ETH zürich

ETH Institute for Particle Physics

Search for *ttH*(→*bb*) using the *Matrix Element Method*

L. Bianchini, F. Canelli, G. Dissertori, G. Kasieczka

ZPW, 08 Jan. 2014, Zurich

MEM: a way towards $ttH(\rightarrow bb)$?

- $ttH(\rightarrow bb)$ affected by large irreducible backgrounds
  - tt+bb "object-wise" irreducible wrt $ttH(\rightarrow bb)$

  $\Rightarrow$ search for a narrow *bb* resonance?

- Not so easy, because of:
  - *b*-quarks from *top* decay
  - lots of radiation (gg-fusion)

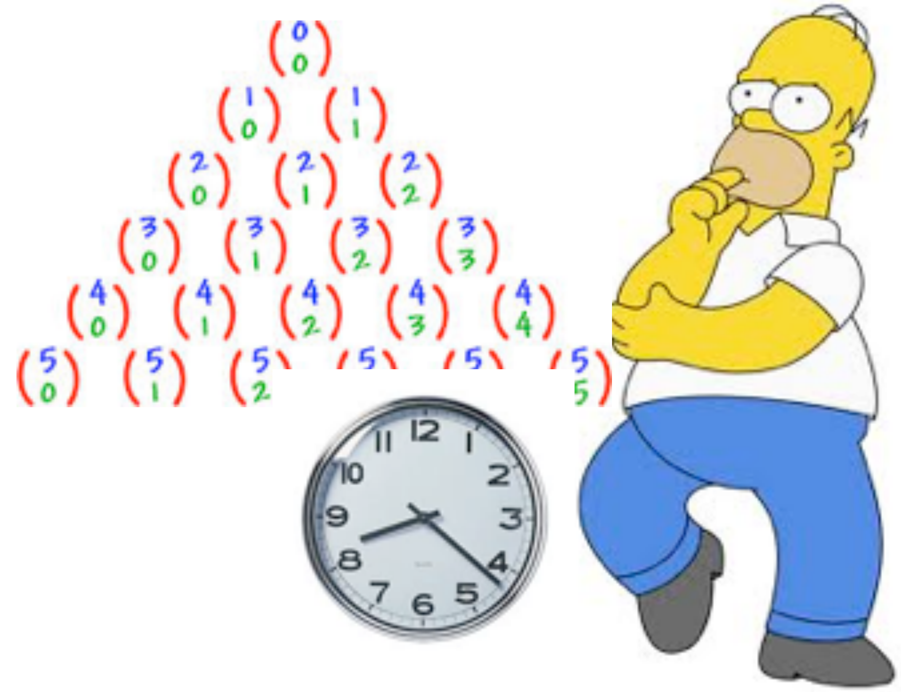
  $\Rightarrow$ combinatorics

- Then: look at the event *differentially* in several variables
  - *multivariate* approach

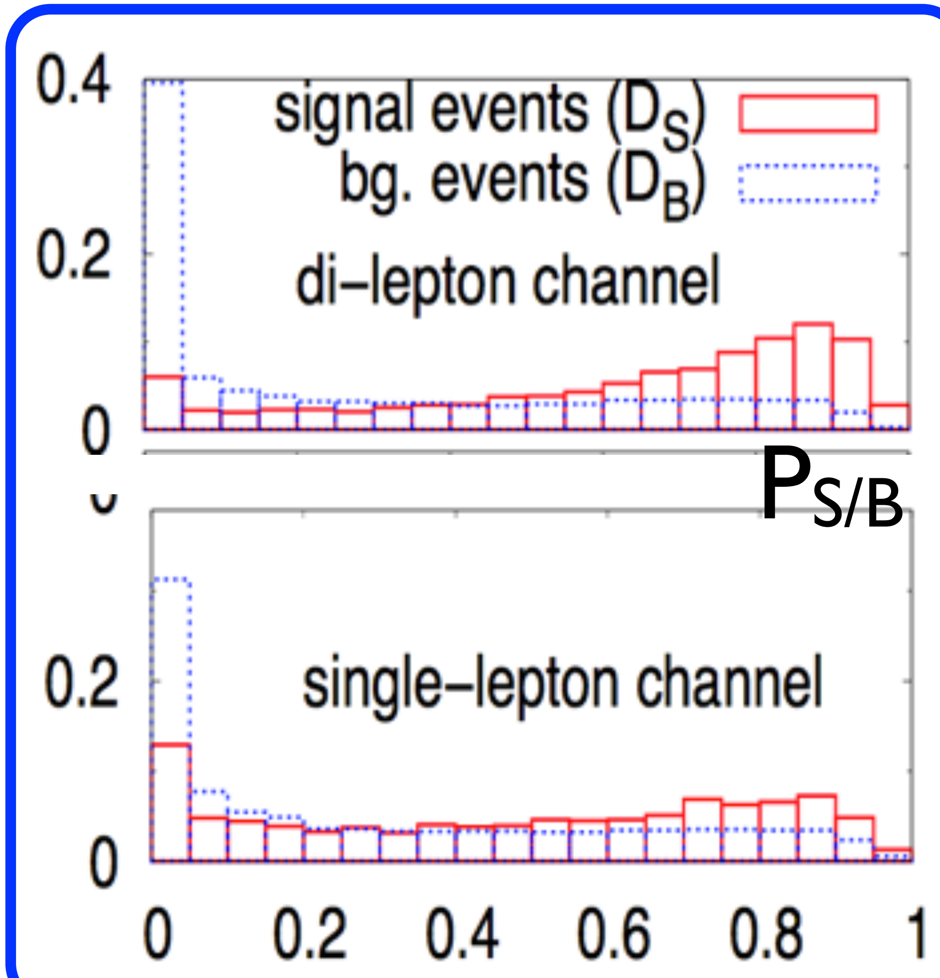
MEM $\Rightarrow$ ✓deals with combinatorics
✓optimal S/B discrimination

Questions... and answers

- But...not that easy!
  - multi-jet final state imply:
    - ✓ ambiguous underlying partonic picture
    - ✓ CPU-bottleneck magnified



- Proof of principle exists in literature
  - P. Artoisenet et al., "*Unraveling tth via the Matrix Element Method*", arXiv:1304.6414
  - based on the MadWeight automated ME program



$P_{S/B}$:=
ratio of *probability density* under sgn & sgn+bkg hyp.

Answers... and more questions

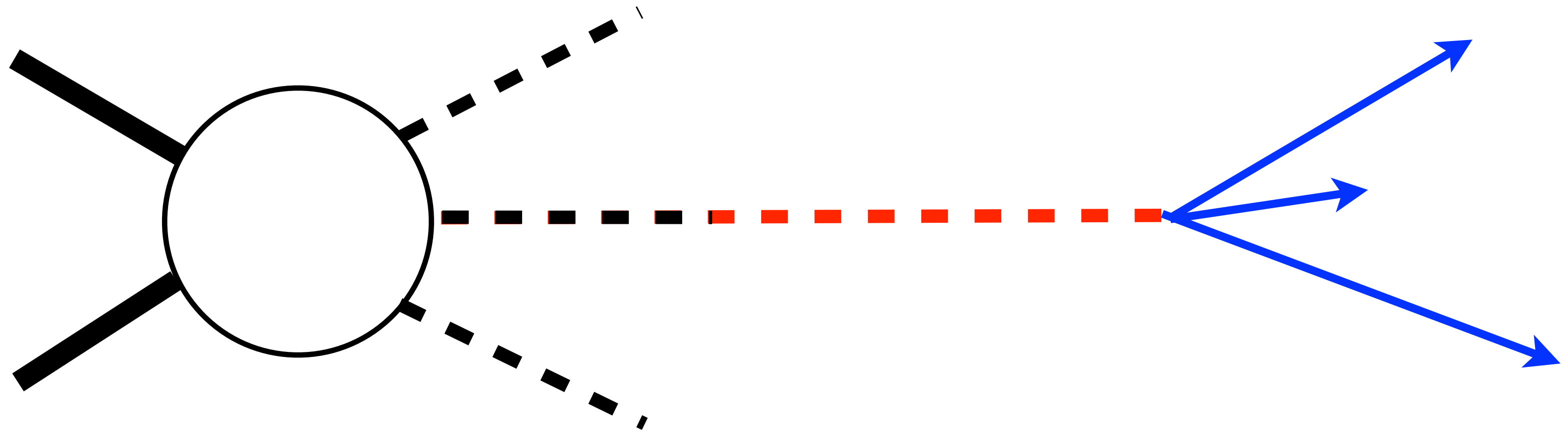
- The pioneering MadWeight result is very encouraging.
- Questions:
  - is a MEM-analysis CPU sustainable for the fast-evolving LHC experiments ?
  - can it be extended to other event topologies ?
  - why is the di-lepton channel more performing than the single-lepton ?
    - ✓ unexpected given CMS PAS-HIG-13-019.
  - where does the separation come from ?
    - ✓ kinematics ? angular-correlations ? the 'Higgs mass' ?

To answer these questions, we have worked out an independent implementation of the *ttH* ME analysis, putting emphasis on code *speed* and *flexibility*

The algorithm

The algorithm: basic principles

- Factorize the reaction $pp \to tt+(bb) \to \Omega$ as a 3-steps process:
  - $gg \to$ 3 on-shell intermediate particles $\propto |\mathcal{M}(g\,g \to t\,t\,H)|^2$
  - intermediate particles propagate: $\propto [(q^2-M^2)^2 - M^2\Gamma^2]^{-1}$
  - intermediate particles decay $\propto \Gamma^{-1}d\Gamma/d\Omega$



- This way:
  - no need to evaluate CPU-intensive $2 \to 8$ amplitudes [only $2 \to 3(4)$]
  - but... spin-correlations and polarizations neglected

Disclaimer: this is an *approximate* ME calculation

Dimensional reduction

- Factorize integration over final-state particles via

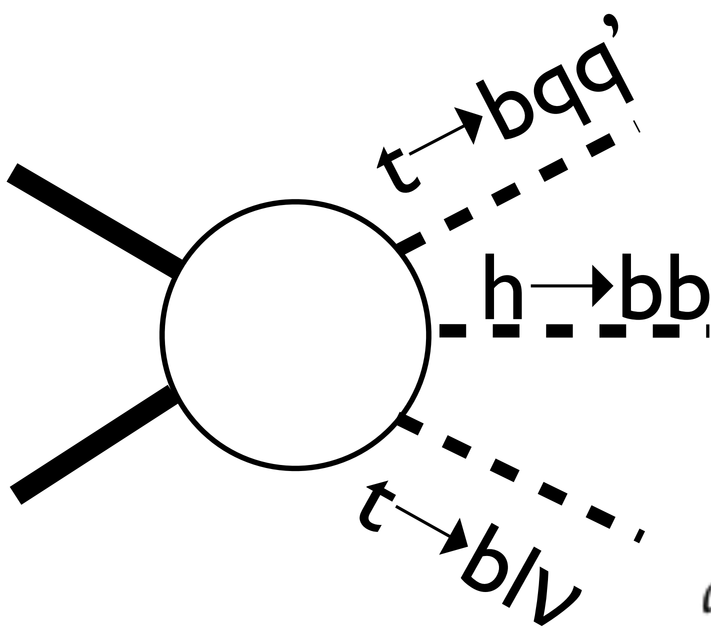
$$d\Phi_n(P;p_1,\ldots,p_n) = d\Phi_j(q;p_1,\ldots,p_j) \times d\Phi_{n-j+1}(P;q,p_{j+1},\ldots,p_n)(2\pi)^3 dq^2$$

- Narrow-width approx: $\frac{1}{(t^2 - M_t^2) + \Gamma_t^2 M_t^2} \rightarrow \frac{1}{(M_t\Gamma_t)^2}\delta(t^2 - M_t^2)$

- Diff. decay amp. from MC: $|\mathcal{M}(t \to bqq')|^2 \propto \frac{1}{\Gamma_t}\frac{M_t}{|\vec{q}^*||\vec{b}|}\frac{d\Gamma}{d\Omega_q^* d\Omega_b}$

- Assume lepton and jet direction perfectly measured

$\Rightarrow$



$$d\Phi_{t_q} \propto \frac{2E_{b_q}E_q E_{q'}^2}{M_W^2 E_{w_q}} \frac{1}{|\frac{\beta_{w_q}}{\beta_{b_q}}\hat{e}_{w_q}\cdot\hat{e}_{b_q} - 1|} dE_q$$

$$d\Phi_h \propto \frac{E_{b_2}}{|\frac{\beta_{b_1}}{\beta_{b_2}}\hat{e}_{b_1}\cdot\hat{e}_{b_2} - 1|} dE_{b_1}$$

$$d\Phi_{t_\ell} \propto \frac{2E_{b_\ell}\hat{E}_\ell E_\nu^2}{M_W^2 E_{w_\ell}} \frac{1}{|\frac{\beta_{w_\ell}}{\beta_{b_\ell}}\hat{e}_{w_\ell}\cdot\hat{e}_{b_\ell} - 1|} d\Omega_\nu$$

Transfer functions

- Encode detector response from *quark* to *jet*
- Parametric dependence on η_q and E_q
  - single-gaussian for *udcsg*
    - μ=1.0 , $\sigma/E \simeq$ 15-20% *
  - double-gaussian for *b*-quarks
    - core: μ=1.0 , $\sigma/E \simeq$ 11-15%
    - tail: $\mu \simeq$0.9 , $\sigma/E \simeq$ 25-35%

} CMS PAS-JME-10-011 ($\sigma/E \simeq$10%) convoluted w/ quark→gen-jet hadronization (PYTHIA)

* @ E=100 GeV

Technical solutions

- *ttH* and *ttbb* $|\mathscr{M}|^2$ computed by OpenLoops
  - LO accuracy [*only compiled libraries needed*]
- PDF from LHAPDF low-memory libraries
  - CTEQ65 set
- Numerical integration by VEGAS
  - interfaced via ROOT
- Quark energies integration restricted by TF
  - integrate over 95% CL intervals given the *observed* jet energy
- Permutations pruning
  - skip permutations that provide poor M_T, M_W or M_H measurements

Results

Monte Carlo Simulation

- *ttH* modeled by PYTHIA
- MadGraph used to model *tt* + ≤2 jets
  - events split into exclusive bins: *tt* + 0/1/2 *b*
- Normalized to 19.5 fb^{-1} at 8 TeV

process	subprocess	generator	cross-section (pb^{-1})
$t\bar{t}H(125)$	$H \to b\bar{b}$	PYTHIA	0.1302·0.569
$t\bar{t}$+jets	$t\bar{t} \to b\bar{b}q\bar{q}'q''\bar{q}'''$	MadGraph	106.9
	$t\bar{t} \to b\bar{b}q\bar{q}'\ell\nu_\ell$	MadGraph	103.0
	$t\bar{t} \to b\bar{b}\ell\nu_\ell\ell'\nu_{\ell'}$	MadGraph	24.8
$Z/\gamma^* \to \ell\ell$	$M_{\ell\ell} \in [10, 50]$	MadGraph	12765
	$M_{\ell\ell} > 50$	MadGraph	3503.71
$W \to \ell\nu$	-	MadGraph	37509
$t\bar{t} + V$	$t\bar{t} + W$	MadGraph	0.232
	$t\bar{t} + Z$	MadGraph	0.2057
single-t	t-channel	POWHEG	56.4
	tW-channel	POWHEG	11.1
	s-channel	POWHEG	3.79
single-$\bar{t}$	t-channel	POWHEG	30.7
	tW-channel	POWHEG	11.1
	s-channel	POWHEG	1.76
VV+jets	WW	PYTHIA	56.75
	WZ	PYTHIA	33.85
	ZZ	PYTHIA	8.297

signal

main background

minor backgrounds

Event reconstruction

- e/μ := p_T>30/20 GeV, |η|<2.5 , 80-90% ID eff.
- Jet := cluster gen-particles with k_T^{-1} 0.5
  - p_T > 30 GeV and |η| < 2.5
  - jet "*b*-tagged" with approx. CMS efficiencies *:
  - smeared by TF

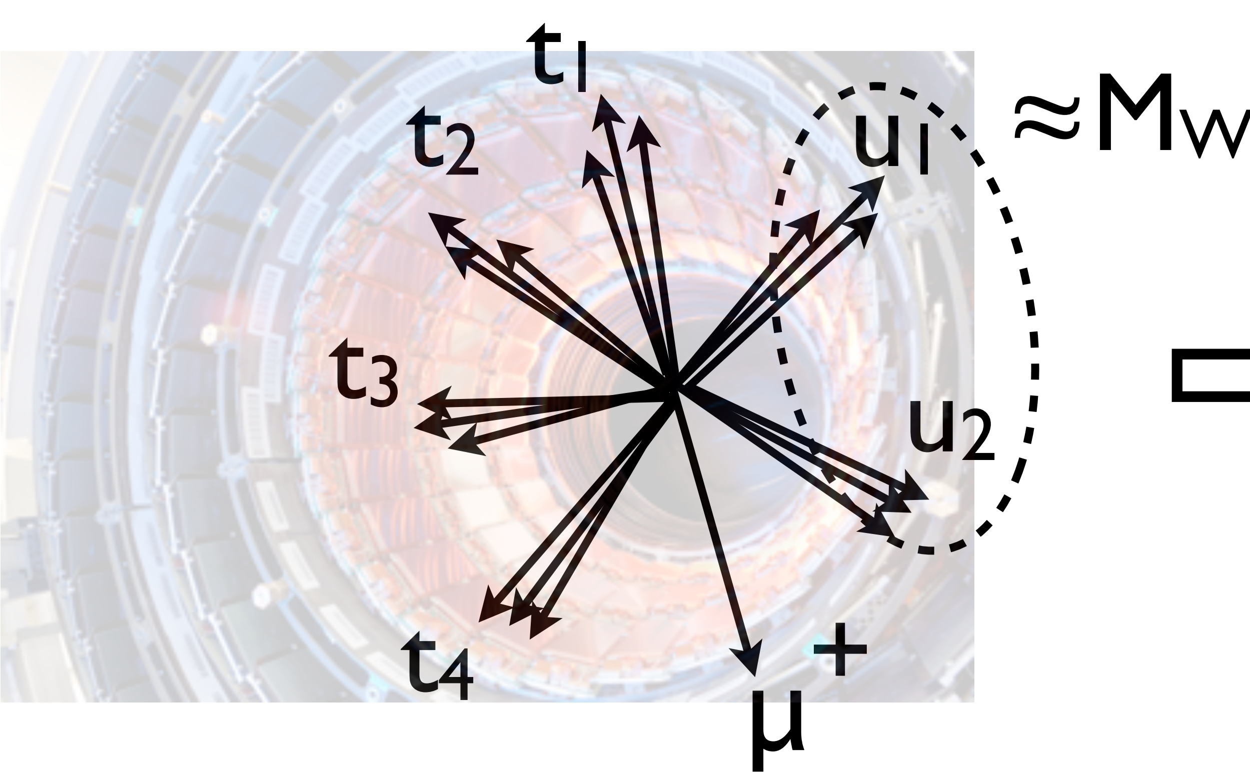
	b	c	udcsg
|η|<1	70%	20%	2%
|η|>1	60%	20%	4%

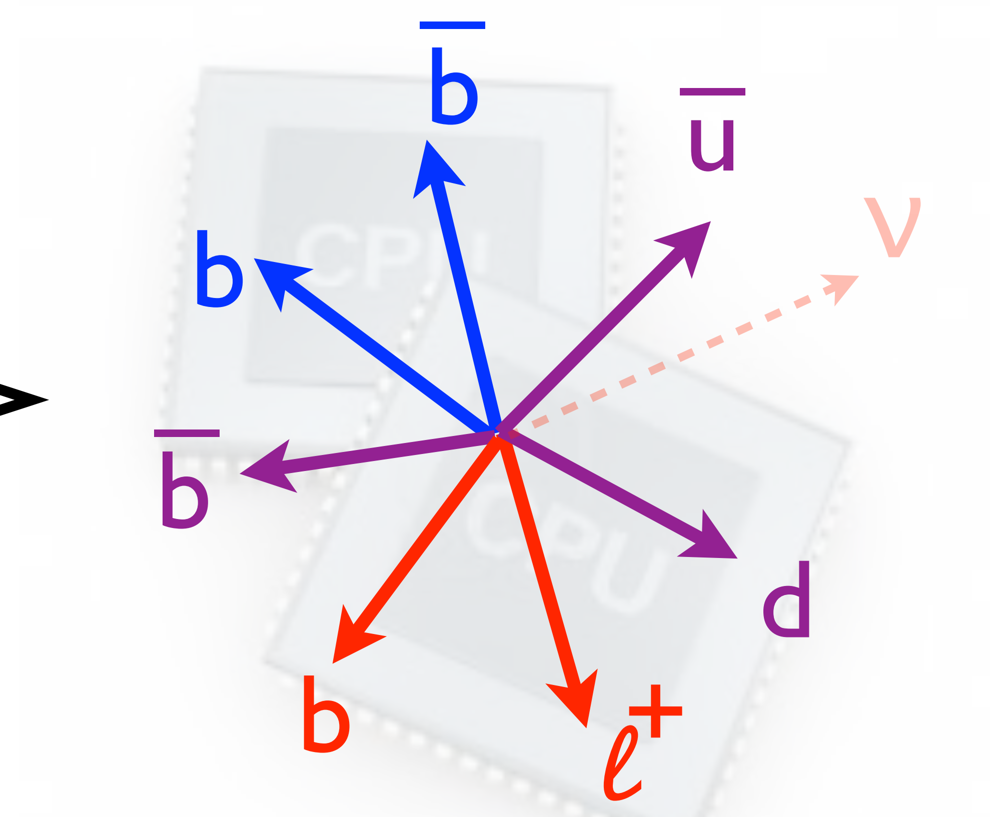
observable	interpretation
tagged jet	*b*-quark
un-tagged jet	W→*qq'*, or ISR/FSR gluon
more untagged jets than expected	ISR/FSR gluons
one untagged jet less than expected	W→*qq'* out of acceptance

- Categorize events in number of leptons, jets, and tags.
  Select events with N=4 tags...

* CMS PAS-BTV-13-001

SL events: all quarks reconstructed

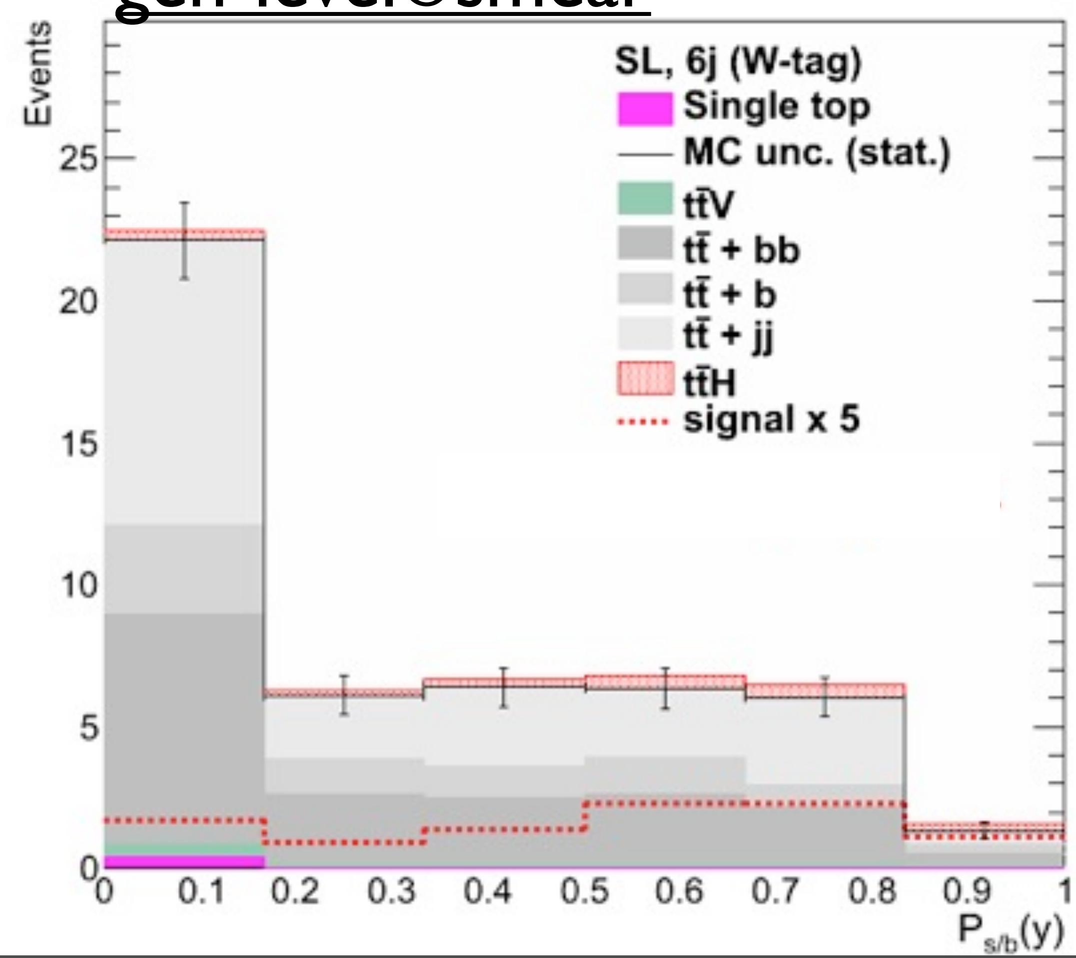




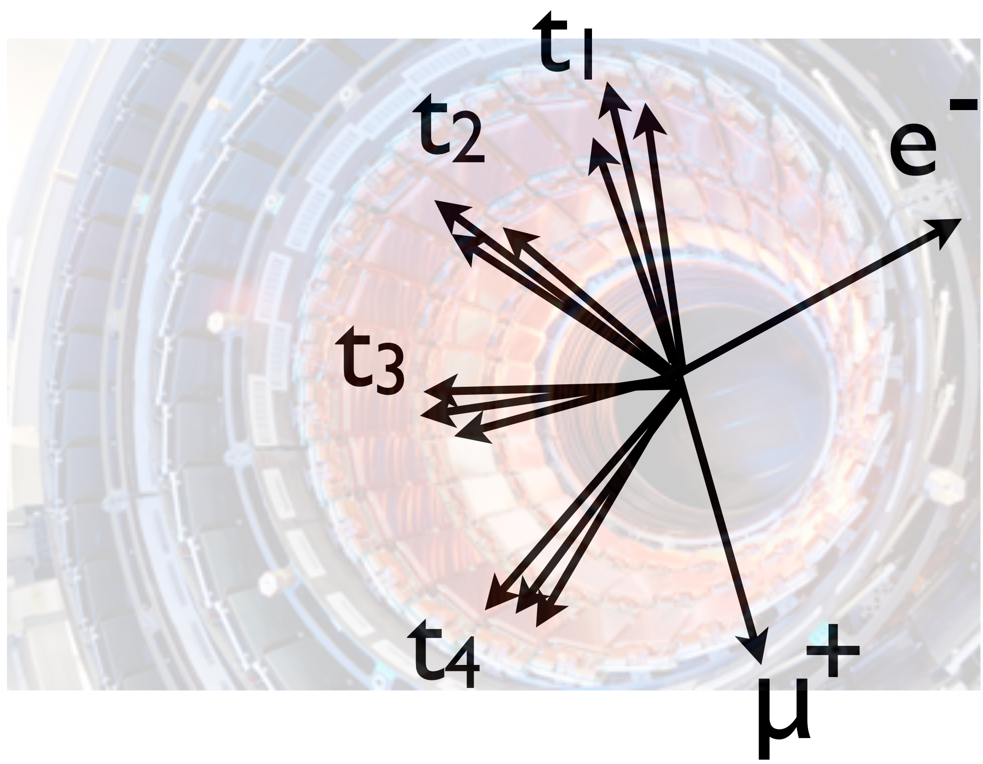
- Observation:
  - one isolated lepton
  - 4 tags + 2 untag'd [60<M<100] GeV
- Interpretation:
  - $pp \rightarrow t(\rightarrow bl\nu)\,\bar{t}(\rightarrow \bar{b}ud)\;(b\bar{b})$
  - all quarks reco's as jets

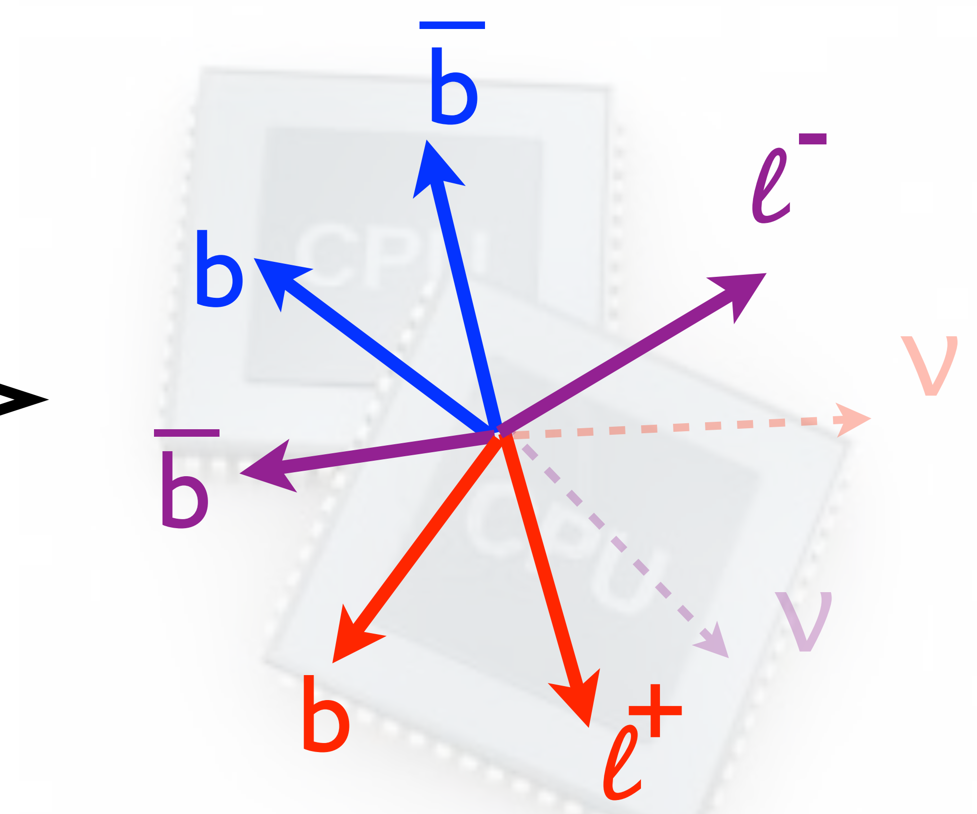
✓ true in ~50% of *ttH* events
✓ S/B ~ 4%

gen-level⊗smear



DL events: all quarks reconstructed

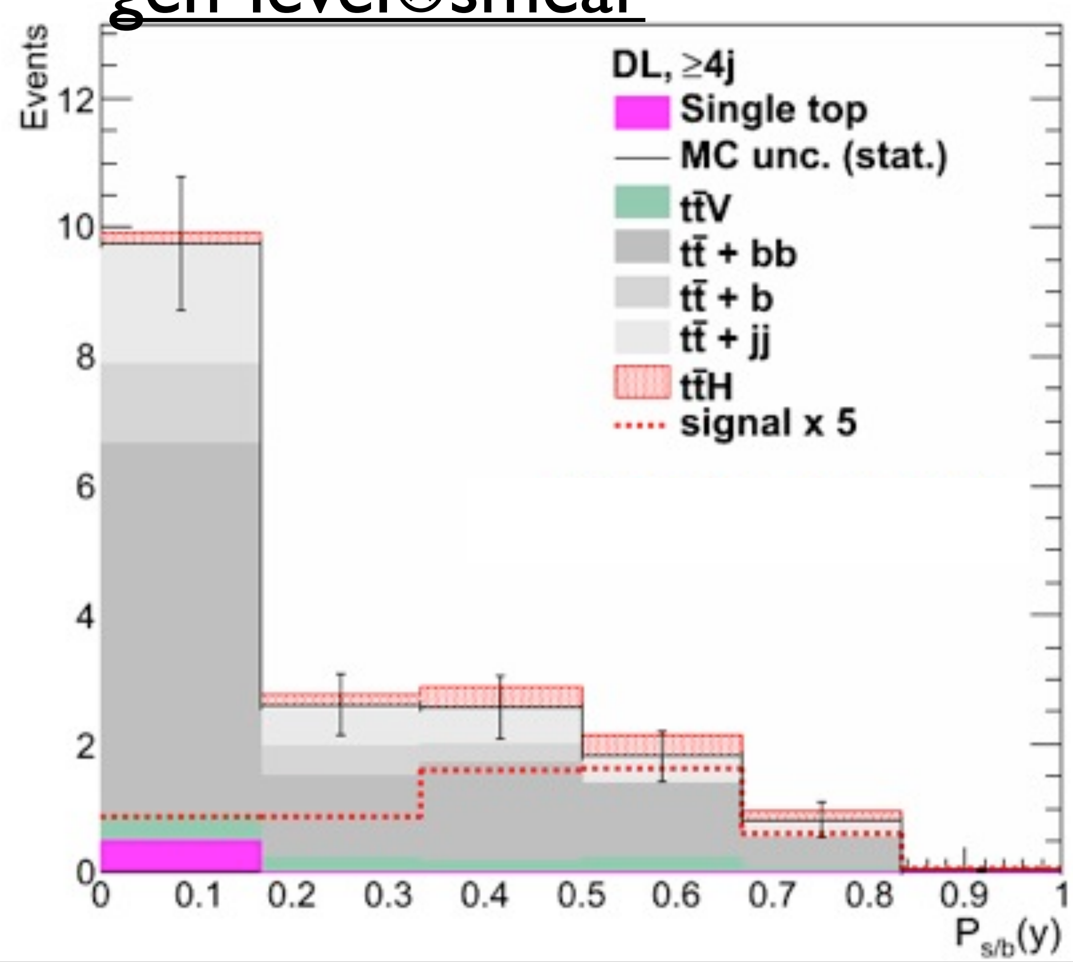




- **Observation:**
  - two OS isolated leptons
  - 4 tags
- **Interpretation:**
  - $pp \to t(\to b l \nu)\,\bar{t}(\to \bar{b} l \nu)\;(b\bar{b})$
  - all quarks reco's as jets

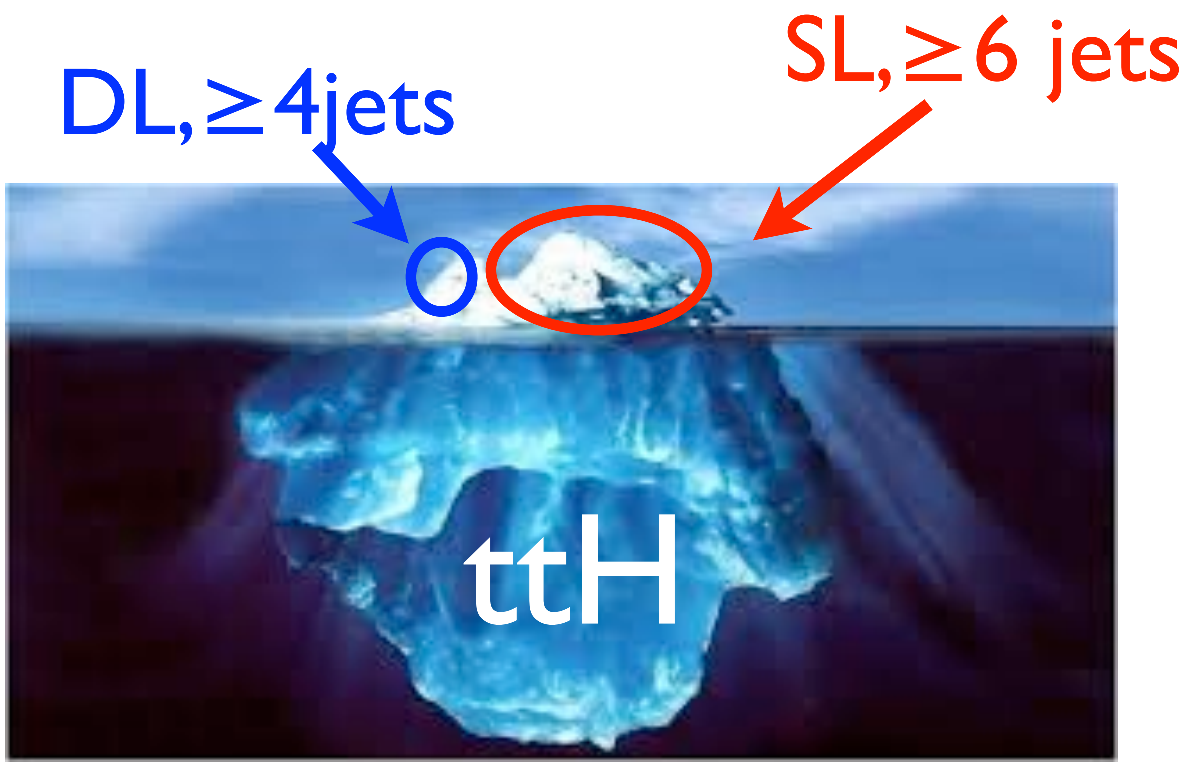
> ✓ true in ~70% of *ttH* events
> ✓ S/B ~ 6%

gen-level⊗smear

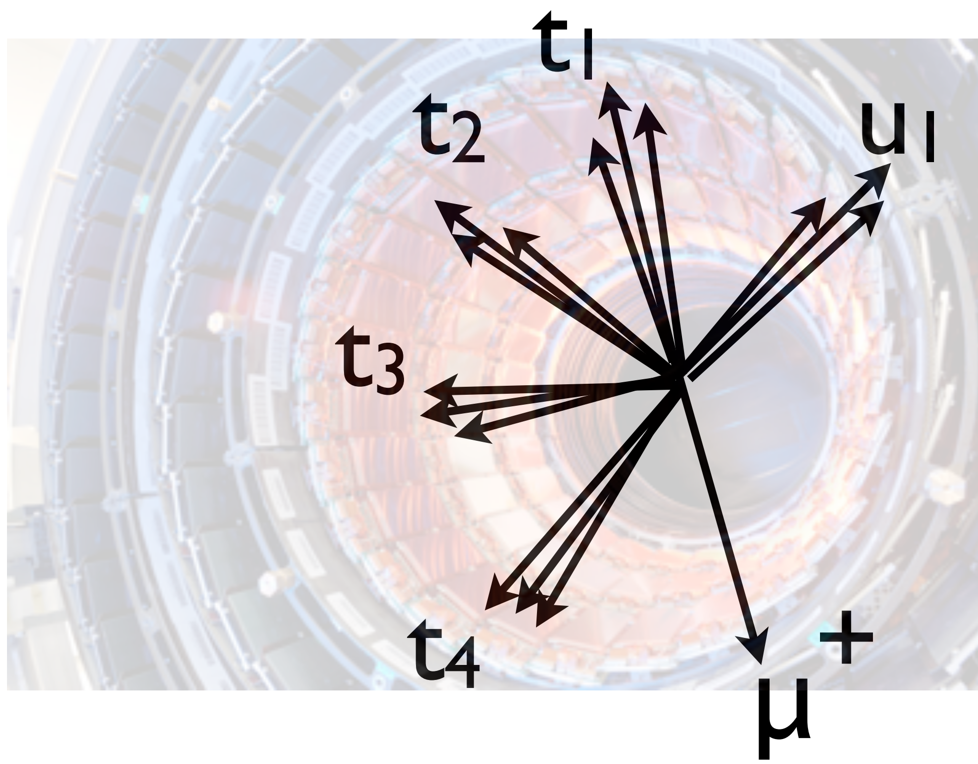


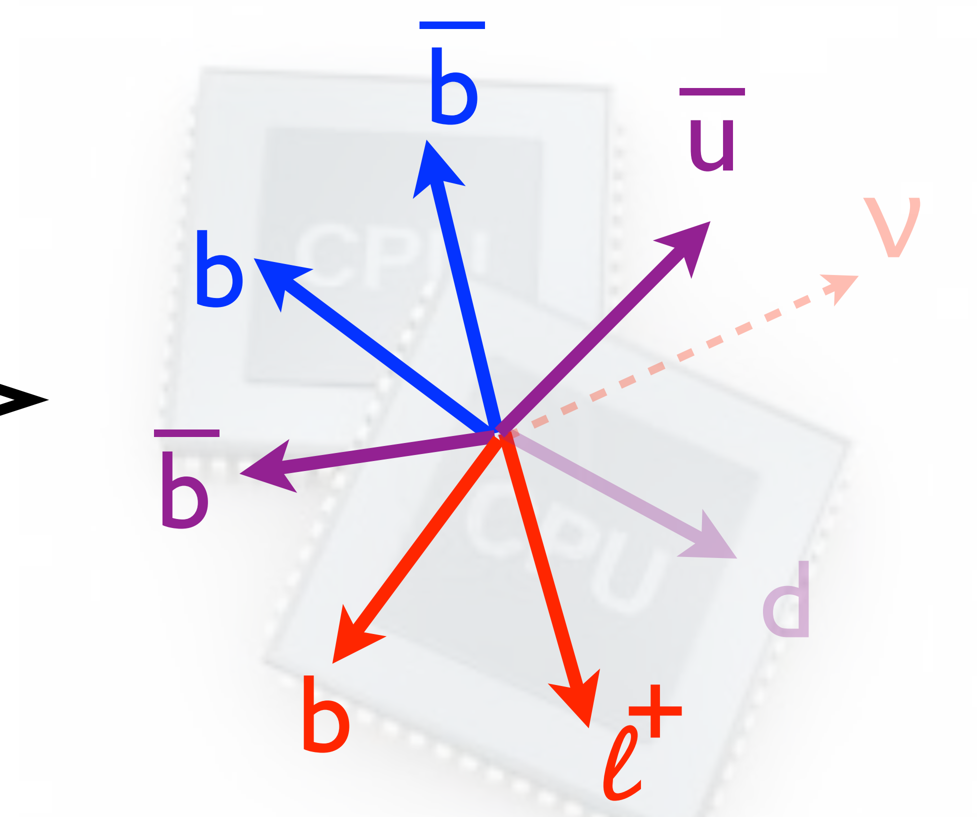
Going into more depth..

- Full event reconstruction ⇒ low acceptance
- MEM can be deployed for any event
  - even if some particles are not reconstructed (e.g. neutrinos)
    - ✓ just integrate over them [*marginalization*]
- Can we exploit less constrained topologies ?
  - E.g.: one quark from W→qq' out-of-acceptance

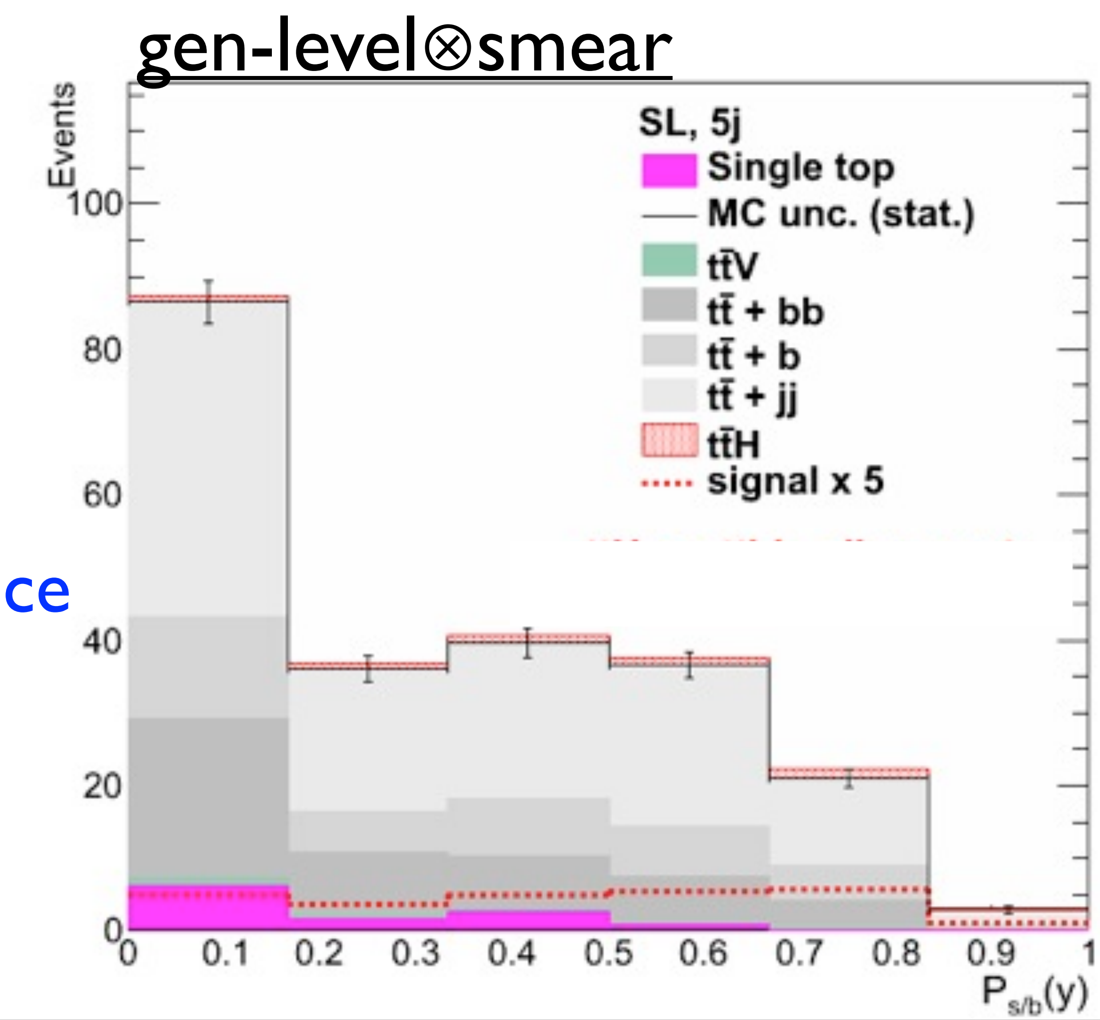


SL events: one quark missed



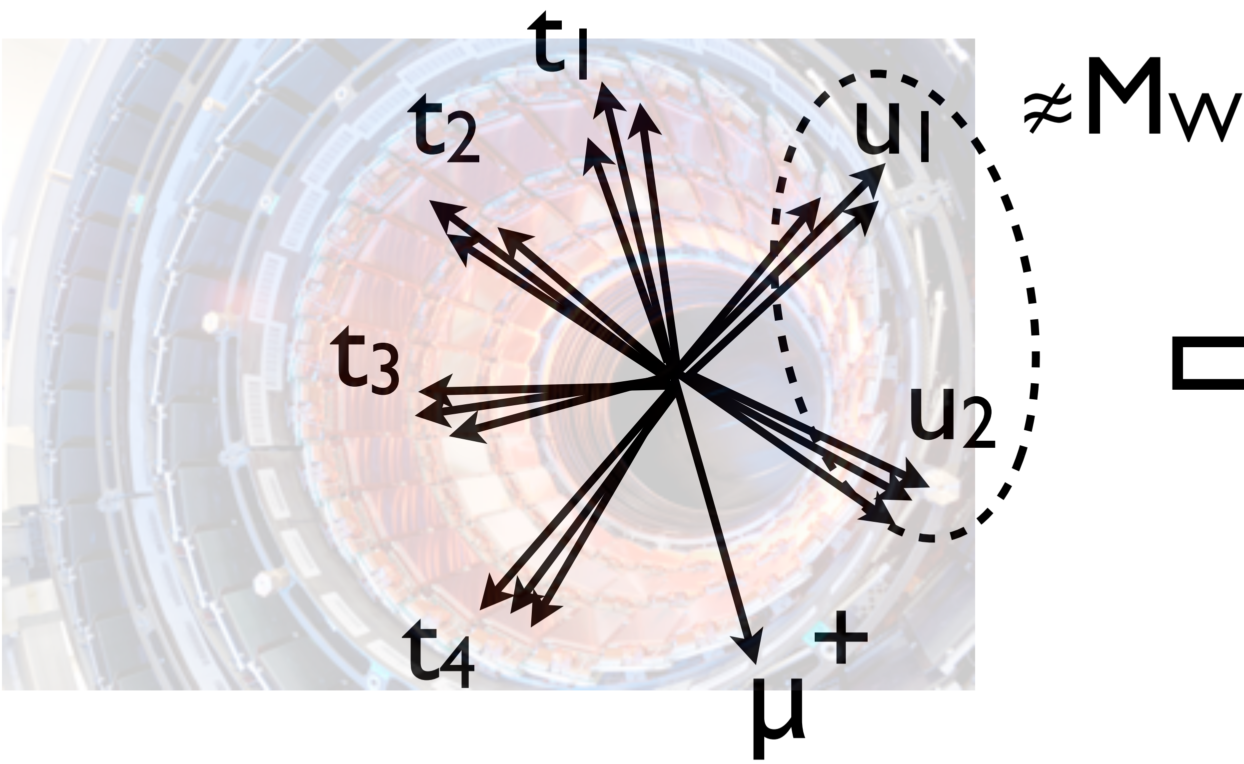


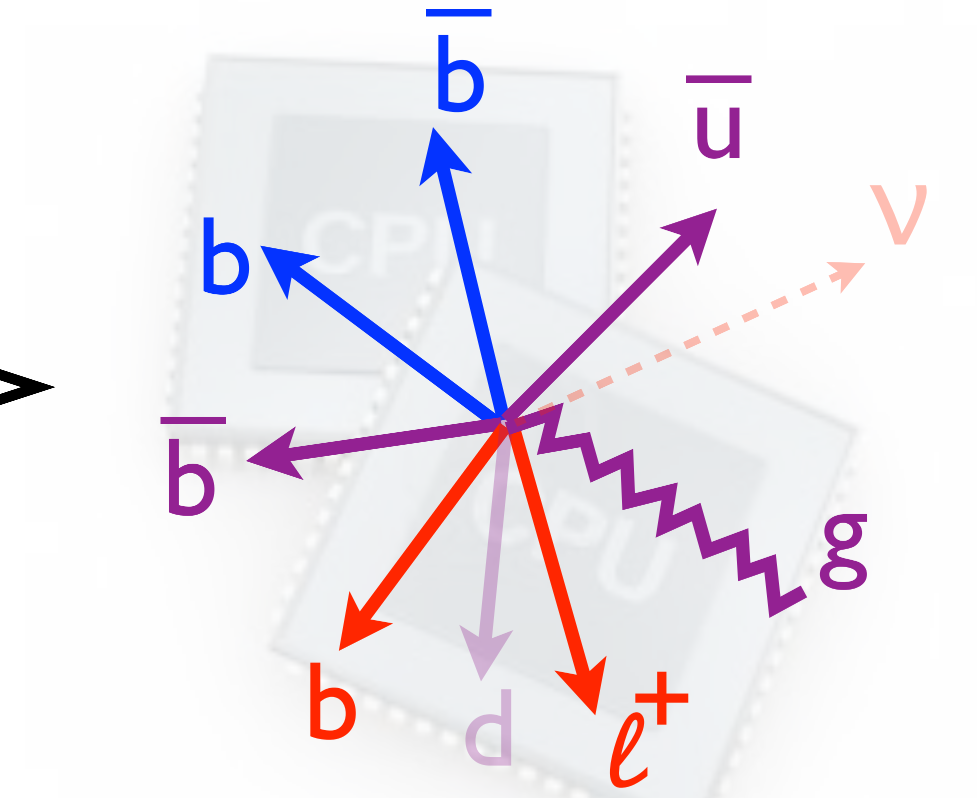
- Observation:
  - one isolated lepton
  - 4 tags + 1 untag'd
- Interpretation:
  - $pp \rightarrow t(\rightarrow bl\nu)\,\bar{t}(\rightarrow \bar{b}ud)\ (b\bar{b})$
  - one quark from W out-of -acceptance



> ✓ true in ~40% of *ttH* events
> ✓ S/B ~ 2.5%

SL events: one quark missed + FSR

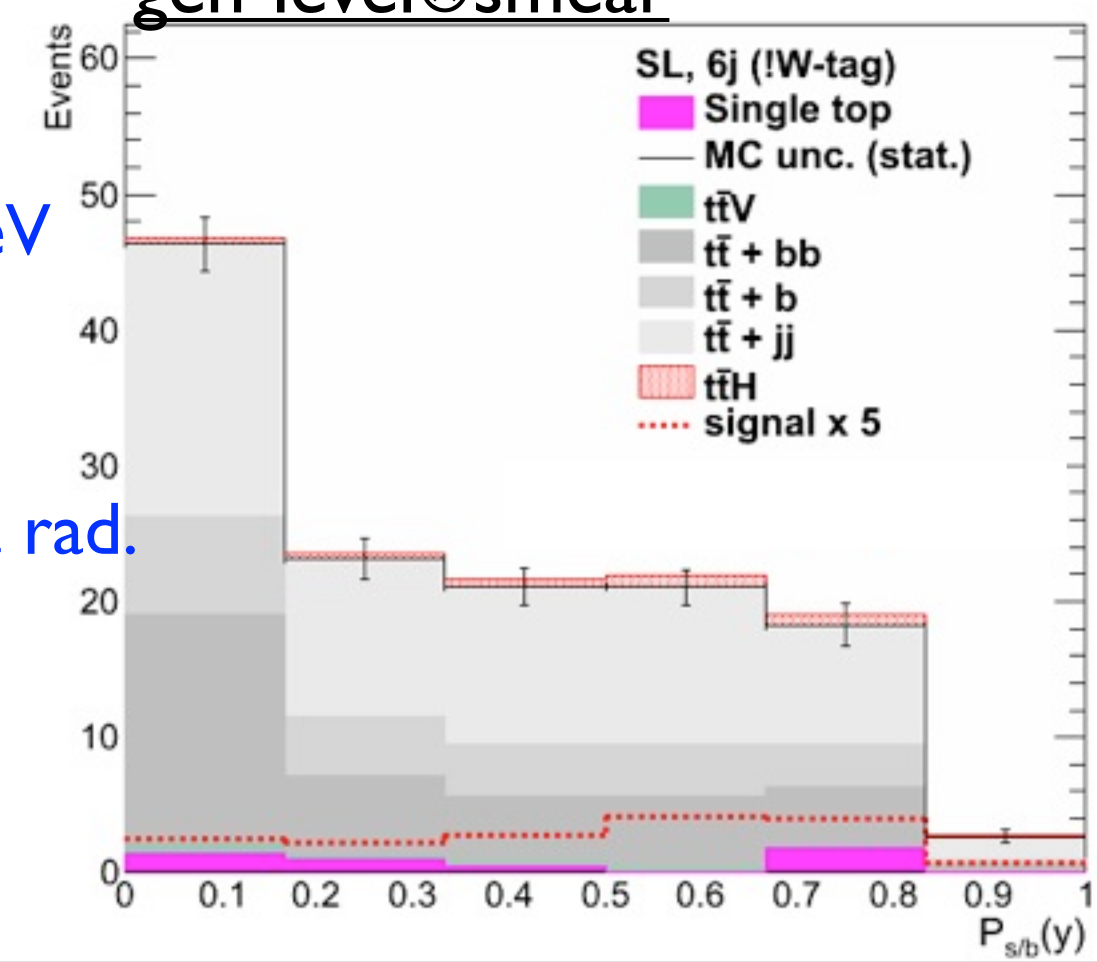




- Observation:
  - one isolated lepton
  - 4 tags + 2 untag'd [! 60<M<100] GeV
- Interpretation:
  - $pp \to t(\to bl\nu)\,\bar{t}(\to \bar{b}ud)\ (b\bar{b})$
  - one untag'd from W, one from extra rad.

> ✓ true in ~35% of *ttH* events
> ✓ S/B ~ 2.5%

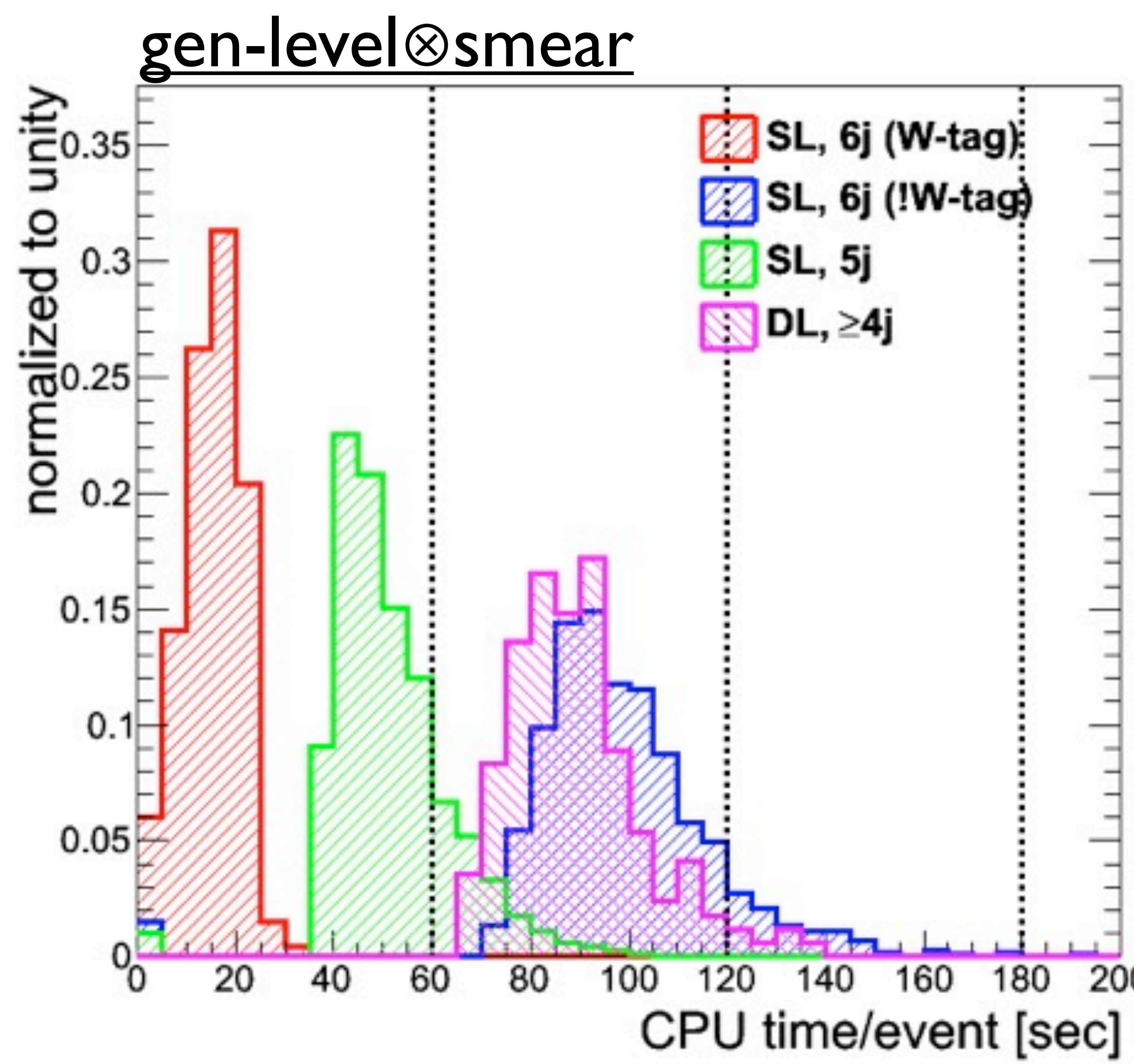
gen-level⊗smear



CPU time per topology

Time* needed to evaluate $P_{S/B}$:

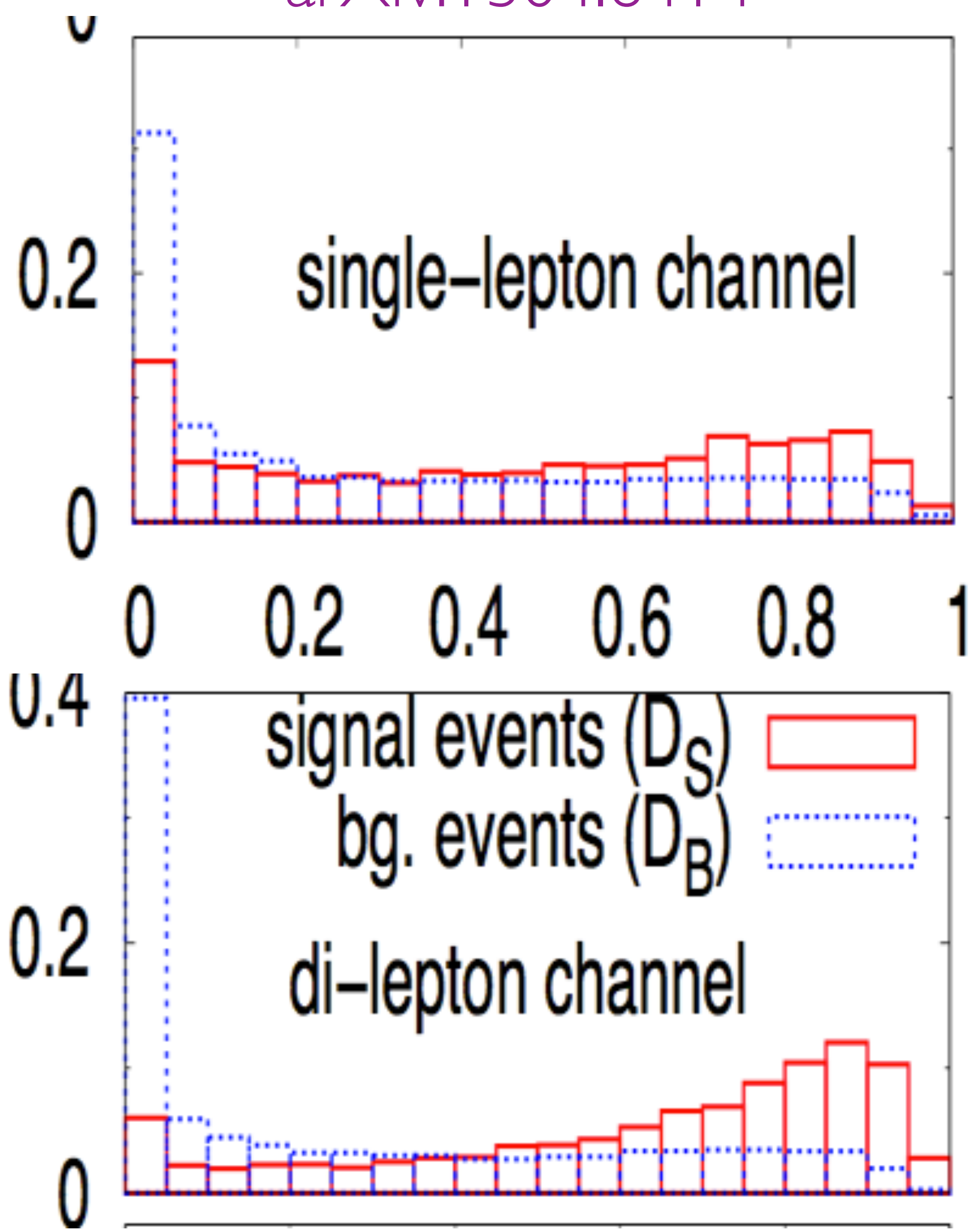
- dominated by bkg weight eval.
- ≲ 2 min. for almost all events
- ≲ 1 min for 60% of events
- <T> ≈15 sec. for the most constrained topology



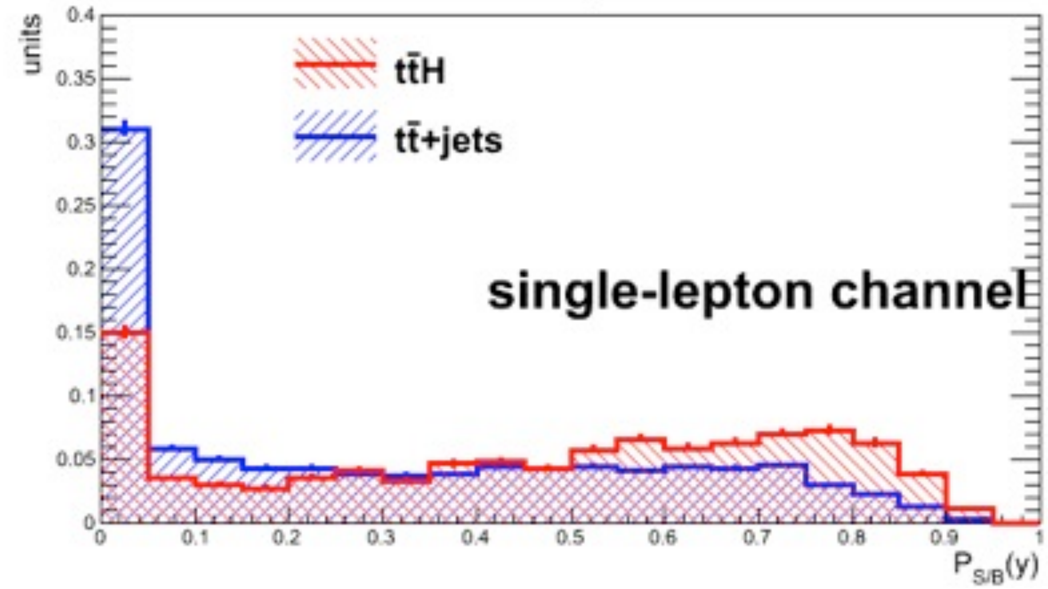
* Intel Xeon CPU E5440 @ 2.83 GHz

Comparing with MadWeight

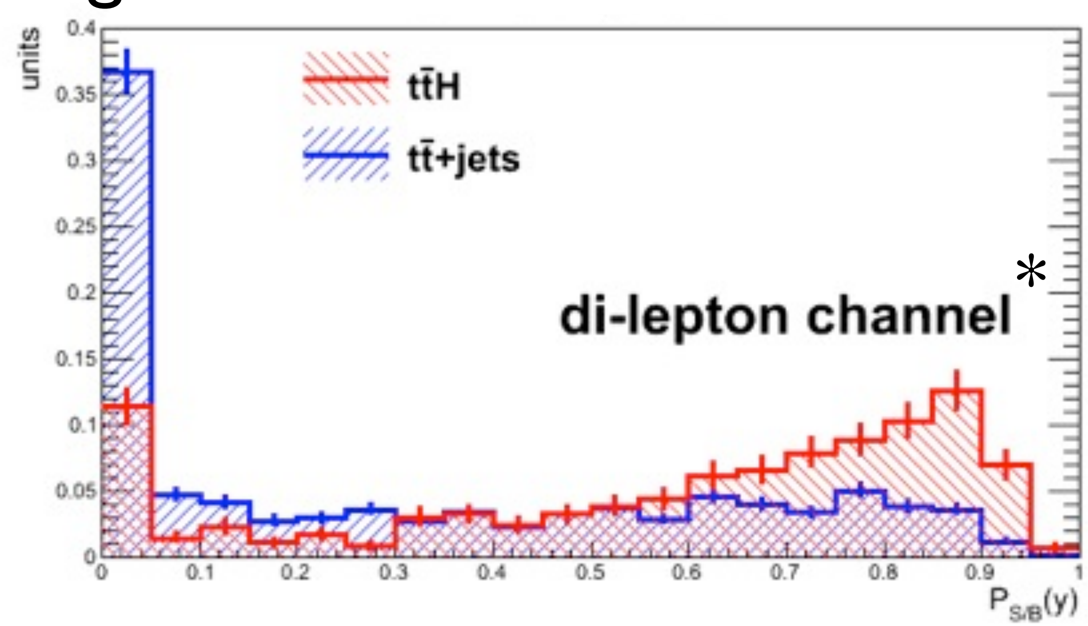
arXiv:1304.6414



<u>gen-level⊗smear</u>



<u>gen-level⊗smear</u>



* looser *b*-tag cuts to enhance MC stat.

Expected sensitivity

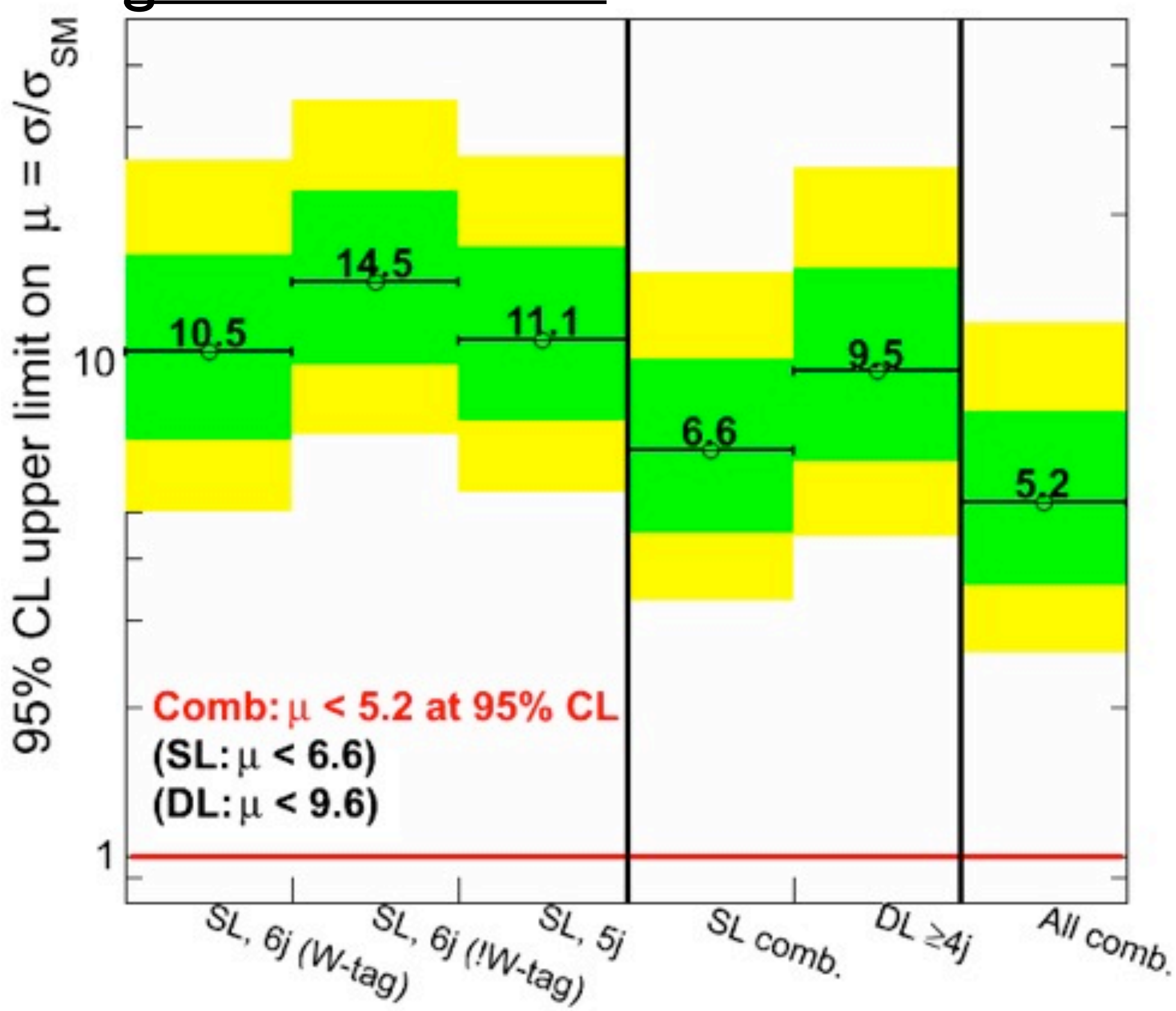
- Estimate sensitivity from simultaneous fit to $P_{S/B}$ distributions
  - systematics treated as nuisance parameters w/ log-normal priors
  - *tt* + 0/1/2 *b* allowed to float independently in the fit
  - asymptotic 95% CL upper limits on σ_{SM}/σ :

nuisance	rel. unc.
lumi	2.6%
ttH x-sec	12%
tt+LF	35%
tt+bb	50%
tt+b	50%
ttV/single-t	20%
gg PDF	3%
JES	10%
b-tag	20%
MC unc.	bin-by-bin

Expected sensitivity

- Estimate sensitivity from simultaneous fit to $P_{S/B}$ distributions
  - systematics treated as nuisance parameters w/ log-normal priors
  - *tt* + 0/1/2 *b* allowed to float independently in the fit
  - asymptotic 95% CL upper limits on σ_{SM}/σ :

gen-level⊗smear



A few remarks

- SL channel ⇒ higher rates, but larger "confusion"
  - *W*→*cs* is a generous source of *b*-tags
- DL channel ⇒ lower rates but cleaner events
- Splitting the SL+6 jet cat. by "W-tag" helps
- SL+5 jet cat. adds extra sensitivity

⇒ *optimized* SL analysis more performing than DL

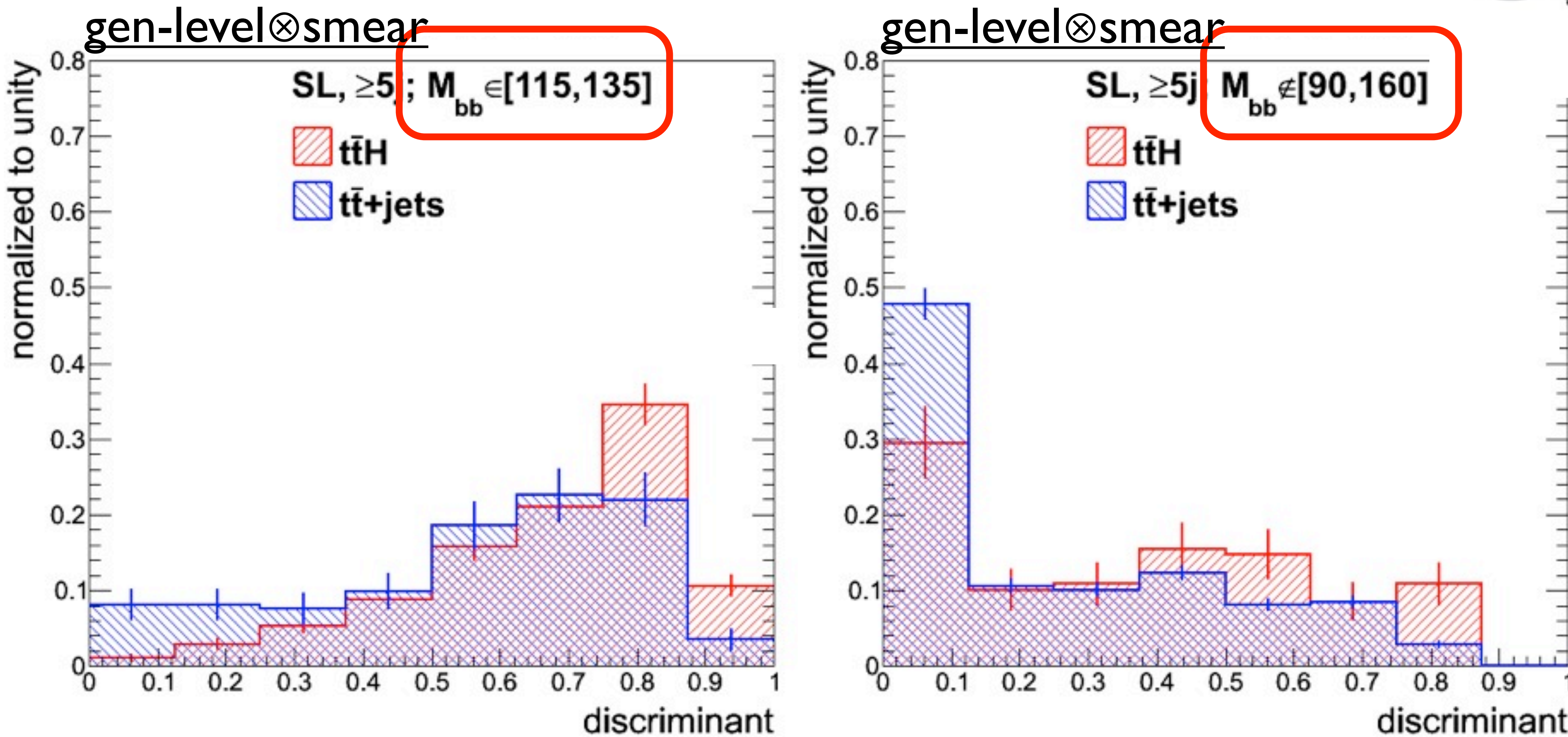
Digression I: the Higgs mass

- What is *really* separating *ttH*(→*bb*) from *ttbb* ?
  - not the "top mass" (same in both)
  - not the angular correlations in top decay (similar in both)
  - M(*bb*) mass is natural candidate

- Does a *ttbb* event w/ M(*bb*)~125 look identical to *ttH*?
  - i.e., can the ME weight still discriminate the two ?

- Select events which satisfy the tested ME hypothesis and have M(*bb*)≈ (≠) 125 GeV ...

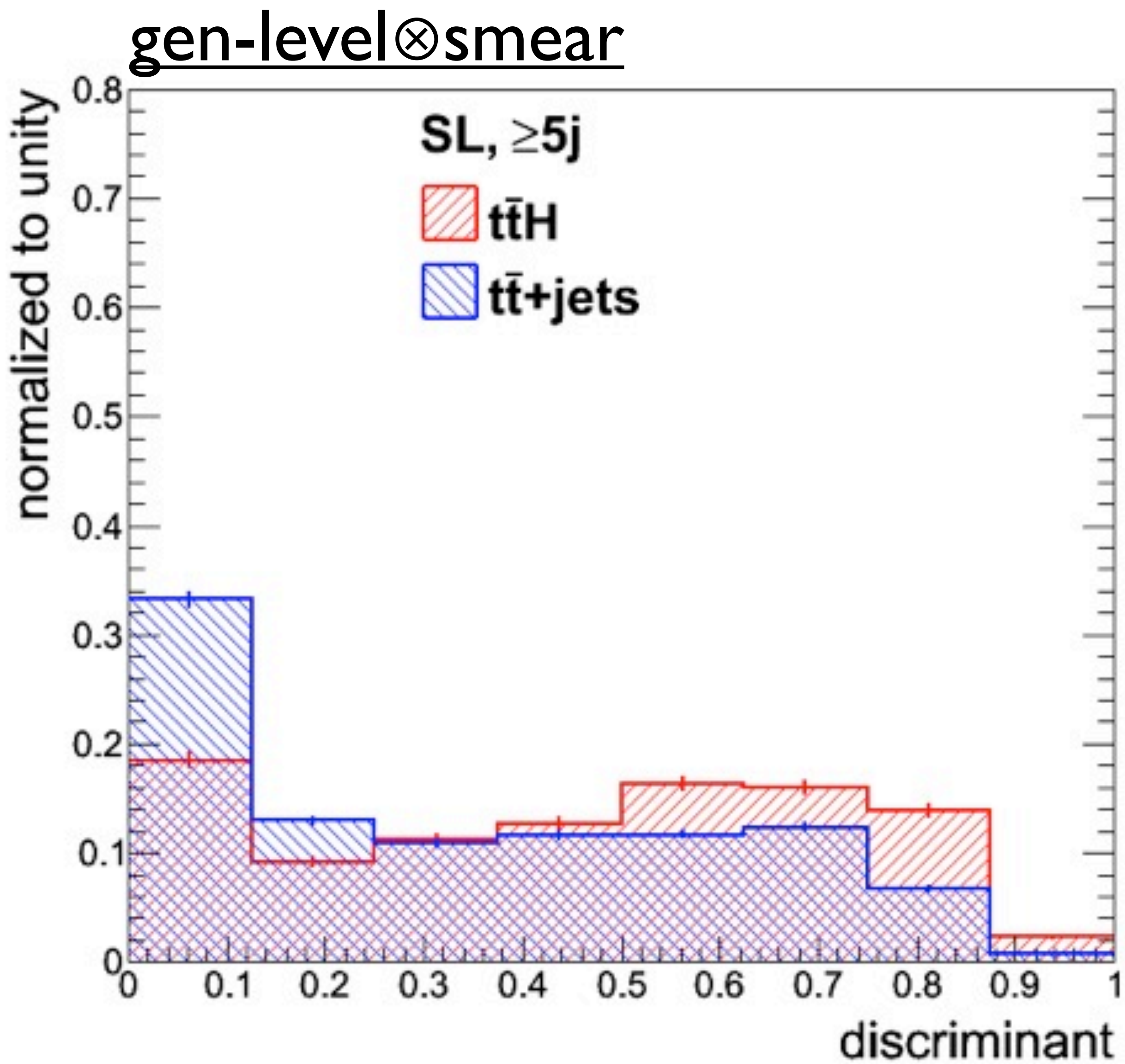
Digression I: the Higgs mass



- *ttbb* events w/ M(*bb*) ≈ 125 indeed look like *ttH*!
  - but not identical ⇔ the ME is sensitive also to the other variables
- *ttH* events w/ M(*bb*) ≠ 125 (e.g. poor resolution) undistinguishable from *ttbb*

Digression II: wrong hypothesis

- If the event does not fulfill the *tested* ME hypo, the weight is broadly distributed
  - yet, *ttH* remains slightly more "signal-like"

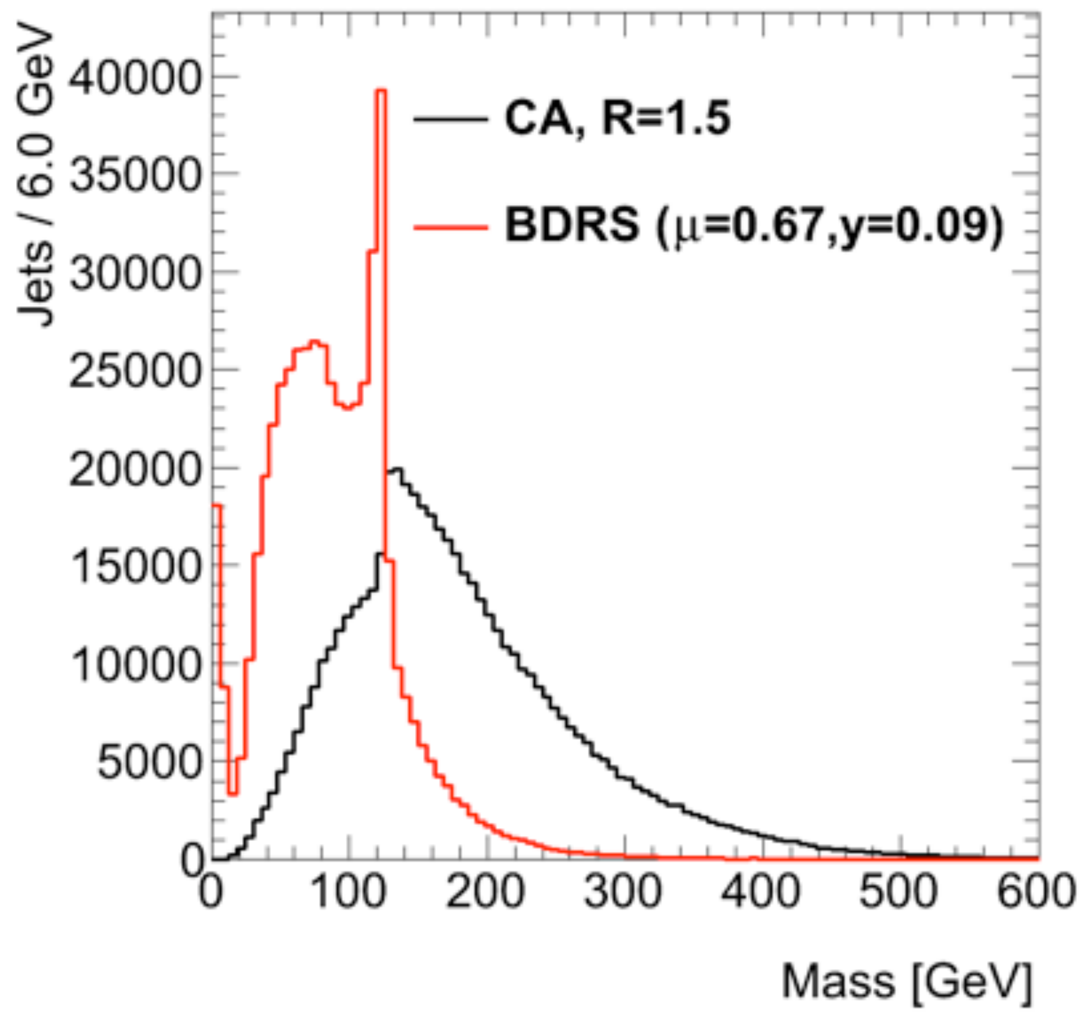


Prospects and conclusions

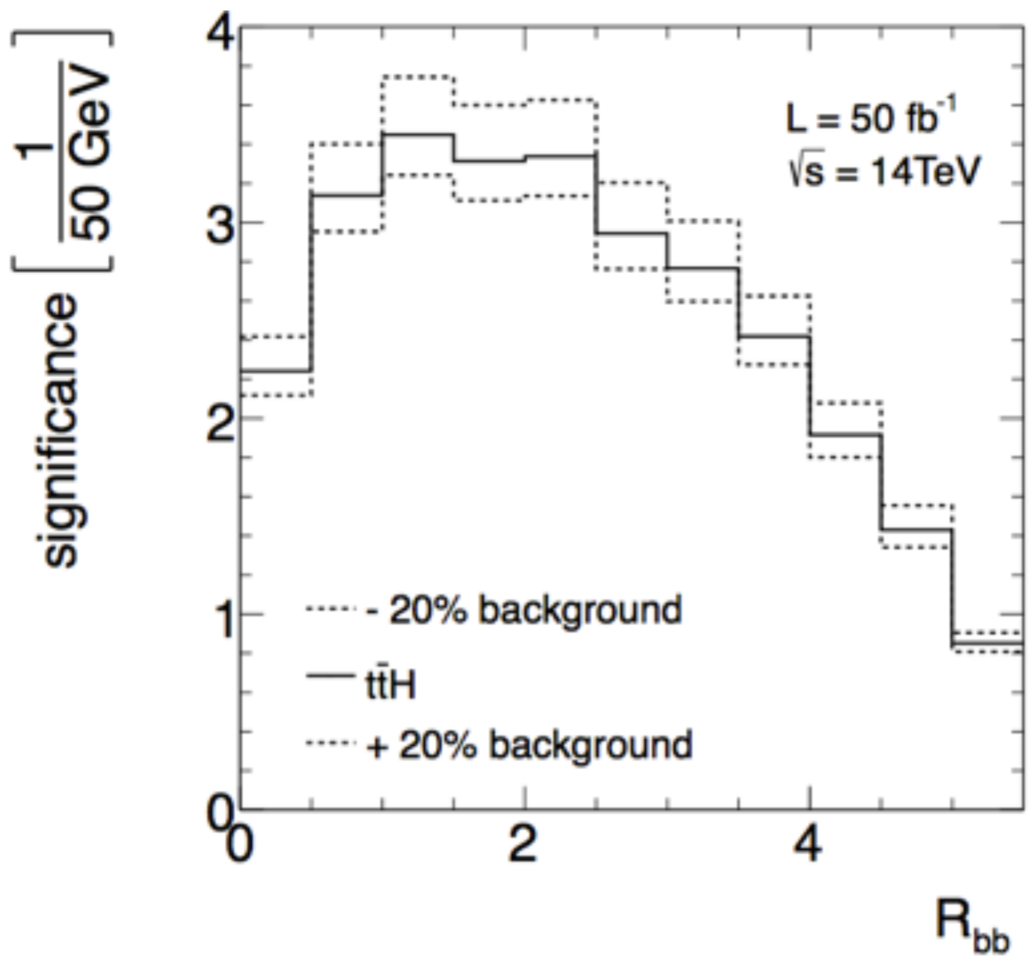
Merging MEM w/ boost: a roadmap (1)

- MEM powerful, but blind to jet substructure, color-connection, jet merging
  - Step I: investigate usage of Higgs-tag in the ME analysis
  - Step II: integrate Higgs & top tags into ME (Higgs→FatJet TF)
  - Step III: open new phase-space
    - ✓ e.g. trade b-tag for boost...

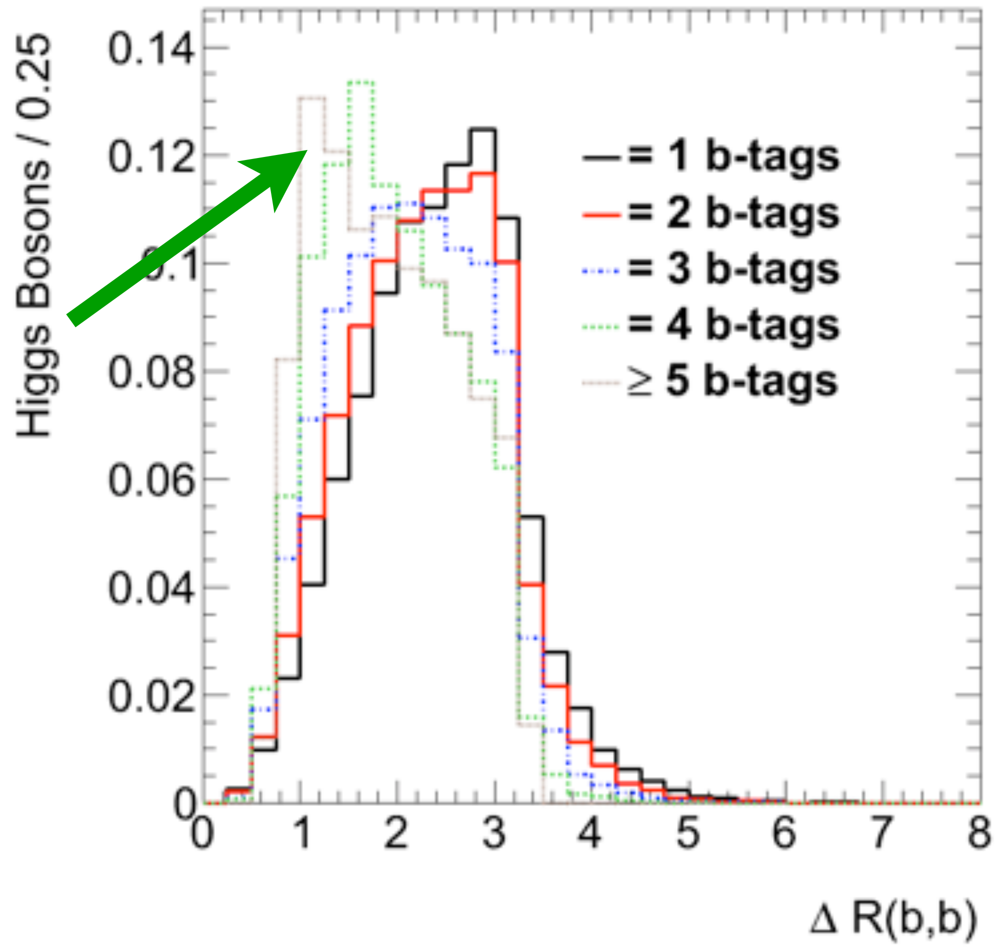
- Tools:
  - Baseline: BDRS
    - ✓ CA, R=1.5, $p_T > 150$ GeV
  - massdrop/filtering
  - two k_T^{-1} R=0.5 b-jets inside



Merging MEM w/ boost: a roadmap (II)



- Most significance from low Higgs/top p_T
  - see e.g. arXiv:1311.2591
- Very challenging environment for substructure methods
  - 13 TeV will certainly help !
- But: MEM already biases towards moderately 'boosted' events !
  - MEM/boost correlation not yet fully exploited



Conclusions

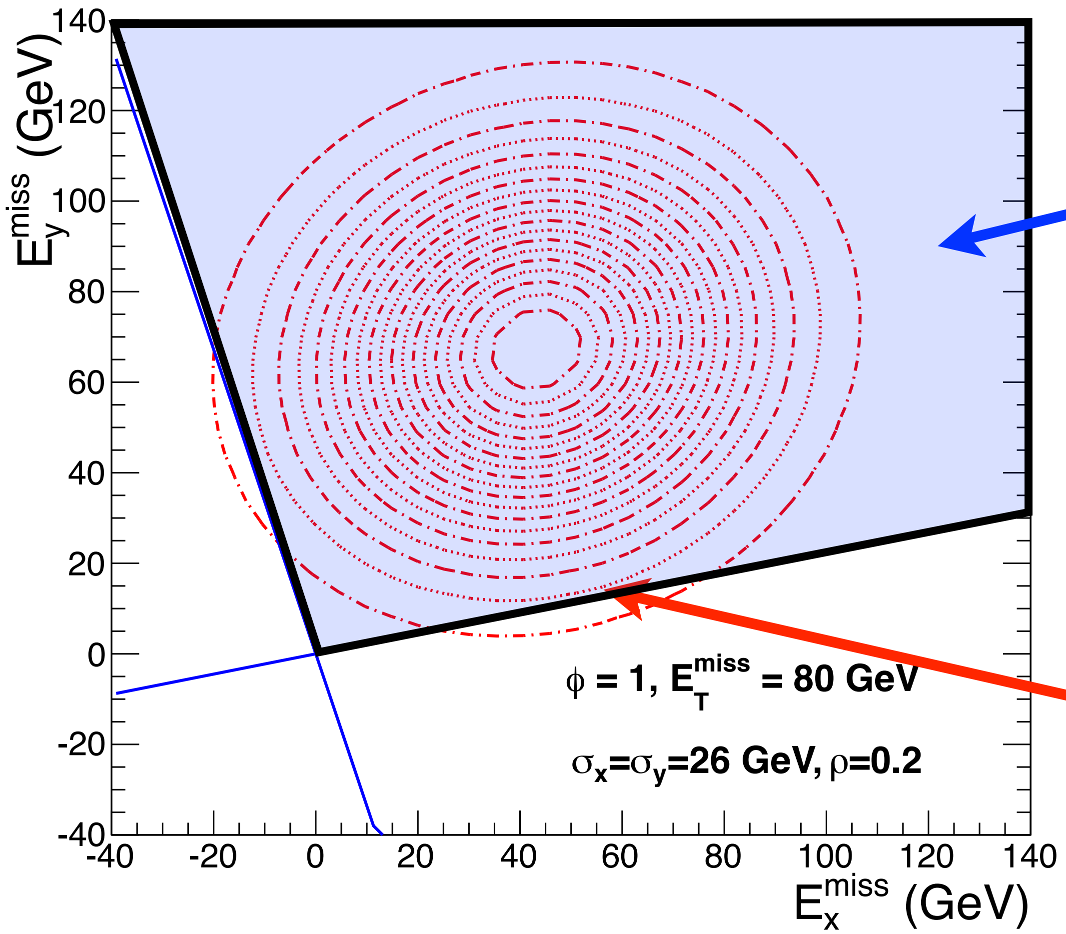
- An end-to-end MEM analysis of $ttH(\rightarrow bb)$
  - emphasis on *speed* and *flexibility*
  - good agreement w/ existing literature
  - ➡ analysis is definitely *sustainable* for LHC experiments
- Extension to classes of events never considered before
  - optimized ME hypothesis deployed in each *event class*
  - significant boost in sensitivity
  - ➡ this study shows a sensitivity comparable to the CMS MVA analysis
- Heading for a merged MEM + boosted analysis
  - exploiting event features not accessible to MEM
  - a *goal* for LHC13 !

Thanks you for your attention!

Back up

P_T balance

- Event-by-event constraint to the *measured* recoil $\boldsymbol{\rho} = - \sum \mathbf{p_T}^{vis} - \mathbf{E_T}^{miss}$ via transfer function
  - for each phase-space point, boost so that $\mathbf{P_T} = \mathbf{0}$, and evaluate $|\mathcal{M}|^2$
- N.B.: at present, we instead constrain ν's $\mathbf{p_T}$ to $\mathbf{E_T}^{miss}$ and the quark energy to jet energy
  - not optimal because E_T^{miss} correlated w/ jet energy.



ν's direction integrated over blue plane w/ prior:

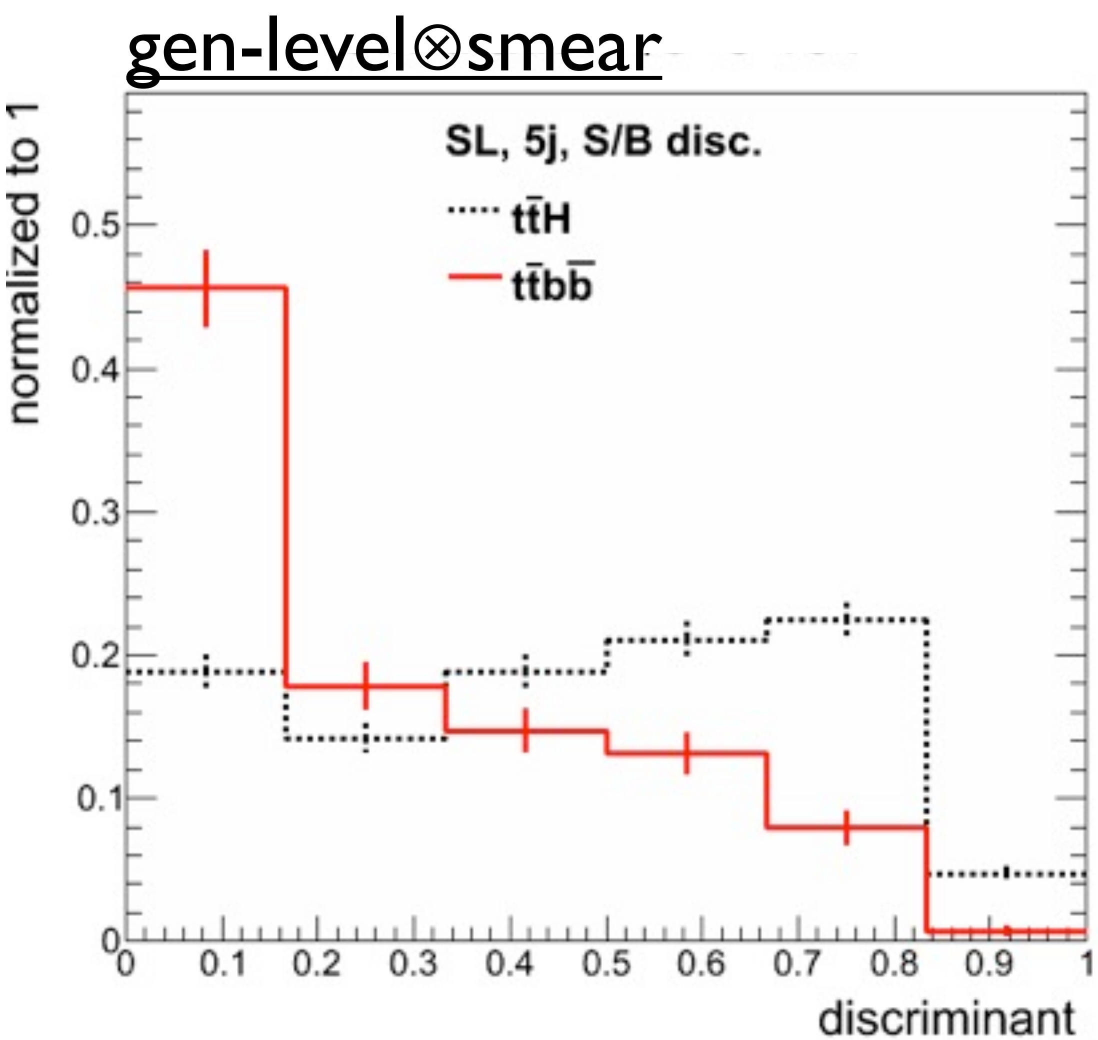
$$\frac{1}{2\pi\sqrt{|V_{x,y}|}}\exp\{-\frac{1}{2}(\vec{E}_T^{miss} - \sum \vec{\nu}_T)^T V_{x,y}^{-1}(\vec{E}_T^{miss} - \sum \vec{\nu}_T)\}$$

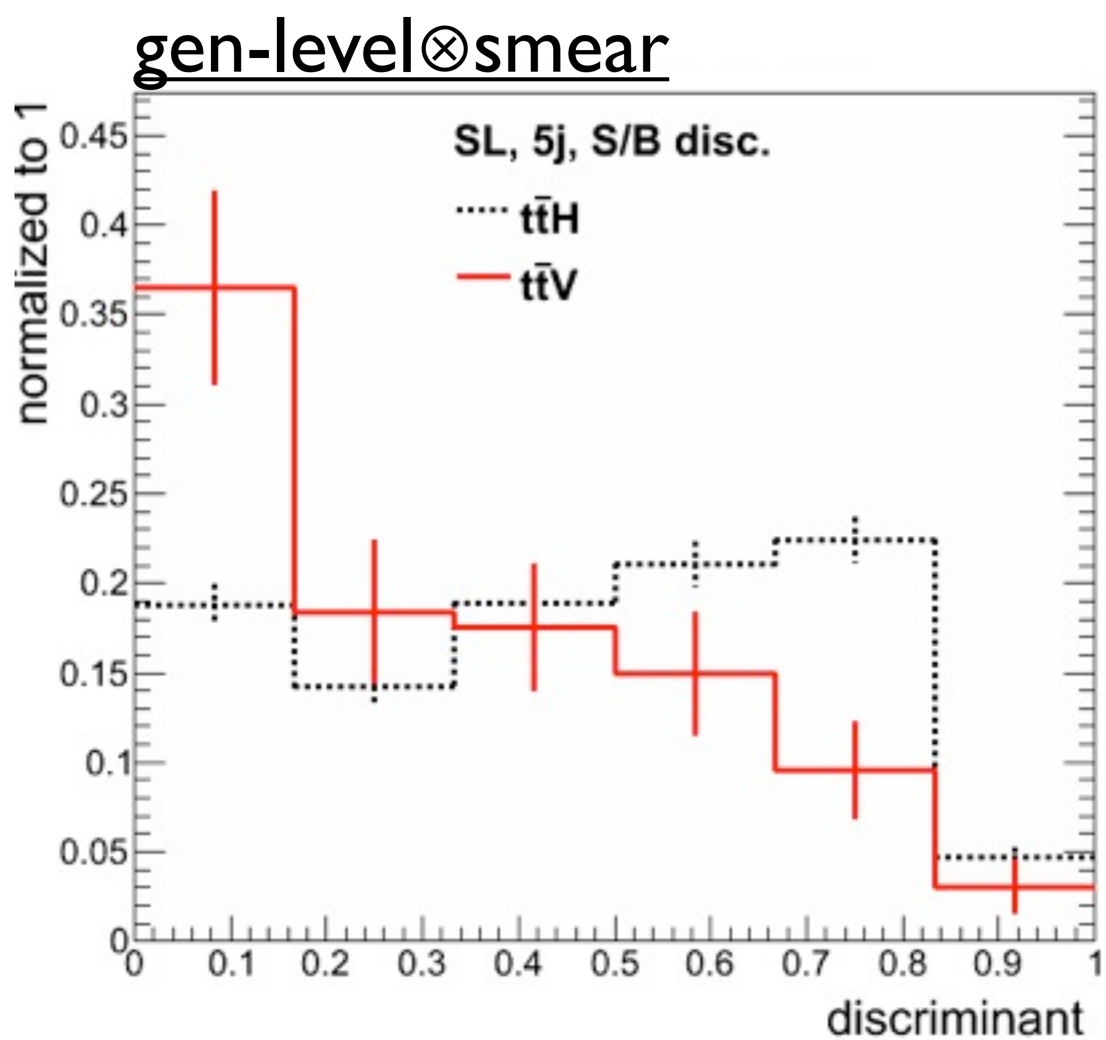
95% CL isocontour

$V_{x,y} = E_T^{miss}$ cov. matrix

Shape comparison

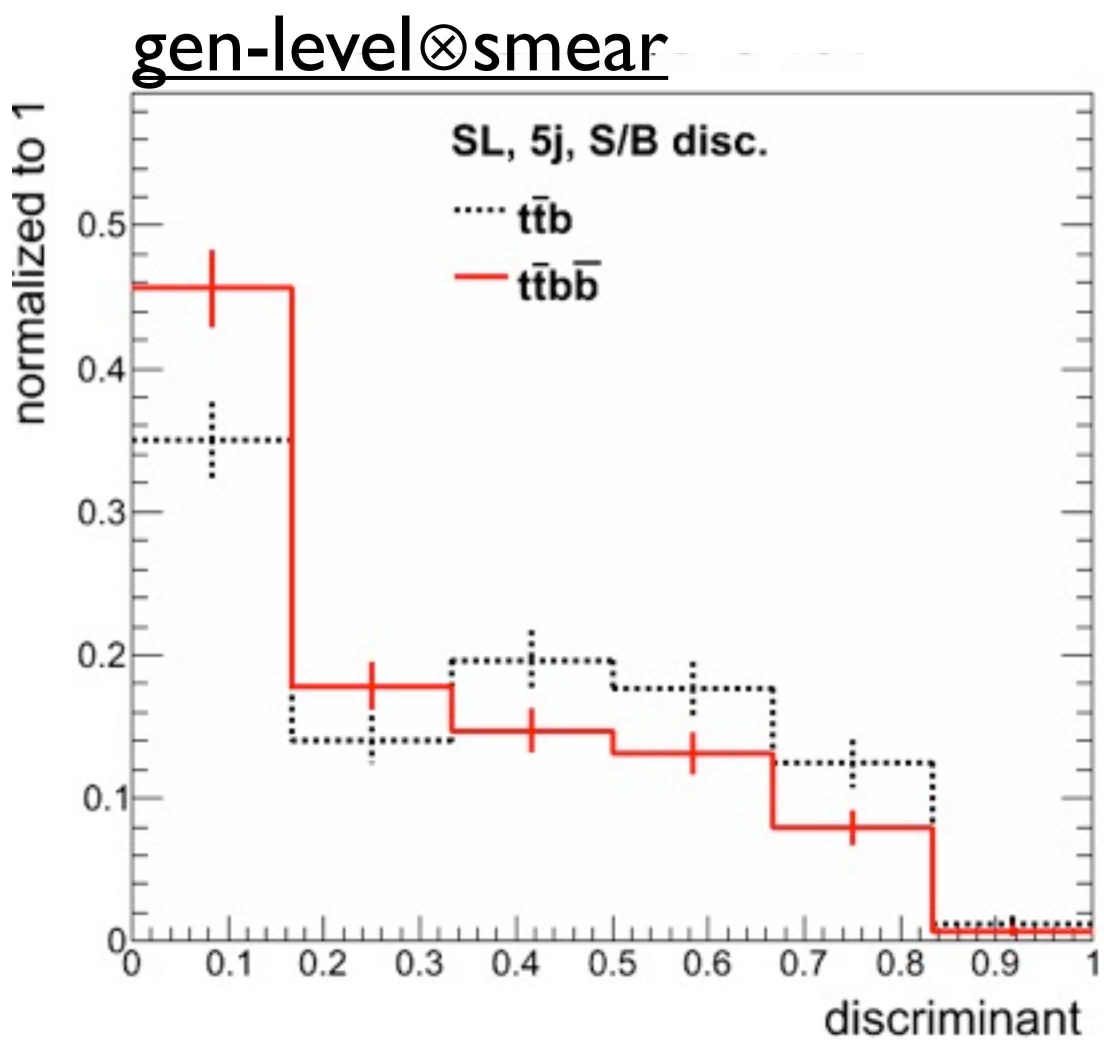
- Good signal separation against both ttbb and ttV
  - NB: ttZ after cuts has similar yield than ttH(→bb)

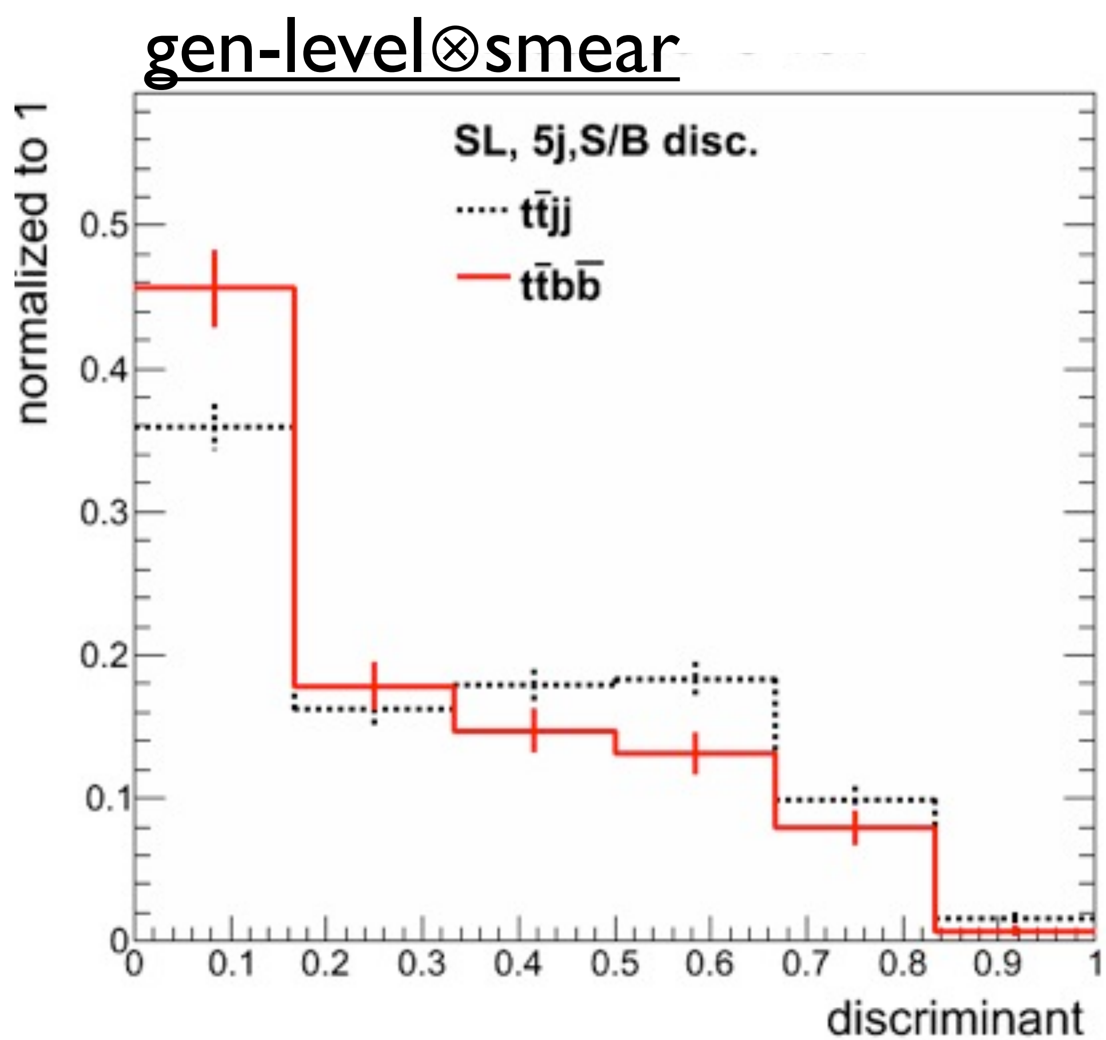




Shape comparison (2)

- tt+0/1/2 b's shape slightly different
  - best separation against ttbb [indeed, ME *optimized* against ttbb !!!]



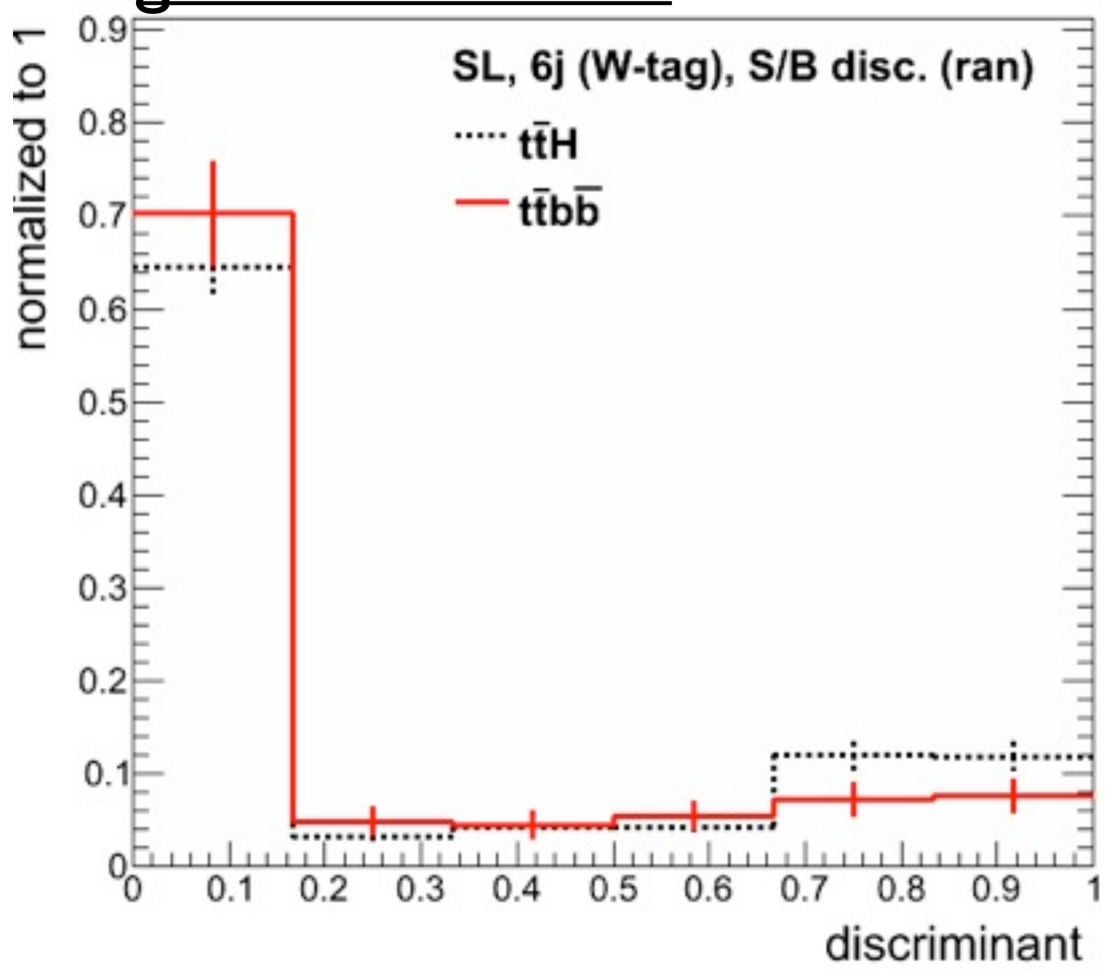


- *In situ* calibration of different sub-processes?
  - crucial, given large scale uncertainty on ttb(b)
  - there are ideas to achieve it

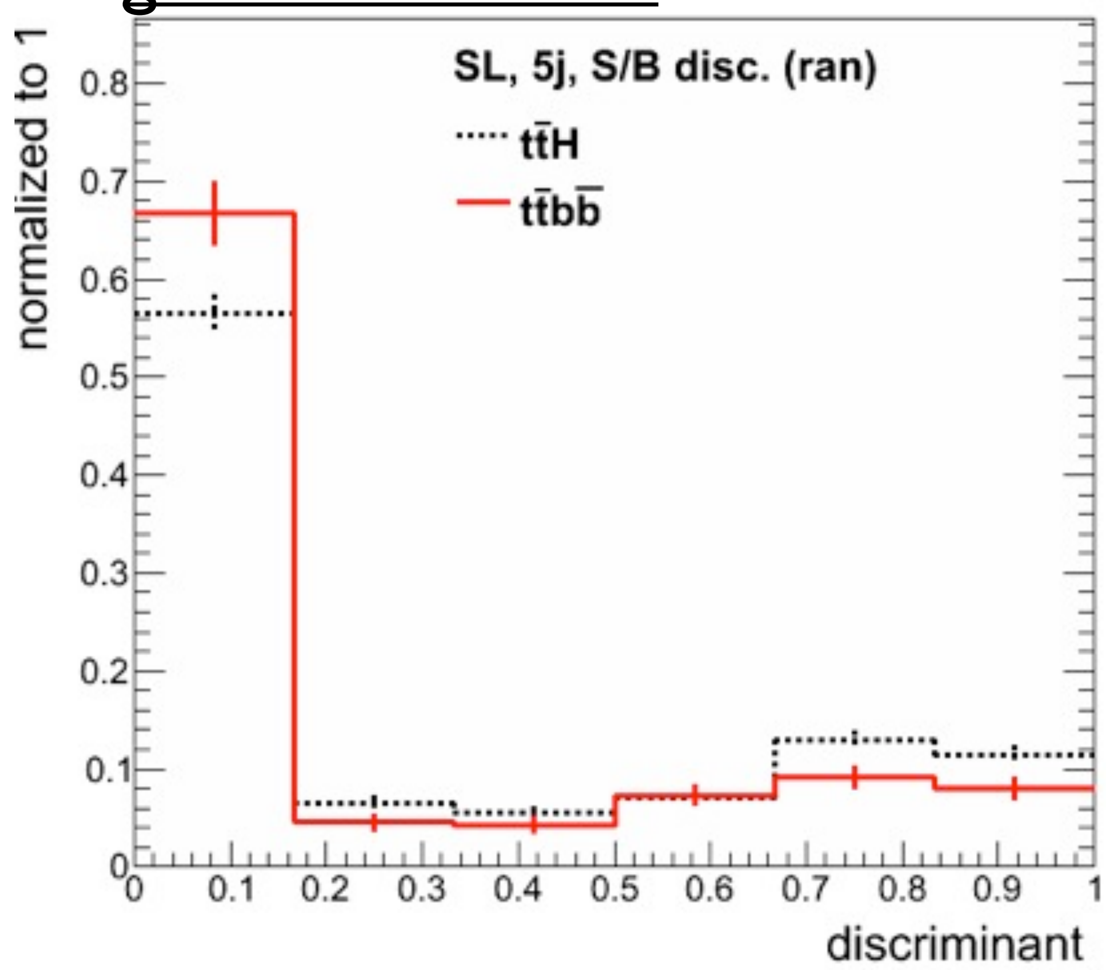
A method to validate the weights

- To assess data/MC agreement in signal box:
  - chose one perm at random
  - plot $P_{S/B}^{RAN} = w_S^{RAN}/(w_S^{RAN}+\rho w_B^{RAN})$
    - ✓ closely related to the "full" weight
    - ✓ $P_{S/B}^{RAN}$ is almost unbiased

gen-level⊗smear

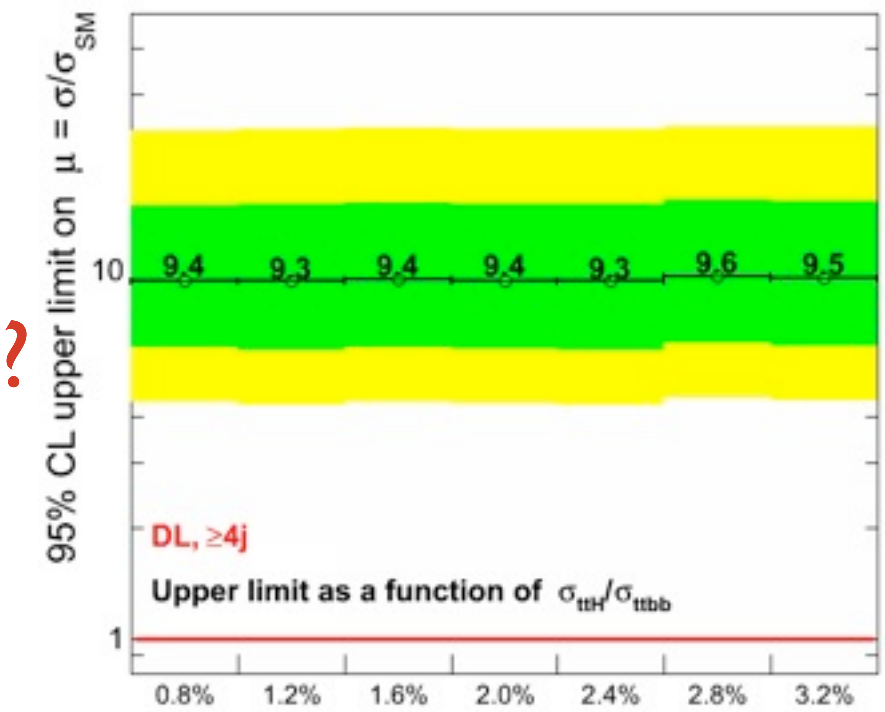


gen-level⊗smear

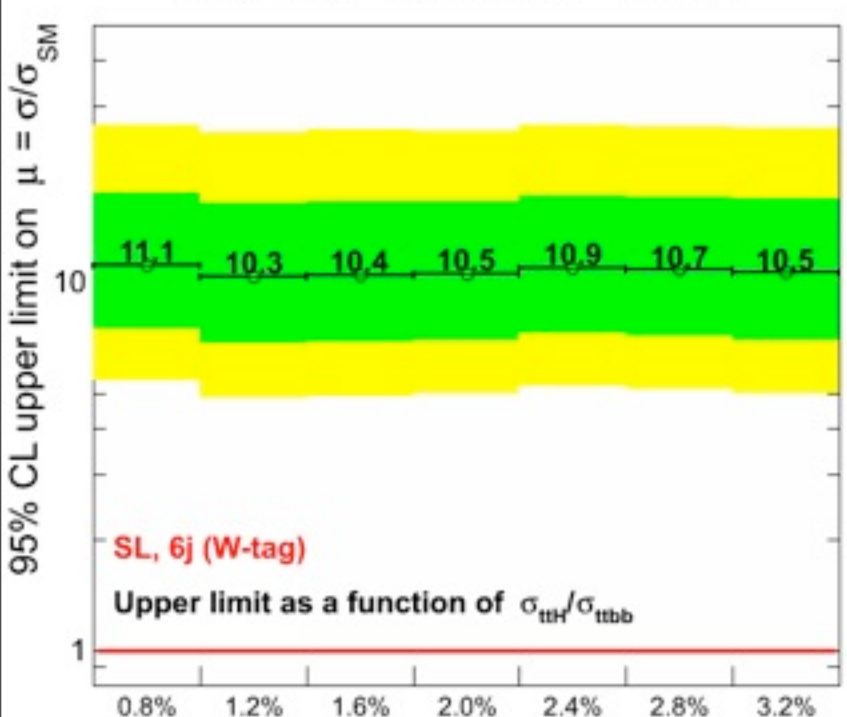


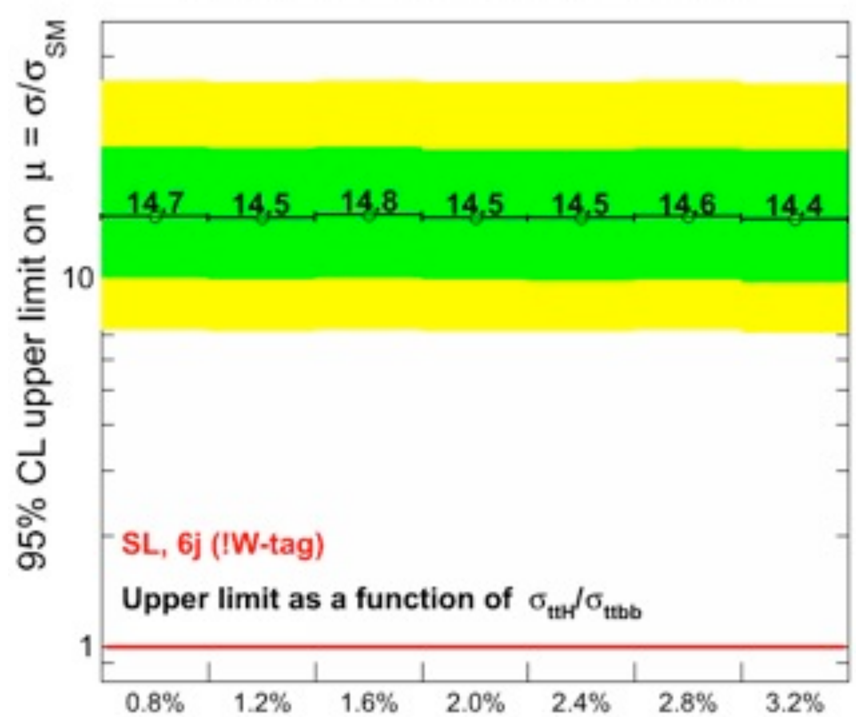
Weight normalization

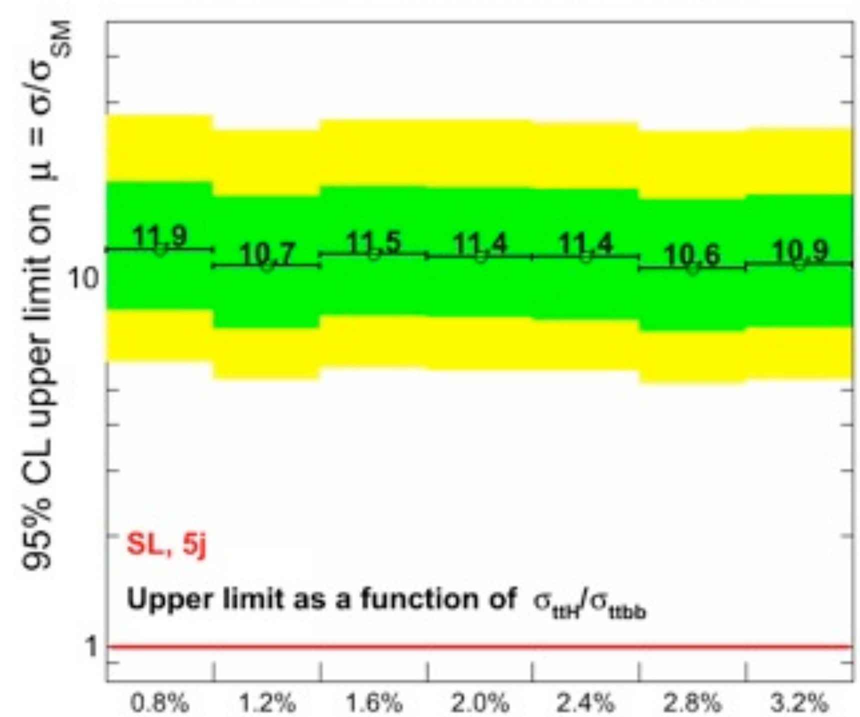
- Weights normalized to unity
  - N.B.: can always use MC to normalize weights
  - actually, only the total x-sec ratio is needed
- How much are we affected by this norm. ?
  - scan expected limits *vs* $\sigma_{ttH}/\sigma_{ttbb}$ ratio



☞ very mild dependence!







Cross-section