Direct Measurement of Higgs-Top CP Phase at Hadron Collider

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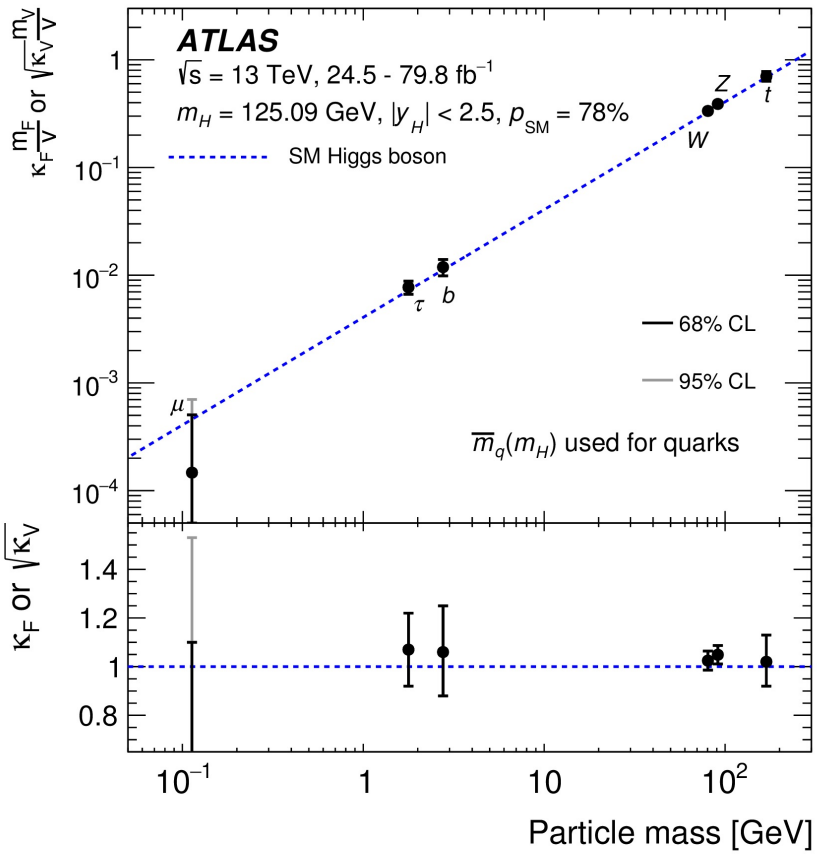
Motivation

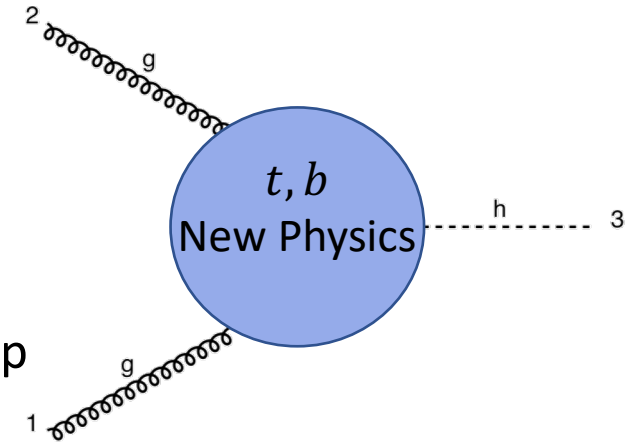
- Higgs Particle

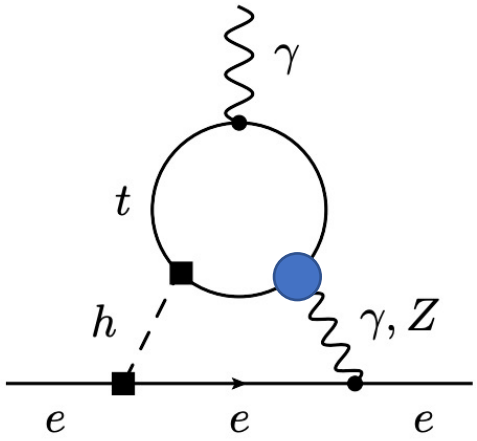


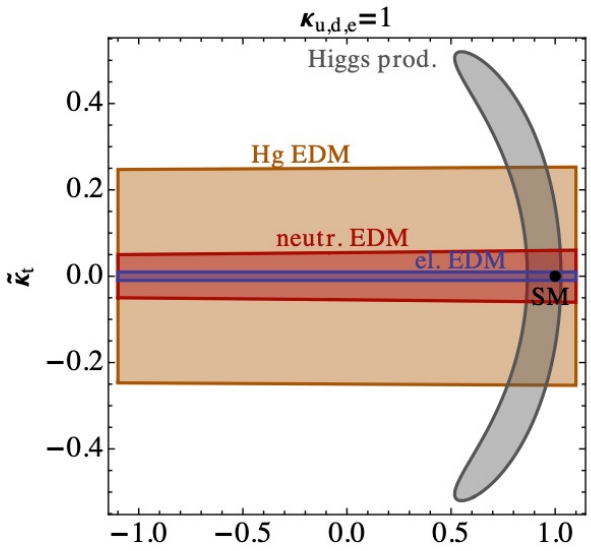
- CP Property:
  - With Gauge Boson
    - CPV appears at high dimension operators:
      - $\mathcal{O}_{\varphi\widetilde{W}} = \varphi^{\dagger}\varphi\widetilde{W}^{I}_{\mu\nu}W^{I\mu\nu}$
  - With Fermions
    - CPV appears already at dim-4:
      - $\bar{f}\left(y_f + i\,\gamma_5\,\tilde{y}_f\right)fh$
    - Third Generation Fermions:
      - $\tau^{\pm}$
      - b-quark
      - top-quark

$Ht\bar{t}$: Indirect Measurement

- $gg \rightarrow h \rightarrow \gamma\gamma$
  - Gluon-gluon fusion and diphoton decay
  - Indirect constraints on the particles in the loop
  - Model-dependent
- EDM
  - Barr-Zee Diagram
  - Model-dependent







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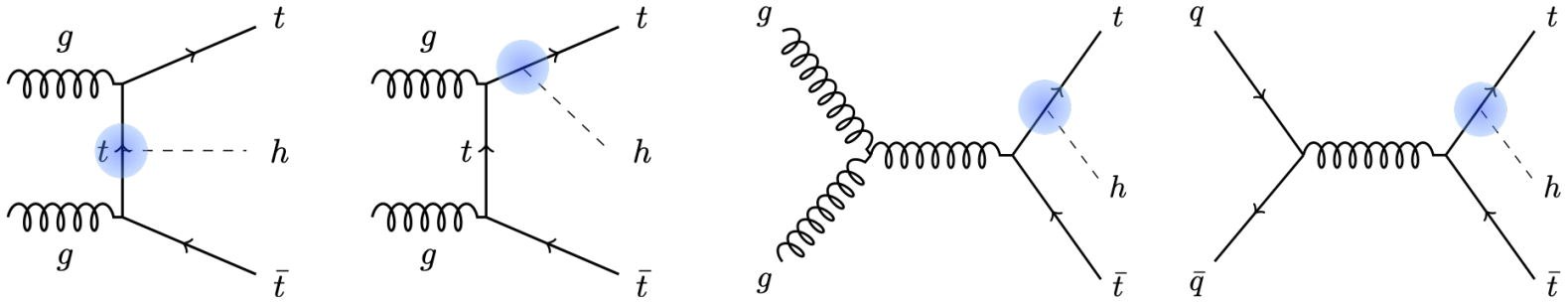
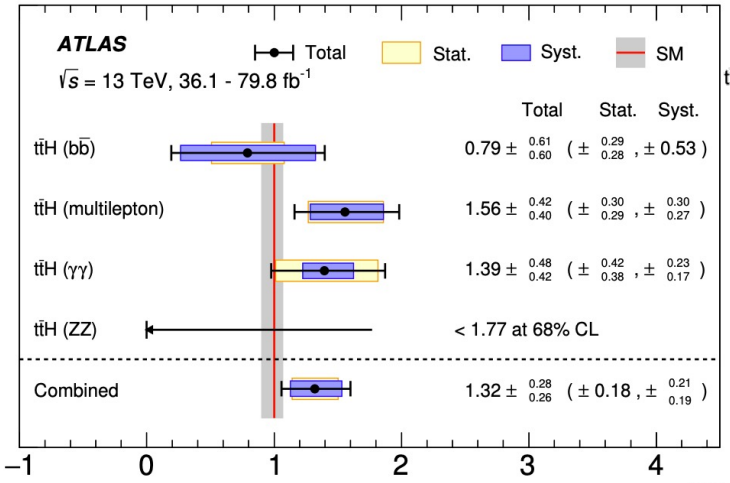
$Ht\bar{t}$: Direct Measurement



- Direct Measurement through $t\bar{t}h$ production
- Current Measurements

$$\mathcal{L} \supset \frac{m_t}{v}\kappa_t \bar{t}(\cos\alpha + i\gamma_5 \sin\alpha)th$$



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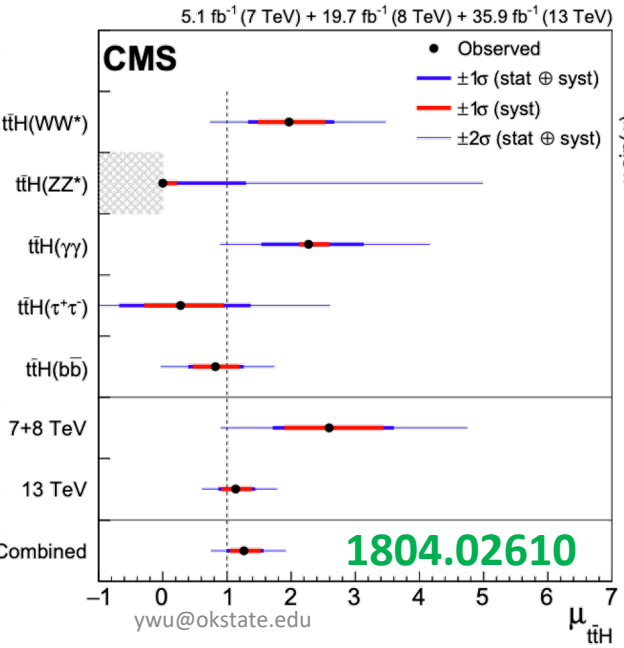

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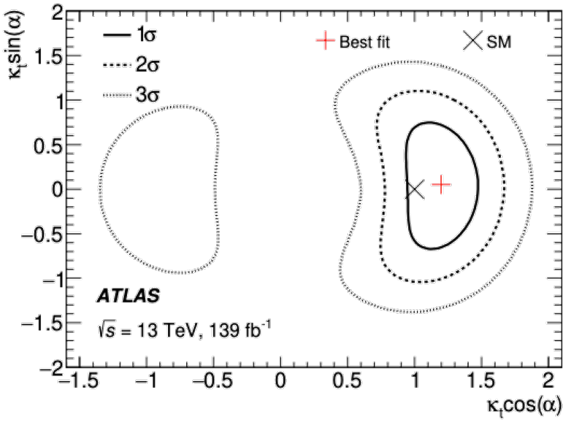

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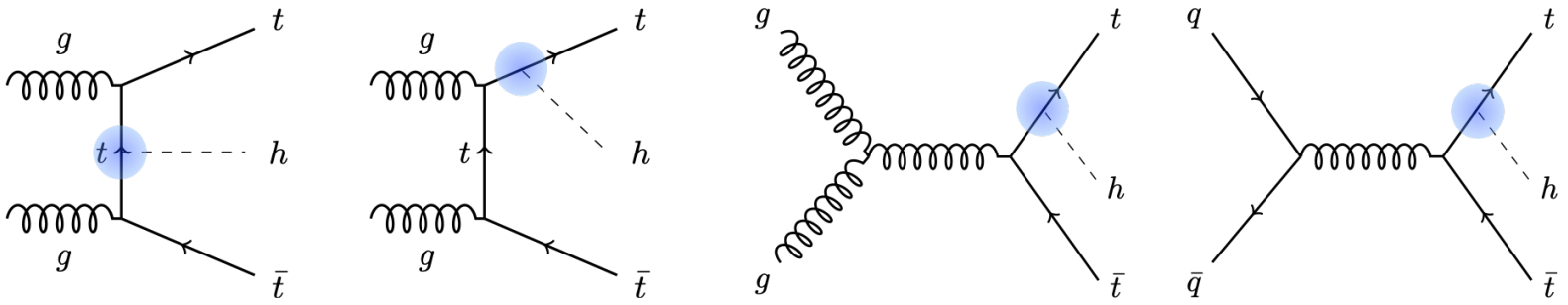
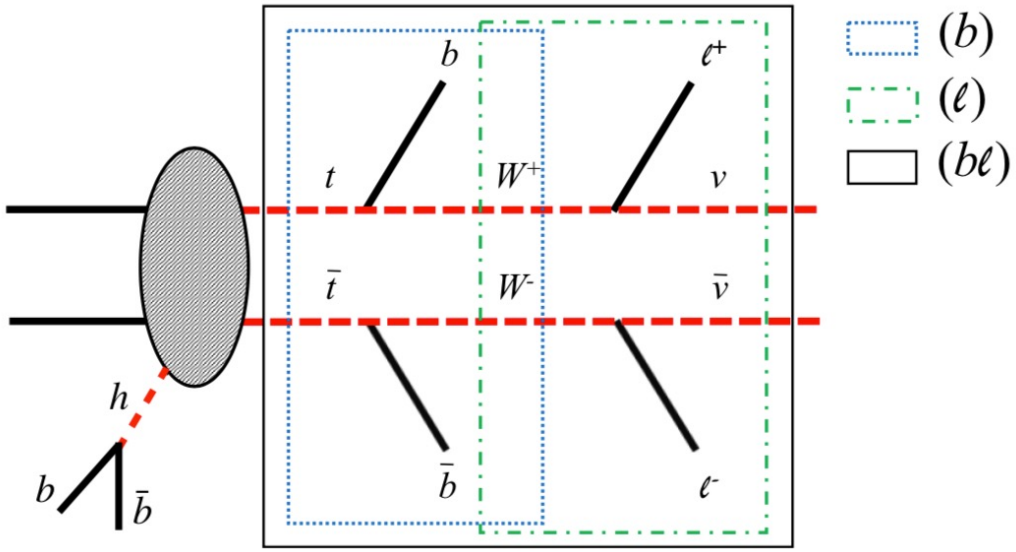
Measurement of the CP Structure



- Higgs-top CP structure affects the spin correlation in the final states

$$\mathcal{L} \supset \frac{m_t}{v}\kappa_t \bar{t}(\cos\alpha + i\gamma_5 \sin\alpha)th$$

- Observables: (In top-pair CM frame)
  - θ^*: The angle of top-quark w.r.t beam-axis
  - $\Delta\phi_{\ell\ell}^{tt}$: Azimuthal angle between the leptons



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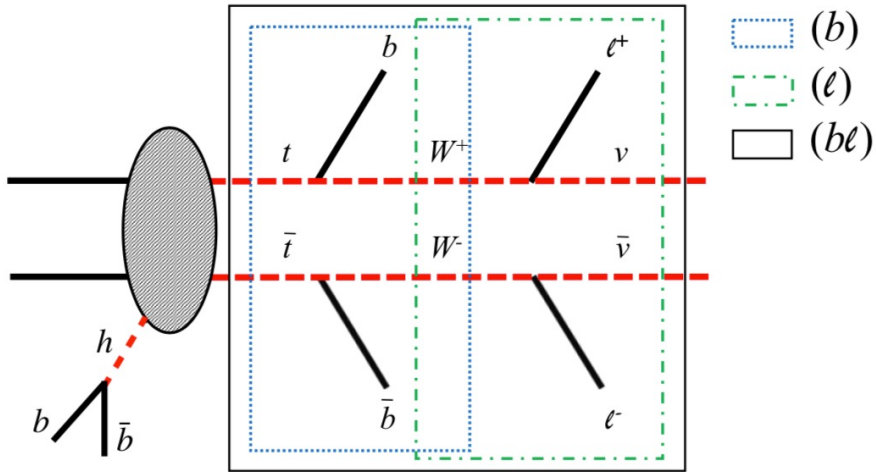
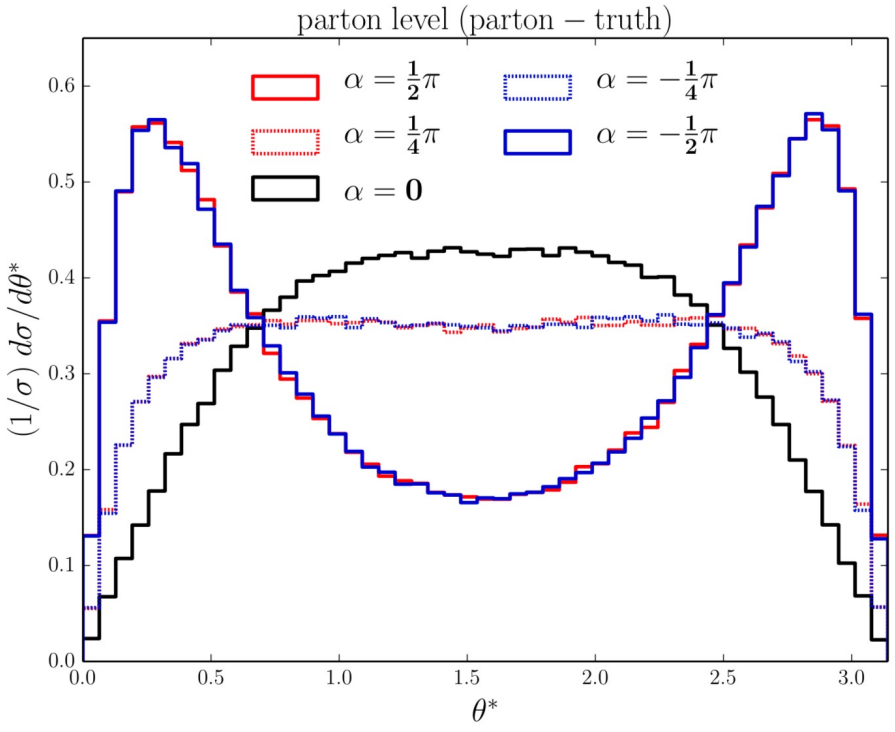
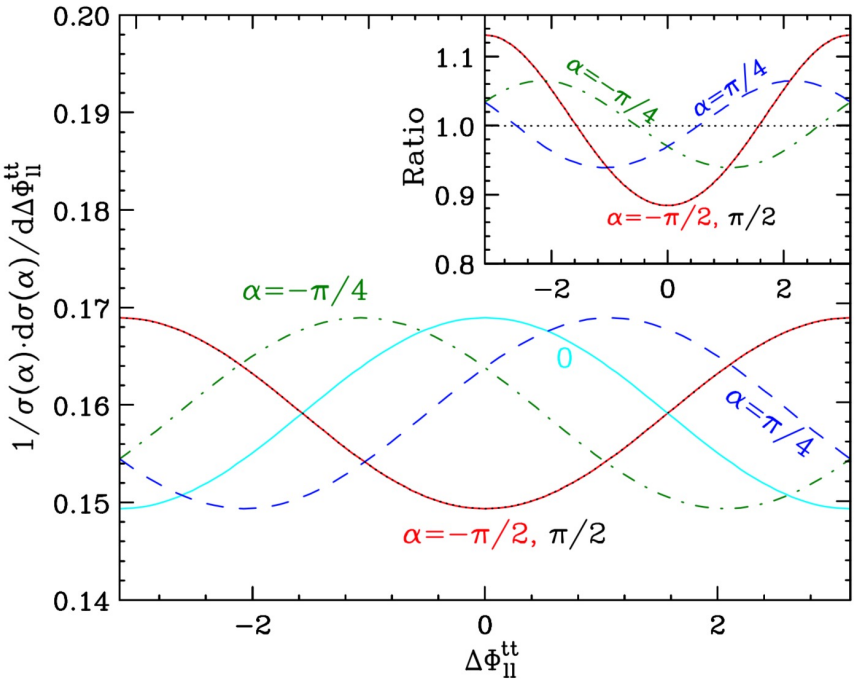






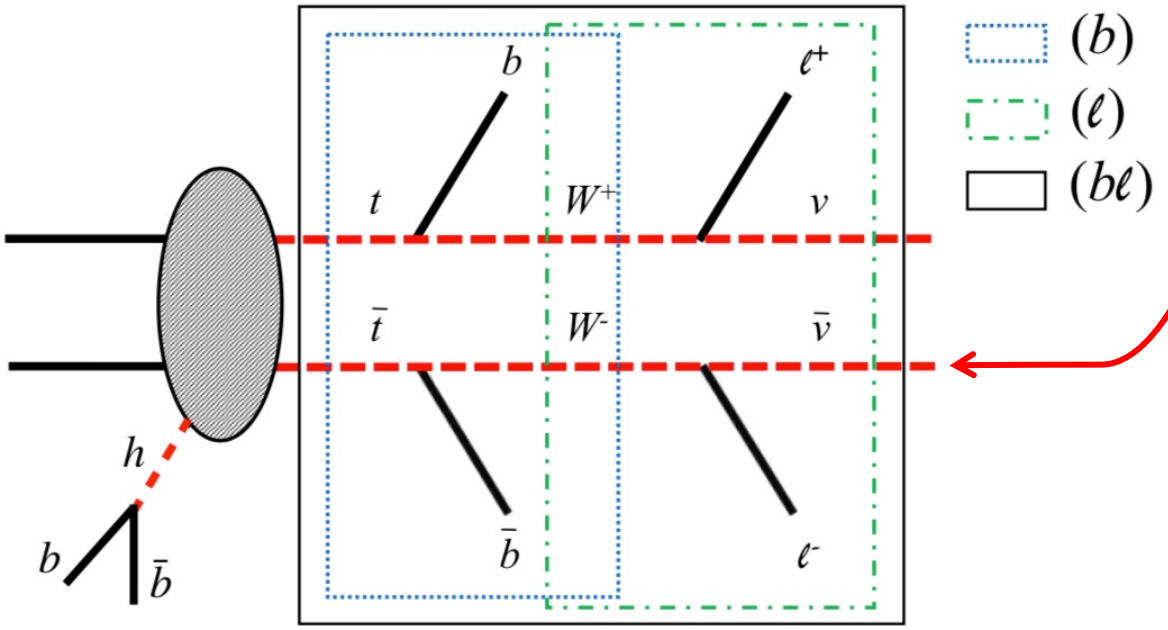
Reconstruction of the System!

Event Reconstruction

$$M_{2CW}^{(b\ell)}(\tilde{m}) \equiv \min_{\vec{q}_1,\vec{q}_2} \{\max[M_{t_1}(\vec{q}_1,\tilde{m}),\ M_{t_2}(\vec{q}_2,\tilde{m})]\}\,,$$
$$\vec{\not{P}}_T = \vec{q}_{1T} + \vec{q}_{2T}\,,$$
$$M_{t_1} = M_{t_2}\,,$$
$$M_{W_1} = M_{W_2} = m_W\,.$$

- Stransverse Mass
  - W mass
  - Top mass

Reconstruct the Neutrino and the top system



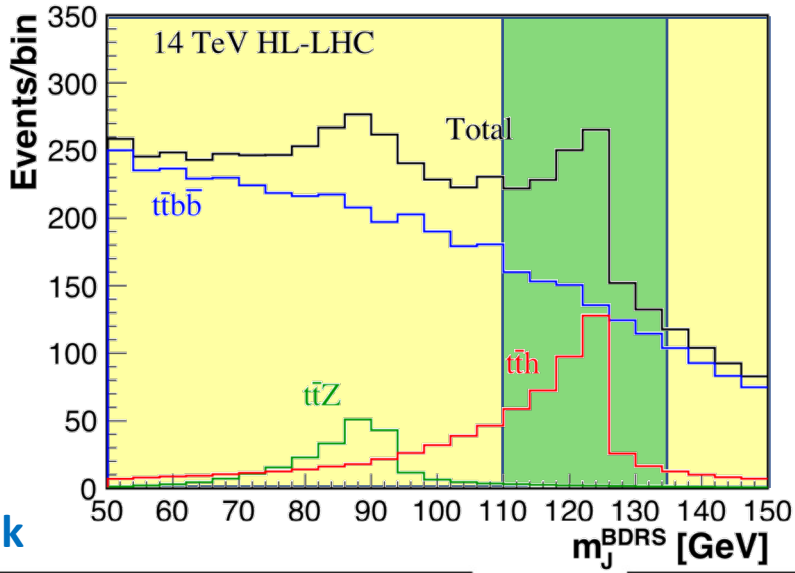
Reconstruct the Higgs

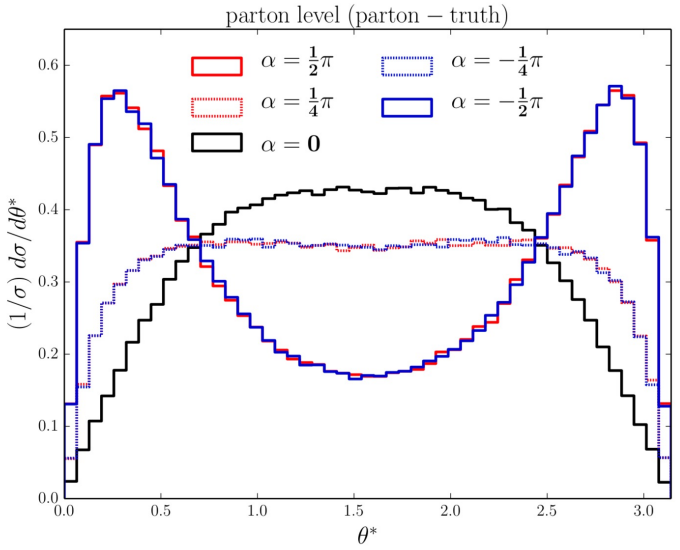
- BDRS Algorithm with $p_T > 200$ GeV
- Boosted region:
  - Better Reconstruction/Rejection
  - Better CP sensitivity

Measurement @ 14 TeV

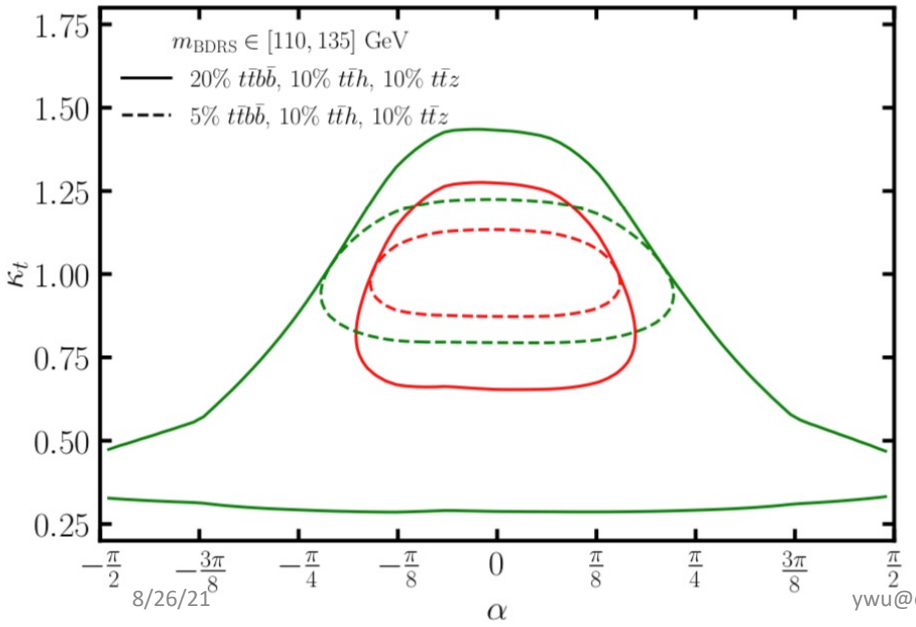
$\mathcal{L} = 3000\ fb^{-1}$

Systematics:
- ttbb: 20%/5%
- ttZ and tth: 10%

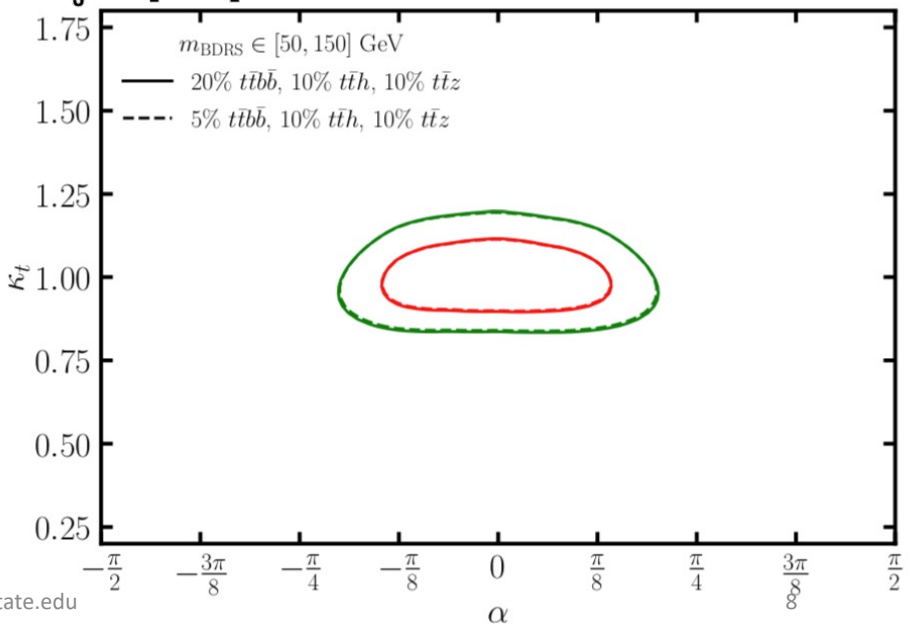




Focus on Higgs Peak



Together with Sideband



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Measurement @ 100 TeV

- Improvement at FCC
  - Larger Cross Section
  - Larger Luminosity $\mathcal{L} = 30\ ab^{-1}$
- Control the uncertainties
  - Similar origin of $t\bar{t}h$ and $t\bar{t}Z$

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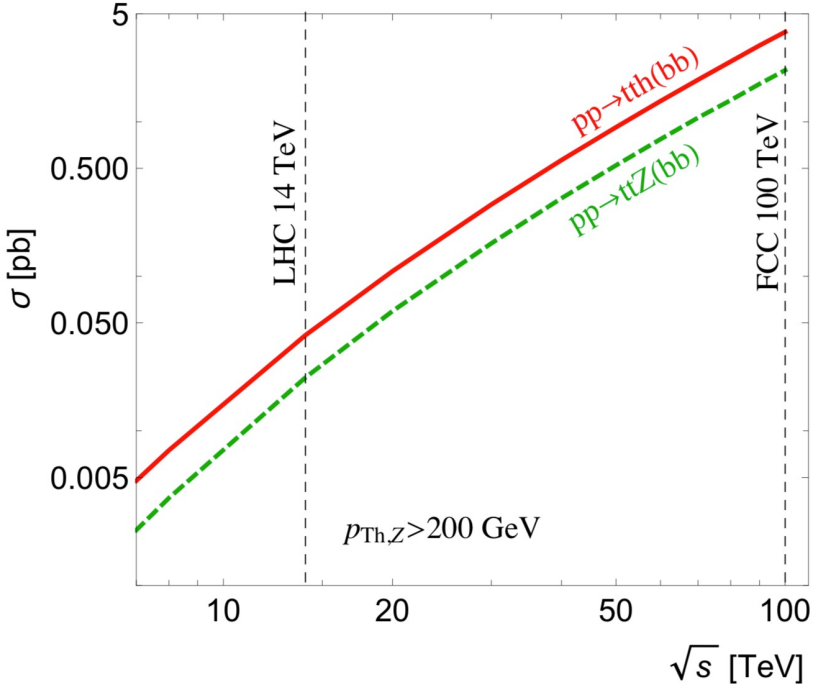
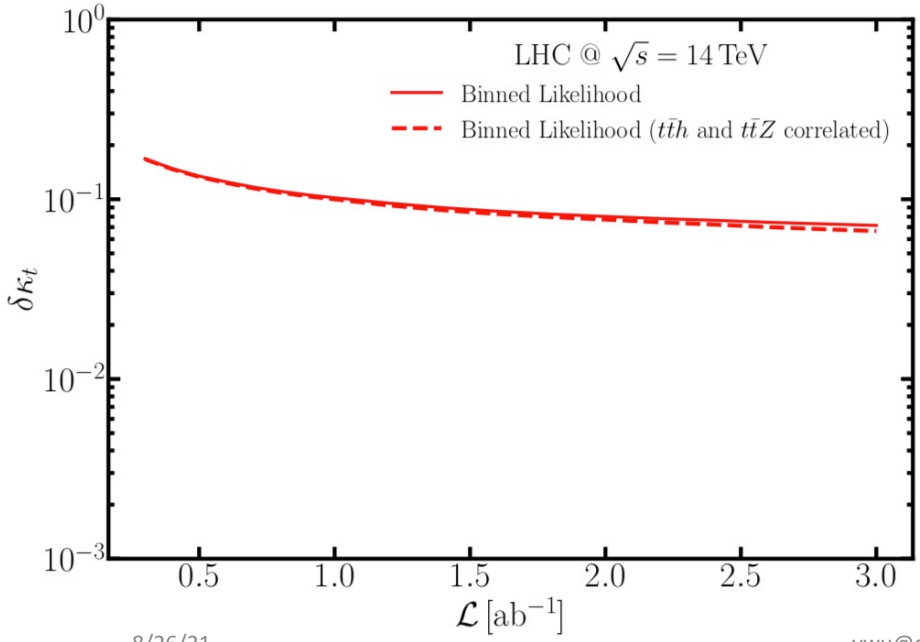
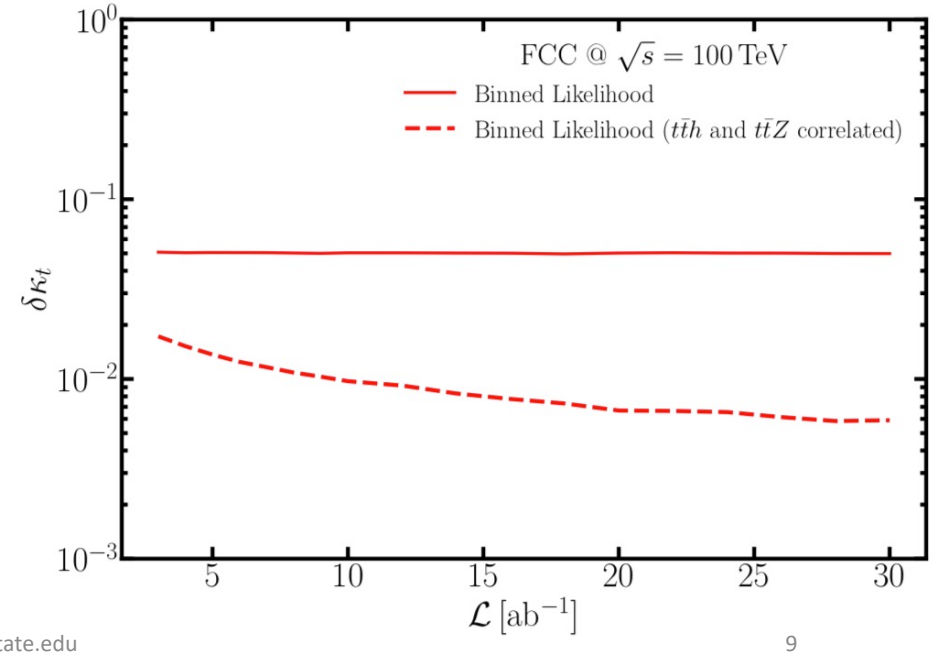
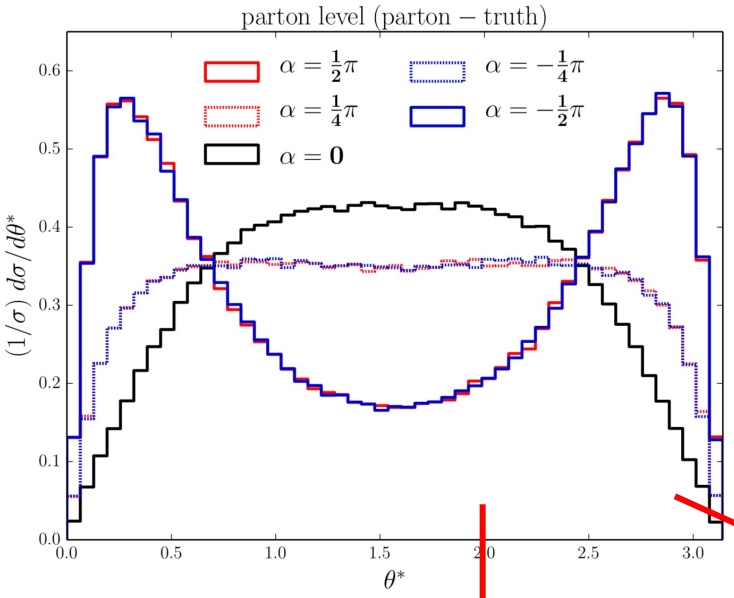
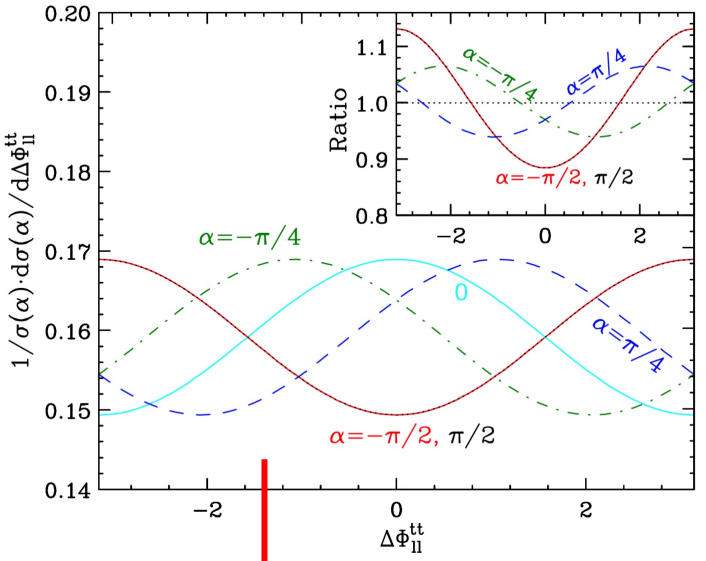


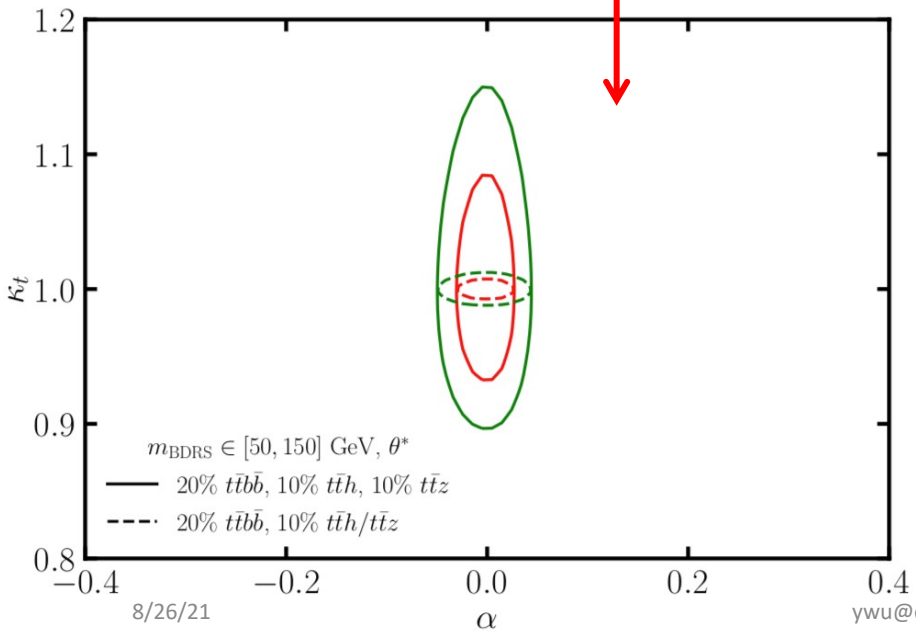


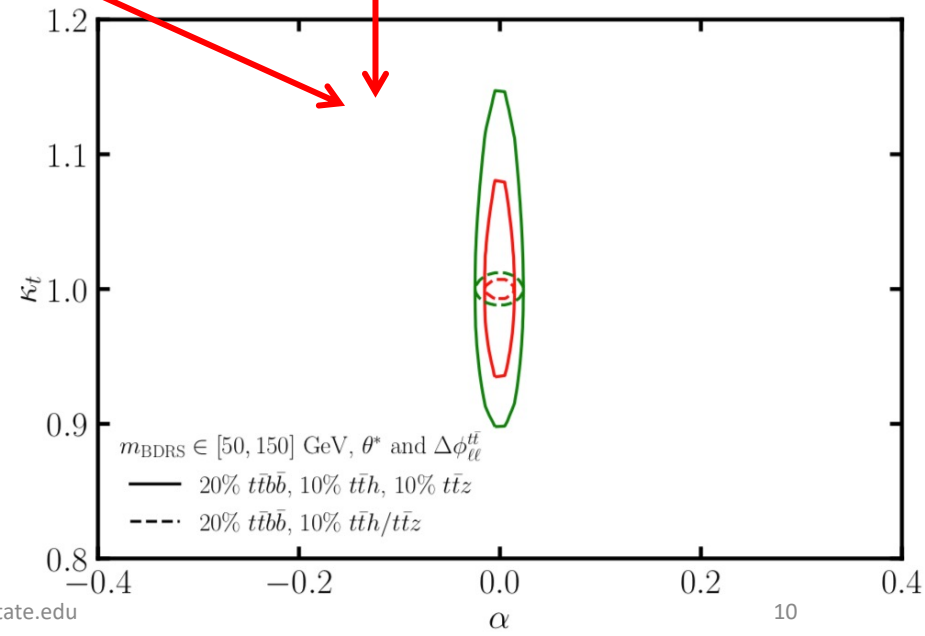


Measurement @ 100 TeV









Summary

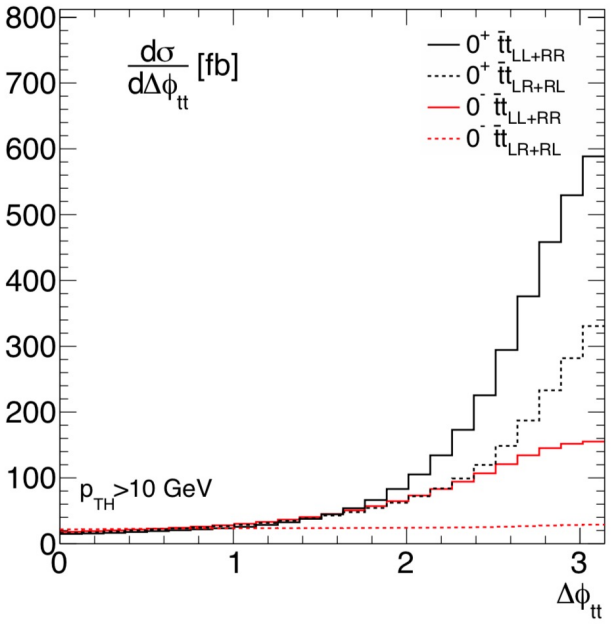
- Top Yukawa coupling as well as CP structure is one of the important targets we want to measurement with high precision
- $t\bar{t}h$ production is used, with $h \to bb$ and dilepton channel for top-pair
- At HL-LHC, we can probe $|\alpha| \lesssim 36^o$, with $\frac{\delta\kappa_t}{\kappa_t} \sim 20\%$:
  - Well control of the systematics of backgrounds is necessary
- At FCC-pp, with huge increase of the cross section and luminosity:
  - $|\alpha| \lesssim 3^o$ and $\frac{\delta\kappa_t}{\kappa_t} \sim 1\%$ is achievable
  - Systematics can be well controlled utilizing the correlation between $t\bar{t}Z$ and $t\bar{t}h$

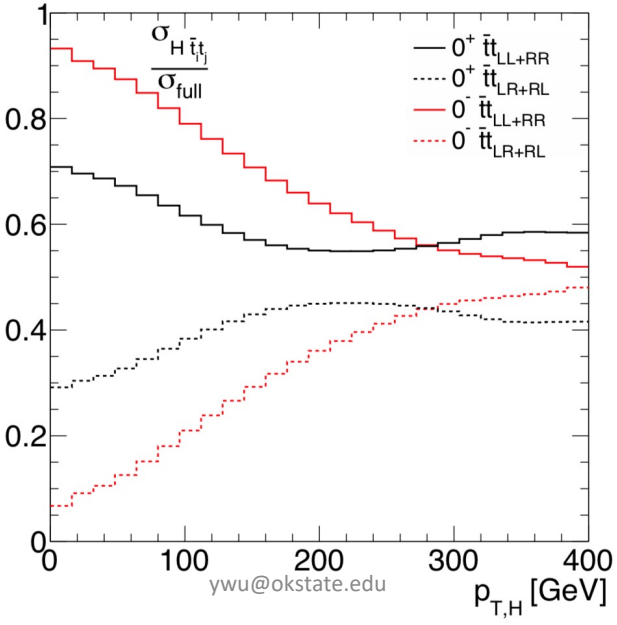
Backups

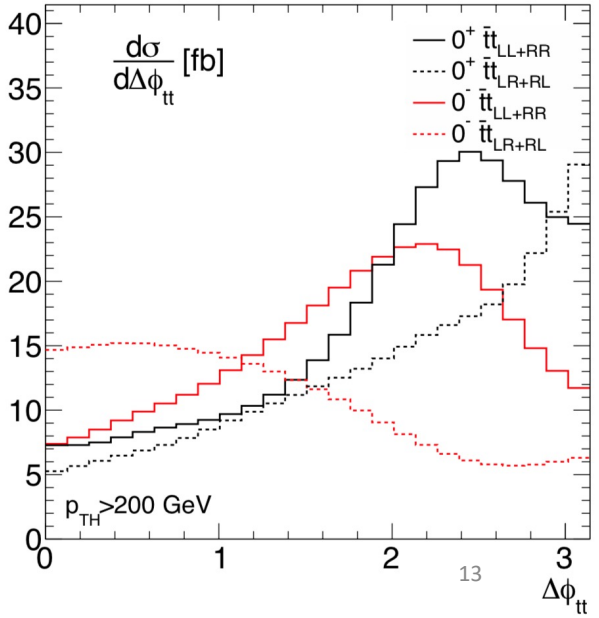
Event Reconstruction

1507.07926

- Higgs:
  - BDRS Algorithm:
    - Focusing on Boosted region $p_T^H > 200$ GeV
- Cons:
  - Smaller Cross Section
- Pros:
  - Better reconstruction of the Higgs
  - Better rejection of backgrounds
  - Better CP sensitivity

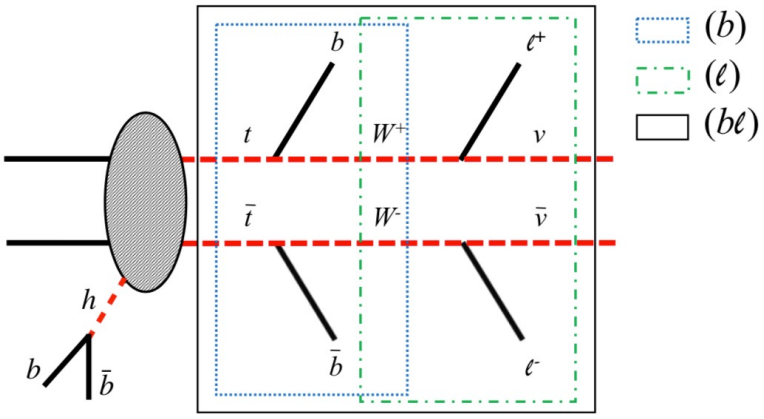






Event Reconstruction

- Constraints in the System
  - W-boson mass
  - Top quark mass
  - MET measurement
- Two combinations of b-quark and lepton



$$M_{2CW}^{(b\ell)}(\tilde{m}) \equiv \min_{\vec{q}_1,\vec{q}_2}\{\max\left[M_{t_1}(\vec{q}_1,\tilde{m}),\ M_{t_2}(\vec{q}_2,\tilde{m})\right]\},$$

$$\vec{\not{P}}_T = \vec{q}_{1T} + \vec{q}_{2T},$$

$$M_{t_1} = M_{t_2},$$

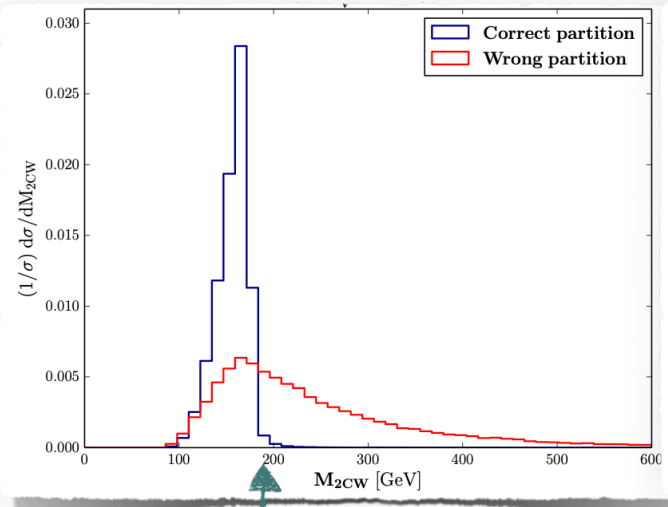
$$M_{W_1} = M_{W_2} = m_W.$$

$$M_{2Ct}^{(\ell)}(\tilde{m}) \equiv \min_{\vec{q}_1,\vec{q}_2}\{\max\left[M_{W_1}(\vec{q}_1,\tilde{m}),\ M_{W_2}(\vec{q}_2,\tilde{m})\right]\},$$

$$\vec{\not{P}}_T = \vec{q}_{1T} + \vec{q}_{2T},$$

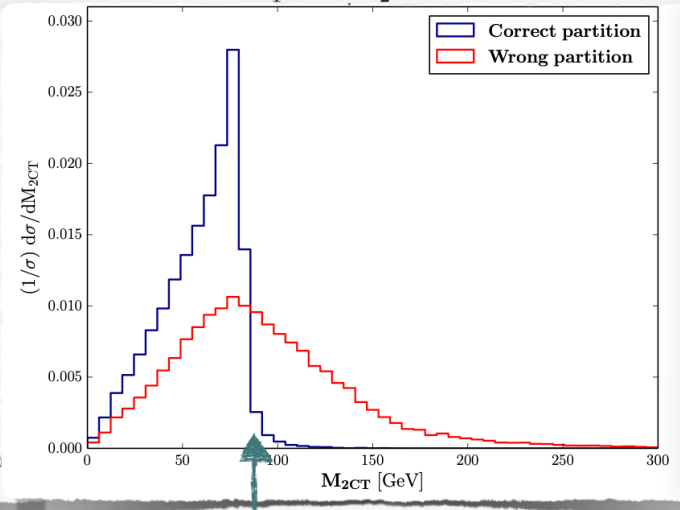
$$M_{W_1} = M_{W_2},$$

$$M_{t_1} = M_{t_2} = m_t.$$



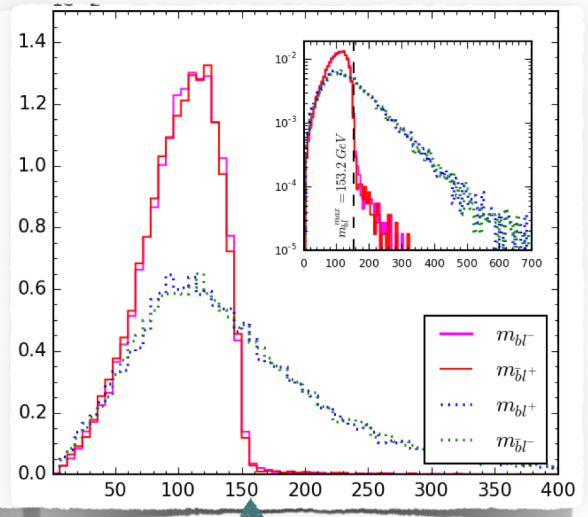
$m_t^{true} = 173$ GeV

M_{2CW}



$m_w^{true} = 80.4$ GeV

M_{2CT}



$m_{b\ell}^{\max} = 153.2$ GeV

$m_{b\ell}$

Event Selection

cuts 14 TeV	$t\bar{t}h$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	σ
$N_h = 1$, $4b$-tags, $p_T^\ell > 20$ GeV, $\lvert\eta^\ell\rvert < 2.5$ $p_T^j > 30$ GeV, $\lvert\eta^j\rvert < 2.5$, $N_j \geqslant 2$, $N_\ell = 2$	0.358	4.08	0.106	9.45
50 GeV $< m_J^{\mathrm{BDRS}} <$ 150 GeV	0.306	2.18	0.0971	10.9
Resolving combinatorics	0.239	1.47	0.0796	10.3

cuts 100 TeV	$t\bar{t}h$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	σ
$N_h = 1$, $4b$-tags, $p_T^\ell > 20$ GeV, $\lvert\eta^\ell\rvert < 2.5$ $p_T^j > 30$ GeV, $\lvert\eta^j\rvert < 2.5$, $N_j \geqslant 2$, $N_\ell = 2$	21.5	351	6.93	194.9
50 GeV $< m_J^{\mathrm{BDRS}} <$ 150 GeV	17.7	177	6.15	223.0
Resolving combinatorics	14.0	116	5.11	216.3