Search for Standard Model Production of Four Top Quarks

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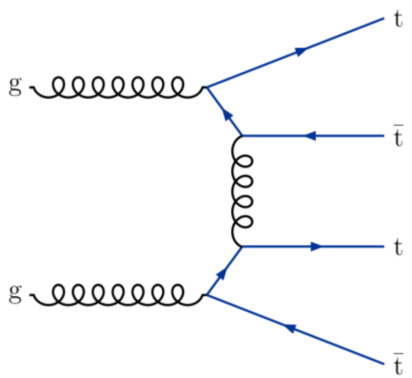
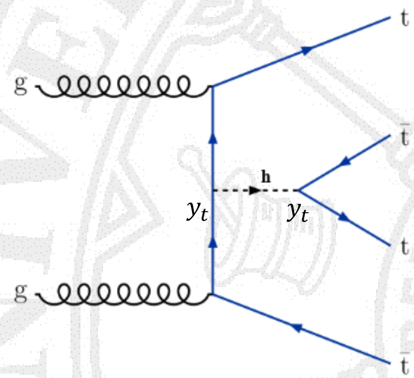
on behalf of the CMS Collaboration

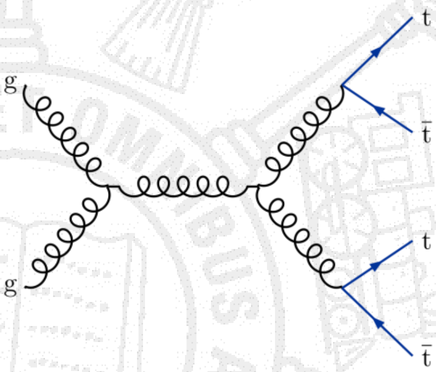
DPF 2019

Why $t\bar{t}t\bar{t}$

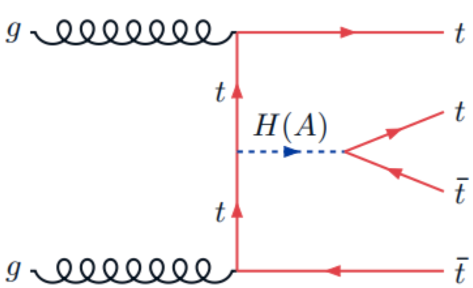
- Rare SM process on the edge of observation
  $\sigma\,(\text{pp} \rightarrow t\bar{t}t\bar{t}) = 12\text{fb} \pm 20\%$ @ NLO (1711.02116)

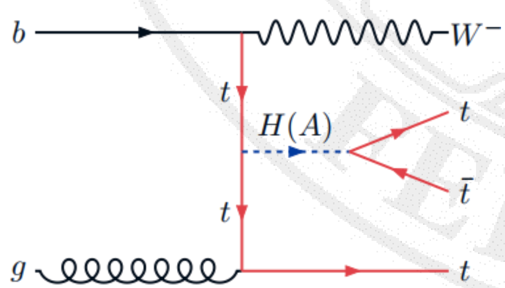


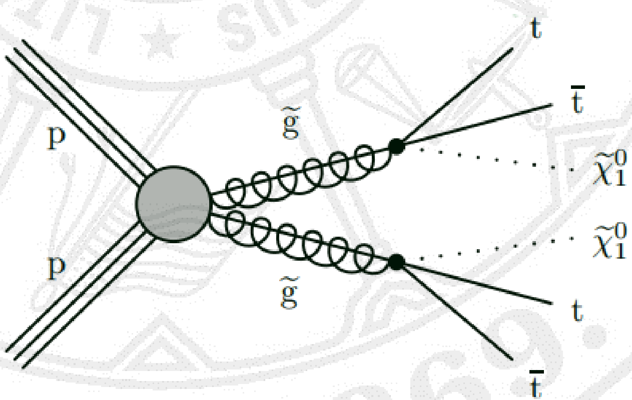




- Four top production is sensitive to interesting BSM models
  - Two Higgs Doublet Models (2HDM)
  - Simplified Dark Matter Theories
  - Effective Field Theory

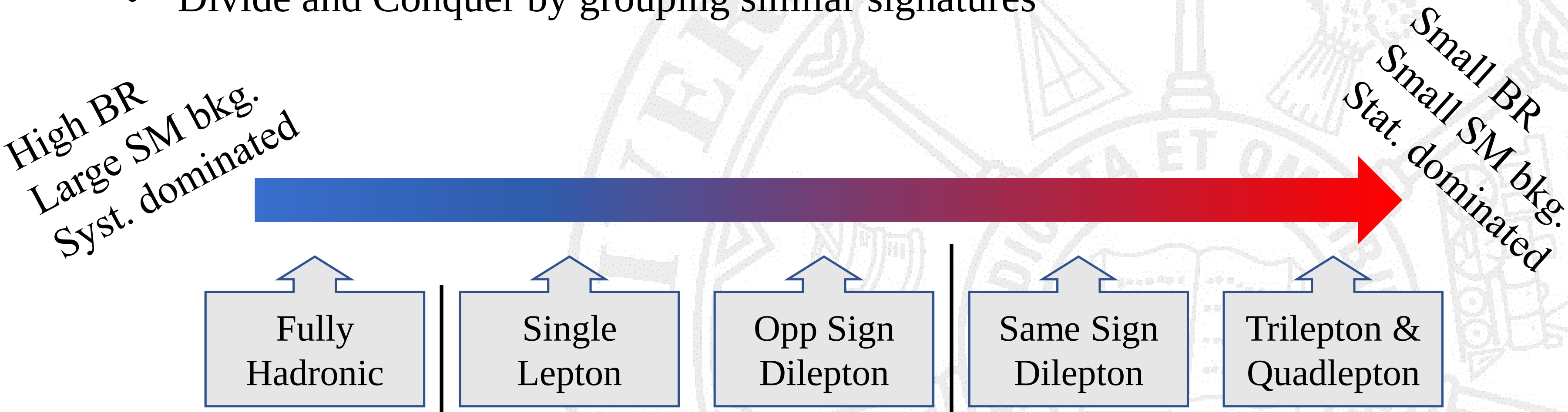






Many Final States

- Signature defined by decay modes of the four W bosons
- Divide and Conquer by grouping similar signatures



- BR ~32%
- In progress

- BR ~56%
- Preliminary result using 36fb $^{-1}$(PAS TOP-17-019)
  - $\sigma_{t\bar{t}t\bar{t}} < 48$fb @ 95%CL

- New analysis ongoing with more data and improved analysis techniques

- BR ~12%
- Published result with 2016 dataset(EPJC78 (2018) 140)
  - $\sigma_{t\bar{t}t\bar{t}} = 17^{+14}_{-11}$fb

- Preliminary result with full Run 2 137fb $^{-1}$ (PAS TOP-18-003)

Many Final States

- Signature defined by decay paths of the four W bosons
- Divide and Conquer by grouping similar signatures

High BR
Large SM bkg.
Syst. dominated

This Talk

Small BR
Small SM bkg.
Stat. dominated

Fully Hadronic	Single Lepton	Opp Sign Dilepton	Same Sign Dilepton	Trilepton & Quadlepton

Fully Hadronic

- BR ~32%
- In progress

Single Lepton

- BR ~56%
- Preliminary result using 36fb $^{-1}$(PAS TOP-17-019)
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Same Sign Dilepton (This Talk)

- BR ~12%
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  - $\sigma_{t\bar{t}t\bar{t}} = 17^{+14}_{-11}$fb

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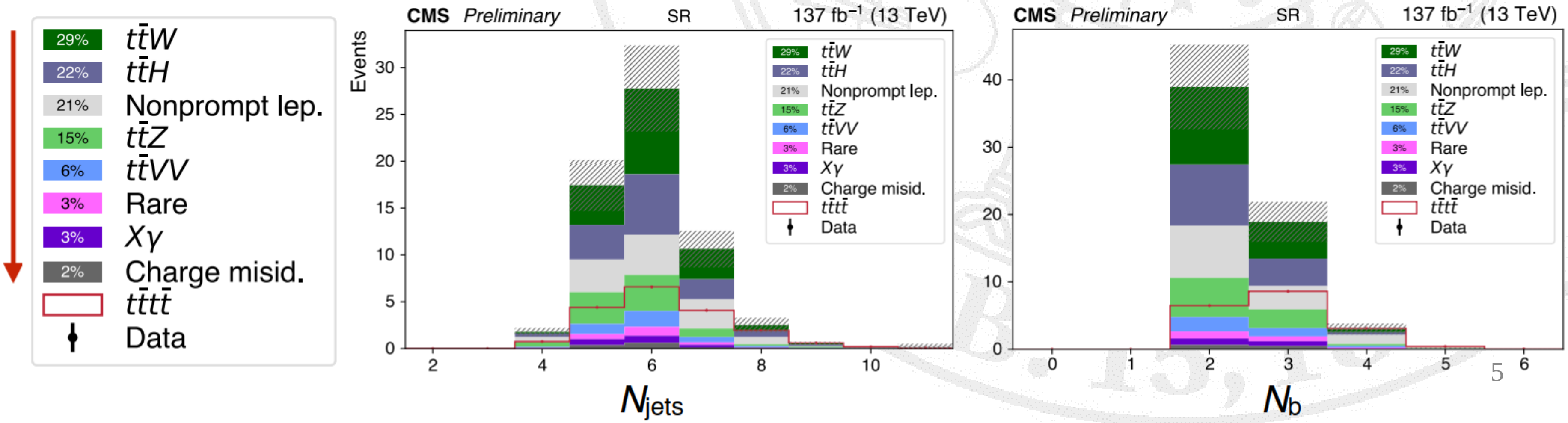
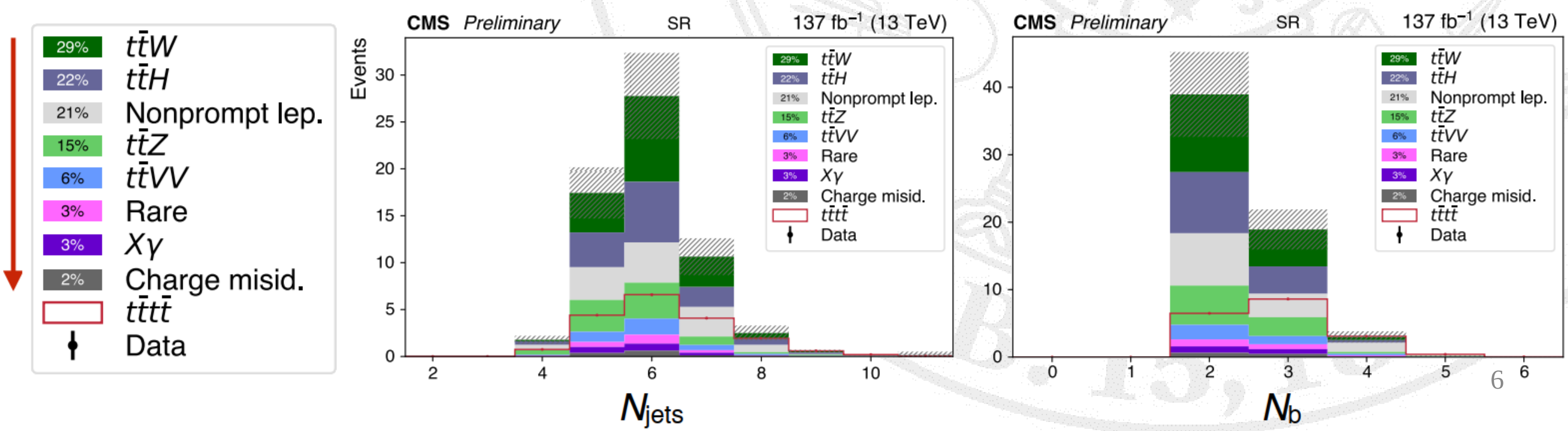
Baseline Event Selection

- Same-sign lepton pair, or ≥3 leptons | $p_T > 25/\,20/\,20\text{GeV}$
- ≥2 jets | $p_T > 40\text{GeV}$
- ≥2 b-tagged jets | $p_T > 25\text{GeV}$
  - Neural Net based tagger (~70% tag eff., 1% mis. tag)
- $H_T > 300$ GeV
- $\not{E}_T > 50$ GeV
- Z-boson veto
  - $|m_Z - m_{ll}| < 15$ GeV for opposite sign, same flavor pair
  - If leptons pass tight ID, promote to separate $t\bar{t}Z$ control region, otherwise discard



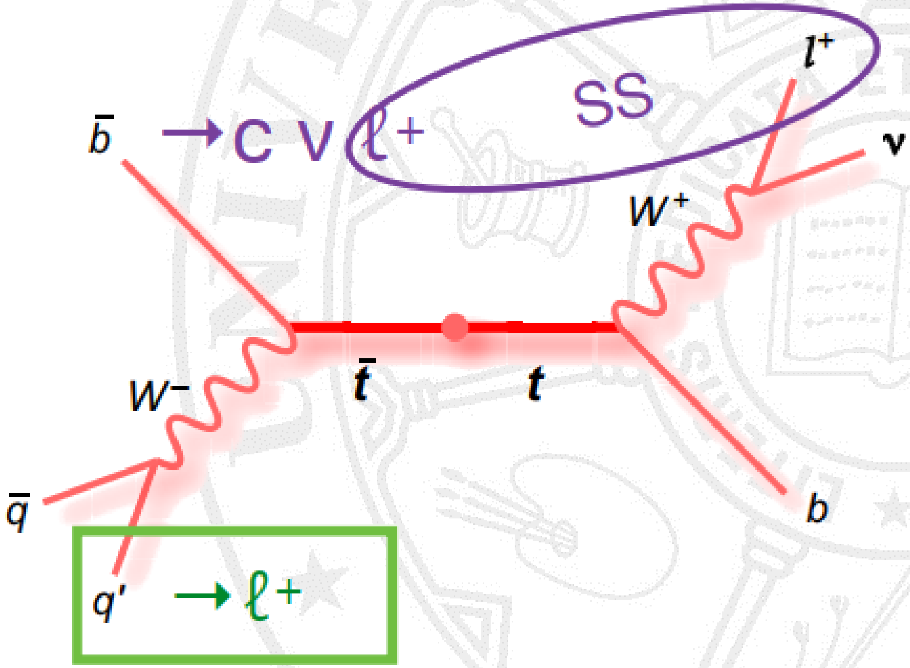
Backgrounds

- Two types of backgrounds survive the Baseline Selection.
  - Processes which produce "fake" same-sign lepton pairs
    - Nonprompt leptons
    - Charge misidentified leptons
  - Processes with **genuine** prompt same-sign leptons
    - $t\bar{t}W$, $t\bar{t}Z$
      - Simulation normalized to data with dedicated control regions
    - $t\bar{t}H$, $t\bar{t}VV$, $X+\gamma$, Rare
      - Taken directly from simulation



Backgrounds: Nonprompt leps

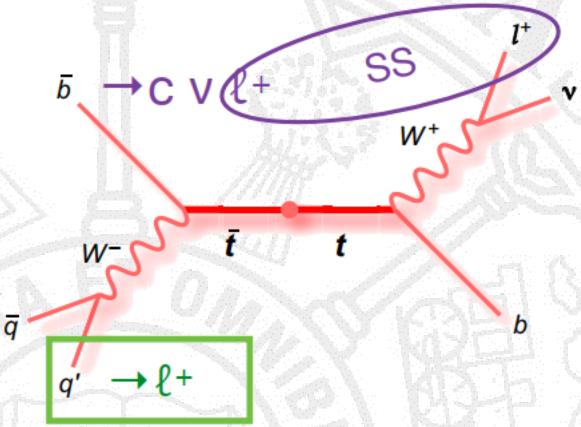
- $t\bar{t}$ (for example) events can enter signal region through **nonprompt leptons**



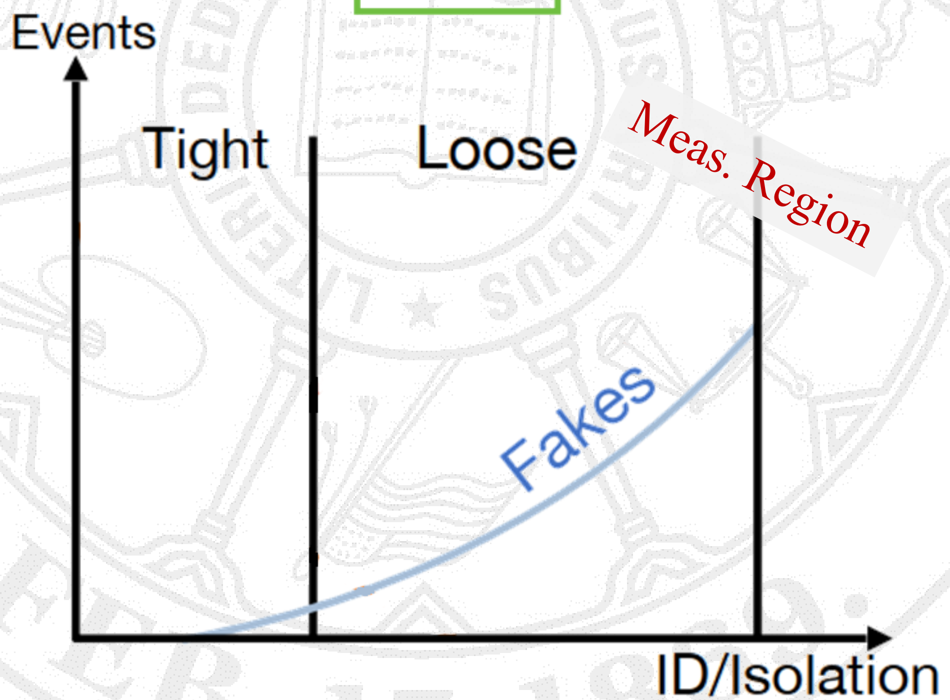
- Not well described in simulation so estimate from data!
- This is the **"tight-to-loose" ratio method**.

Backgrounds: Nonprompt leps

- Define a measurement region that has many fakes and few prompt leptons
  - Single Lepton Selection
  - $\not{E}_T < 20\text{GeV}$, $M_T < 20$ GeV
- Measure the proportion of “loose” leptons that pass the “tight” selection
- Do this differentially in flavor, p_T, and η

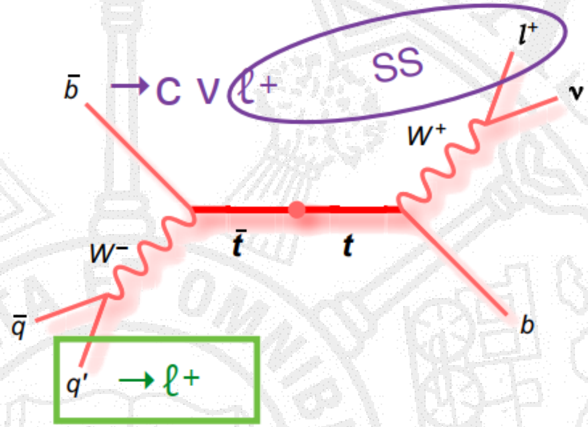


$$P(tight|loose) = \frac{\#tight}{\#loose}$$



Backgrounds: Nonprompt leps

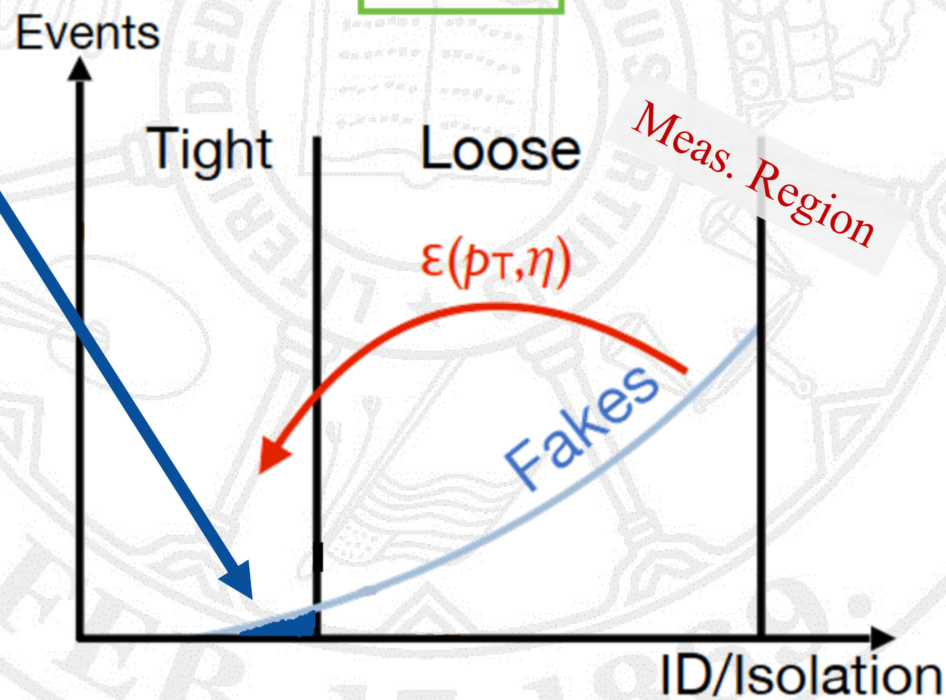
$$P(tight|loose) = \frac{\#tight}{\#loose}$$



- Next, calculate a transfer factor that weights loose events to give the count of "fake" tight events.

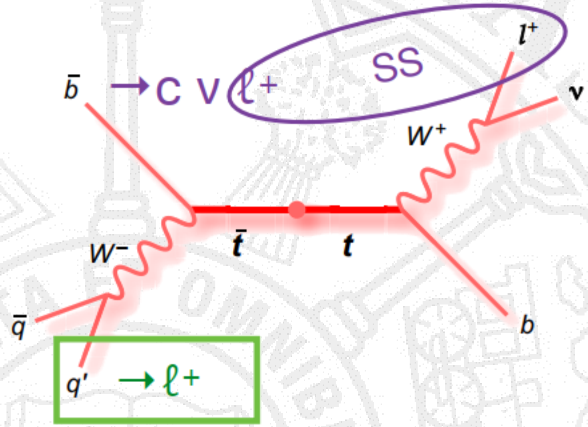
$$\varepsilon(f, p_T, \eta) = \frac{P}{1 - P}$$

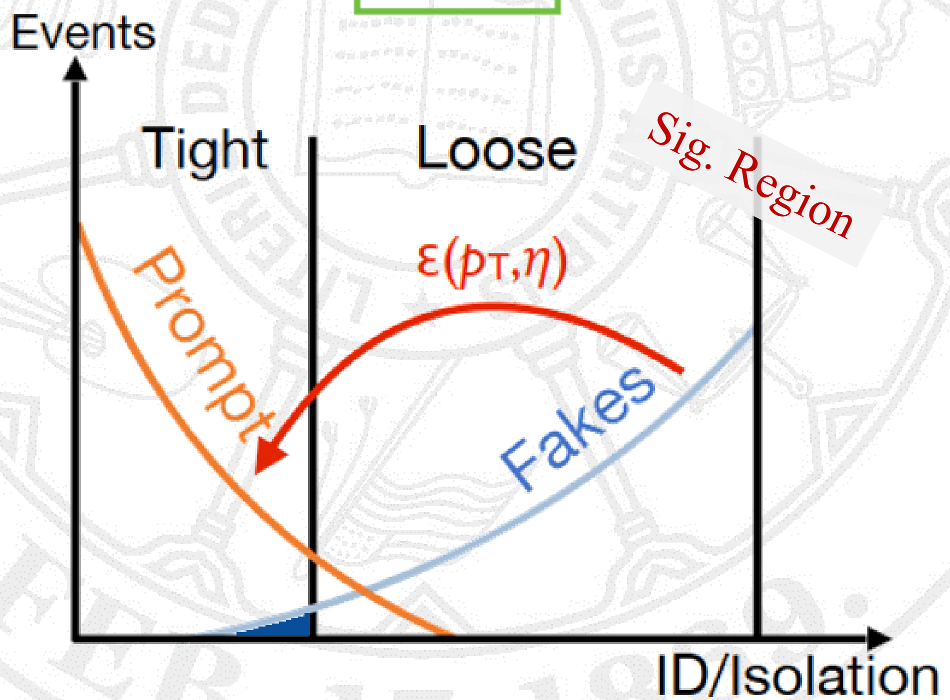
$$\#tight = \sum_{\text{l!t leps}} \varepsilon(f_i, p_{T_i}, \eta_i)$$



Backgrounds: Nonprompt leps

- Finally, in the signal region, the number of "fakes" that pass the tight selection can be estimated.
- For dilepton events, the sum is over events with 1 tight lepton and one loose-not-tight lepton.
- ~17% background contribution.

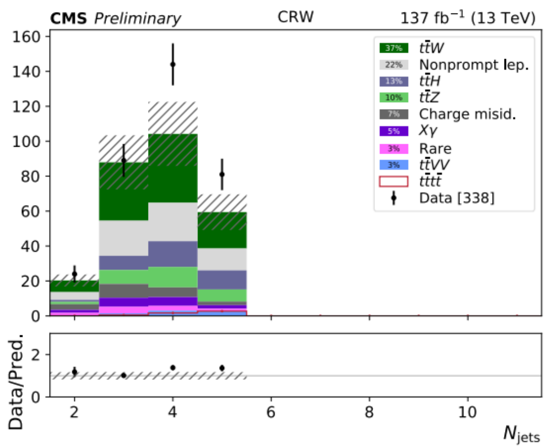


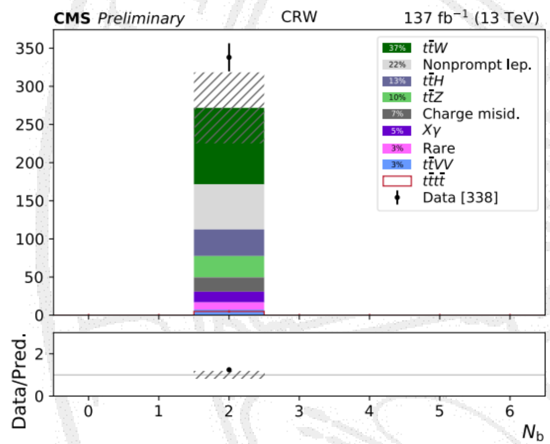


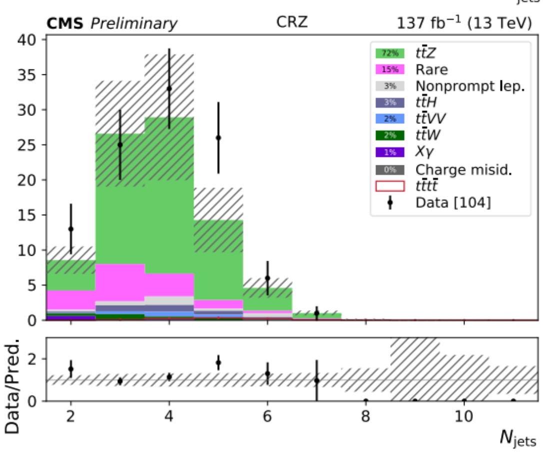
$$\#fakes = \sum_{\text{l!t leps}} \varepsilon(f_i, p_{T_i}, \eta_i)$$

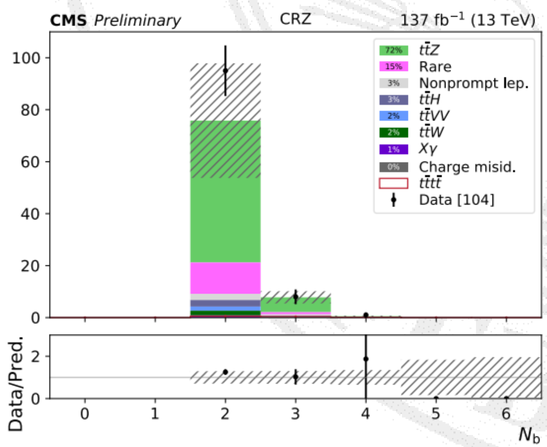
Backgrounds: $t\bar{t}W, t\bar{t}Z$

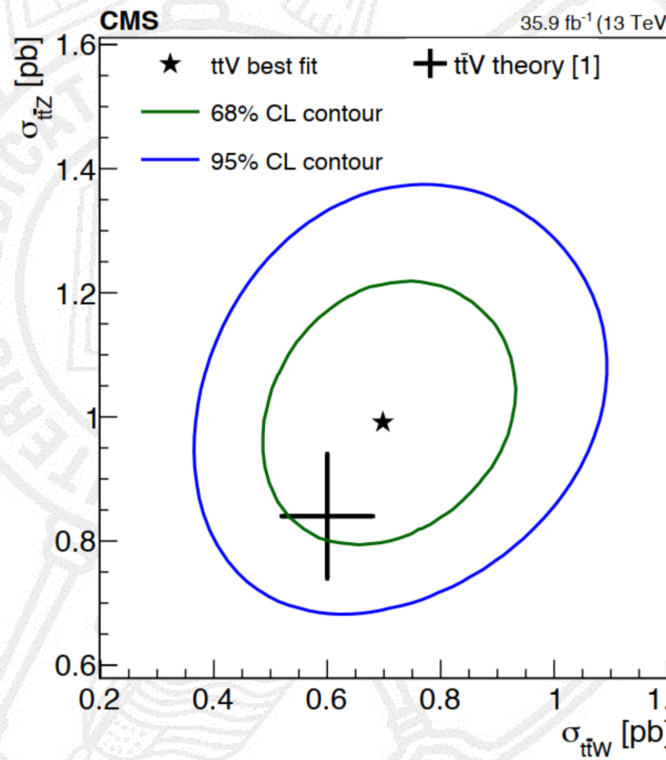
- Regions CRW and CRZ show 20-30% scale factor for $t\bar{t}W$, and $t\bar{t}Z$.
- Consistent with dedicated 2016 measurements being 20% (25%) higher than NLO calculations for $t\bar{t}W$ ($t\bar{t}Z$).







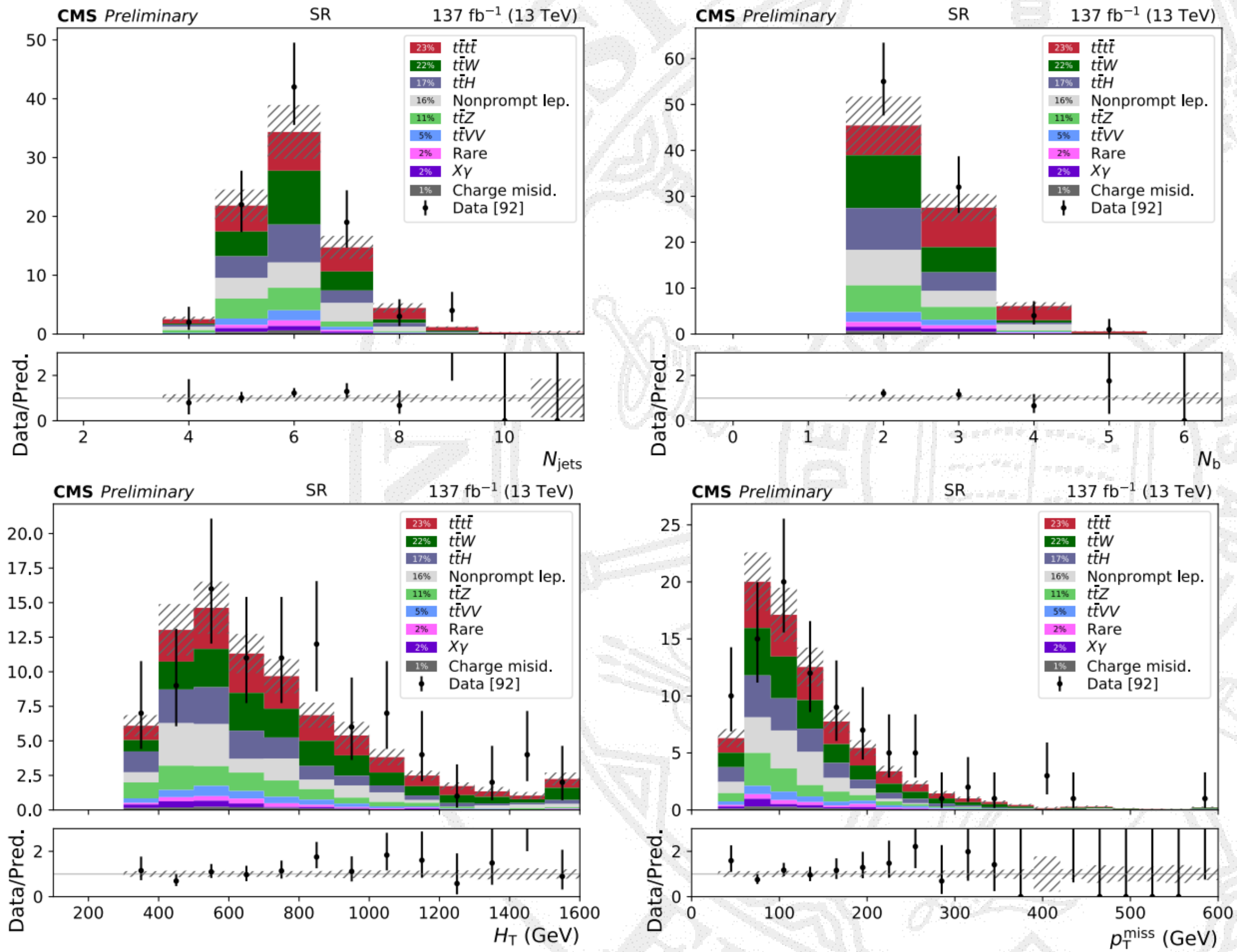




JHEP 08 (2018) 011

PAS TOP-19-009

Signal Region Kinematics

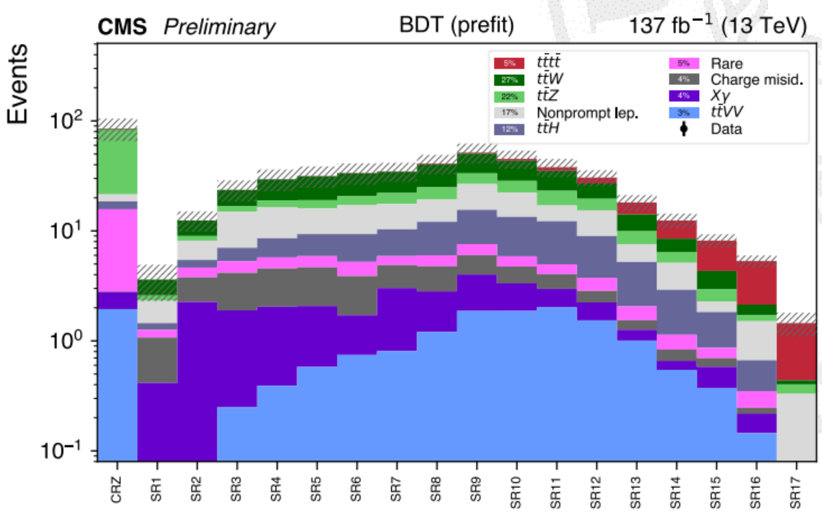


- Pre-fit signal region kinematic distributions show good agreement when including signal.

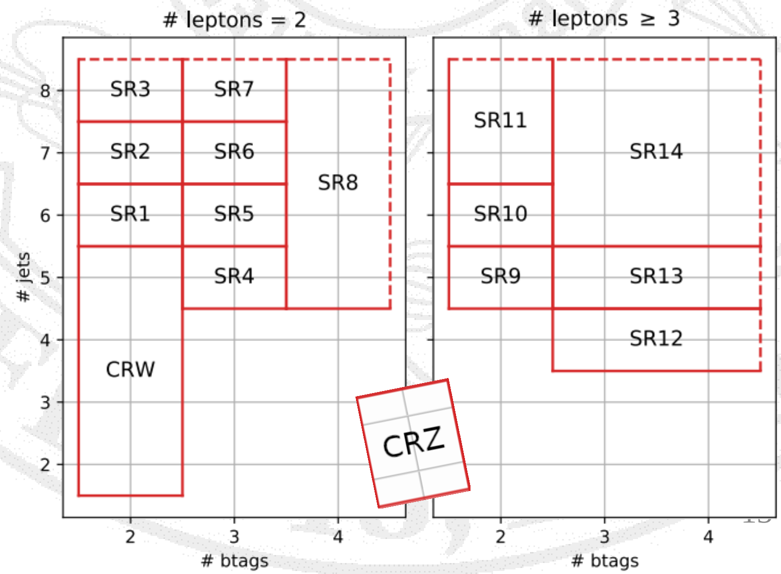
Signal Extraction

- A 19-variable `xgboost` BDT is trained with kinematic information to separate signal from background
  - $N_{jet}, N_b, N_{lep}, H_T$, Jet p_T, Lepton p_T, $\Delta\varphi$, $\Delta\eta$, …
- Along with a separate control region for $t\bar{t}Z$ (“CRZ”), 17 bins of the BDT discriminant are used in a maximum likelihood fit
- Cut based approach used as a cross check
  - 16 bins based on N_{jet}, N_b, and N_{lep}
  - In addition to CRZ, include a control region for $t\bar{t}W$ (“CRW”)

BDT signal regions

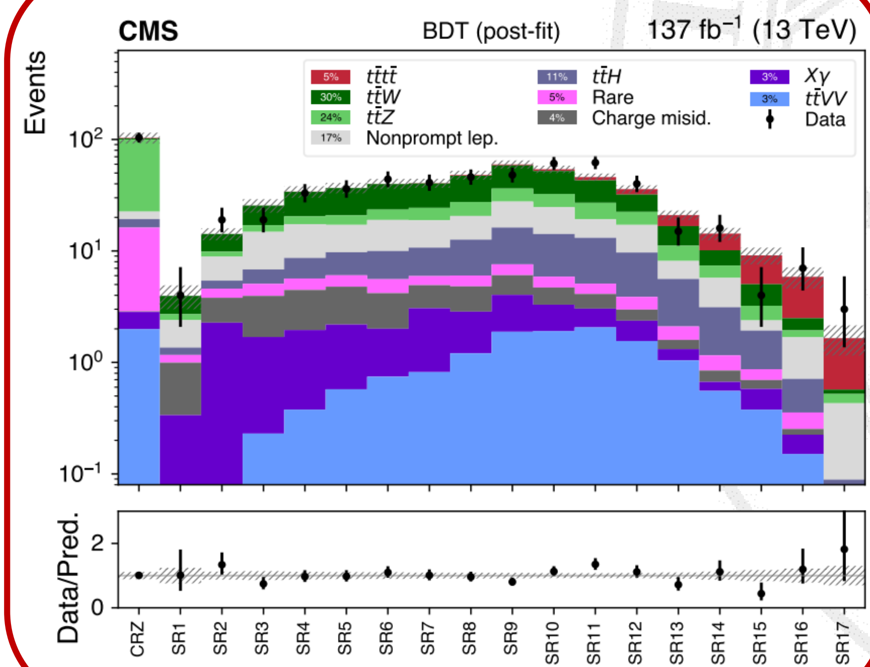


Cut-based signal regions

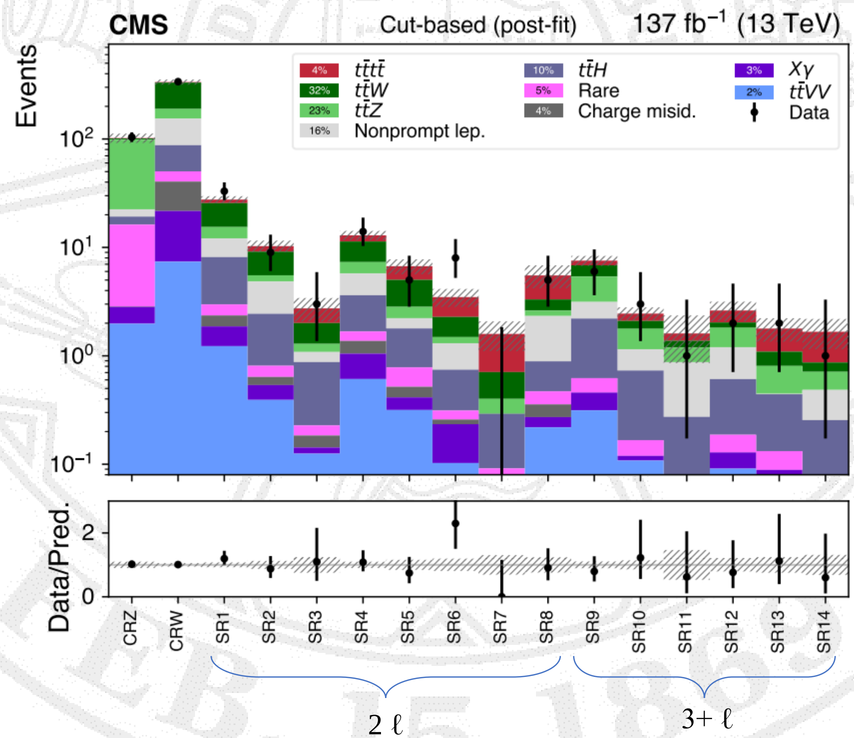


Results

- Full Run 2 BDT analysis ($137 fb^{-1}$)
  - 2.6σ obs. (2.7σ exp.) → $\sigma_{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2}$fb

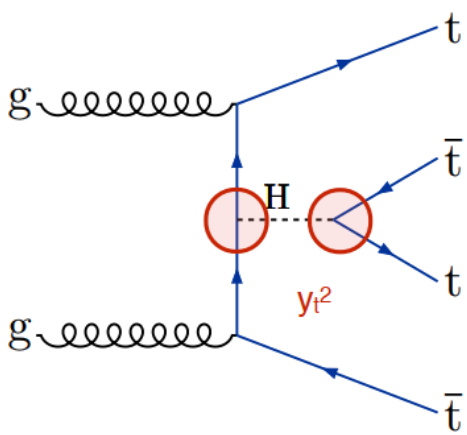


- Consistent with cut-based cross-check
  - 1.7σ obs. (2.5σ exp.) → $\sigma_{t\bar{t}t\bar{t}} = 9.4^{+6.2}_{-5.6}$fb

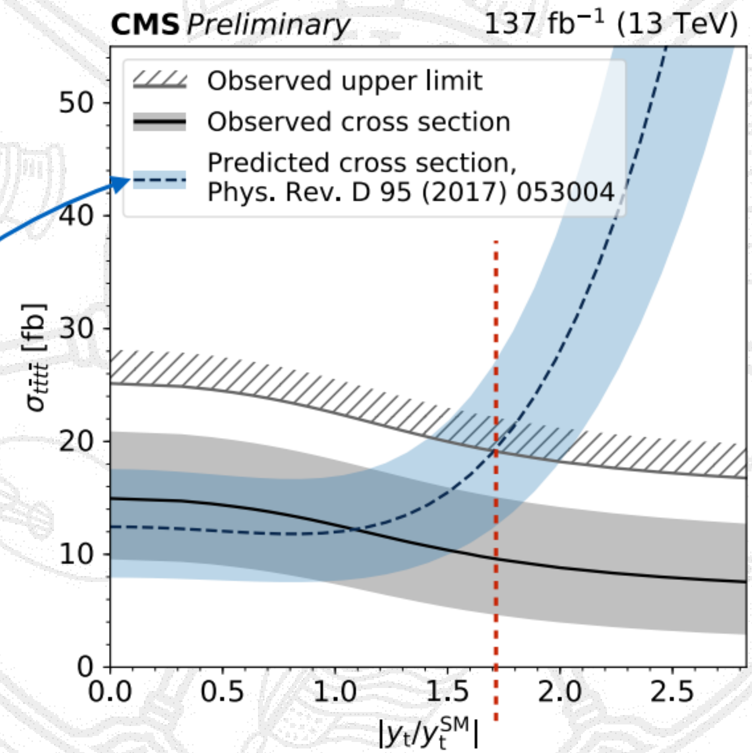


Interpretations: Top Yukawa

- Higgs-mediated contribution grows with y_t.
- Sloped $\sigma_{t\bar{t}t\bar{t}}$ from growing $t\bar{t}H$ background ($\propto {y_t}^2$)



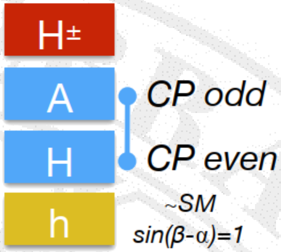
$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2 \sigma_{\rm int}^{\rm SM} + \kappa_t^4 \sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$



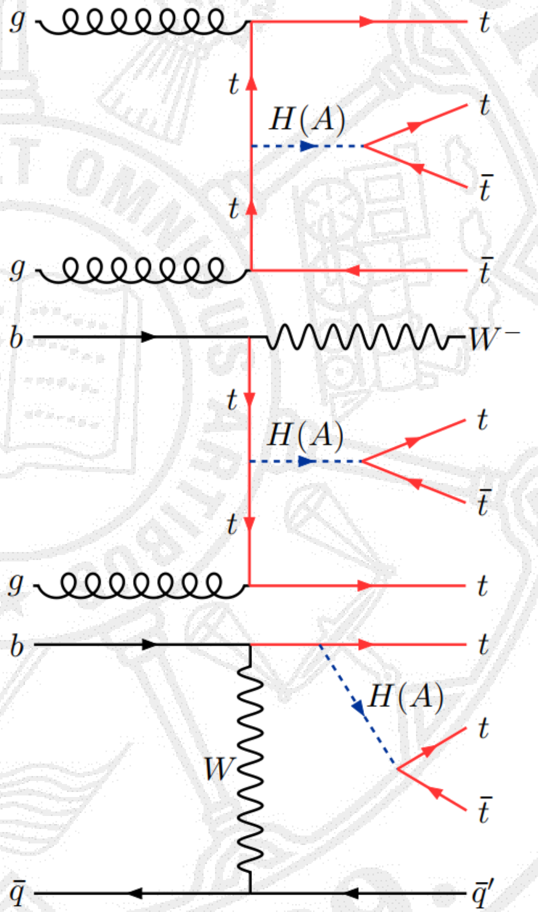
(1602.01934)

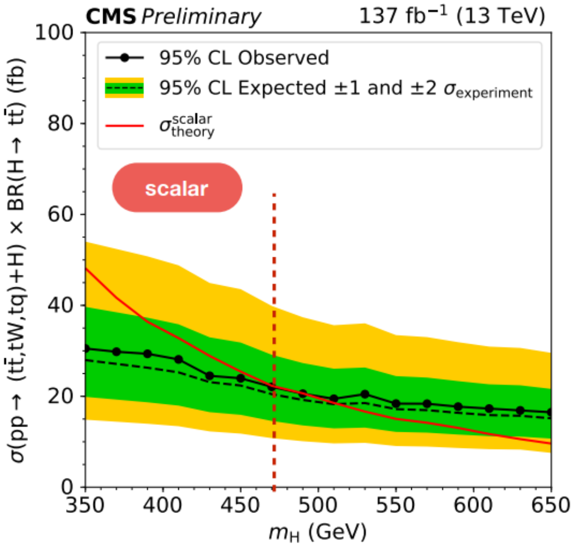
$|y_t/{y_t}^{SM}| < 1.7$ @ 95% CL

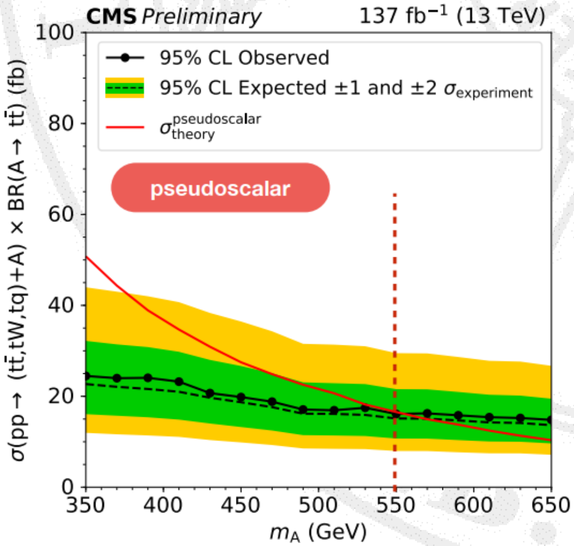
Interpretations: 2HDM



- General 2HDM predict an additional Higgs doublet → four new particles
  - Type-II, $\tan\beta = 1$ – prefer decays of H/A → $t\bar{t}$
  - $\sin\beta - \alpha = 1$, "alignment condition", makes light CP-even higgs h SM-like
- Probe **associated production** modes giving 3 and 4 top final states
  - Consider H and A separately, decoupling other particles
- Exclude heavy ($m > 2m_t$) scalar (pseudoscalar) bosons up to ~470 (550) GeV



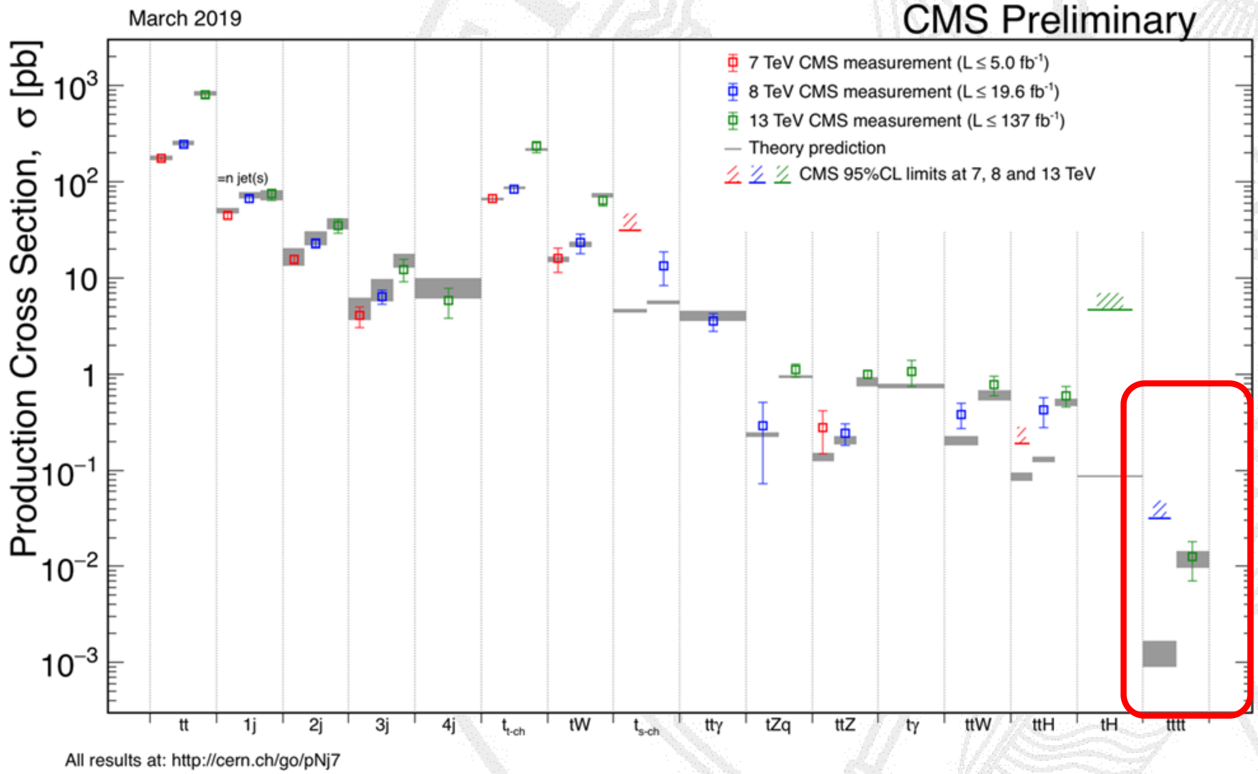




Summary

- Latest CMS measurement of $t\bar{t}t\bar{t}$ cross-section with 2L SS and $\geq$ 3L final state

$$\sigma_{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2}\text{fb (2.6}\sigma\text{ obs.)}$$



- Rich Phenomenology – Can constrain Top Yukawa coupling, exotic mediators, …

- Exciting prospects for Run 2/3 – Larger dataset, all final states

Backup

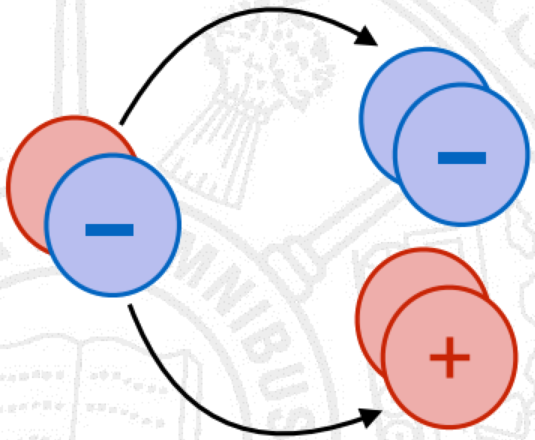
Systematic Uncertainties

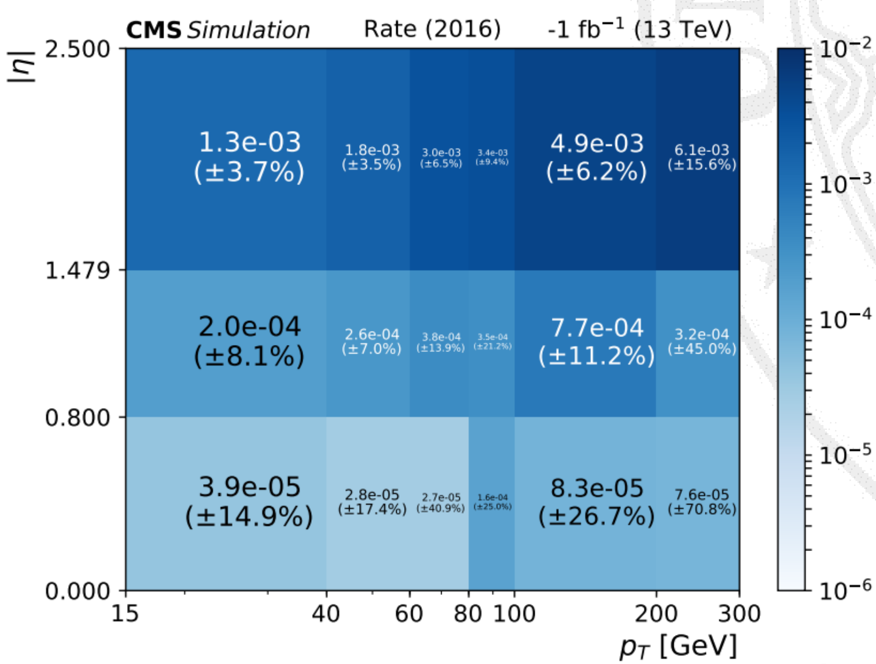
Source	Uncertainty (%)	Impact on $\sigma(\mathrm{t\bar{t}t\bar{t}})$ (%)
Integrated luminosity	2.3–2.5	3
Pileup	0–5	1
Trigger efficiency	2–7	2
Lepton selection	2–10	2
Jet energy scale	1–15	9
Jet energy resolution	1–10	6
b tagging	1–15	6
Size of simulated sample	1–25	<1
Scale and PDF variations †	10–15	2
ISR/FSR (signal) †	5–15	2
$\mathrm{t\bar{t}H}$ (normalization) †	25	5
Rare, $X\gamma$, $\mathrm{t\bar{t}VV}$ (norm.) †	11–20	<1
$\mathrm{t\bar{t}Z}$, $\mathrm{t\bar{t}W}$ (norm.) †	40	3-4
Charge misidentification †	20	<1
Nonprompt leptons †	30–60	3
$N_{\mathrm{jets}}^{\mathrm{ISR/FSR}}$	1–30	2
$\sigma(\mathrm{t\bar{t}b\bar{b}})/\sigma(\mathrm{t\bar{t}jj})$ †	35	11

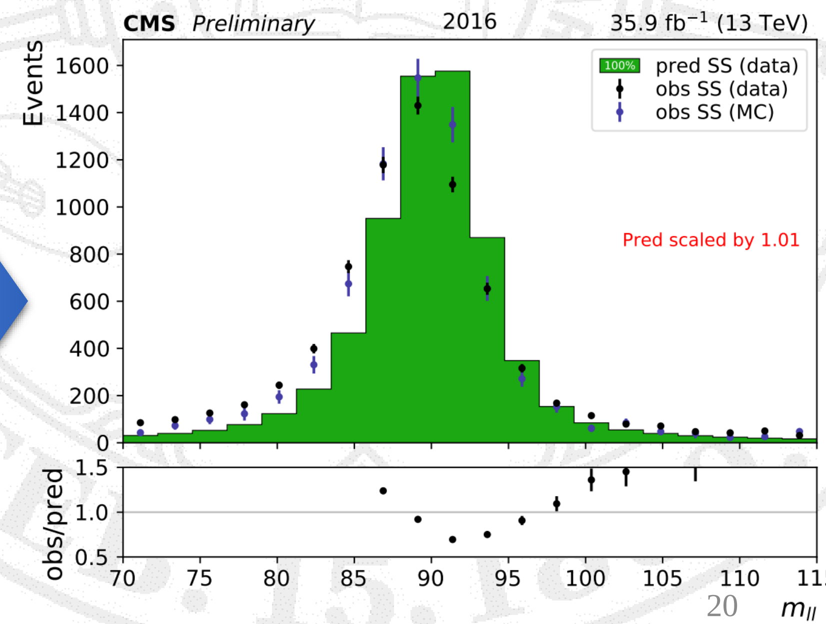
†Correlated across years

Backgrounds: Charge misid.

- Charge mismeasurement in dilepton OS events fakes a SS event.
  - Measure flip probability in simulated SR events
  - Verify normalization closure in Z-dominated CR
  - Reweight OS ee events to predict SS region contribution







Interpretations: Higgs Oblique Parameter

"…The Higgs boson oblique parameter $\widehat{H}$ [is] the hallmark of off-shell Higgs physics. $\widehat{H}$ is defined as the Wilson coefficient of the sole dimension-6 operator that modifies the Higgs boson propagator, within a Universal EFT"

(1903.07725)

$$\delta\sigma_{t\bar{t}t\bar{t}} \equiv \frac{\sigma_{\hat{H}} - \sigma_{\mathrm{SM}}}{\sigma_{\mathrm{SM}}} \approx 0.03 \left(\frac{\hat{H}}{0.04}\right) + 0.15 \left(\frac{\hat{H}}{0.04}\right)^2$$

- We generate $t\bar{t}t\bar{t}$ with different values of $\widehat{H}$ to account for changes in acceptance
- Scale $t\bar{t}H$ cross section by $\left(1-\widehat{H}\right)^2$ to account for its $\widehat{H}$ dependency.
- Combining this with the BDT analysis results yields a limit of

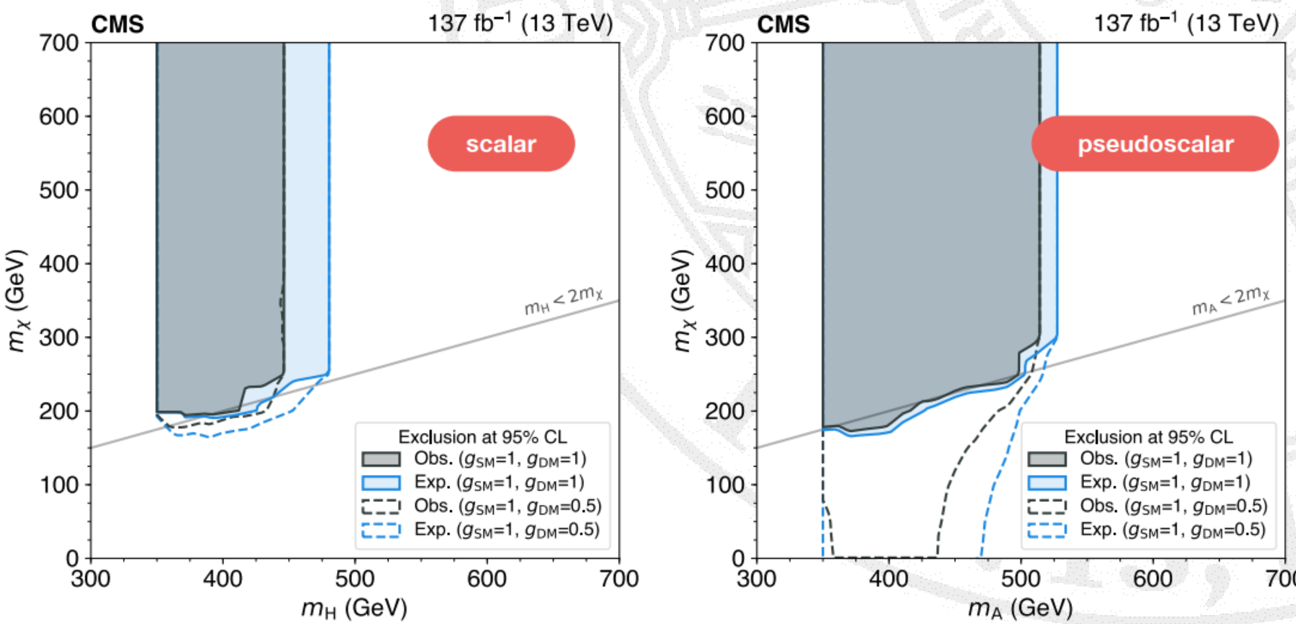
$$\widehat{H} < 0.16 \text{ @ } 95\% \text{ CL}$$

Interpretations: Dark Matter

- $t\bar{t} + DM$(1807.06522) and $t + DM$(1901.01553) can potentially give rise to multi-top final states
  - Complements traditional MET-based searches with $t\bar{t}t\bar{t}$ above (and slightly past) the $m_{\text{mediator}} = 2m_{DM}$ diagonal.
- Parameters
  - Mediator mass (scalar ϕ or pseudoscalar A)
  - DM particle χ mass
  - DM-mediator coupling, fermion-mediator coupling
- Simplified model assumes the two couplings to be unity

$$\mathcal{L}_\Phi \supset g_\chi \Phi \bar{\chi}\chi + \frac{g_v \Phi}{\sqrt{2}} \sum_f (y_f \bar{f} f)$$

$$\mathcal{L}_A \supset i g_\chi A \bar{\chi}\gamma^5 \chi + \frac{i g_v A}{\sqrt{2}} \sum_f (y_f \bar{f} \gamma^5 f)$$



Interpretations: Off-Shell Mediators

- New neutral particles with $m < 2m_t$?
- Consider scalar ϕ and vector Z' that are top-philic (1611.05032)
  - Constrain couplings above 1.1 (0.1-0.9) for scalar (vector) mediators