Search for *ttH* events using the Matrix Element Method

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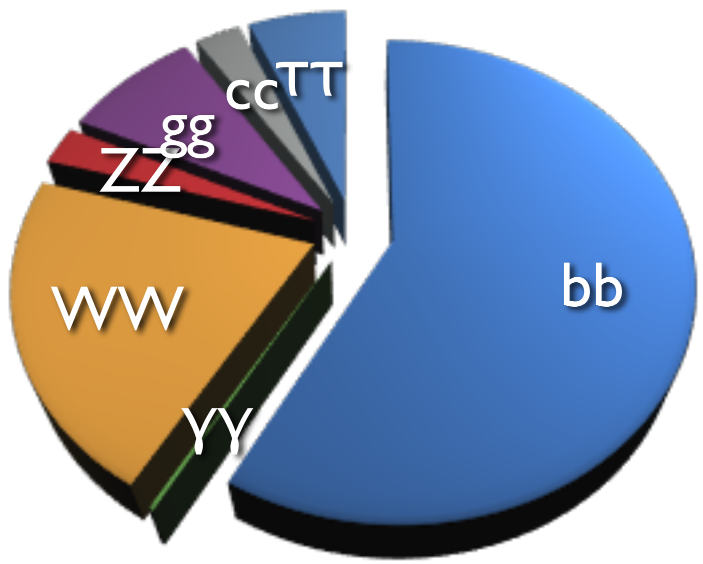
GDR Terascale @ Heidelberg, 12 Dec. 2014

Tackling ttH, H→bb final states

$\sigma_{ttH} \times BR(H \to X) \propto |y_t|^2$



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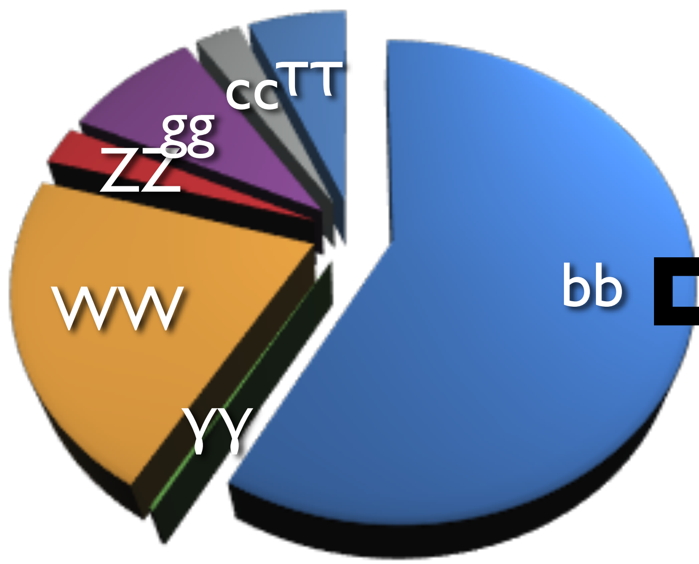

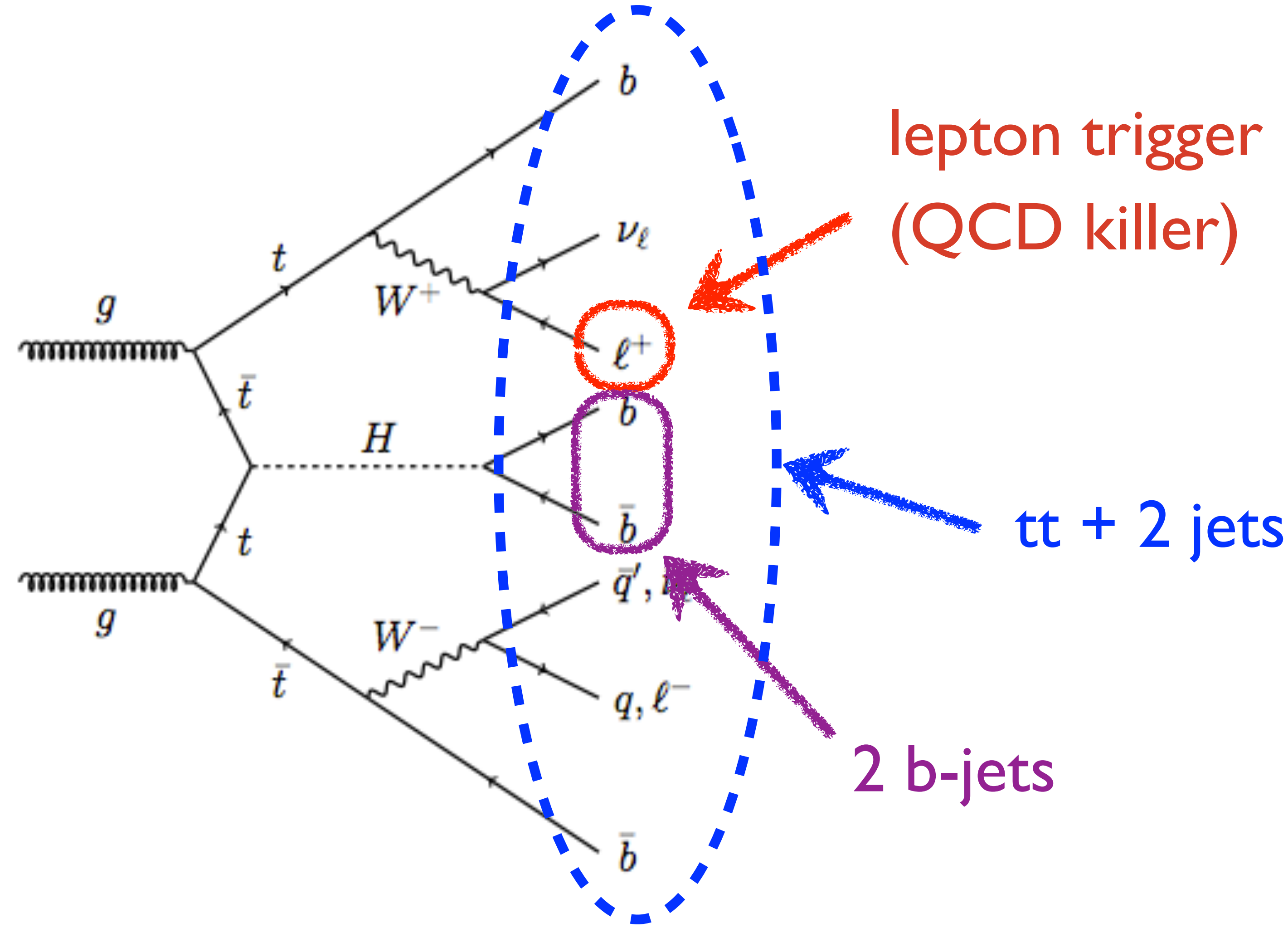

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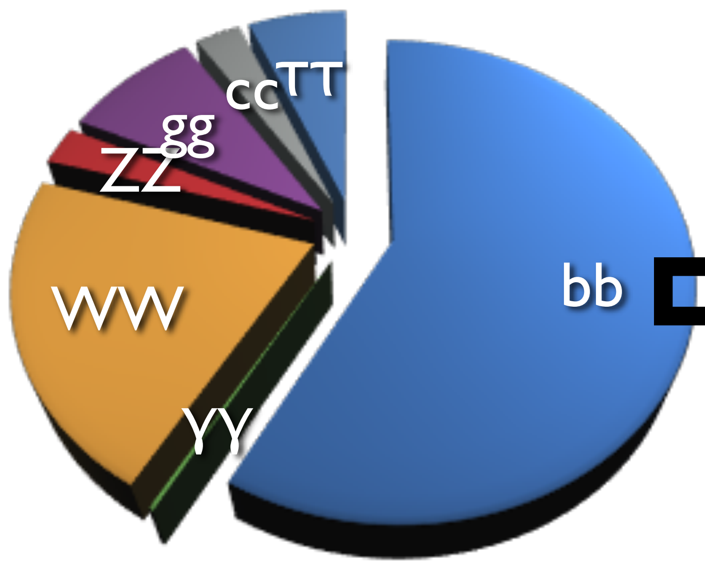
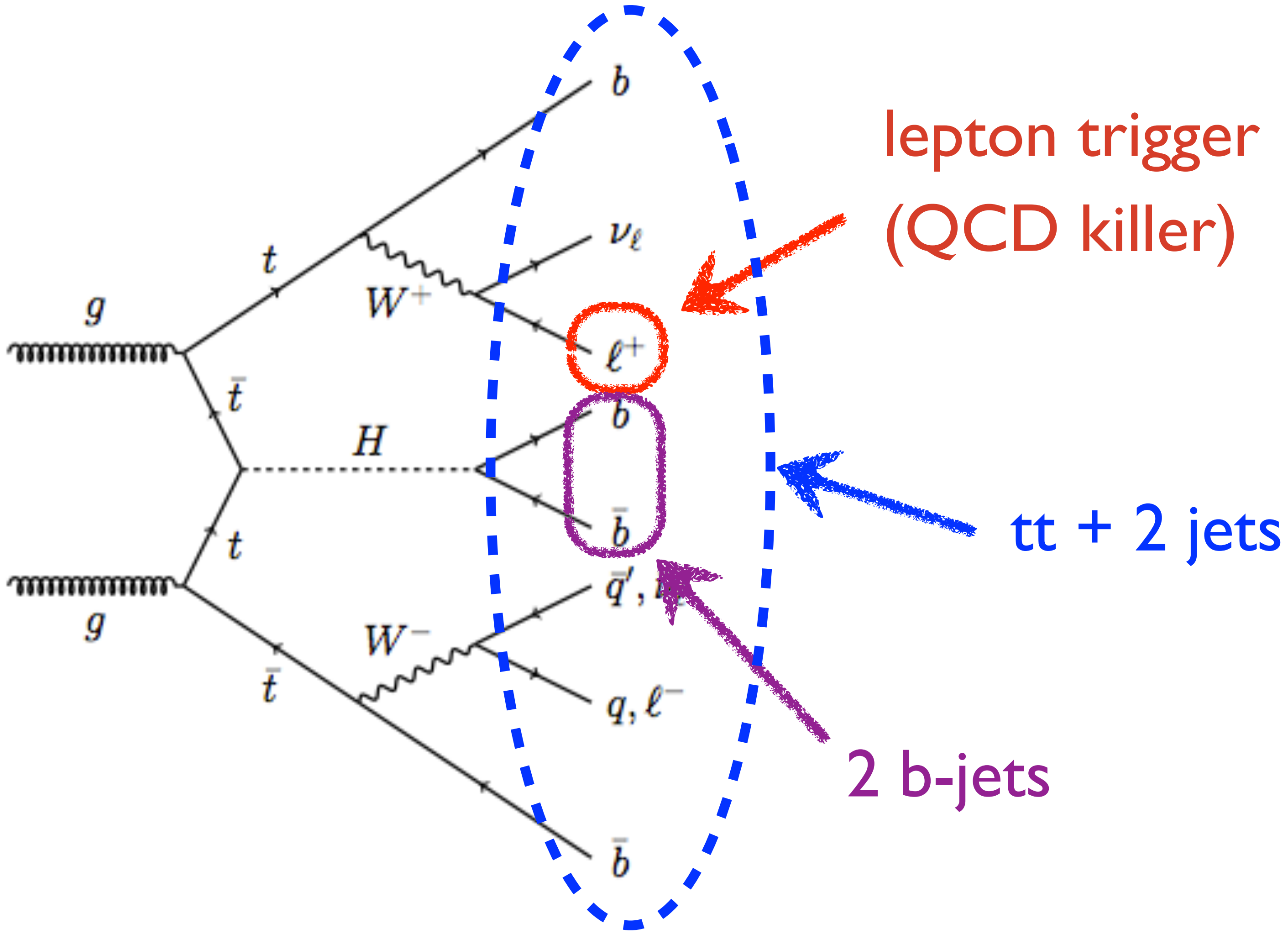
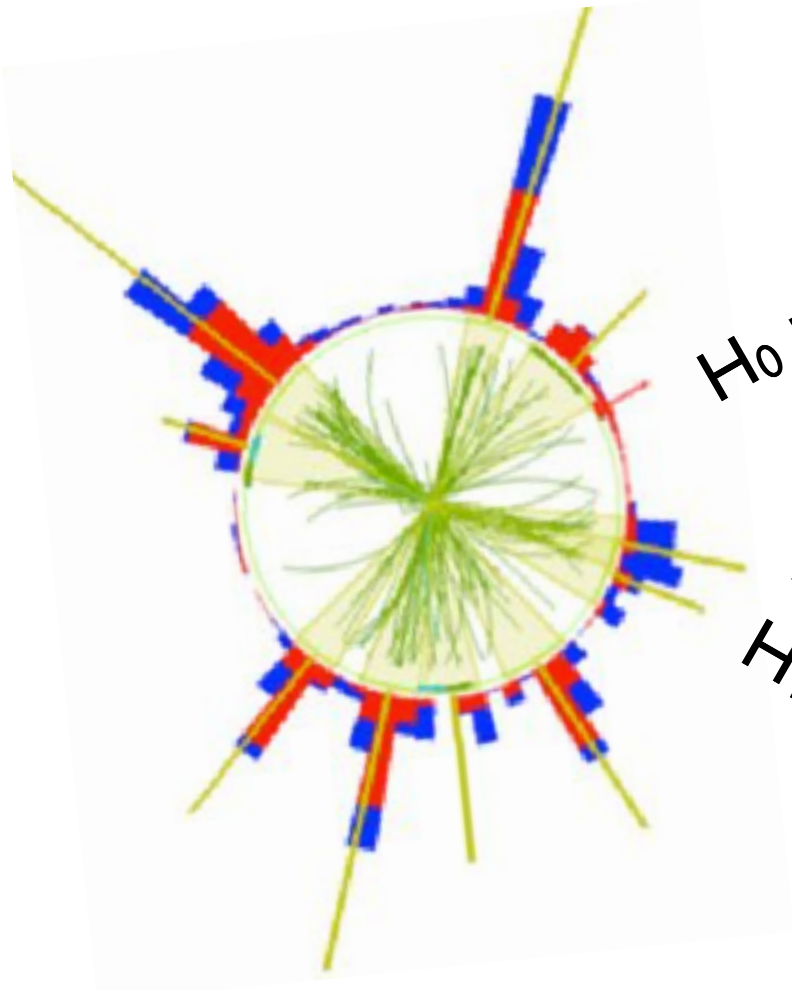




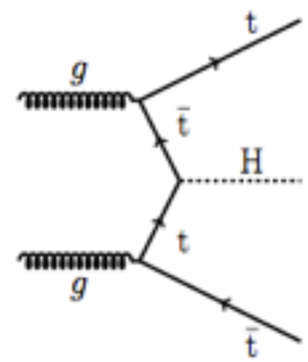
- **tt+bb background** irreducible and plagued by large unc. (≳35% @NLO)
  - counting experiment not feasible
  - extra handles: m_{bb} spectrum
  - separable using mass peak ?
- Not so easy: b's from top quarks complicate mass peak extraction
  - **combinatorial** self-background ⇒ need for **multidimensional** analyses

A possible analysis strategy

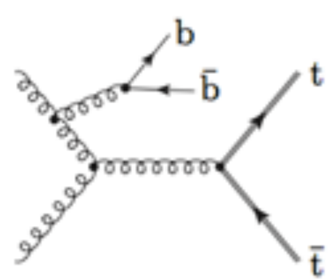
Matrix Element Method (**MEM**) suited to the task



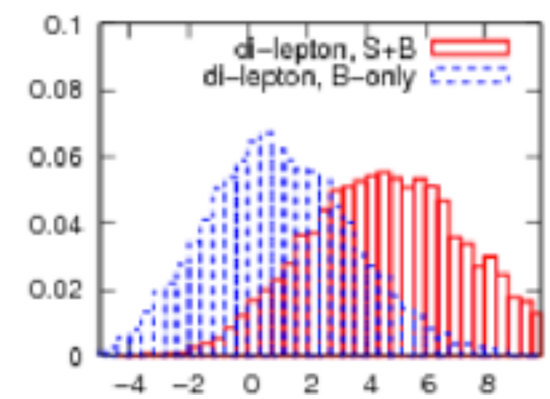
H_0 = signal



H_1 = bkg



$$\frac{d\sigma_{H0}/d\Omega}{d\sigma_{H1}/d\Omega}$$



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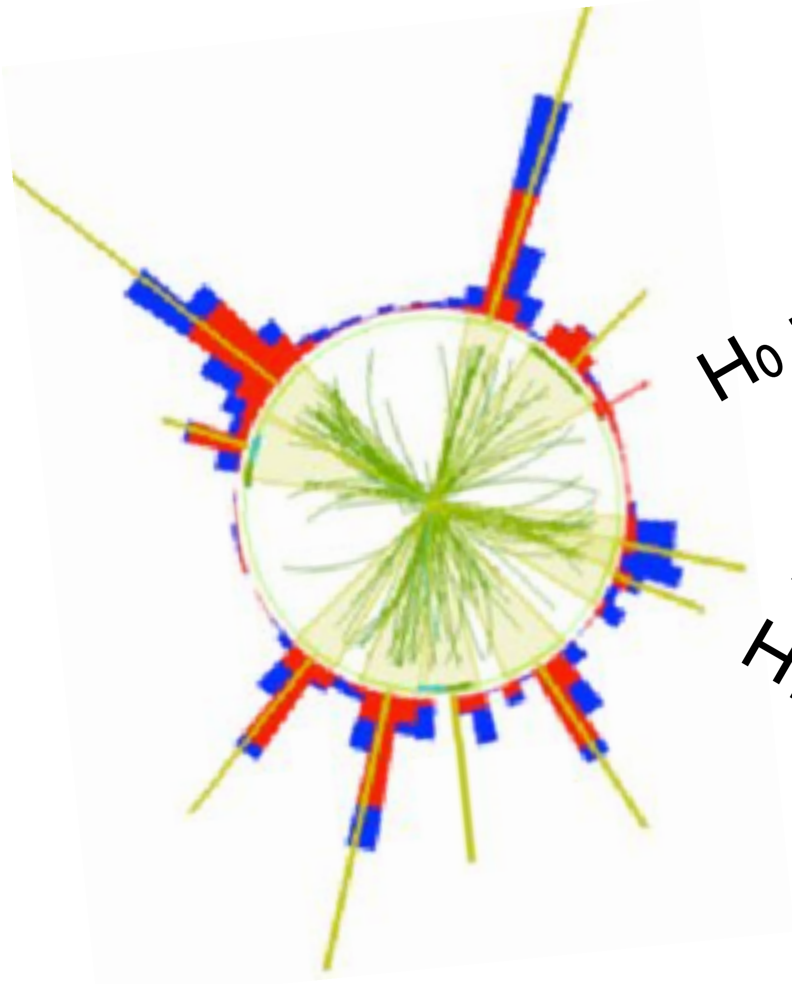

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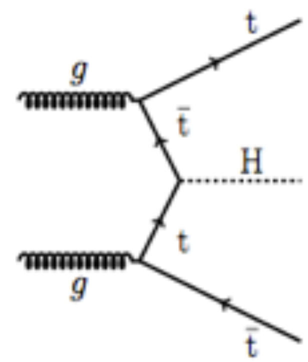

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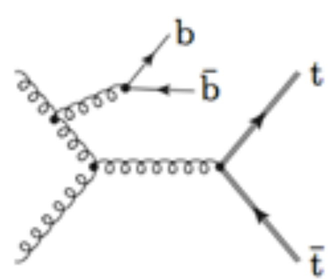

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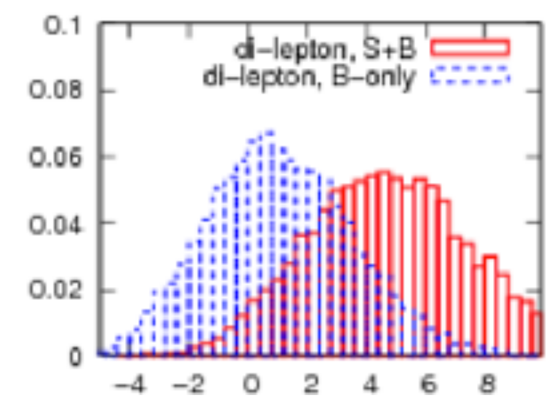

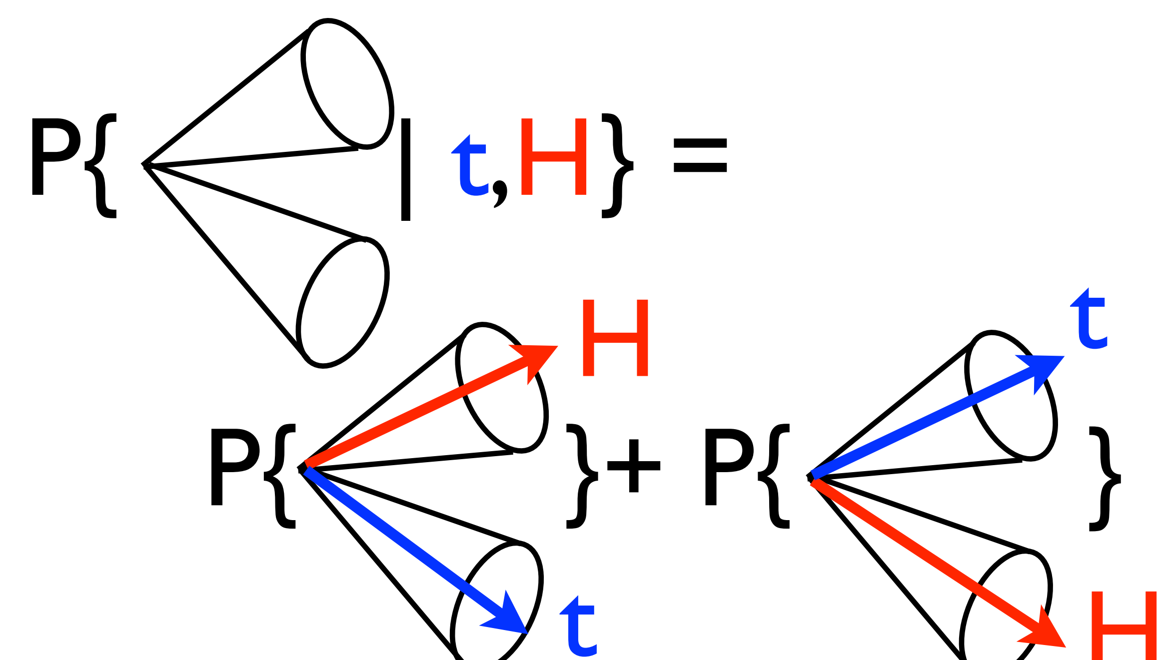

Virtues of the MEM:

- combinatorial issue properly addressed:
- optimal usage of kinematics and dynamics for S/B separation (**Neyman lemma**)

Master formula

$$d\sigma_{S/B}/d\vec{\mathbf{Y}} = w_{S/B}(\vec{\mathbf{Y}}) =$$

$$\int d\Phi_{\mathbf{x}}\, dx_a dx_b\, f(x_a,x_b)\, \delta^4(x_a P_a + x_b P_b - \vec{\mathbf{X}})\, |\mathcal{M}_{S/B}(\vec{\mathbf{X}})|^2\, W(\vec{\mathbf{Y}},\vec{\mathbf{X}})$$

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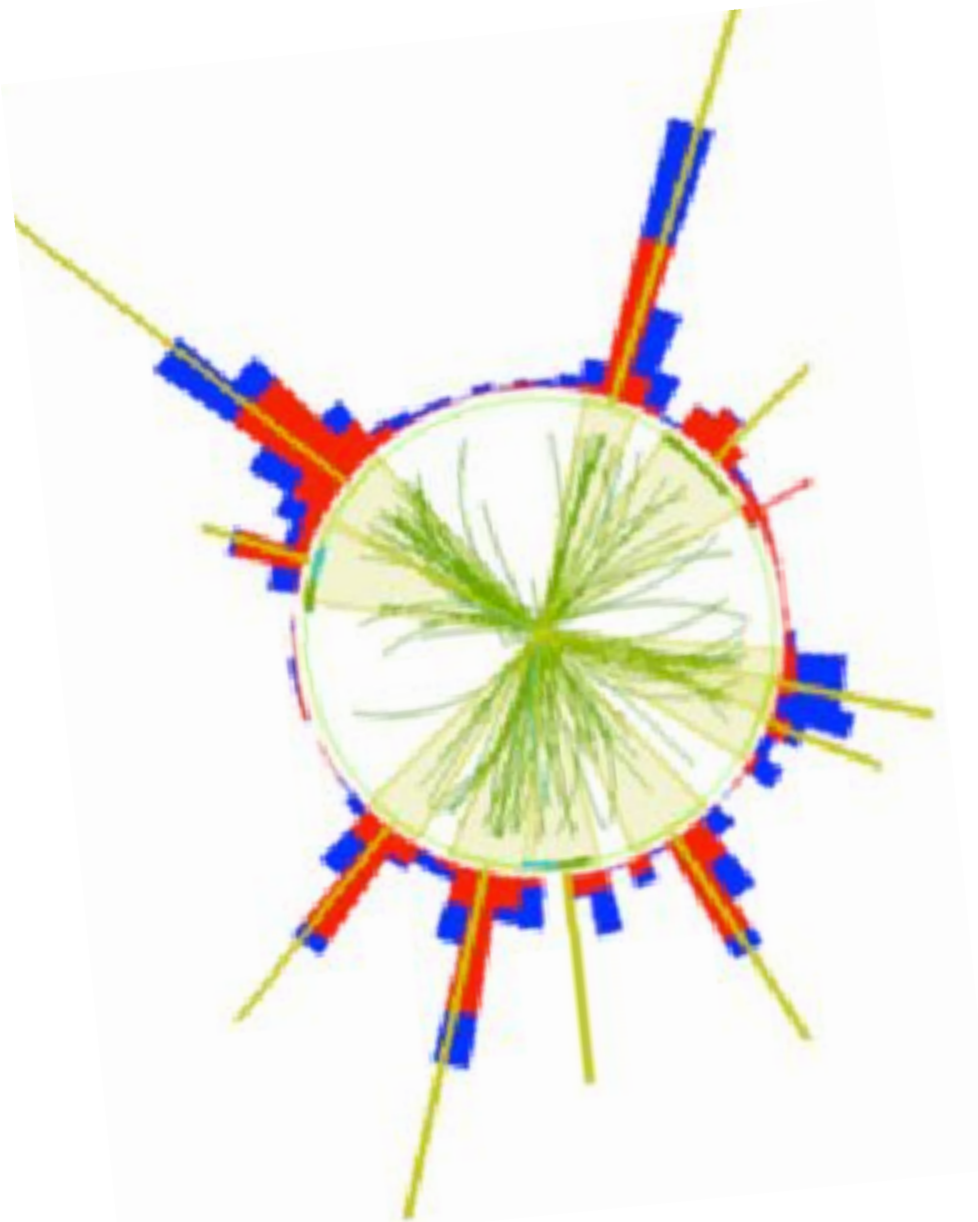

reconstructed jet and lepton momenta

Master formula

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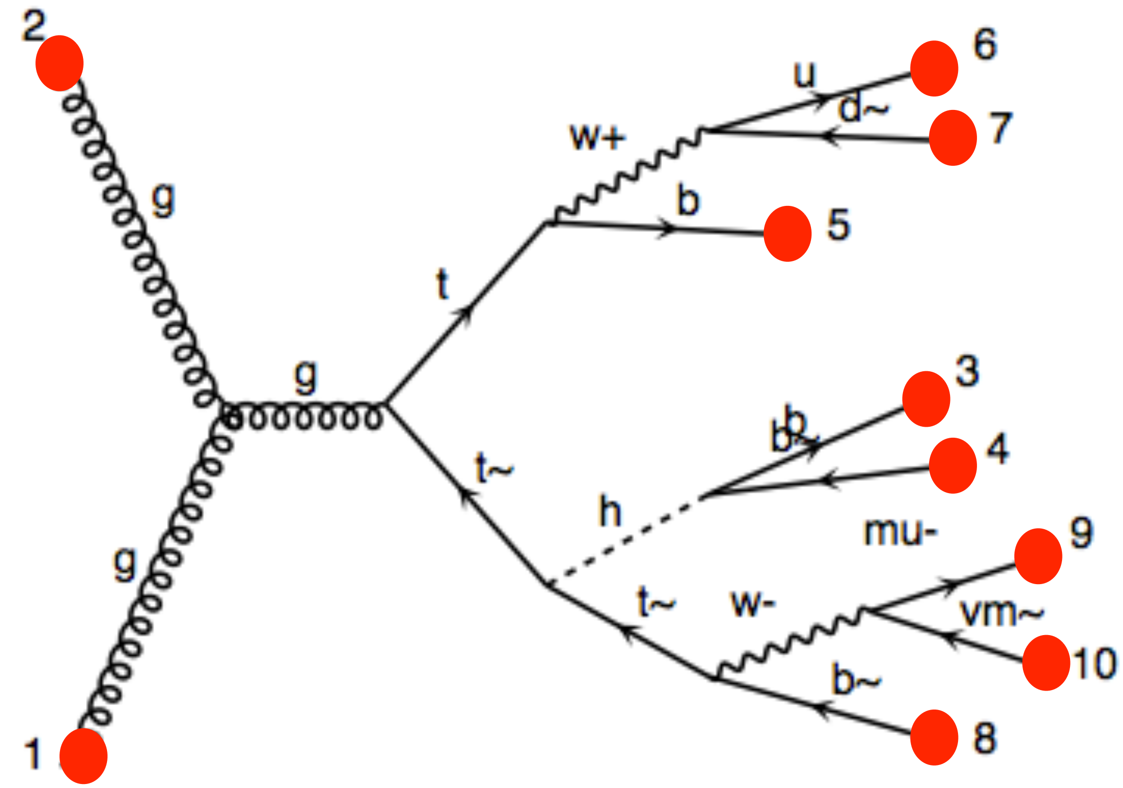
generated particles;
numerical integration
(VEGAS)



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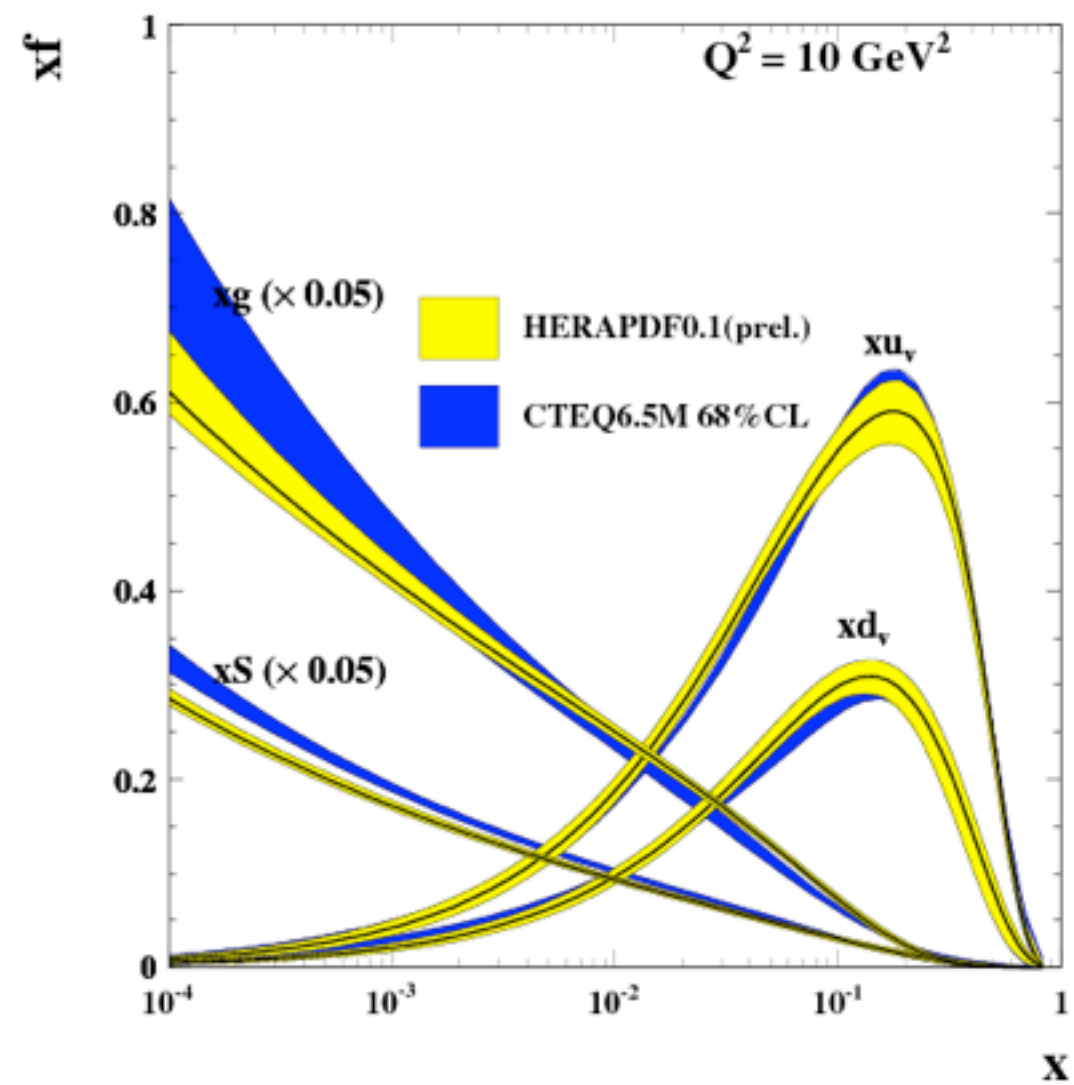
PDF from LHAPDF
(CTEQ6.5m set)



Master formula

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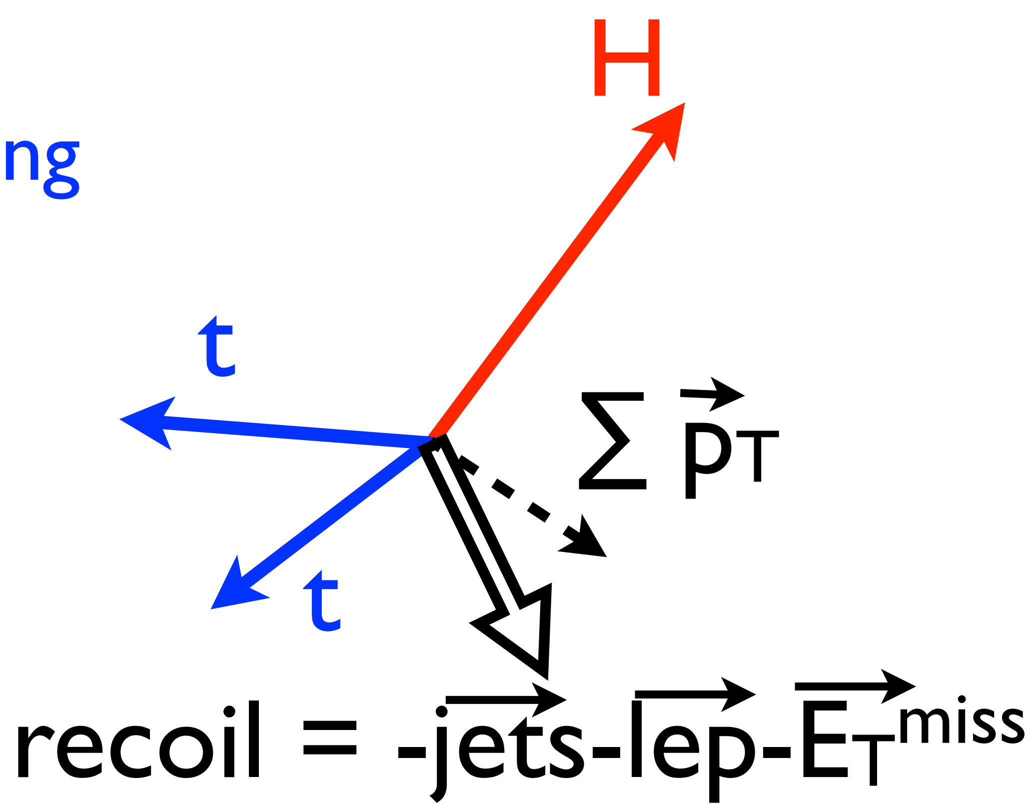
$$\int d\Phi_{\mathbf{X}}\, dx_a dx_b\, f(x_a,x_b)\, \boxed{\delta^4(x_a P_a + x_b P_b - \vec{\mathbf{X}})}\, |\mathcal{M}_{S/B}(\vec{\mathbf{X}})|^2\; W(\vec{\mathbf{Y}}, \vec{\mathbf{X}})$$

Momentum balancing

N.B.: $\sum \vec{p}_T = 0$ @ LO

Here: p_T balance not imposed.

$\sum \vec{p}_T$ constrained to measured recoil via a TF



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$$|\mathcal{M}(\mathbf{x})|^2 \propto \cdot\mathcal{M}_{\mathrm{ME}}(\mathbf{x}) \cdot \mathcal{M}_{\mathrm{BW}}(\mathbf{x}) \cdot \mathcal{M}_{\Gamma}(\mathbf{x})$$

calculated by OpenLoops (LO in α_S)

Narrow-width approximation

analytical (w/o spin-correlations)

Master formula

$$d\sigma_{S/B}/d\vec{\mathbf{Y}} = w_{S/B}(\vec{\mathbf{Y}}) =$$

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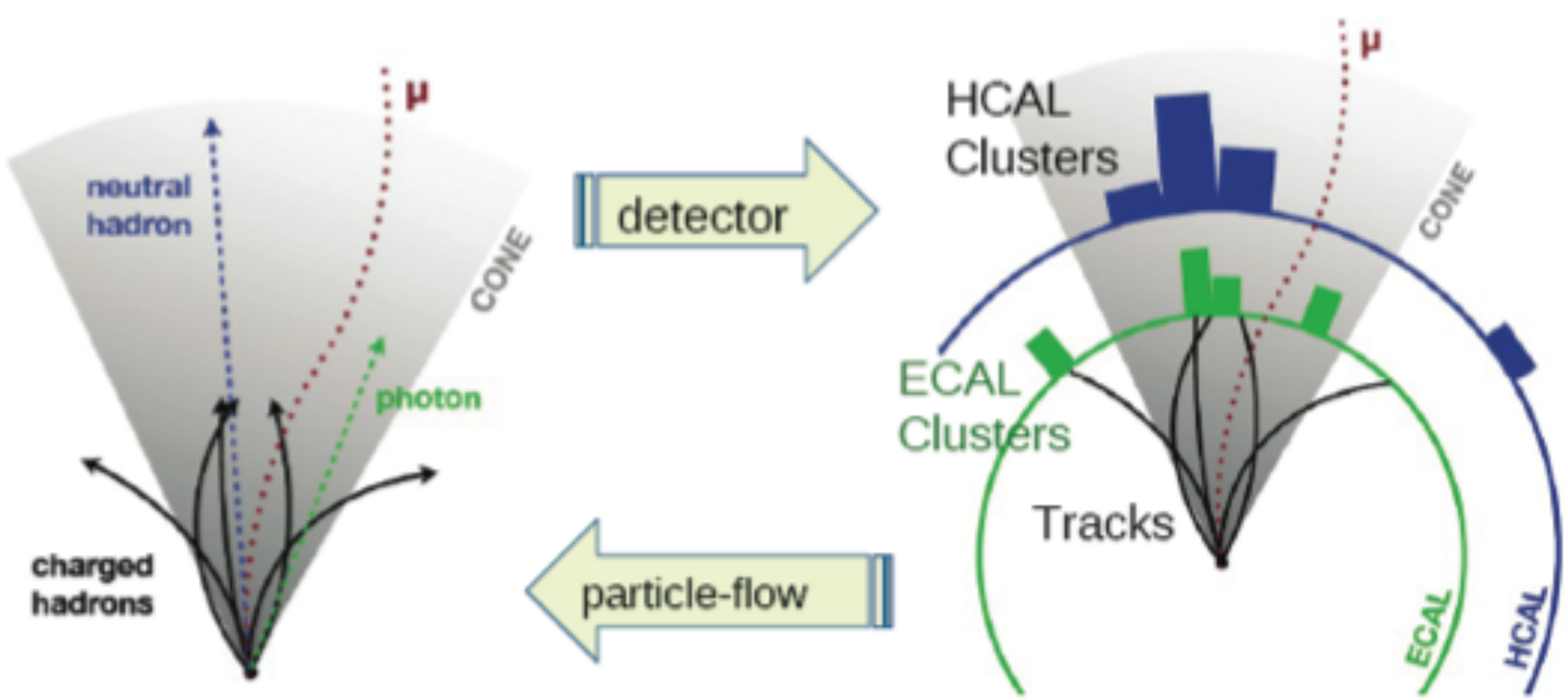
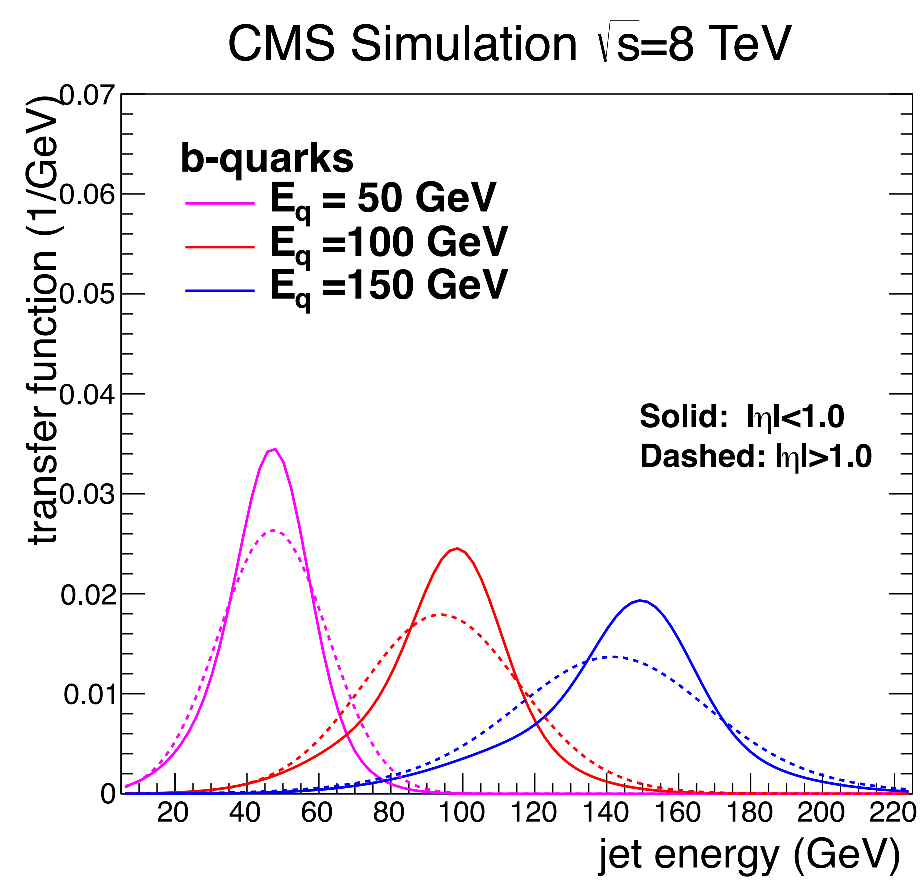
Transfer function





Implementation

SL

DL

Categorize events as to

aid evaluation of ME at LO

category ⇔ event interpretation

Implementation

SL
$N_j \geq 5$

b tag

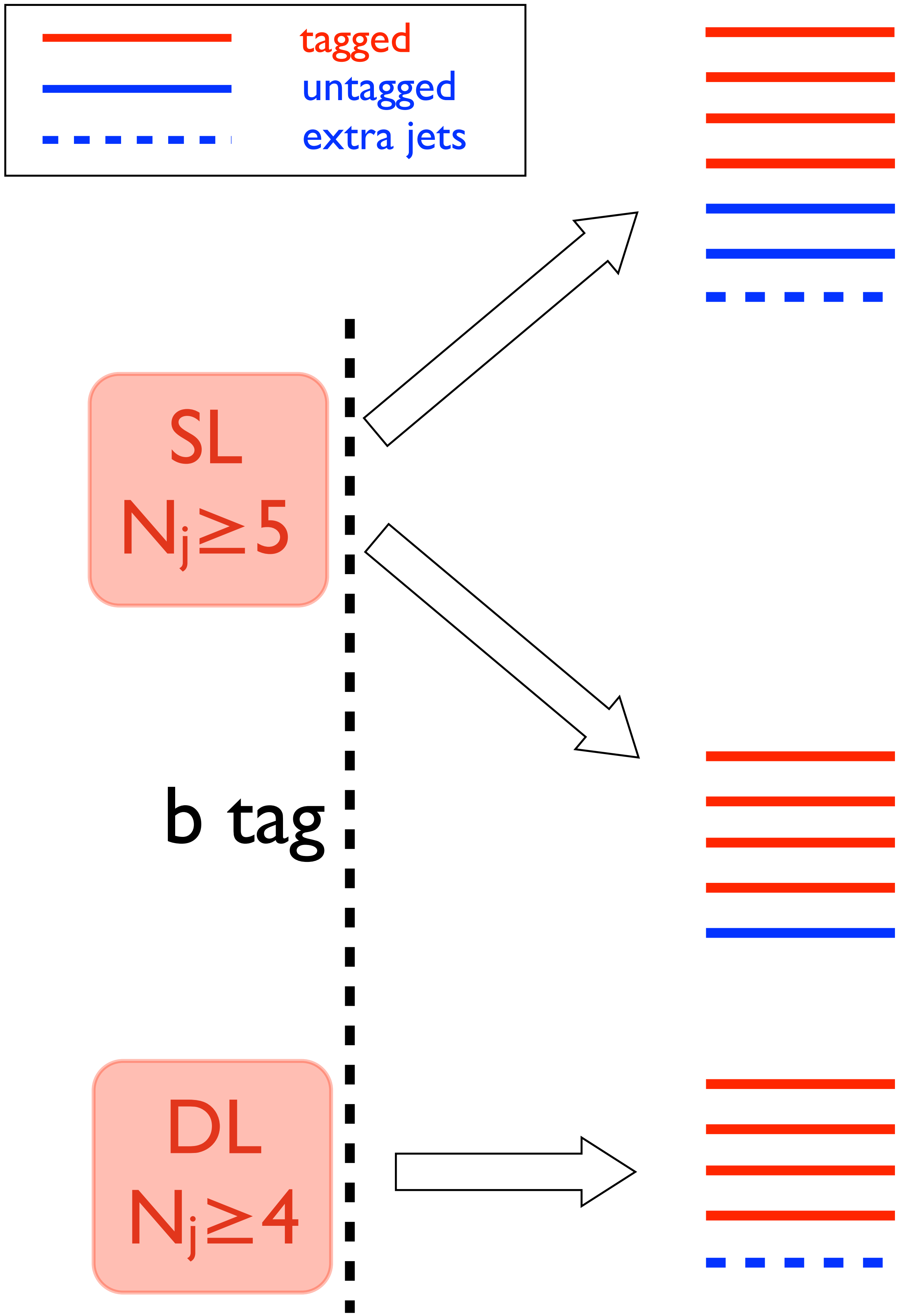
DL
$N_j \geq 4$

Reduction of V+jets and tt+jets requires cut on

number of jets, b tagging

Implementation

assignment based on jet permutation w/ largest btag



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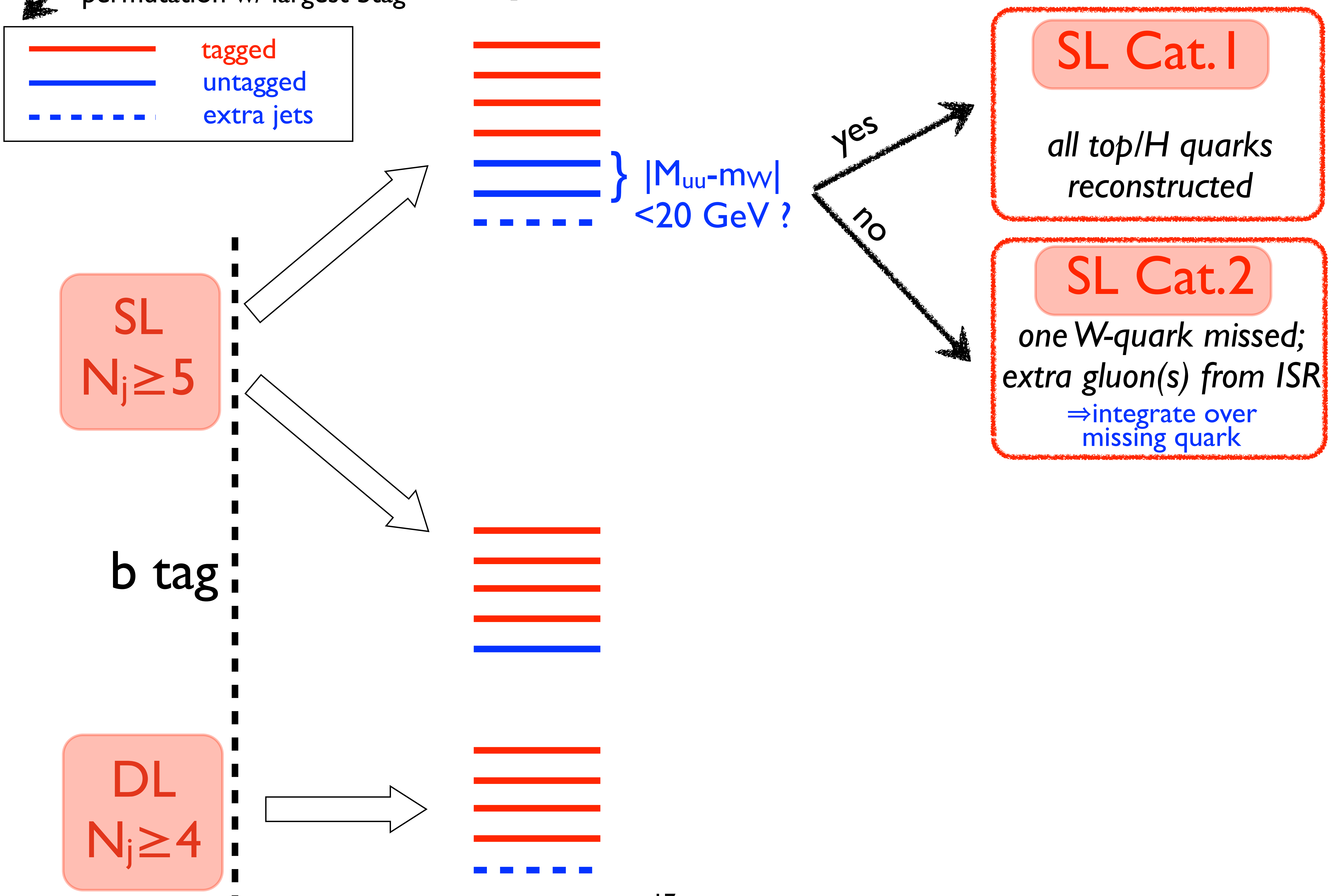

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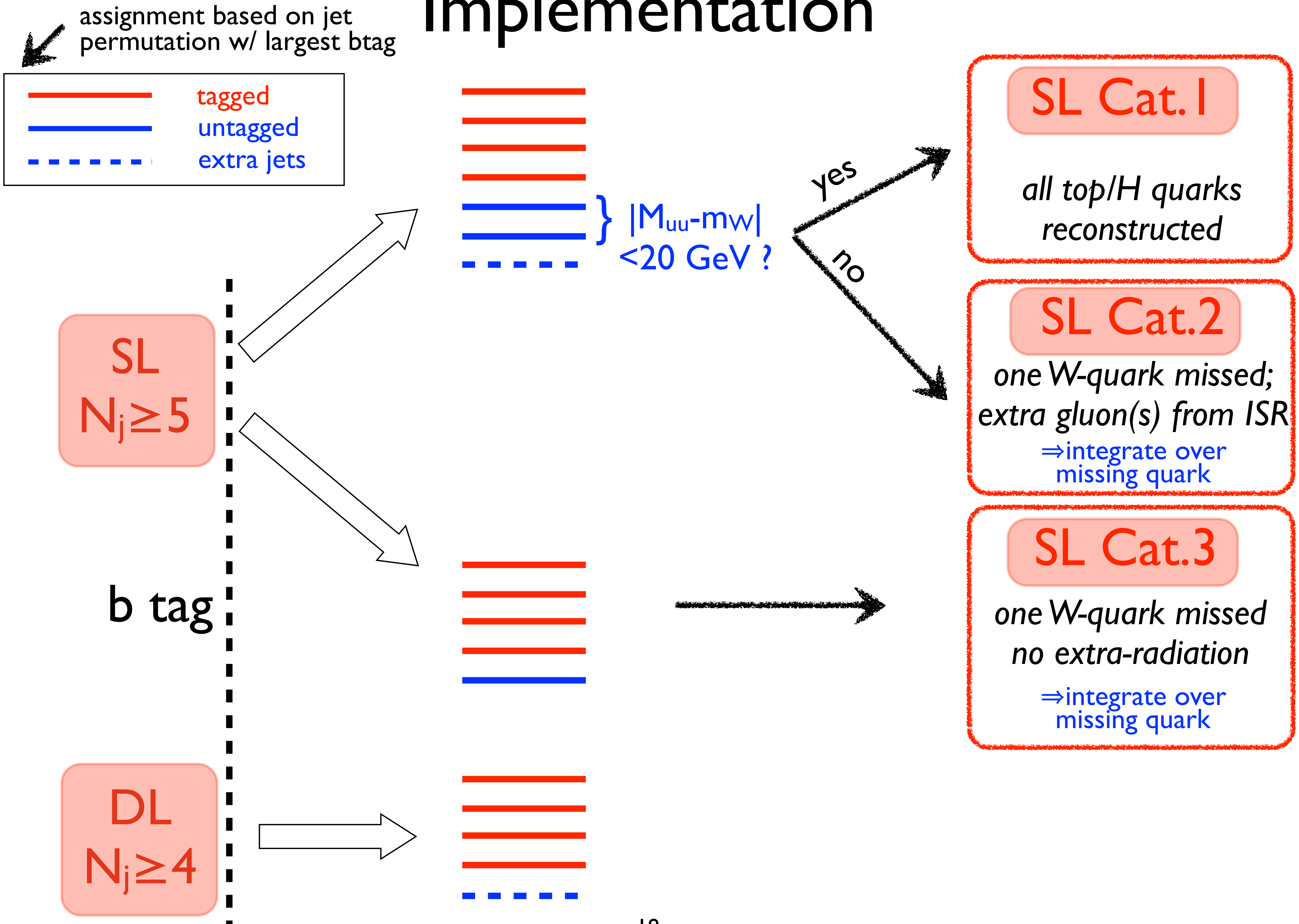

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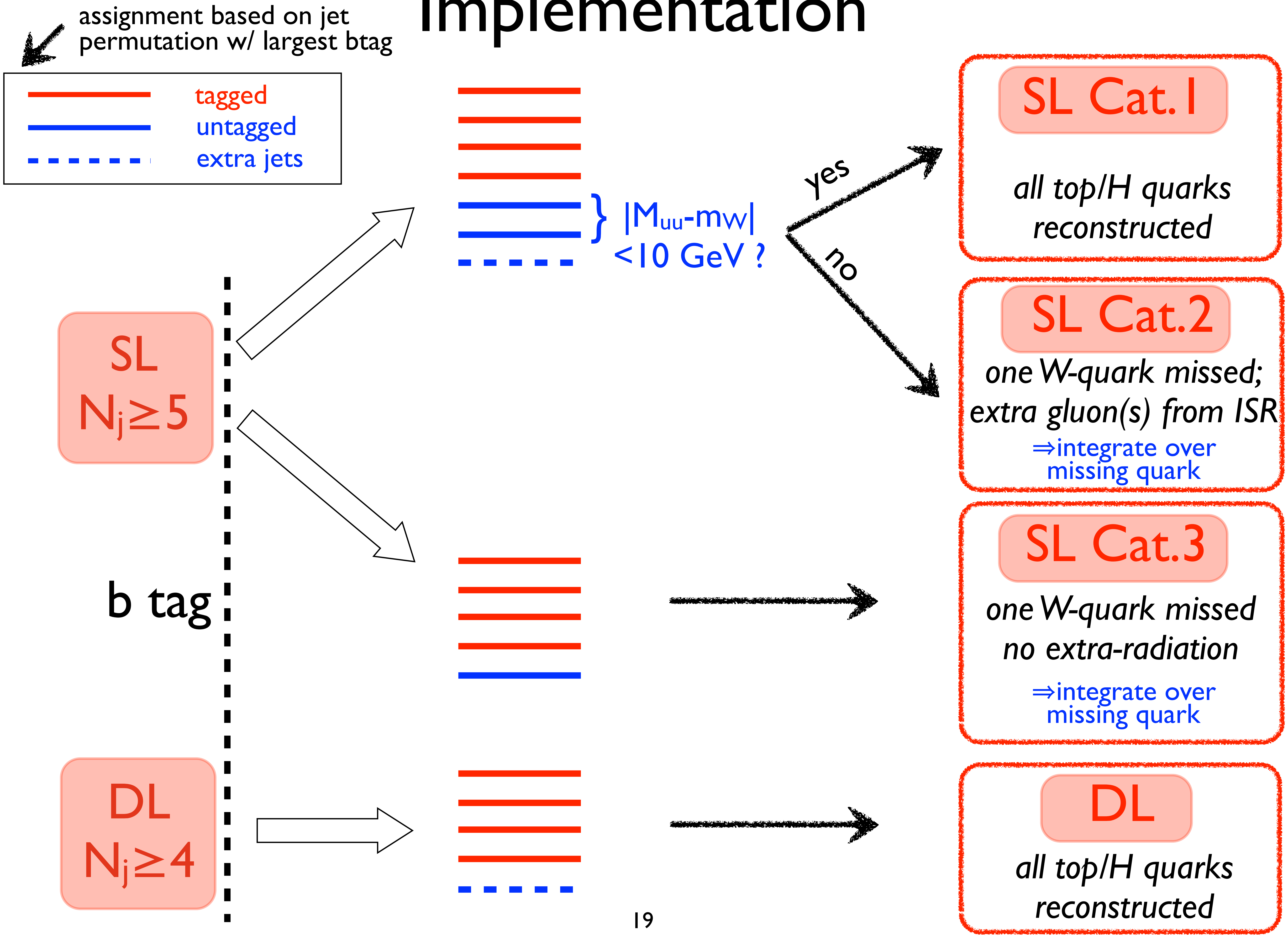
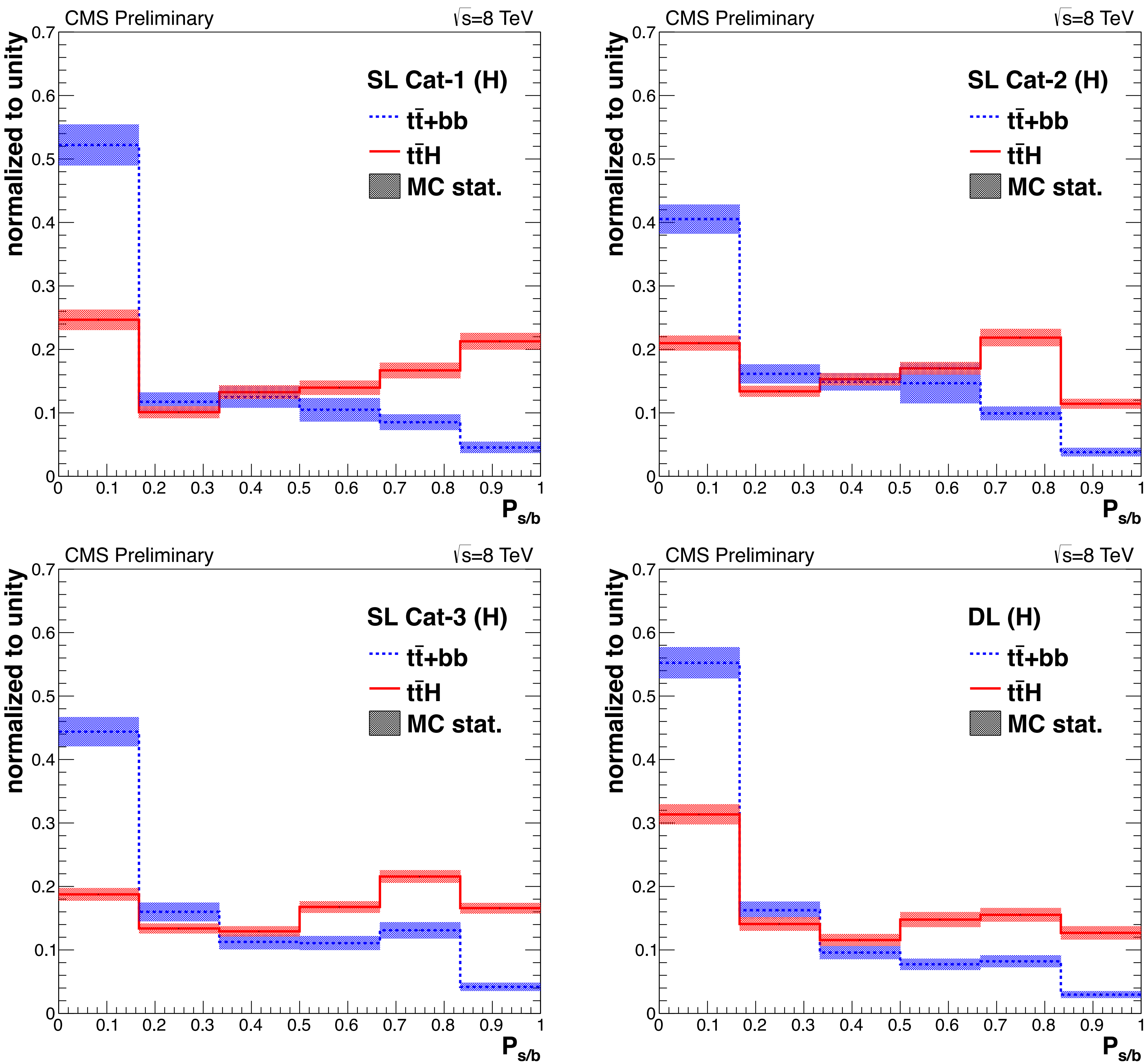


Shape comparison: tt+bb vs ttH



$P_{s/b}=(1+w_B/w_S)^{-1}$

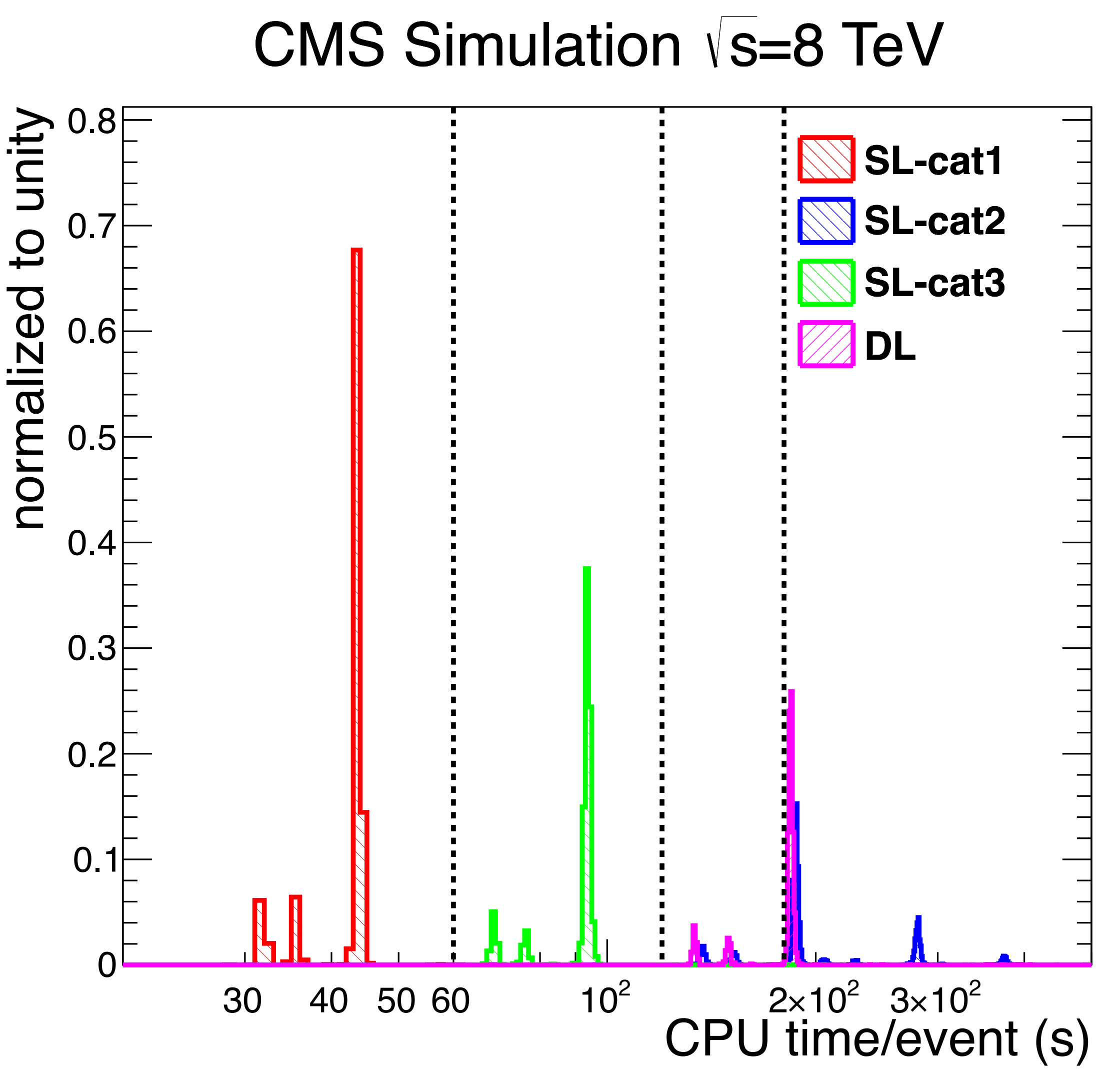
In situ validation of shapes

- sidebands with low b tagging score
- in signal region, validate low-sensitivity version of $P_{s/b}$
  - one random permutation only
  - testing different values of m_H

FAQ: is CPU time an issue ?

Not really; compromise between **performance** and **timing**:

- run only on the good "events"
- filter-out permutations using b tagging (6! → 4!)
- test one background hypothesis only
  - optimize separation against tt+bb
- parallelize (by event) as much as possible
- neglect spin/correlations
- JEC/JER systematics: bookkeep VEGAS grid result from "nominal" for faster evaluation
- ...



Number of variables	4 (+1)	6 (+1)	5 (+1)
Number of iterations	5	5	5
Function calls	2000	4000	10000
Numerical precision (mode of σ_w/w)	0.8%	1.2%	0.8%
CPU-time per integral (mean)	0.5 (1.5) s	1.1 (3.2) s	2.3 (6.2) s
Time budget for $\lvert\mathcal{M}\rvert^2_{\mathrm{ME}}$	30% (80%)	30% (80%)	30% (80%)

S (B) integration

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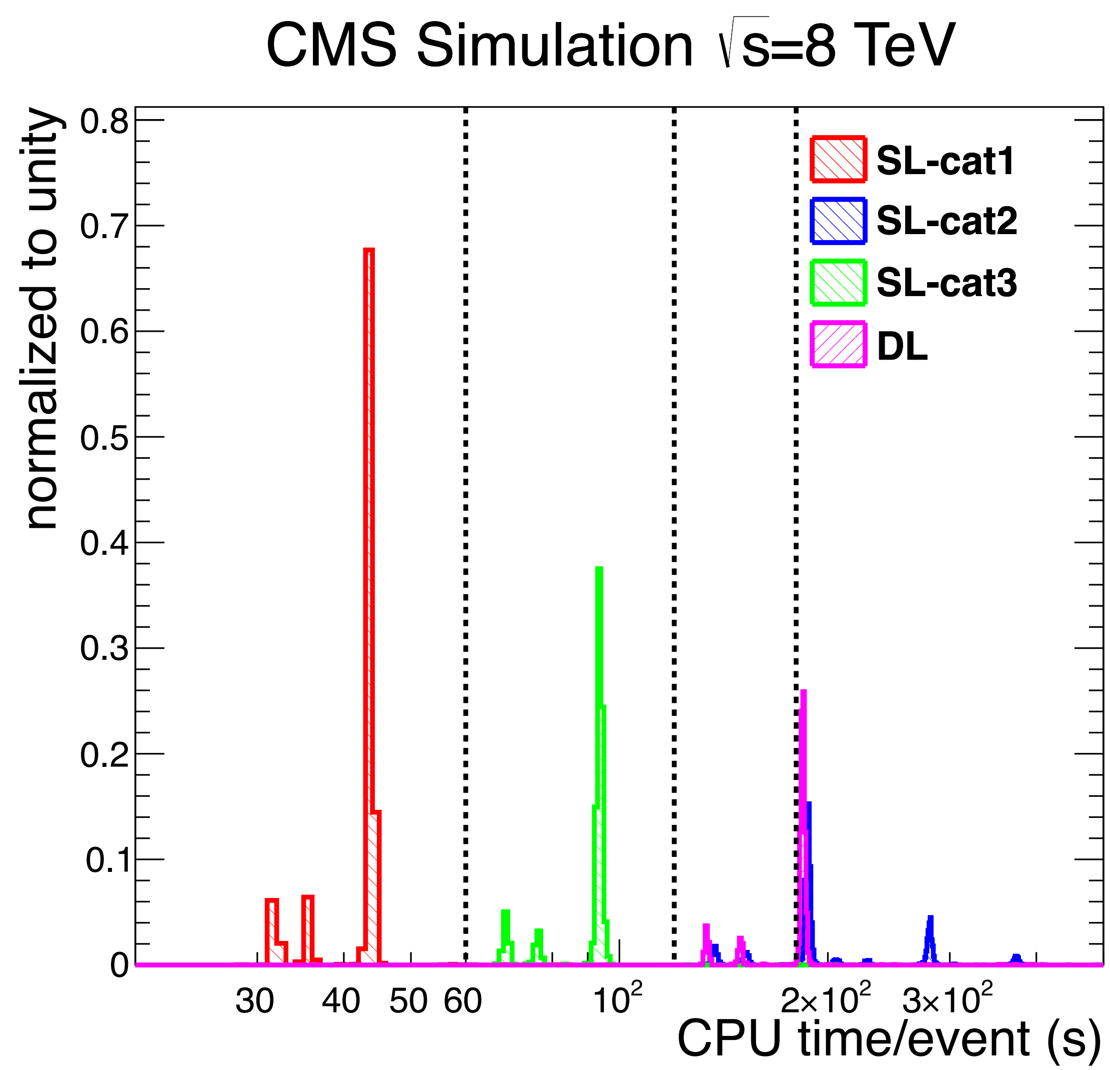

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⇨ complete analysis round in ~10h using the batch system of a T3

S (B) integration

Overview of systematic uncertainties

ttH modeling: PYTHIA

tt+jets: MadGraph **(≤3 partons)**+PYTHIA

nuisance	treatment
luminosity	lnN 2.6%
ID/trigger	lnN 2-4%
ttH	lnN 12%
tt+bb	lnN 50%
tt+cc	lnN 50%
tt+b	lnN 50%
QCD scale	lnN 17-3%
fact/renorm. scale	shapes (tt +1p/2p/3p/bb/b/jj/cc)
PDF	lnN 3-9%
JES	shape
JER	shape
btagging	8 shapes
top p_T model	shape
MC stat.	shape (all bins)

50% normalization uncertainty on tt+HF (tt+bb, tt+cc, tt+b)

α_S scale uncertainty (QCD scale, fact/renorm. scale)

JEC/JER, b tagging (JES, JER, btagging)

top p_T modeling

statistical uncertainty

lnN = normalization uncertainty

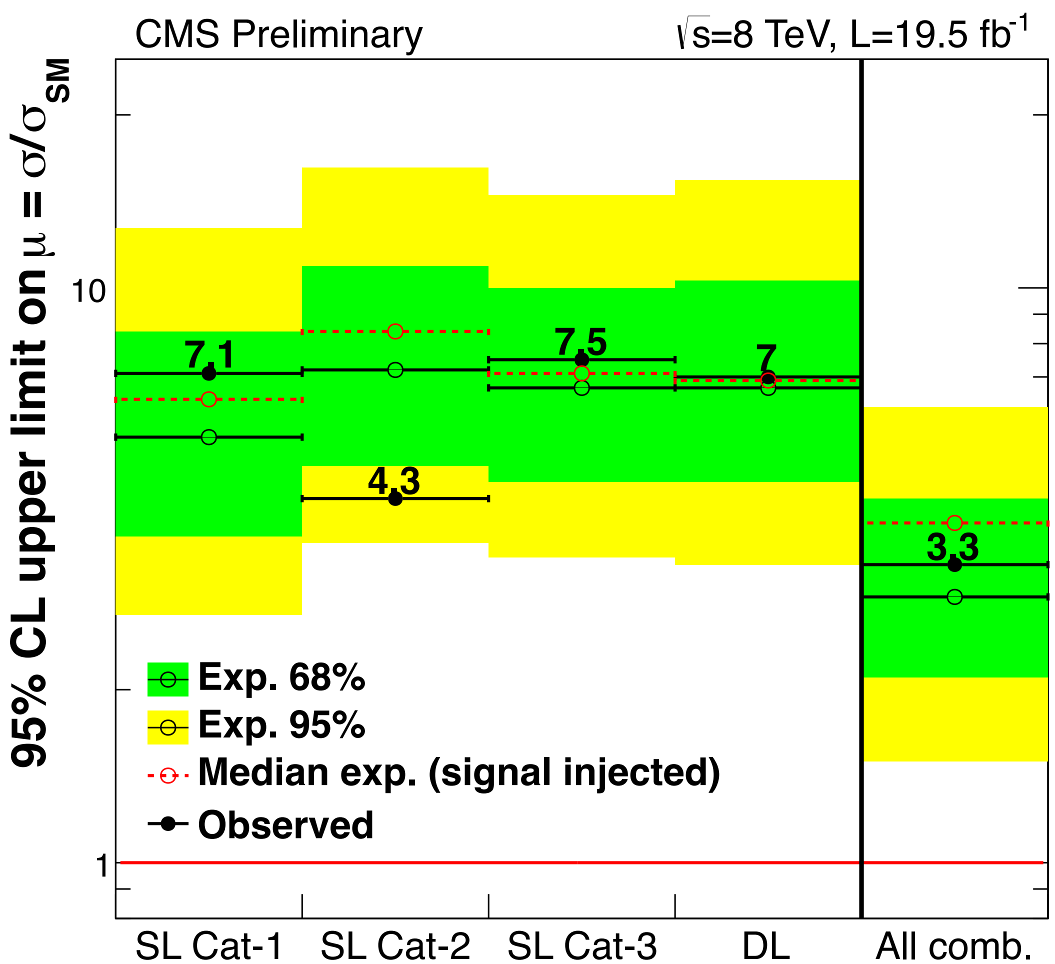
shape = vertical morphing

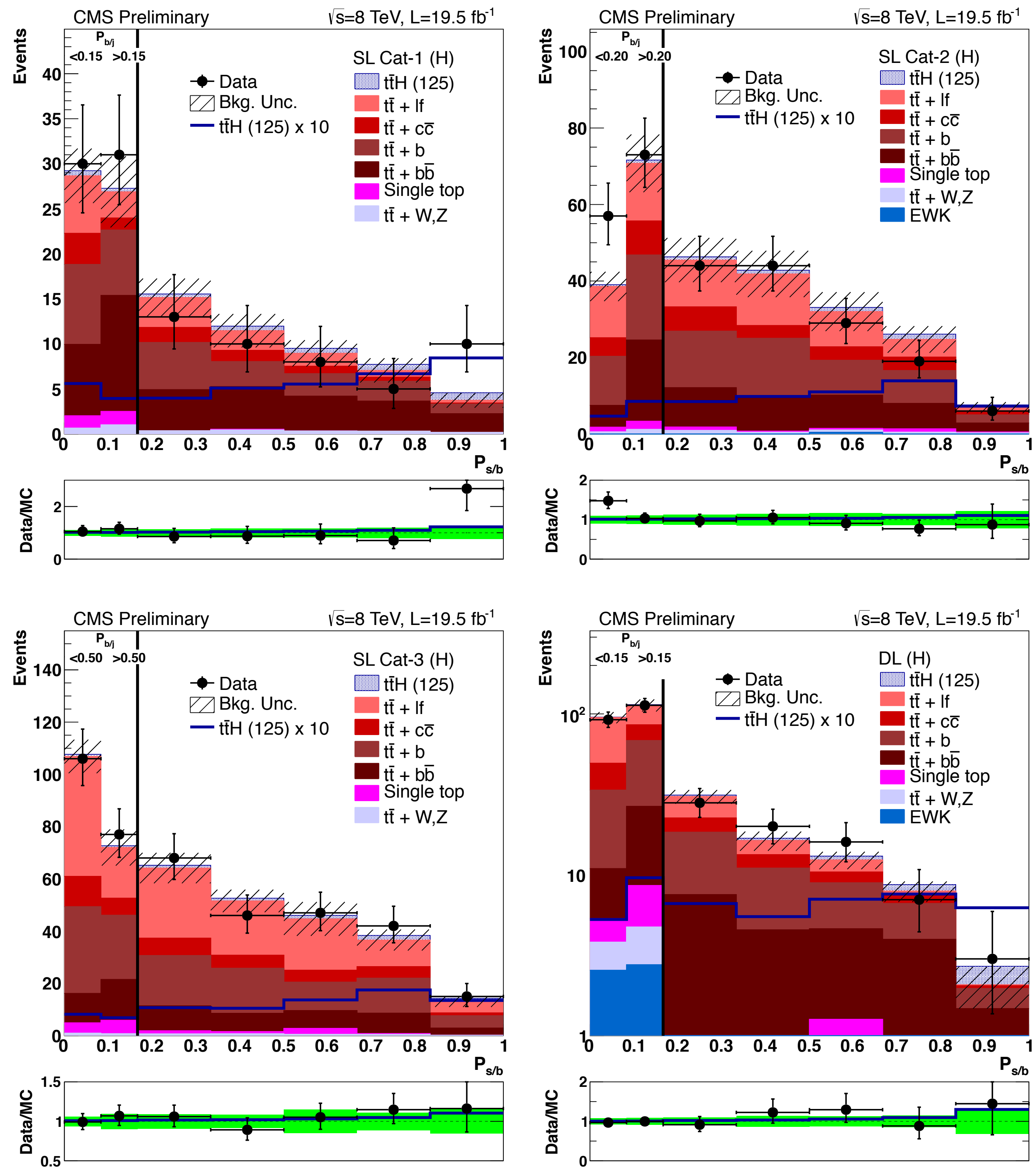
Results (8 TeV)

Combined fit to ME discriminant:

Median Exp. 95% CL	Median Exp. (signal injected)	Obs.
μ<2.9	μ<3.9	<3.3

- Best-fit value μ_{ttH} = 0.7±1.4





[CMS-PAS-HIG-14-010](CMS-PAS-HIG-14-010)

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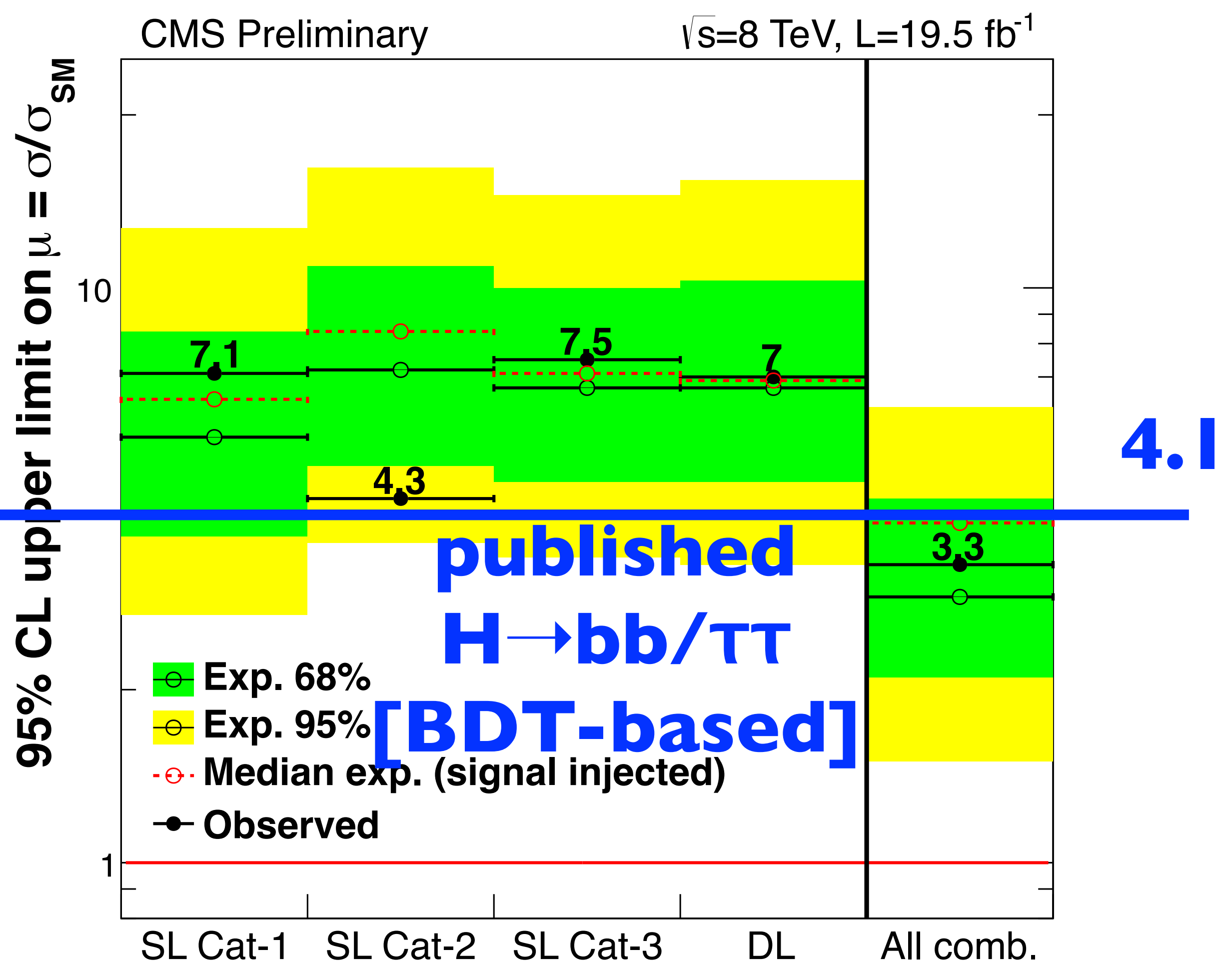

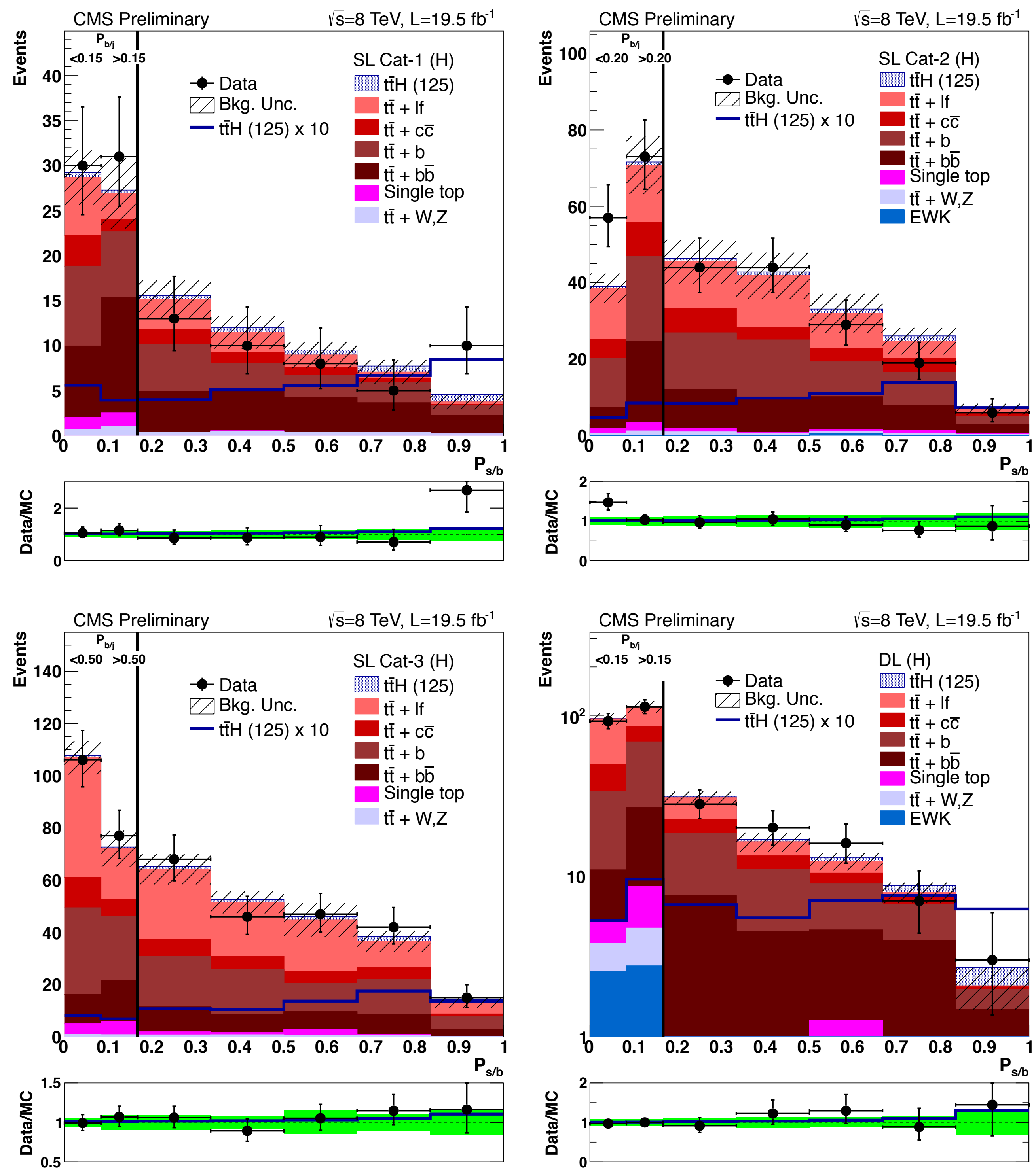

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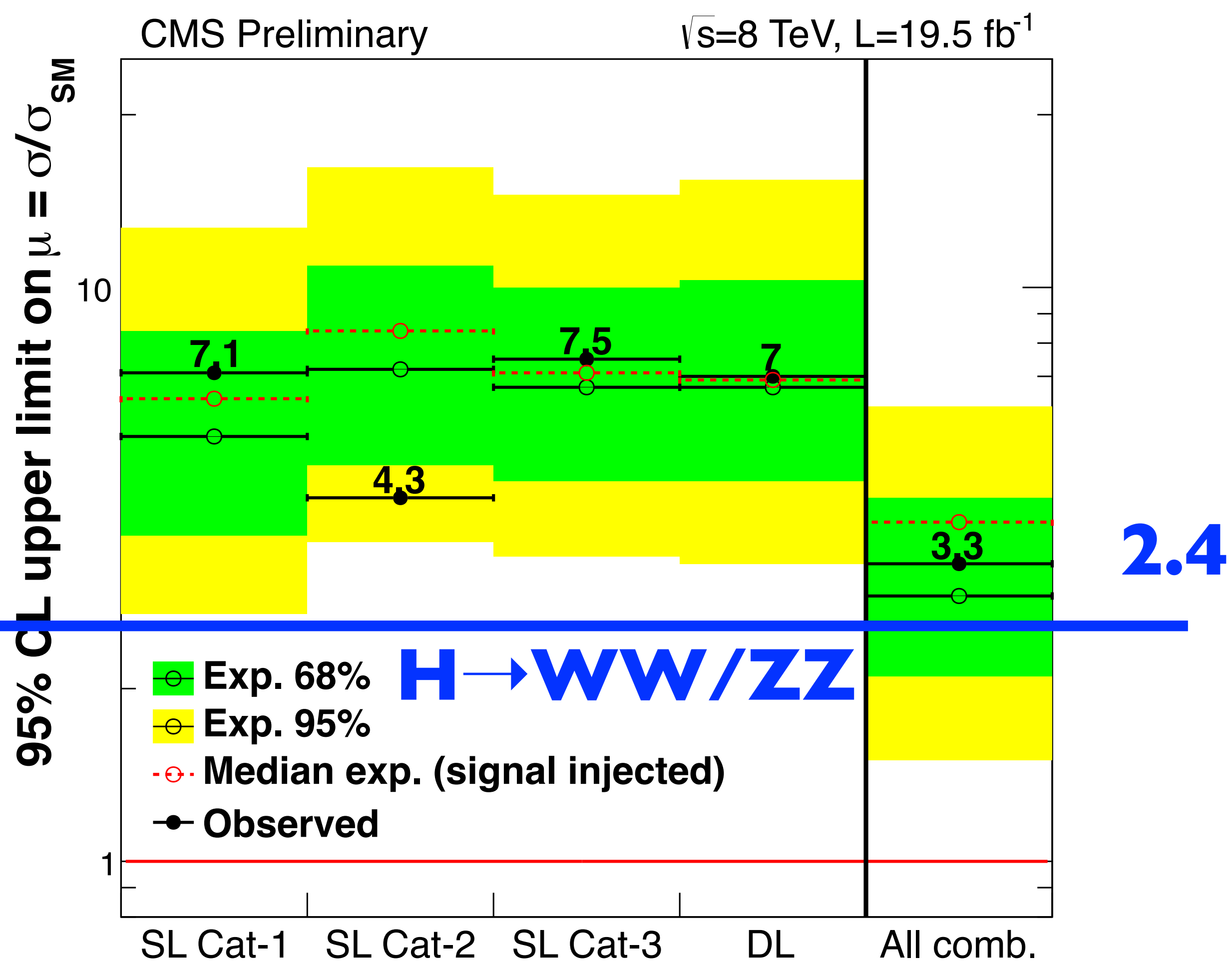

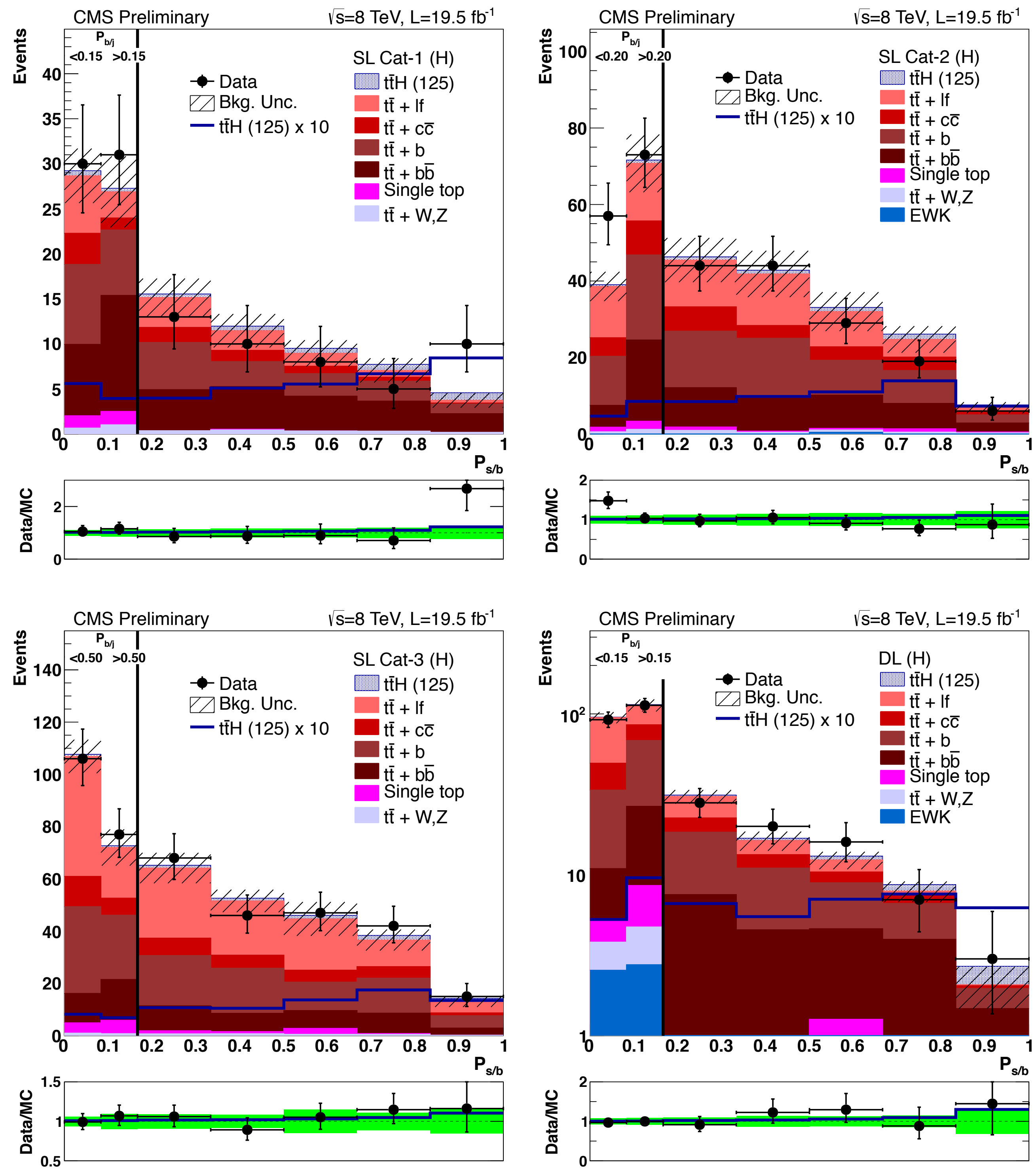

CMS-PAS-HIG-14-010

Summary & outlook

- First ttH search based on the MEM at a collider
  - new algorithm developed and optimized for CMS
    - 20-30% better expected limit compared to previously published analysis
    - CPU & human-time sustainable
    - Run I: results in agreement with SM expectation ($\Delta\mu/\mu \sim 1.4$)
- The 13 TeV challenge is behind the corner
  - with more data, theoretical uncertainties will become relevant
    - use of NLO programs will make analysis more solid
    - definition proper sidebands for background estimation/calibration
    - ttZ($\rightarrow$bb) as a standard candle?
  - further improvements:
    - spin-correlations as an extra handle (?)
    - inclusion of more event topologies (?)
    - inclusion of boosted top tagging variables (?)

Thanks for your attention

Back up

Motivation

Determination of top-quark Yukawa **coupling** (***y_t***) is a major goal

- gather direct evidence of Higgs coupling to up-type fermions
- implication on EWSB

Cross sections of top+Higgs channels can unravel value/sign of ***y_t***

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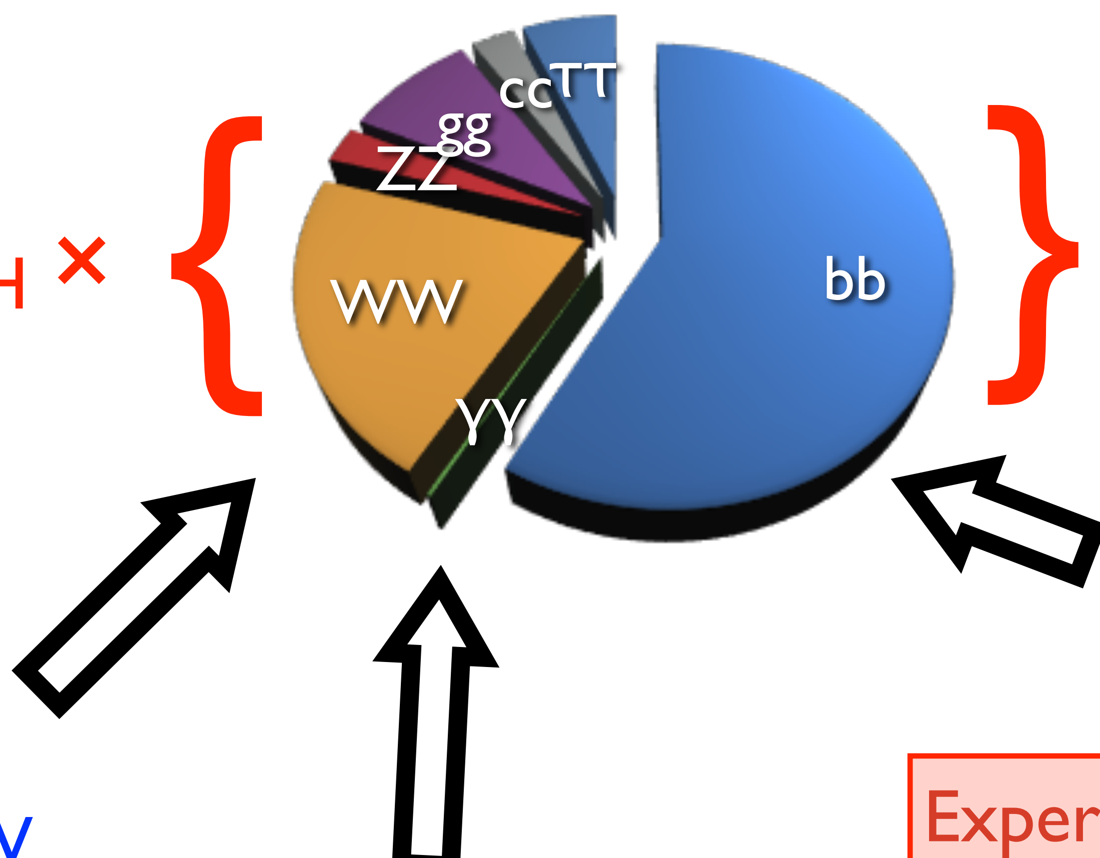


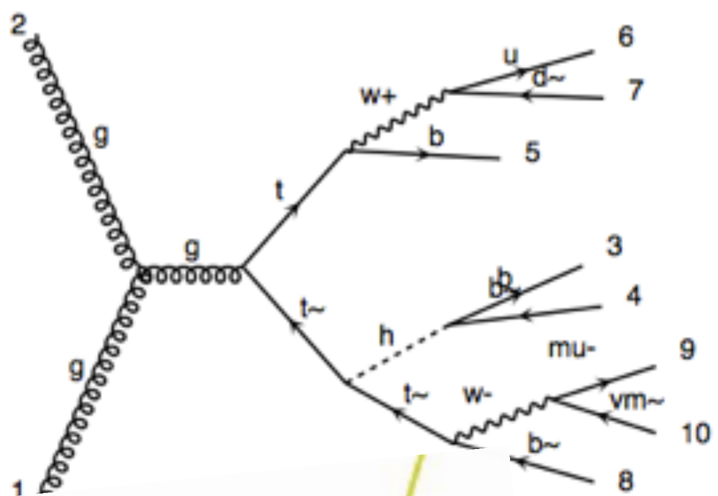
H→leptons:
Clean states.
Coupling to Z/W better known

H→γγ:
Mass peak.
High-purity.
Low systematic uncertainty

H→bb:
Large BR.
Mass peak.

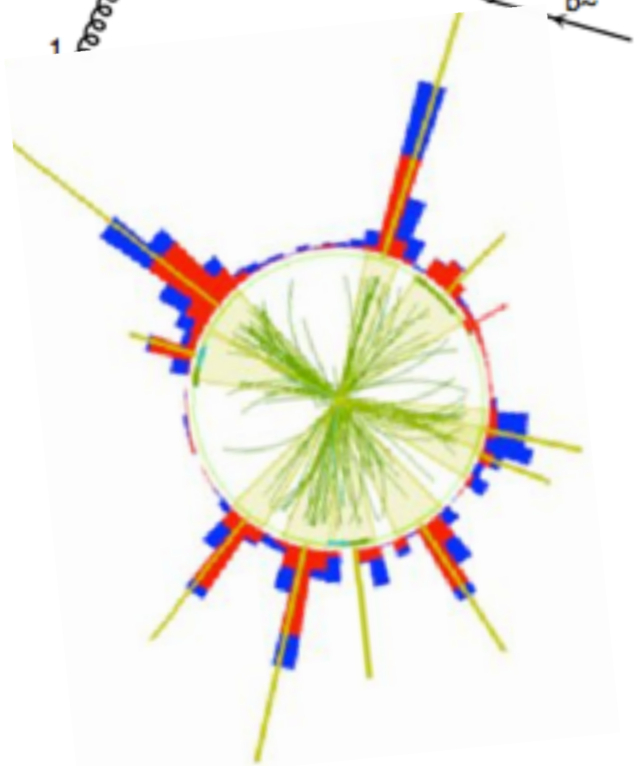
Experimental challenge posed by:
- low signal cross section
- irreducible SM background
  - often challenging at NLO
  - e.g. tt+bb, tt+γγ, tt+Z/W
- complicated final states

Building bricks

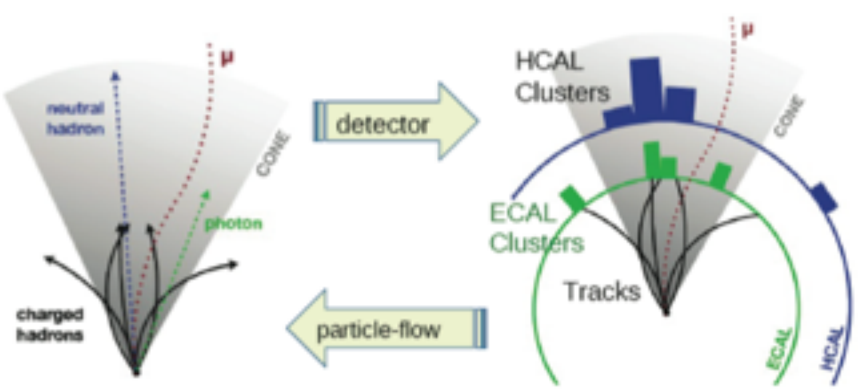


$\Rightarrow$ $\vec{\boldsymbol{X}}$ = (generated particles)

$\mathscr{M}(\vec{\boldsymbol{X}})$ = scattering amplitude



$\Rightarrow$ $\vec{\boldsymbol{Y}}$ = (reconstructed particles)



$\Rightarrow$ “metric” $W(\vec{\boldsymbol{Y}}, \vec{\boldsymbol{X}})$

Dimensional reduction

- Factorize integration over final-state particles via

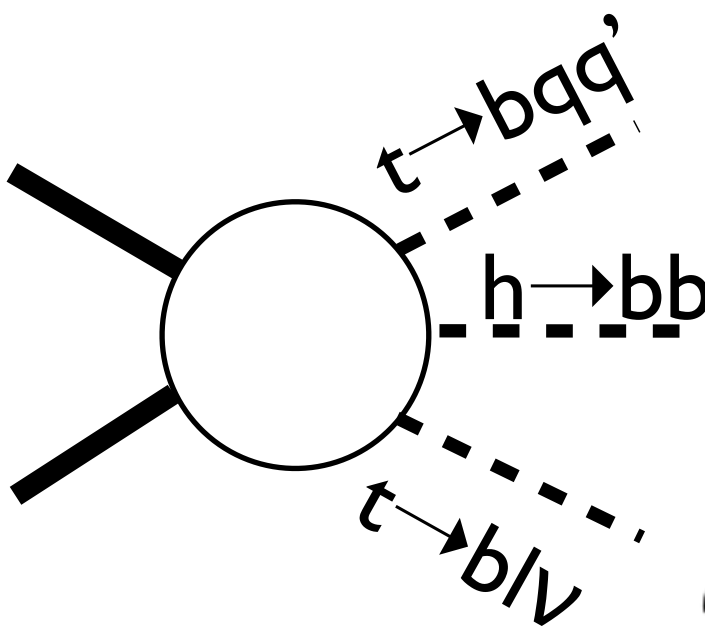
$$d\Phi_n(P;p_1,\ldots,p_n) = d\Phi_j(q;p_1,\ldots,p_j) \times d\Phi_{n-j+1}(P;q,p_{j+1},\ldots,p_n)(2\pi)^3 dq^2$$

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

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

- Assume lepton and jet direction perfectly measured

$\Rightarrow$



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

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

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

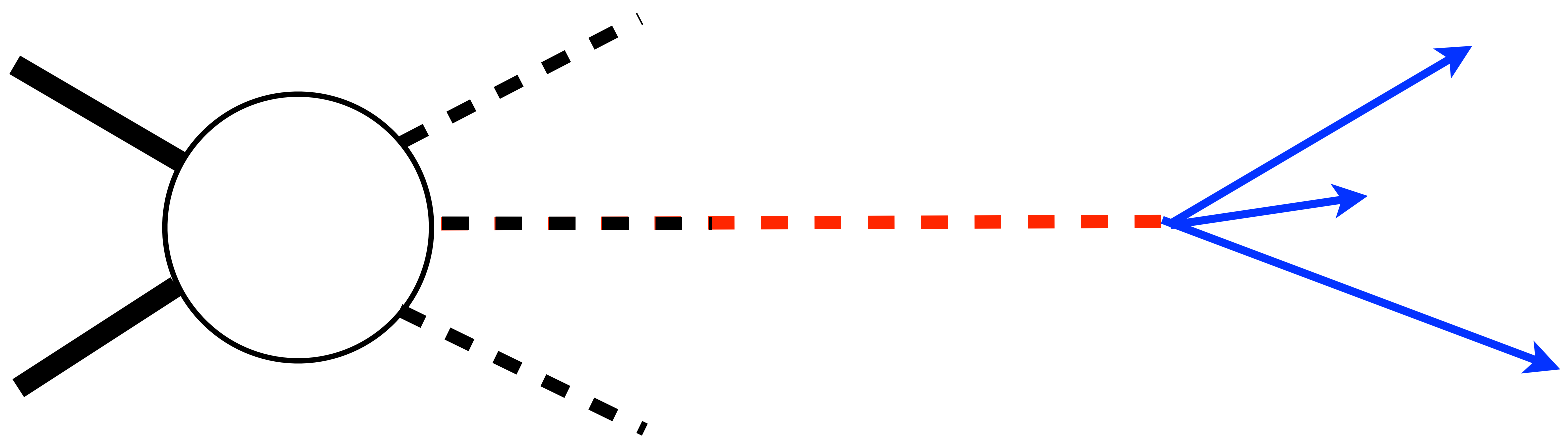
The Matrix Element Method (MEM)

Given event *j*, find its probability $w_j(\cdot|H_i)$ under hypothesized process H_i

- w_j is a function of detector-level observables **Y** (technically, a differential prob. density on **Y**)
- can depend parametrically on unknown model parameters **λ**
- is the relative weight with which a MC generator of process H_i would generate ev. *j*
  - for N>>1 events, $(\sum^N w_j / N) \rightarrow 1$
- N.B.: a HEP process H_i is known (⇔ can be simulated) fully differentially only to some approximation (typically not better than NLO). Conversely, nature is "to all orders" :
  - a certain approximation is implicit in the method
  - this does not invalidate the method *per se*', rather makes it not optimal

The algorithm: basic principles

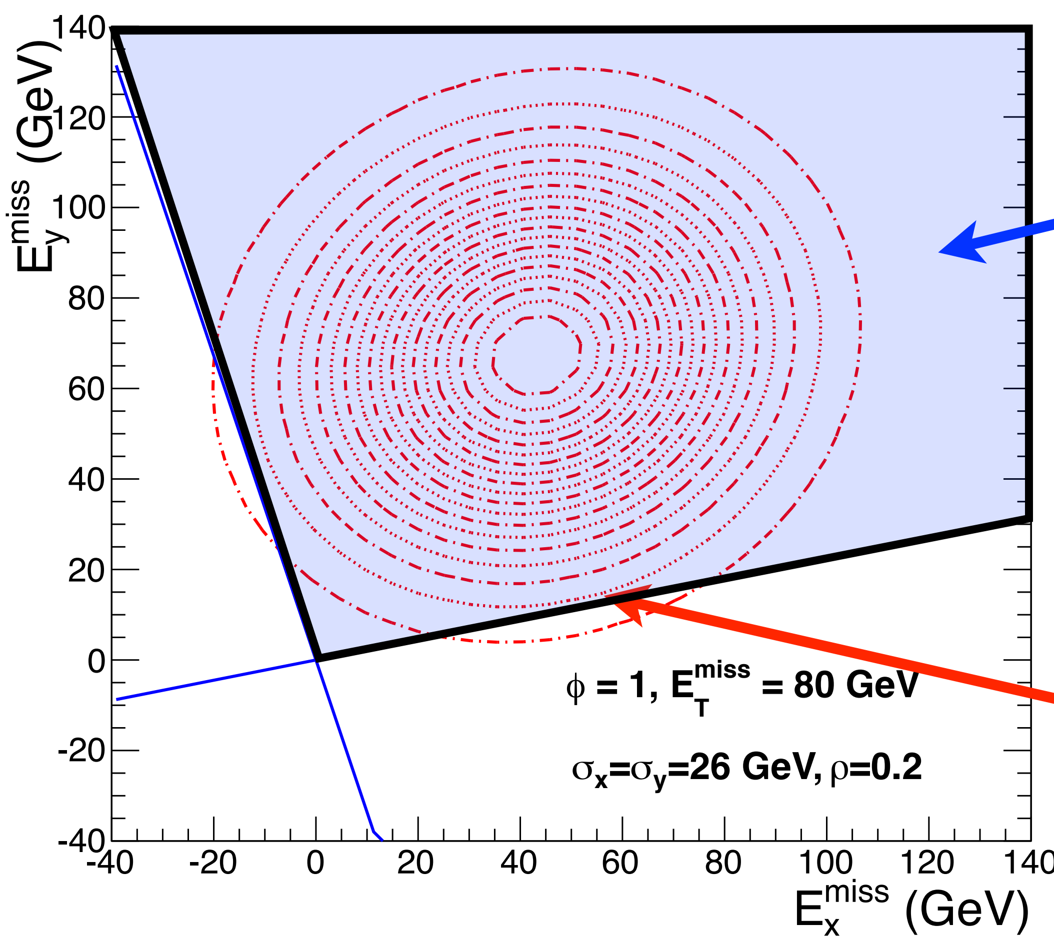
- Factorize the reaction $pp \to tt+(bb) \to \Omega$ as a 3-steps process:
  - $gg \to$ 3 on-shell intermediate particles $\propto |\mathscr{M}(g\,g \to t\,t\,H)|^2$
  - intermediate particles propagate: $\propto [(q^2-M^2)^2 - M^2\Gamma^2]^{-1}$
  - intermediate particles decay $\propto \Gamma^{-1}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



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

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:

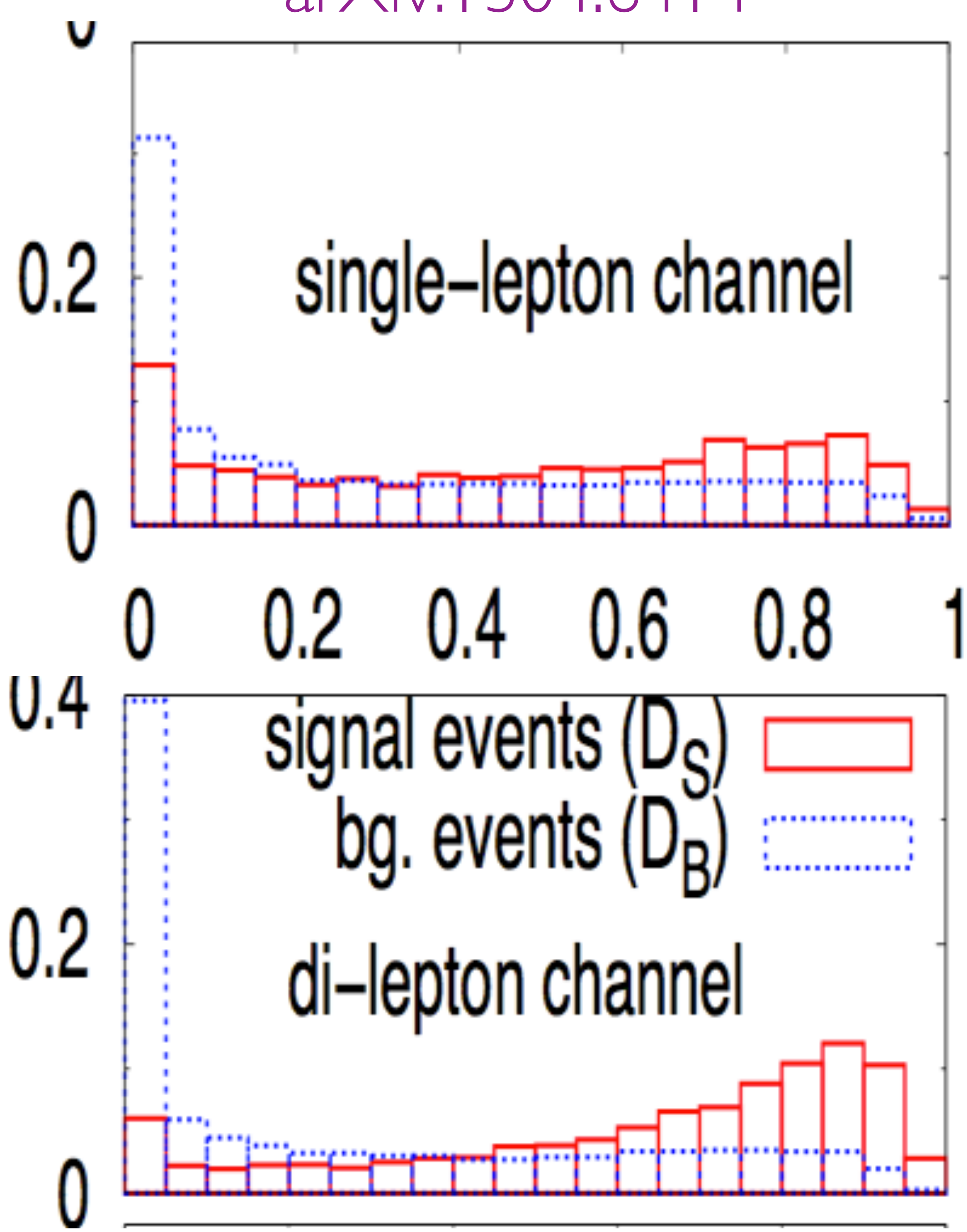
$$\frac{1}{2\pi\sqrt{|V_{x,y}|}}\exp\{-\frac{1}{2}(\vec{E}_T^{miss} - \sum \vec{\nu}_T)^T V_{x,y}^{-1}(\vec{E}_T^{miss} - \sum \vec{\nu}_T)\}$$

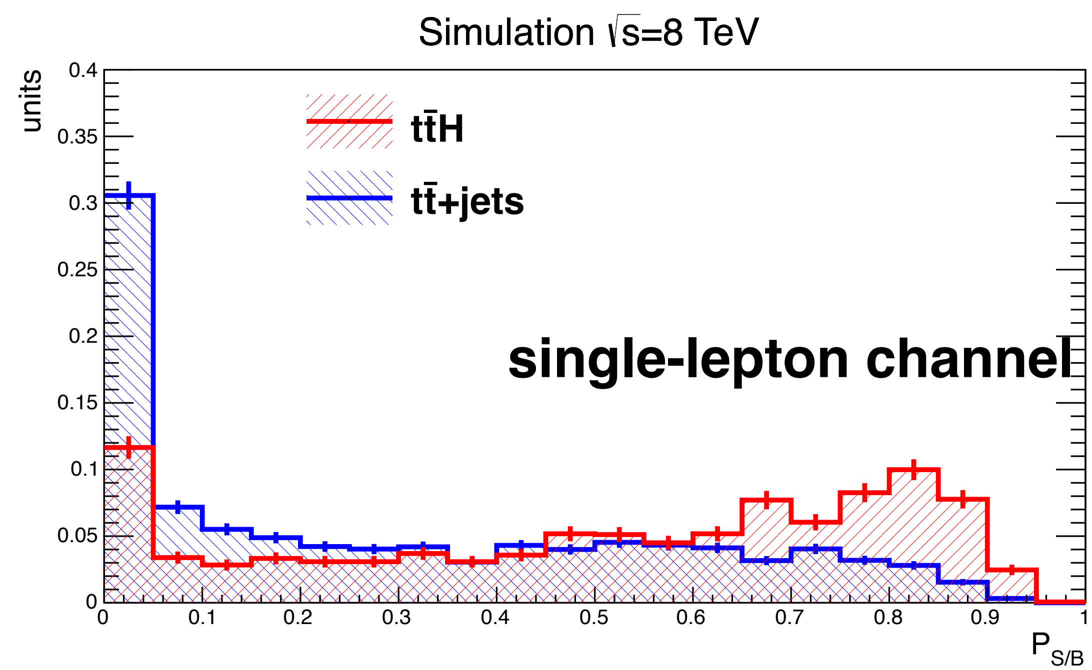
95% CL isocontour

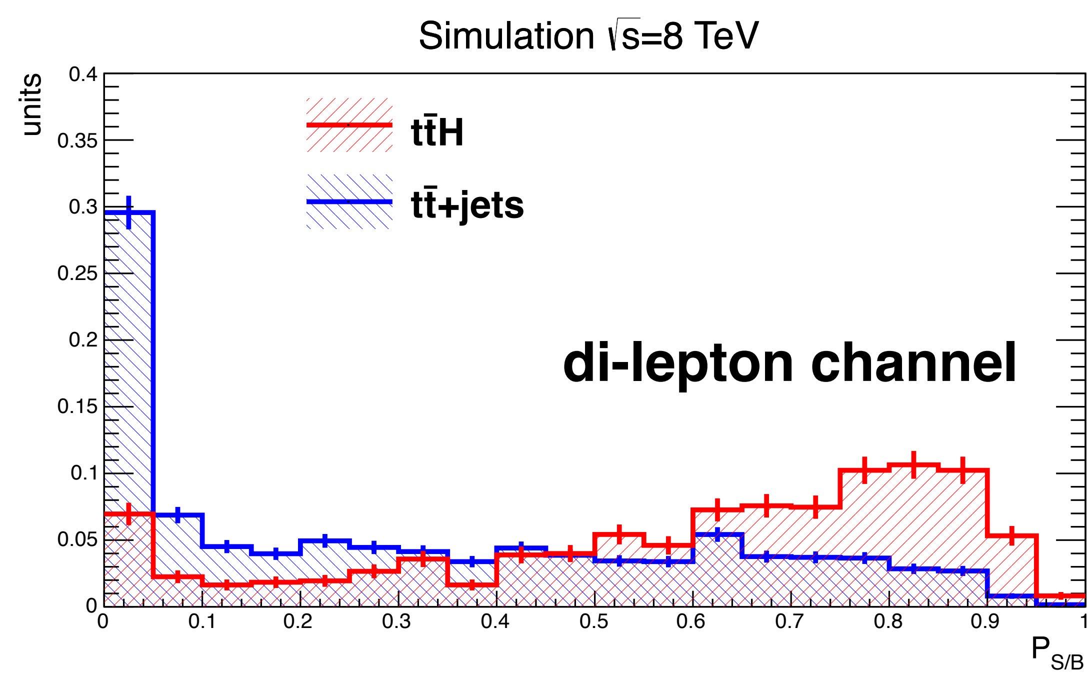
$V_{x,y} = E_T^{miss}$ cov. matrix

Comparing with MadWeight

arXiv:1304.6414

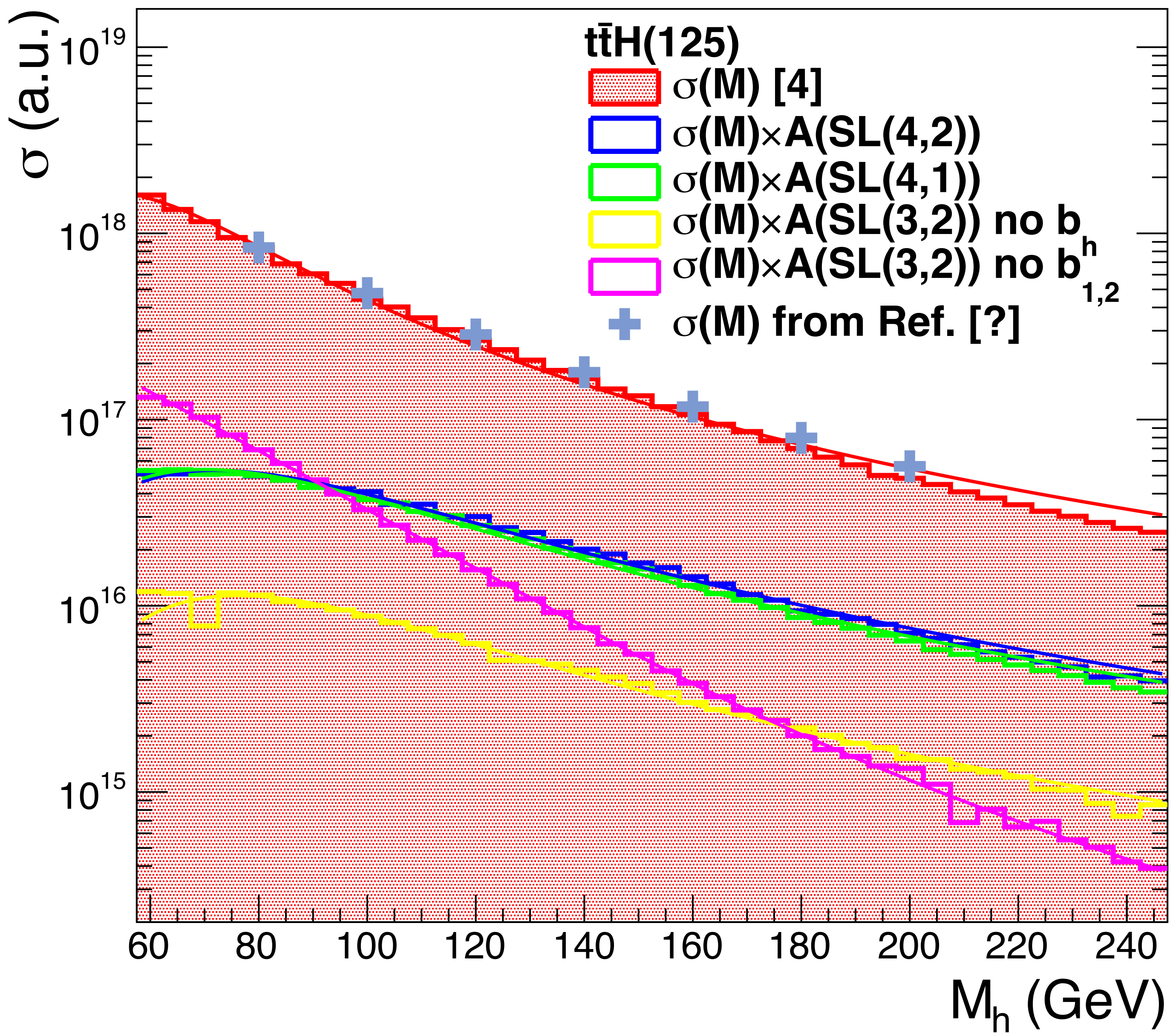




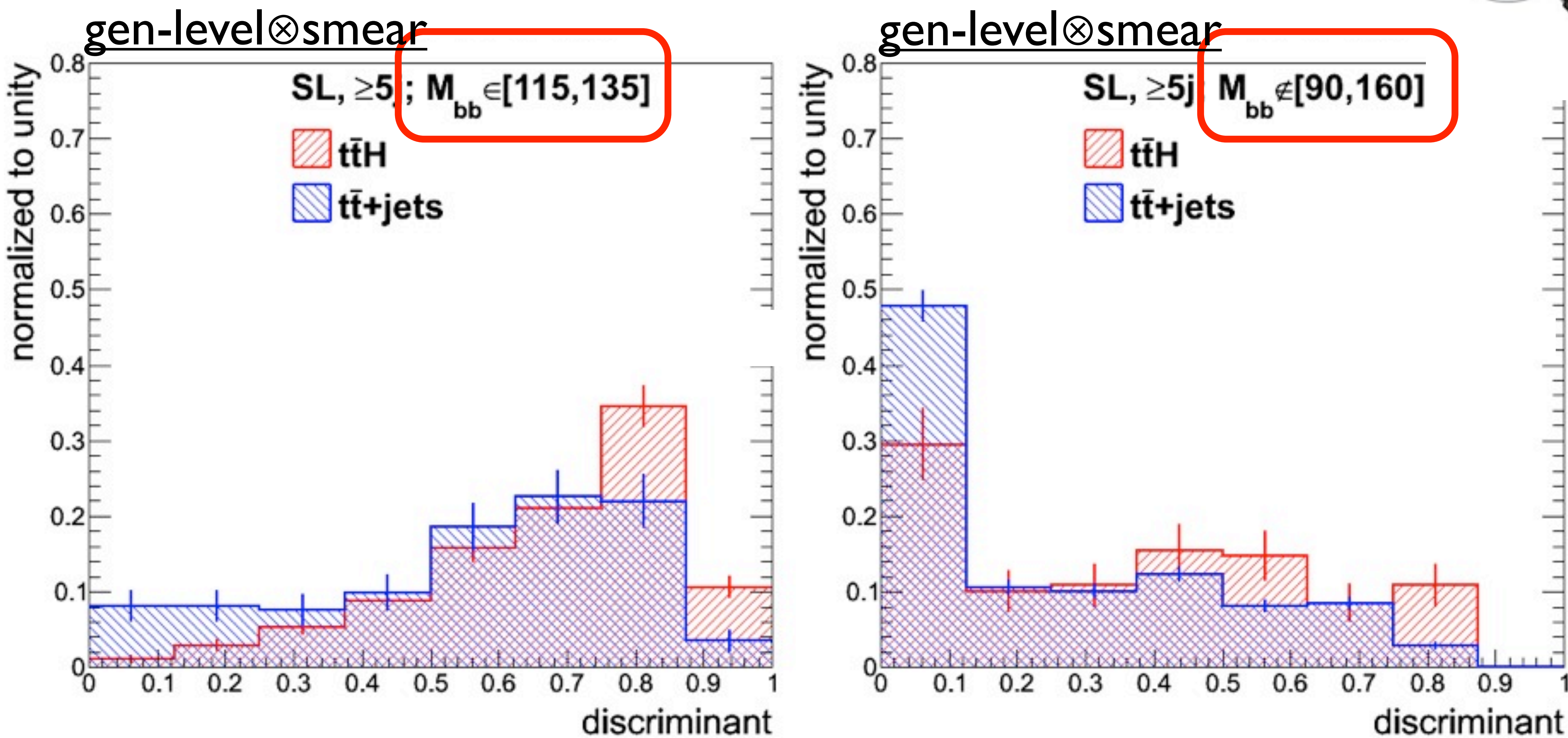


* looser *b*-tag cuts to enhance MC stat.

Cross-section



Digression I: the Higgs mass

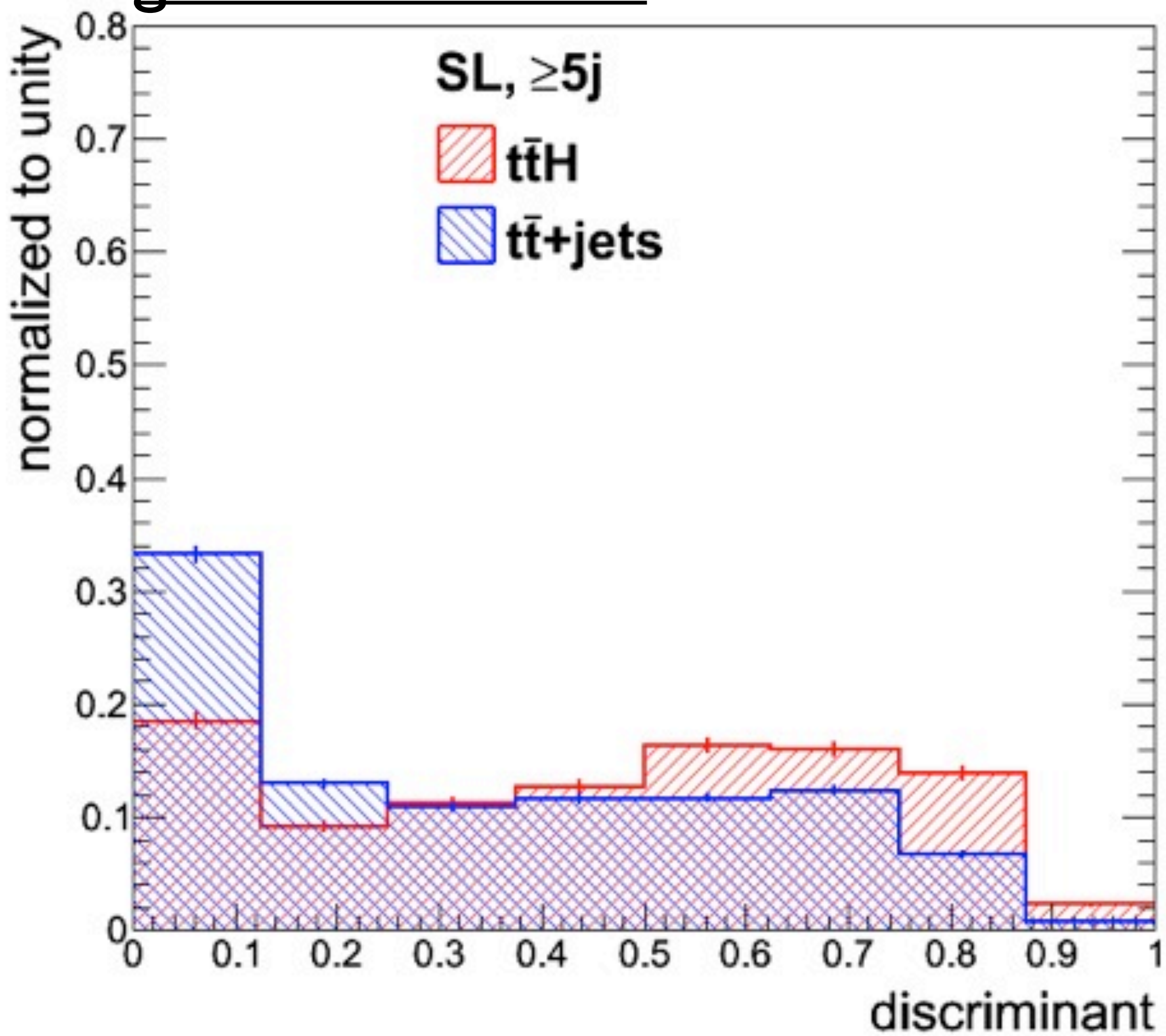


- *ttbb* events w/ M(*bb*) ≈ 125 indeed look like *ttH*!
  - but not identical ⇔ the ME is sensitive also to the other variables
- *ttH* events w/ M(*bb*) ≠ 125 (e.g. poor resolution) undistinguishable from *ttbb*

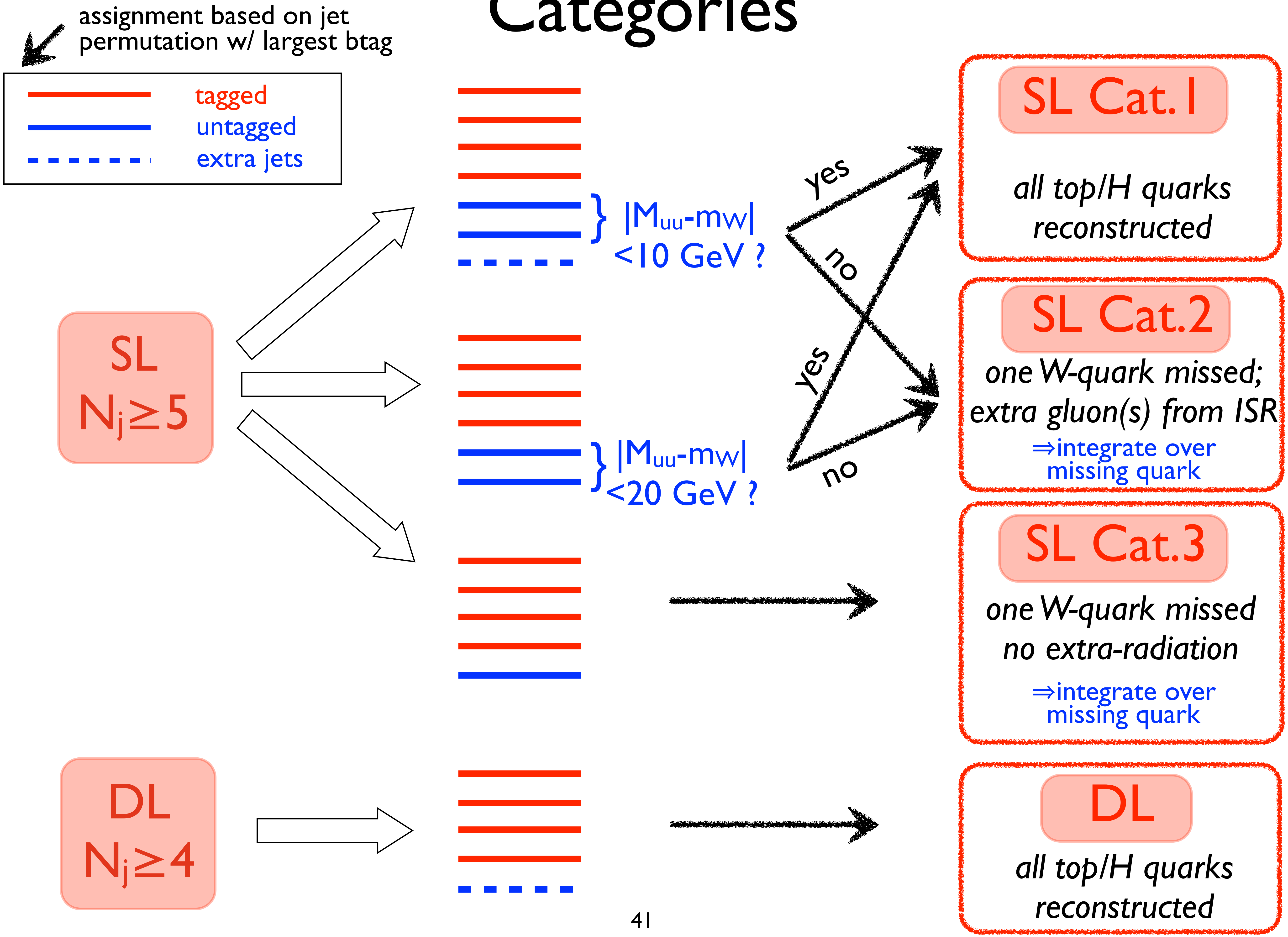
Digression II: wrong hypothesis

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

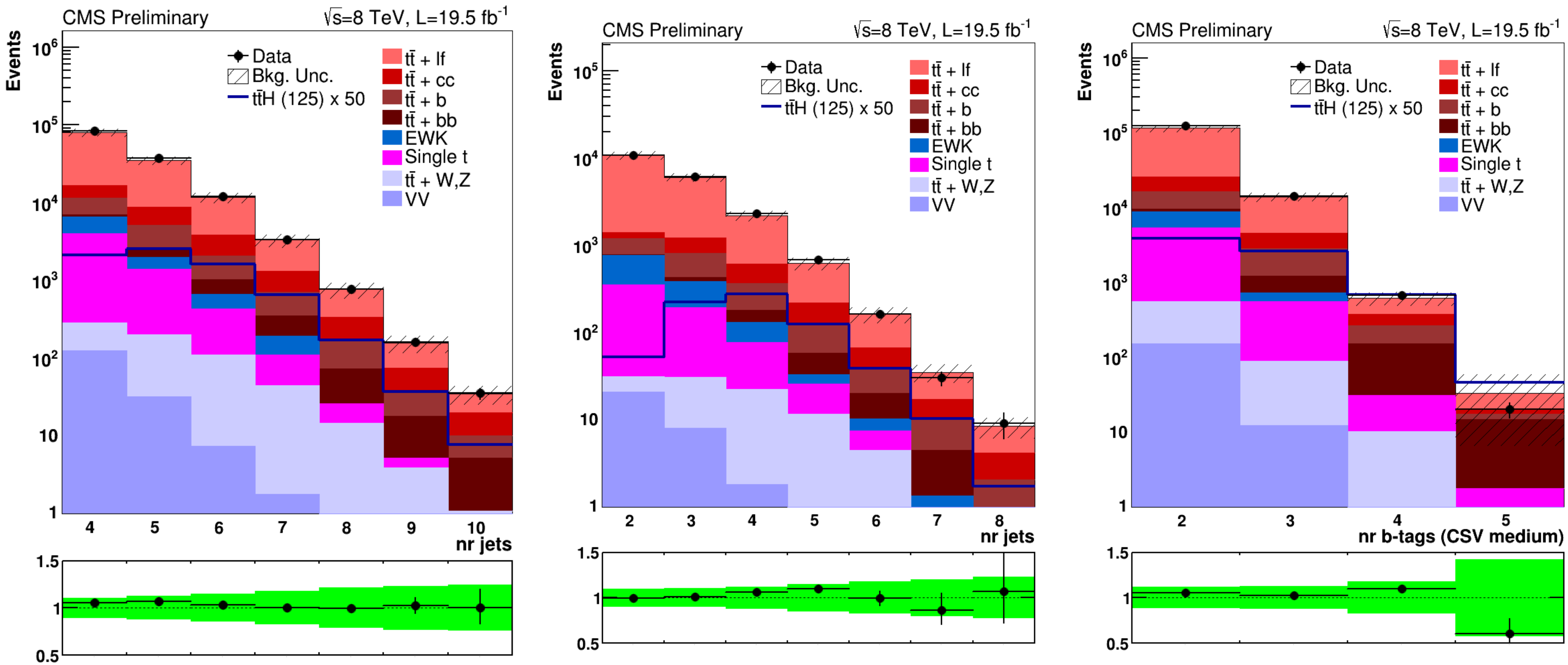
gen-level⊗smear



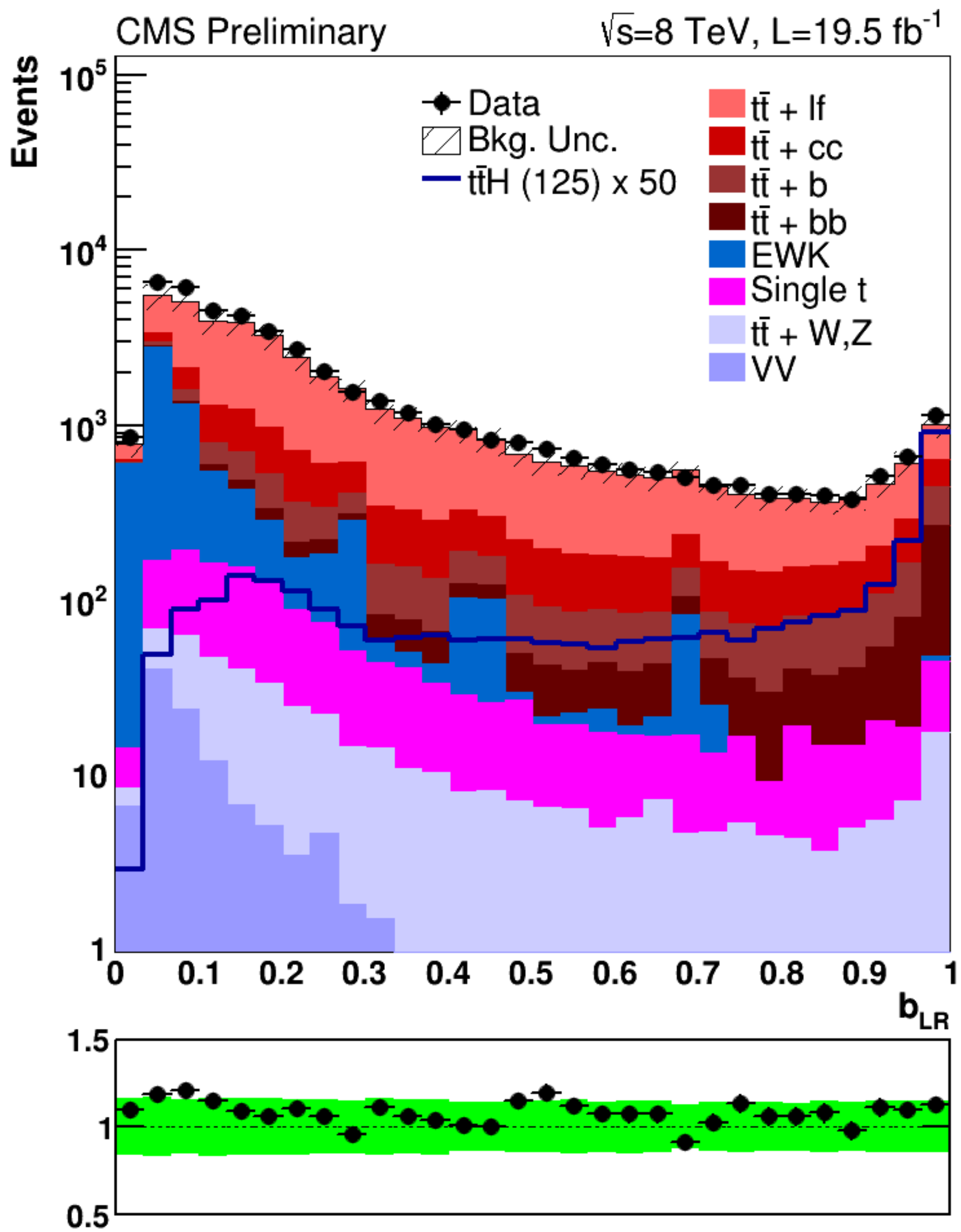
Categories

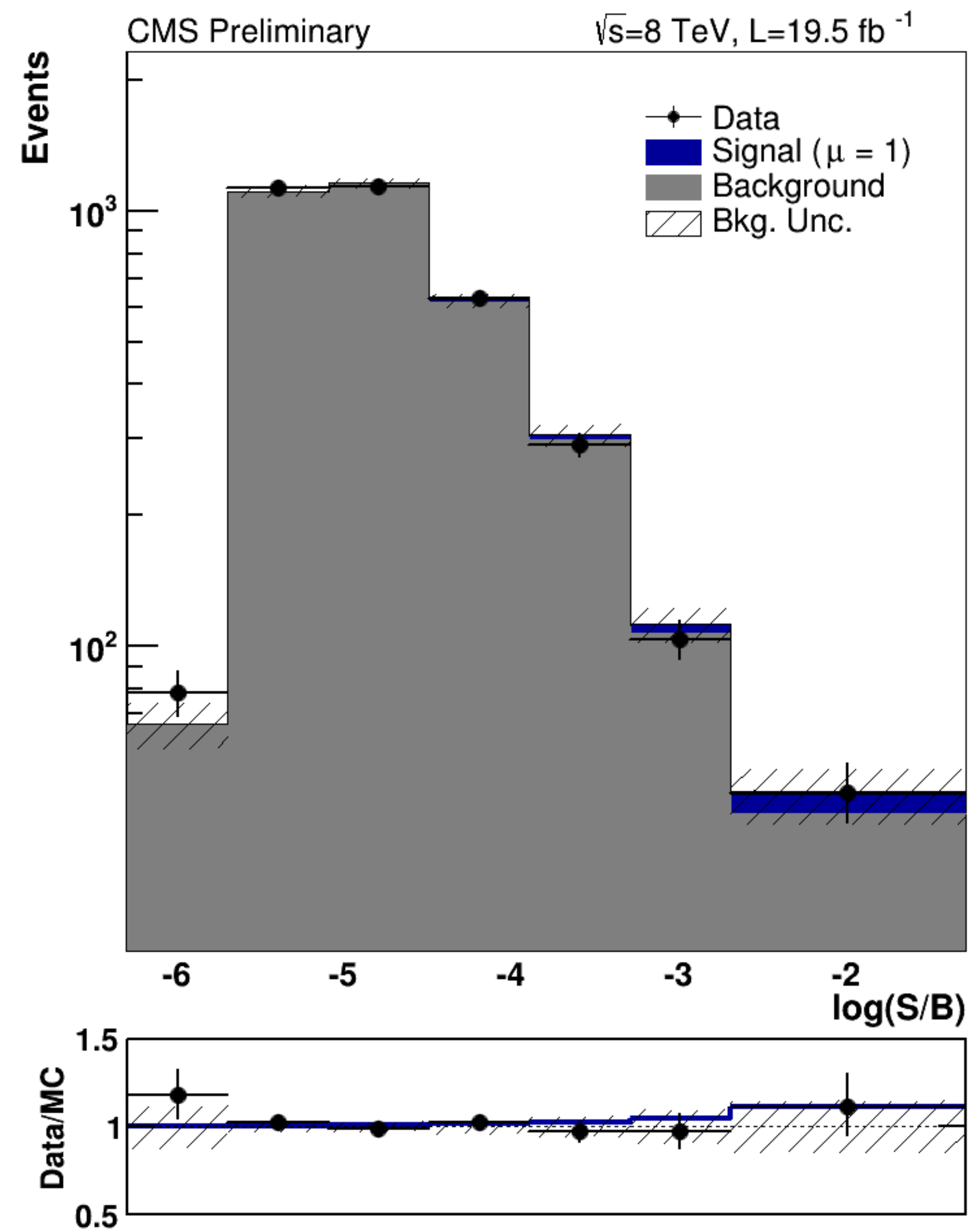

assignment based on jet
permutation w/ largest btag
tagged
untagged
extra jets
SL
$N_j \geq 5$
DL
$N_j \geq 4$
} $|M_{uu}-m_W|$ <10 GeV ?
} $|M_{uu}-m_W|$ <20 GeV ?
yes
no
yes
no
SL Cat.1
all top/H quarks reconstructed
SL Cat.2
one W-quark missed; extra gluon(s) from ISR
⇒integrate over missing quark
SL Cat.3
one W-quark missed no extra-radiation
⇒integrate over missing quark
DL
all top/H quarks reconstructed

Control plots



Control plots





$$\mathcal{L}_{\mathrm{bbbb}}(\xi_1,\ldots,\xi_6) \equiv \sum_{\{\mathrm{i}_1,\ldots,\mathrm{i}_6\}} f_{\mathrm{b}}(\xi_{\mathrm{i}_1})\cdot f_{\mathrm{b}}(\xi_{\mathrm{i}_2})\cdot f_{\mathrm{b}}(\xi_{\mathrm{i}_3})\cdot f_{\mathrm{b}}(\xi_{\mathrm{i}_4})\cdot f_{\mathrm{u}}(\xi_{\mathrm{i}_5})\cdot f_{\mathrm{u}}(\xi_{\mathrm{i}_6})$$