Karlsruhe Institute of Technology

# Search for H $\longrightarrow$ $b\bar{b}$ in association with Single Top Quarks

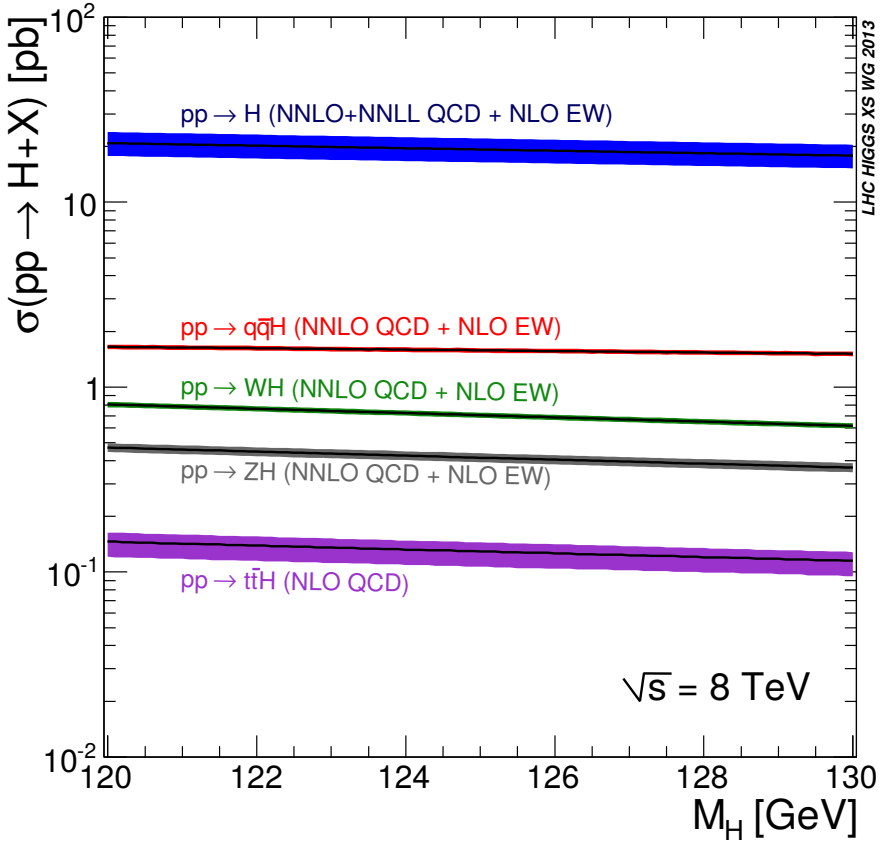
Workshop des Graduiertenkollegs - Freudenstadt-Lauterbad

Simon Fink | 28.09.2015

INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK

# Introduction I

- many different Higgs production mechanisms
- Higgs discovered in gluon-gluon fusion, evidence for VBF production
- looking for an increased cross section



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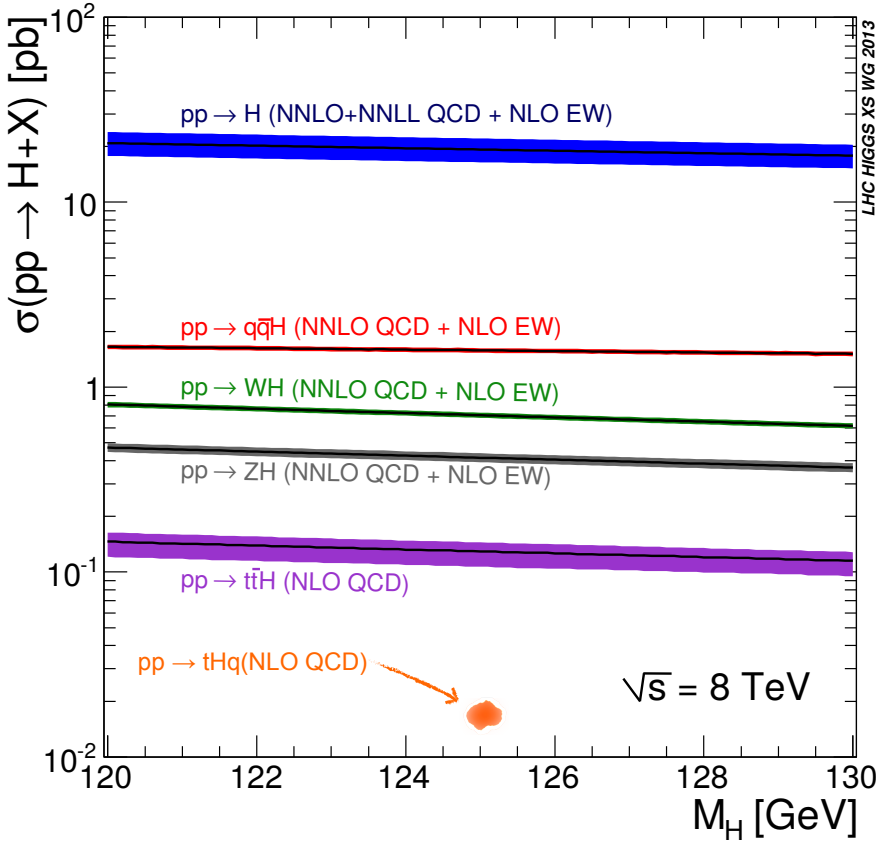


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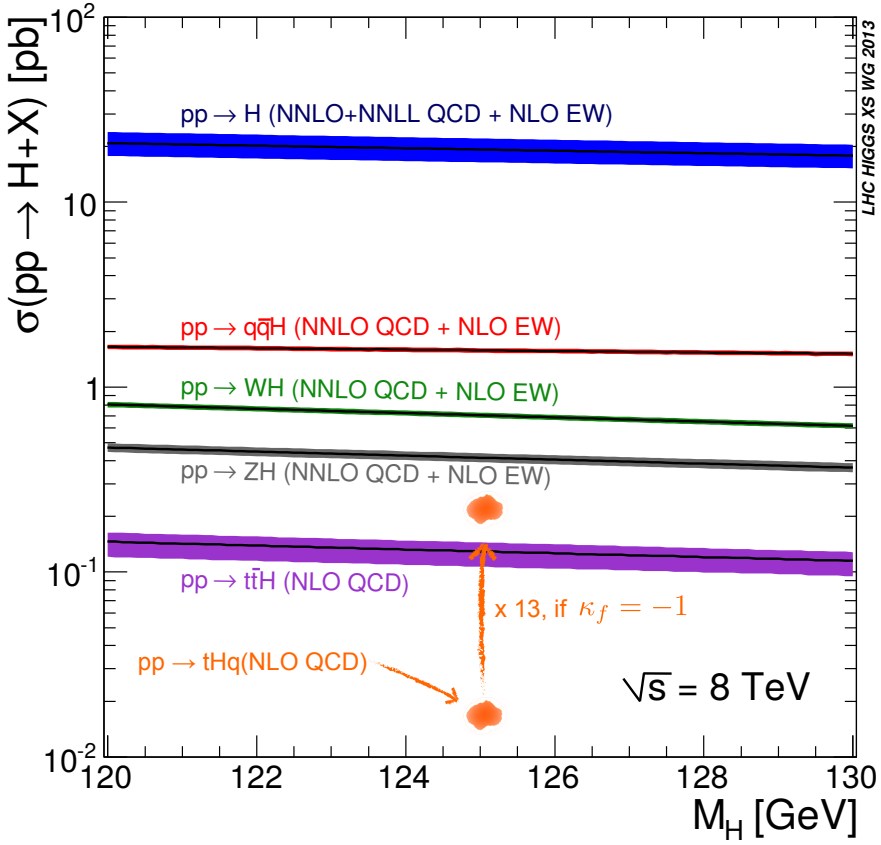


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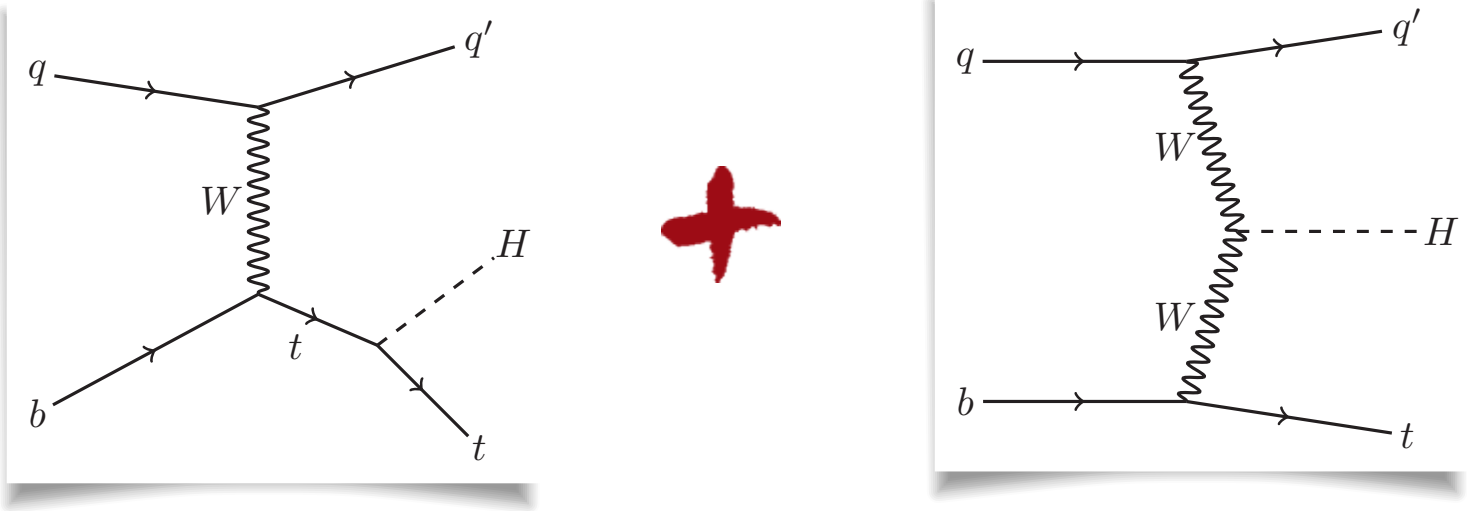
# Introduction II

- two feynman diagram for the tHq production in SM



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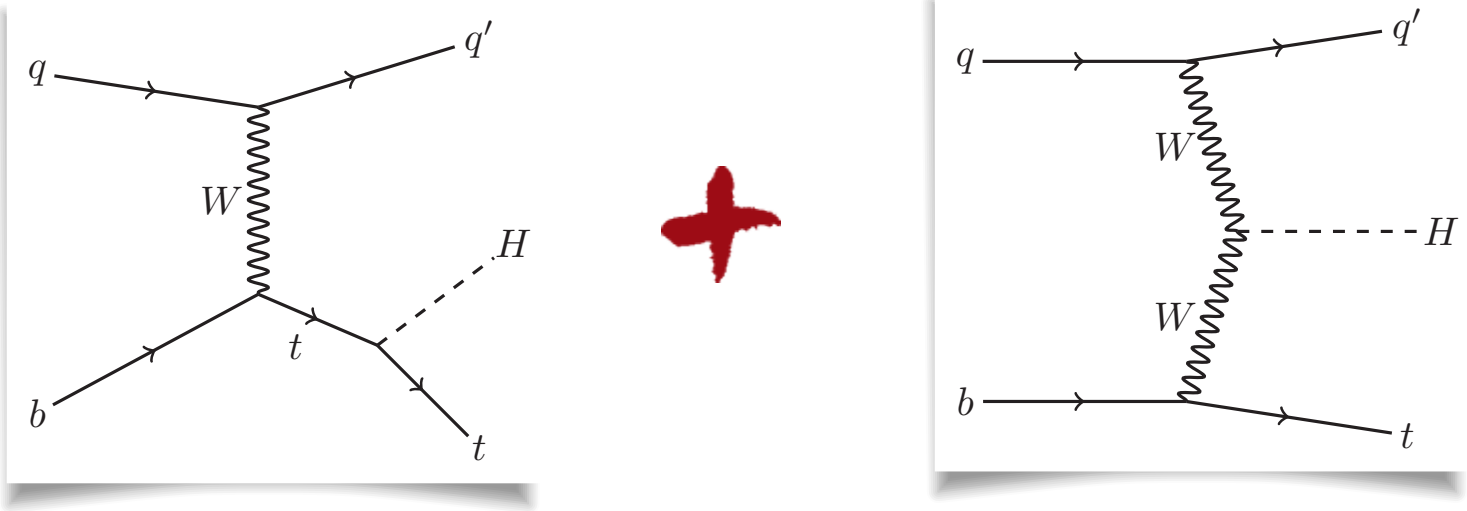


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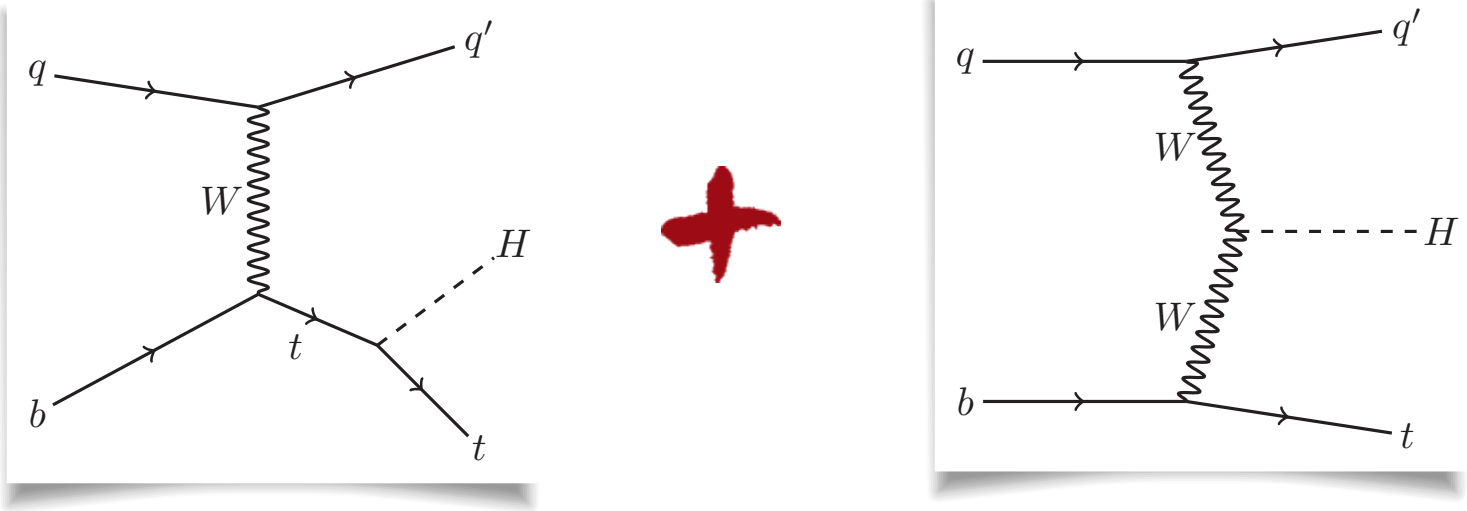


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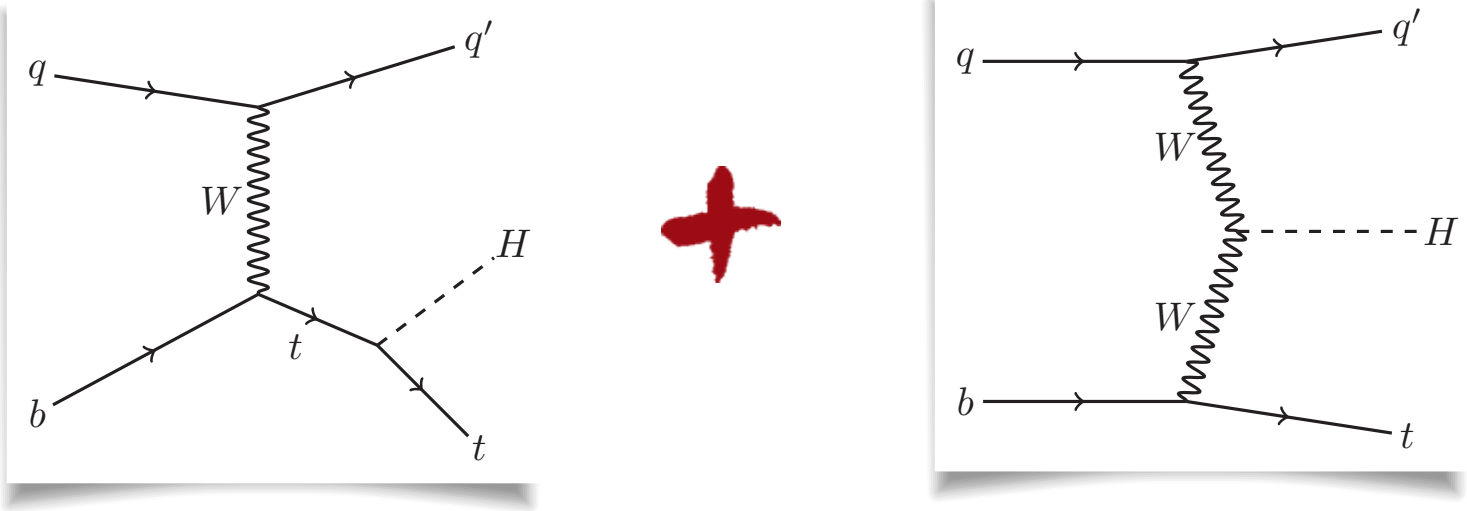


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interference can increase production cross section by $\sim 13$

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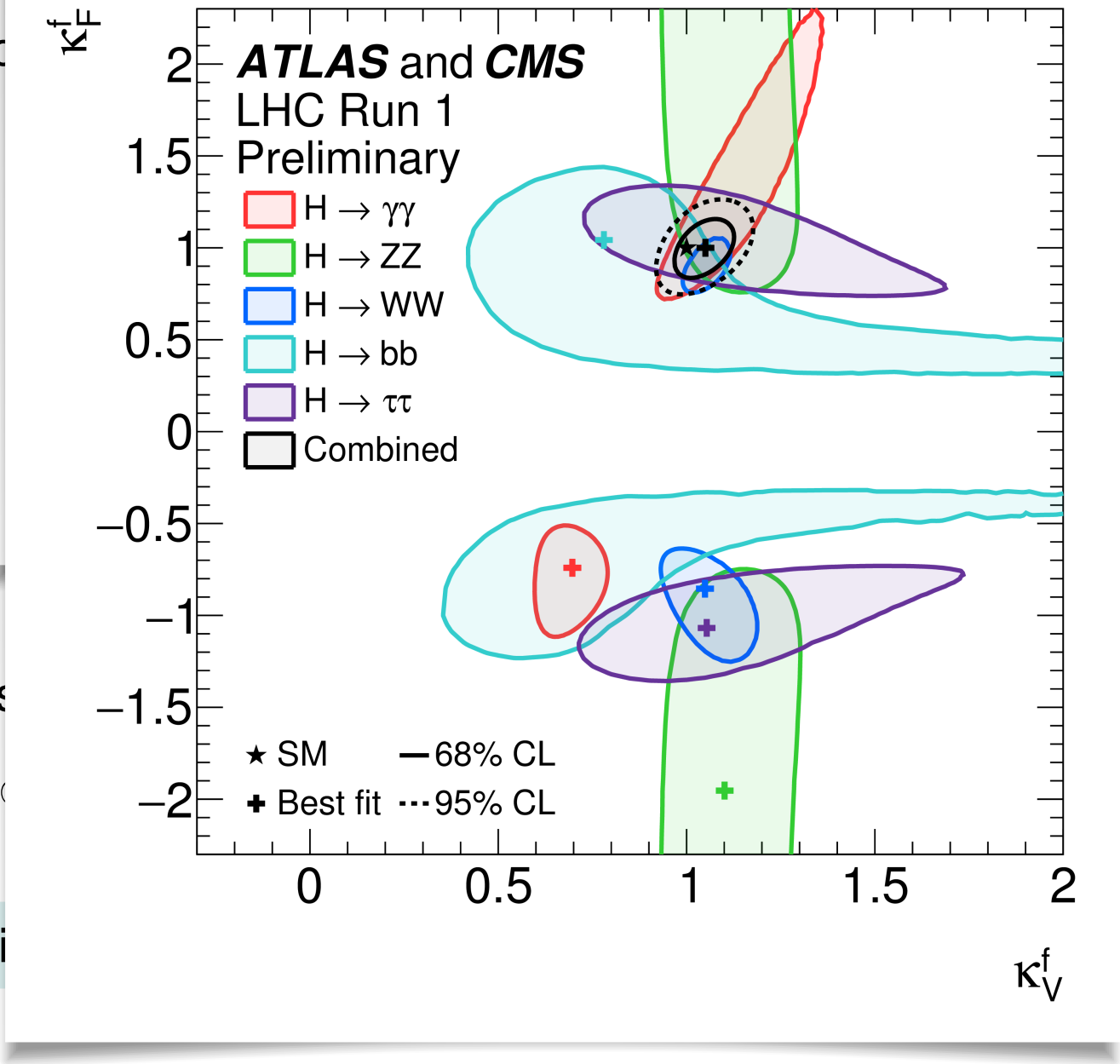


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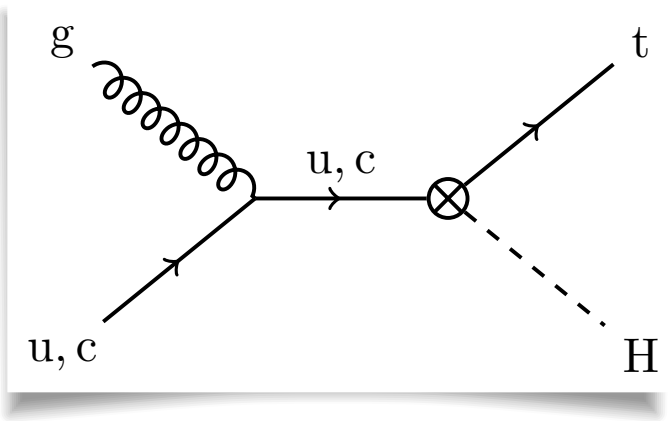


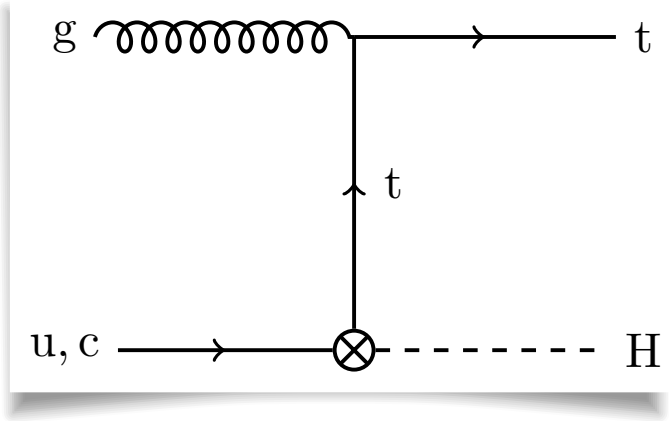


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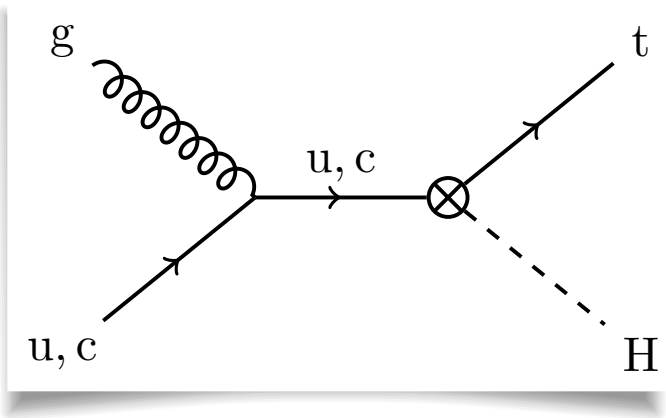


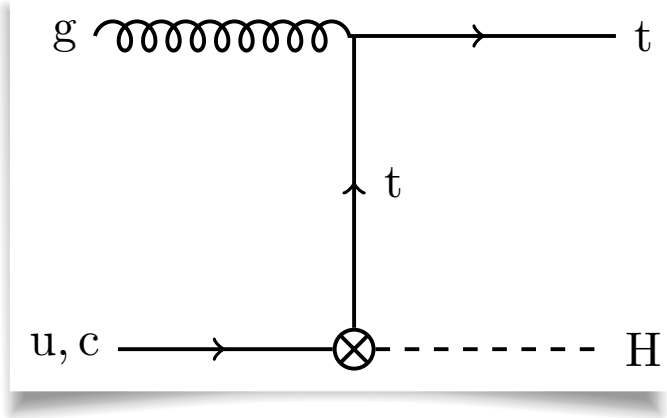


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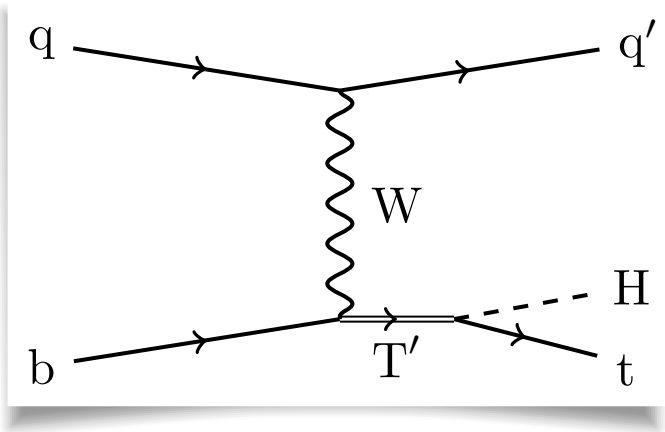

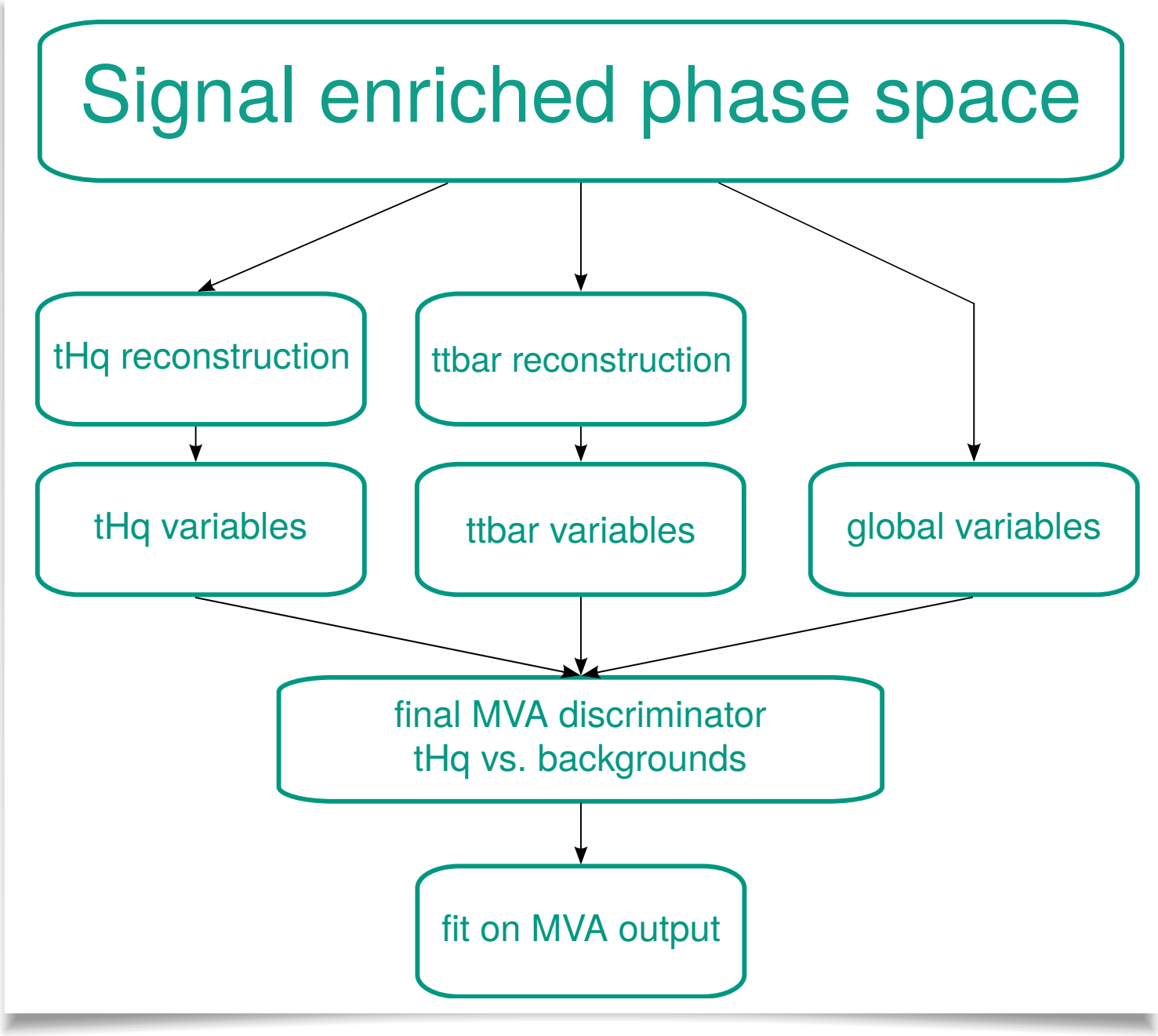
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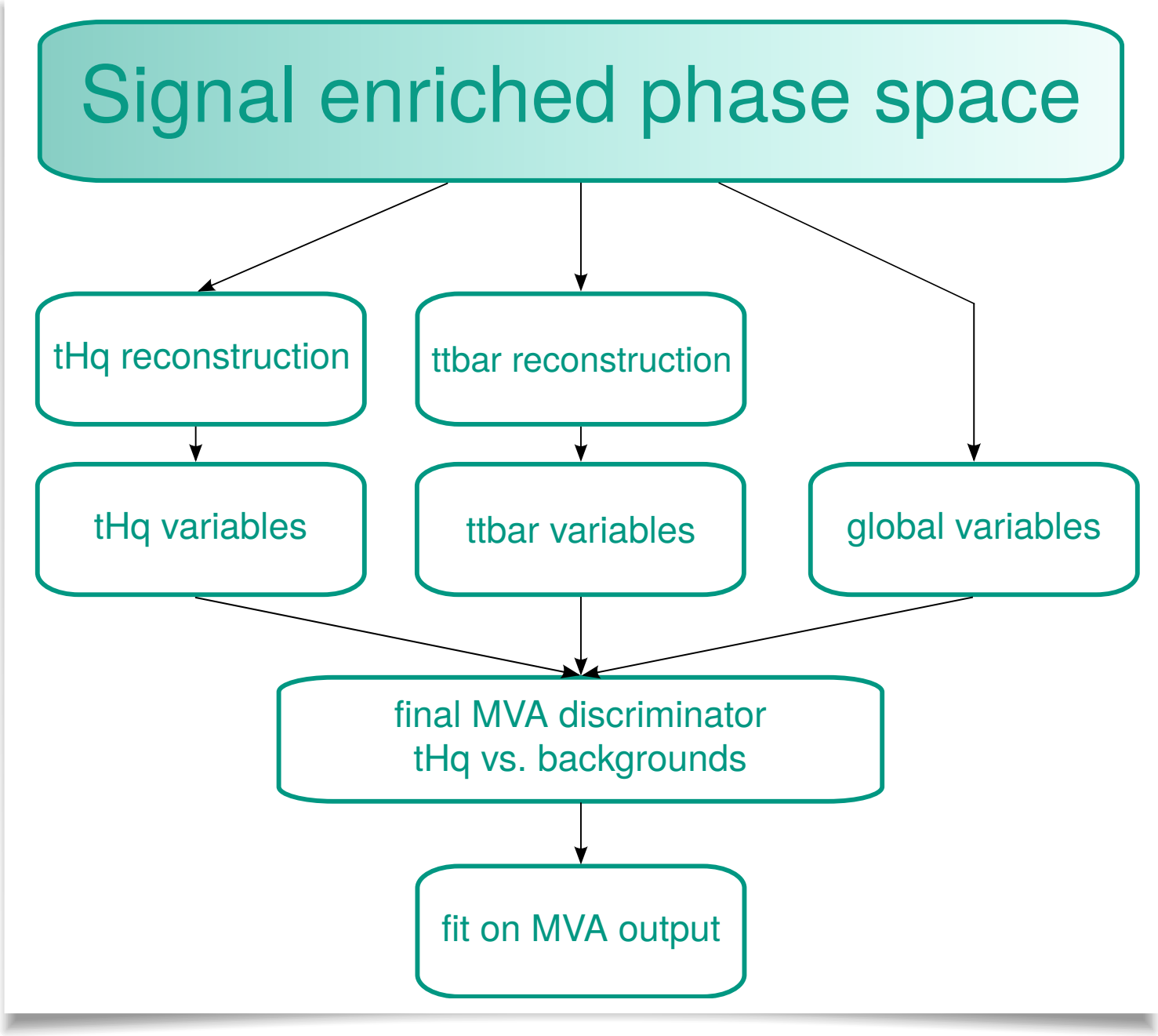
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  - 4 $b$ quarks
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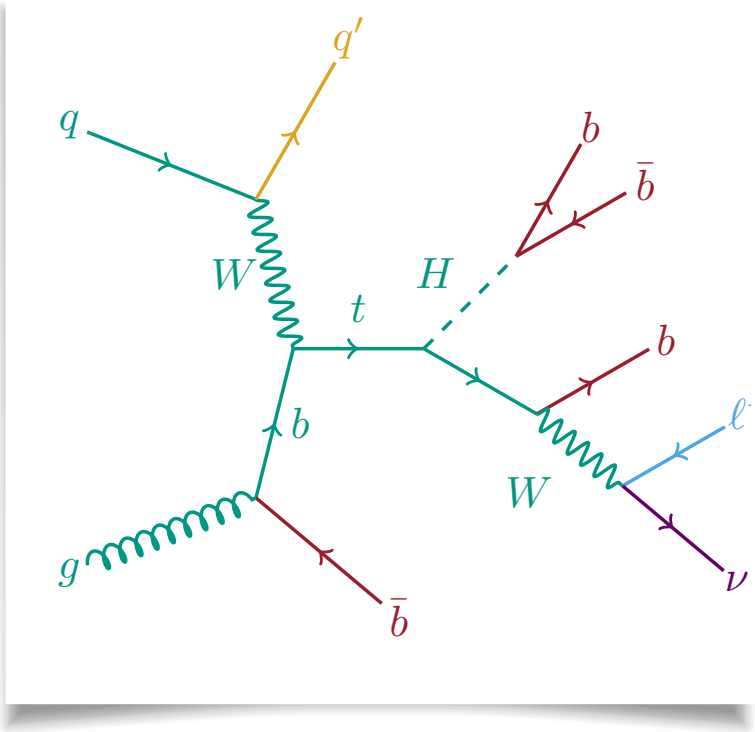
  - 1 light forward jet
  - missing energy



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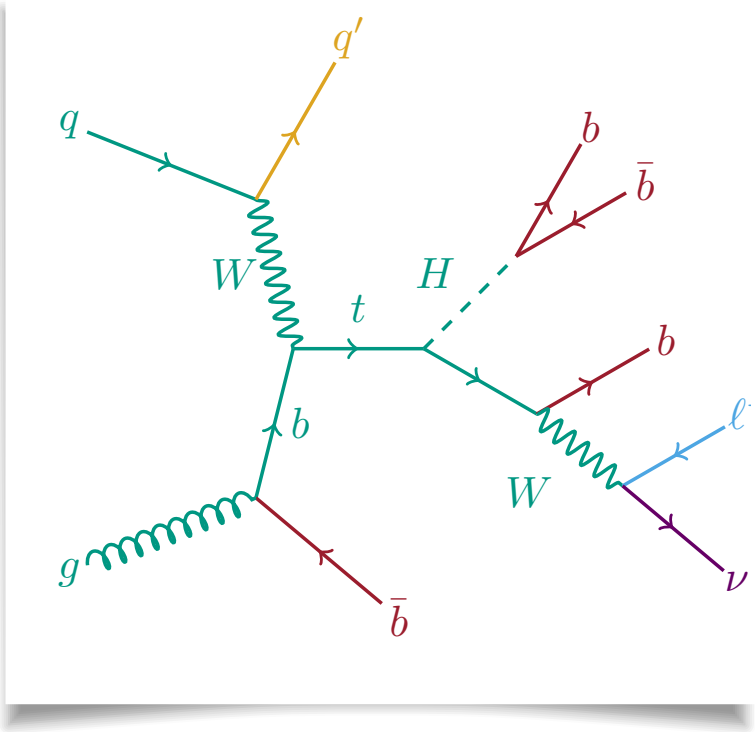

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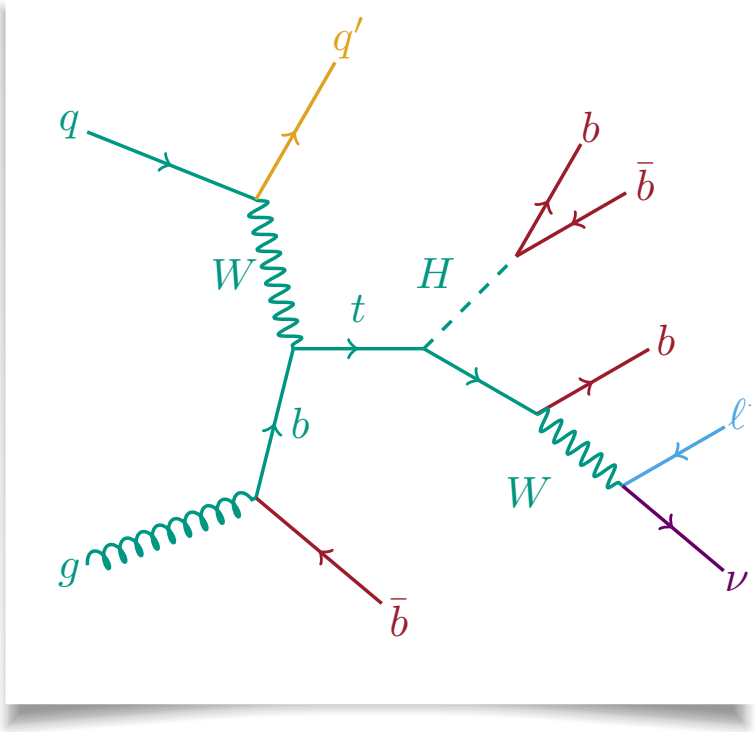

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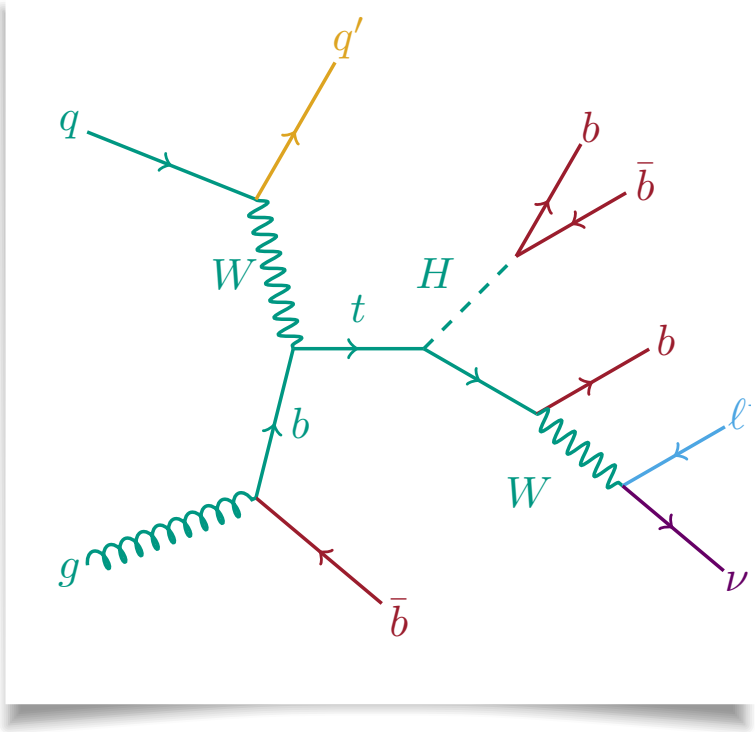

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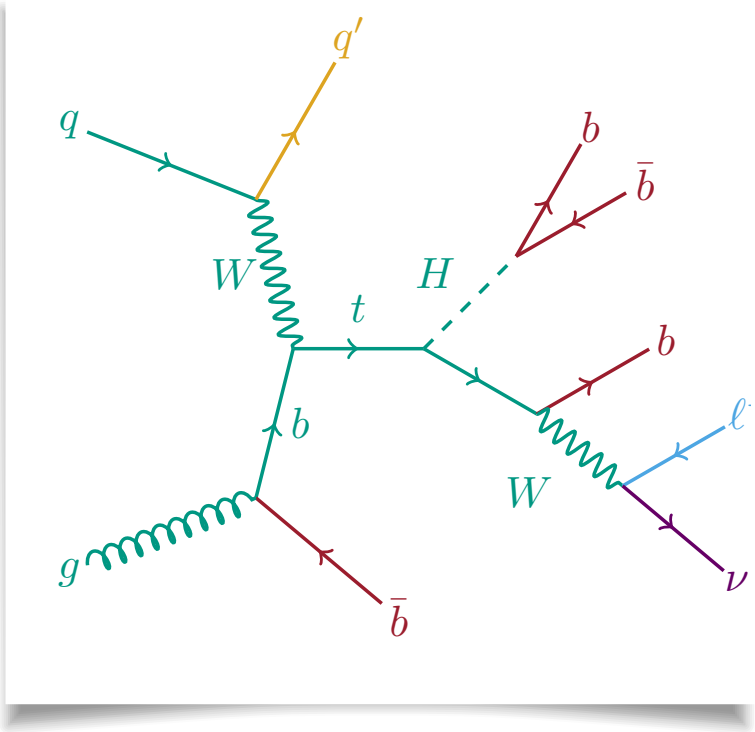

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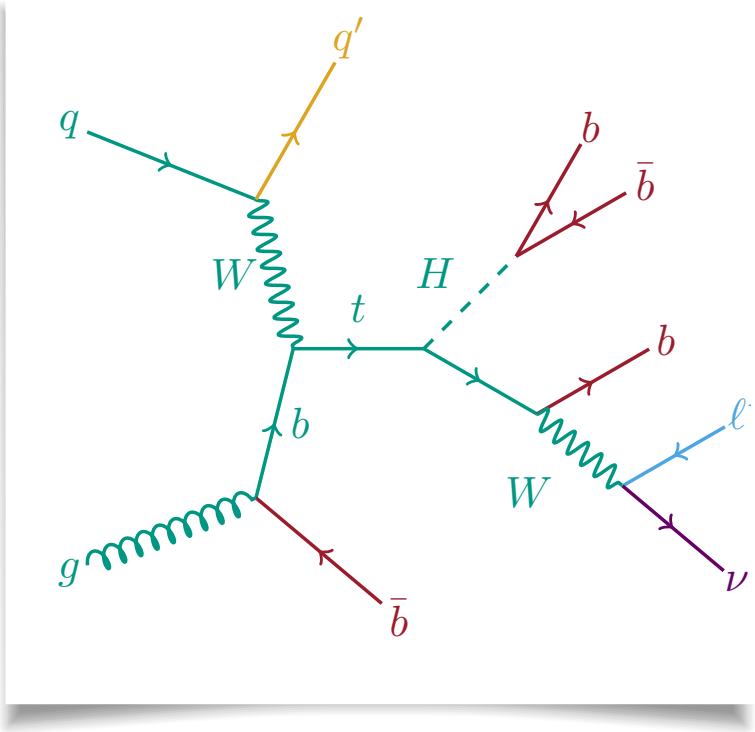


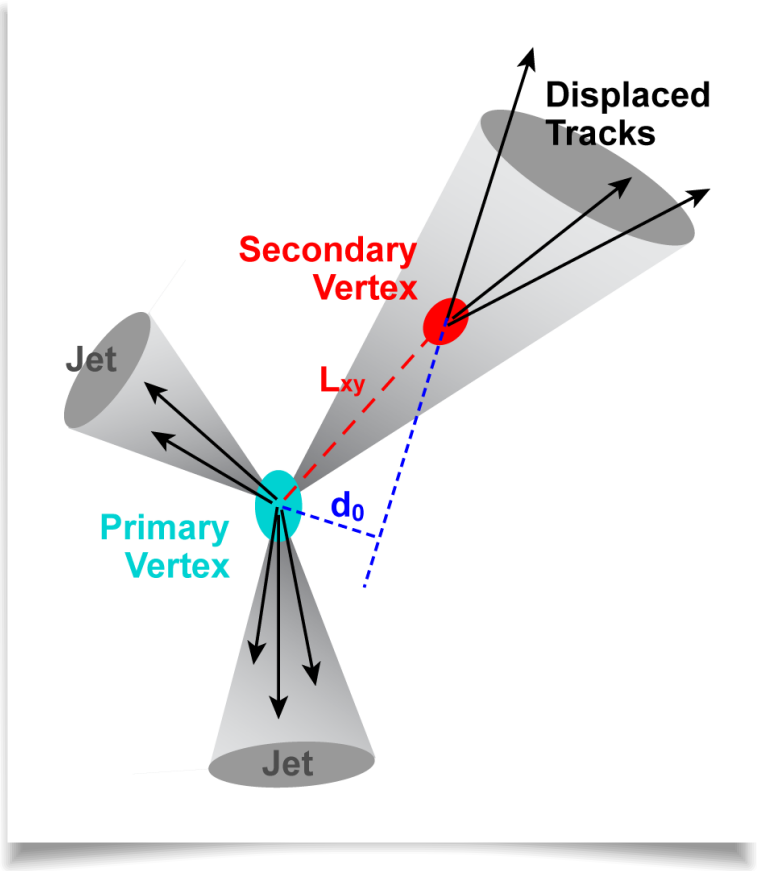

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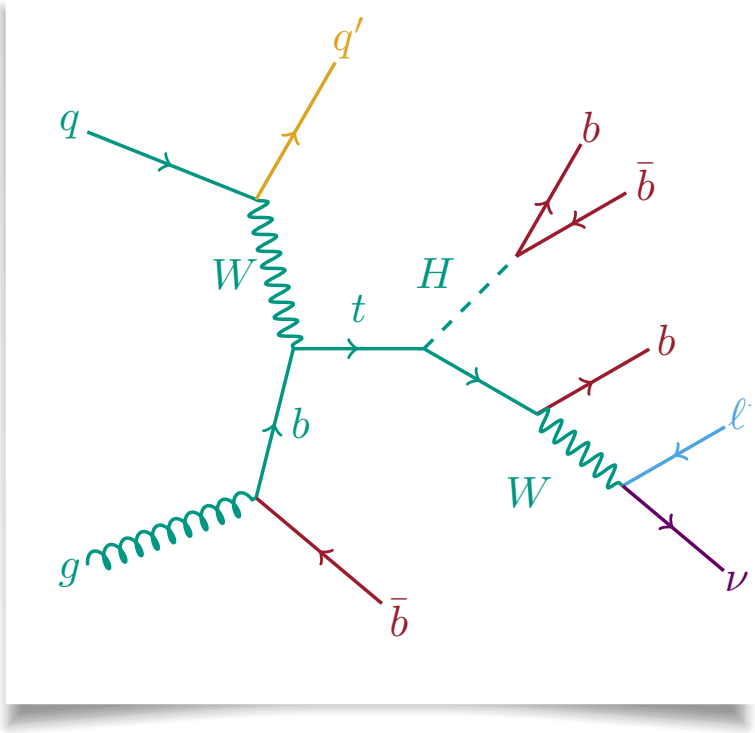


- 3 tag signal region
  - 3 *b*-tags (CSVT)
  - # jets $\geq 4$
  - exactly one muon/electron

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  - 4 *b*-tags (CSVT)
  - # jets $\geq 5$
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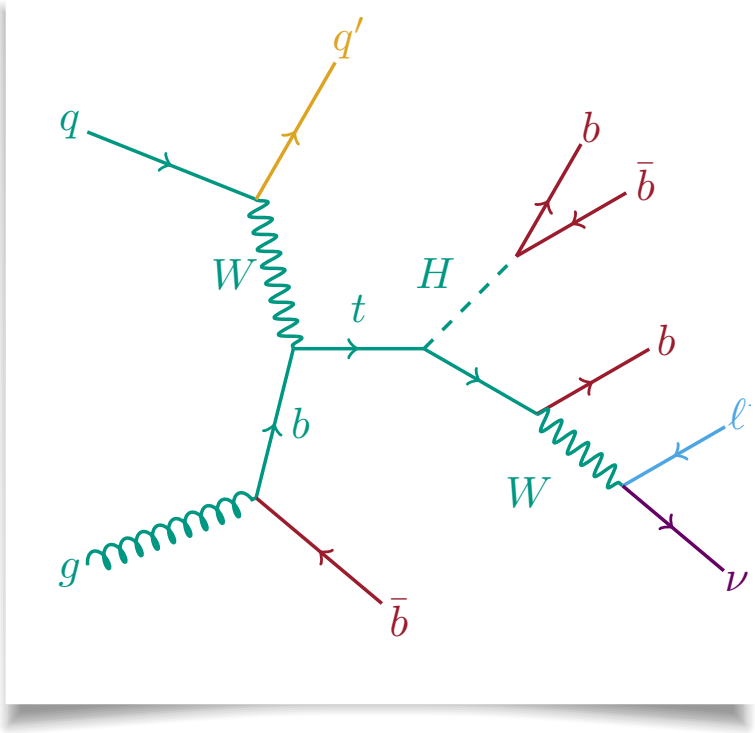


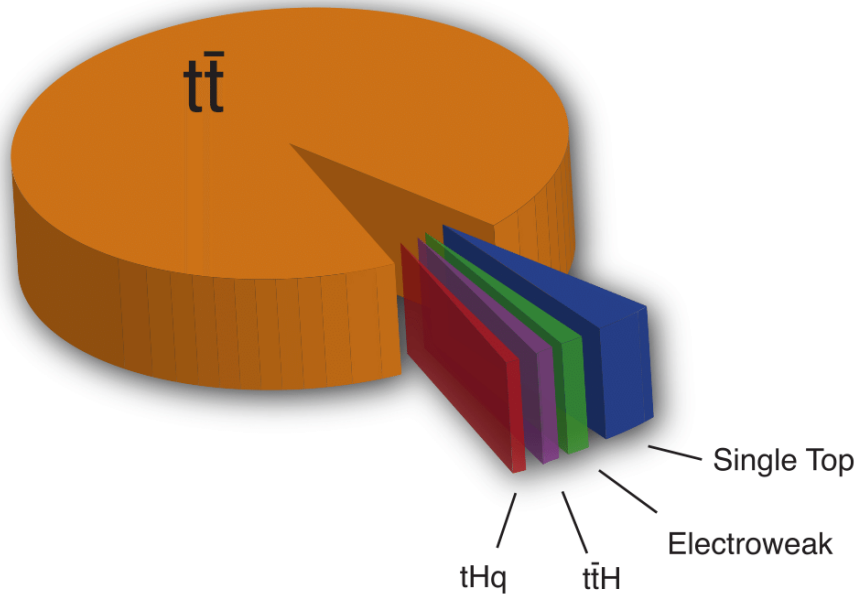

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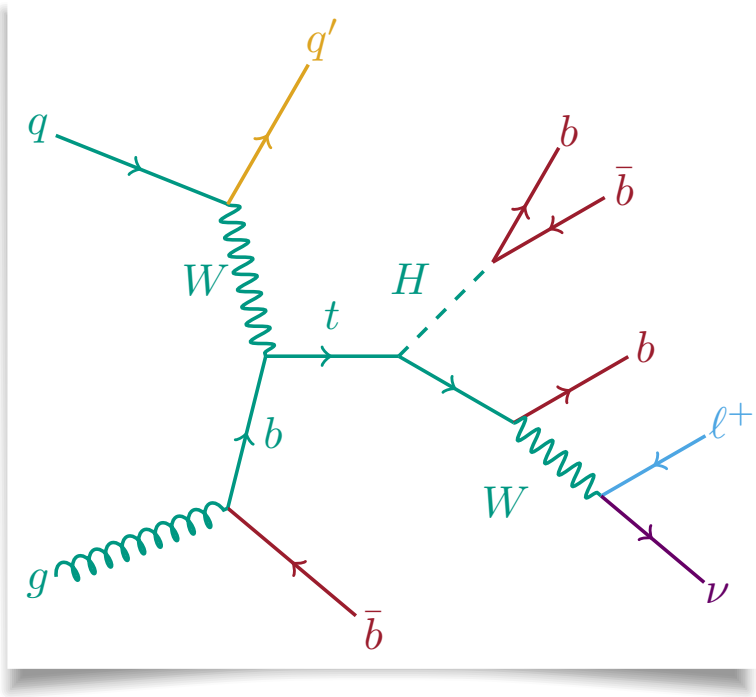


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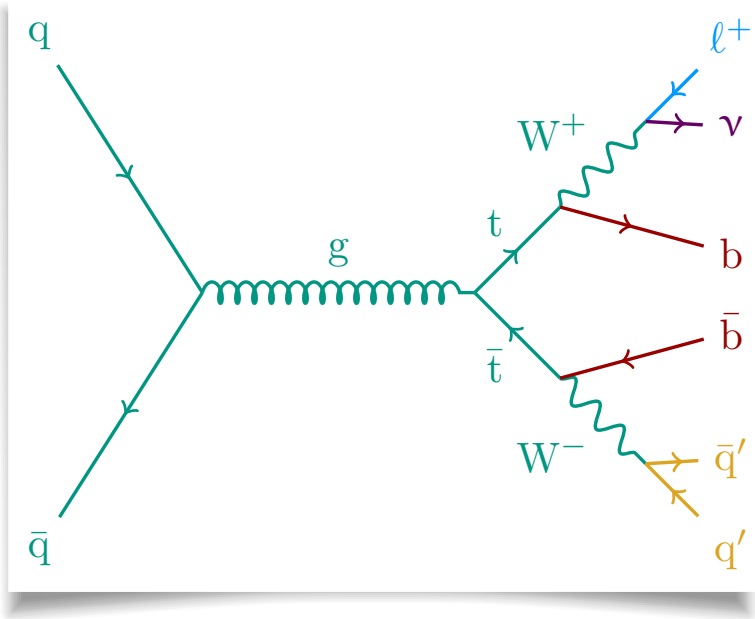

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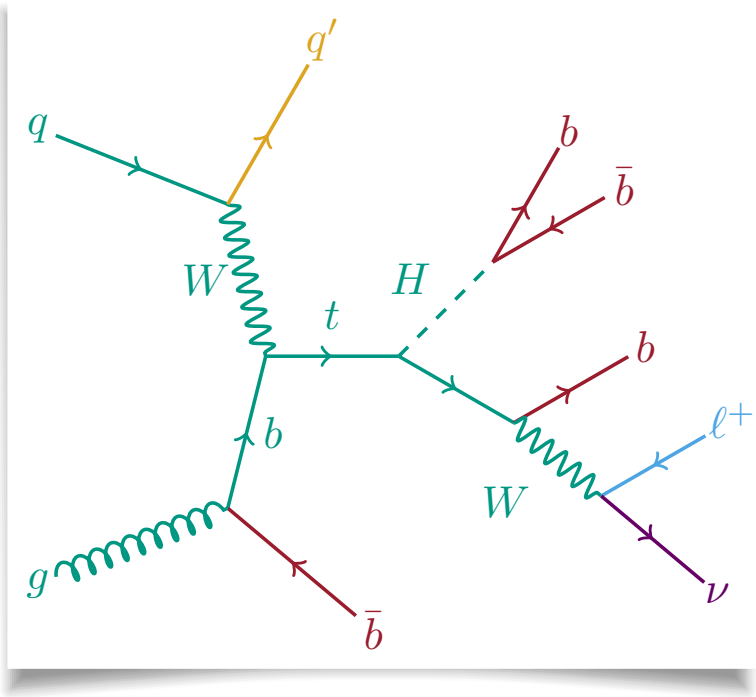


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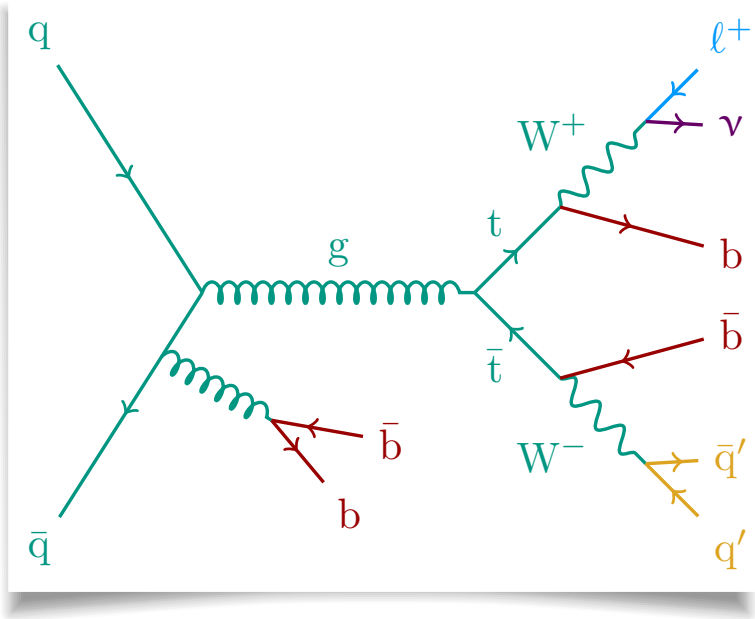

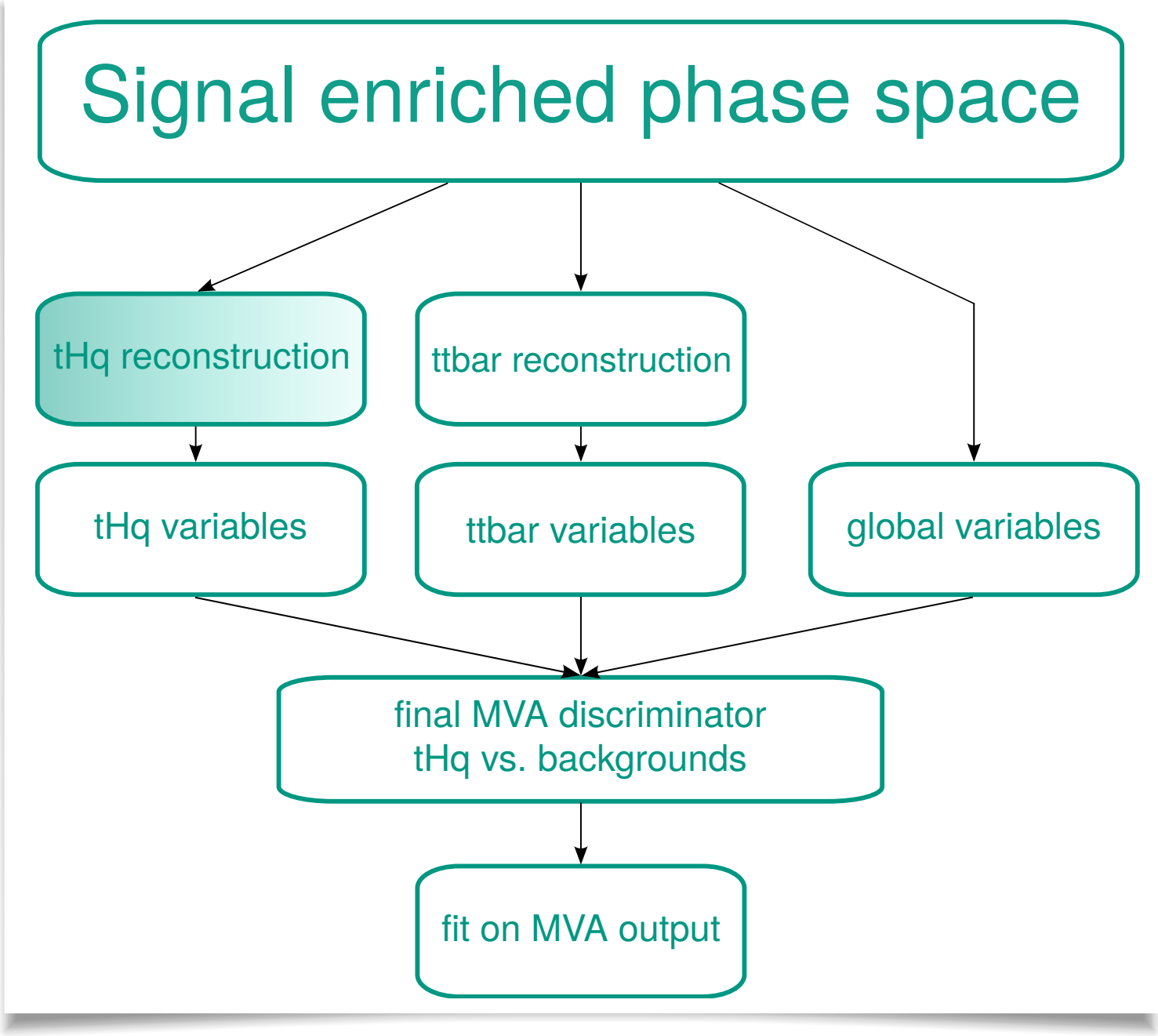
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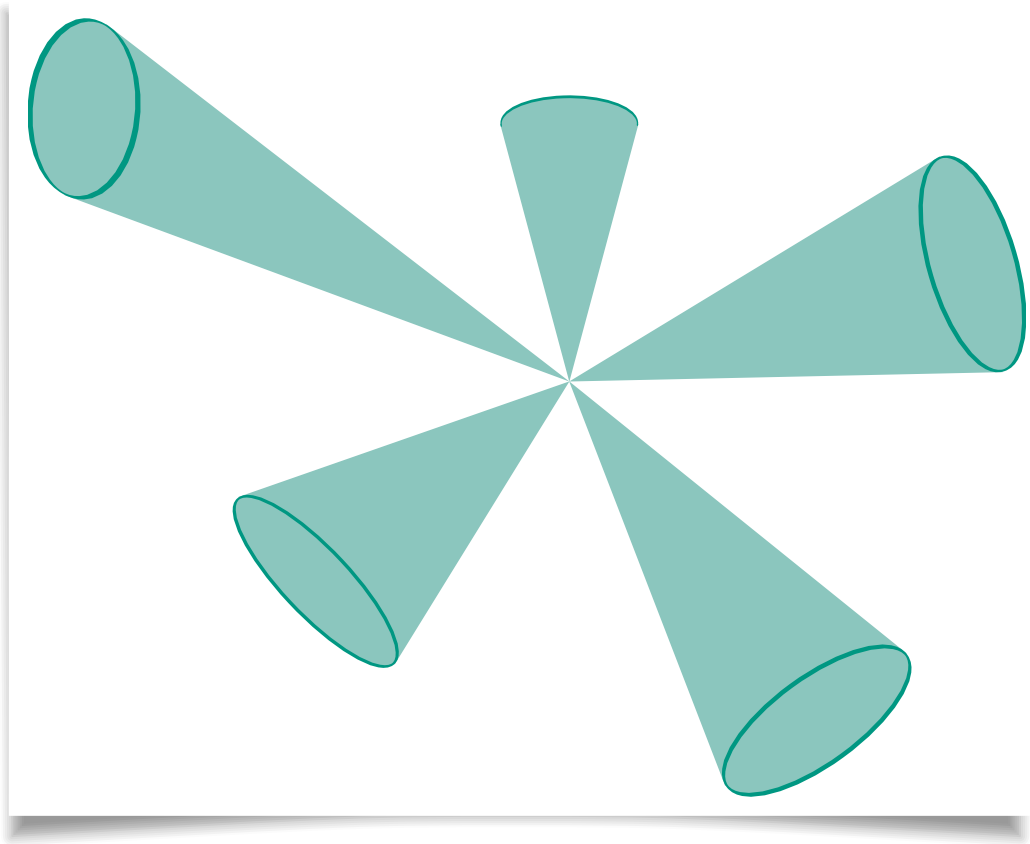
- jet assignment is a combinatorial problem
- use constraints to reduce number of possible permutations
- look at distributions for all possible assignments and all events
- use such variables to find right assignments



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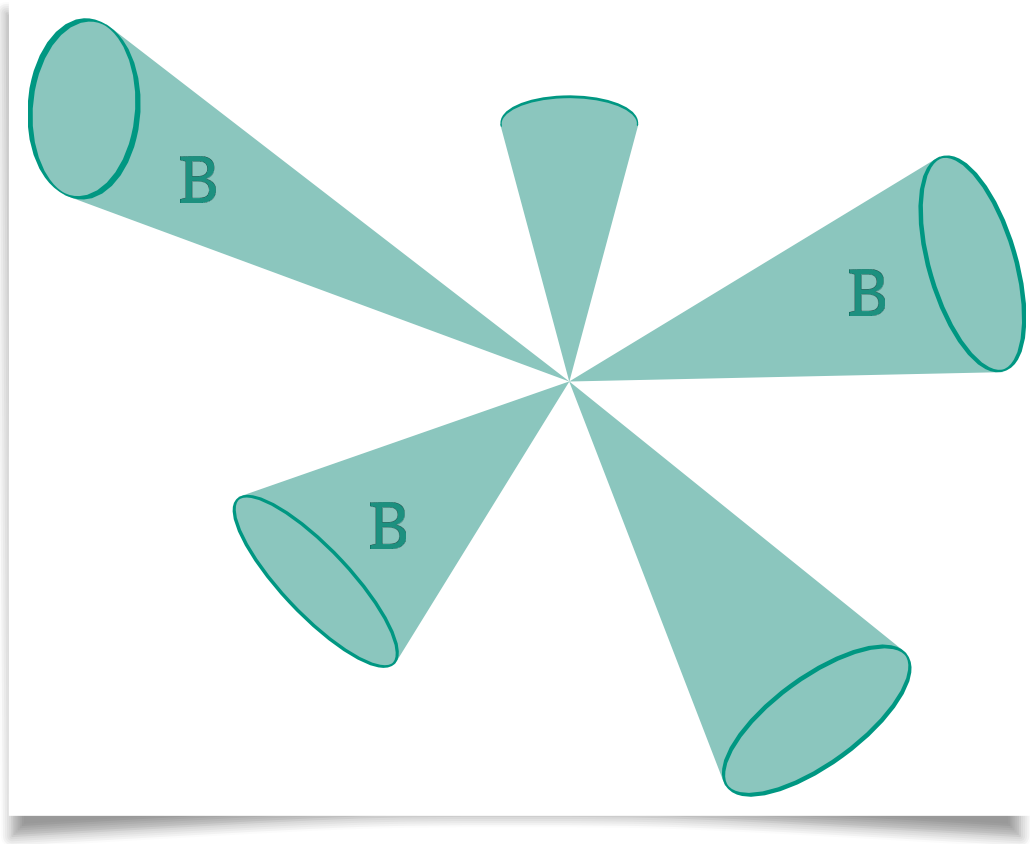

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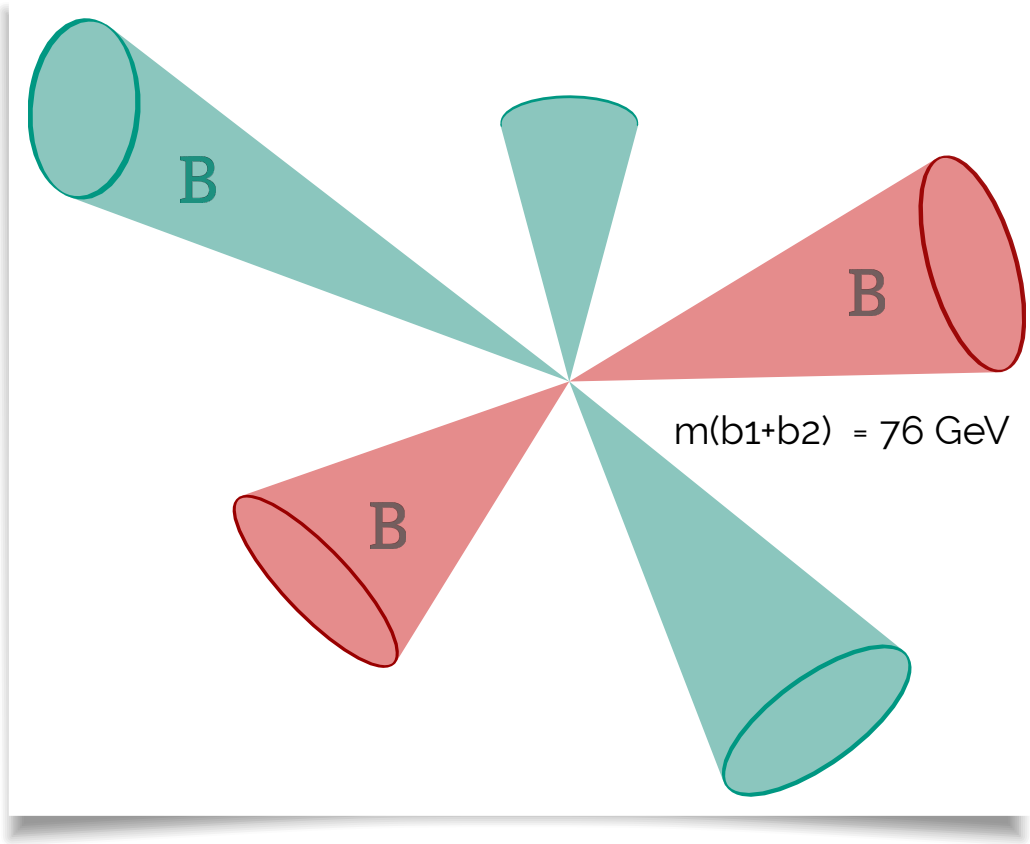

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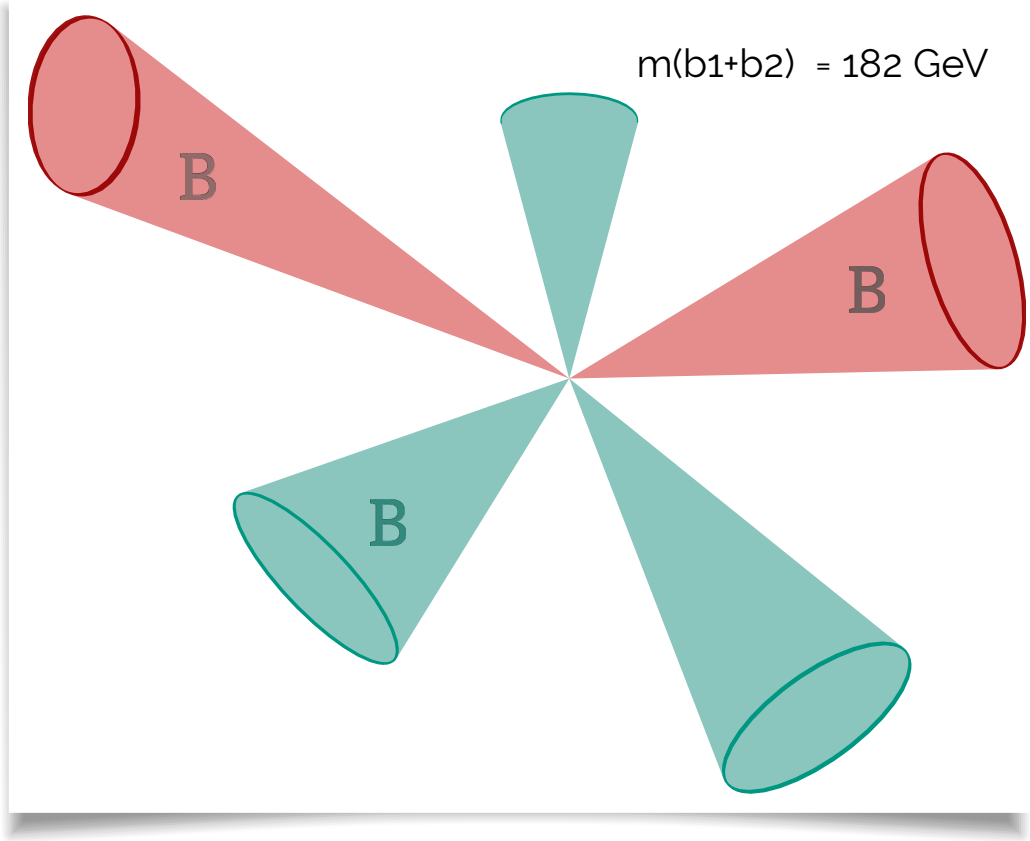

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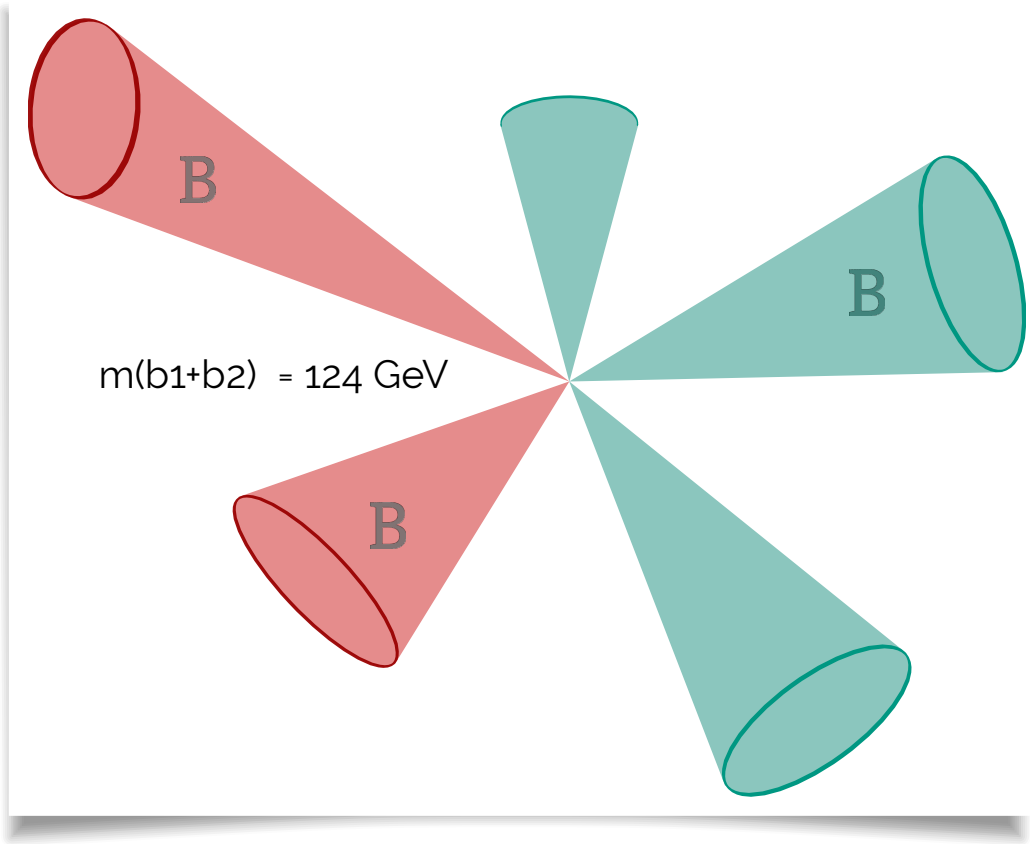

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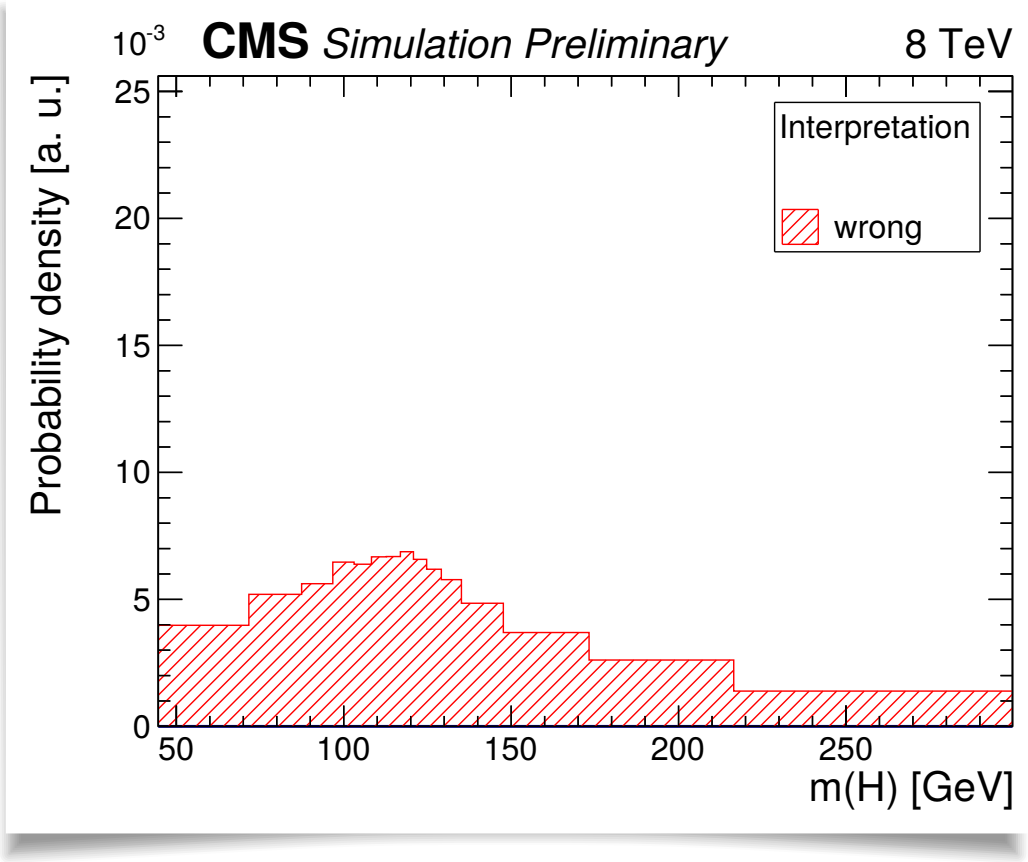

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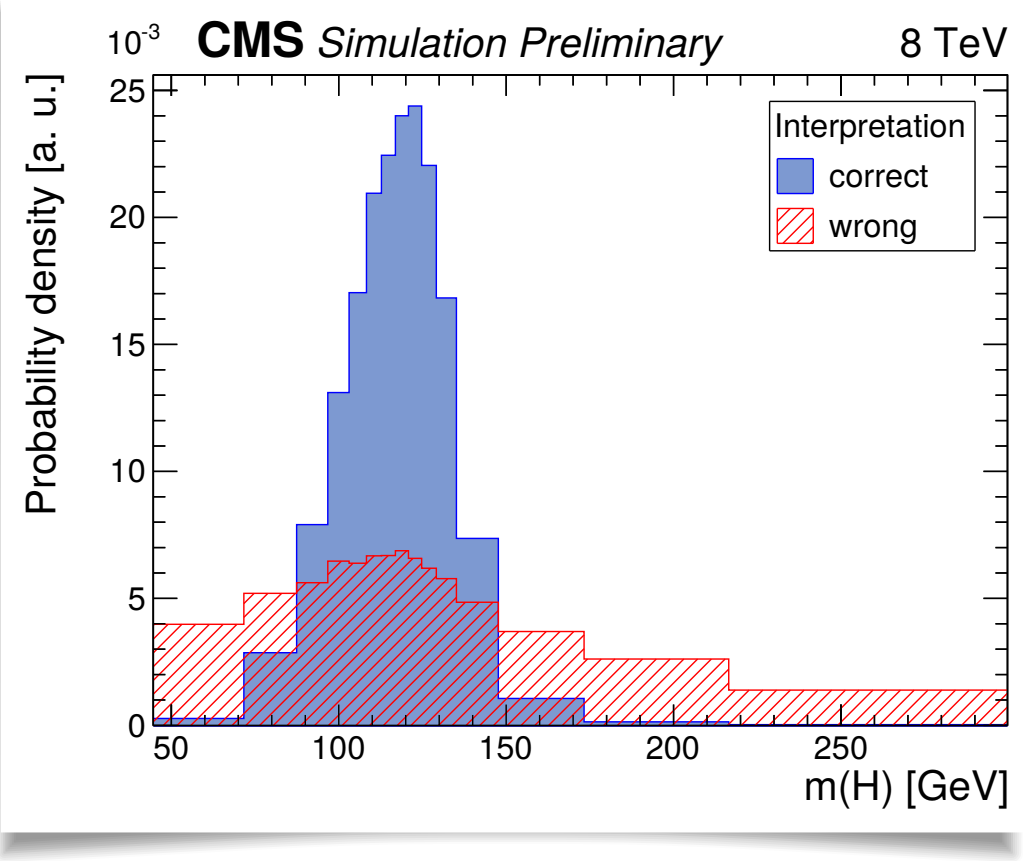
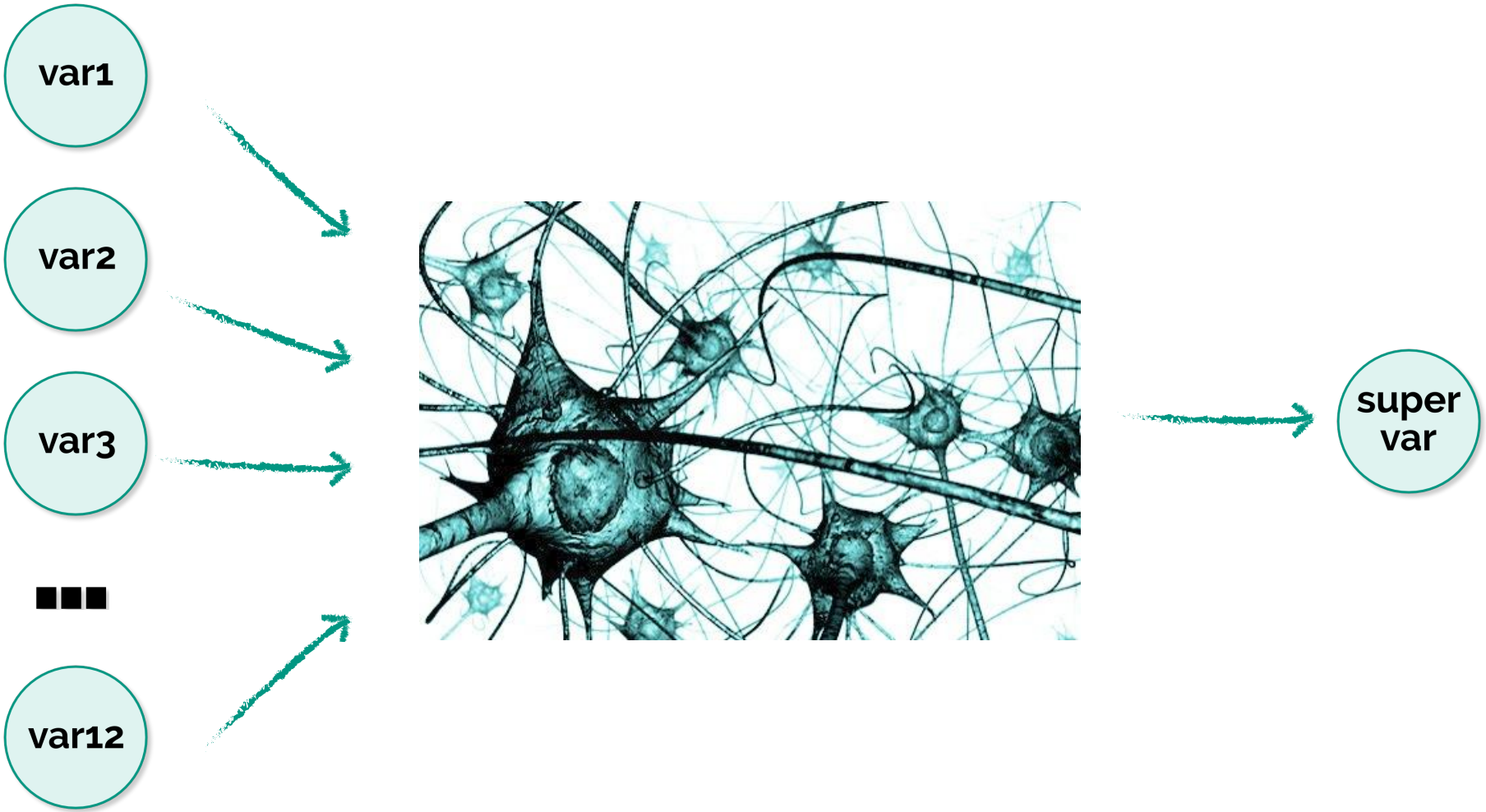


# Neural Nets



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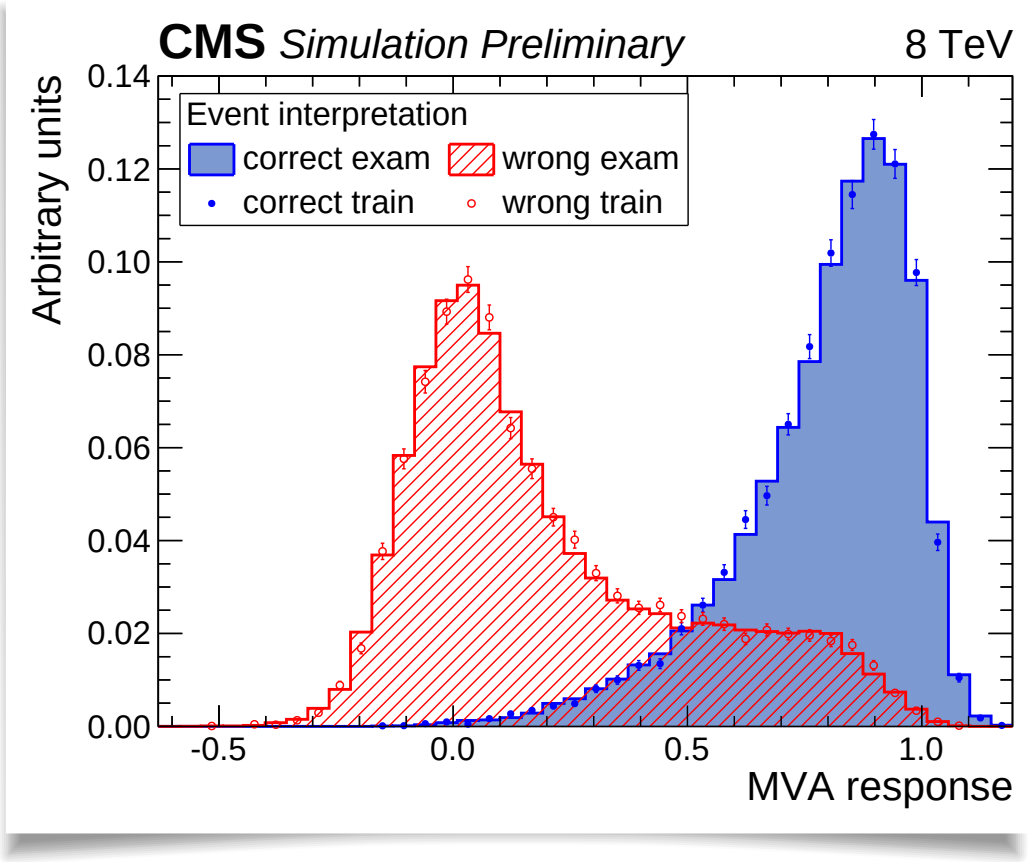

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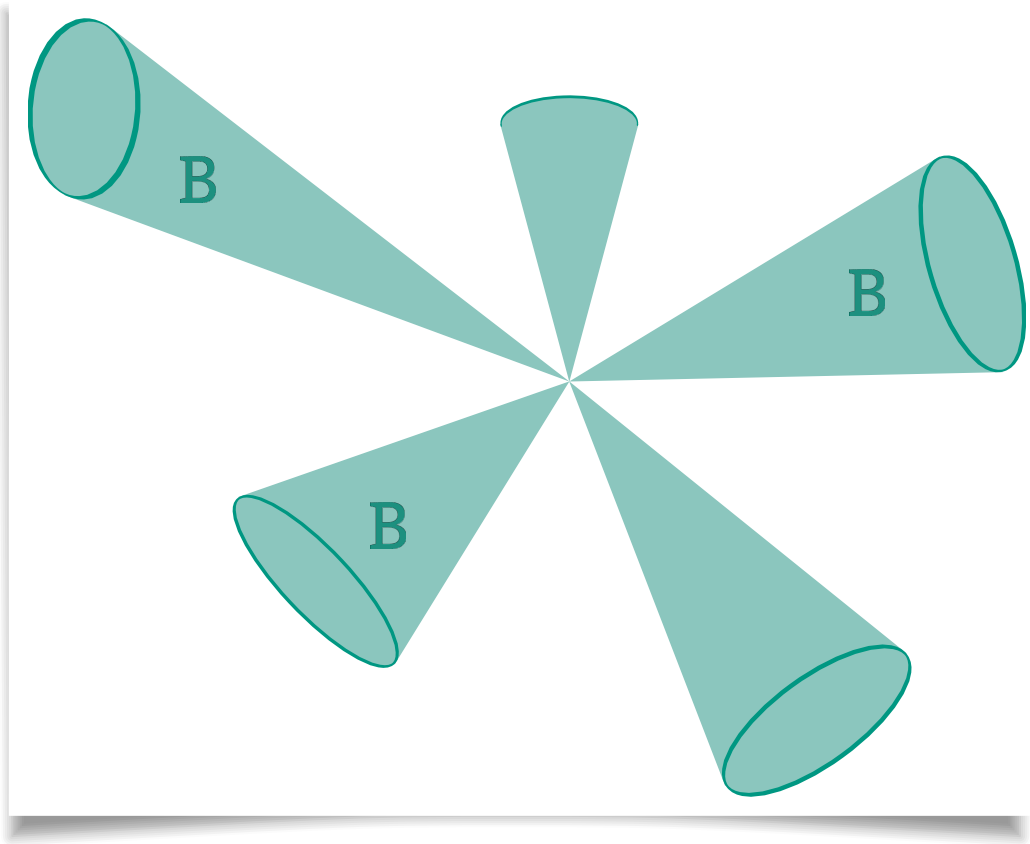

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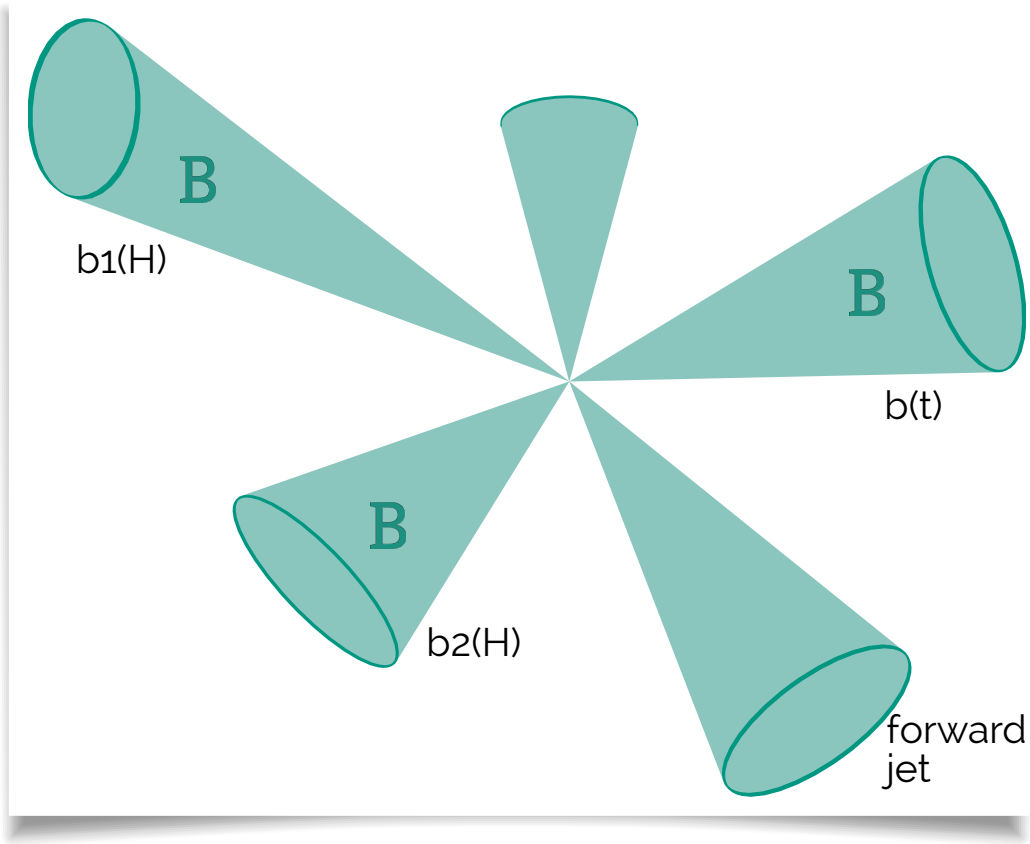

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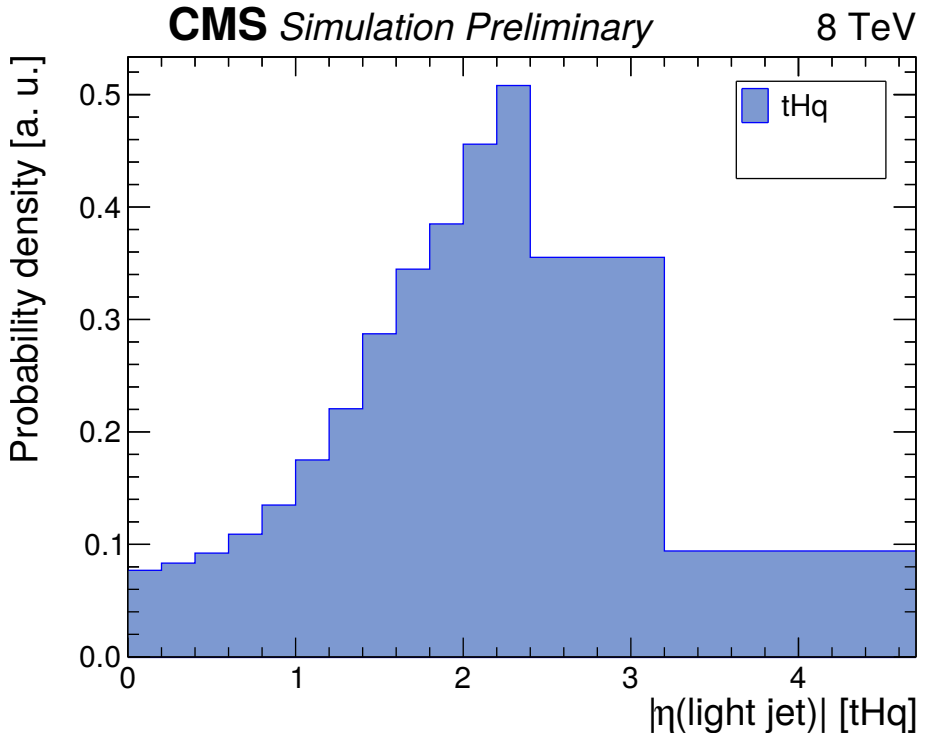

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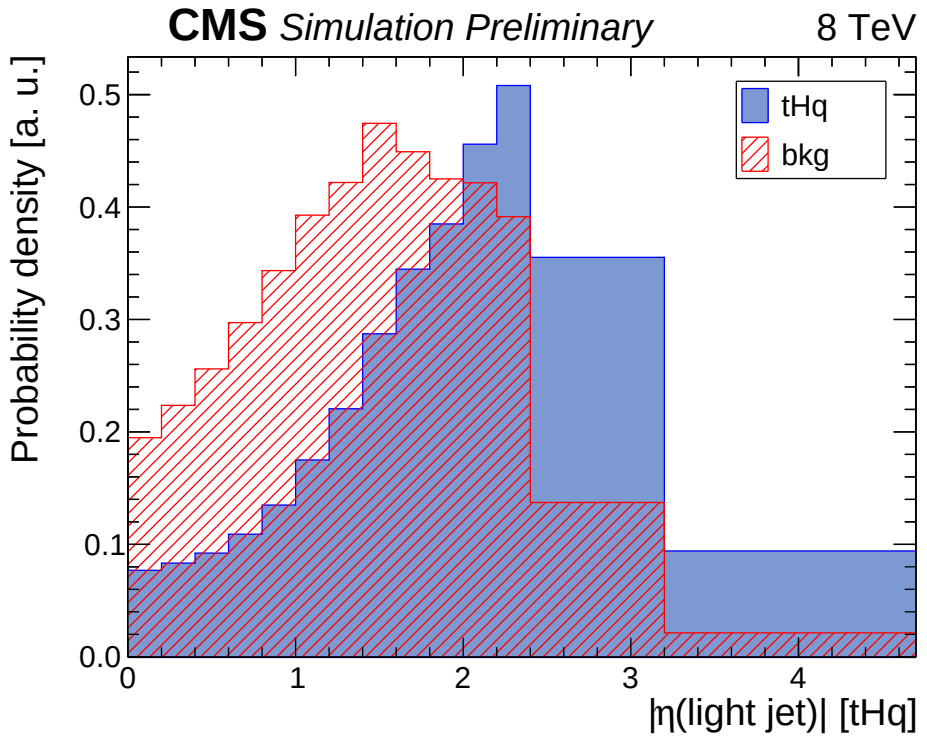

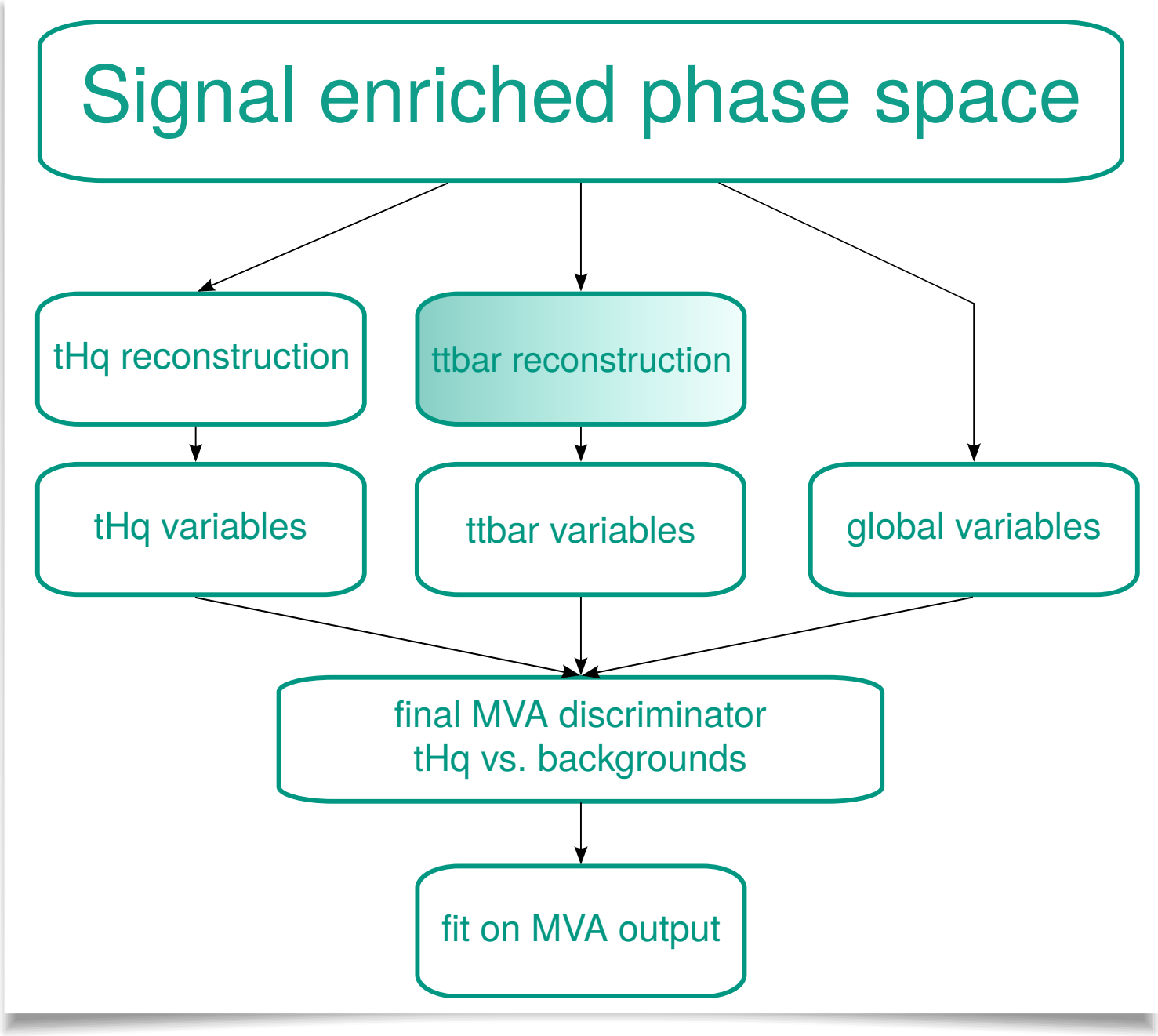
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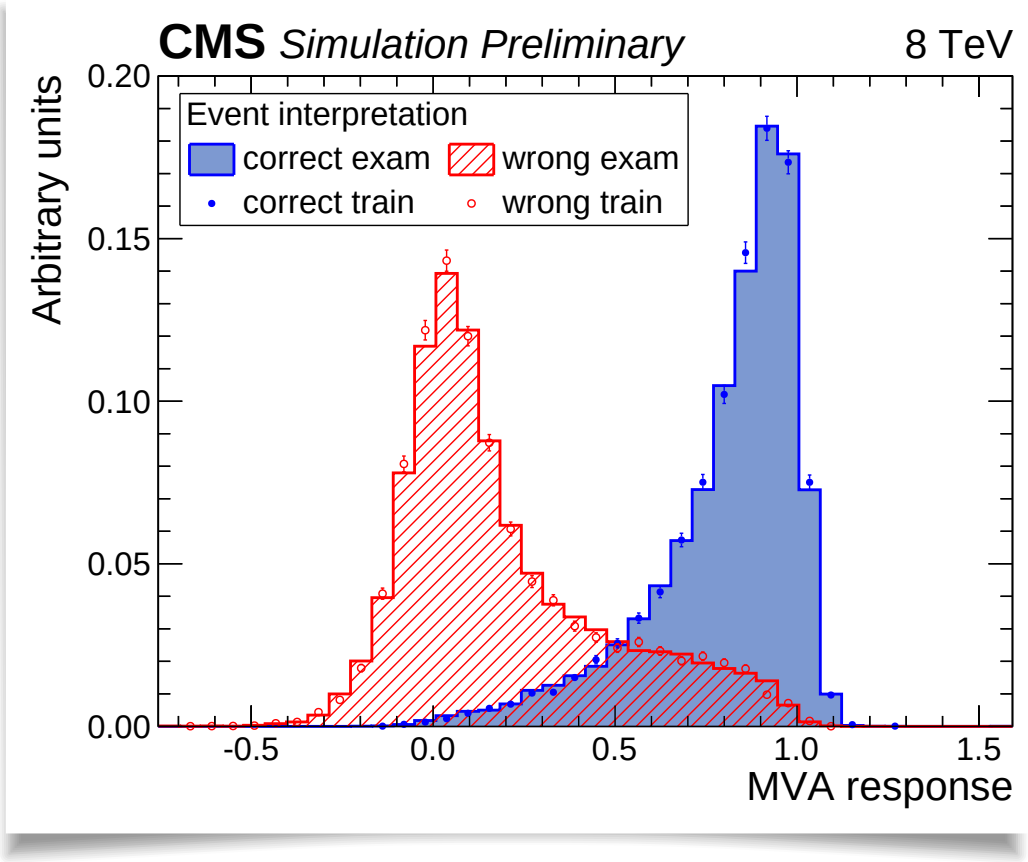

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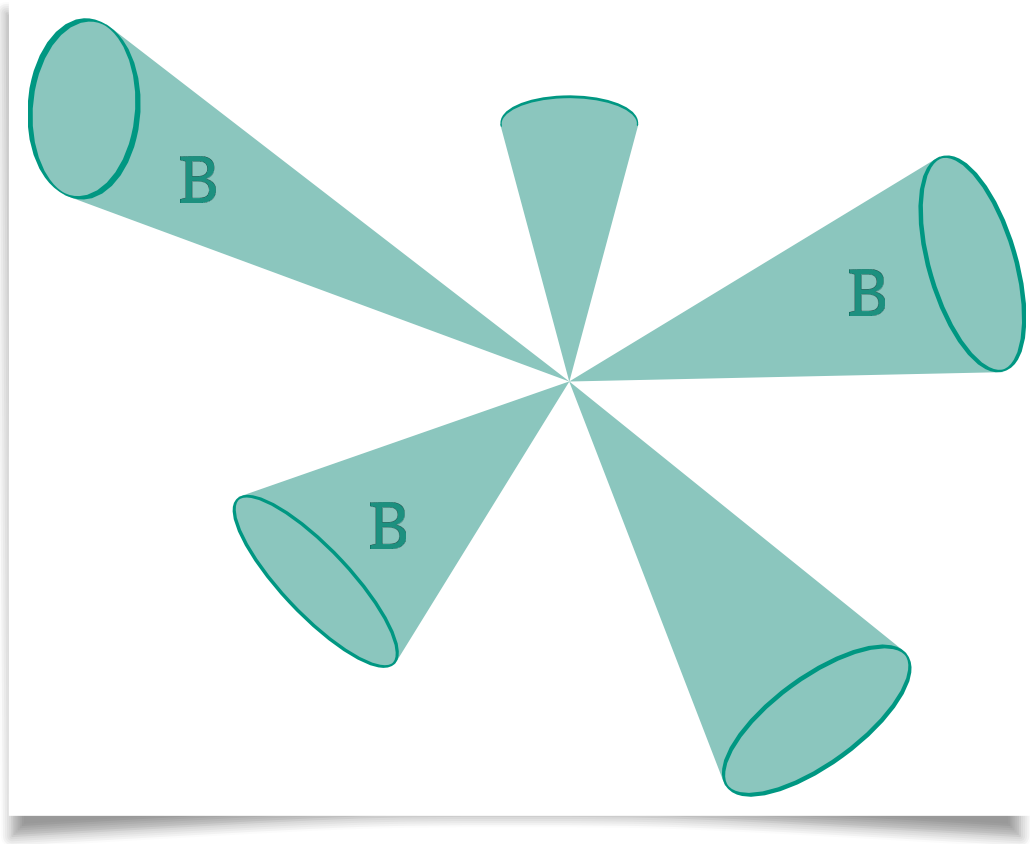

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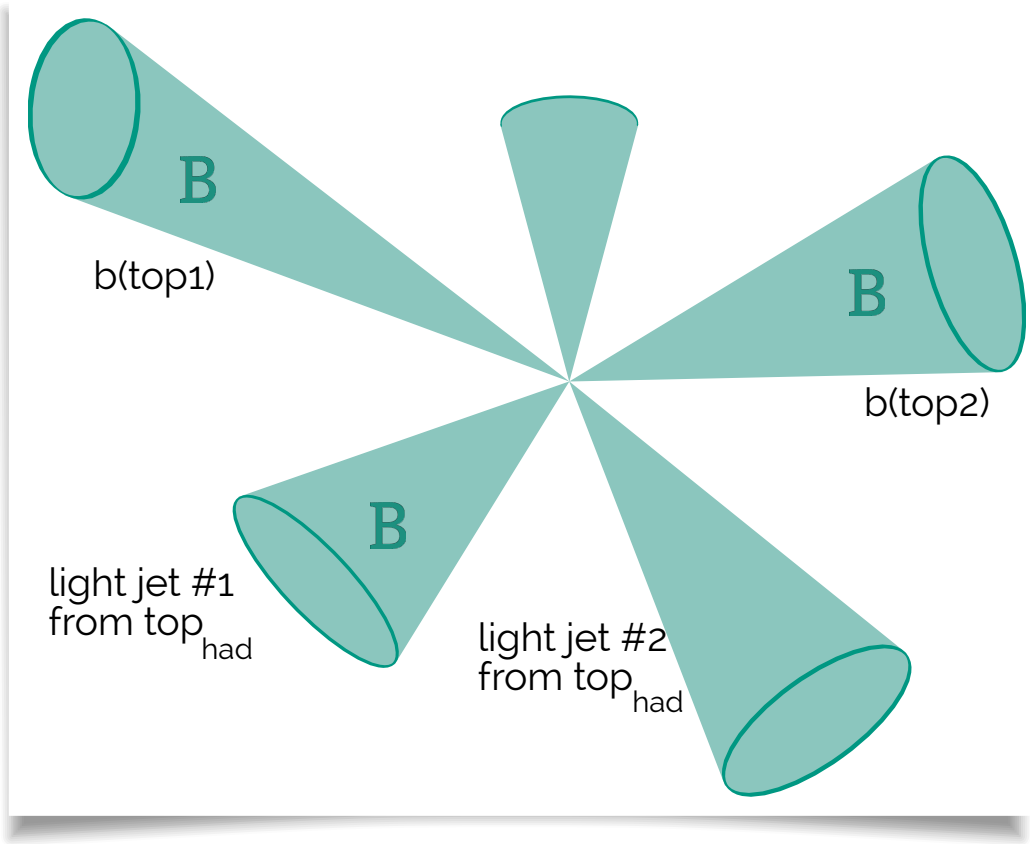

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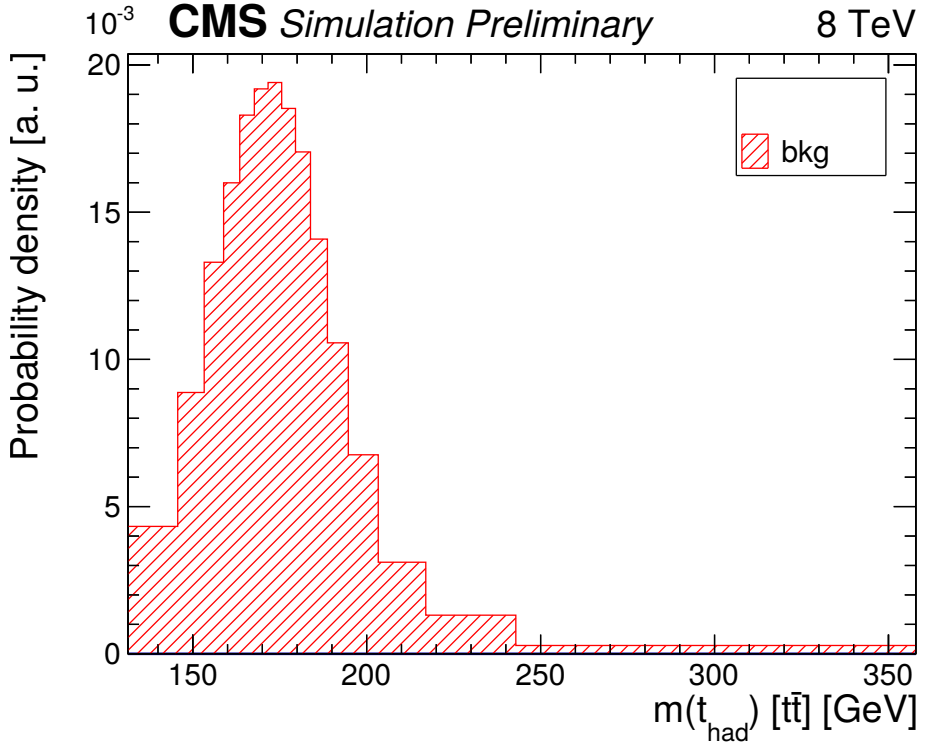
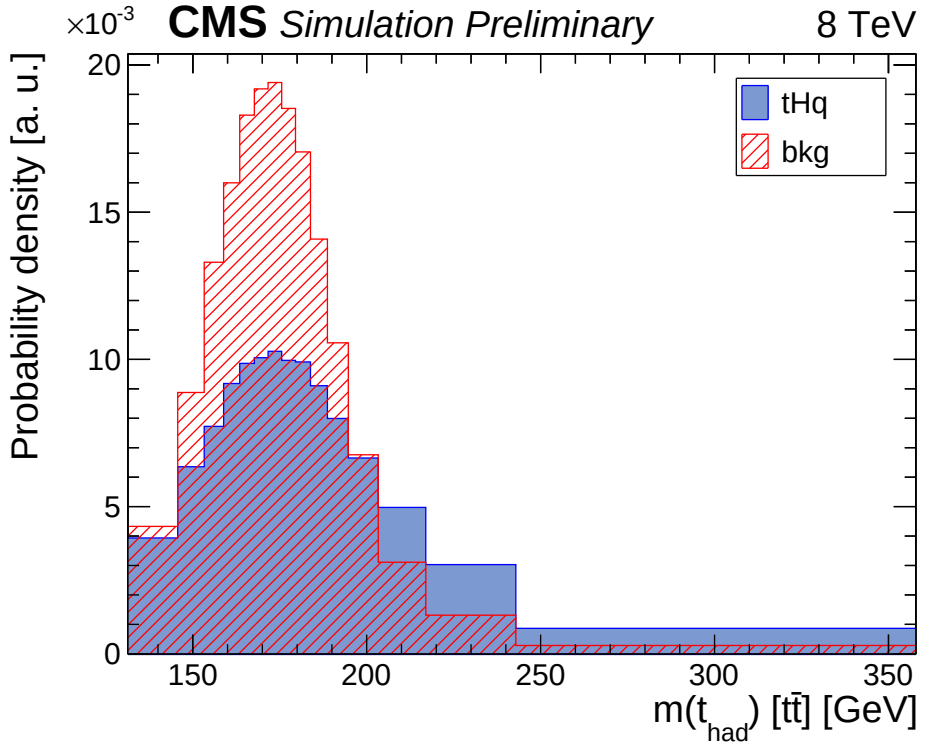


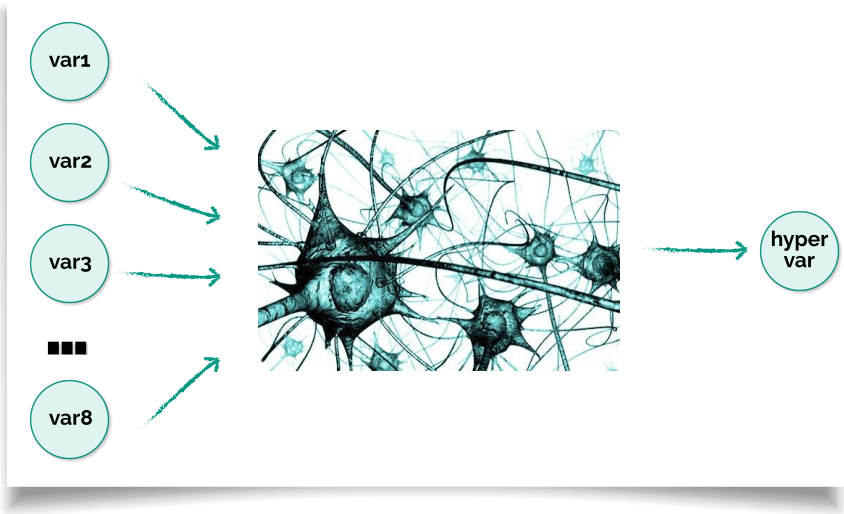
# $t\bar{t}$ reconstruction

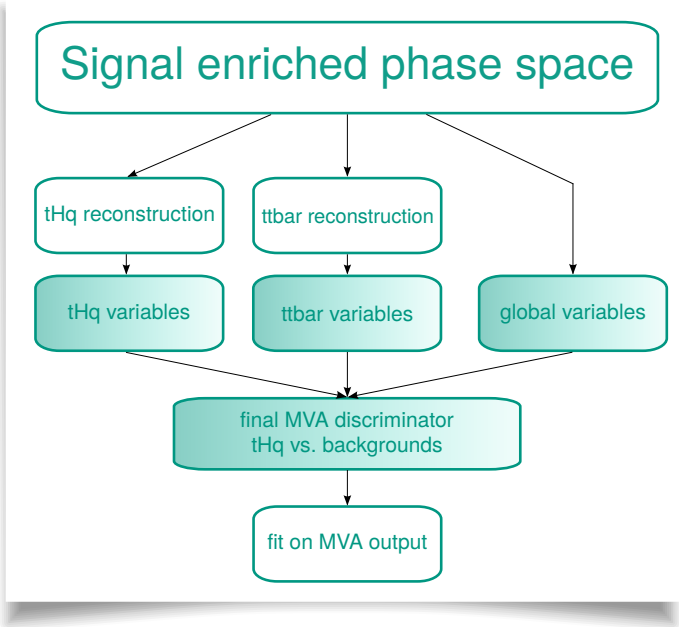
- assignment with highest NN output gets chosen
- build your new objects
- look at object distributions
- variables distinguish between signal and background



# MVA input variables

- obtain variables dependent on the reconstruction, e.g.:
  - $\eta_{q'}$ - pseudorapidity of the light forward jet
  - $m_{t_{had}}$ - mass of the hadronically decaying top quark
  - ...
- additionalyl reconstruction-independent lepton charge used
- train MVA to separate signal from background



# MVA input variables

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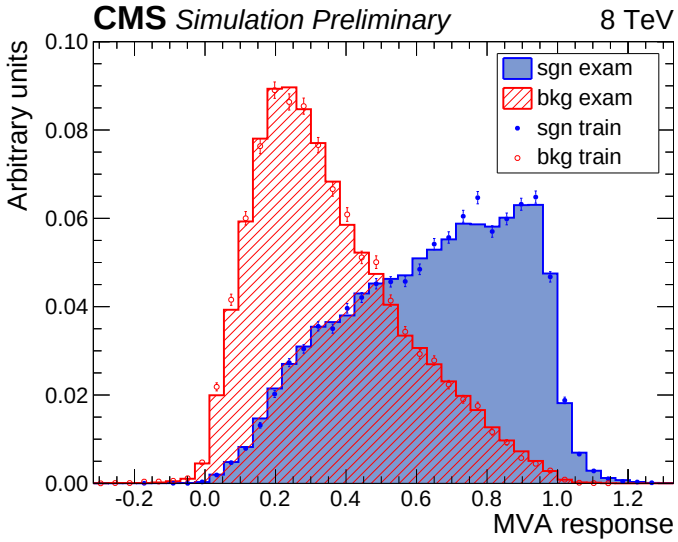
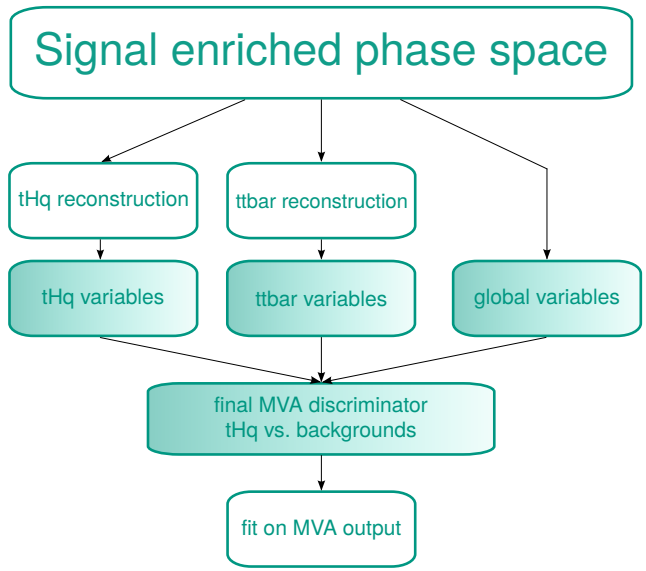
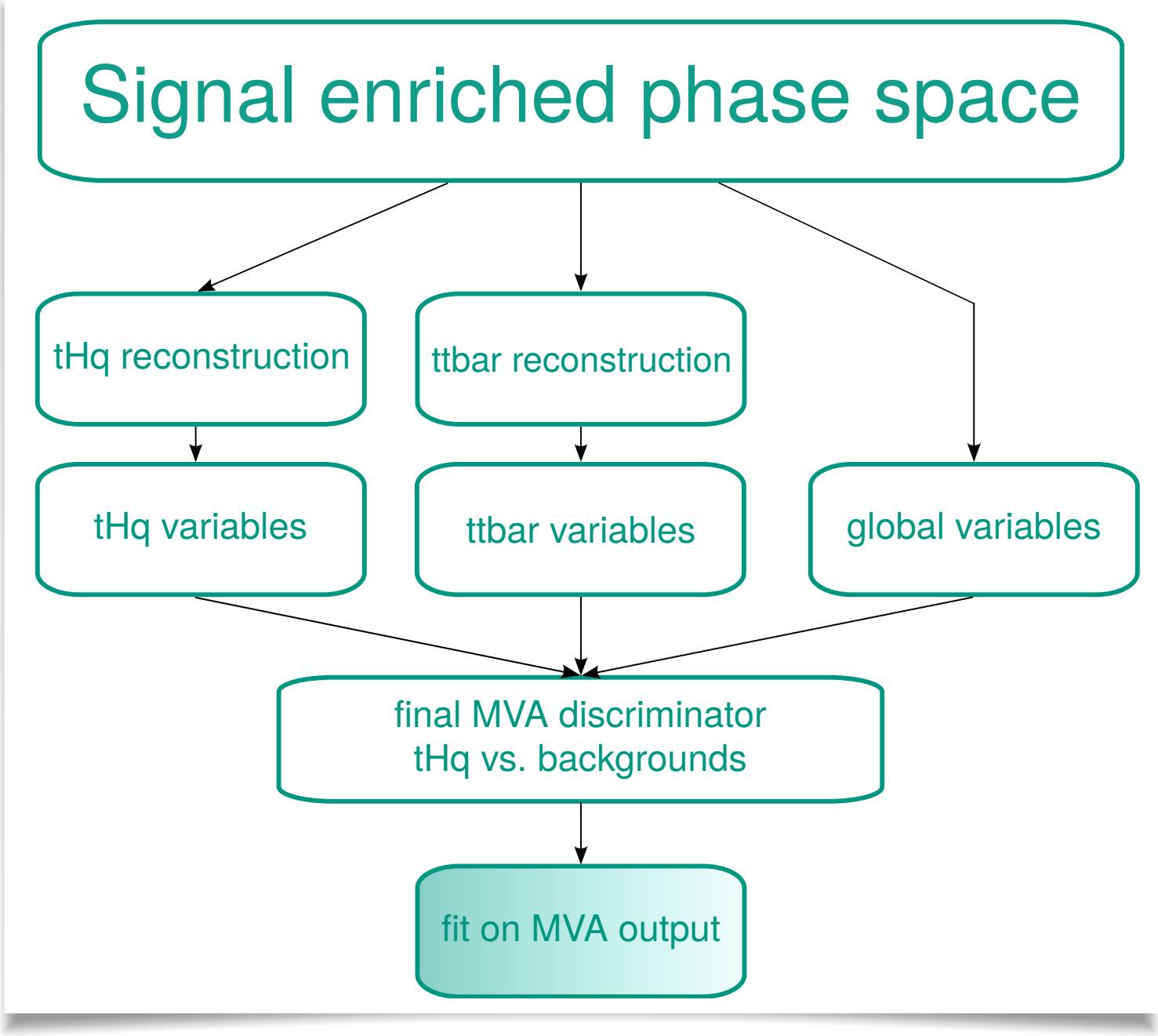
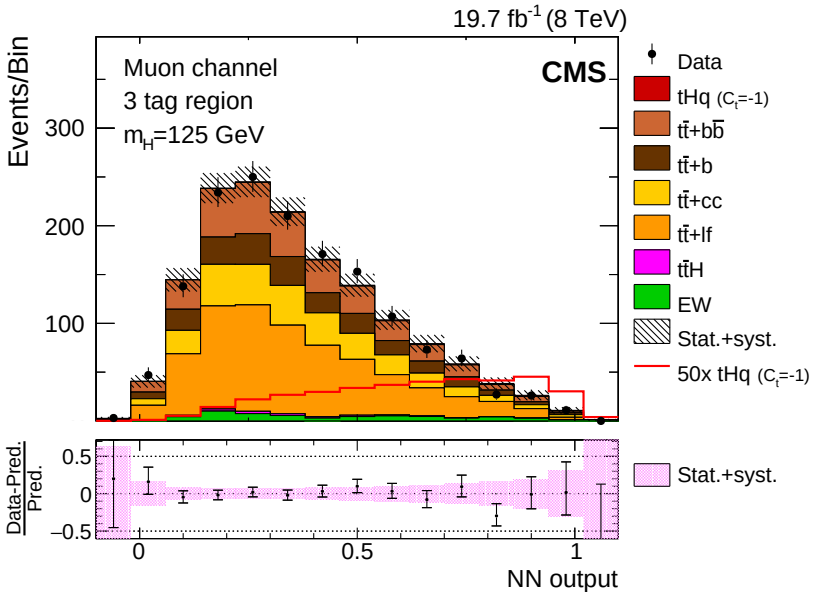


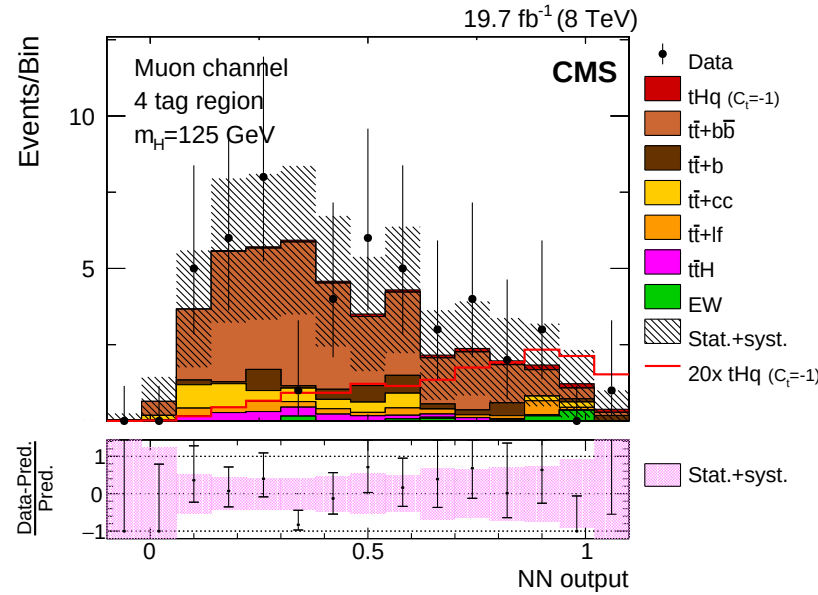




Signal enriched phase space
tHq reconstruction
ttbar reconstruction
tHq variables
ttbar variables
global variables
final MVA discriminator
tHq vs. backgrounds
fit on MVA output

# Classification MVA

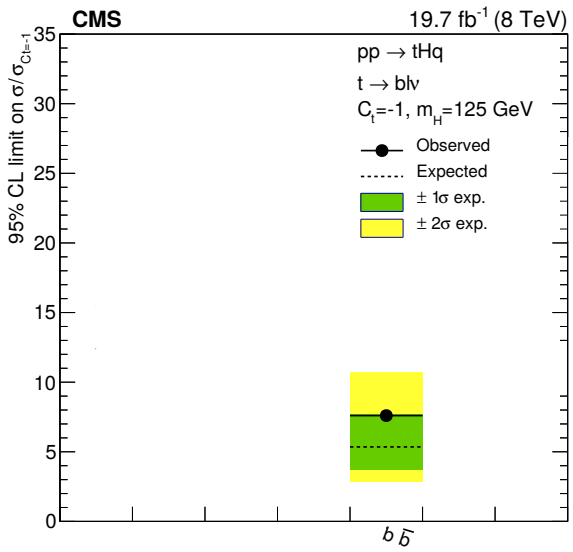
- fit both signal regions and both channels simultaneously
- systematic uncertainties implemented either as rate or shape uncertainties
  - largest impact from $Q^2$ scale and jet energy scale



# Limits

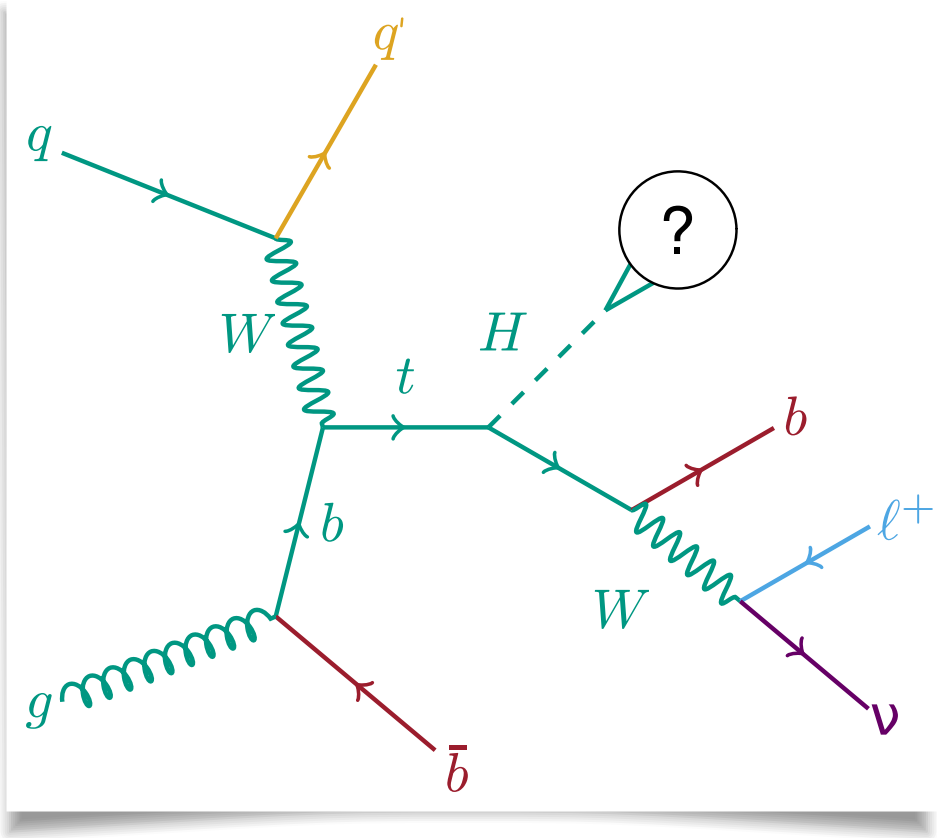
- set limits on tHq with $H \to b\bar{b}$ and $\kappa_t = -1$
- exclude production cross section larger than 1.77 pb at 95% C.L.



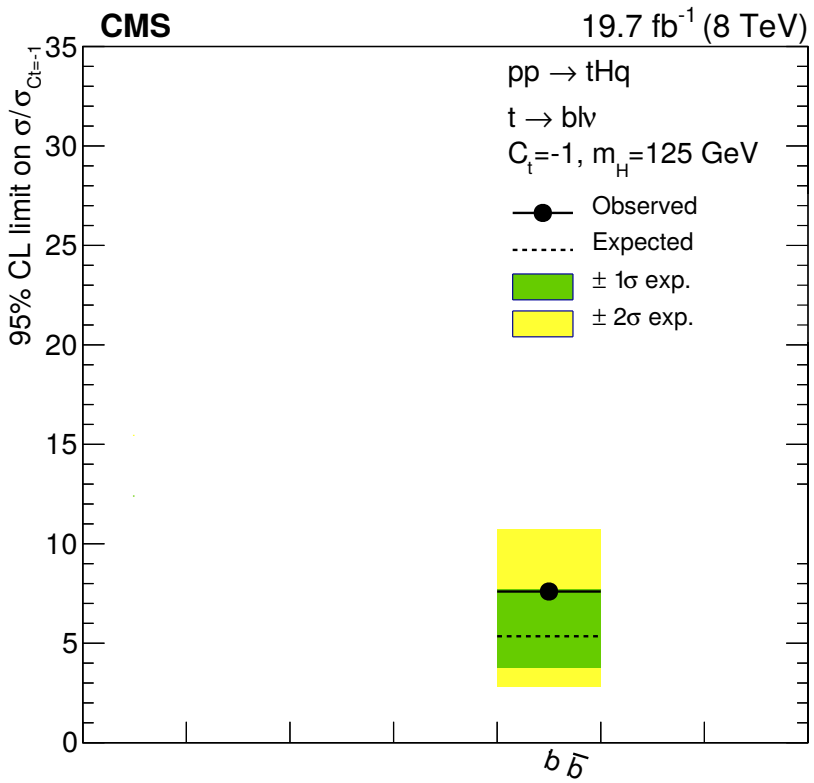

| | Expected* | Observed* |
|---|---|---|
| **MC-driven** | $\mathbf{5.14^{+2.14}_{-1.44}}$ | **7.57** |

* in units of $\sigma/\sigma_{y_t=-1}$

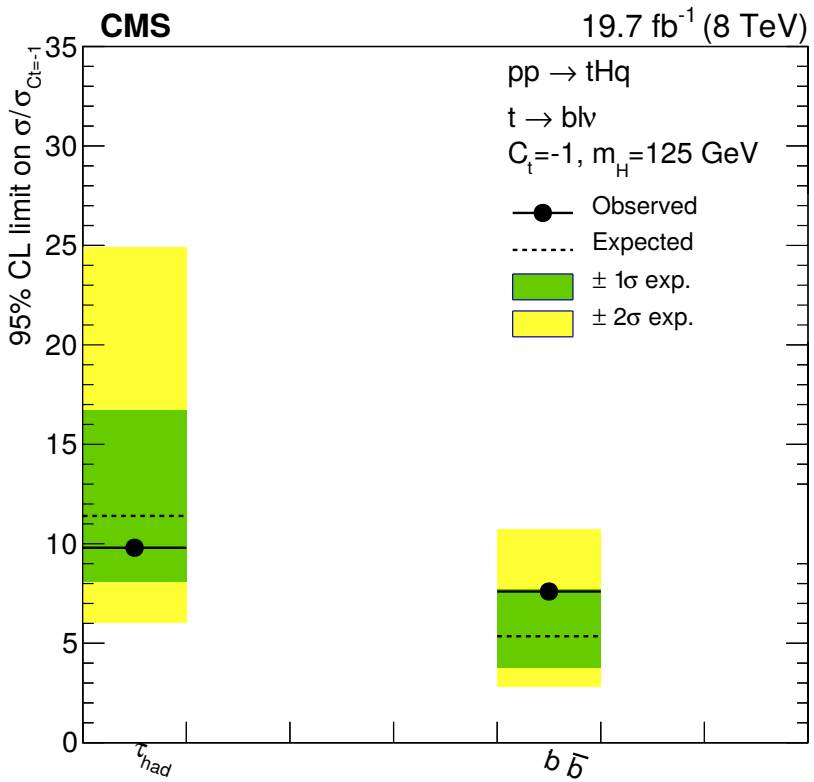
# Other Channels



# Other Channels

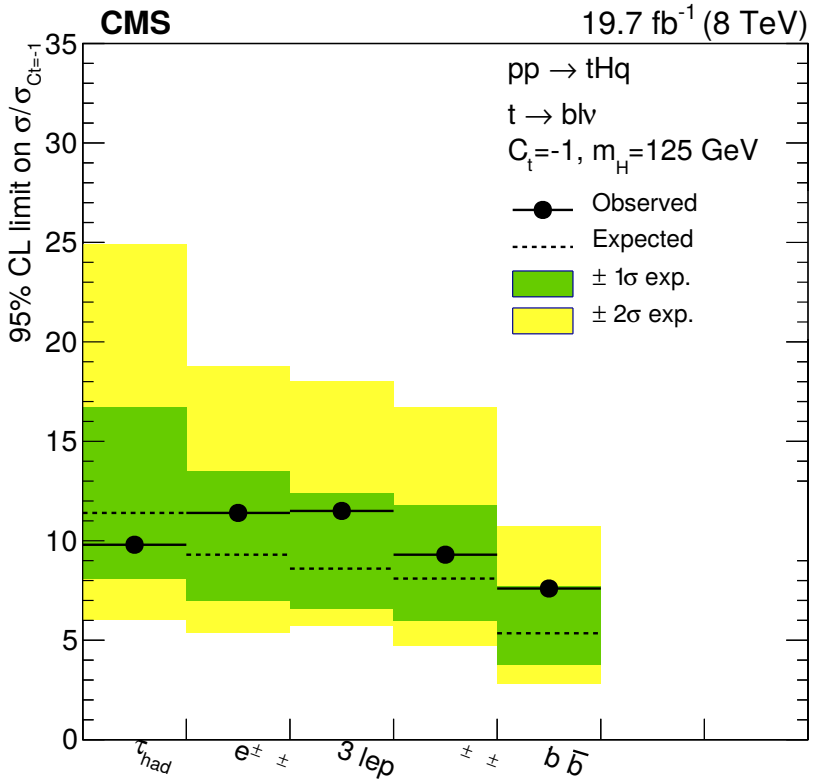


# Other Channels



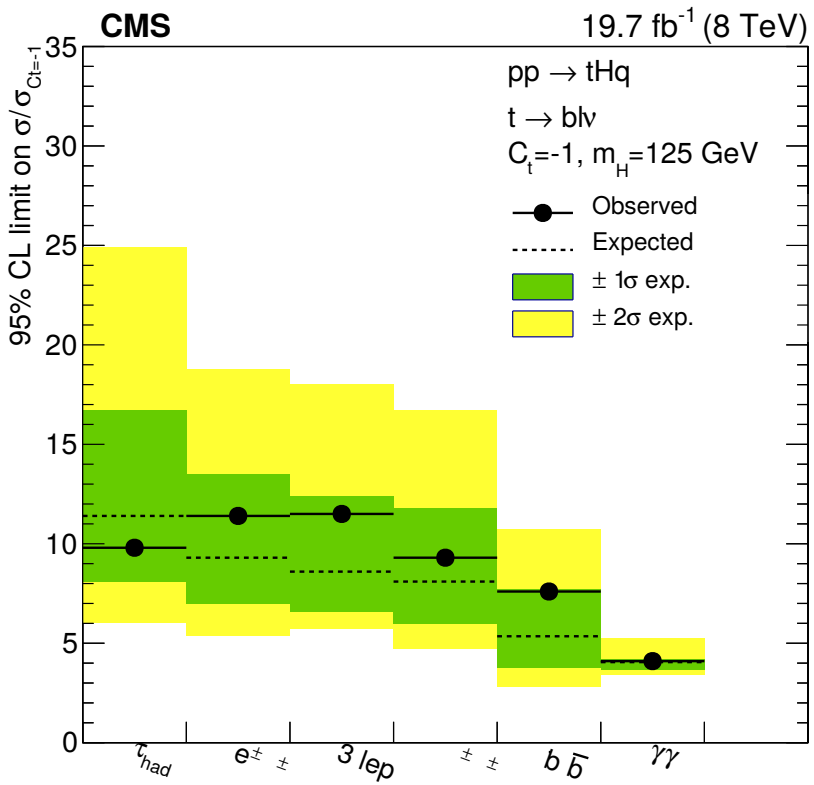

- $\tau_{lep}\tau_{had}$
  - using the $e\mu\tau_{had}$ or $\mu\mu\tau_{had}$ channel
  - expects $\approx$ 10 events each

# Other Channels



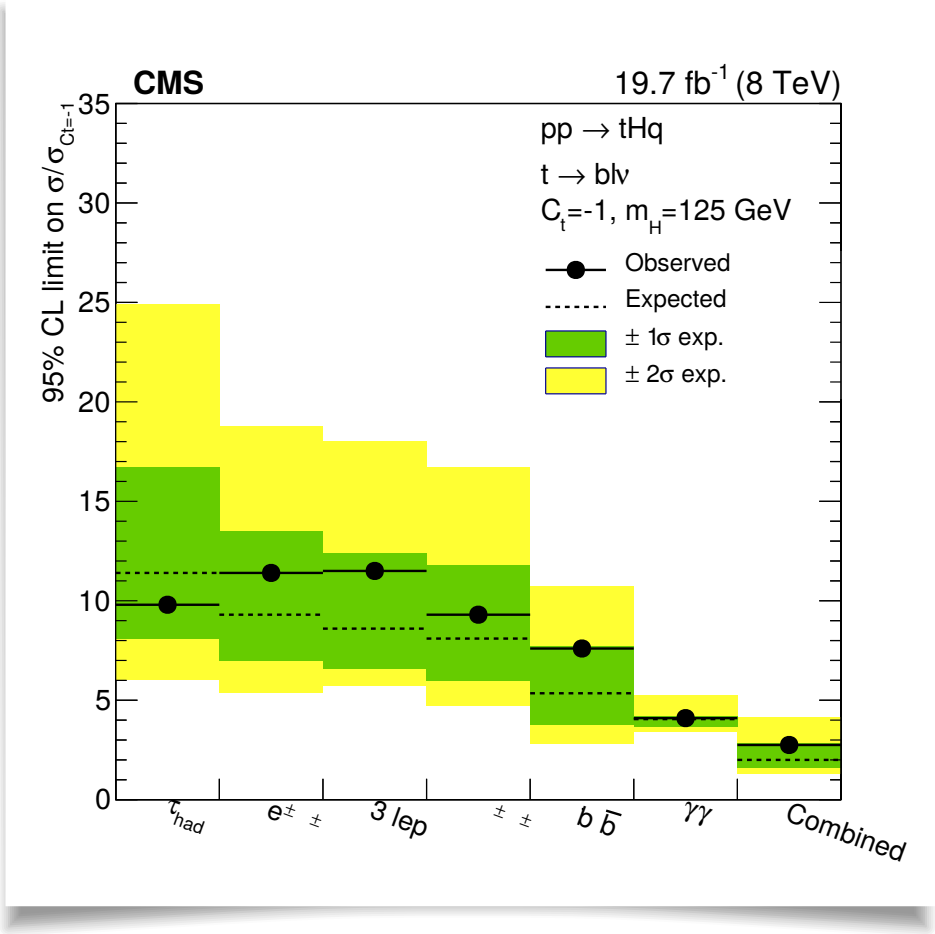

- $\tau_{lep}\tau_{had}$
  - using the $e\mu\tau_{had}$ or $\mu\mu\tau_{had}$ channel
  - expects $\approx$ 10 events each
- H $\rightarrow$ WW/$\tau_{lep}\tau_{lep}$
  - 3 channels: SS $e\mu$, SS $\mu\mu$ and 3 leptons
  - large non-prompt lepton background

# Other Channels




- $\tau_{lep}\tau_{had}$
  - using the $e\mu\tau_{had}$ or $\mu\mu\tau_{had}$ channel
  - expects $\approx$ 10 events each
- H $\rightarrow$ WW/$\tau_{lep}\tau_{lep}$
  - 3 channels: SS $e\mu$, SS $\mu\mu$ and 3 leptons
  - large non-prompt lepton background
- H $\rightarrow \gamma\gamma$
  - almost entirely background-free
  - would expect 0.67 signal events, observes none

# Other Channels

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  - large non-prompt lepton background
- H $\rightarrow \gamma\gamma$
  - almost entirely background-free
  - would expect 0.67 signal events, observes none

# Conclusions

- presented search for tHq with $H \to b\bar{b}$ and $\kappa_t = -1$
- presented pioneering use of reconstruction techniques
- excluded production cross section larger than 1.77 pb at 95% C.L.
- results public under *HIG-14-015*
- combination paper submitted to journal


BACKUP

# tHq input variables

| |
|---|
| Electric charge of b-quark jet from decay of top quark, multiplied by lepton's charge. The jet charge is defined as in Eq. (1) in Ref. [37], with $\kappa = 1$ |
| $\Delta R$ between the two jets from decay of Higgs boson |
| $\Delta R$ between b-quark jet and W boson from decay t $\rightarrow$ bW |
| $\Delta R$ between reconstructed top quark and Higgs boson |
| Pseudorapidity of recoil jet |
| Invariant mass of b-quark jet from decay of top quark and charged lepton |
| Mass of reconstructed Higgs boson |
| Pseudorapidity of the most forward jet from decay of H |
| Tranverse momentum of the softest jet from decay of H |
| Number of b-tagged jets among the two jets from decay of H |
| Boolean variable that equals 1 if the b-quark jet from decay of t is b-tagged, 0 otherwise |
| Relative $H_{\mathrm{T}}$, $(p_{\mathrm{T}}(\mathrm{t}) + p_{\mathrm{T}}(\mathrm{H}))/H_{\mathrm{T}}$ |

# $t\bar{t}$ input variables

| |
|---|
| Difference of electric charges of b-quark jets from decays of $t_{had}$ and $t_{lep}$, multiplied by lepton's charge |
| $\Delta R$ between the two light-flavor jets from decay of $t_{had}$ |
| $\Delta R$ between b-quark jet and W boson from decay $t_{had} \rightarrow bW$ |
| $\Delta R$ between b-quark jet and W boson from decay $t_{lep} \rightarrow bW$ |
| Difference between masses of $t_{had}$ and W from decay of $t_{had}$ |
| Pseudorapidity of $t_{had}$ |
| Invariant mass of b-quark jet from decay of $t_{lep}$ and charged lepton |
| Mass of W from decay of $t_{had}$ |
| Number of b-tagged jets among the two light-flavor jets from decay of $t_{had}$ |
| Boolean variable that equals 1 if the b-quark jet from decay of $t_{had}$ is b-tagged, 0 otherwise |
| Boolean variable that equals 1 if the b-quark jet from decay of $t_{lep}$ is b-tagged, 0 otherwise |
| Transverse momentum of $t_{had}$ |
| Transverse momentum of $t_{lep}$ |
| Relative $H_T$, $(p_T(t_{had}) + p_T(t_{lep}))/H_T$ |
| Sum of electric charges of the two light-flavor jets from decay of $t_{had}$, multiplied by lepton's charge |

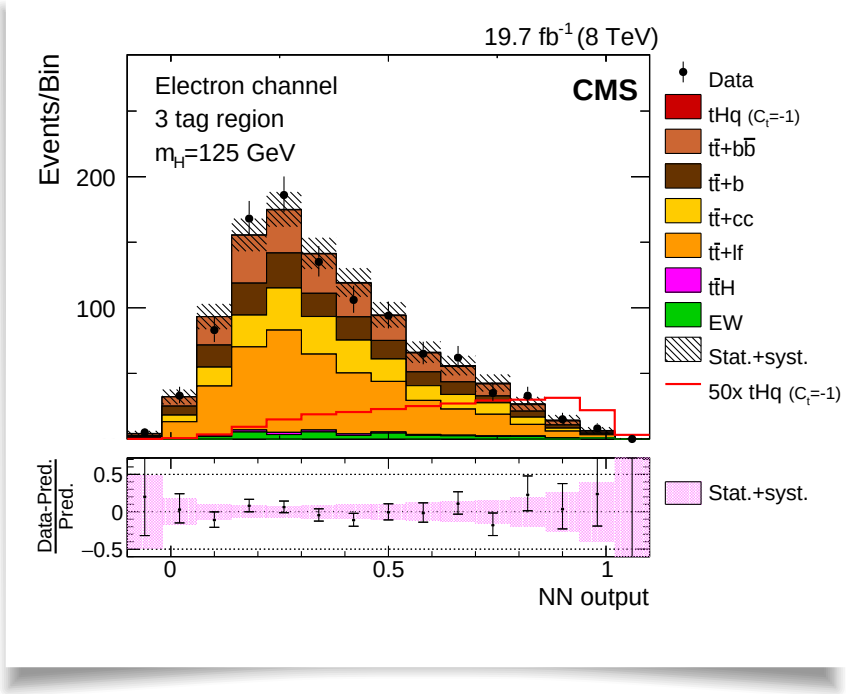
# MVA input variables

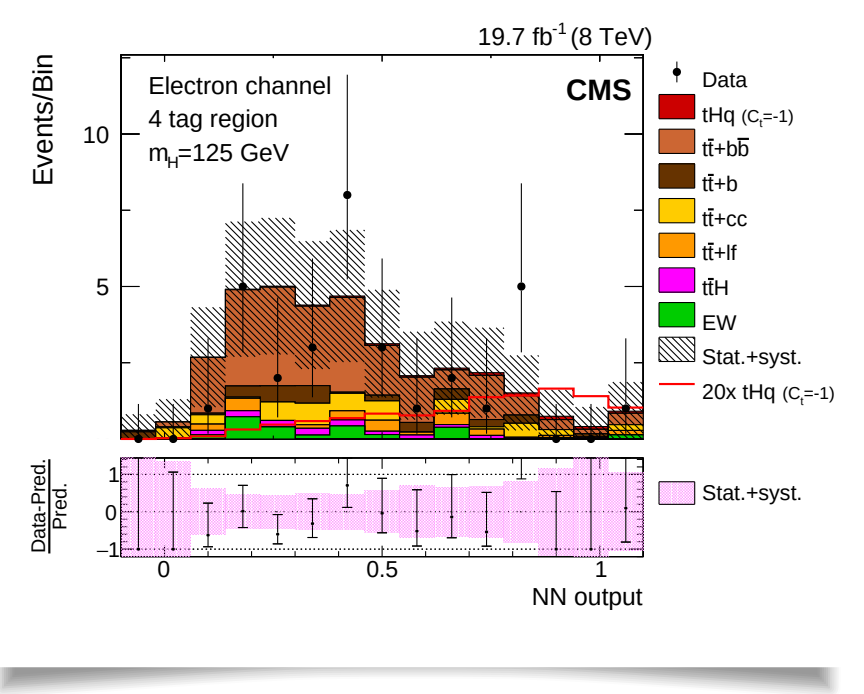
| |
|---|
| Electric charge of the lepton |
| Pseudorapidity of the recoil jet |
| Number of b-tagged jets among the two jets from the Higgs boson decay |
| Transverse momentum of the Higgs boson |
| Transverse momentum of the recoil jet |
| $\Delta R$ between the two light-flavor jets from the decay of $t_{had}$ |
| Mass of $t_{had}$ |
| Number of b-tagged jets among the two light-flavor jets from the decay of $t_{had}$ |

# impact of systematic sources

| Source | Type | impact as exclusive source on final limit [%] | improvement of final limit after removal [%] |
|---|---|---|---|
| JES | shape | 17 | 3 |
| JER | shape | $< 1$ | $< 1$ |
| BTag light flavor | shape | 13 | $< 1$ |
| BTag heavy flavor | shape | 17 | $< 1$ |
| Pile up | normalization | $< 1$ | $< 1$ |
| Unclustered energy | shape | 3 | 1 |
| Lepton efficiency | normalization | 5 | $< 1$ |
| Luminosity | normalization | 10 | $< 1$ |
| Cross section (PDF) | normalization | 8 | $< 1$ |
| Cross section (Scale) | normalization | 9 | $< 1$ |
| MC Bin-by-Bin unc. | shape | $< 1$ | $< 1$ |
| $Q^2$ scale ($tHq + t\bar{t}$) | shape | 20 | 4 |
| Matching | shape | 2 | 2 |
| Top $p_T$ reweighting | shape | 19 | 2 |
| $t\bar{t}$ HF rates ($b$) | normalization | 13 | $< 1$ |
| $t\bar{t}$ HF rates ($b\bar{b}$) | normalization | 15 | $< 1$ |
| $t\bar{t}$ HF rates ($c$ / $c\bar{c}$) | normalization | 13 | 1 |

# post-fit electron channel

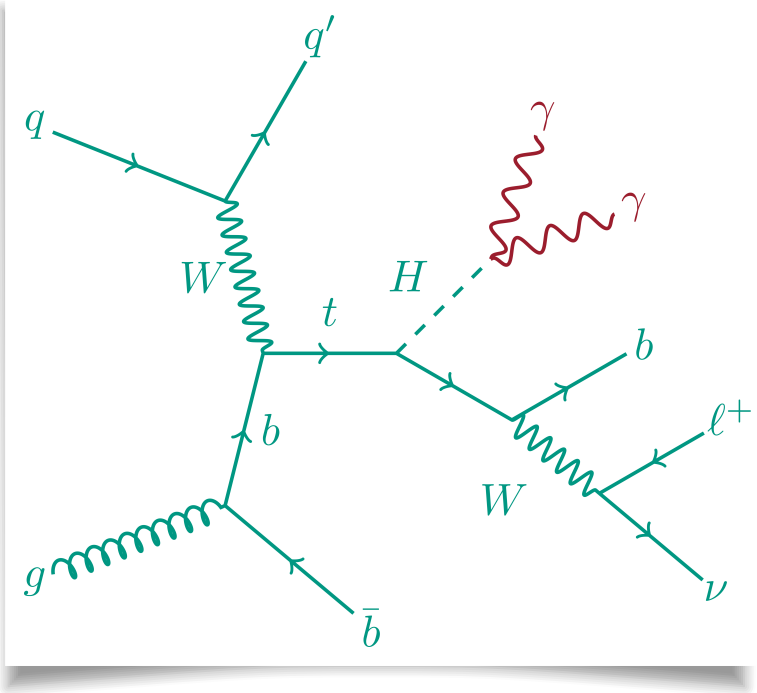


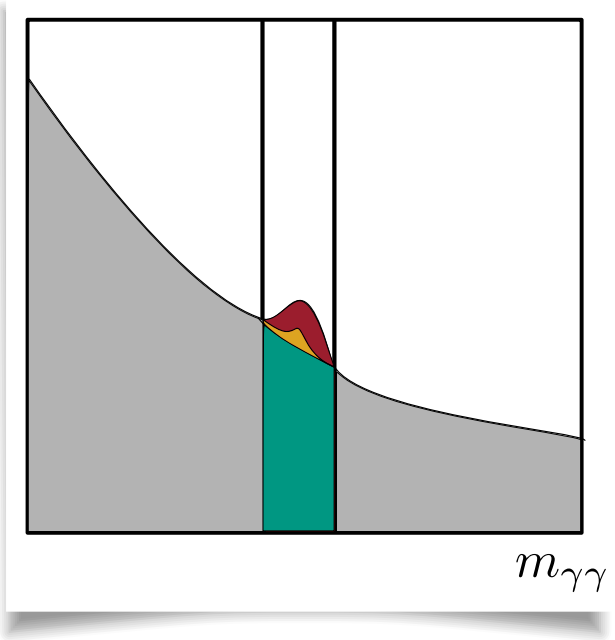
# tHq, H $\rightarrow \gamma\gamma$

- Analysis looking for an excess in the $m_{\gamma\gamma}$ distribution at $\sim$ 125 GeV
  - Very low event numbers - signal and background
  - $\kappa_t = -1$ would also increase decay BR by $\times 2.4$

- Event selection:
  - Two photons
  - Exactly one muon or electron
  - One untagged jet with $|\eta| > 1$
  - At least one $b$-tagged jet



- Dealing with two different types of backgrounds
  - Resonant backgrounds
    - BGs with $H \to \gamma\gamma$
    - Appear under the signal peak
    - Dominated by $t\bar{t}H$
    - Suppression of $t\bar{t}H$ with a 5-variable likelihood product discriminant
    - Small VH contribution
    - Taken from simulation

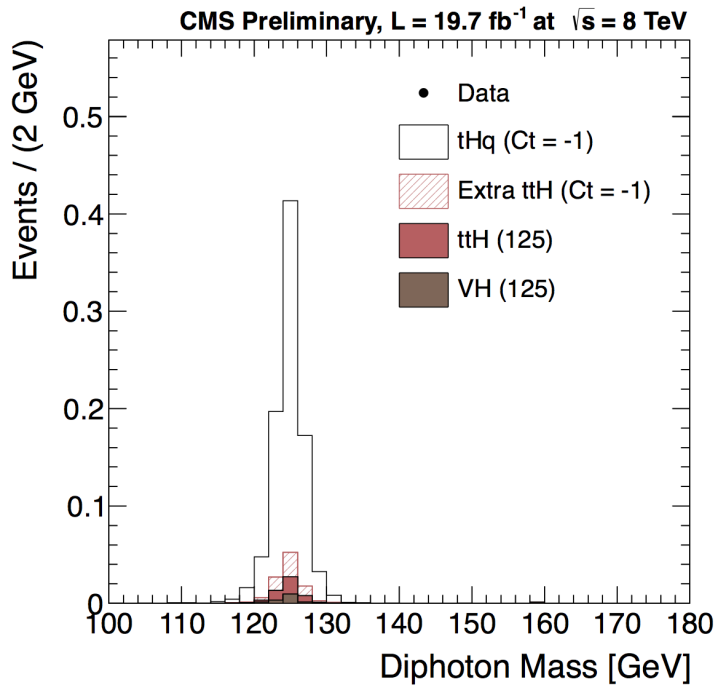



  - Non-resonant backgrounds
    - Main backgrounds: $\gamma\gamma$+jets, $\gamma$+jets, $t\gamma\gamma$, $t\bar{t}\gamma\gamma$
    - Evaluated from data in the $m_{\gamma\gamma}$ sidebands

| Process | Yield |
|---|---|
| tHq ($\kappa_t = -1$) | 0.67 |
| $t\bar{t}H$ | 0.03 + 0.05$^\dagger$ |
| VH | 0.01 + 0.01$^\dagger$ |
| other $H$ | 0 |

# $H \to \gamma\gamma$ Results

- Careful treatment of non-resonant background results in a 33% rate uncertainty
  - Shape taken from control regions
  - Dominant systematic
- Other systematics included as pure rate systematics
- No data observed in signal region
  - Observed (and expected) limit of **4.1** $\sigma/\sigma_{\kappa_t=-1}$




| Limit | Expected | Observed |
|---|---|---|
| $H \to \gamma\gamma$ ($\kappa_t = -1$) | **4.1** | **4.1** |

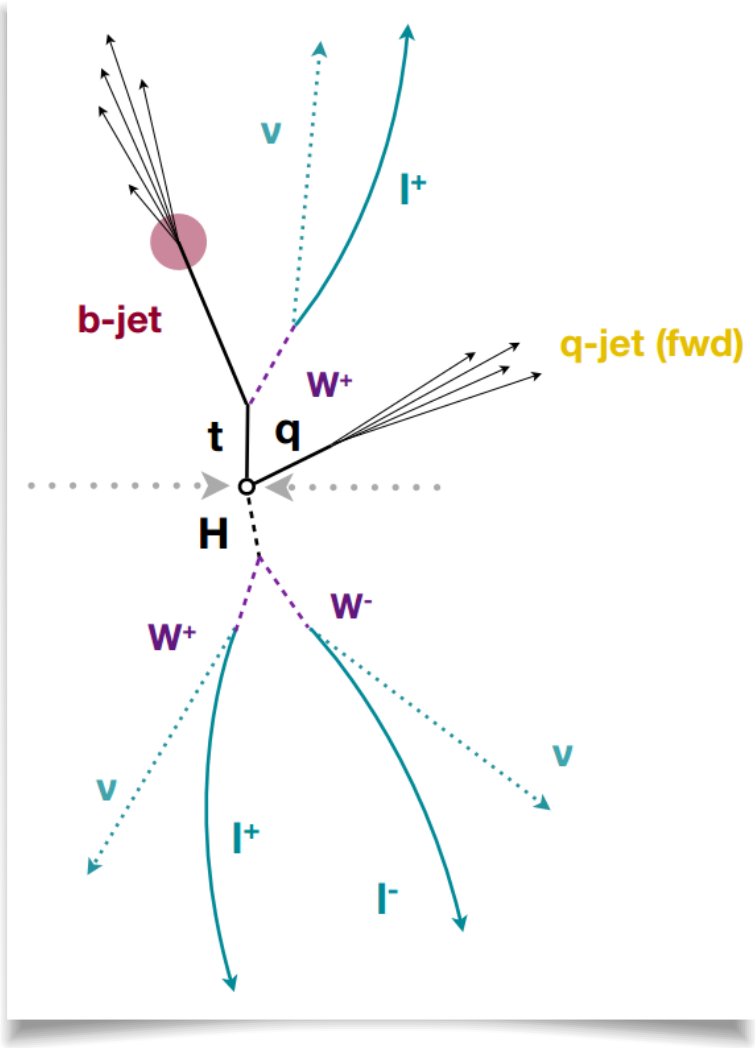
# tHq, H $\longrightarrow$ WW, $\tau_{lep}\tau_{lep}$

# $H \rightarrow WW, \tau_{lep}\tau_{lep}$ TOPOLOGY

- Performed in two channels
  - Two same-sign leptons, $\mu^{\pm}\mu^{\pm}$ or $e^{\pm}\mu^{\pm}$
  - Three leptons, $\mu\mu\mu$, $\mu\mu e$, $\mu ee$ or $eee$

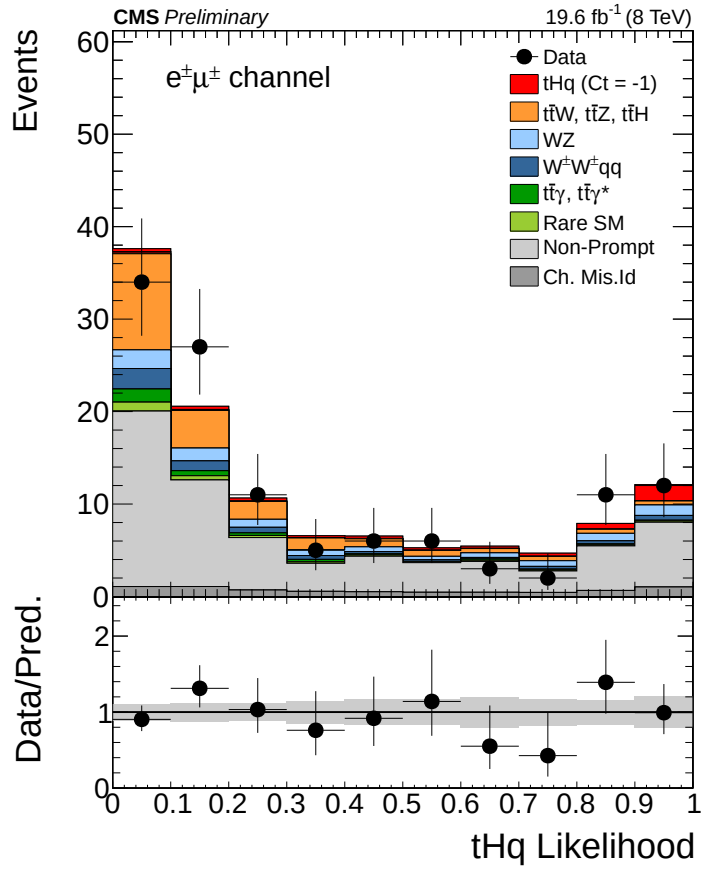
- SS leptons
  - Two same-sign leptons $>$ 20GeV
  - At least one central jet
  - At least one *b*-tagged jet
  - At least one untagged, forward jet $|\eta| > 1$
  - Reject events with $\tau_{had}$

- Three leptons
  - Three leptons $>$ 20/10/10 GeV
  - Exactly one *b*-tagged jet
  - One untagged, forward jet with $|\eta| > 1.5$
  - Missing Energy in the event
  - Z veto for leptons



# $H \to WW$, $\tau_{lep}\tau_{lep}$ BACKGROUNDS

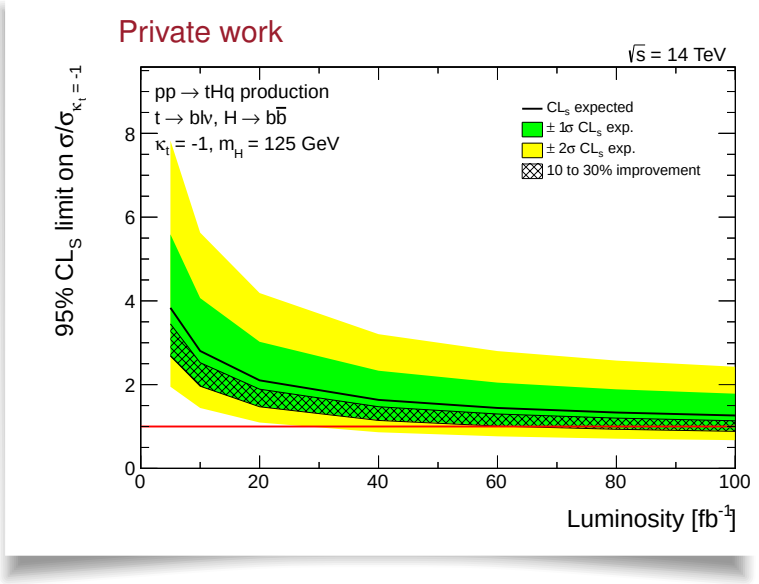
- Background dominated by non-prompt leptons
  - Mostly $t\bar{t} \to \ell +$ jets, where a b jet fakes a lepton
  - Perform a data-driven estimation of this background
- Apply a likelihood product discriminator to suppress backgrounds
  - Trained to discriminate against both irreducible and non-prompt backgrounds
- Input variables vary in the different channels
- Fit is performed in the output of the likelihood



# Outlook for Run II PRIVATE WORK

- In Run II at 13 TeV $\sigma_{\mathrm{tHq}_{\kappa_t=-1}}$ will increase by factor 4
- Simple scaling for first 20 fb $^{-1}$ of Run II results in these limits for $\sigma/\sigma_{\kappa_t=-1}$

| | $H\to\gamma\gamma$ | $H\to b\bar{b}$ | $H\to WW$ |
|---|---|---|---|
| Exp. | $\sim 1.0$ | $\sim 2.1$ | $\sim 2.1$ |




- Dedicated projection study only for $b\bar{b}$
- Naive combination results in an upper limit of $\sim 0.8$
- Will be sensitive to $\kappa_t = -1$ soon in Run II