Boosted tth

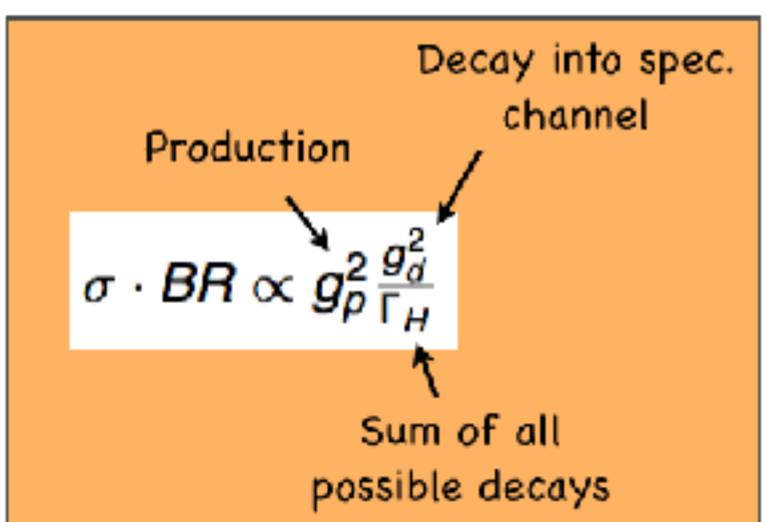
Michael Spannowsky

IPPP, Durham University

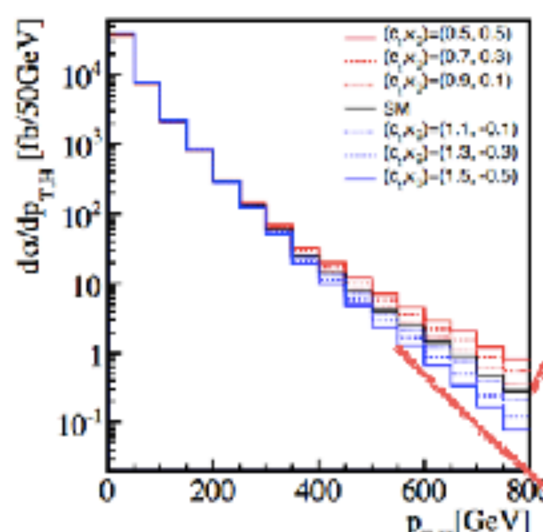
Connecting measurements with UV physics

Kappa Framework	EFT	Simplified Models	Full (UV) Model
• NP models simple rescaling of couplings $\sigma(g_p) \times \mathrm{BR}(g_d)$ • 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



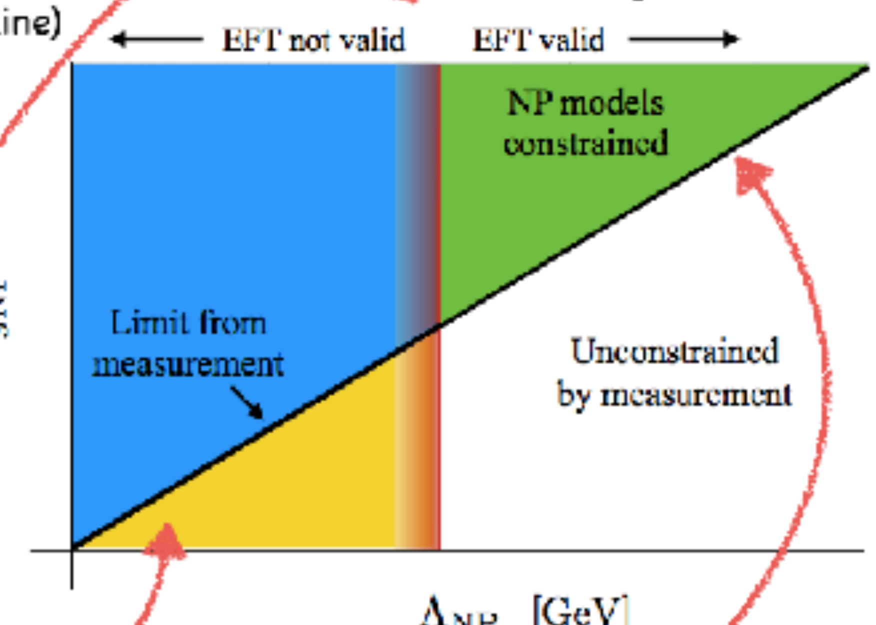
Endpoint of kinematic distribution sets lower cut-off for NP (red line)



shape sets limit on Wilson coefficient (black line)

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

[Englert, MS '14]



Any UV (weakly coupled) models left?

Operators in top-Higgs sector

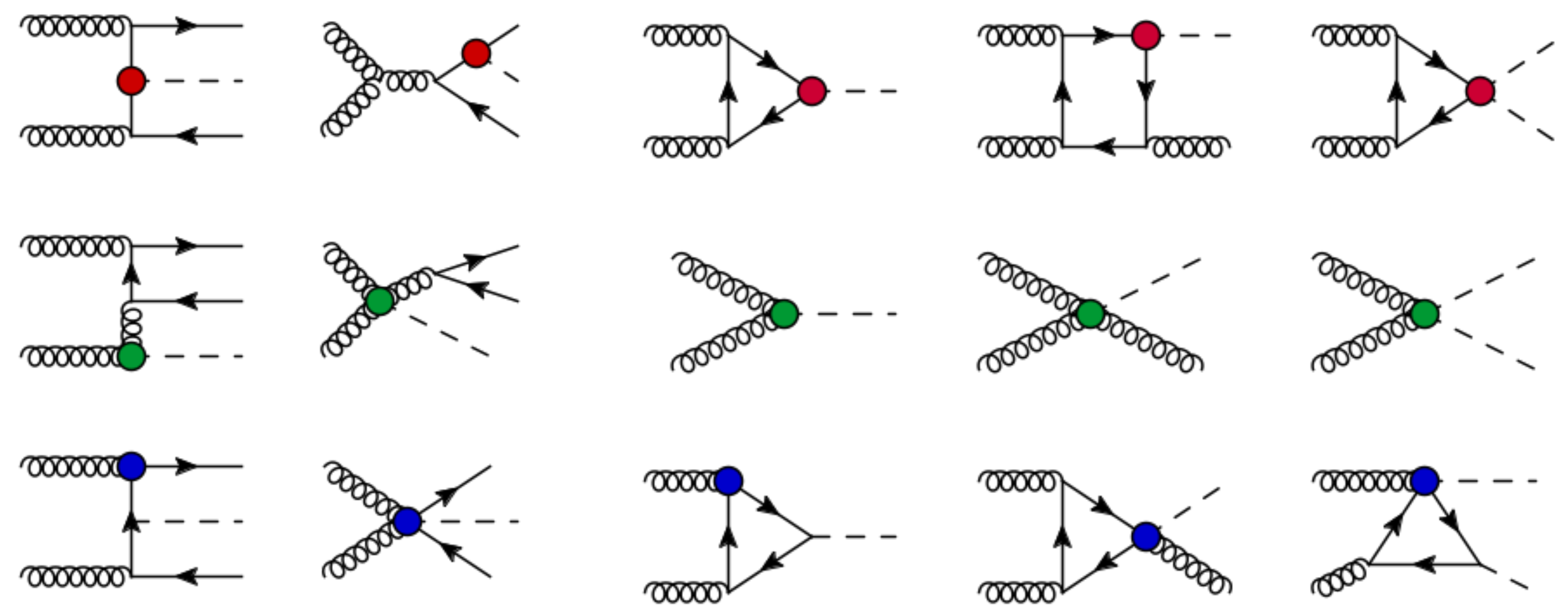
Thanks to Eleni Vryonidou

Starting from a subset:

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q}t\right) \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

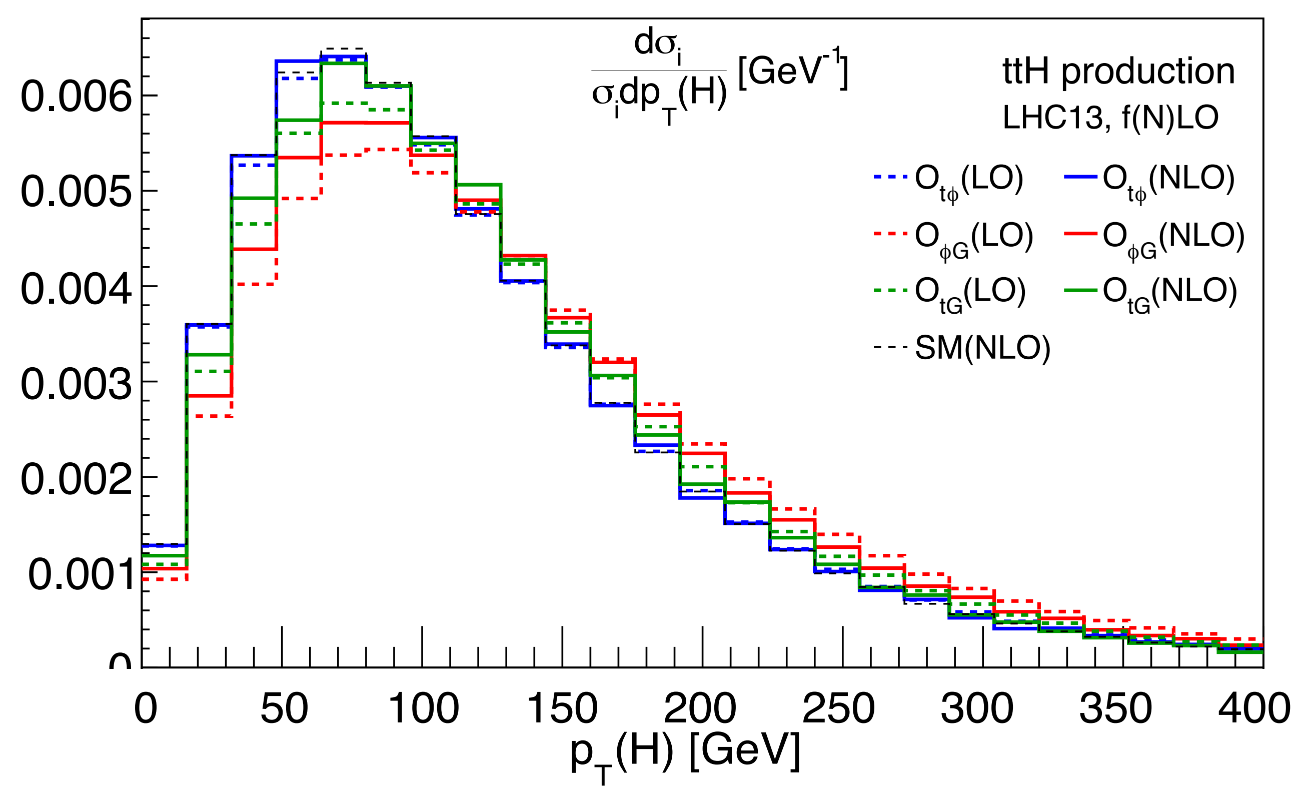
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

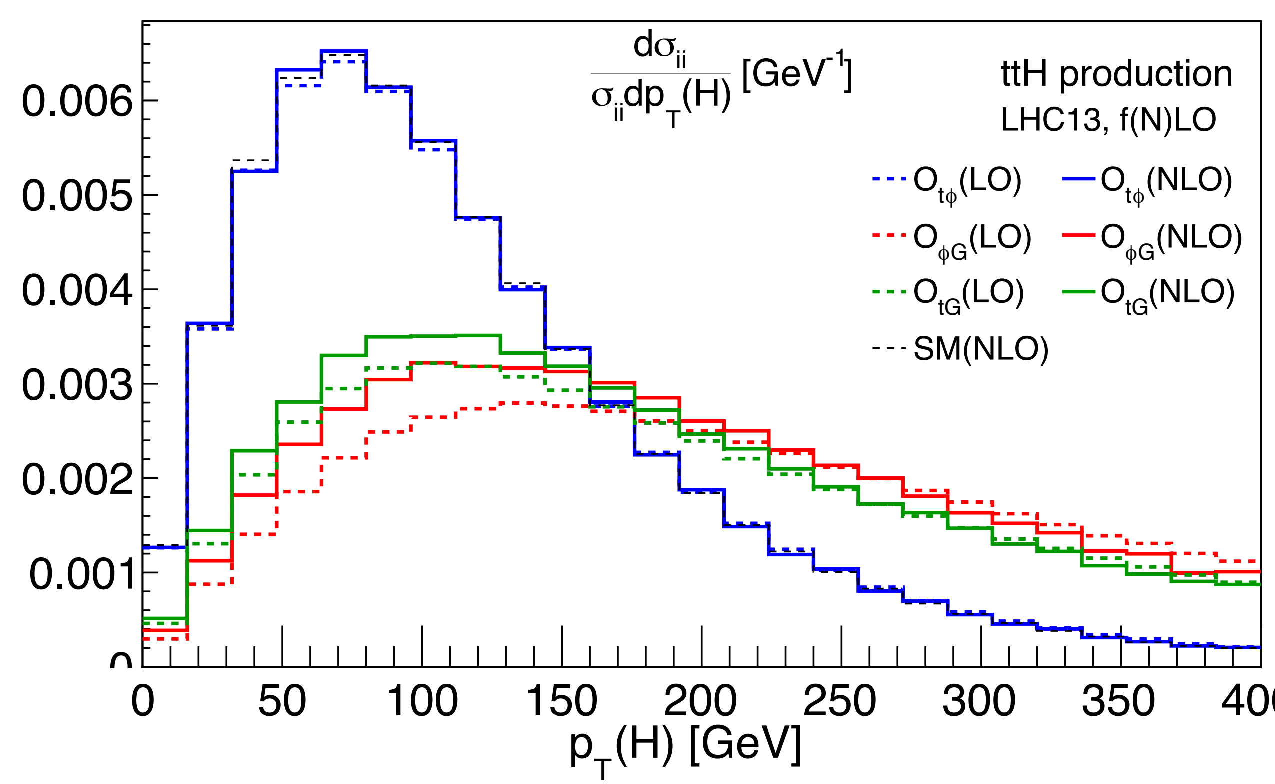


ttH

H, H+j, HH

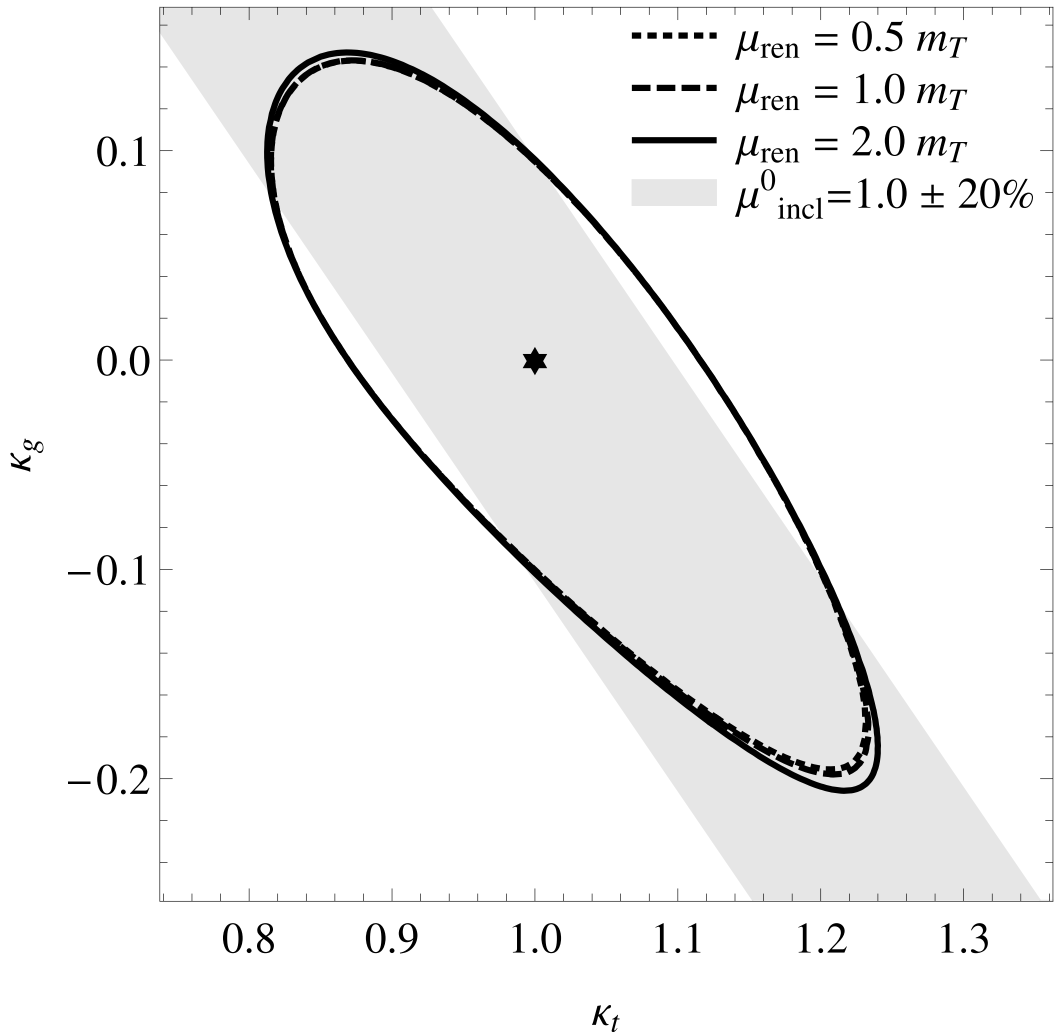
See also
Degrande et al. arXiv:1205.1065
Grojean et al. arXiv:1312.3317
Azatov et al arXiv:1608.00977





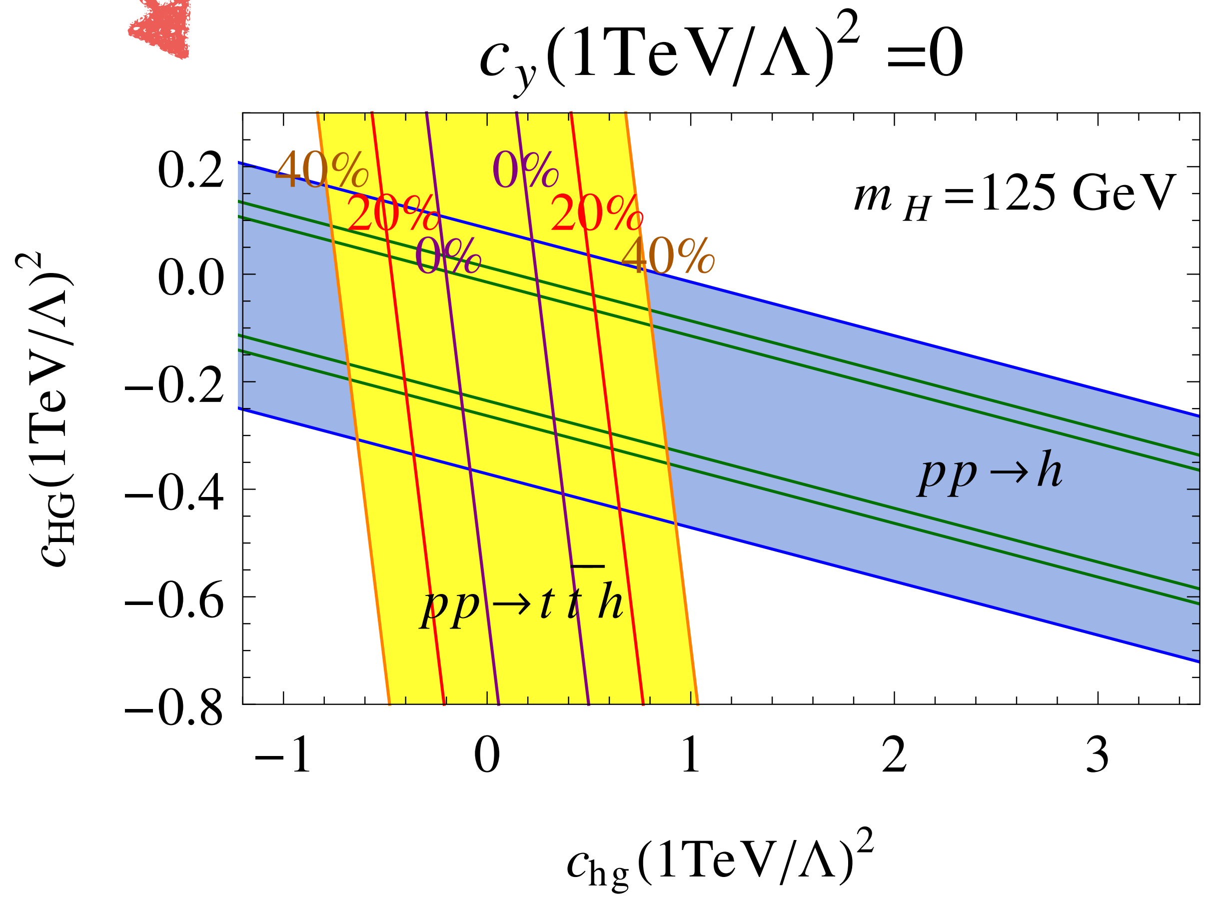
Problem flat direction
flat direction

tth breaks degeneracy



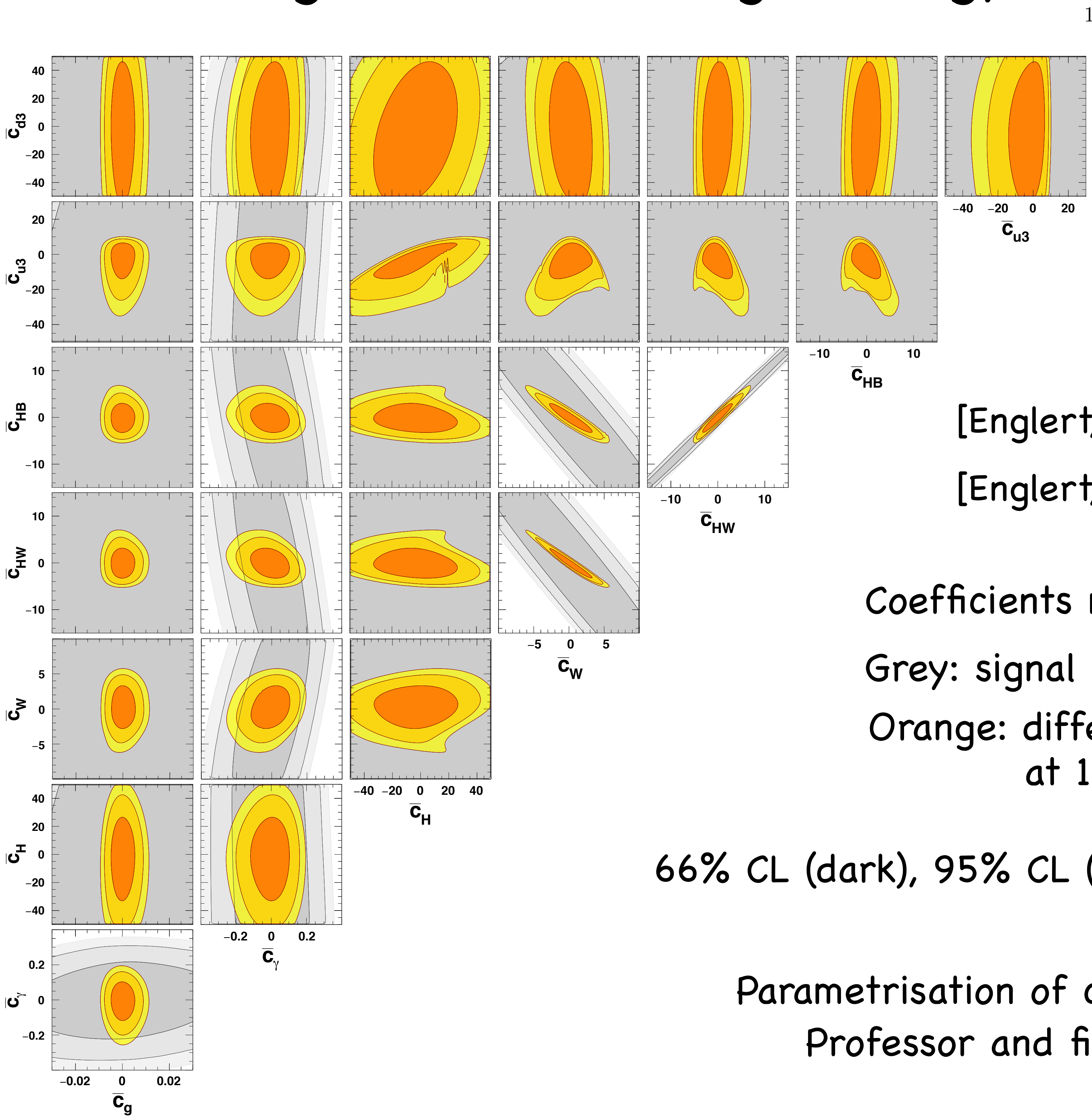
[Grojean, Salvioni, Schlaffer '13]

[Schlaffer, MS, Weiler, Takeuchi '14]



[Degrande, Gerard, Maltoni, Servant '13]

Boost is huge benefit for high-energy hadron collider



[Englert, Kogler, Schulz, MS '15]

[Englert, Kogler, Schulz, MS '17]

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

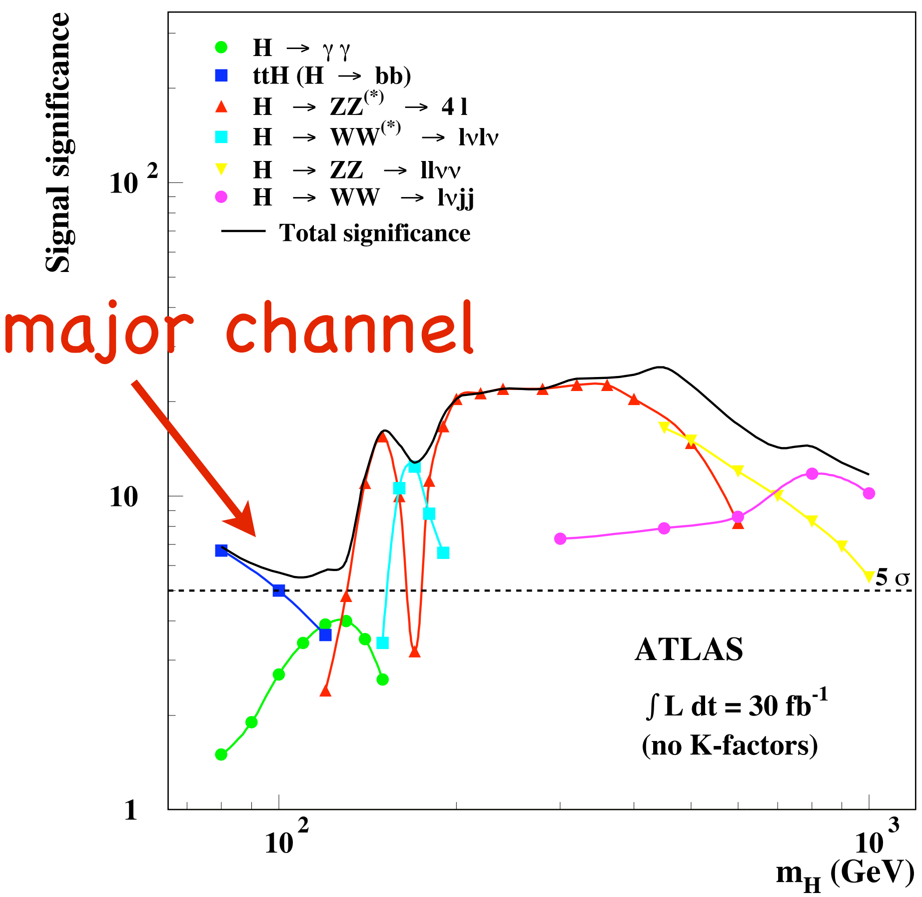
tth

as busy as it gets in the SM

Motivation:
- sizable cross-section
- Higgs discovery contribution in low mass range
- access to t- and b-Yukawa couplings

High expectations:

tth major channel



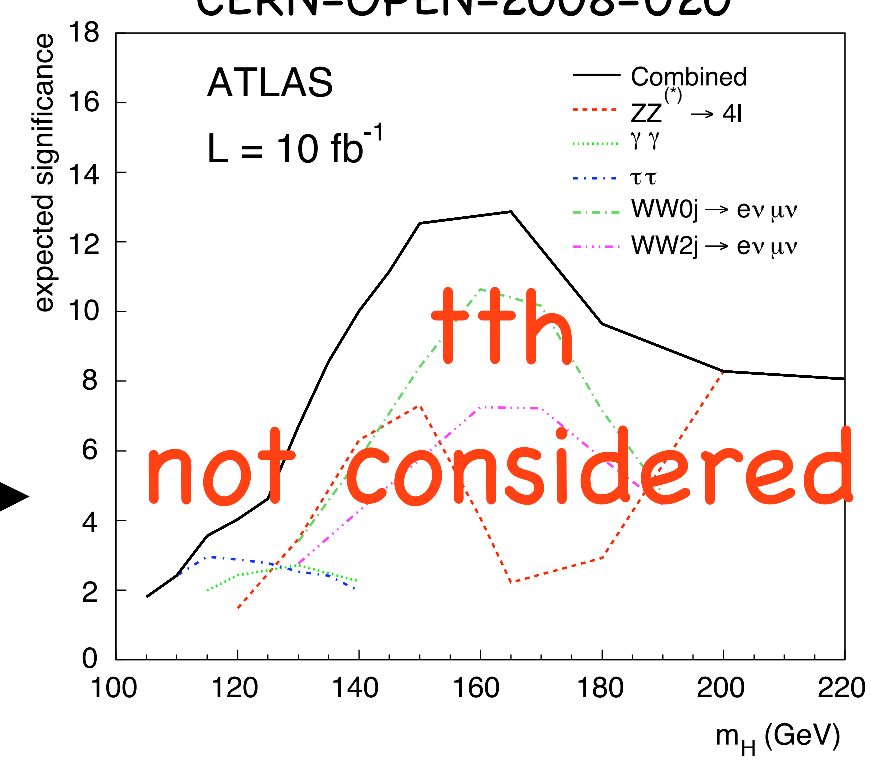
[ATLAS TDR 1999]

Cammin and Schumacher (ATLAS)

$S/B \simeq 1/9$

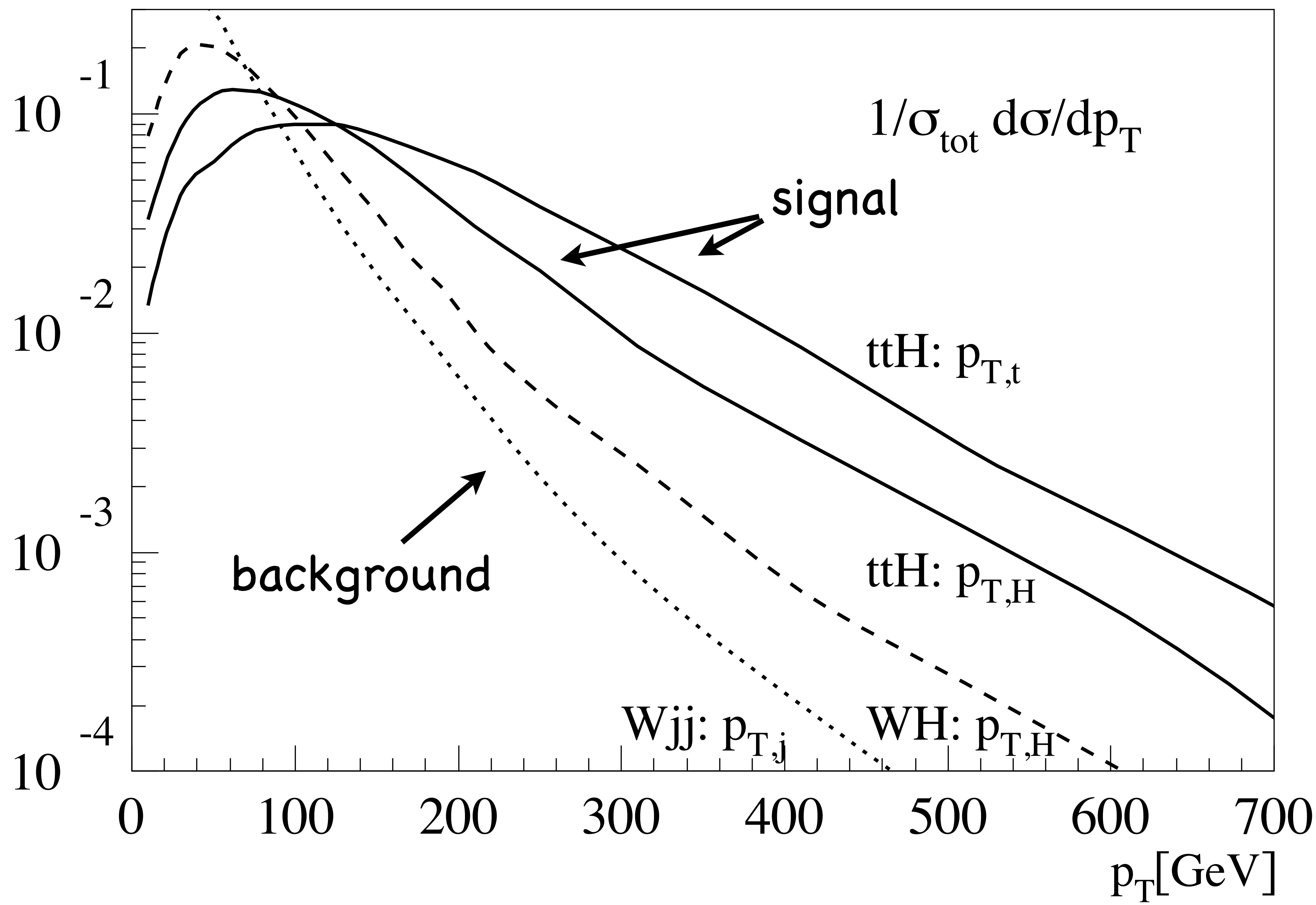
$S/\sqrt{B} \simeq 2.2$

Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020



pT distributions relevant for tth

[Plehn, Salam, MS '09]



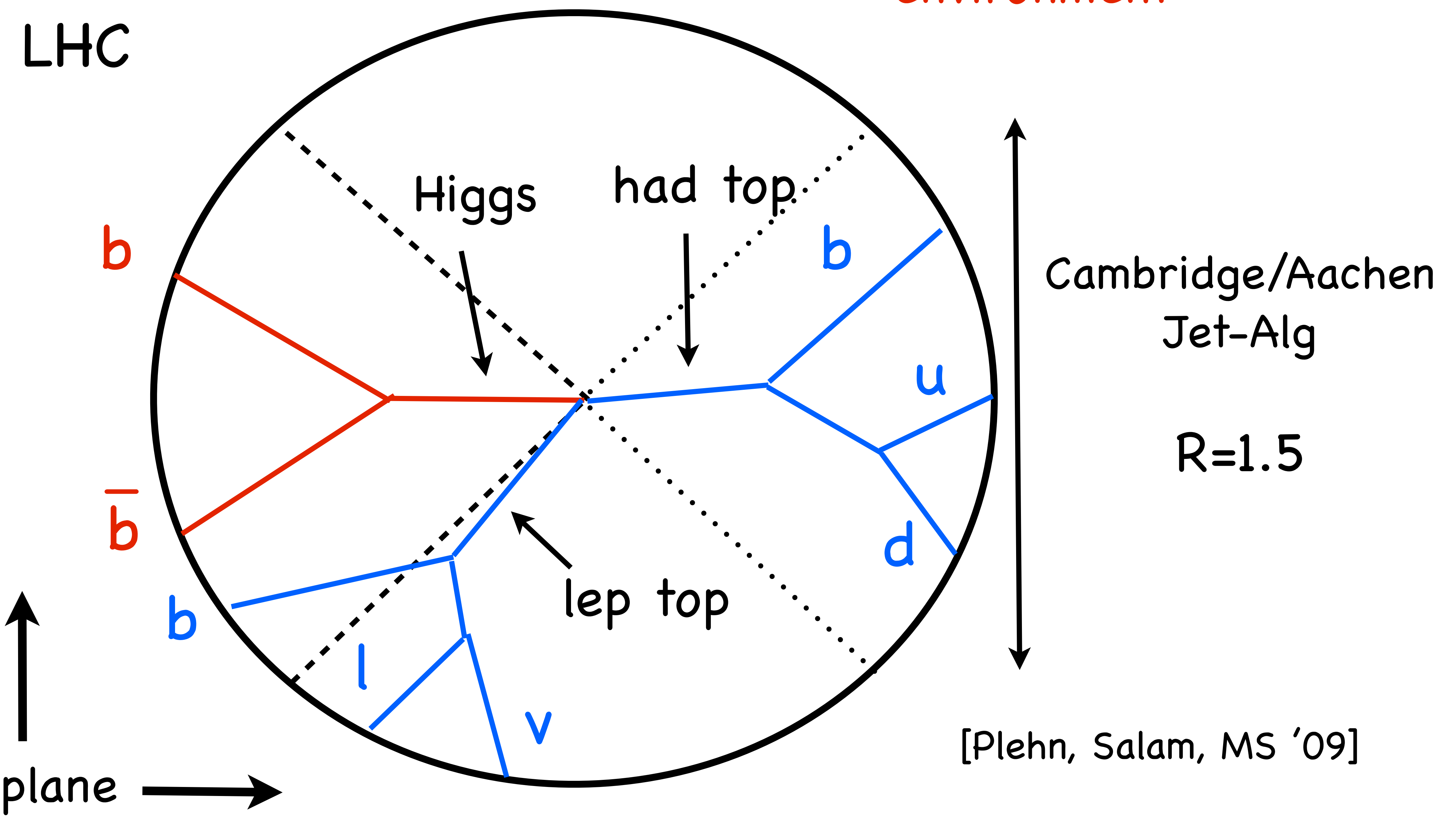
Problems in event reconstruction:

- (b-)jet multiplicity
- reconstruction efficiency

Boost should help

but

need tagger for this environment



[Plehn, Salam, MS '09]

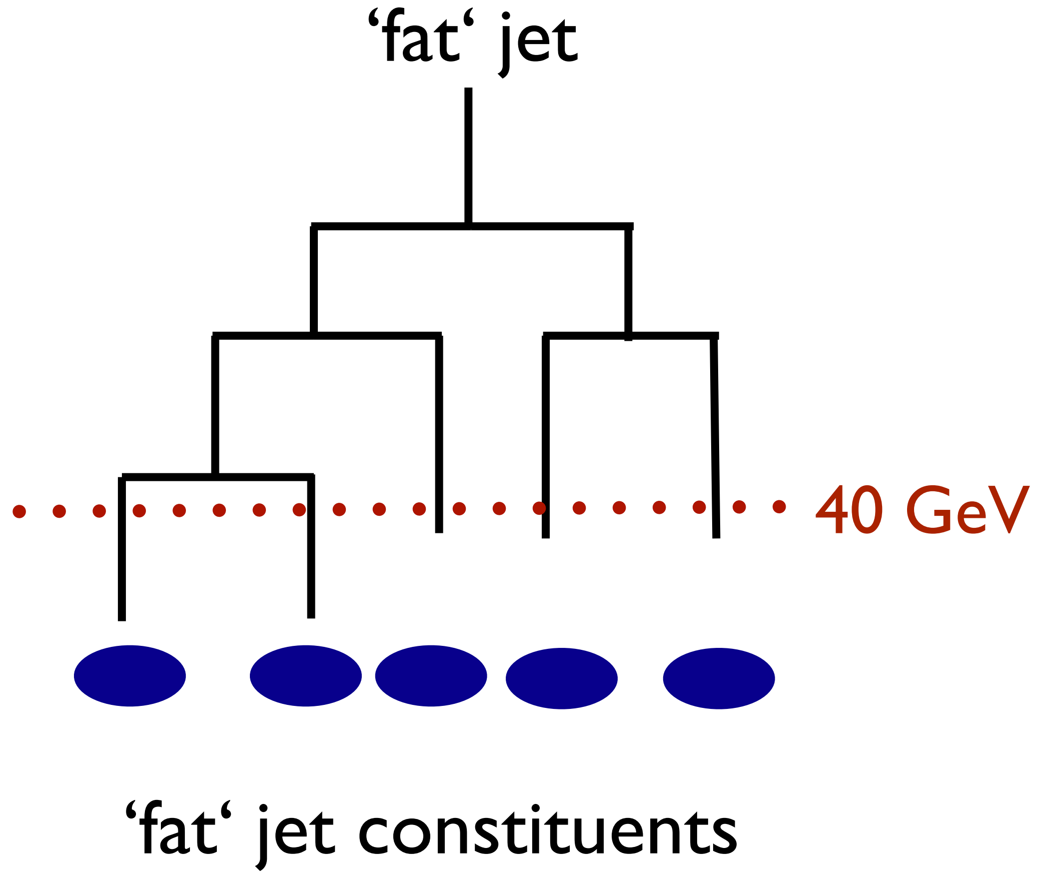
Higgs tagger

Start with ‘fat jet‘

Reverse merging procedure with the condition $\max m_j^{\rm soft} < 0.8\, m^{\rm hard}$

Sort the constituents according to $J = p_{T,1} p_{T,2} \left(\Delta R_{12}\right)^4$ and book the first three combinations after filtering

Ask for two b-tags in the reconstructed Higgs jet



HEPTopTagger - a low-pT Tagger

(Plehn, Salam, MS, Takeuchi)

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

II. Find hard substructure using mass drop criterion

Undo clustering, $m_{j_1} < 0.8\, m_j$ to keep j_1 and j_2

III. Filter and choose pairing

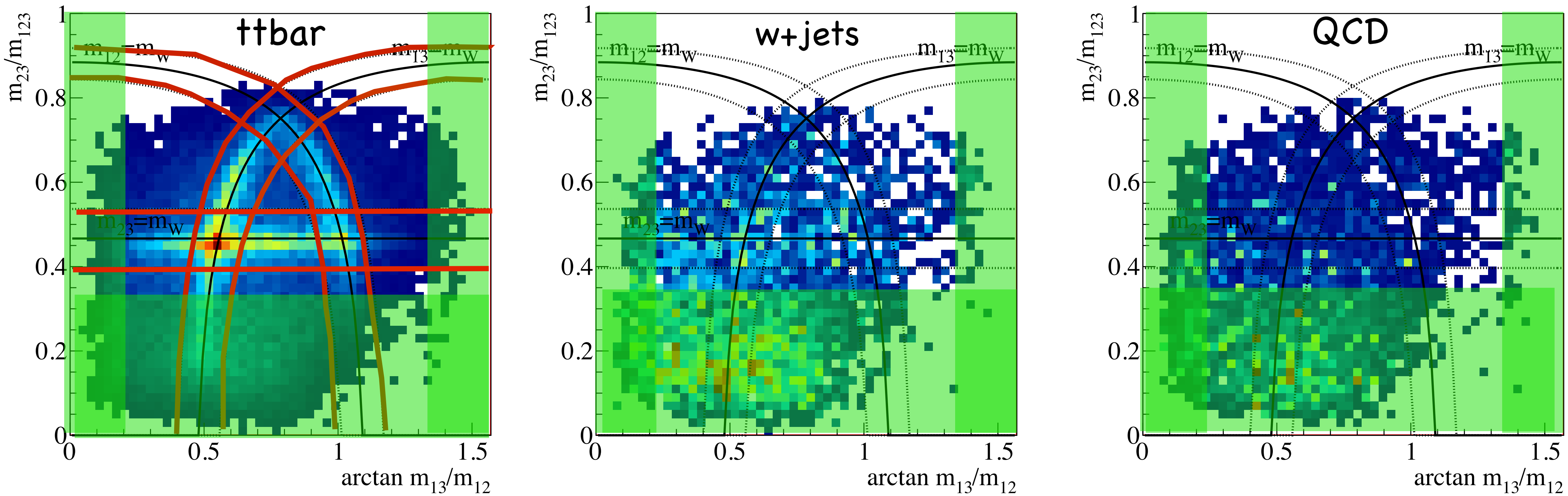
Take 3 hard objetcs, filter them, take 5 filered subjets, keep pairing with best top mass

top candidate $|m_{jjj} - 172.3\ \mathrm{GeV}| < 25\ \mathrm{GeV}$

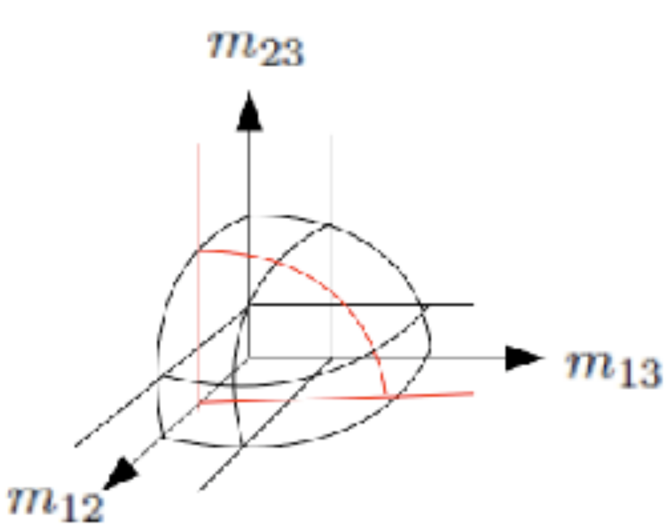
no b-tag, no W mass cut yet

IV. check mass ratios

Cluster top candidate into 3 subjets j_1, j_2, j_3



$$m_t^2 \equiv m_{123}^2 = (p_1+p_2+p_3)^2 = (p_1+p_2)^2 + (p_1+p_3)^2 + (p_2+p_3)^2 = m_{12}^2 + m_{13}^2 + m_{23}^2$$



$$R_{\min} < \frac{m_{23}}{m_{123}} < R_{\max} \quad \text{and} \quad 0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$$

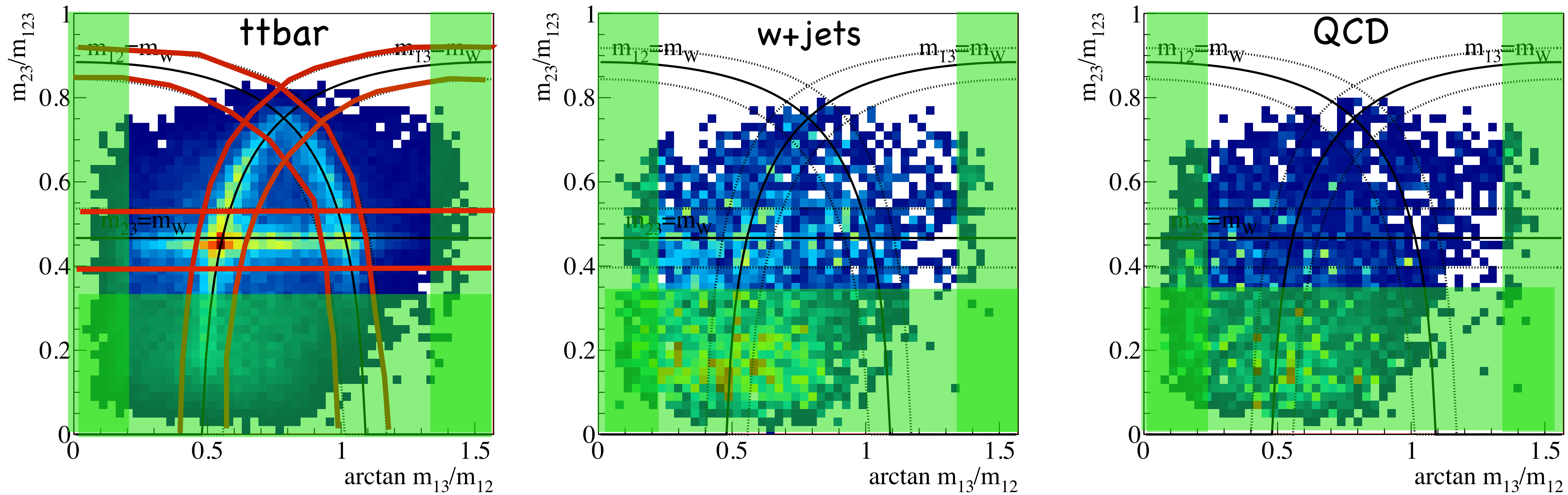
$$R_{\min}^2\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right) < 1-\left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.3$$

$$R_{\min}^2\left(1+\left(\frac{m_{12}}{m_{13}}\right)^2\right) < 1-\left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2\left(1+\left(\frac{m_{12}}{m_{13}}\right)^2\right) \quad \text{and} \quad \frac{m_{23}}{m_{123}} > 0.3$$

$R_{\min} = 85\% \times m_W/m_t \qquad R_{\max} = 115\% \times m_W/m_t$

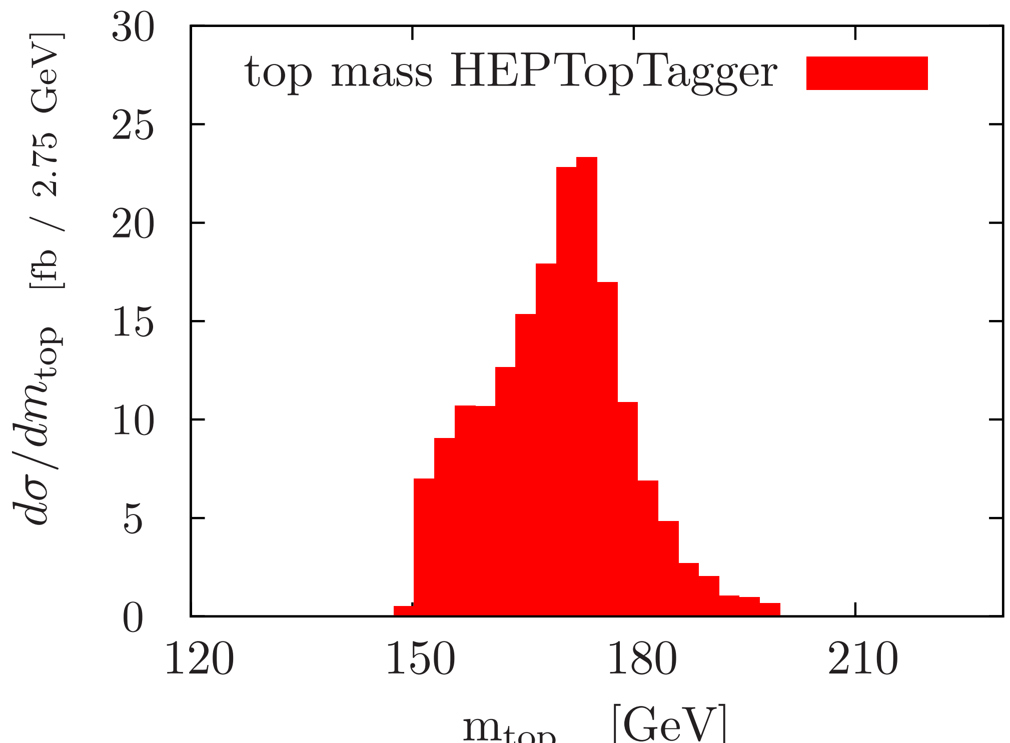
IV. check mass ratios

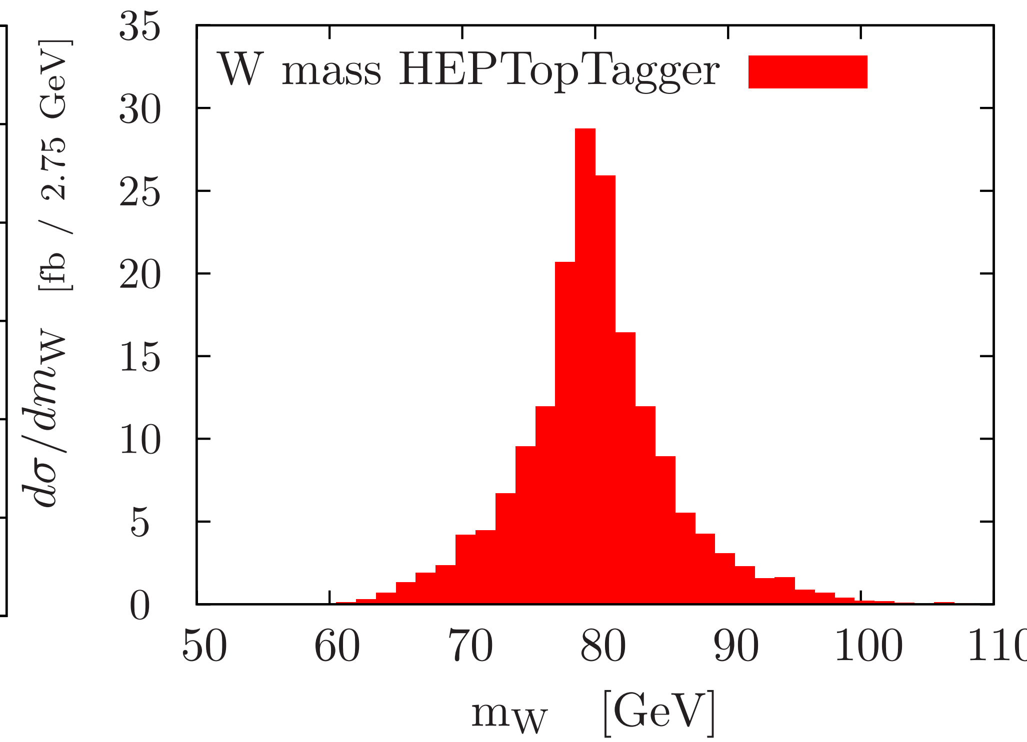
Cluster top candidate into 3 subjets j_1, j_2, j_3



No fix pairing for W mass reconstruction

Only invariants for reconstruction





Analysis proceeds along following lines

Cluster 2 fatjets with R=1.5 CA, pTj > 200 GeV [Moretti, Petrov, Pozzorini, MS '15]

1. Each fatjet tagged as $t_{\rm had}$ or $\text{non-}t_{\rm had}$ by applying HEPTopTagger

   -> require at least 1 top-tag, (2 possible Higgs can be mis-id as top)

2. If more than one top tag use $\Delta m_{\rm tot} \equiv |m_{\rm t,reco} - m_{\rm t}| + \min_{\rm ij}|m_{\rm ij} - m_{\rm W}|$

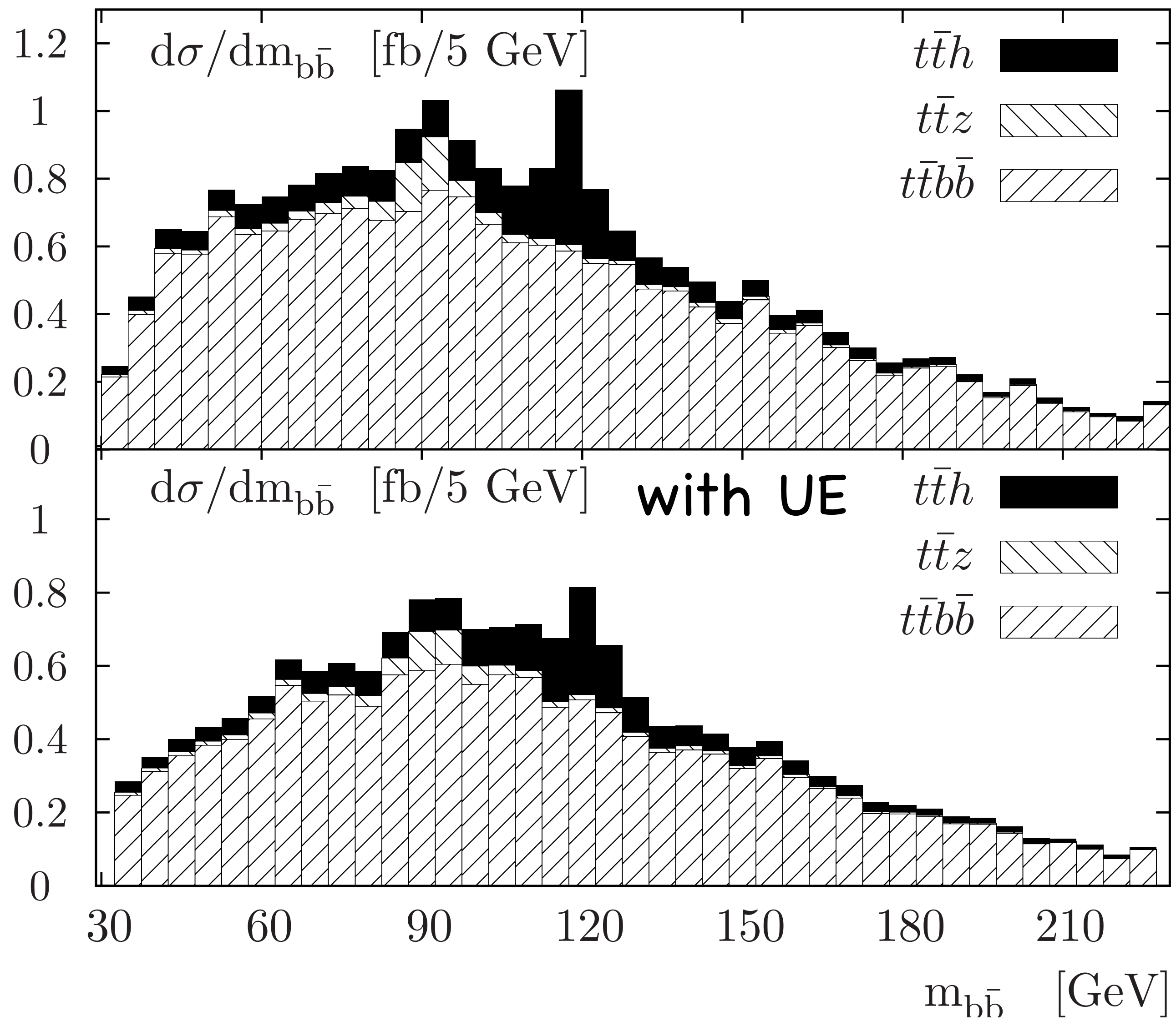
   to identify top candidate

3. For all remaining fat jets use Higgs tagger from [Plehn, Salam, MS '09] to identify the Higgs candidate.
   Require exactly 2 tagged b-jets from filtered subjets

4. Remove tagged Higgs and top constituents and require exactly 1 additional b-tag in the event

5. Identify Higgs if its invariant mass $m_{\rm c}$ is in [100, 130] GeV window

Results for tth



- 5 sigma sign. with 100 1/fb
- Development of Higgs and top tagger for busy final state
- Improvement of S/B from 1/9 to 1/2

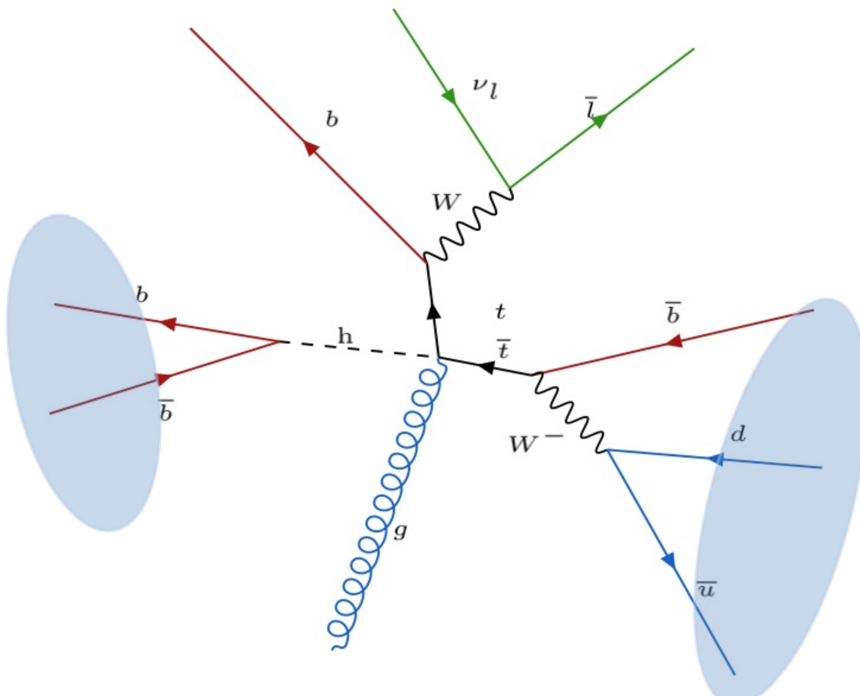
→ tth might contribute to Higgs discovery

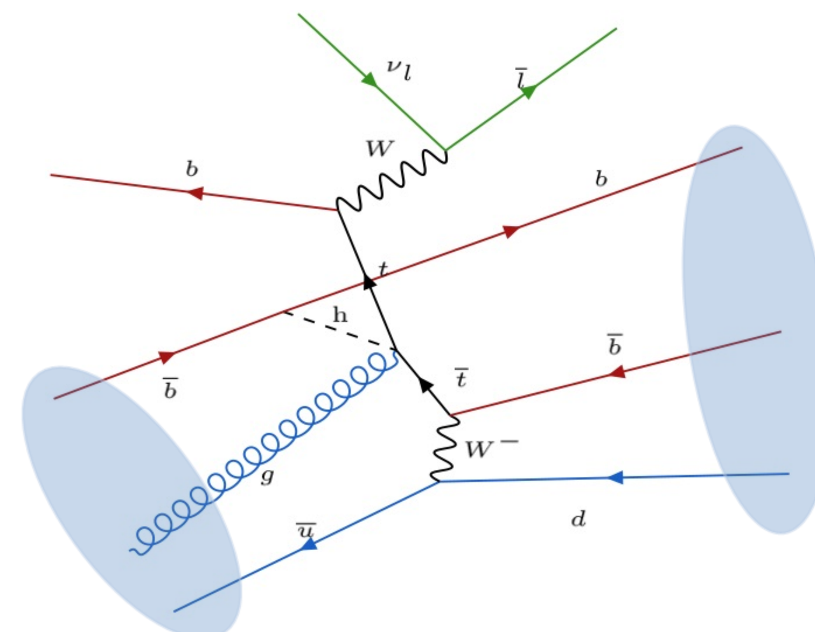
→ tth might be a window to Higgs-top coupling

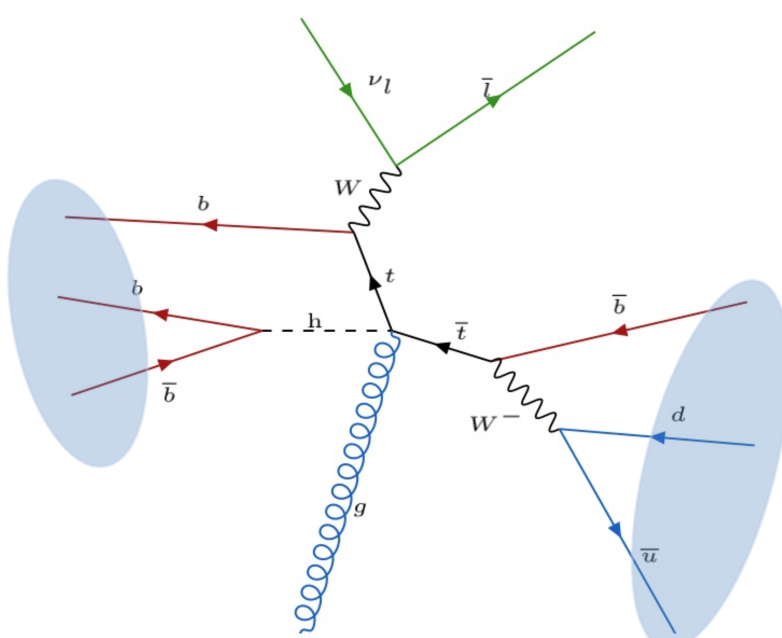
In detail study of configurations contributing to boosted tth

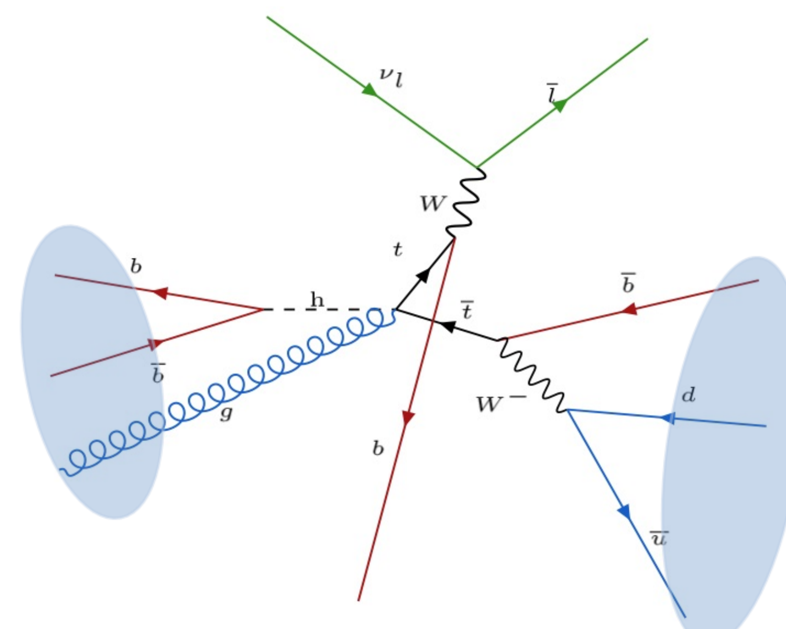
Many different event configurations

[Moretti, Petrov, Pozzorini, MS '15]









Categorisation of top reconstruction from fat jet:

1. $t_{\rm had}$: the hadronic top quark is boosted ($p_{\rm T,t_{had}} > 150\,{\rm GeV}$)
2. $t_{\rm had}$: the hadronic top quark overlaps with the jet ($\Delta R_{\rm jet,t_{had}} < R_{\rm fat}$)
3. $t_{\rm lep} \to b\ell\nu$: the b-quark from $t_{\rm lep}$ belongs to the jet
4. $H \to b\bar{b}$: the harder b from the Higgs belongs to the jet
5. $H \to b\bar{b}$: the softer b from the Higgs belongs to the jet
6. $t_{\rm had} \to bjj$: the b-quark from $t_{\rm had}$ belongs to the jet
7. $t_{\rm had} \to bjj$: the harder light quark from $t_{\rm had}$ belongs to the jet
8. $t_{\rm had} \to bjj$: the softer light quark from $t_{\rm had}$ belongs to the jet

normalised distr. of fat jets

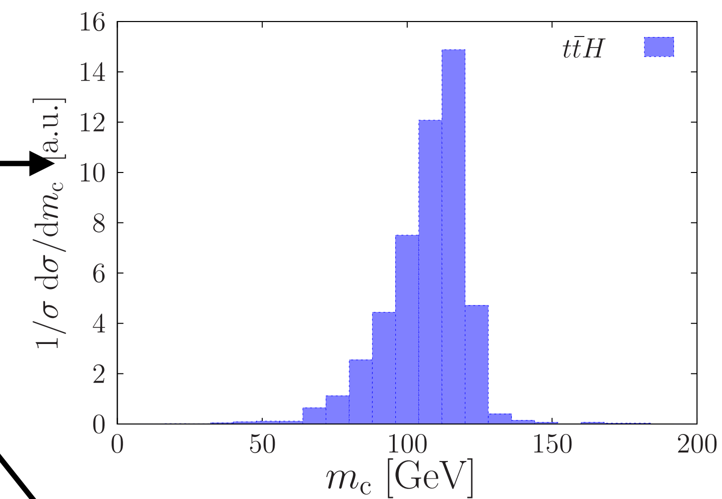
label	bin	before top tag	after top tag	tagging efficiency
A_1	11000111	0.12	0.32	0.40
A_2	11001111	0.03	0.08	0.42
A_3	10111000	0.06	0.07	0.18
A_4	11010111	0.02	0.06	0.40
A_5	11100111	0.02	0.04	0.41
A_6	11011111	0.01	0.04	0.39

HEPTopTagger
eff. very stable

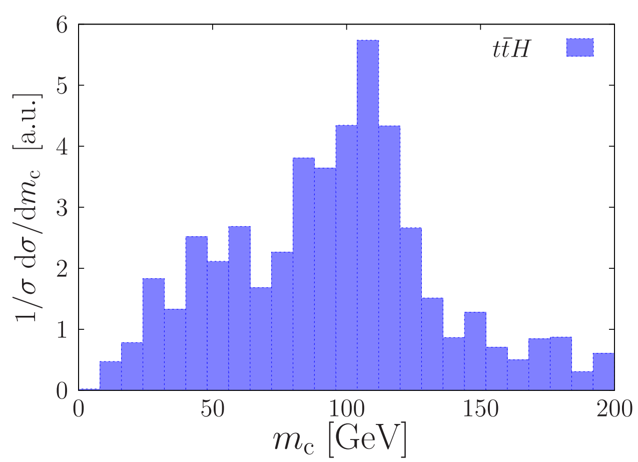
Categorisation of Higgs reconstruction from fat jet:

1. H: the Higgs boson is boosted ($p_{\mathrm{T,H}} > 150\,\mathrm{GeV}$)
2. H: the Higgs boson overlaps with the jet ($\Delta R_{\mathrm{jet,H}} < R_{\mathrm{fat}}$)
3. $t_{\mathrm{had}} \to bjj$: the b quark from t_{had} belongs to the jet
4. $t_{\mathrm{lep}} \to b\ell\nu$: the b quark from t_{lep} belongs to the jet
5. $H \to b\bar{b}$: the number of b-quarks from the Higgs decay the jet contains is 0/1/2
6. $H \to b\bar{b}$: the number of $b\bar{b}$ Higgs candidates in the fat jet is 0/1/3

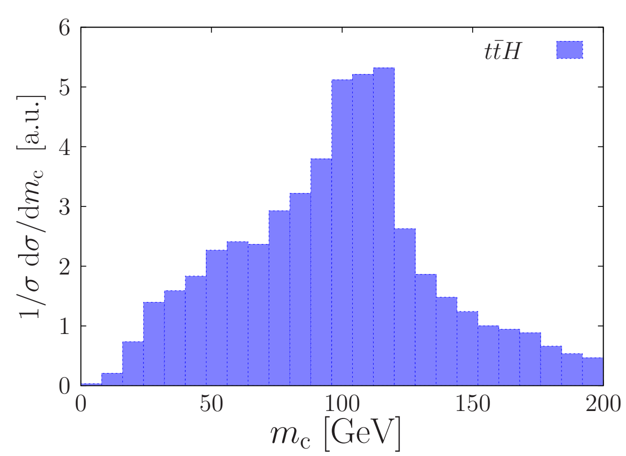
label	bin	before b-tags	after b-tags	after m_c cut	tag efficiency
B_1	110021	0.05	0.08	0.17	0.77
B_2	110023	0.10	0.16	0.24	0.53
B_3	110123	0.09	0.40	0.38	0.32
B_4	111023	0.01	0.03	0.03	0.31



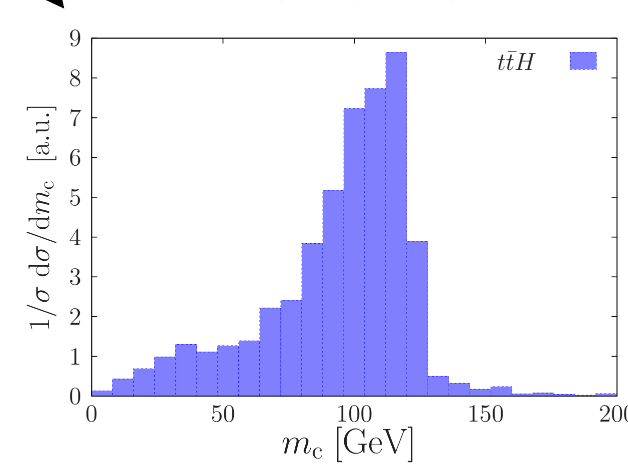
(a) B_1 (110021)



(d) B_4 (111023)

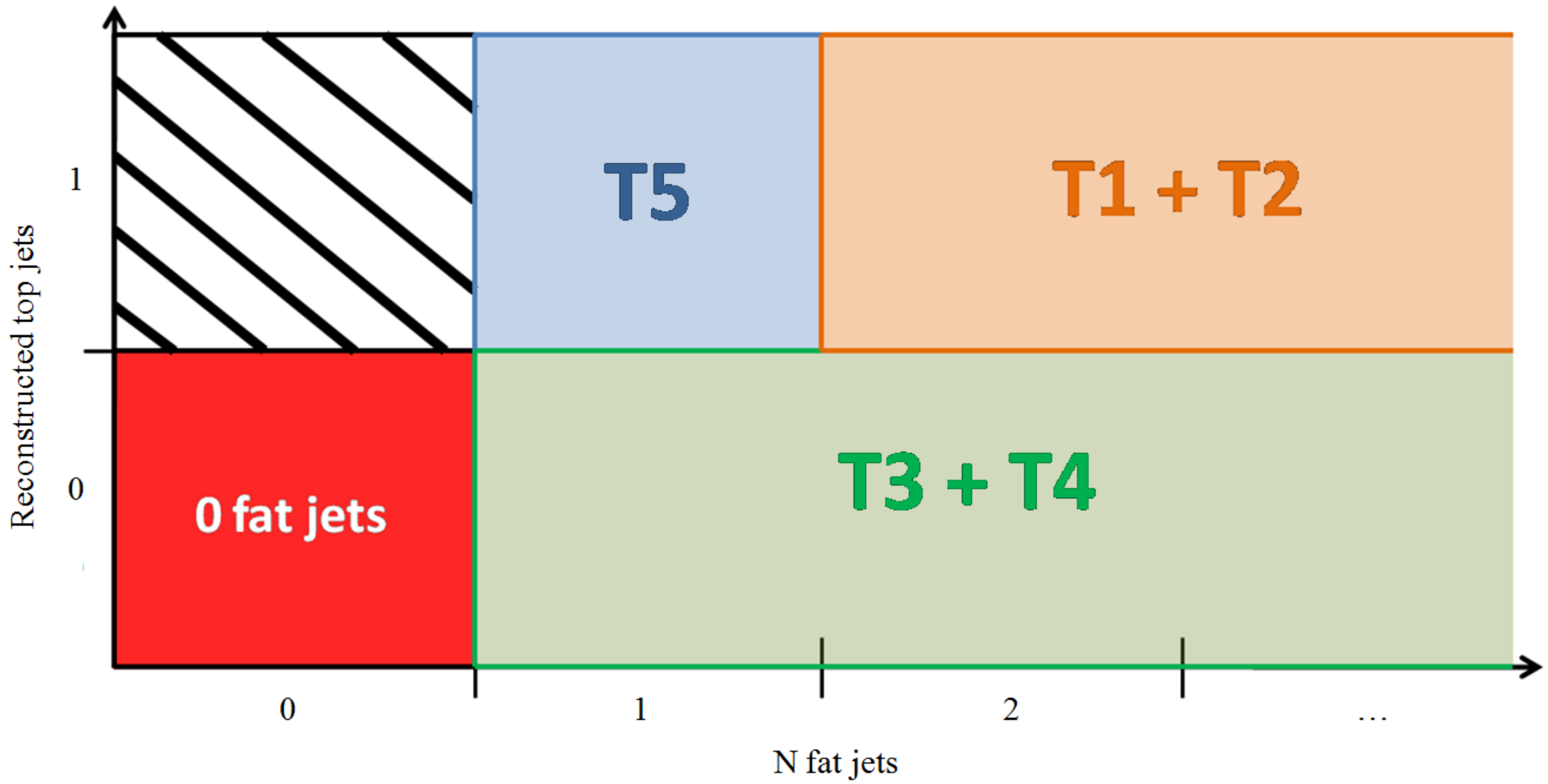


(c) B_3 (110123)



(b) B_2 (110023)

Improved reconstruction for difficult kinematics



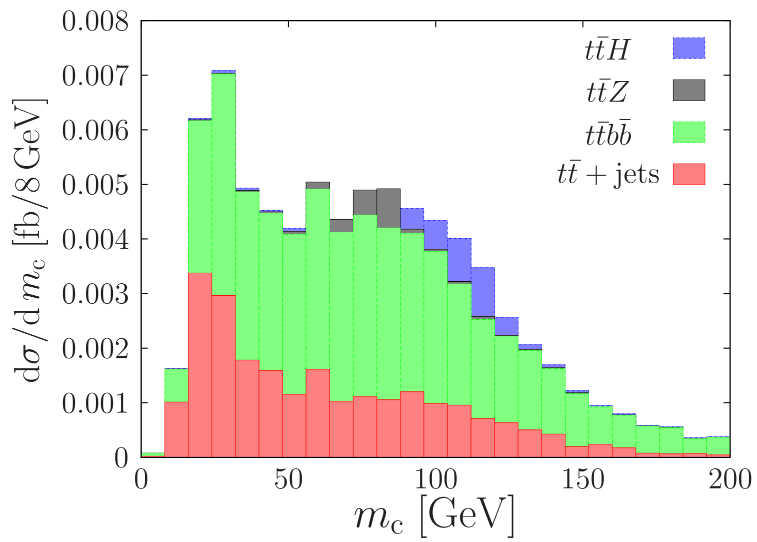
T1: ≥ 2 fat jets, 1 tagged boosted top, 1 Higgs candidate
T2: ≥ 2 fat jets, 1 tagged boosted top, 3 Higgs candidates
} standard boosted analysis

T3: ≥ 1 fat jets, no tagged boosted tops, 1 Higgs candidate
T4: ≥ 1 fat jets, no tagged boosted tops, 3 Higgs candidates
} boosted t OR boosted h

T5: exactly 1 fat jet, 1 tagged boosted top, unboosted Higgs candidate

Measures to improve individual topologies

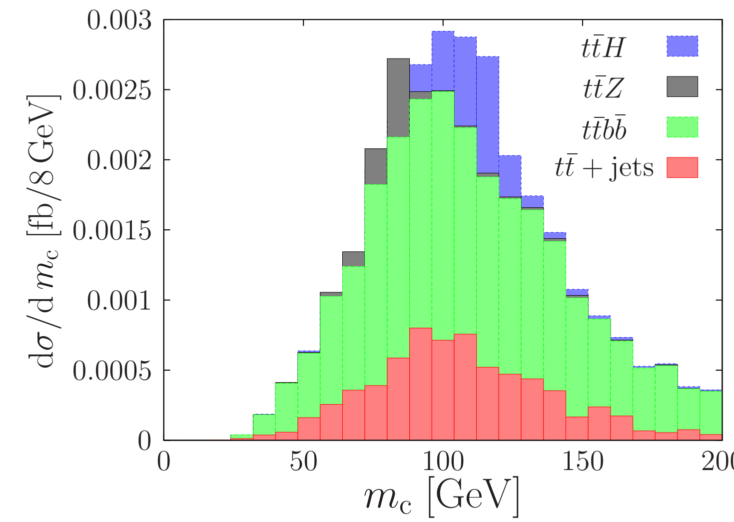
Categories T1 and T2 (boosted top and Higgs)



Use jet ellipticity

$$\hat{t} \; = \; \frac{T_{\min}}{T_{\text{maj}}}$$

[Krauss, Petrov, Schoenherr, MS '14]



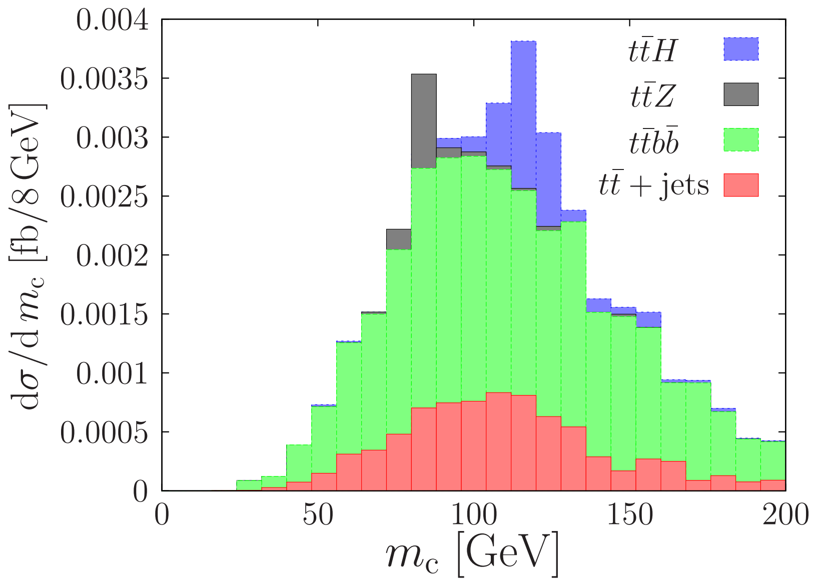
Categories T3 - T5 (only boosted top or Higgs)

- In case of unboosted hadronic top use chi2 minimisation to resolve degeneracy to assign b-quarks

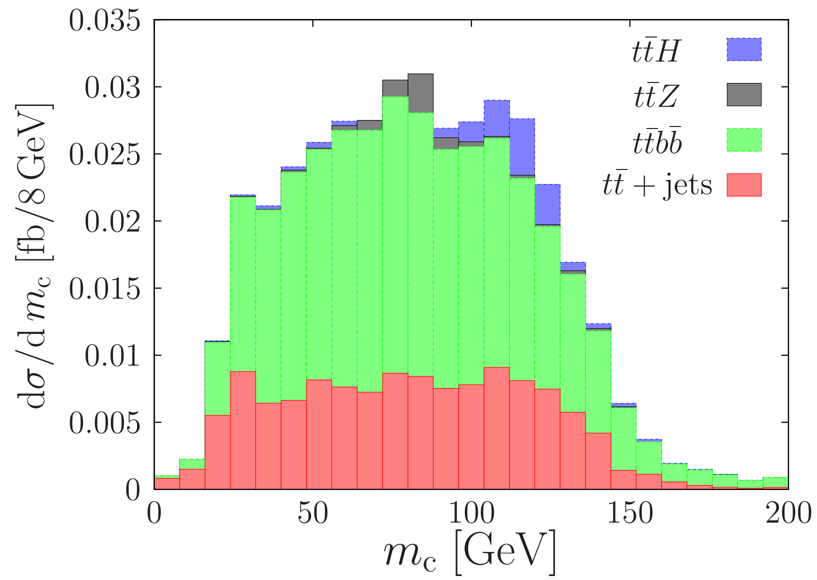
$$\chi^2 \;=\; \chi^2_{\text{top}} + \chi^2_{\text{W}} + \chi^2_{\text{Higgs}},$$

$$\chi^2_{\text{top}} \;=\; \frac{(m_{\text{t}_{\text{had}},\text{reco}} - m_{\text{t}_{\text{had}},\text{max}})^2}{\sigma^2_{\text{t}_{\text{had}}}},$$

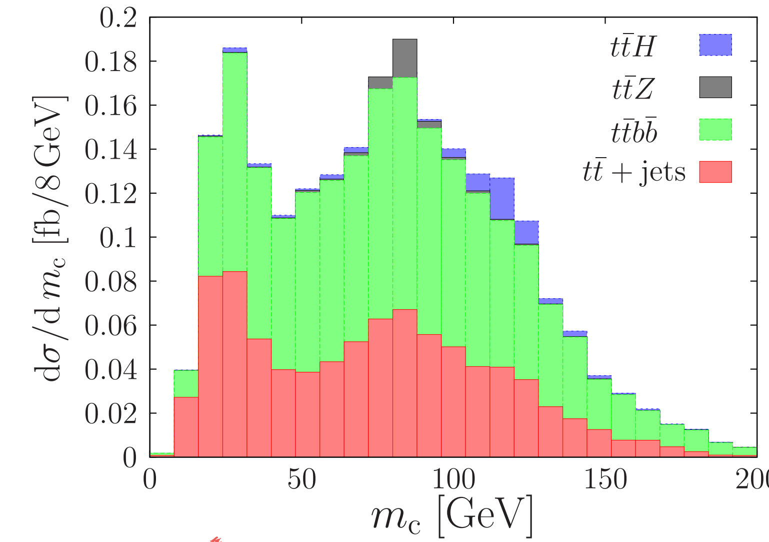
$$\chi^2_{\text{W}} \;=\; \frac{(m_{\text{W}_{\text{had}},\text{reco}} - m_{\text{W}_{\text{had}},\text{max}})^2}{\sigma^2_{\text{W}_{\text{had}}}}.$$



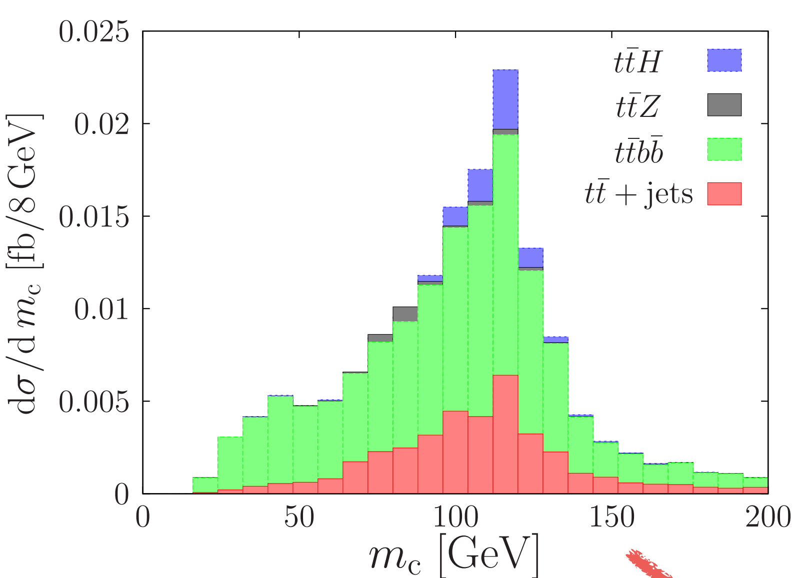
(a) **T1**



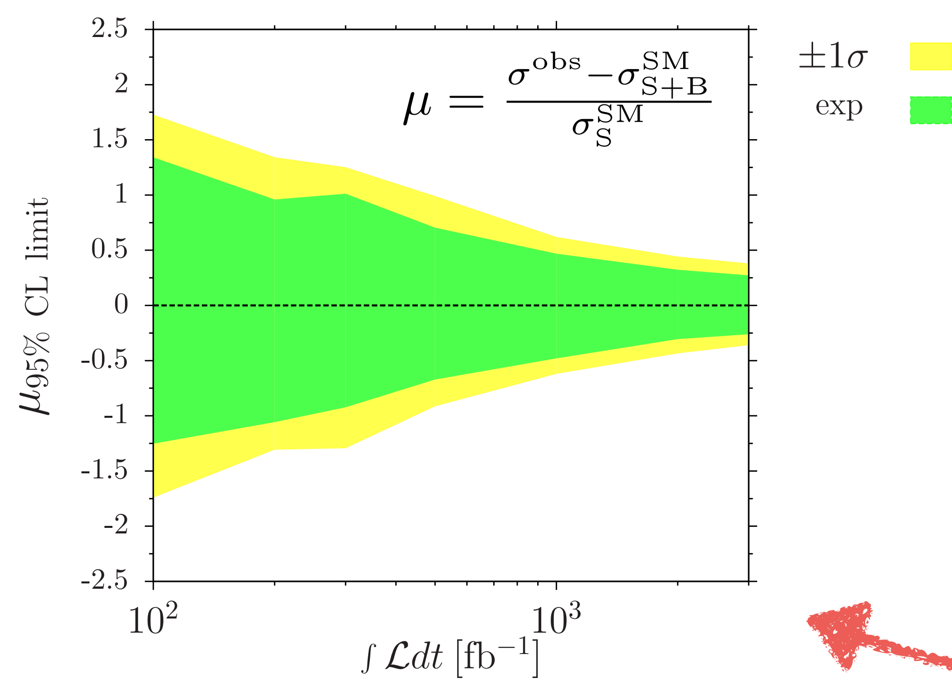
(b) **T2**



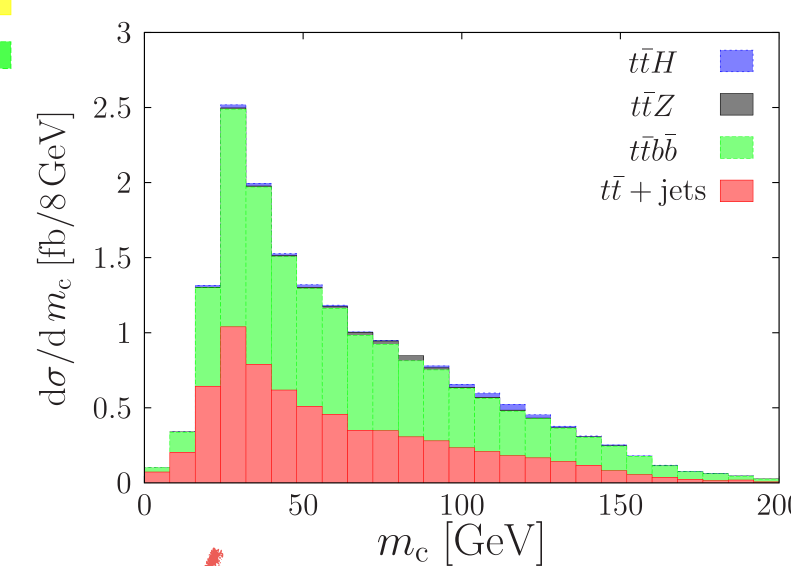
(c) **T3**



(e) **T5**



(d) Analysis of Sec. IV including all topologies (**T1**–**T5**).



(d) **T4**

Reconstruction of boosted tth can be improved

Experiments want:

- obtain sensitivity from whole phase space
- want optimal separation of signal and background
- not to have to optimise S/B by hand
- use established idea to ease approval process ;-)

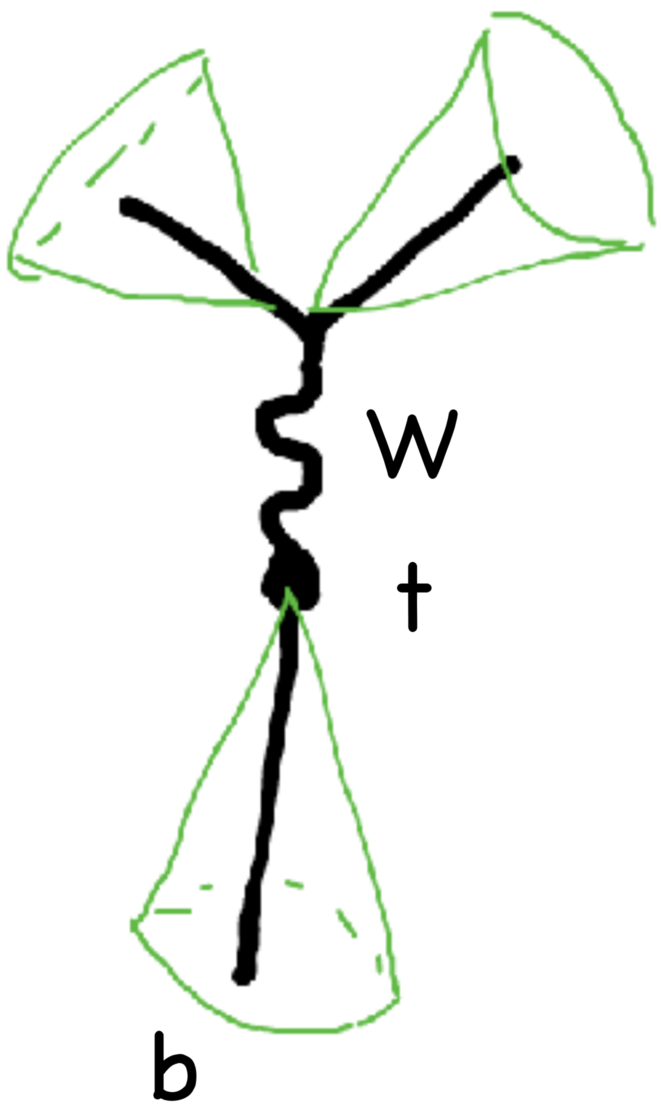
→ Matrix Element Method way to go

however LO MEM not ideal for tth

Different scenarios based on pT vs mass

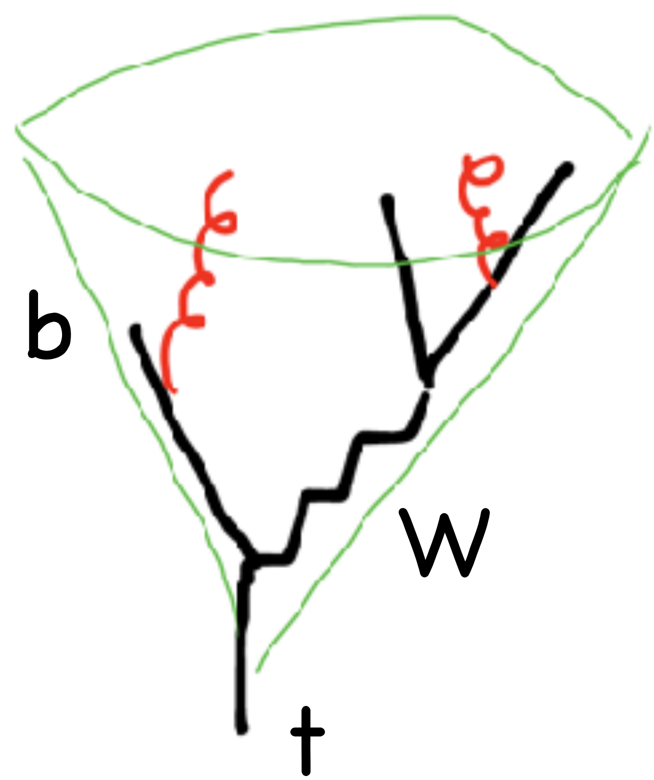
Scenario 1

$$m_{t\bar{t}} \simeq 2\ m_t$$



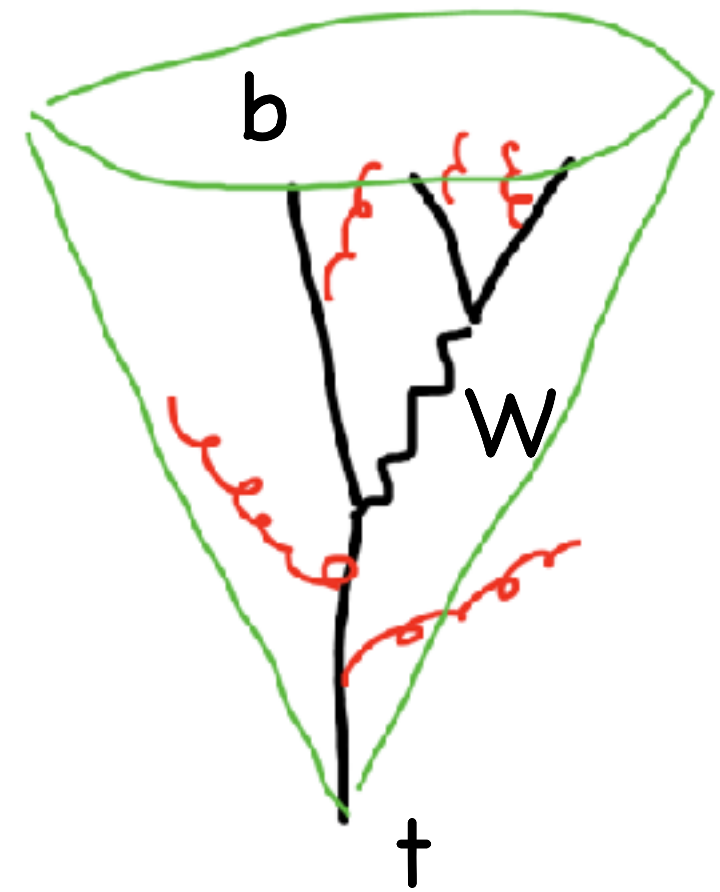
Scenario 2

$$m_{t\bar{t}} > 2\ m_t$$



Scenario 3

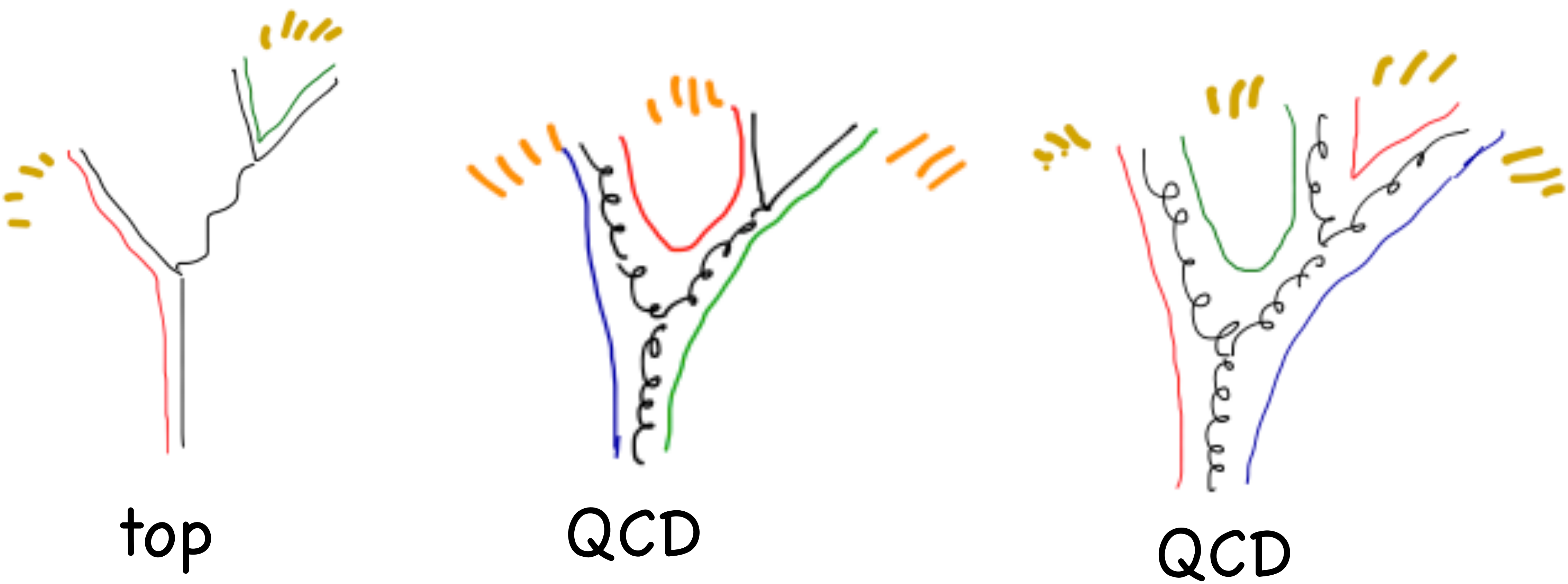
$$m_{t\bar{t}} \gg 2\ m_t$$



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)

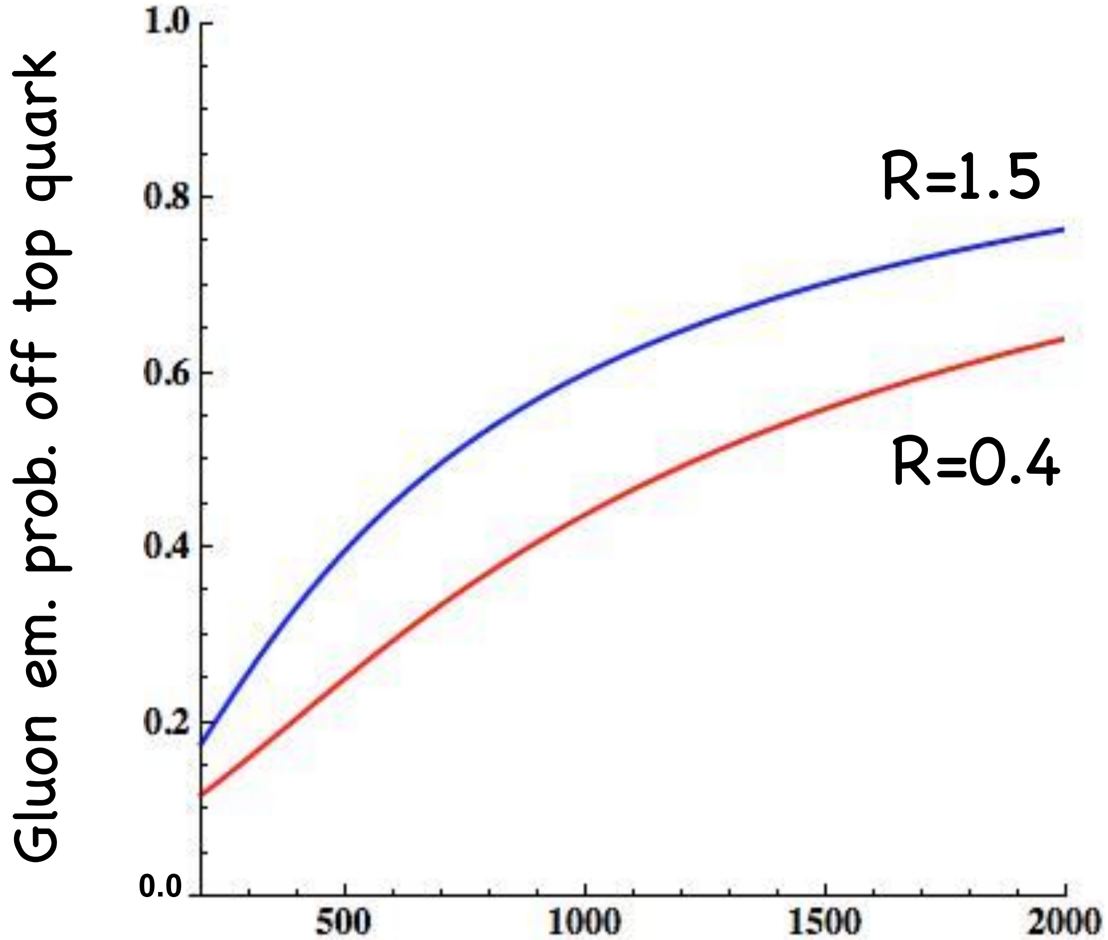
However, QCD radiation pattern are left mostly aside.



One can be more quantitative...

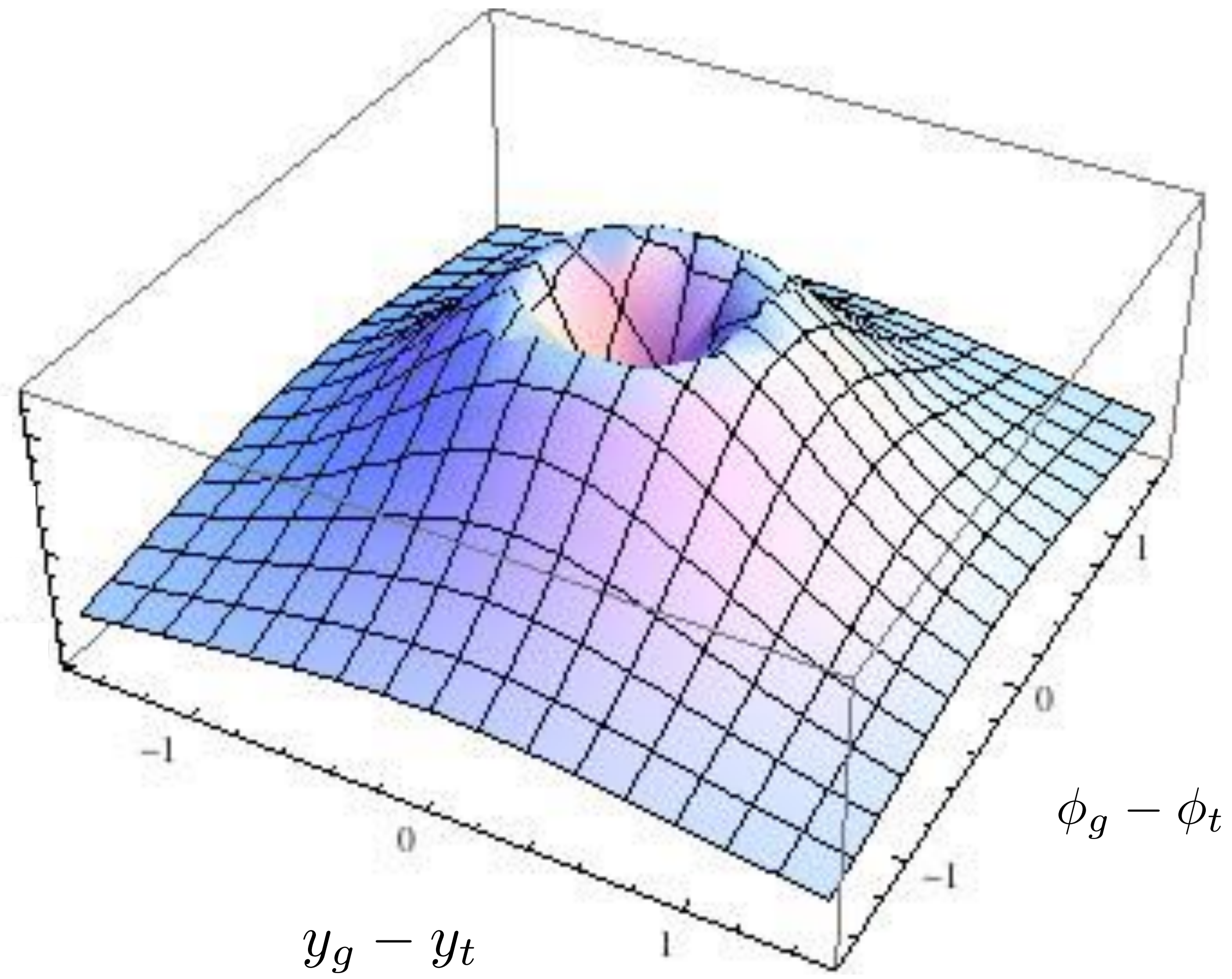
use emission prob. from [Soper, MS PRD 87]

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



pT top quark [GeV]

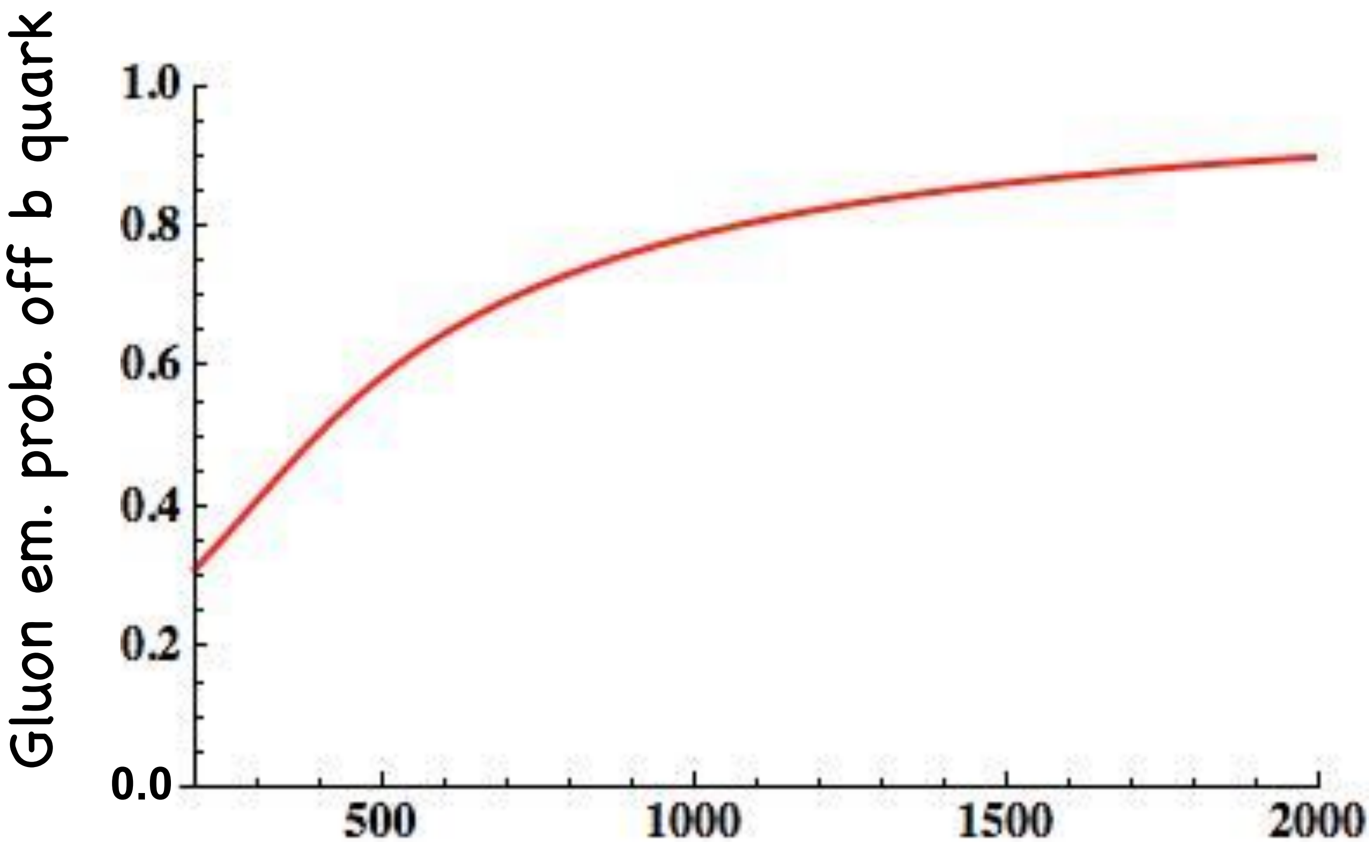
Dead cone region around top



pT top 500 GeV, pT gluon 20 GeV

Radiation off bottom quark down to hadronization scale

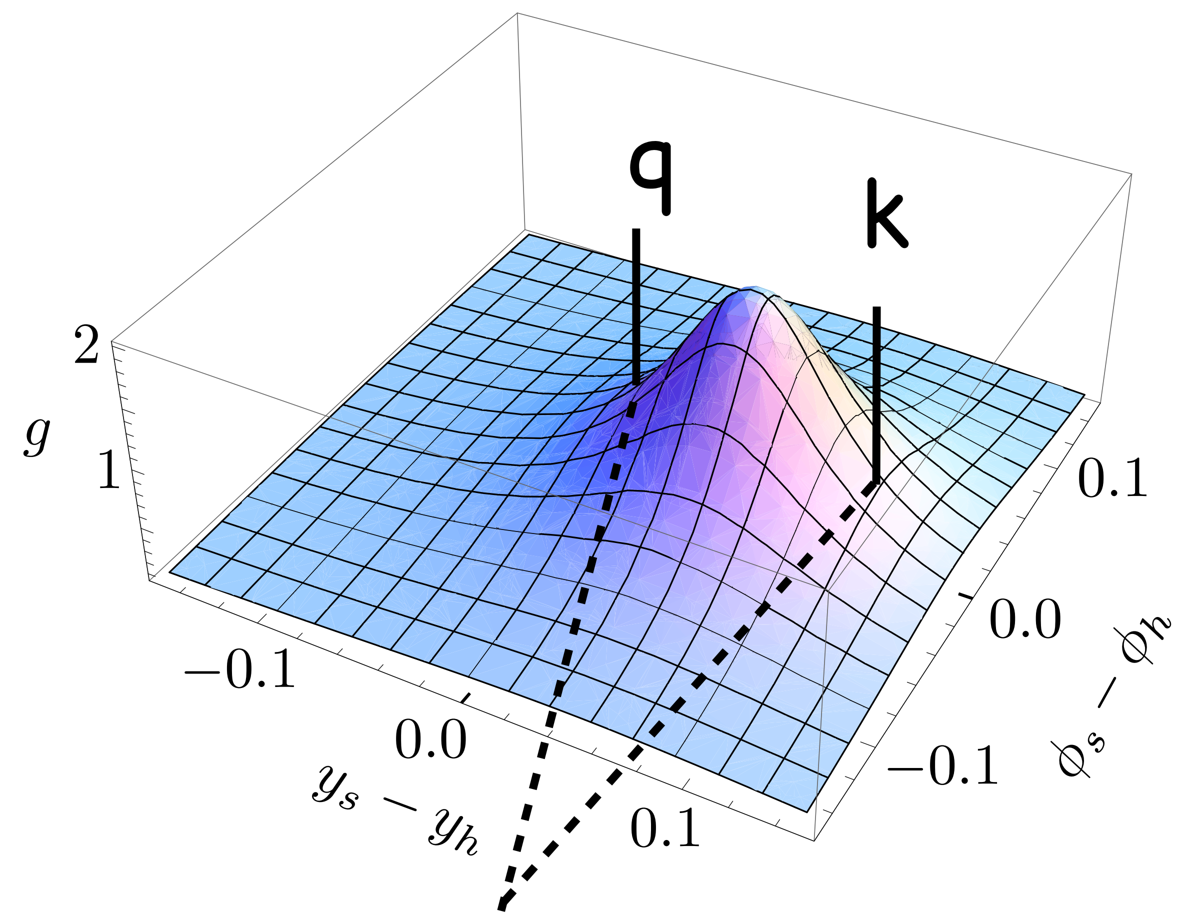
$$\mathcal{P} = 1 - e^{-S_{bbg}}$$



pT top quark [GeV]

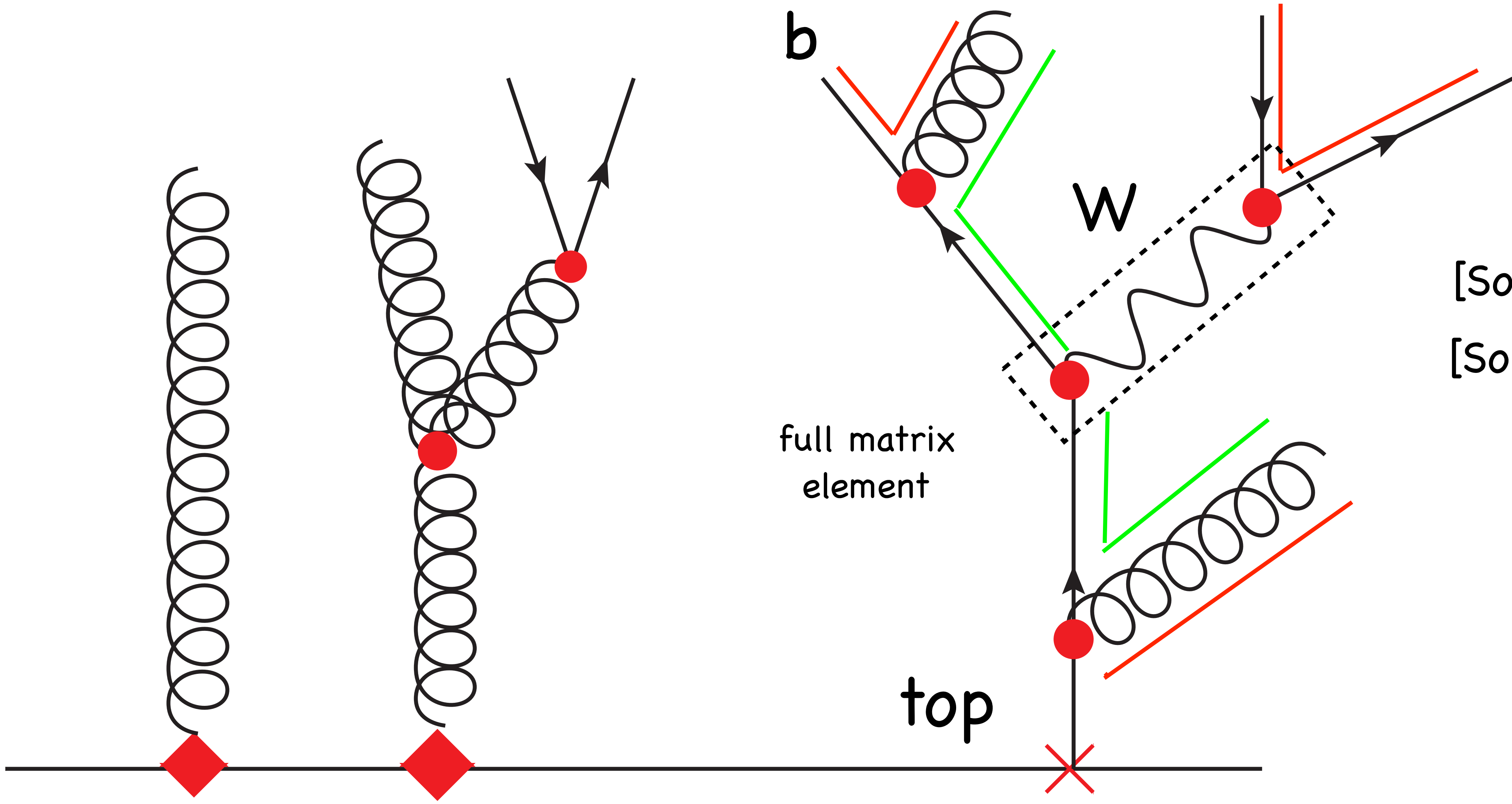
pT bottom = pT top / 3

angular distribution for radiation off H/W decay products



H/W decay products

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



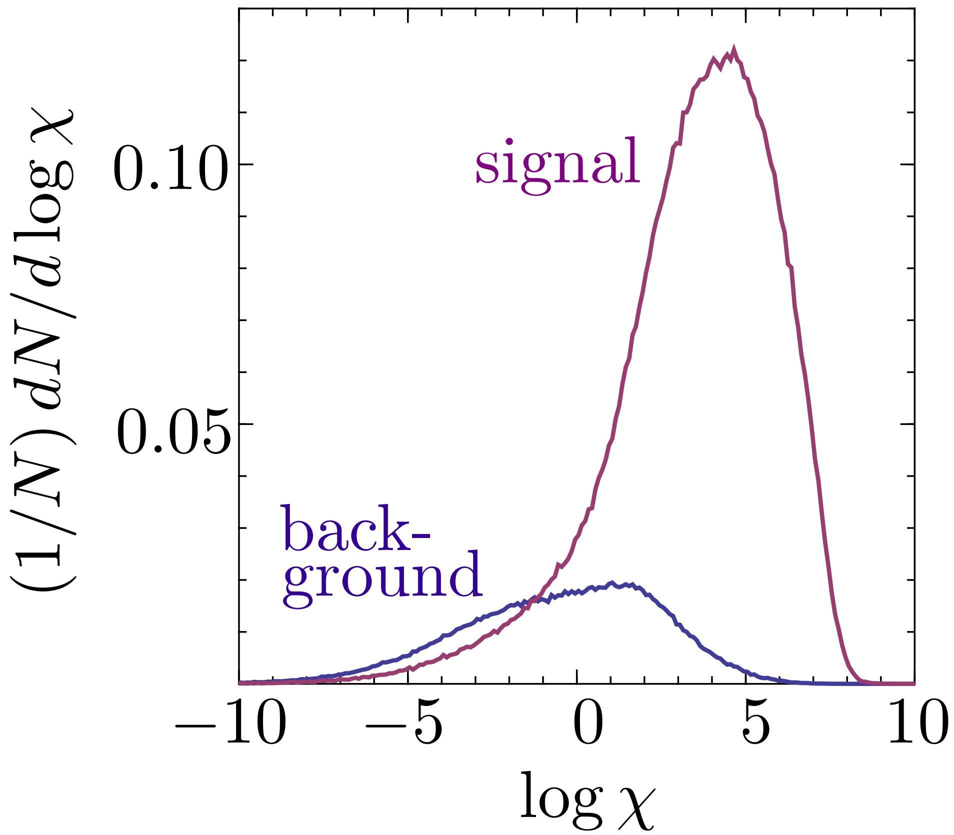
[Soper, MS '11]

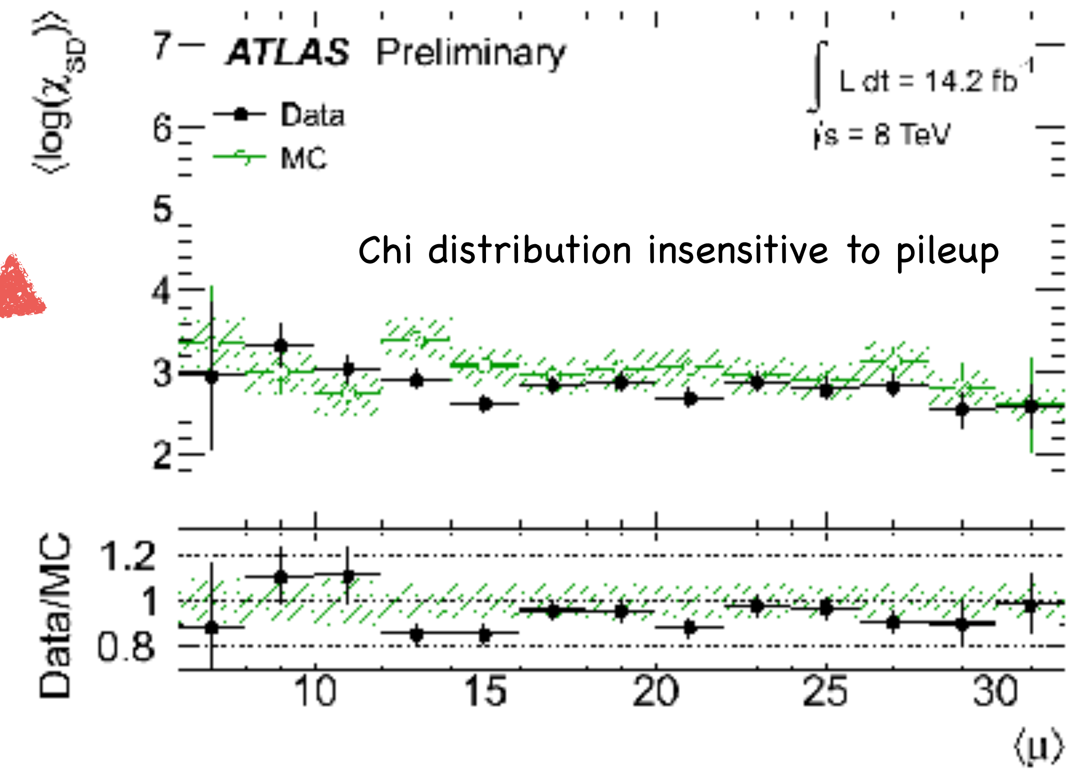
[Soper, MS '12]

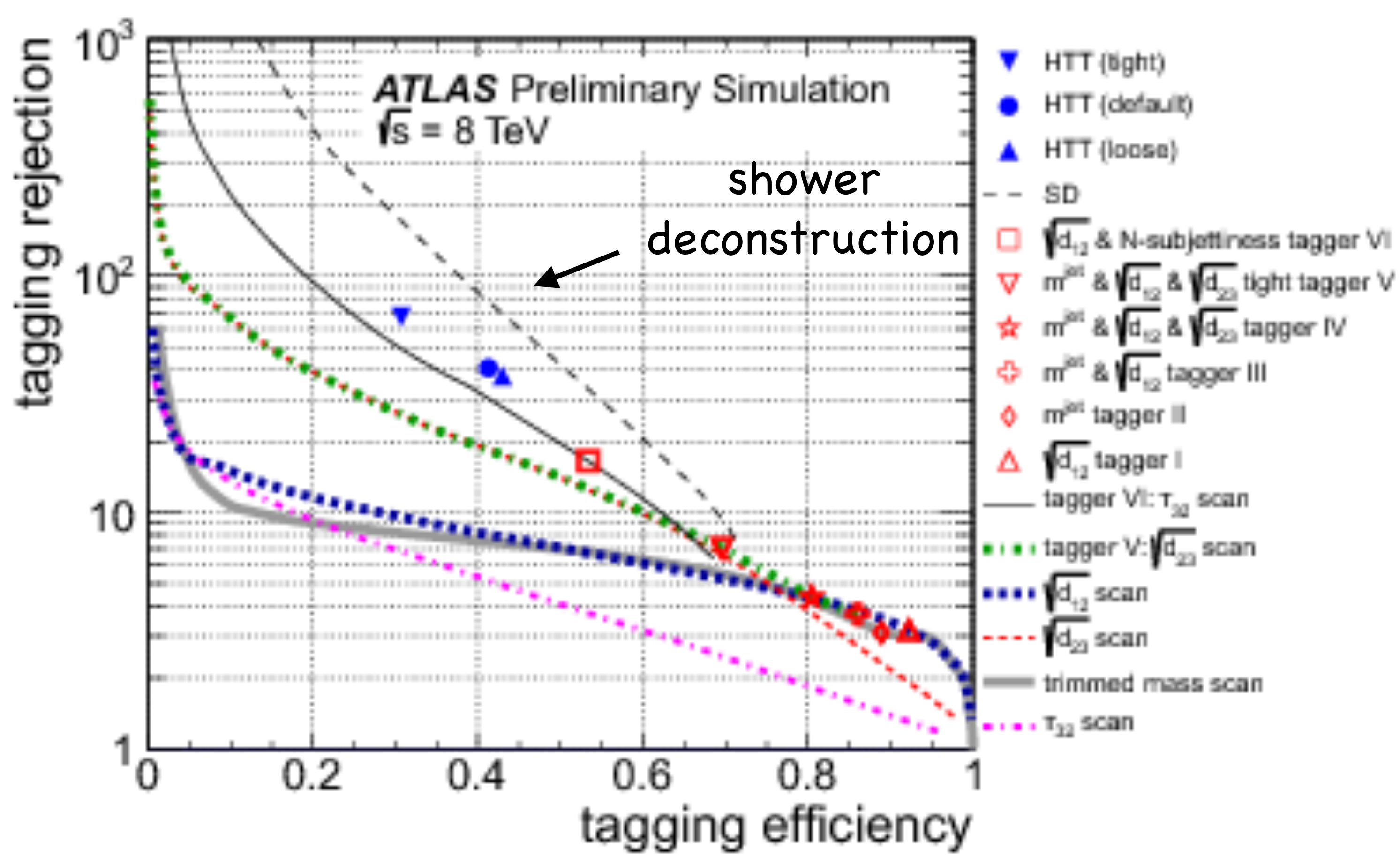
Conceptional difference compared to Higgs from last year:

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

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

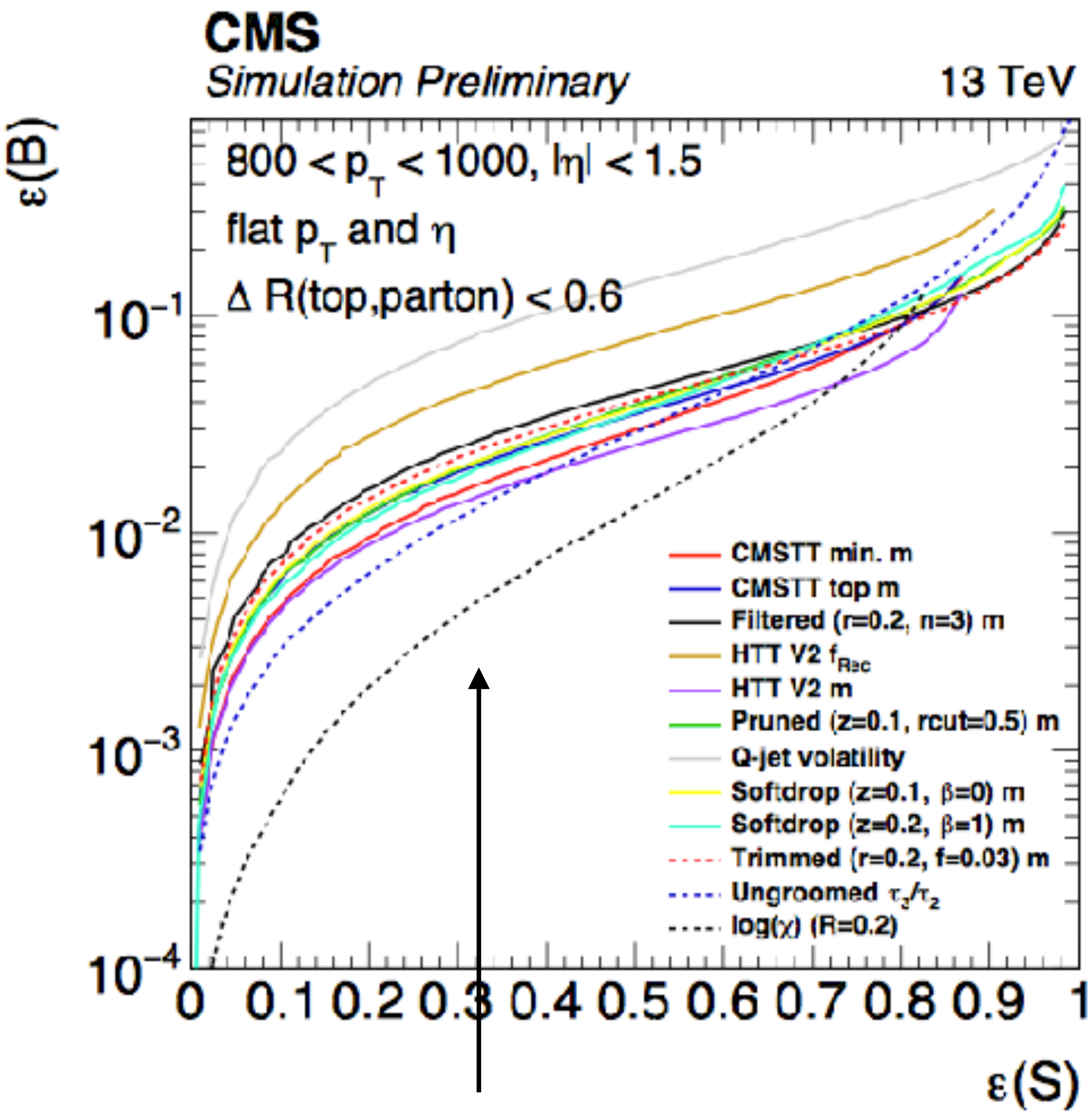


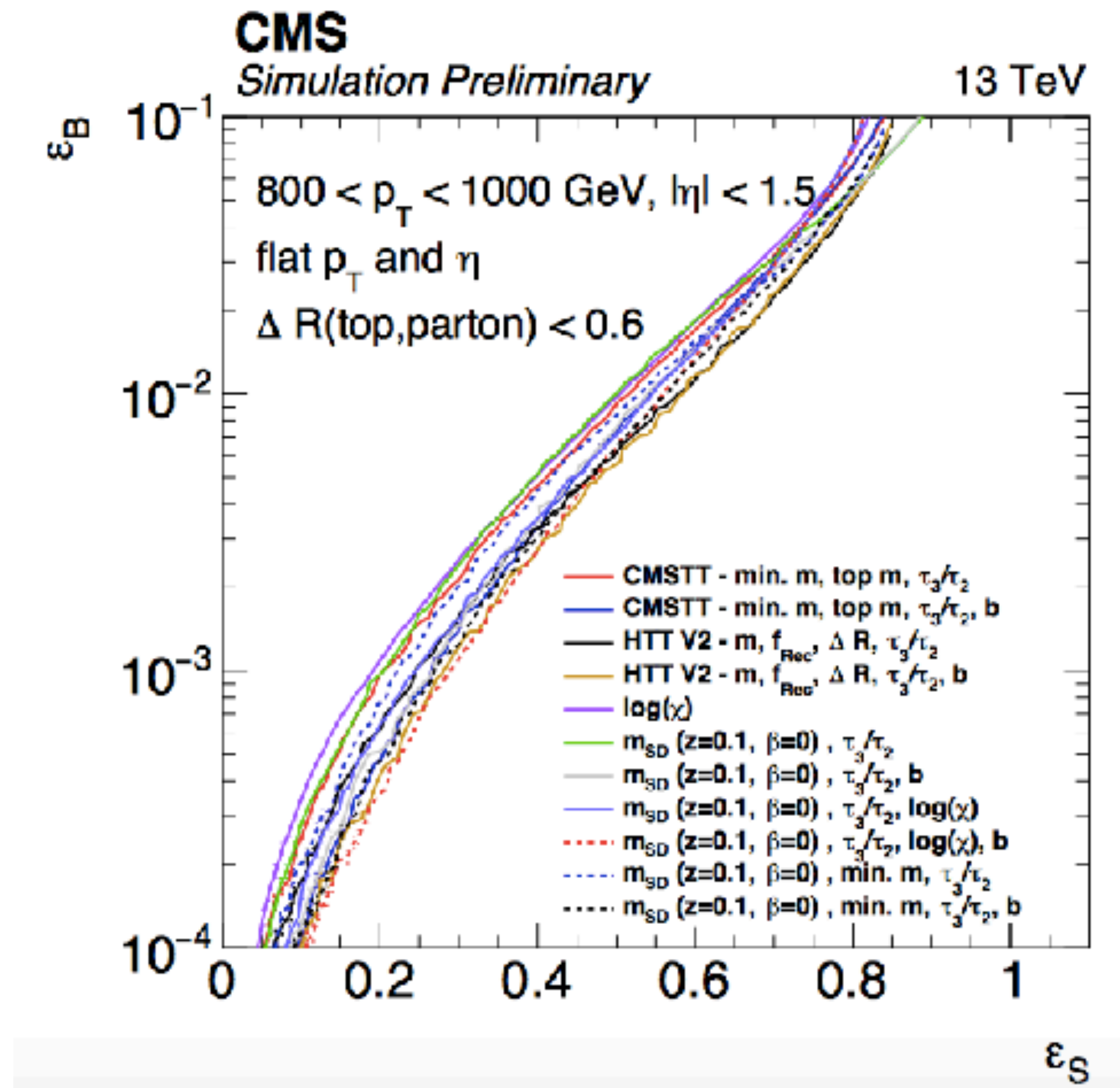




Shower deconstruction improves on best taggers by factor 2-4 in S/B

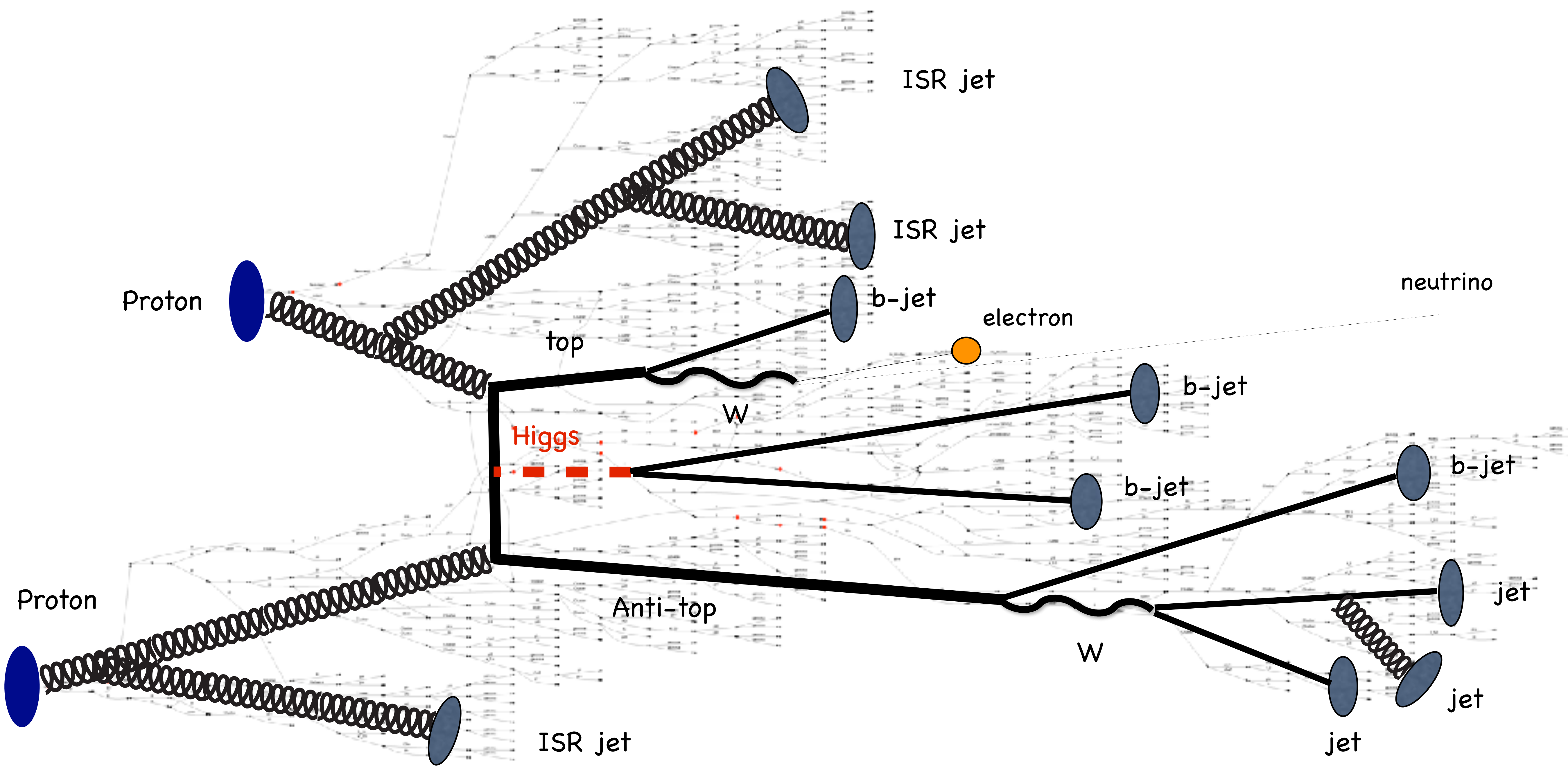
Results by CMS



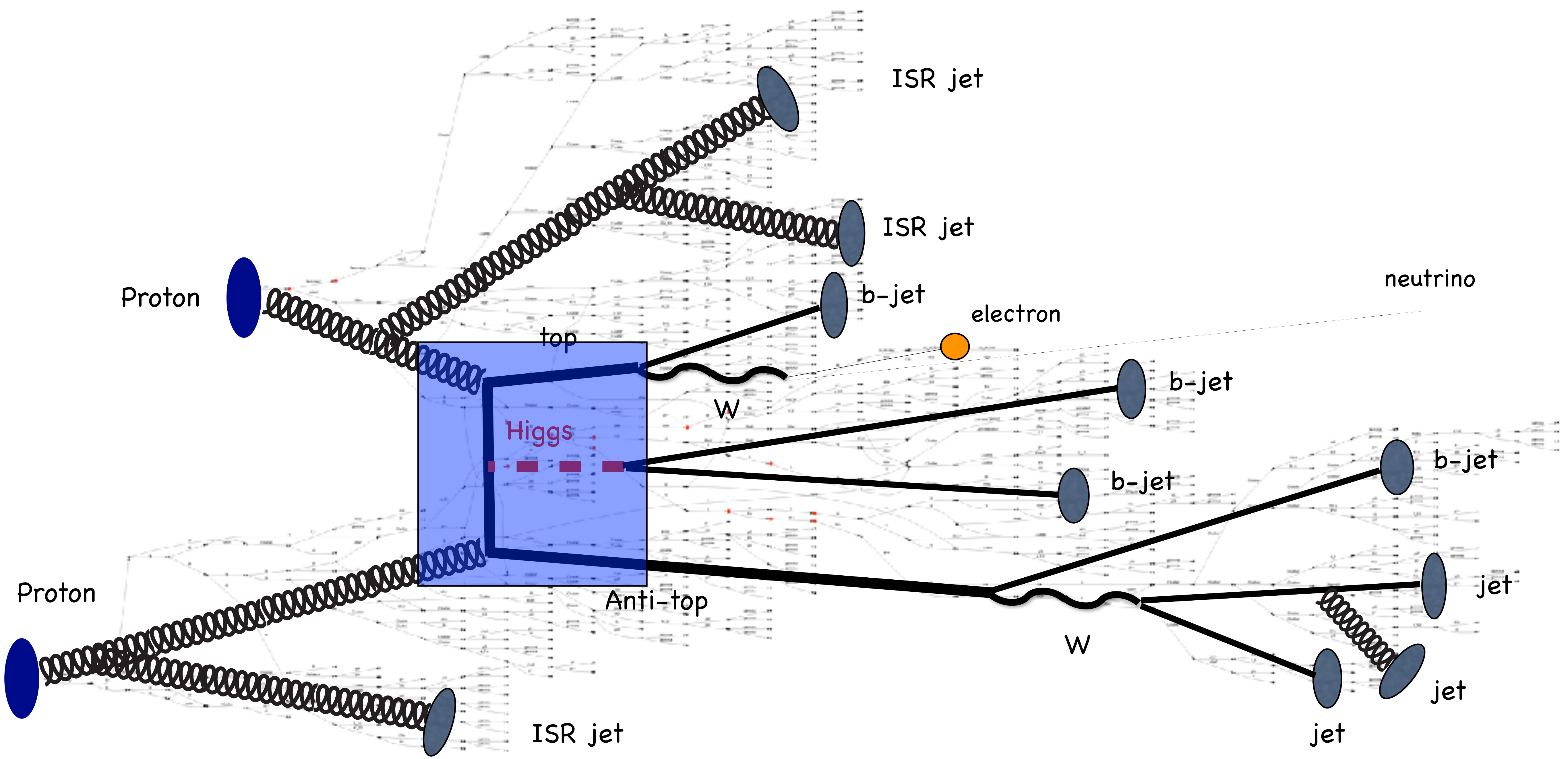


- Shower deconstruction best single variable
- Efficiencies matched if taggers combined

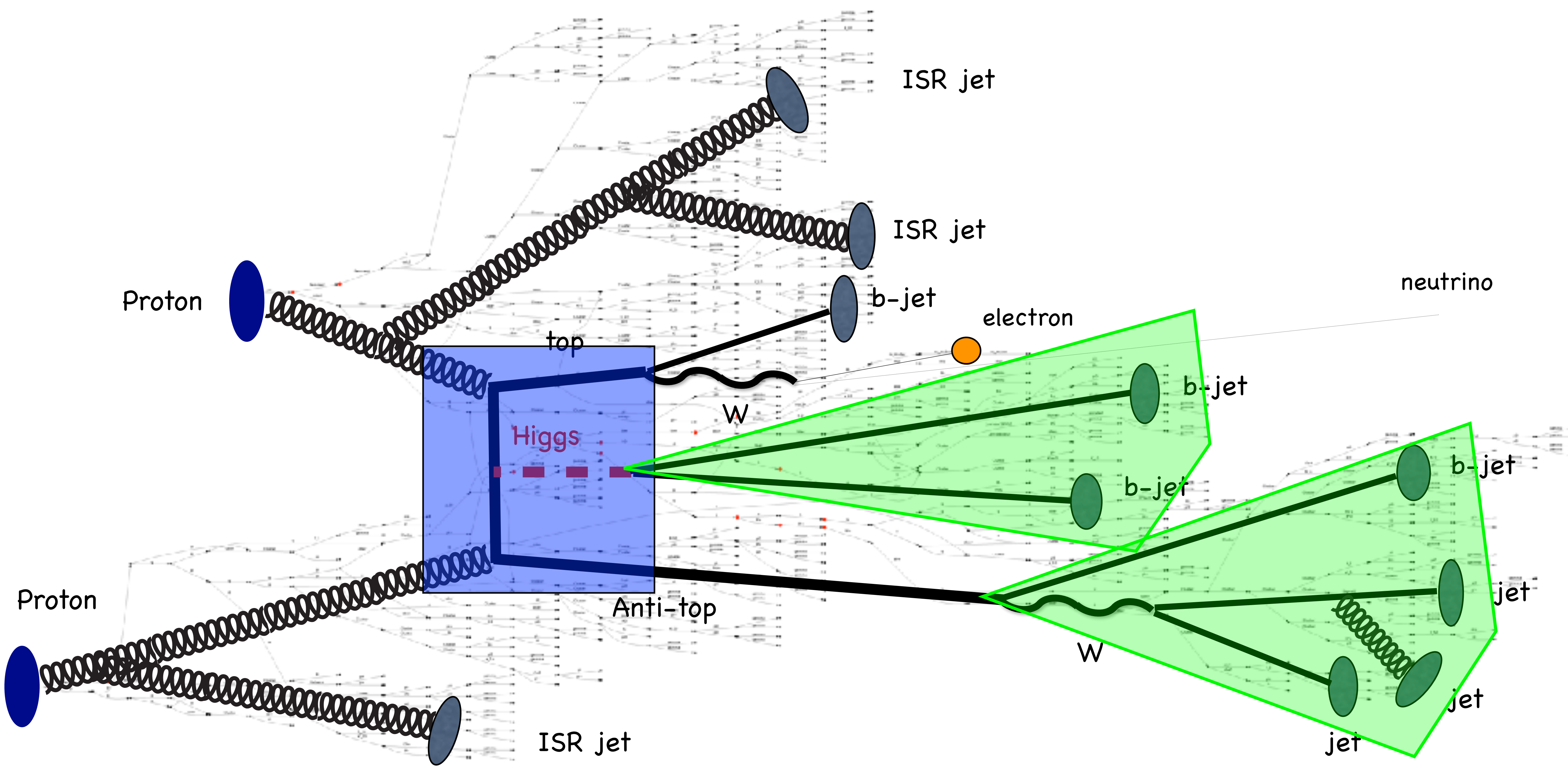
Event Deconstruction = Matrix. Method + Shower Deconstruction



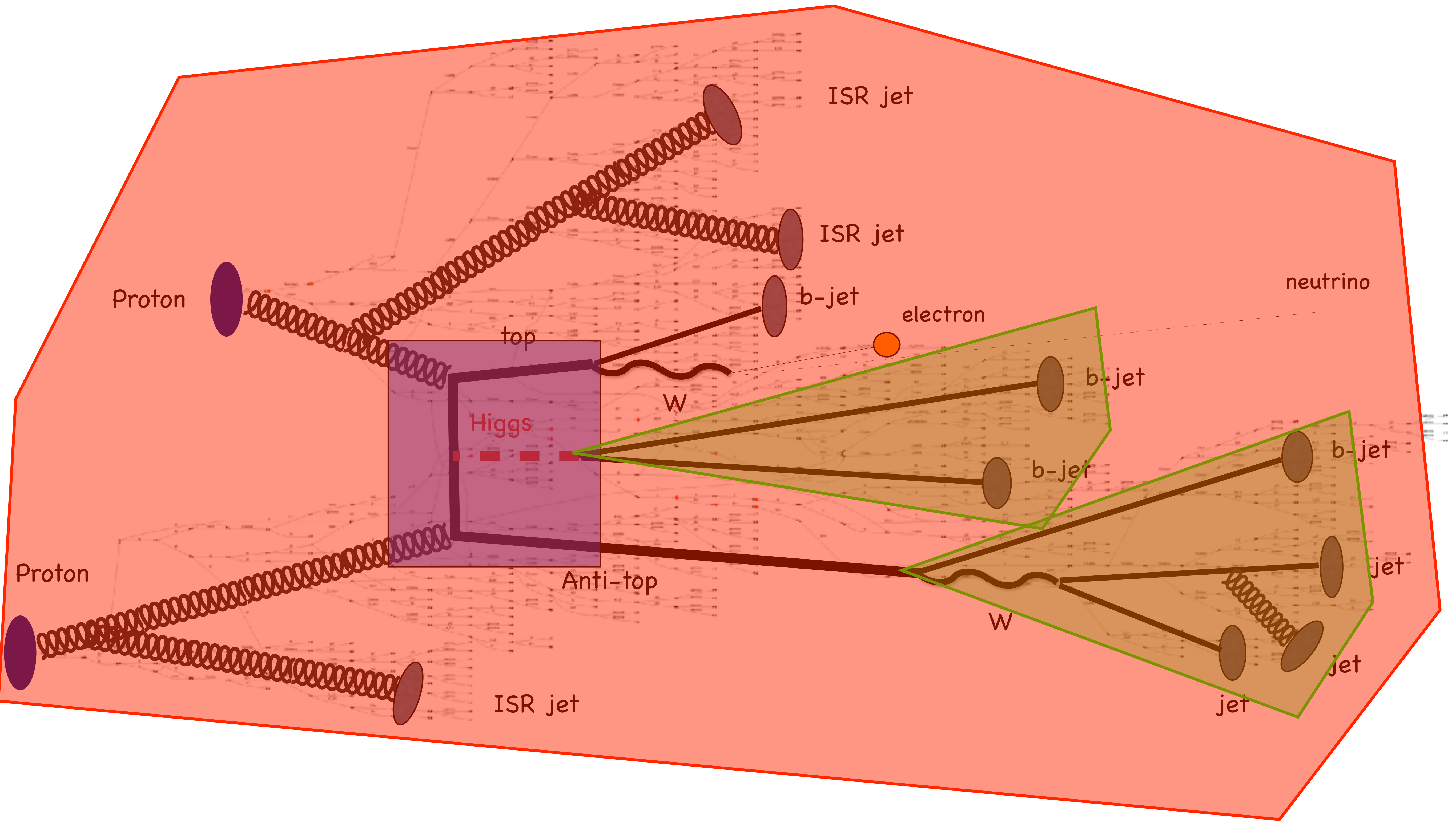
Event Deconstruction = Matrix. Method + Shower Deconstruction



Event Deconstruction = Matrix. Method + Shower Deconstruction



Event Deconstruction = Matrix. Method + Shower Deconstruction

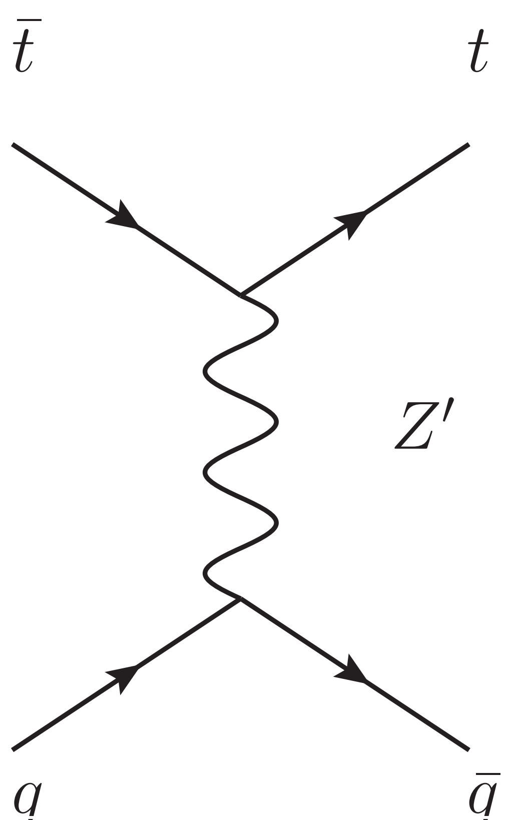


First application of Event Deconstruction

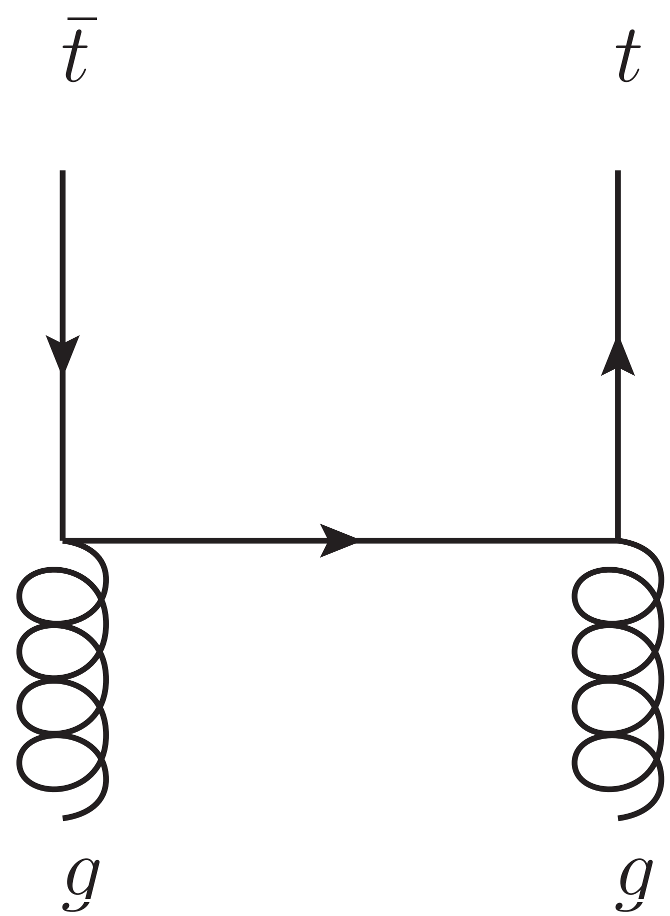
[Soper, MS '14]

fully hadronic Z' -> tt

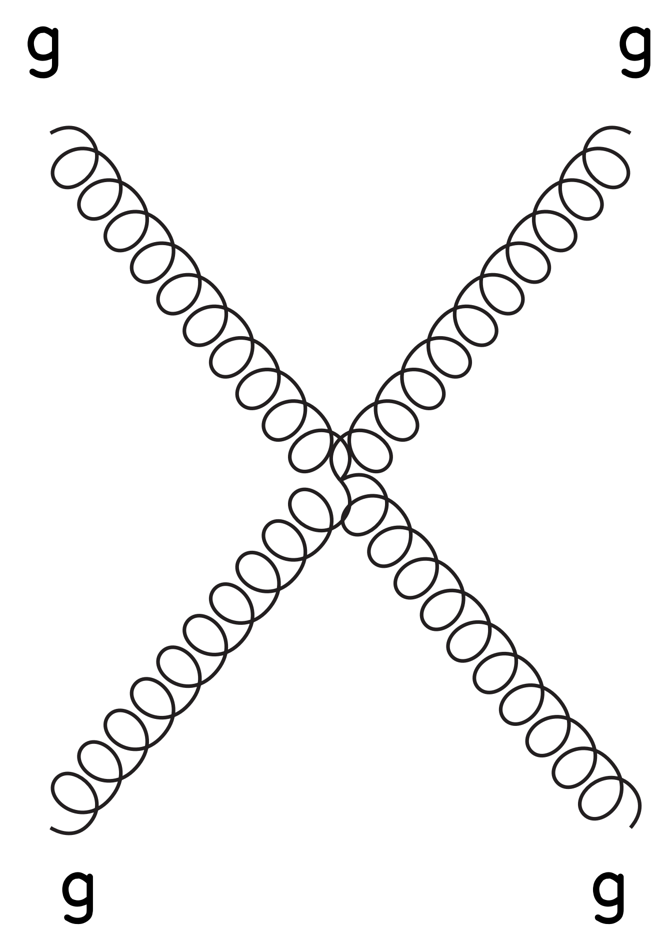
Signal



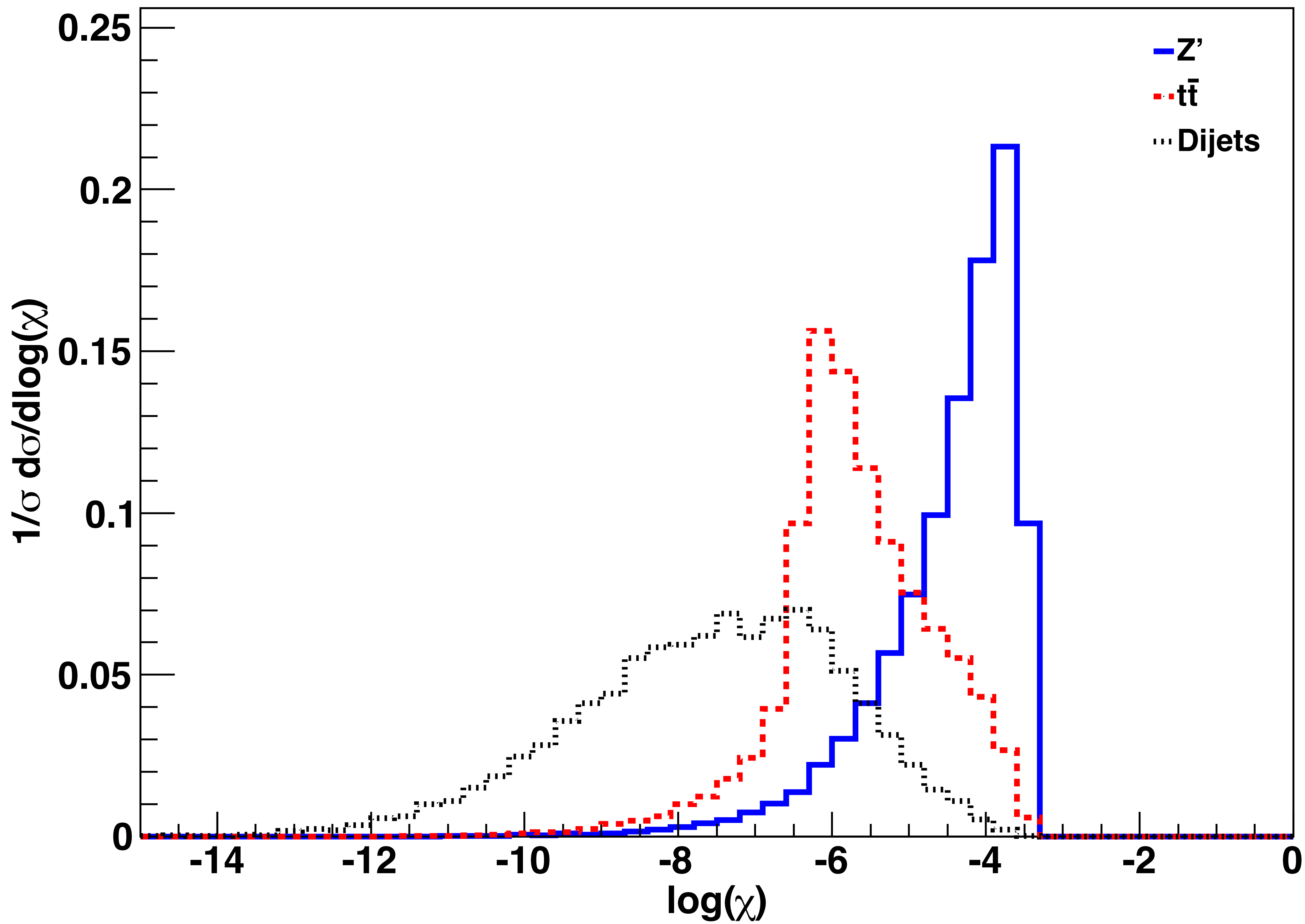
$t\bar{t}$

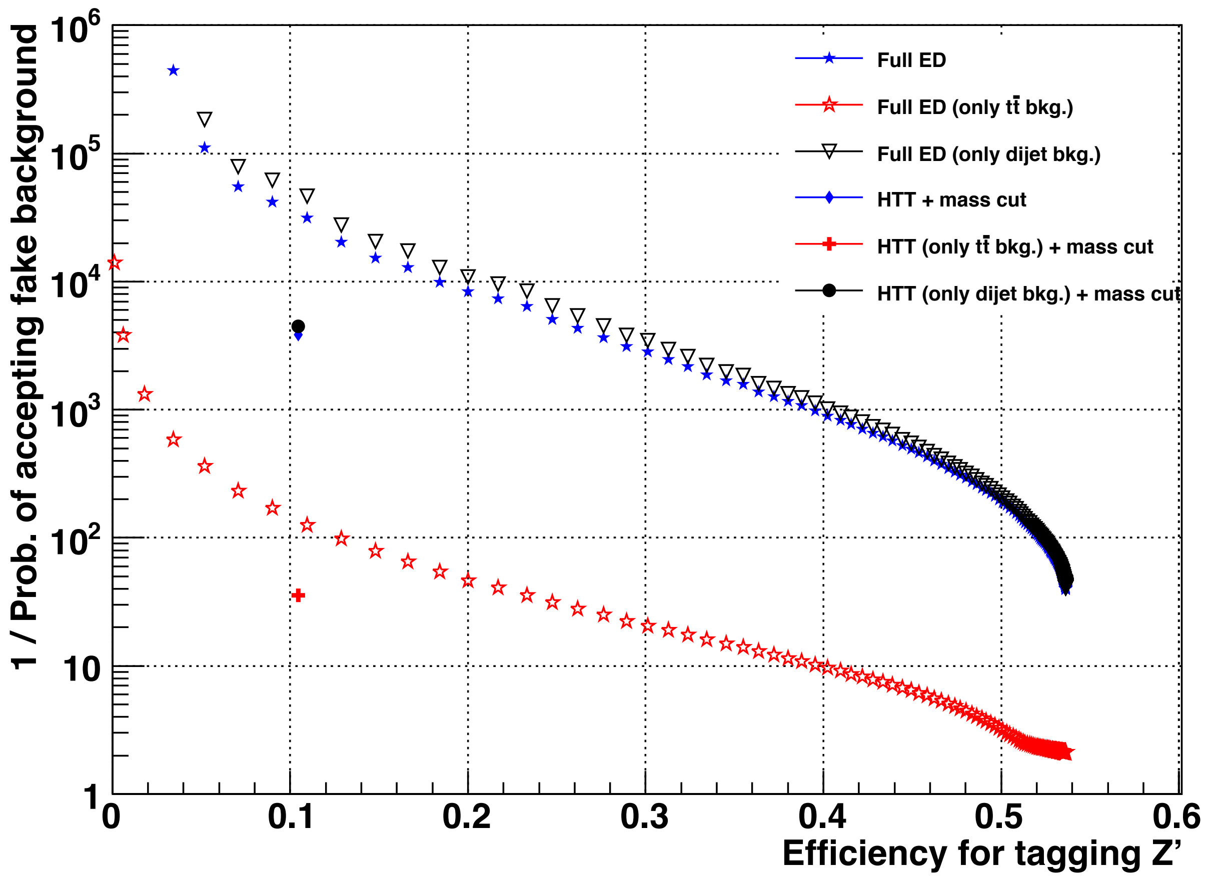


dijets

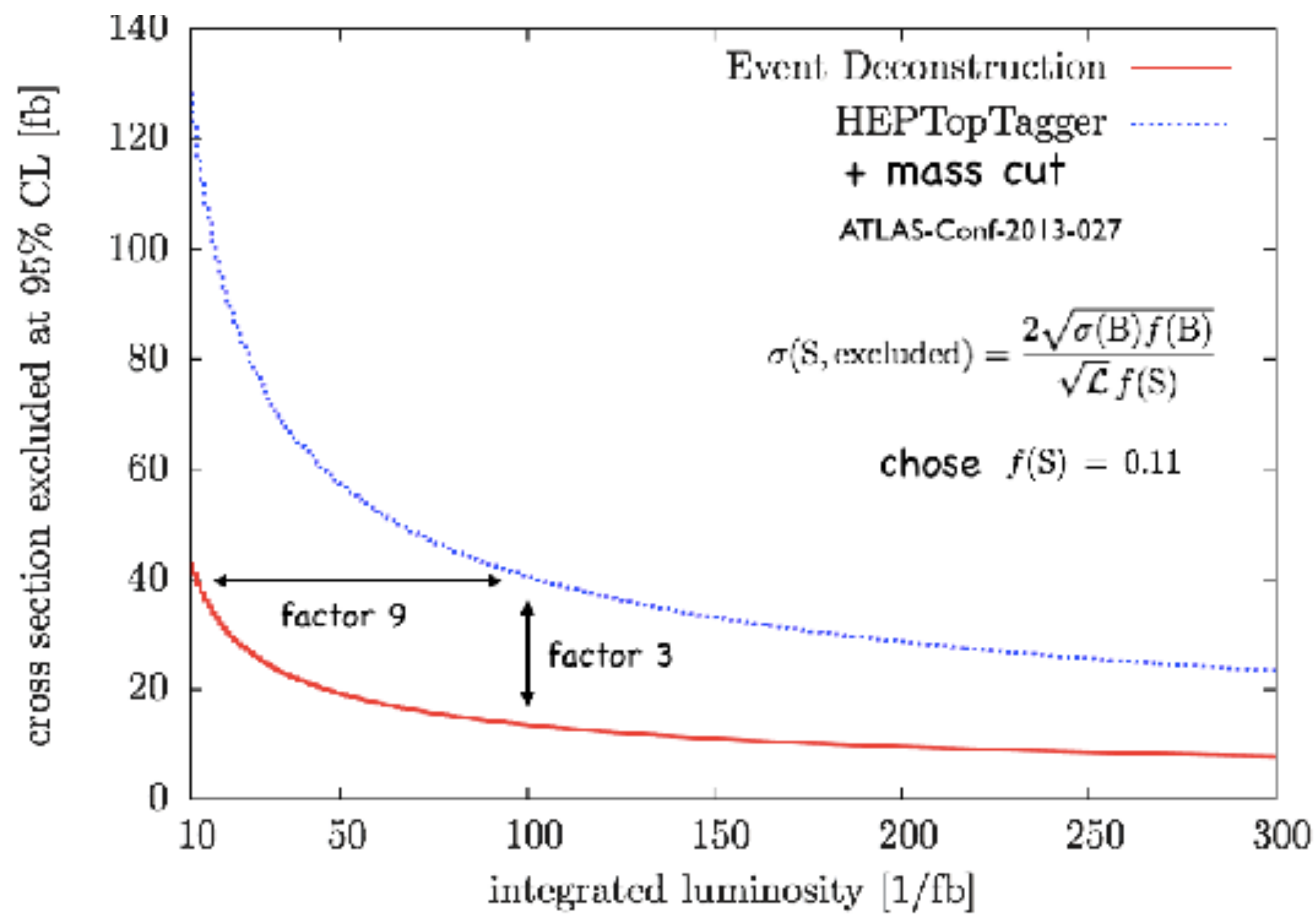


$$\chi = \frac{P(X|Z')}{P(X|t\bar{t} + \text{dijets})}$$



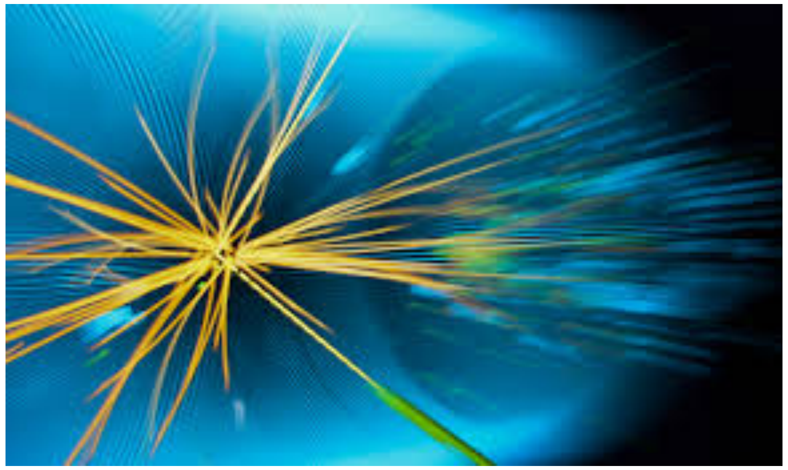


Discovery 9 times faster or for 3 times smaller cross section

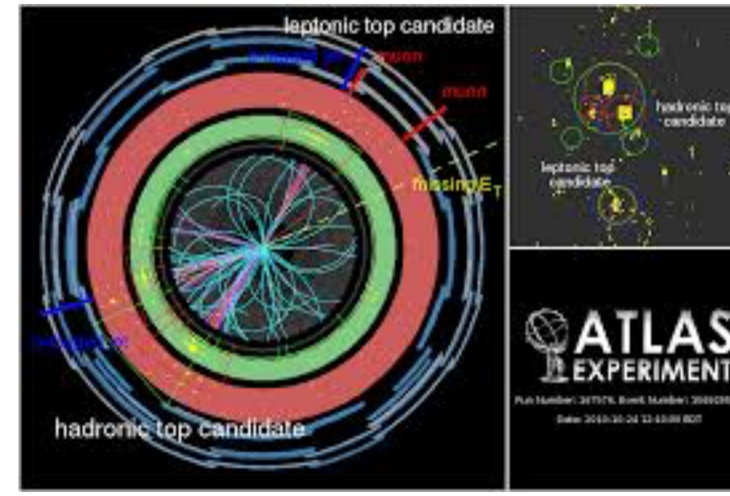


Event Dec: eff : 0.109538
fkr : 3.20063e-05
1/fkr : 31243.8

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



Summary



Studying Higgs-top interactions most important deliverable during upcoming LHC runs

→ direct impact on BEH mechanism, SM extensions, global fit

Boosted category important to improve our understanding of nature

However, final states highly complex!
Need combination of channels and different phase space regions to get optimal result

Backup

Detailed comparison between LO analysis sample and NLO samples from Openloops+Sherpa

[Moretti, Petrov, Pozzorini, MS '15]