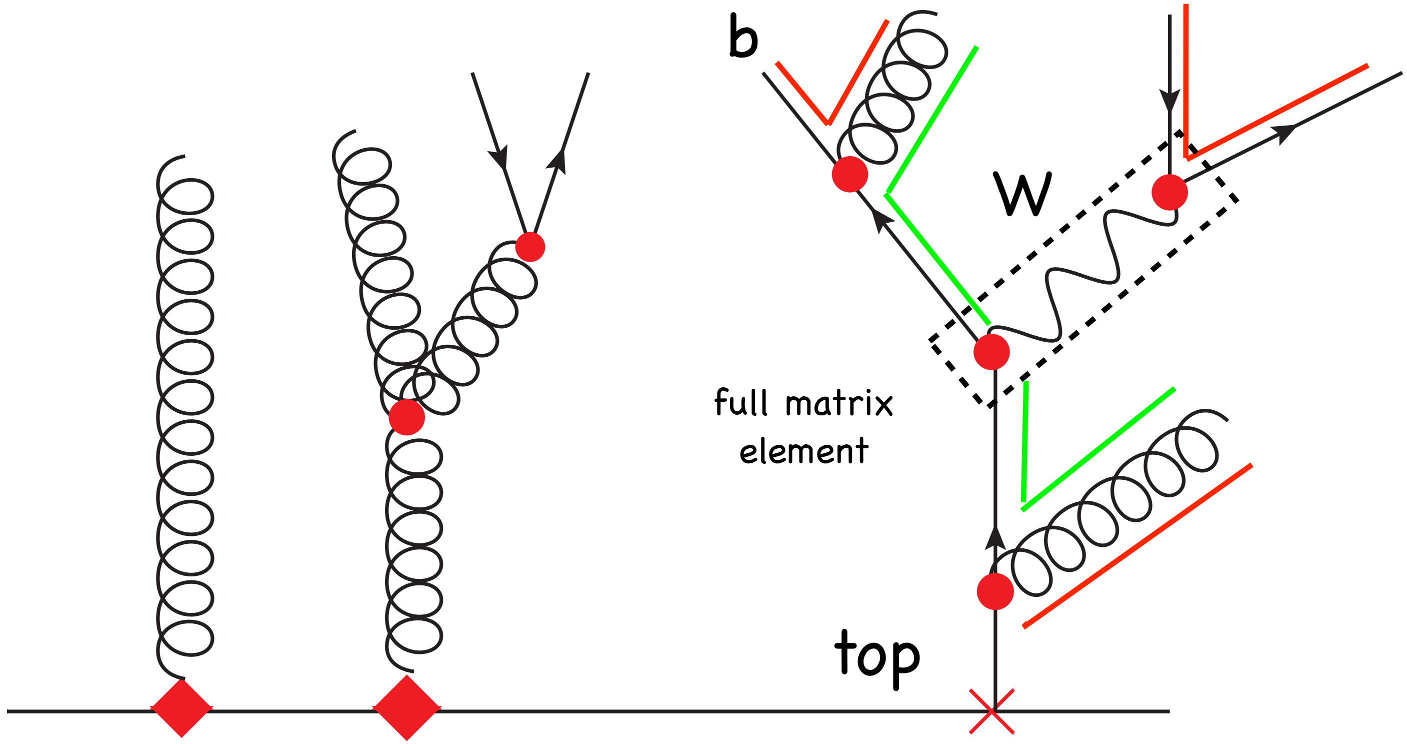
Here $\mathrm{Signal_1} = \mathrm{H_H H_{split} e^{-S_{split}} H_{bbg} e^{-S_b'} e^{-S_b'''} e^{-S_g'} H'_{bbg} e^{-S_b''} e^{-S_b} e^{-S_g''}}$





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

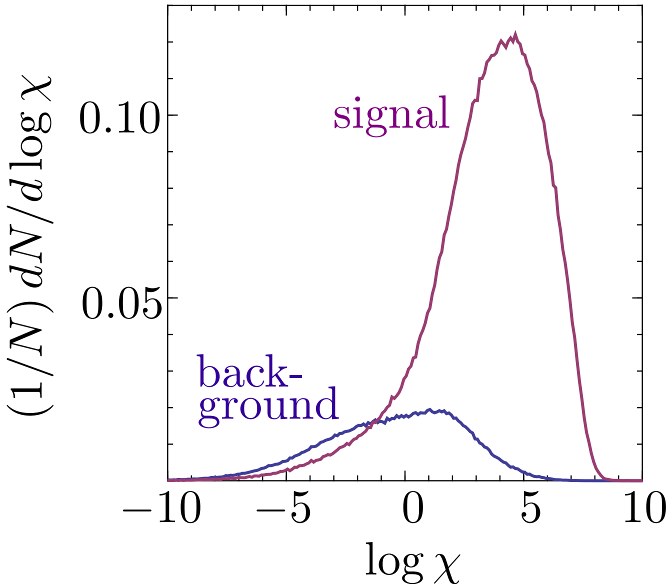
Analogously for the top decay (more involved as top colored)

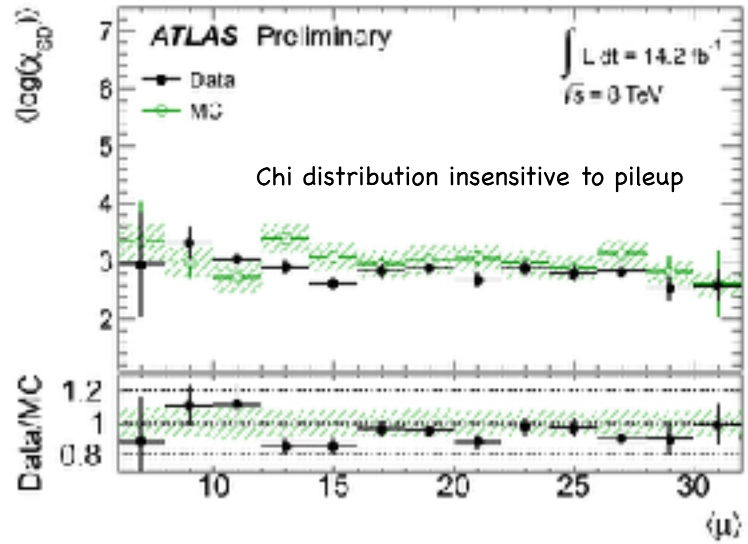


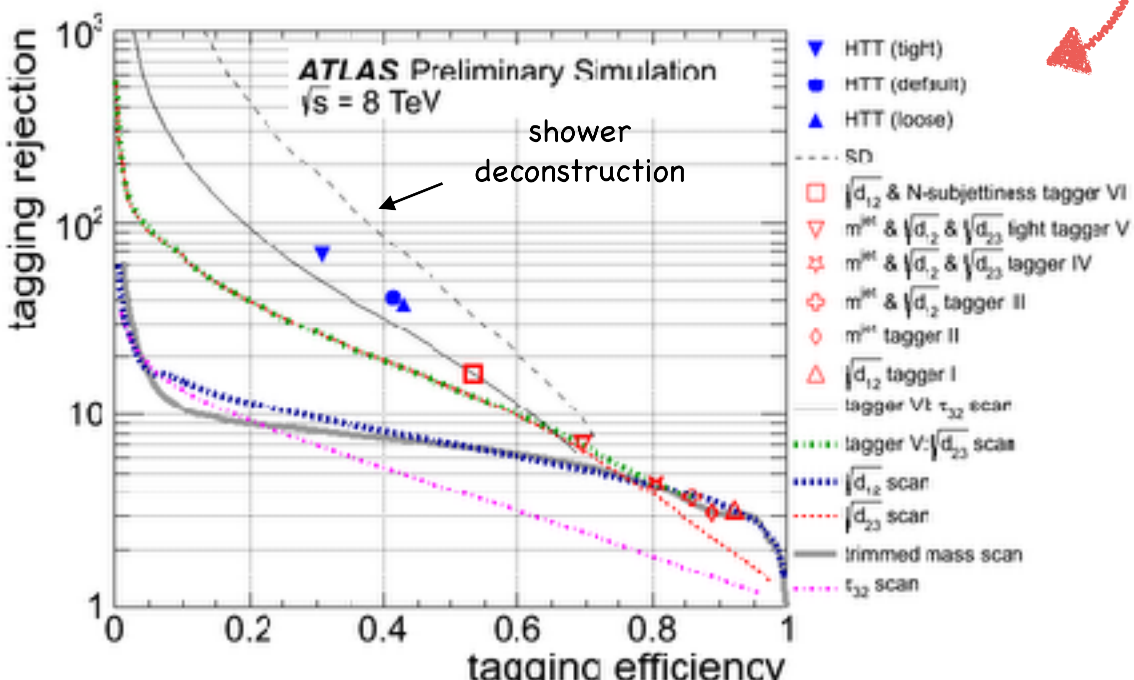
Conceptional difference compared to Higgs from last year:

- Splitting functions for massive emitter and spectator
- Full matrix element for top decay

$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})} = \frac{\sum_{\text{histories}} H_{ISR} \cdots \sum_{\text{histories}} |\mathcal{M}|^2 H_{\text{top}} e^{-S_{t_1}} H^s_{tg} e^{-S_g} \cdots}{\sum_{\text{histories}} H_{ISR} \cdots \sum_{\text{histories}} H^b_g e^{S_g} H_{ggg} \cdots}$$

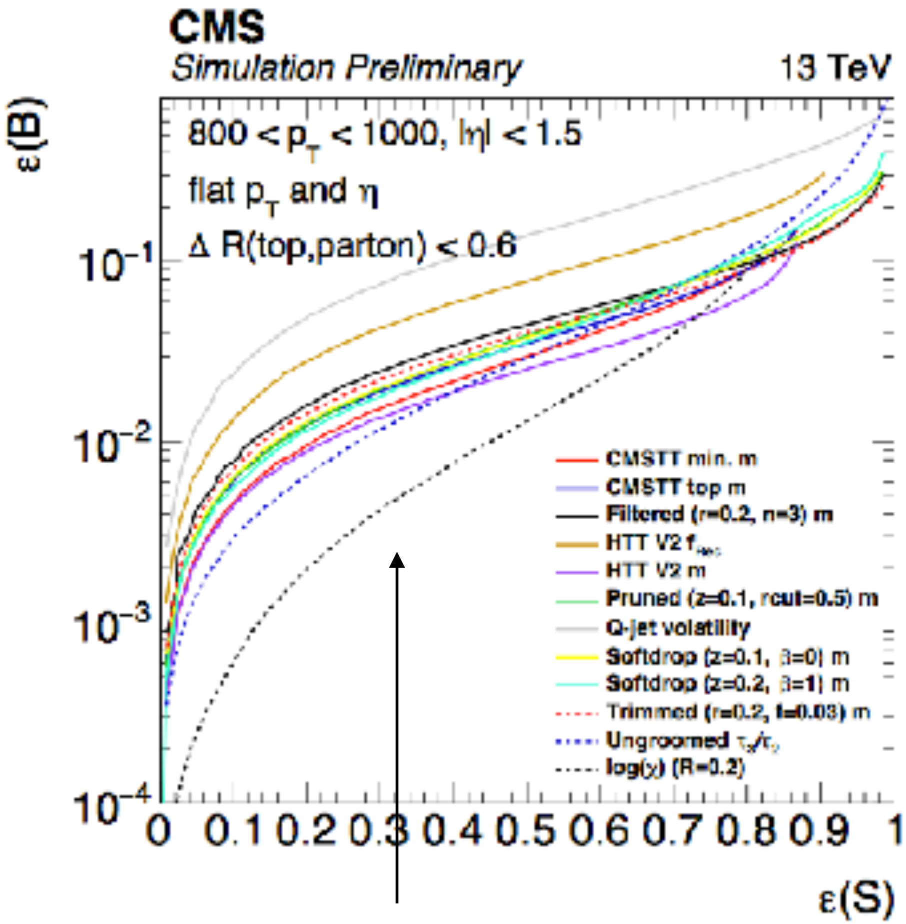




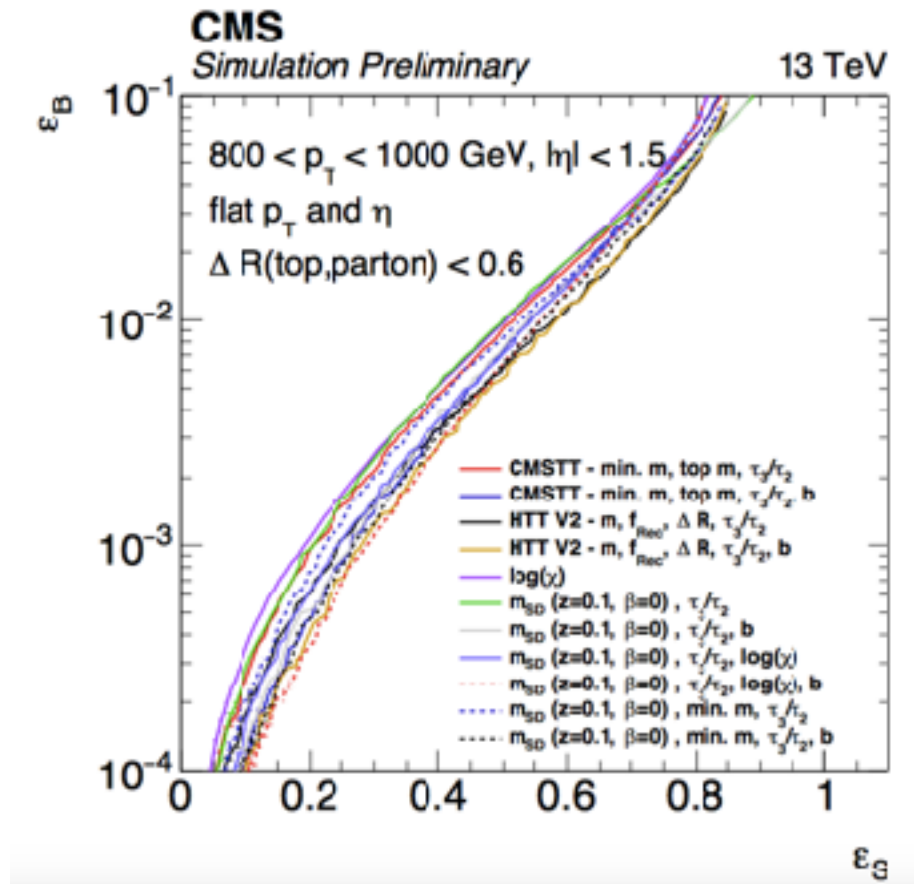


Shower deconstruction improves on best taggers by factor 2-4 in S/B

Results by CMS



- Shower deconstruction best single variable



- Efficiencies matched if taggers combined

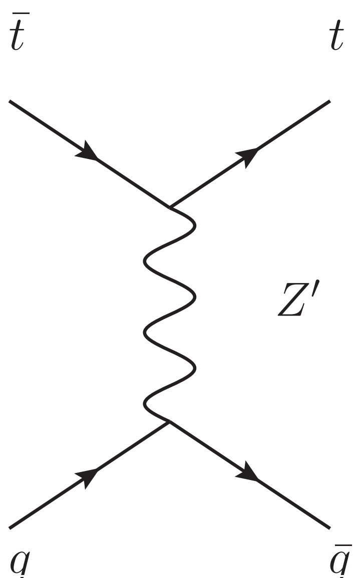
code available at https://www.ippp.dur.ac.uk/~mspannow/shower-deconstruction.html

First application of Event Deconstruction

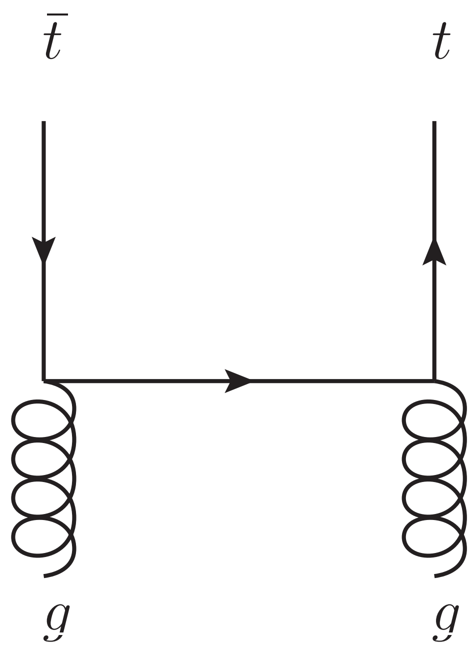
[Soper, MS '14]

fully hadronic Z' -> tt

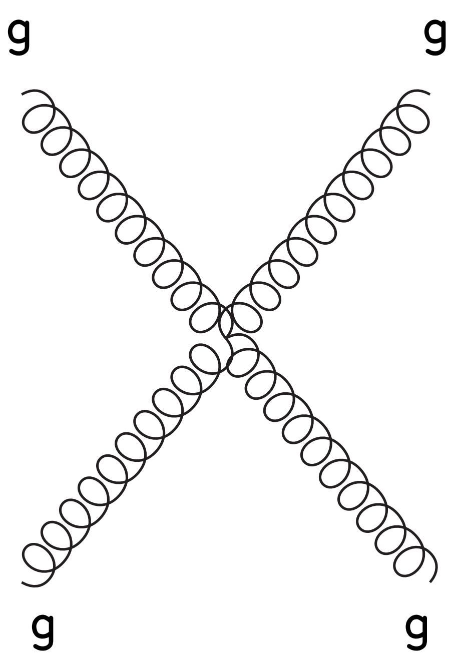
Signal



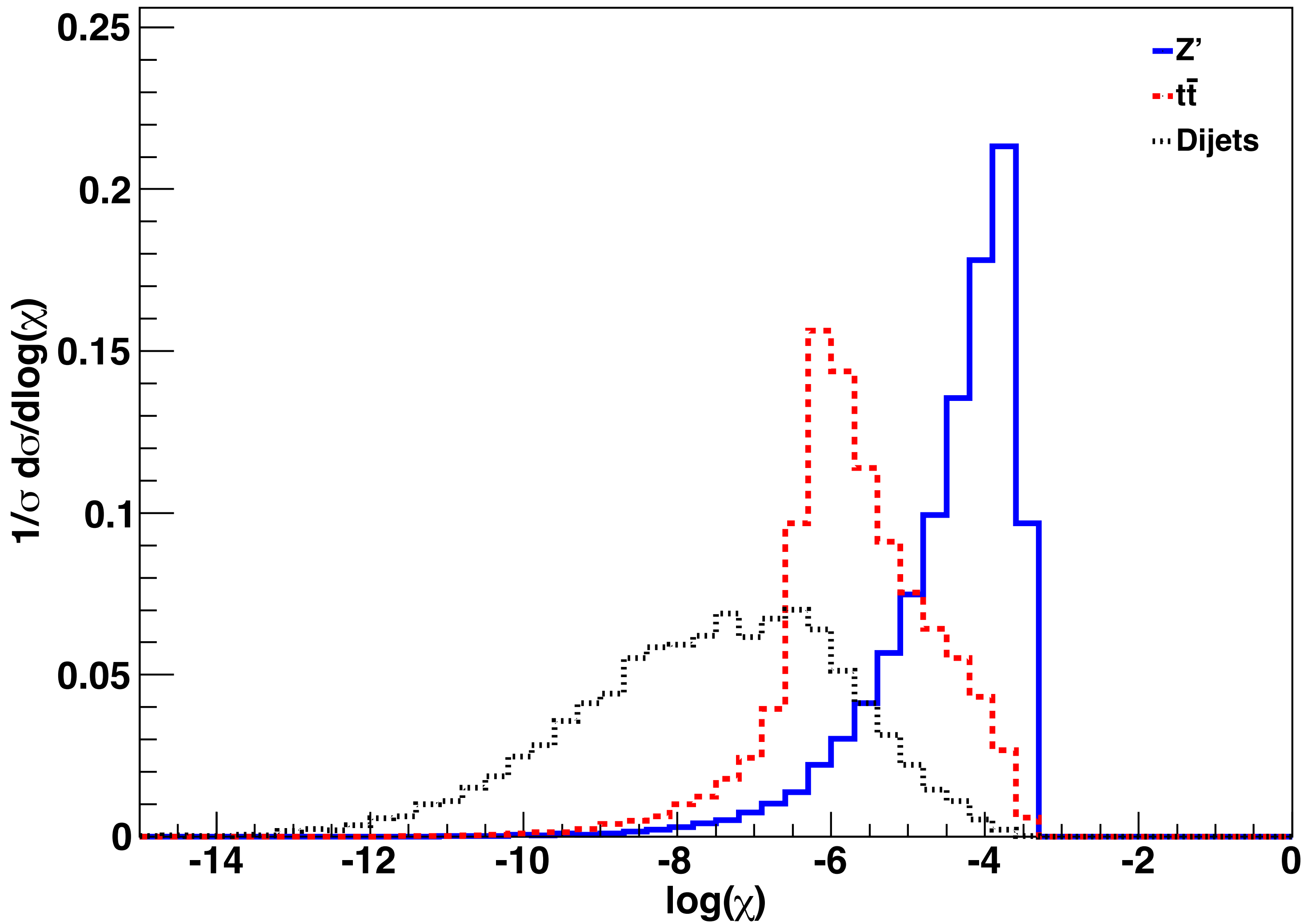
$t\bar{t}$

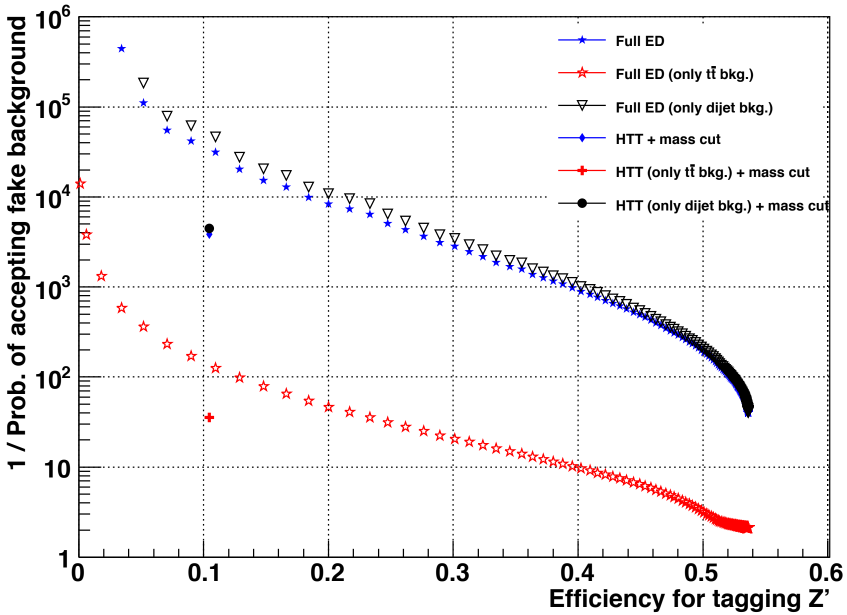


dijets



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

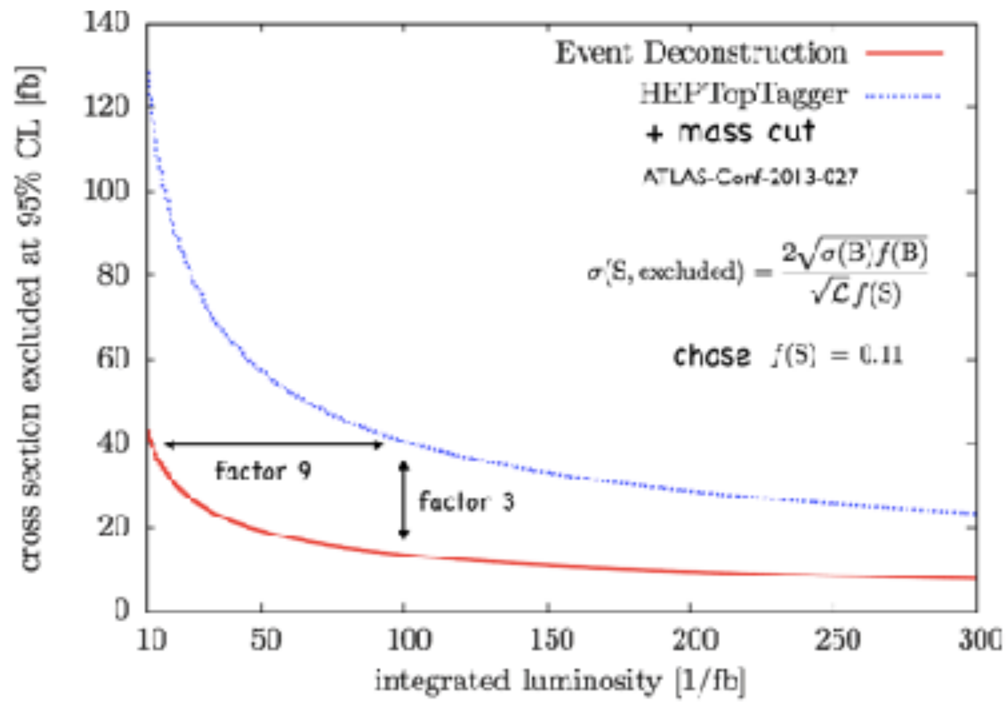




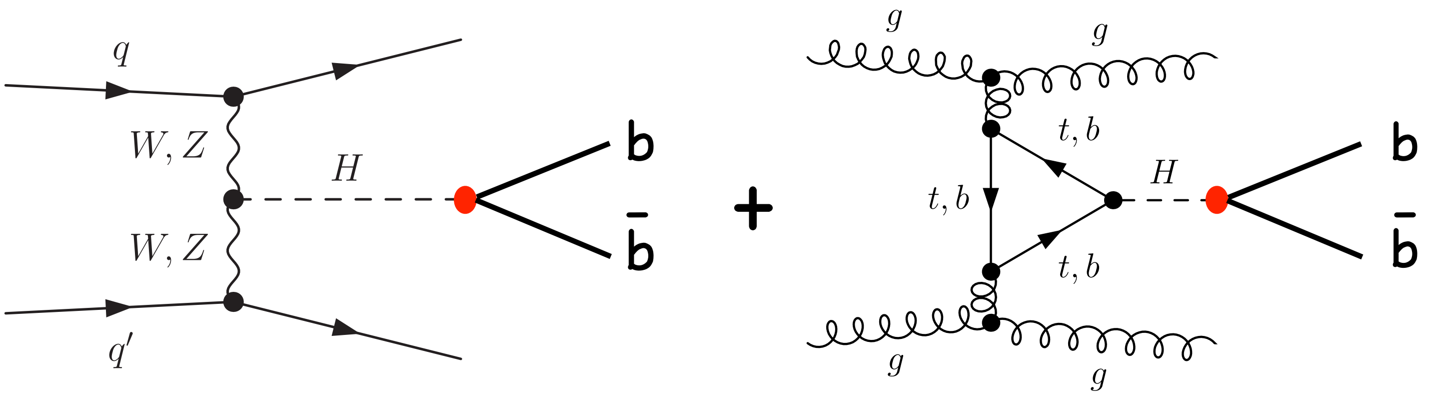
Discovery 9 times faster or for 3 times smaller cross section

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

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



Measuring the Higgs-bottom coupling in VBF



Attempt of cut and count analysis [Mangano, et al '02]

Table 3: Same as Table 1, with $p_T^j > 80$ GeV.

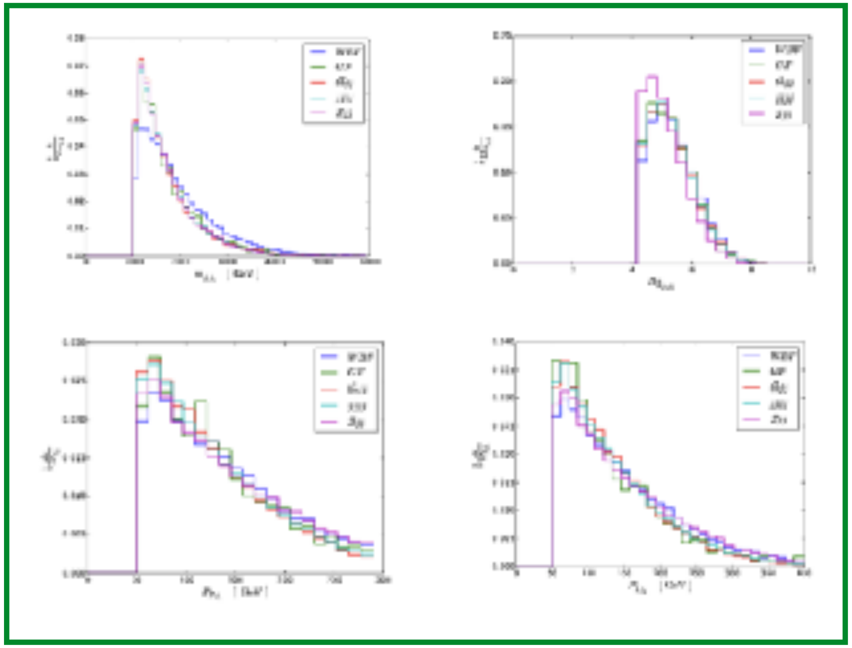
m_H	115 GeV	120 GeV	140 GeV
Signal	1.3×10^3	1.2×10^3	5.2×10^2
$b\bar{b}jj$	2.4×10^5	2.3×10^5	1.9×10^5
$j_b j_b jj$	2.6×10^3	2.3×10^3	1.8×10^3
$(Z^*/\gamma^* \to b\bar{b})jj$	1.1×10^2	6.6×10^1	1.3×10^1
$(Z \to b\bar{b})_{\mathrm{res}}jj$	6.2×10^2	3.4×10^2	0.5×10^1
$j_b j \oplus j_b j$	2.9×10^2	3.2×10^2	4.5×10^2

S/B ~ 1/200

Will render channel due to systematic uncertainties insensitive

Higgs-bottom difficult to measure

- Add new channel to measure this coupling:

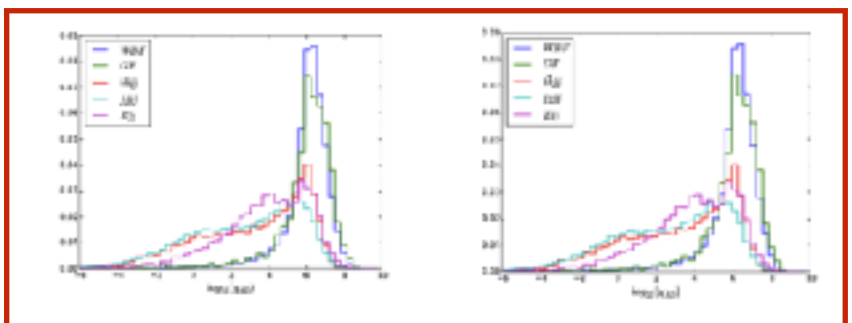


[Englert, Mattelaer, MS '15]

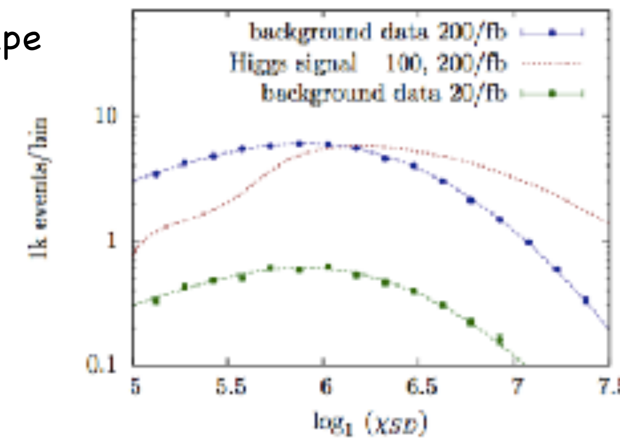
		WBF	GF	$b\bar{b}jj$	Zjj	$jjjj$
(i)	fat jet	48.50	17.32	205109	553.16	$2.23 \cdot 10^7$
(ii)	wbf cuts	21.23	4.11	48441.9	127.98	$5.18 \cdot 10^6$
(iii)	mercedes star	18.44	2.82	31874.5	84.975	$3.39 \cdot 10^6$
(iv)	fatjet b-tags	4.59	0.578	3800.99	12.57	323.74

Standard cuts are not discriminative enough

However, matrix element and shower still discriminative



Exploit shape



$0.82 < y_b/y_b^{\rm SM} < 1.14$ with 600 ifb

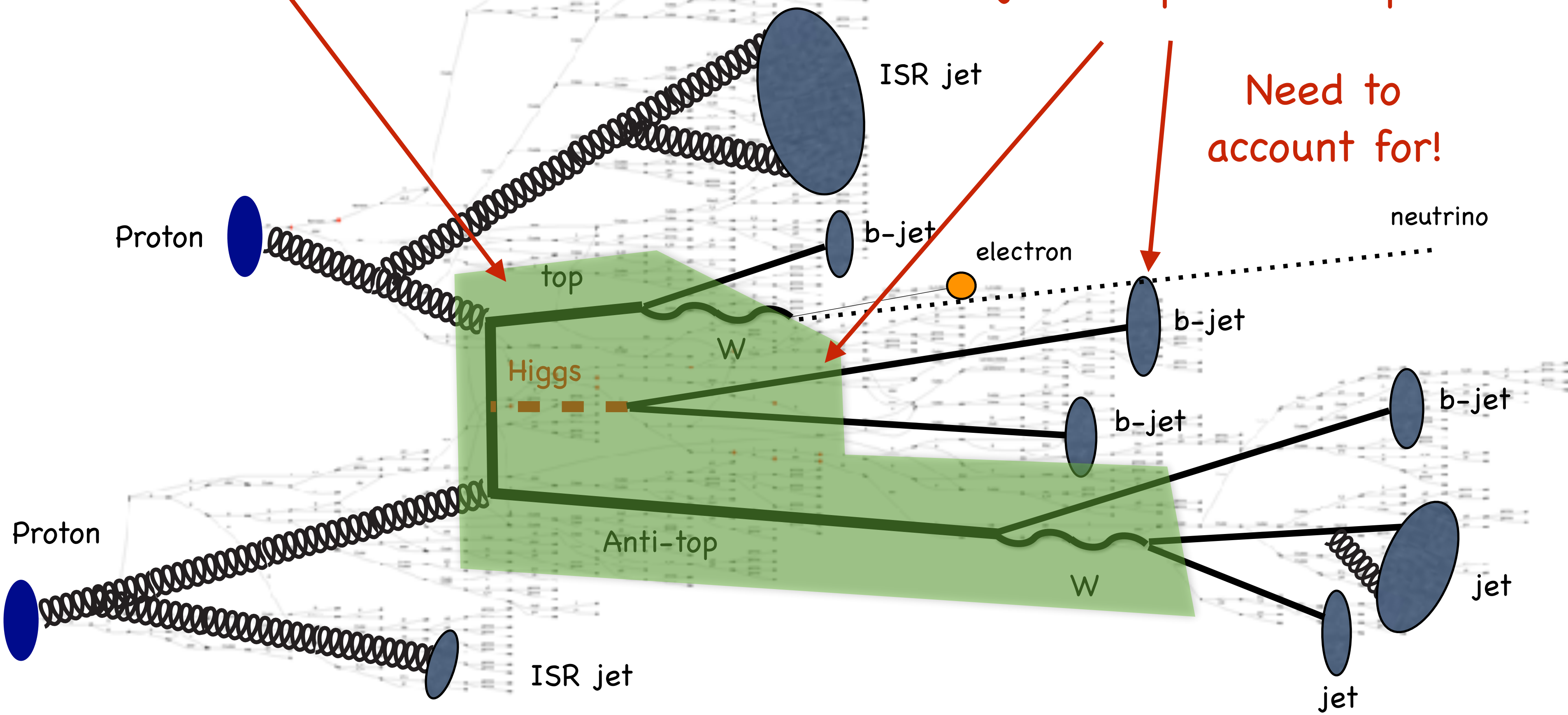
tth: di-lepton vs semileptonic channel

[Artoisenet et al. PRL 111 (2013)]

Hard Interaction

Matching between 4-momentum of jet and parton not perfect

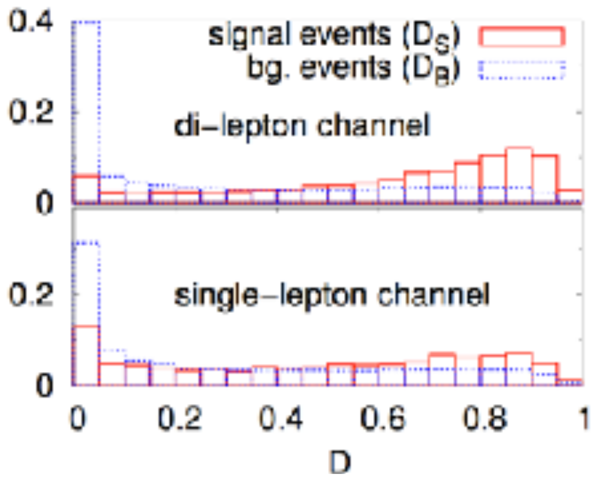
Need to account for!



- Analysis with 4 b-jets and std reconstruction as input to MEM
- Full integration over invisible particles

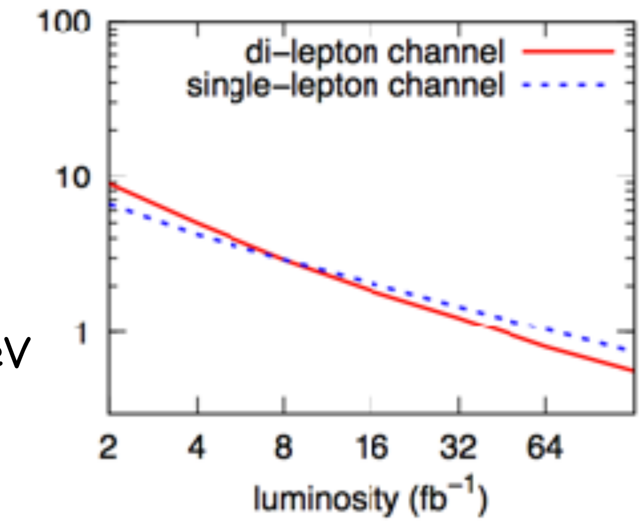
[Artoisenet et al. PRL 111 (2013)]

process	incl. σ	efficiency	σ^{rec}
$t\bar{t}h$, single-lepton	111 fb	0.0485	5.37 fb
$t\bar{t}h$, di-lepton	17.7 fb	0.0359	0.634 fb
$t\bar{t}$+jets, single-lepton	256 pb	0.463×10^{-3}	119 fb
$t\bar{t}$+jets, di-lepton	40.9 pb	0.168×10^{-3}	6.89 fb



$$D_i = \frac{P(x_i|S)}{P(x_i|S) + P(x_i|B)}$$

Projection at 14 TeV



- Using Matrix Element Method di-lepton channel as or more sensitive than single-lepton channel

- However, single-lepton channel uses standard input, **boosted region not captured** [Plehn, Salam, MS PRL 104 (2009)]

Maximisation vs Integration

- To speed up the evaluation one can maximise over the phase space volume Φ, rather than integrate

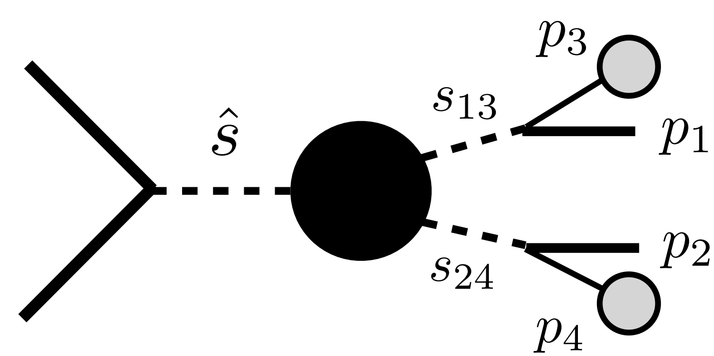
$$w_\alpha(x) = \max_{y \in \Phi} \left(|M_\alpha|^2(y) W(x,y) \right)$$

Generic method for multiple source of MEM

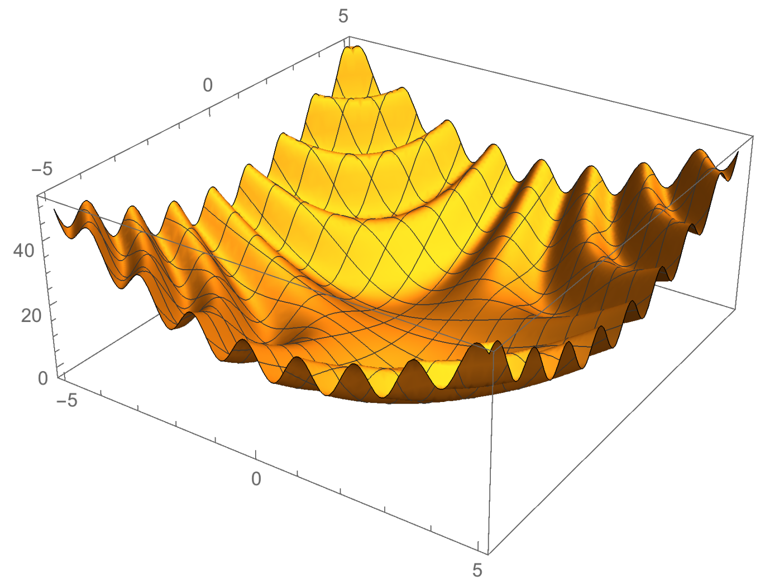
Example: $pp \rightarrow H \rightarrow W^+W^-$ with $W^+W^- \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$

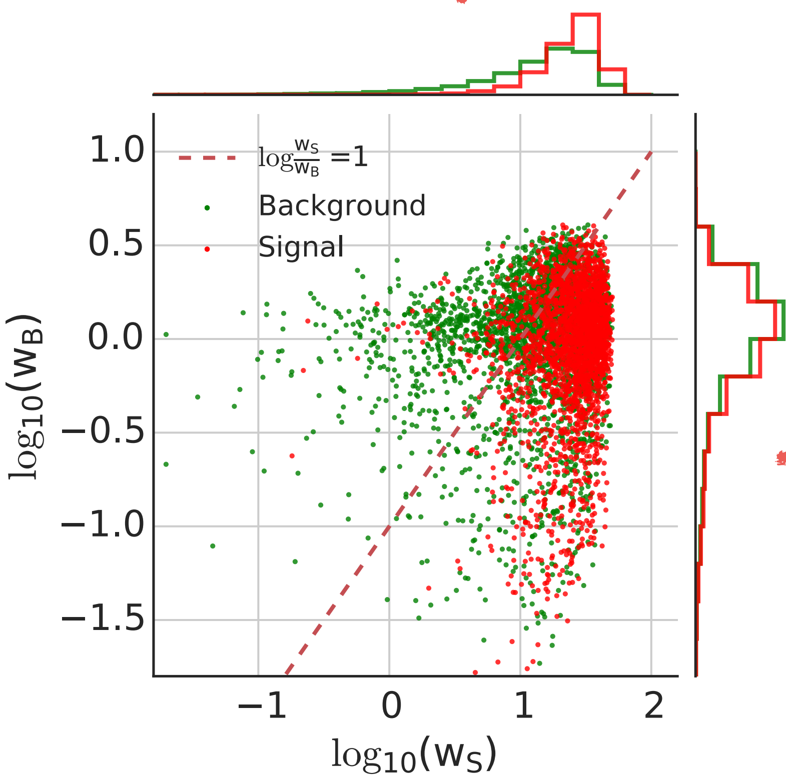
Phase space has 4 free parameters

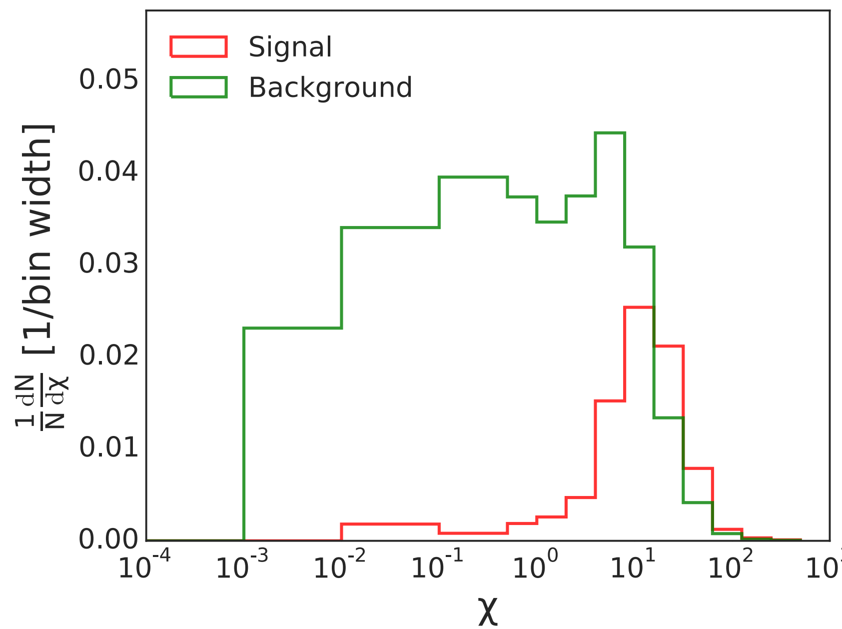
$\hat{s},\ s_{13},\ s_{24},\ y_{\text{all}}$



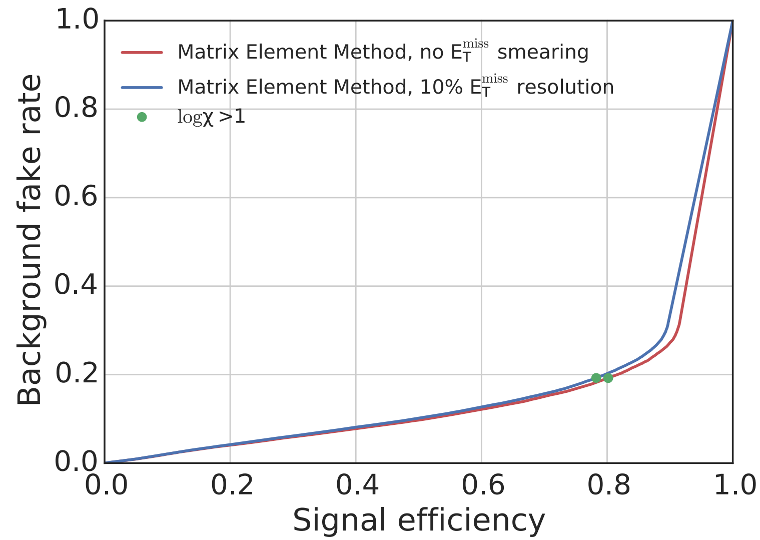
Maximise over phase space repeatedly with different starting conditions to find global minimum







Strong improvement in S/B on top of event selection and purification cuts on visible objects



	Signal	Background	s/b	$s/\sqrt{b}$
Basic event selection cuts	327	11451	0.029	3.058
Assuming perfect E_T^{miss} reconstruction				
Veto $\chi S, B(S,B) = 0$	299	3724	0.080	4.912
$\log(\chi) > 1$	262	2200	0.119	5.592
$\log(\chi) > 1.5$	118	808	0.146	4.157
Assuming a 10% resulution effect in E_T^{miss}				
Veto $w_{S,B}(S,B) = 0$	294	3742	0.079	4.806
$\log(\chi) > 1$	256	2204	0.116	5.455
$\log(\chi) > 1.5$	114	811	0.141	4.016

limit already better than ATLAS combined 7 + 8 TeV data

$g_{H,WW} \in [0.65, 1.25] \times g_{H,WW,SM}$ at 95% CL

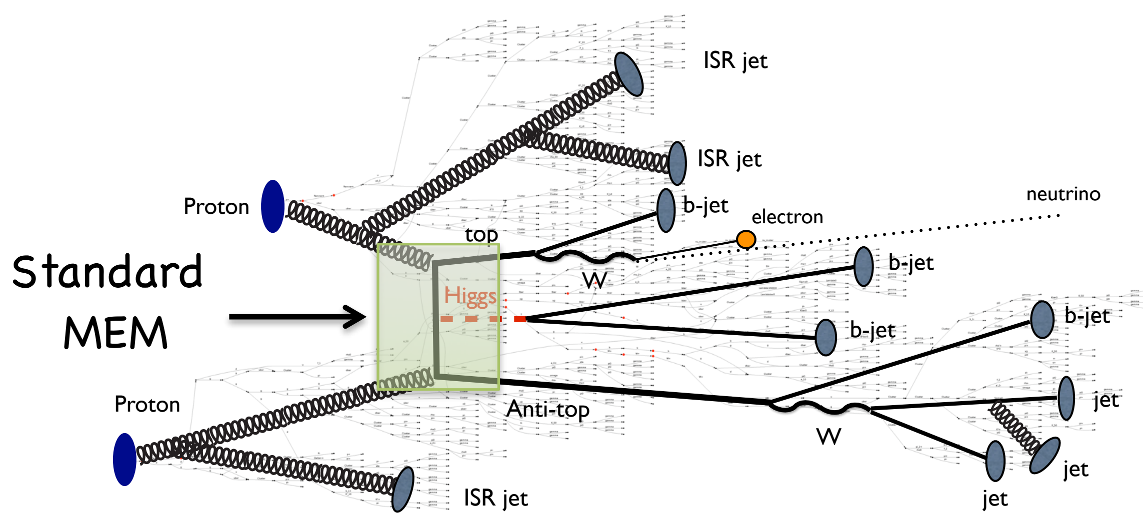
Summary

- Matrix Element Method is active field of research

- Current interest in machine-learning is not taking matrix element methods out of the picture! MEM can help to check MVAs

- MEM can be discovery tool → Cure from Big Mac Blues

- My personal view:



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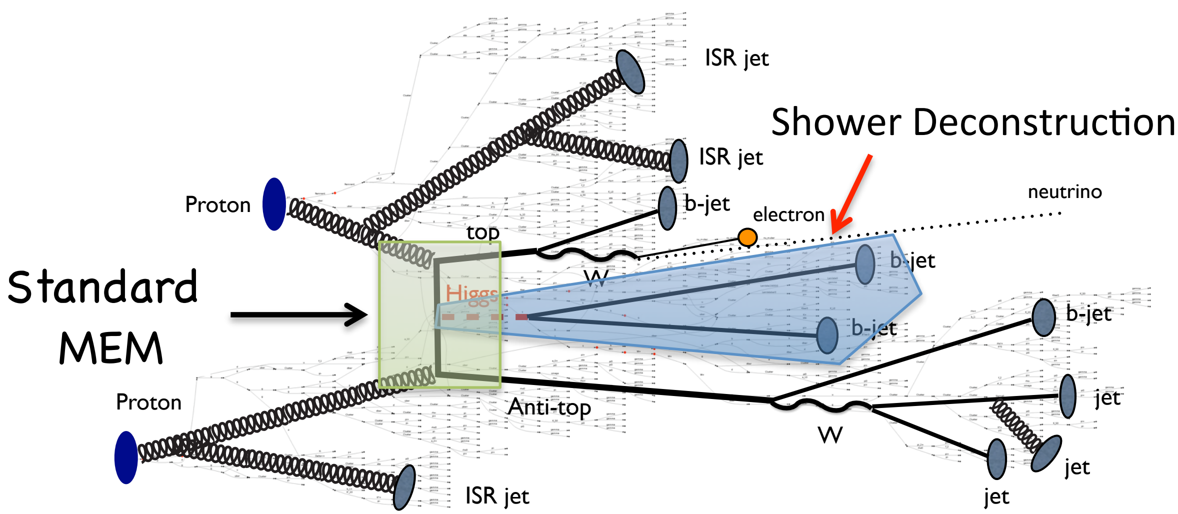

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Future MEM