

Top quark production with vector bosons and heavy flavor quarks

Kirill Skovpen (Ghent University)

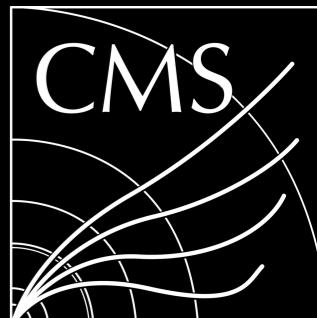
on behalf of the CMS Collaboration

 ICHEP 2022
BOLOGNA



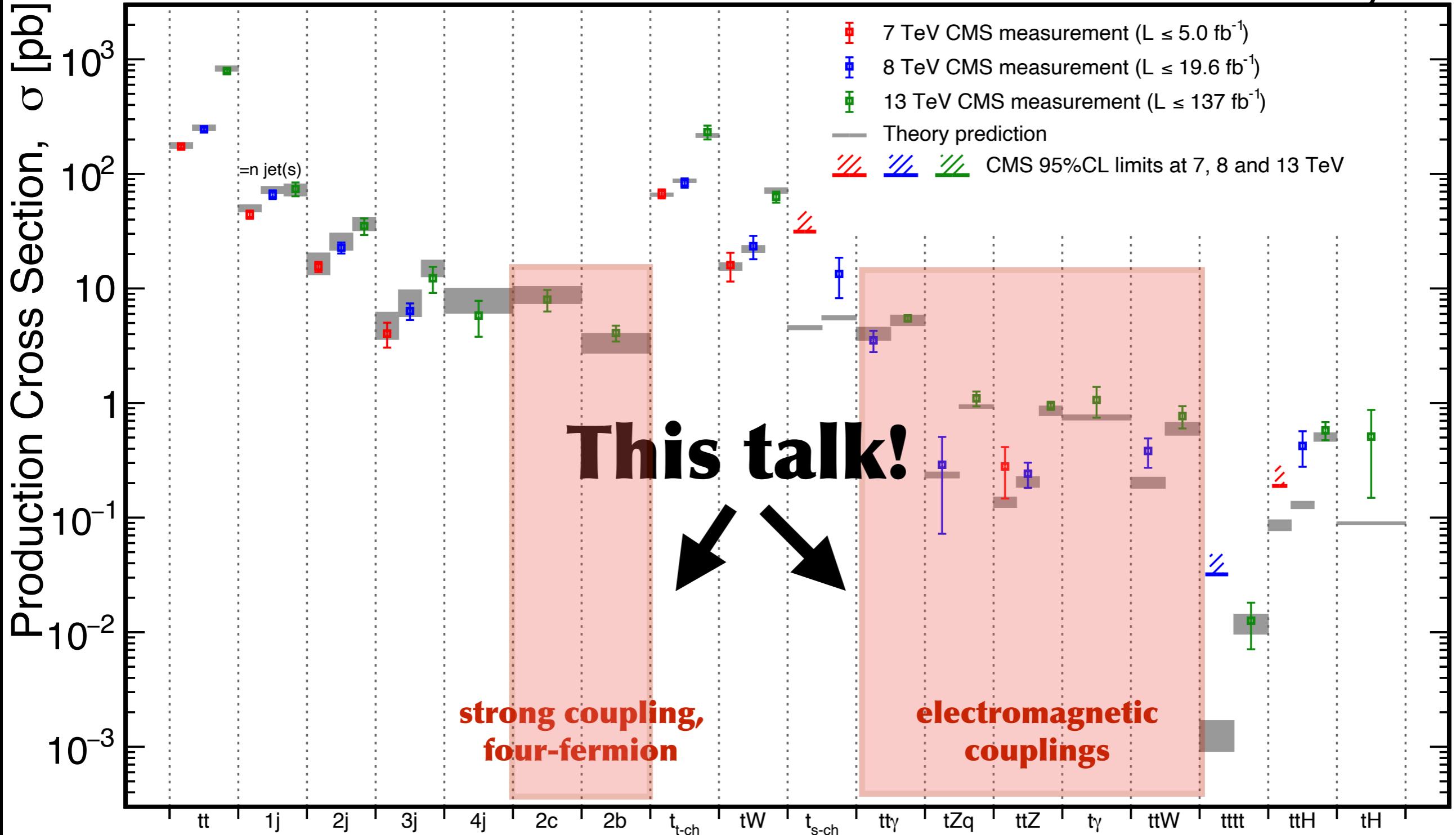
ICHEP 2022
XLI
International Conference
on High Energy Physics
Bologna (Italy)

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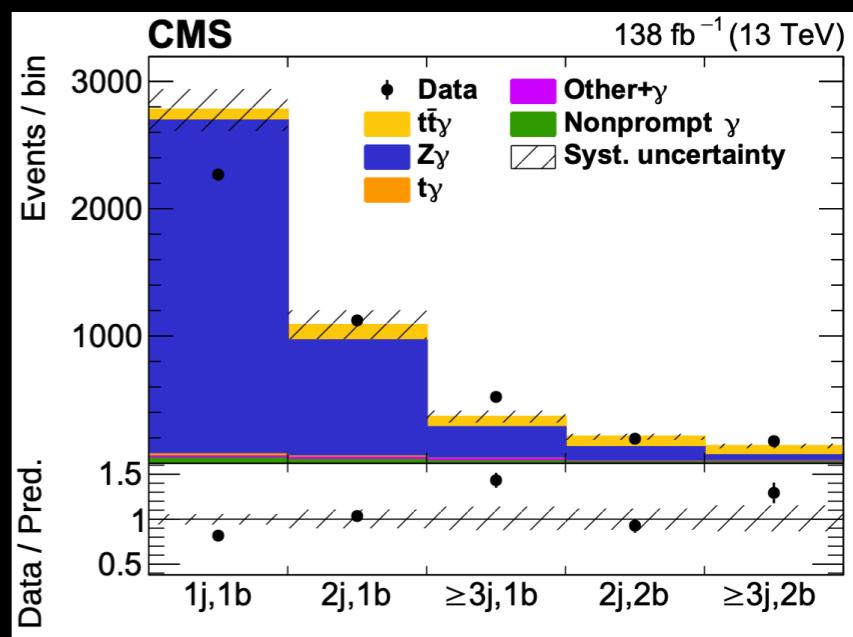
May 2021

CMS Preliminary

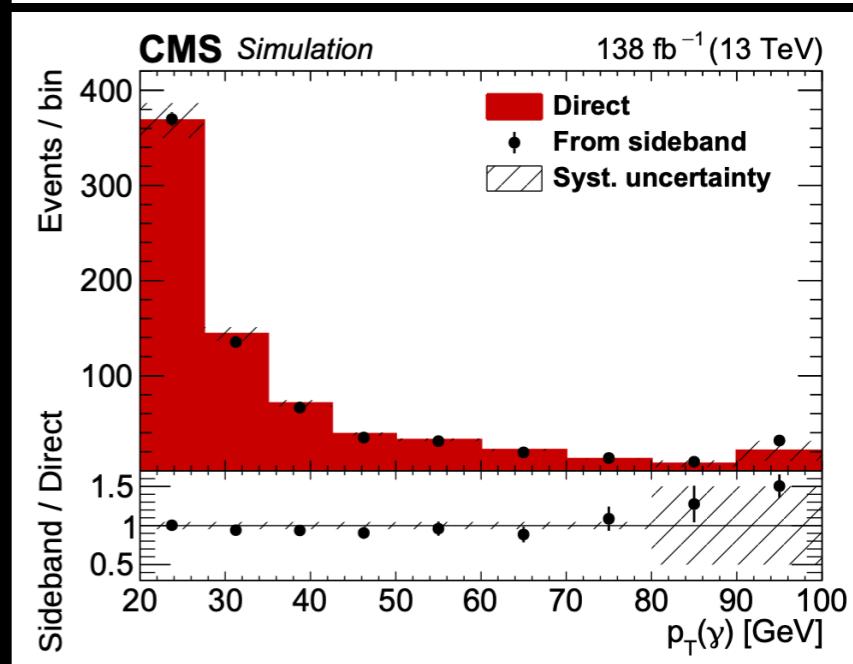


- Dilepton channels
- Inclusive and differential cross sections
- $N(\gamma) = 1$; $N(\ell) = 2$ (OS); $N(b) \geq 1$
- **Backgrounds:**
 - **nonprompt** photons (from data): tight-to-loose ratio with $\text{Iso}_{\text{ch}}(\gamma)$ and $\sigma_{\eta\eta}$
 - **prompt** photons ($Z\gamma$): reduce by $|m(\ell\ell) - m_Z| > 15 \text{ GeV}$, $|m(\ell\ell\gamma) - m_Z| > 15 \text{ GeV}$; derive correction factors in data as function of $N(j)$ for $|m(\ell\ell\gamma) - m_Z| < 15 \text{ GeV}$
- **Uncertainties:** integrated luminosity, signal modeling (fact. and renorm. scales, ISR/FSR), limited statistics in data

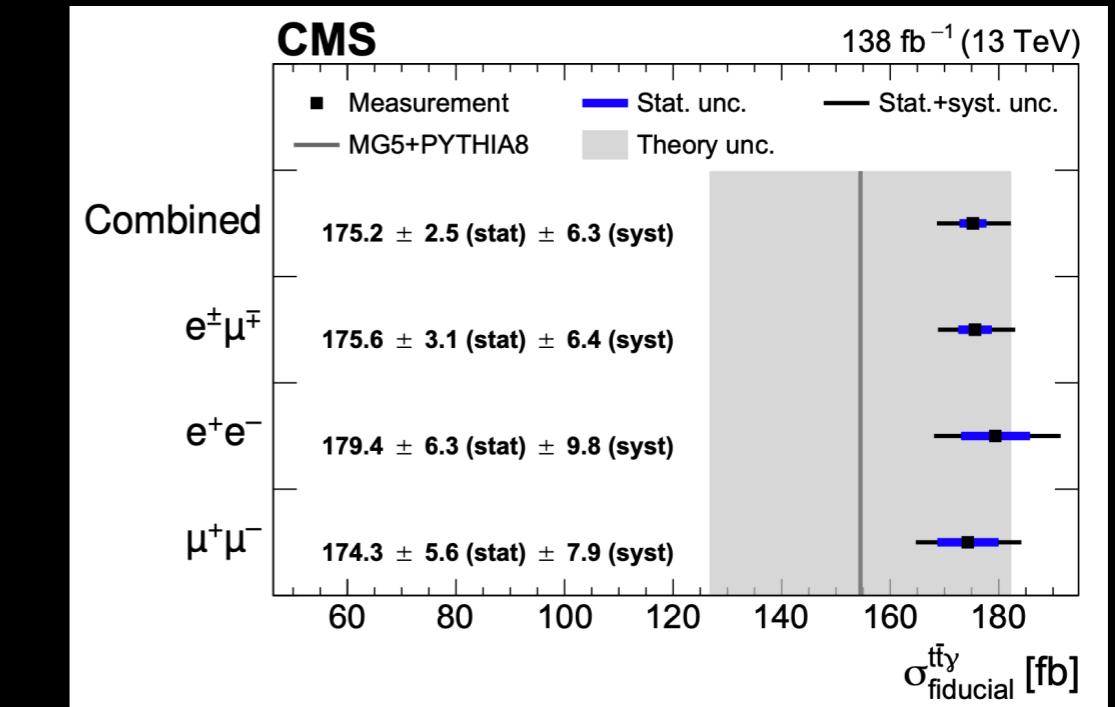
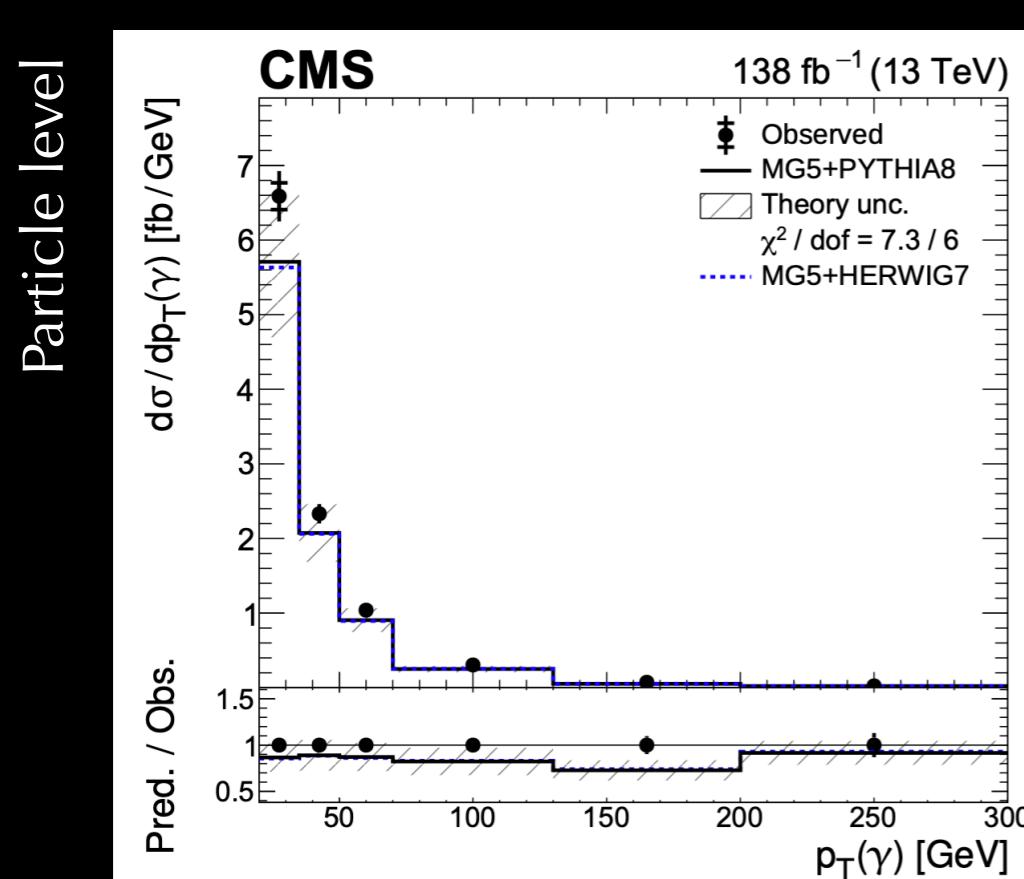
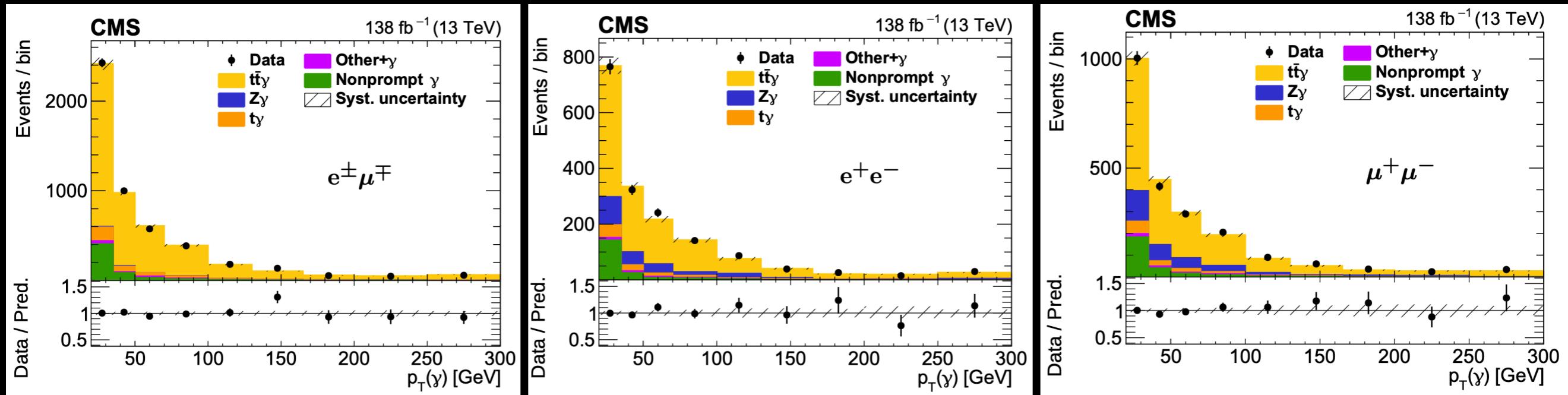
Prompt photon background



Nonprompt photon background



Fiducial region:	Leptons	Photons	Jets	b jets	Events
	$p_T > 25 (15) \text{ GeV}$	$p_T > 20 \text{ GeV}$	$p_T > 30 \text{ GeV}$	$p_T > 30 \text{ GeV}$	$N_\ell = 2 (\text{OC})$
	$ \eta < 2.4$	$ \eta < 1.44$	$ \eta < 2.4$	$ \eta < 2.4$	$N_\gamma = 1$
		$\Delta R(\gamma, \ell) > 0.4$	$\Delta R(\text{jet}, \ell) > 0.4$	$\Delta R(\text{jet}, \ell) > 0.4$	$N_b \geq 1$
		isolated	$\Delta R(\text{jet}, \gamma) > 0.1$	$\Delta R(\text{jet}, \gamma) > 0.1$	$m(\ell\ell) > 20 \text{ GeV}$
				matched to b hadron	



$$\sigma(t\bar{t}\gamma) = 175 \pm 3 \text{ (stat)} \pm 6 \text{ (syst)} \text{ pb}$$

$$\sigma^{\text{NLO}}(t\bar{t}\gamma) = 155 \pm 27 \text{ pb}$$

$t\bar{t} + \gamma$

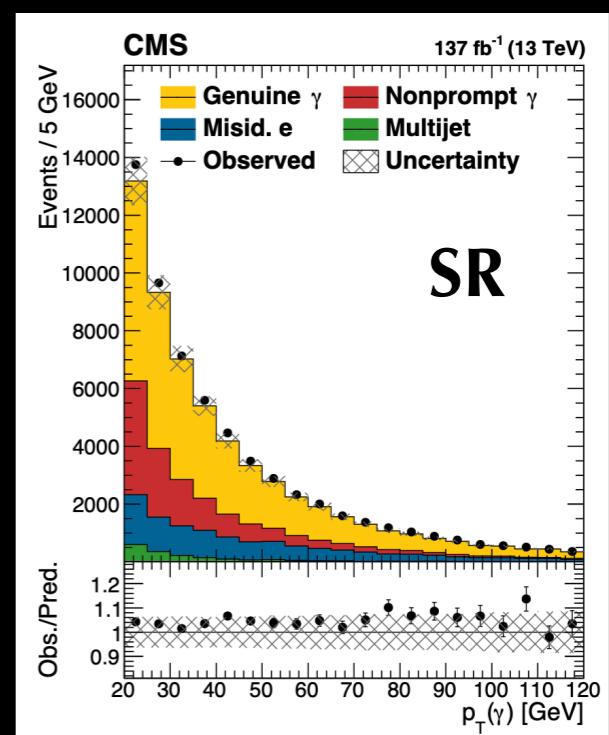
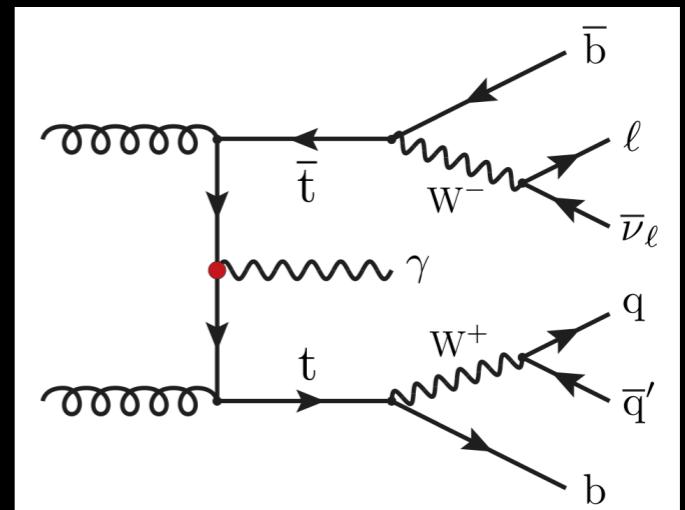
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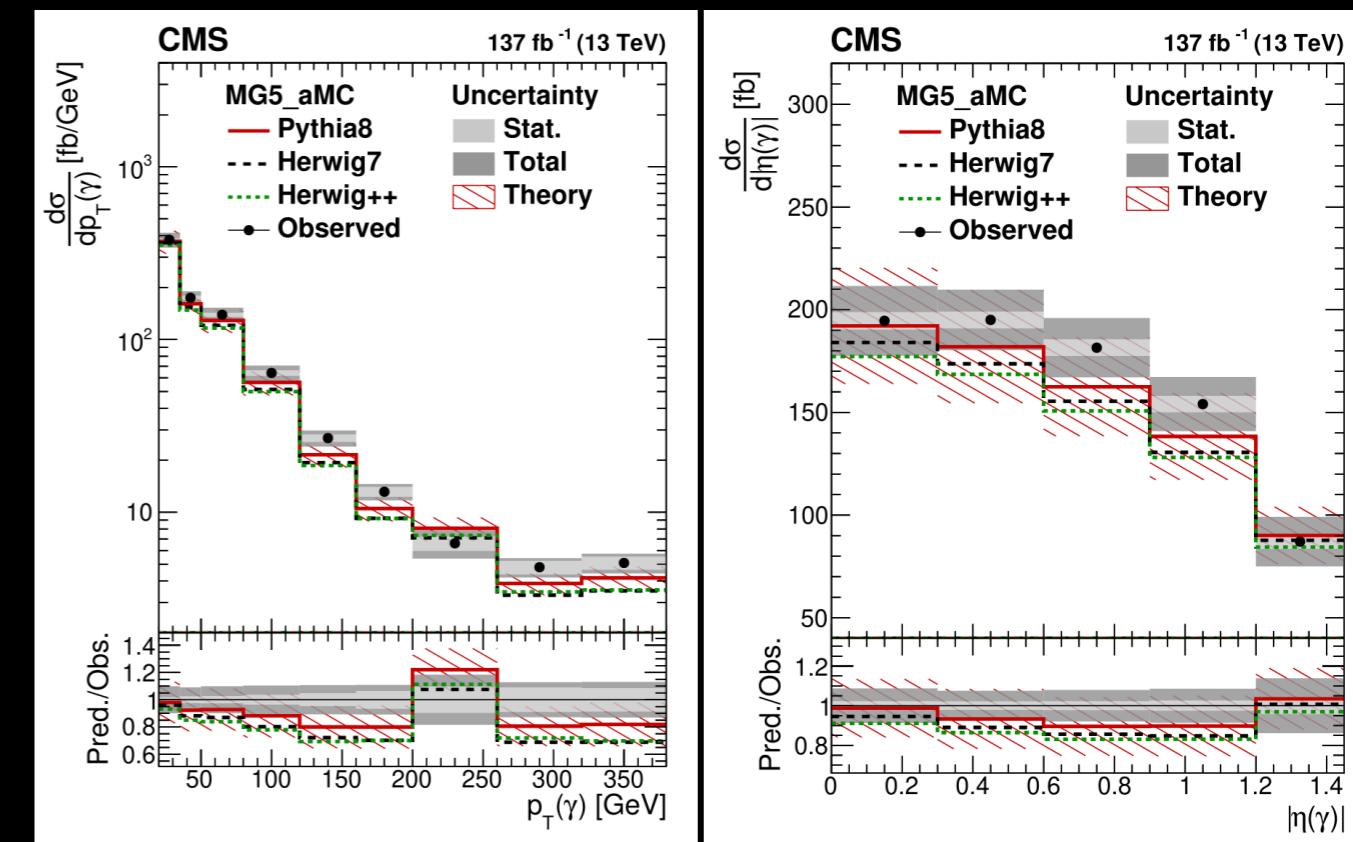
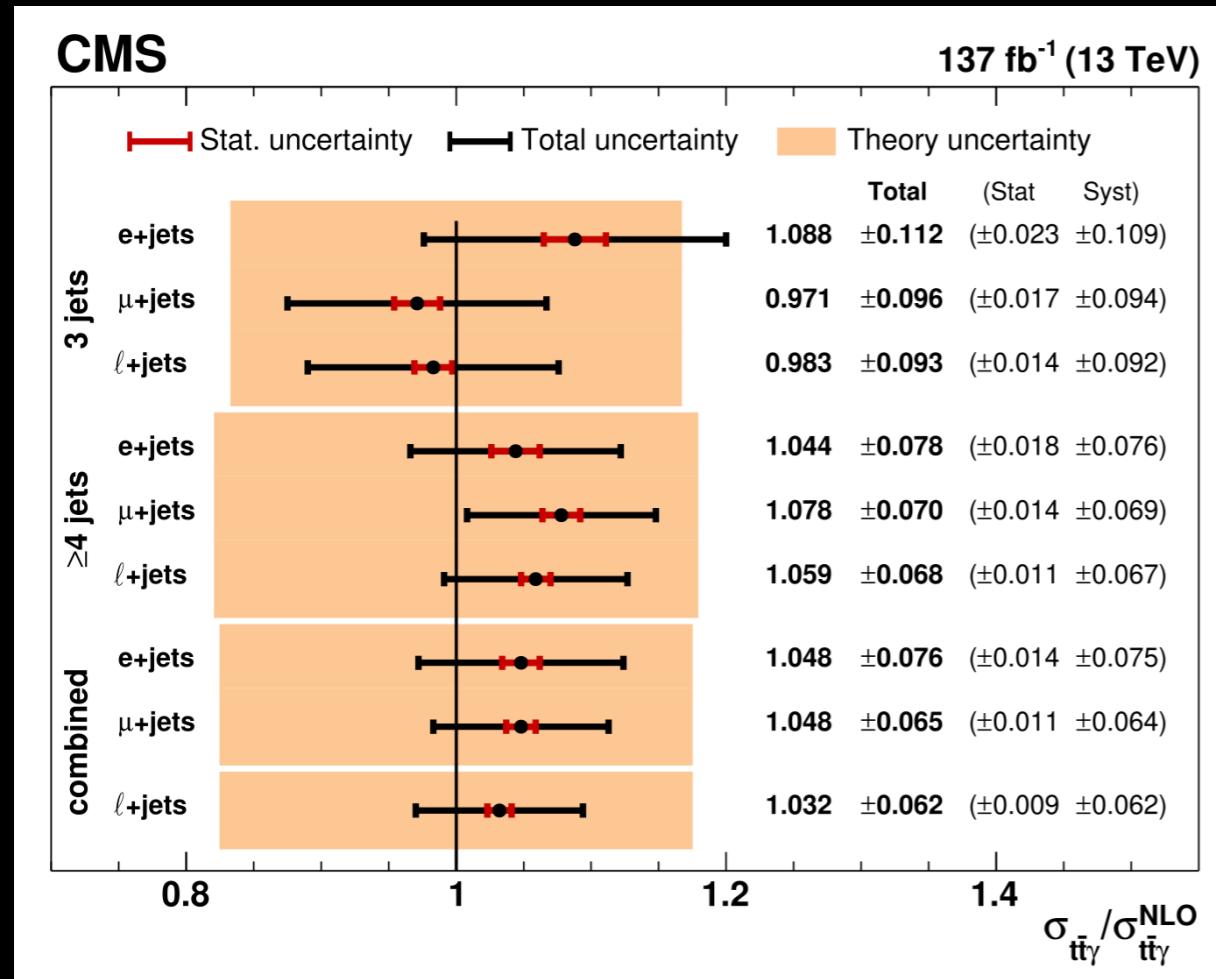
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Fiducial region:

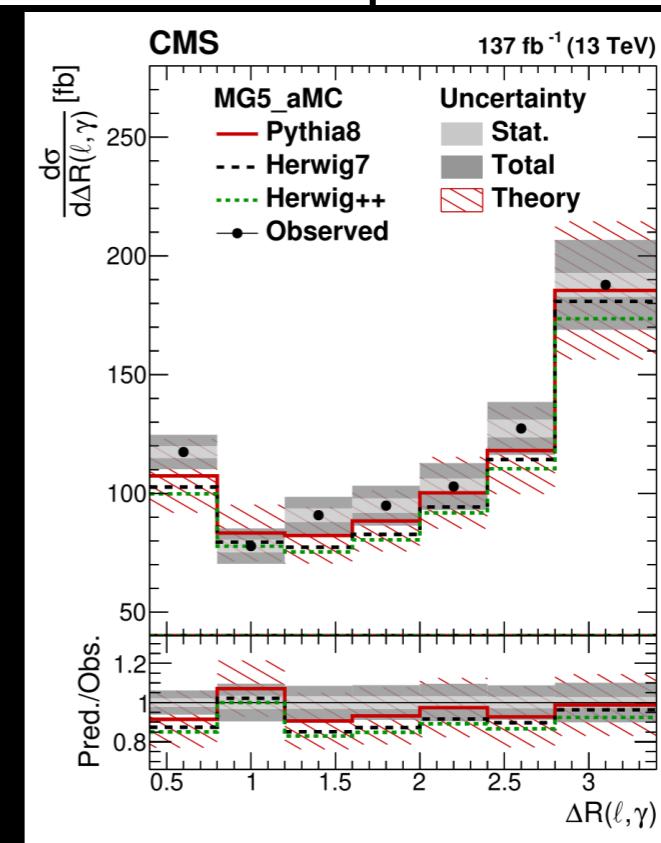
- ⦿ Single lepton + jets
- ⦿ Inclusive and differential cross sections
- ⦿ $N(\gamma) = 1; N(\ell) = 1; N(j) \geq 3$, where $N(b) \geq 1$
- ⦿ Photons: « **genuine** » (matched to generator photon from W, lepton or quark), « **missId** » (matched to electron), « **nonprompt** » (generated photon from hadrons, pileup)
- ⦿ **Backgrounds** (from data):
 - missId electrons
 - nonprompt photons: **tight-to-loose ratio** with $\text{Iso}_{\text{ch}}(\gamma)$ and $\sigma_{\eta\eta}$
 - QCD multijet
 - $W\gamma, Z\gamma$ (from control regions)
- ⦿ **Uncertainties**: integrated luminosity, data-driven backgrounds, signal modeling (ISR/FSR)

Photon	e (μ)	Jet	b jet
$p_T > 20 \text{ GeV}$	$p_T > 35 (30) \text{ GeV}$	$p_T > 30 \text{ GeV}$	$p_T > 30 \text{ GeV}$
$ \eta < 1.4442$	$ \eta < 2.4$	$ \eta < 2.4$	$ \eta < 2.4$
no hadronic origin	no hadronic origin	$\Delta R(\text{jet}, \ell) > 0.4$	$\Delta R(\text{b jet}, \ell) > 0.4$
$\Delta R(\ell, \gamma) > 0.4$		$\Delta R(\text{jet}, \gamma) > 0.1$	$\Delta R(\text{b jet}, \gamma) > 0.1$
isolated			matched to b hadrons





$\sigma(t\bar{t}\gamma) = 798 \pm 7 \text{ (stat)} \pm 48 \text{ (syst)} \text{ pb}$
 $\sigma^{\text{NLO}}(t\bar{t}\gamma) = 773 \pm 135 \text{ pb}$

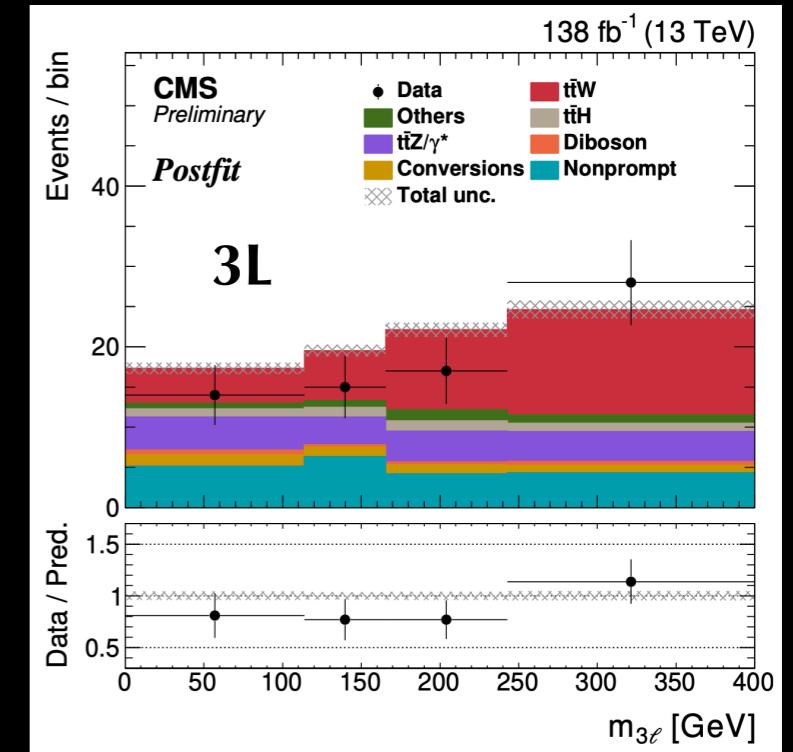
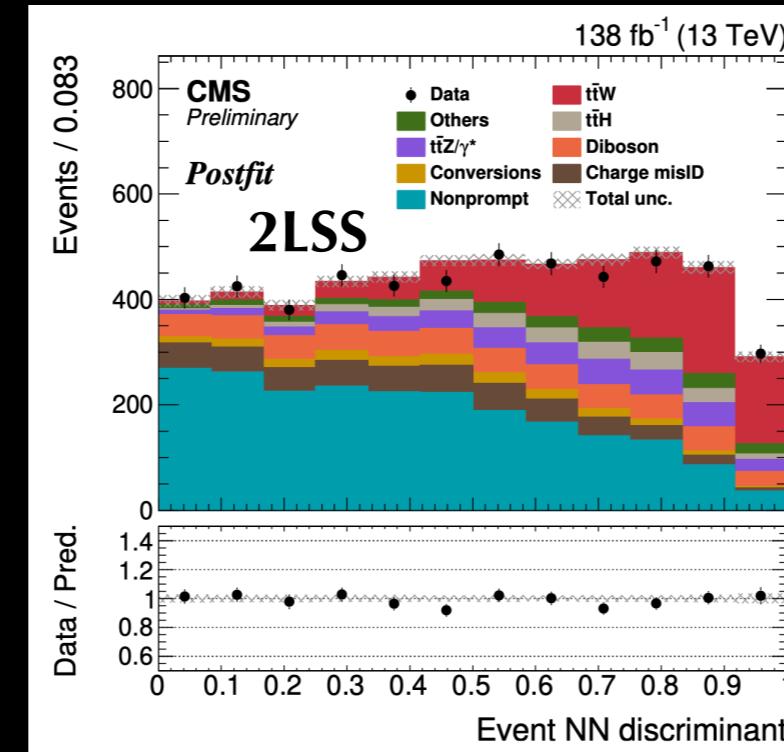
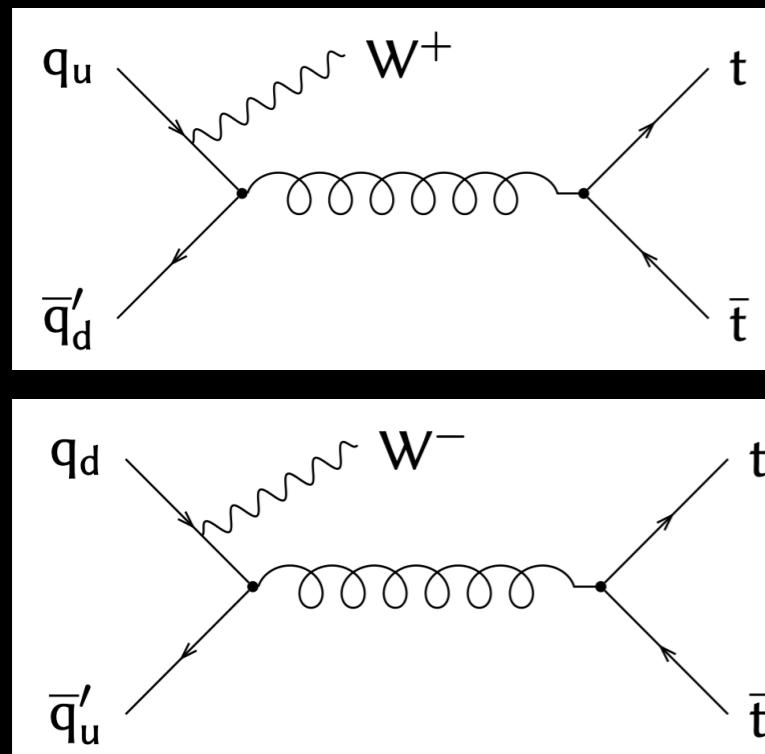


Particle level

$t\bar{t} + W$

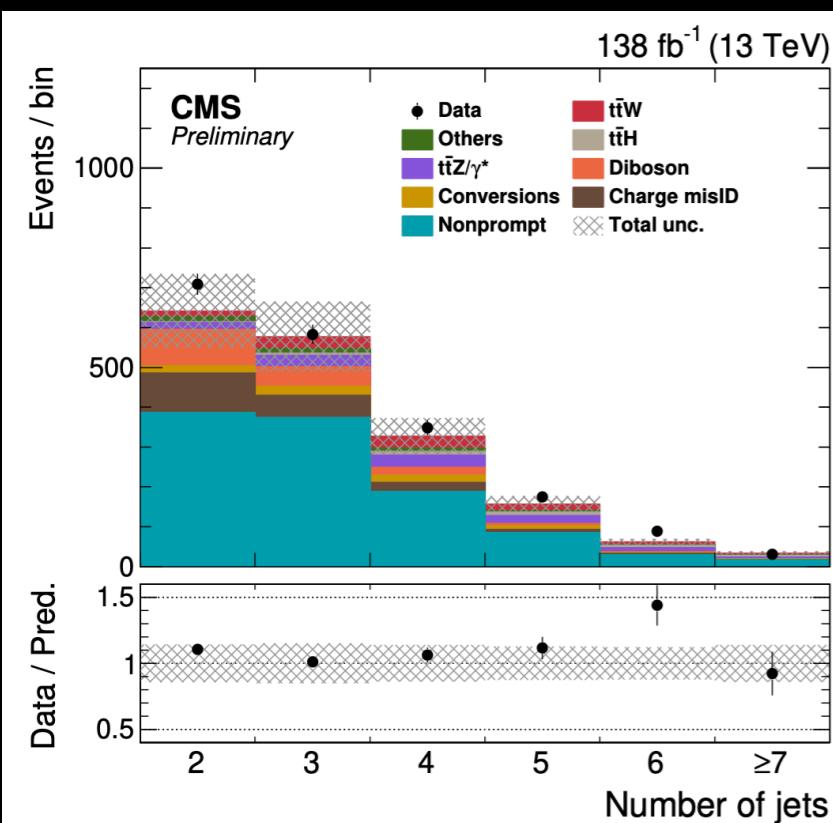
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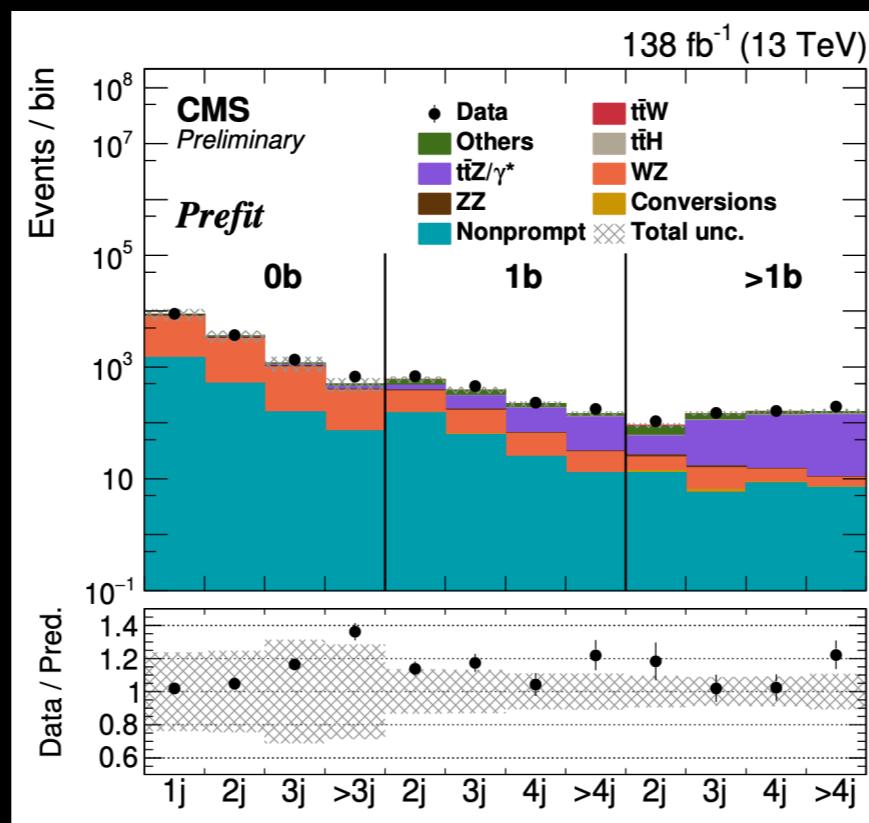


- ⦿ Sizable difference in production between ttW^+ and ttW^- processes (no gg-initiated production)
- ⦿ Inclusive cross section
- ⦿ $N(\ell) = 2$ (SS): $N(j) \geq 2$, where $N(b^L) \geq 2$ or $N(b^T) \geq 1$; $E_T^{\text{miss}} > 30 \text{ GeV}$, $|m(ee) - m_Z| > 15 \text{ GeV}$
- ⦿ $N(\ell) = 3$: $N(j) \geq 2$, where $N(b^M) \geq 1$, $|m(\ell\ell) - m_Z| > 10 \text{ GeV}$
- ⦿ Strategy: **NN** discriminant in 2LSS, **m(3 ℓ)** in 3L
- ⦿ **Backgrounds:** **nonprompt** leptons, **charge misId** (from Drell-Yan and ttbar MC events, validated using Z events in data), **photon conversions** (from MC), **prompt** leptons
- ⦿ **Uncertainties:** ttH normalization, integrated luminosity, statistical uncertainty, data-driven background, signal modeling, ttVV and VVV normalizations

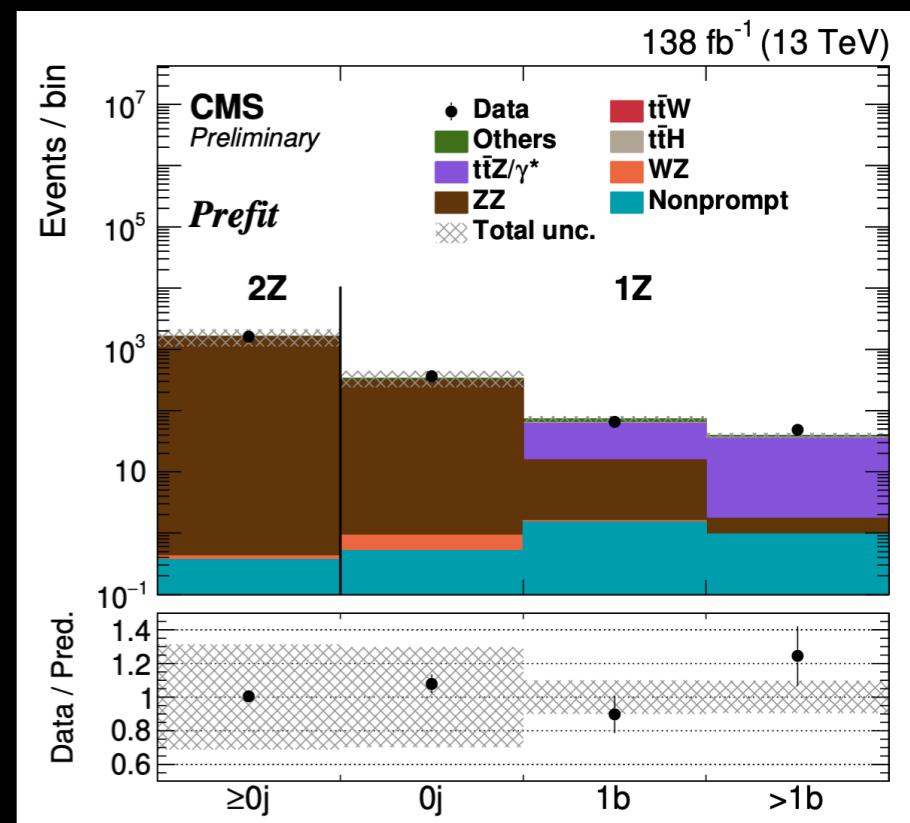
Nonprompt leptons



Prompt leptons (WZ, ttZ)



Prompt leptons (ZZ)



- ⌚ Tight-to-loose ratio, from template fit using m_T^{fixed} ($p_T^{\text{fixed}} = 35 \text{ GeV}$)

- ⌚ Control region (2LSS), $E_T^{\text{miss}} < 30 \text{ GeV}$

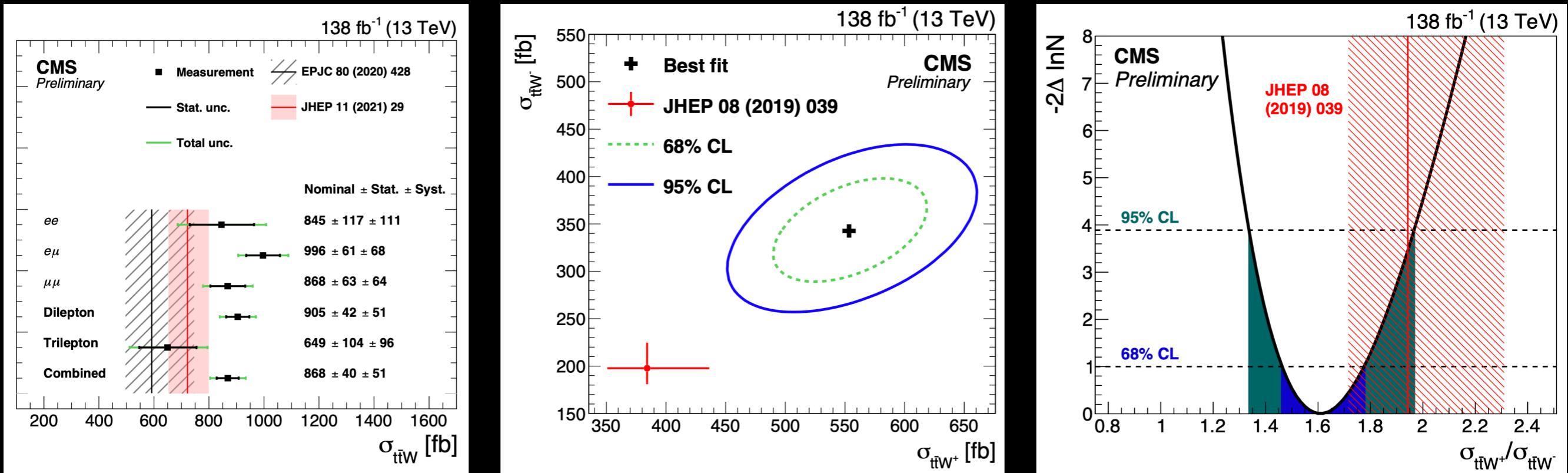
- ⌚ Control region (3L)
- ⌚ $|m(\ell\ell) - m_Z| < 10 \text{ GeV}$

- ⌚ Control region (4L)
- ⌚ $|m(\ell\ell) - m_Z| < 10 \text{ GeV}$

$t\bar{t} + W$

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CMS PAS TOP-21-011

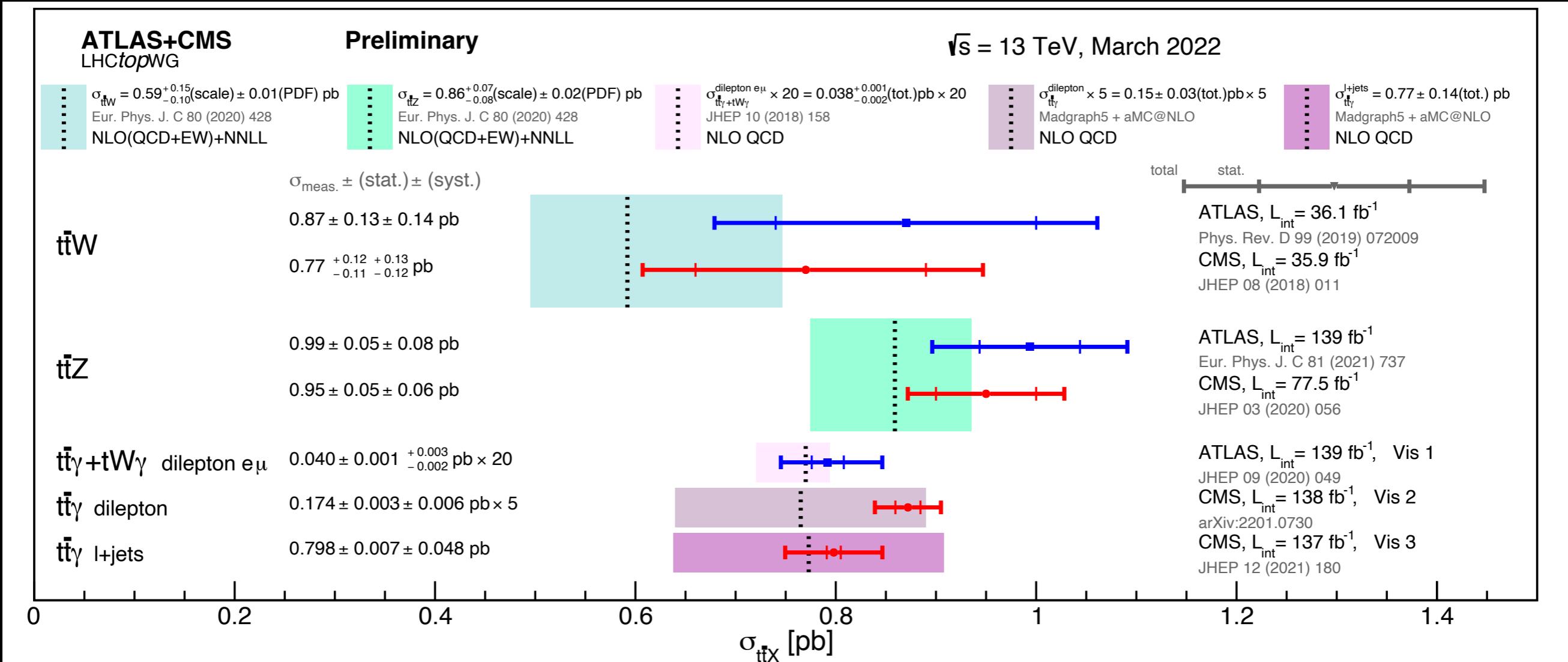


$$\sigma(t\bar{t}W) = 868 \pm 40 \text{ (stat)} \pm 52 \text{ (syst)} \text{ pb}$$

$$\sigma^{\text{NLO+NNLL}}(t\bar{t}W) = 592^{+155}_{-96} \text{ (scale)}^{+12}_{-12} \text{ (PDF)} \text{ pb} [\text{Eur. Phys. J. C 80 (2020) 428}]$$

$$\sigma^{\text{NLO}}(t\bar{t}W) = 722^{+70}_{-78} \text{ (scale)}^{+7}_{-7} \text{ (PDF)} \text{ pb} [\text{JHEP 11 (2021) 29}]$$

$t\bar{t} + V$: Overview

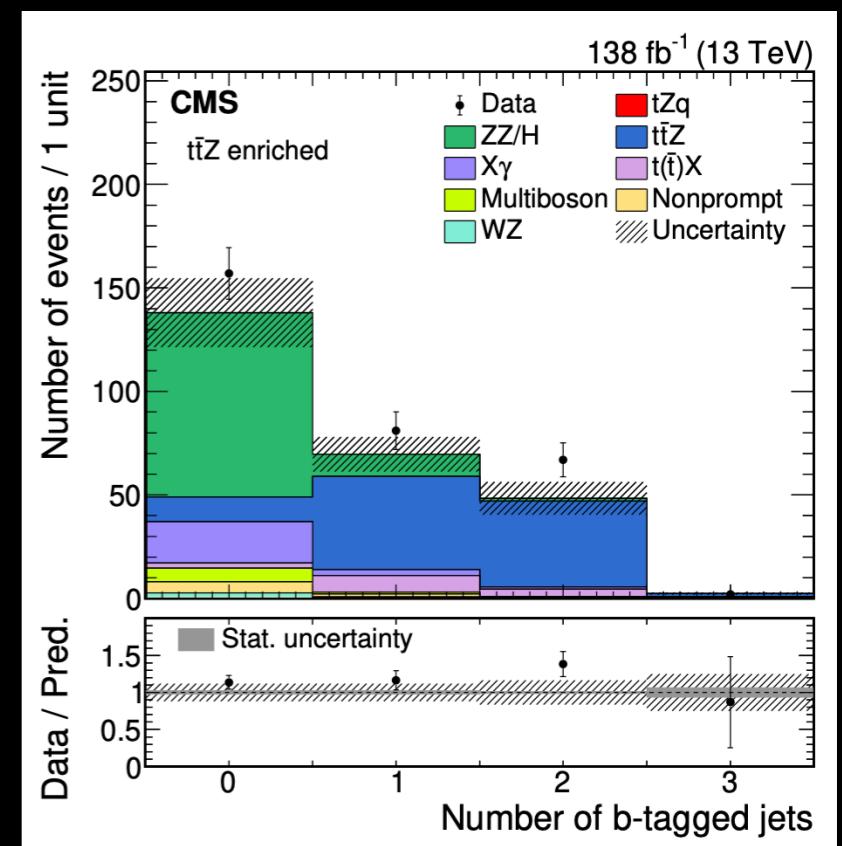
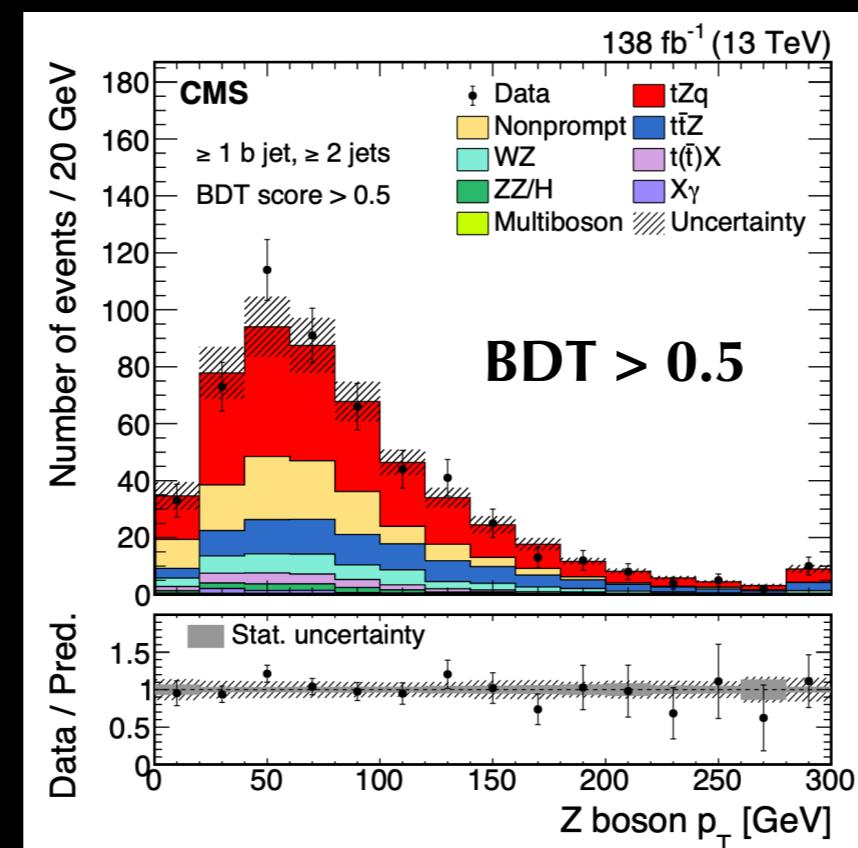
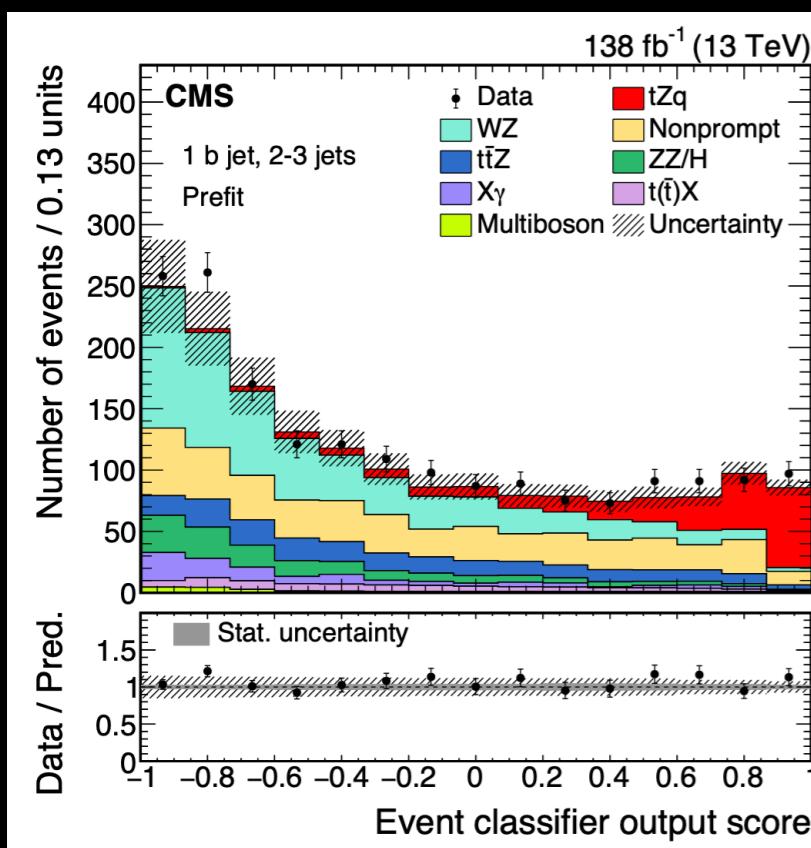
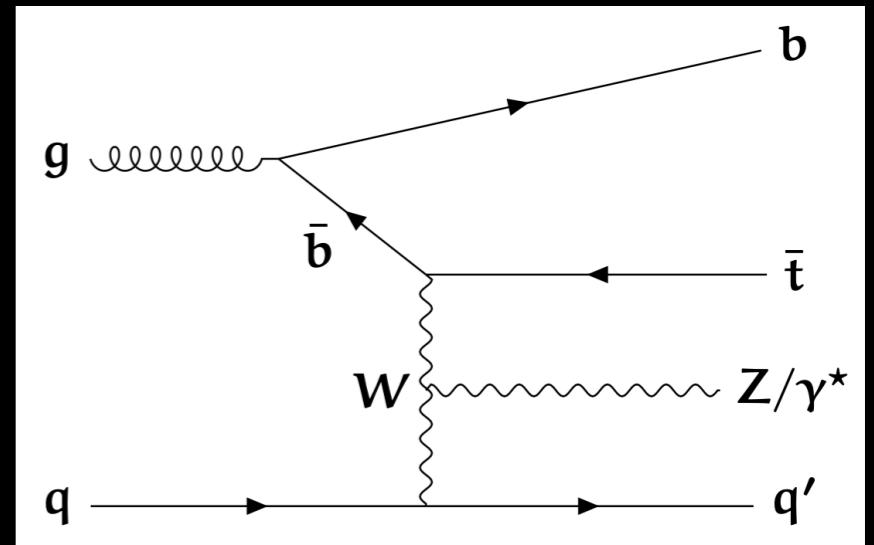


$t(\bar{t}) + Z + q$

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- Top quark is strongly **polarized**
- $N(\ell) = 3$; $N(j) \geq 2$, where $N(b) \geq 1$; $|m(\ell\ell) - m_Z| < 15 \text{ GeV}$
- Inclusive and differential cross sections
- BDT** to suppress backgrounds
- Backgrounds:**
 - **prompt** leptons (from data and MC):
 - **nonprompt** leptons (tight-to-loose ratio)
- Uncertainties:** signal modeling, nonprompt, WZ normalization



- ttZ:** four-lepton CR, no second on-Z lepton pair (reduce ZZ)

$t(\bar{t}) + Z + q$

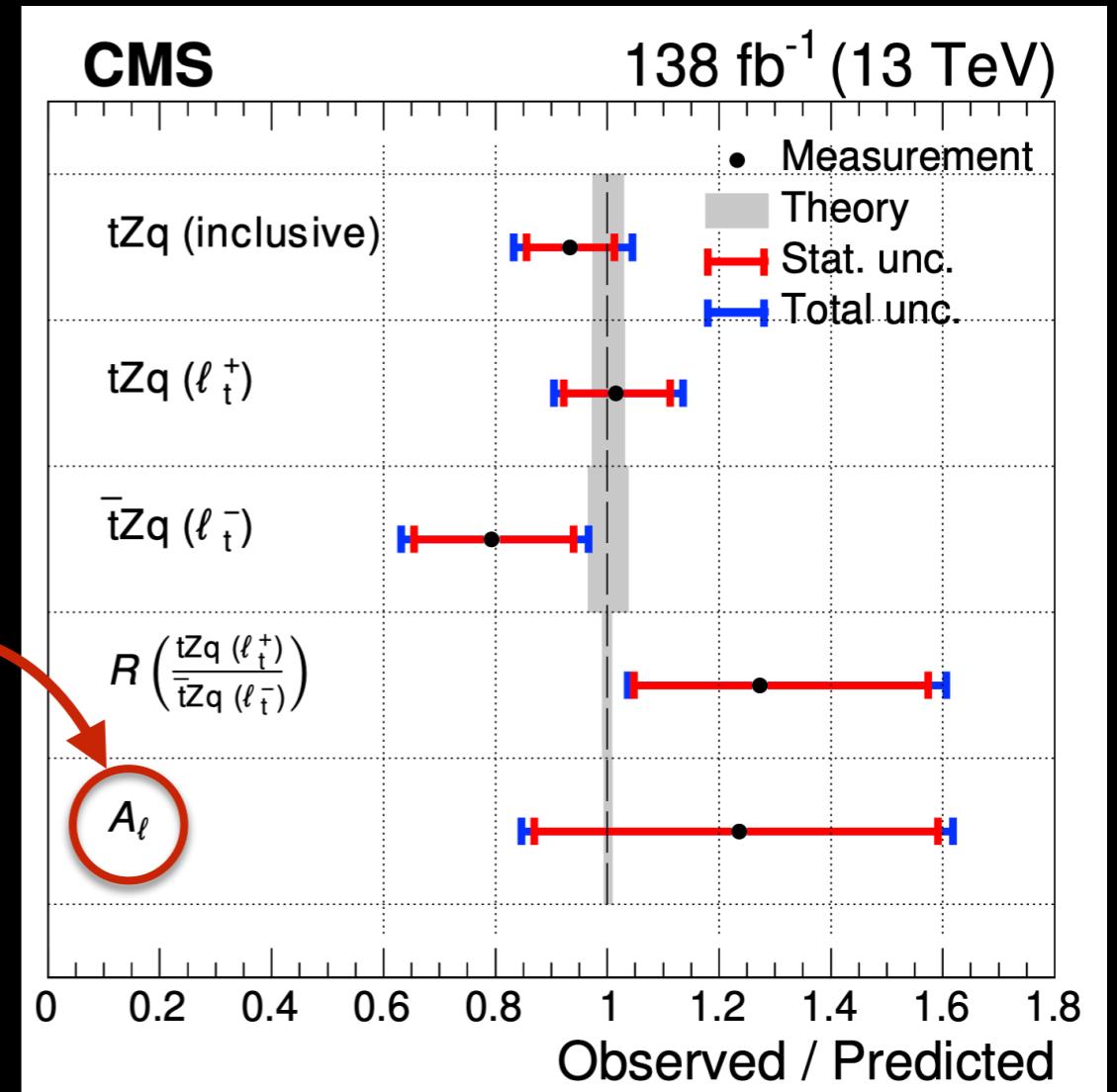
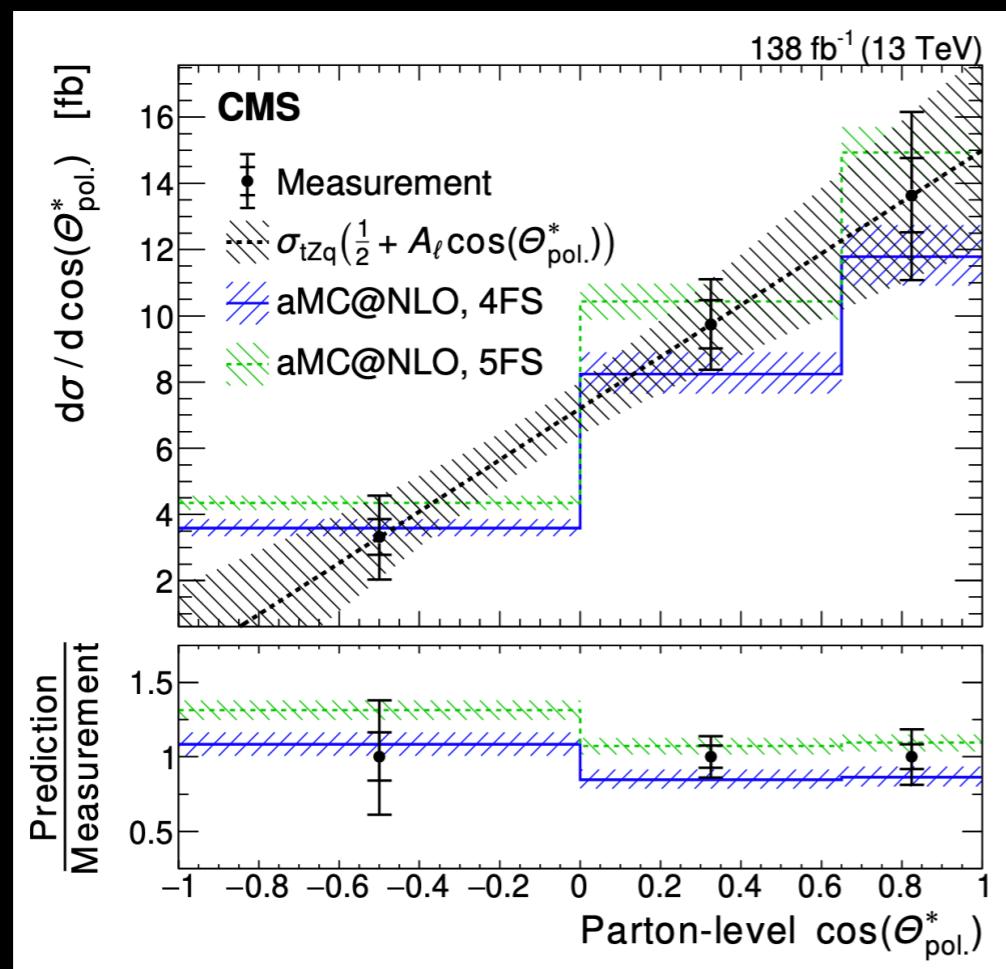
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- For the **first time**:

- differential cross sections (parton and particle level)
- ratio of cross sections
- spin asymmetry (A_ℓ)

$$\cos(\theta_{\text{pol}}^*) = \frac{\vec{p}(q'^*) \cdot \vec{p}(\ell_t^*)}{|\vec{p}(q'^*)| |\vec{p}(\ell_t^*)|}$$



$$\begin{aligned}\sigma(t(\bar{t})Z) &= 88^{+8}_{-7} \text{ (stat)}^{+7}_{-6} \text{ (syst)} \text{ pb} \\ \sigma^{\text{NLO}}(t(\bar{t})Z) &= 92 \pm 2 \text{ (scale)} \pm 3 \text{ (PDF)} \text{ pb}\end{aligned}$$

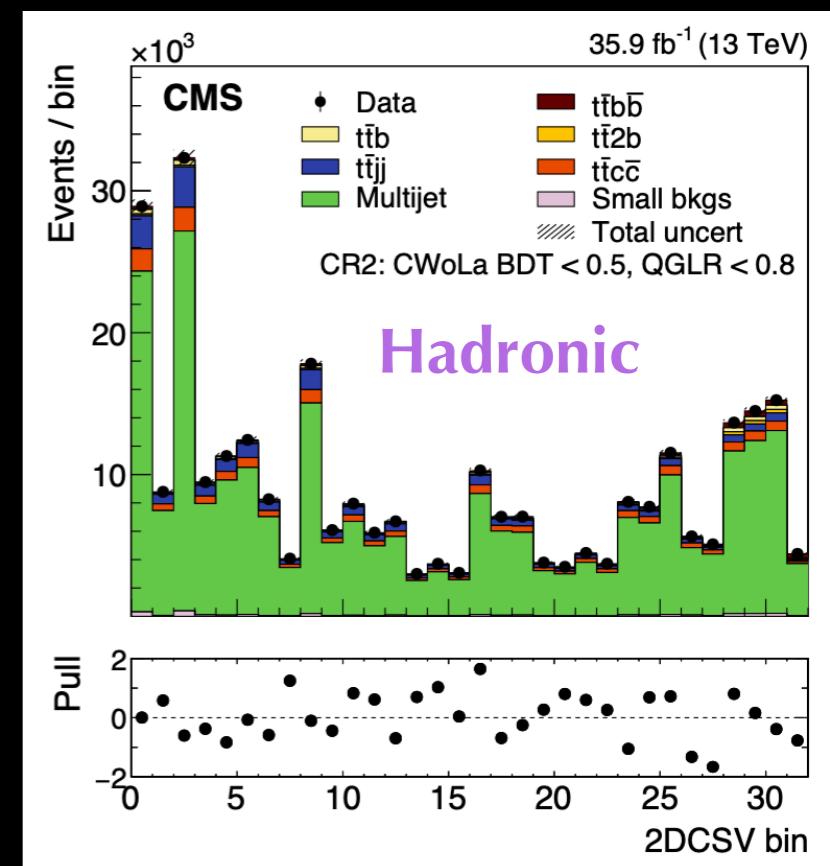
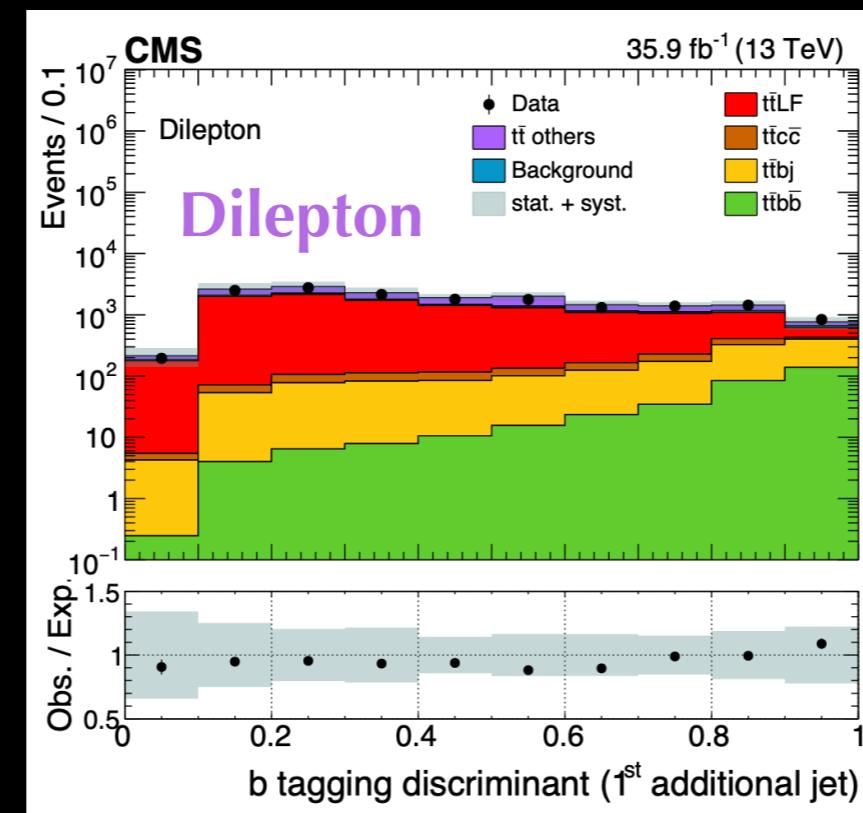
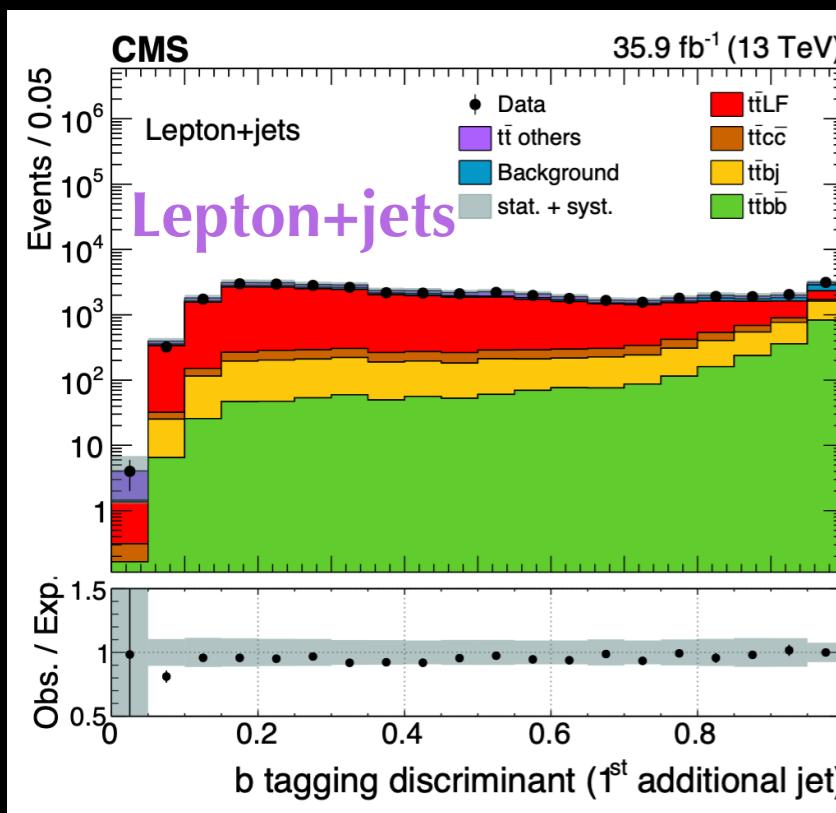
$t\bar{t}$ + beauty

138 fb⁻¹

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Phys. Lett. B 803 (2020) 135285

- $t\bar{t} + HF$: challenging to model - two **different energy scales** (b quarks and $t\bar{t}$ system)
- Important background to **$t\bar{t}H$** and **$t\bar{t}tt$**
- **Lepton+jets**: 1L, $N(j) \geq 6$, kinematic fit for jet assignment
- **Dilepton**: 2L OS, $N(j) \geq 4$, 3rd and 4th highest b-tag scores as additional jets
- **Hadronic**: $N(j) \geq 8$, dominant **QCD multijet** background (from data using ABCD with MVA scores) - likelihood-based **MVA** discriminants, jet permutations with **BDT**
- Fit **2D b-tag scores**
- **Uncertainties**: jet-related uncertainties, b-tagging, signal modeling



$t\bar{t}$ + beauty

138 fb^{-1}

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CMS
Preliminary

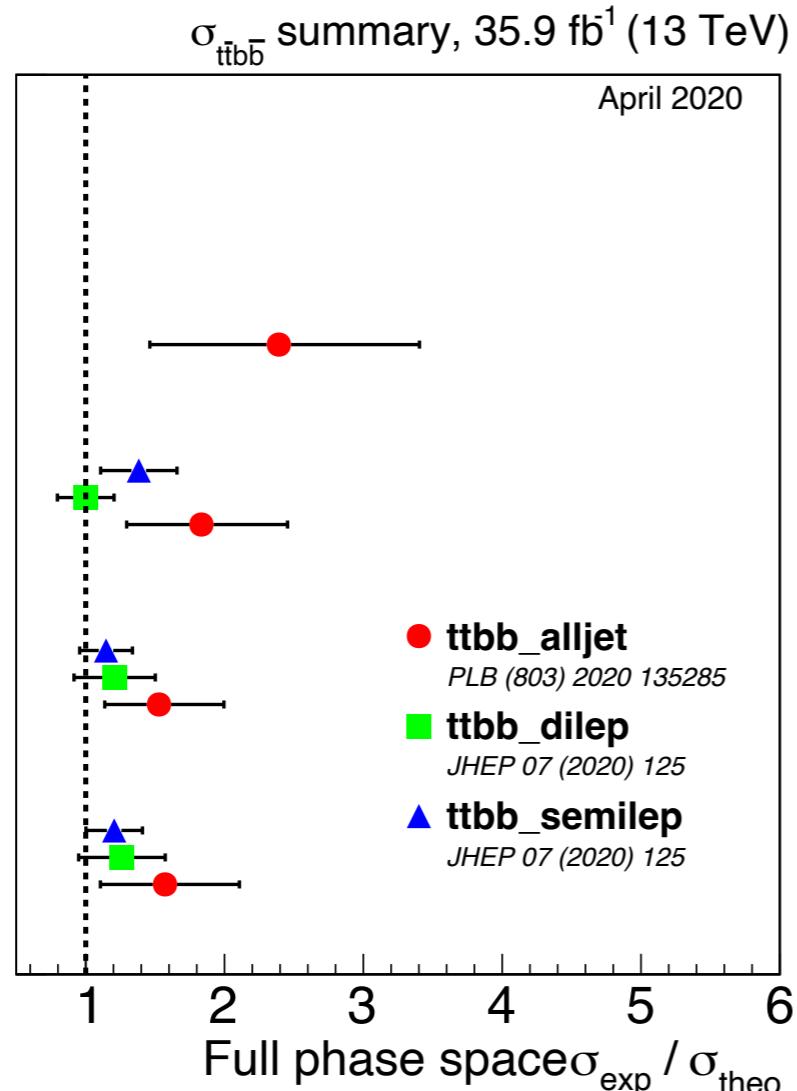
Reference for σ_{theo}

MG5_aMC@NLO +
PYTHIA8 4FS

POWHEG +
HERWIG++

MG5_aMC@NLO +
PYTHIA8 5FS [FxFx]

POWHEG +
PYTHIA8

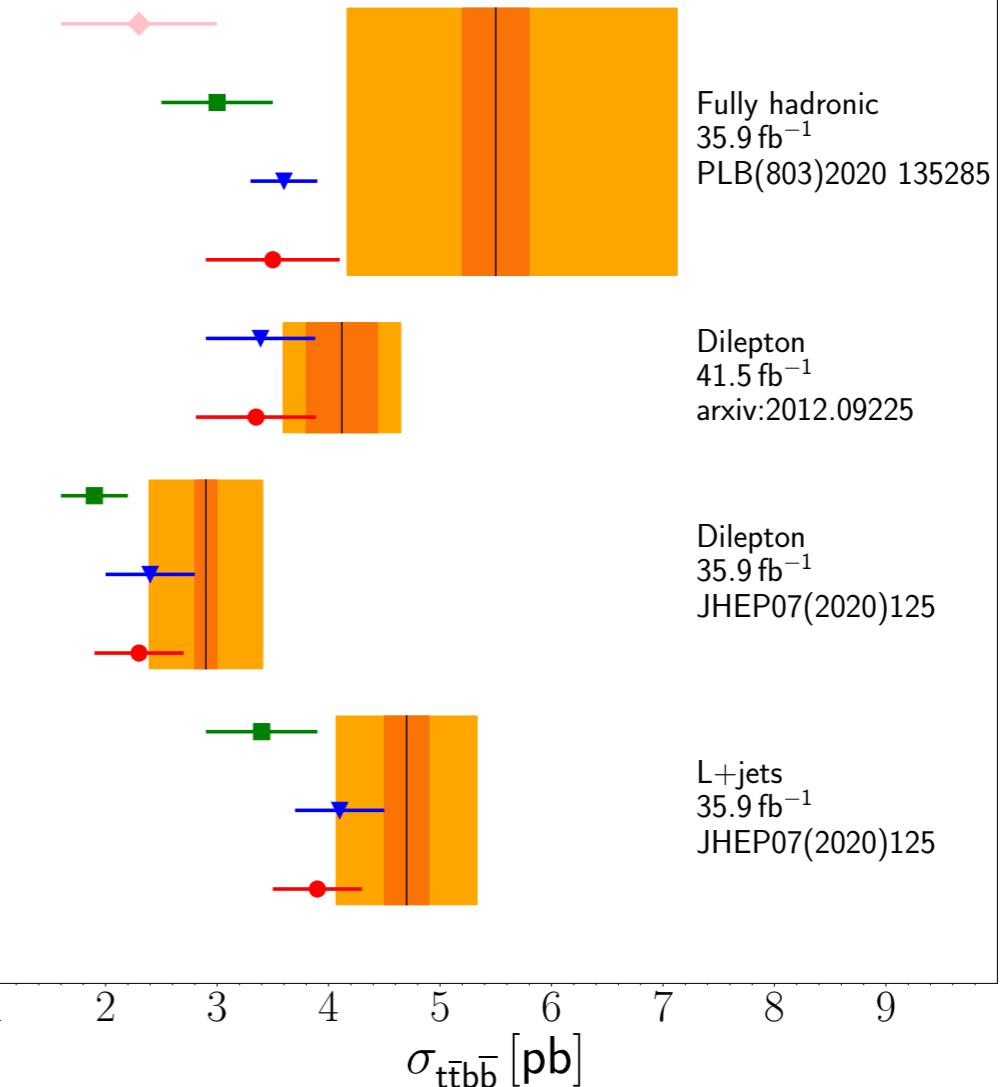


CMS Preliminary

June 2021

Measurement
 $\delta_{\text{stat.}}$
 $\delta_{\text{stat.}} \oplus \delta_{\text{syst.}}$

● POWHEG+PYTHIA8
 ▲ aMC@NLO+PYTHIA8(FxFx)
 ■ POWHEG+HERWIG++
 ♦ aMC@NLO+PYTHIA8



$t\bar{t}$ + charm

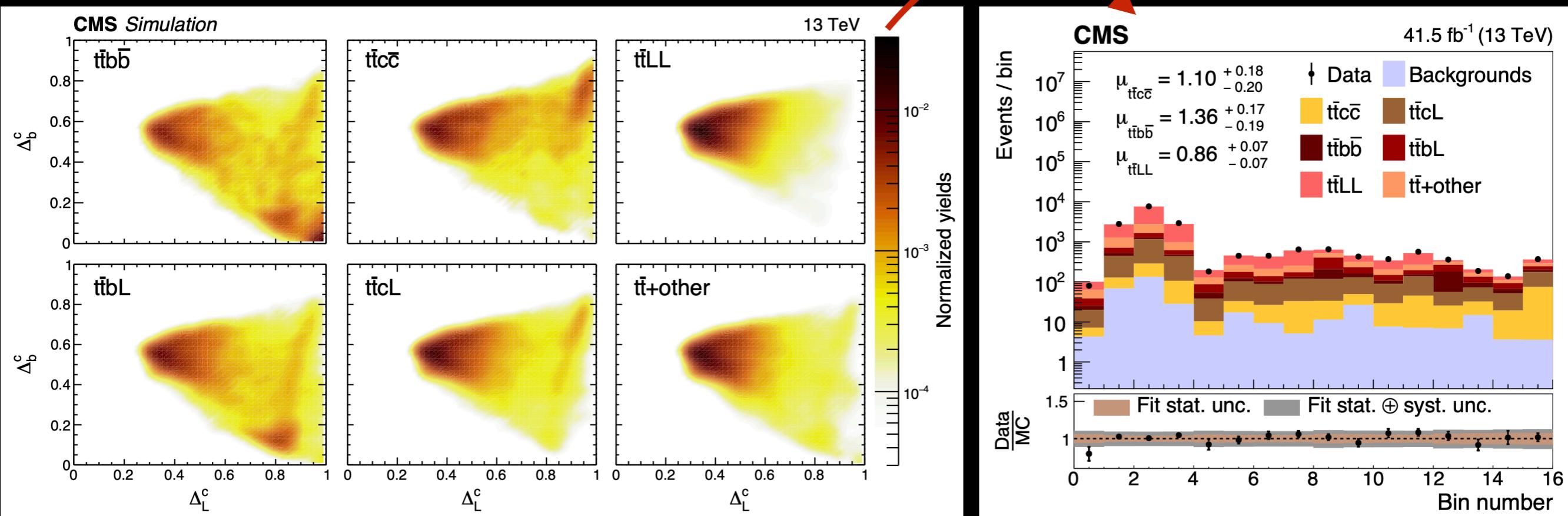
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Phys. Lett. B 820 (2021) 136565

- Challenging both theoretically and experimentally
- Measured for the **first time**
- Apply dedicated **charm identification** for jets, **calibrate** with an iterative fit in DY, $t\bar{t}$ and $W+c$ events in data
- **NN** to select the best jet permutation
- Fit to 2-D **NN** discriminant
- **Uncertainties**: jet-related uncertainties, b-tagging, signal modeling

$$\Delta_b^c = \frac{P(t\bar{t}cc\bar{c})}{P(t\bar{t}cc\bar{c}) + P(t\bar{t}bb\bar{b})},$$

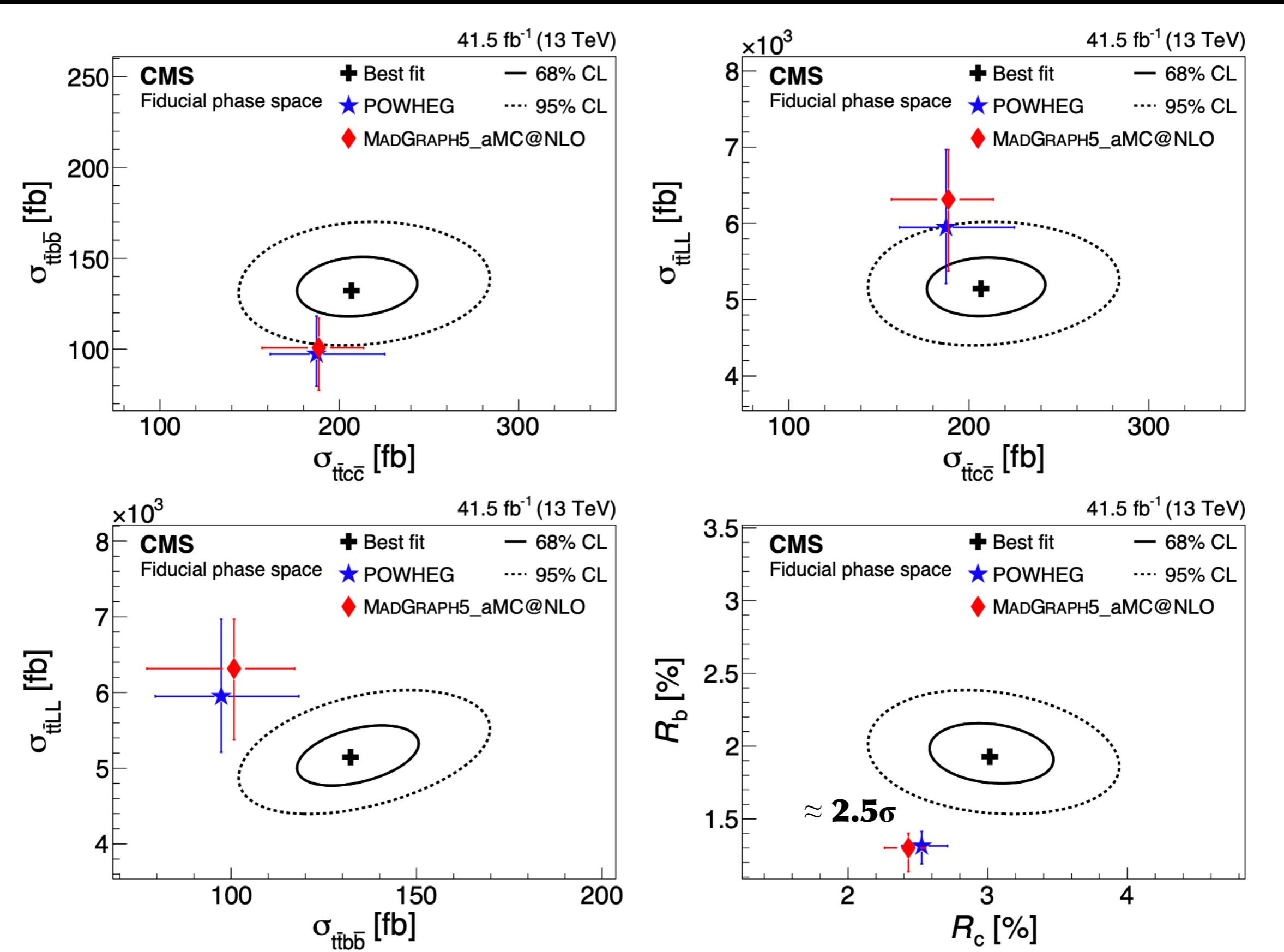
$$\Delta_L^c = \frac{P(t\bar{t}cc\bar{c})}{P(t\bar{t}cc\bar{c}) + P(t\bar{t}LL)}.$$



$t\bar{t}$ + charm

138 fb^{-1}

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Summary

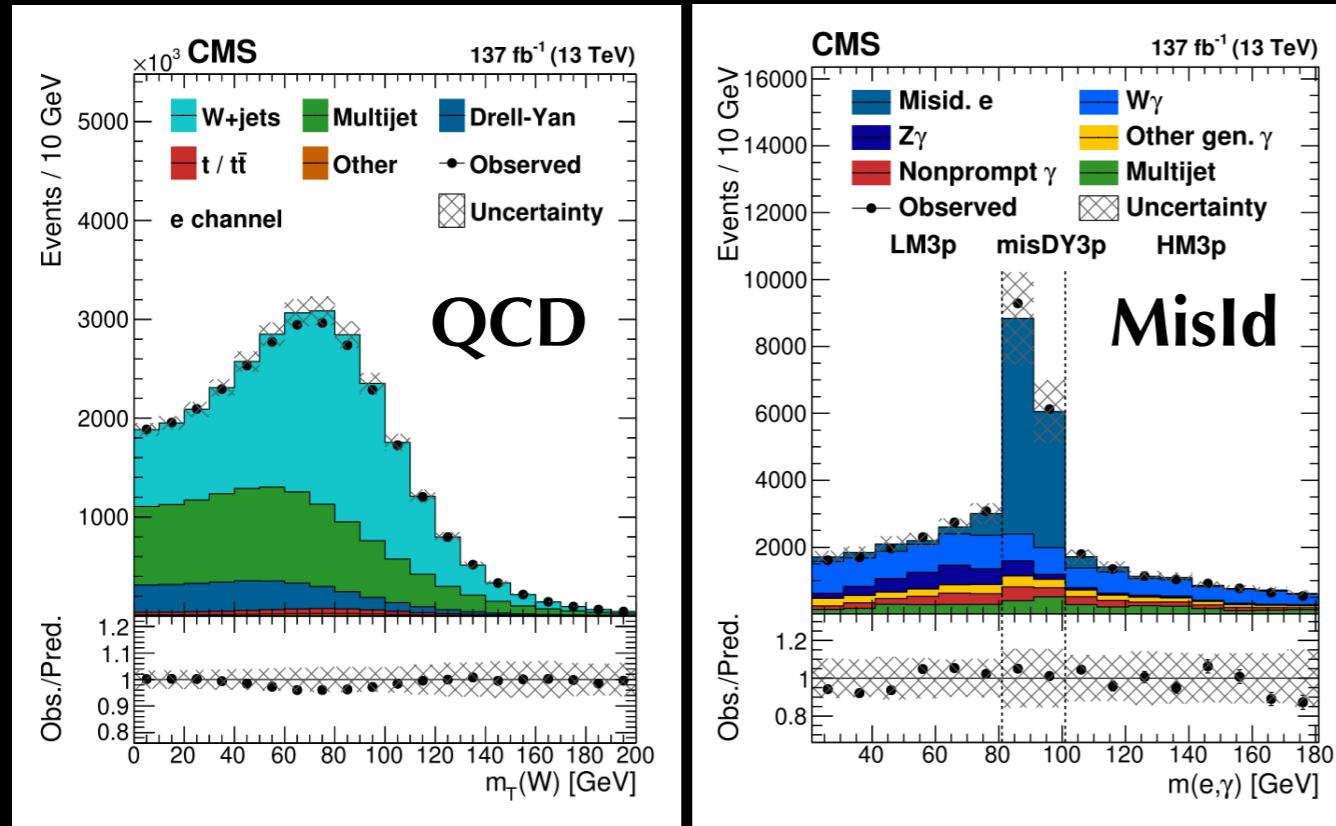
- ⌚ Degustation of **Run 2** results is still ongoing
- ⌚ Several of the top quark associated productions were recently observed for the **first time**
- ⌚ Increasing appetite for **Run 3**: looking forward for more data and better precision
- ⌚ Need to continue exploring possible ways to further **reduce systematics** in the measurements!



Backup slides

$t\bar{t} + \gamma$

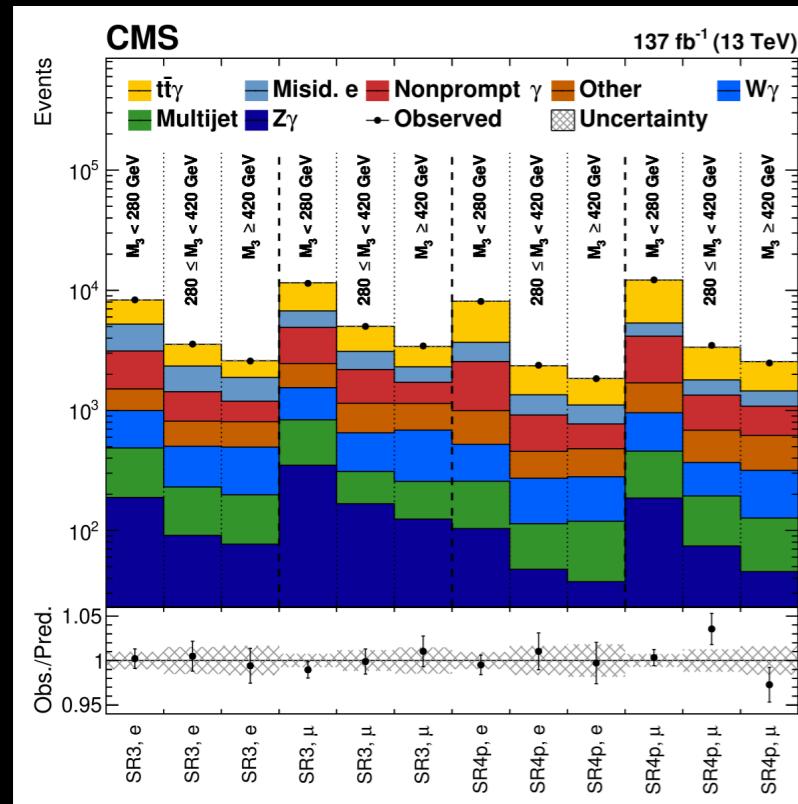
Background estimation:



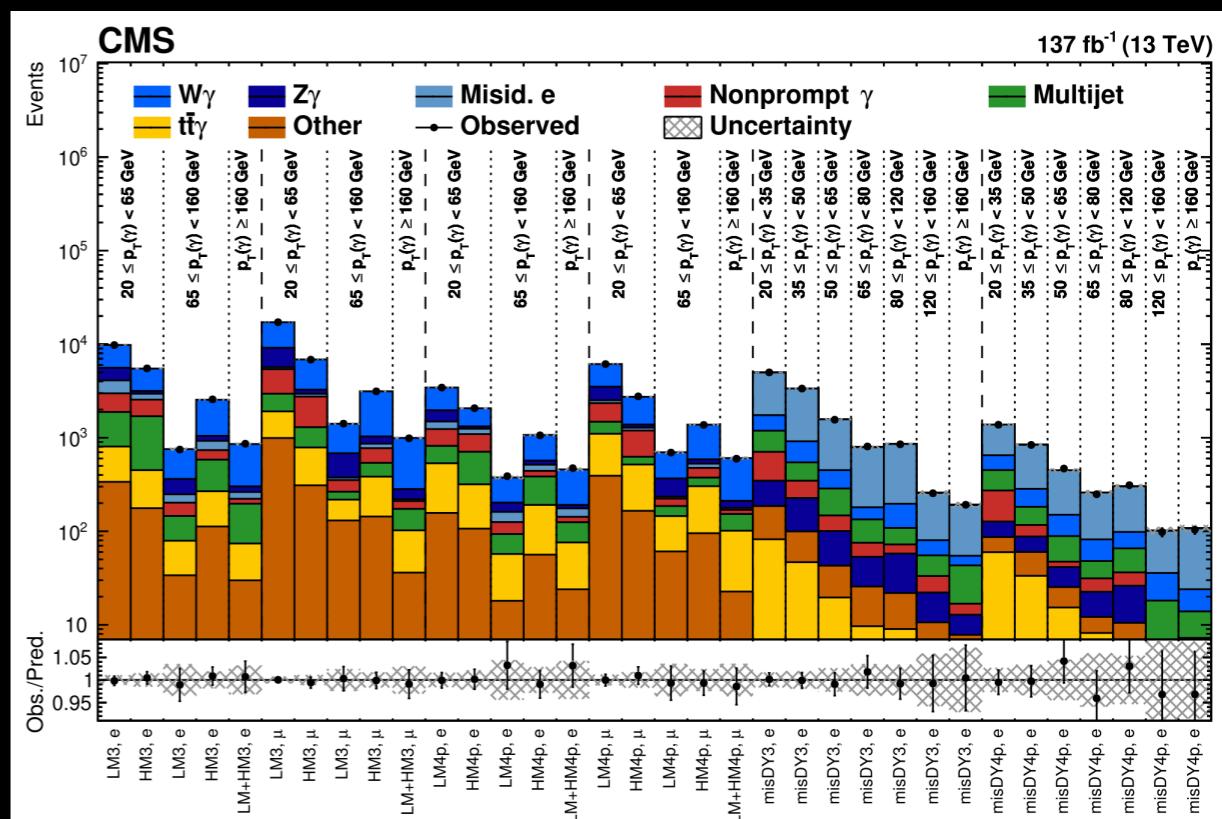
- QCD multijet: template from high Iso(ℓ) sideband for each N(j), lepton is not tight, $N(\gamma) = 1$; measure transfer factor (tight/loose lepton) using $m_T(W)$ in $N(j) = 2$, $N(\gamma) = 0$
- MisId electrons: normalization from $N(b) = 0$, $|m(e, \gamma) - m_Z| < 10 \text{ GeV}$

Control regions:

Signal regions:



- Inclusive: SRs split in $m(3j)$: [0-280], [280-420], [420-] GeV
- Differential: SRs split in $p_T(\gamma)$, $\eta(\gamma)$, $\Delta R(\ell, \gamma)$

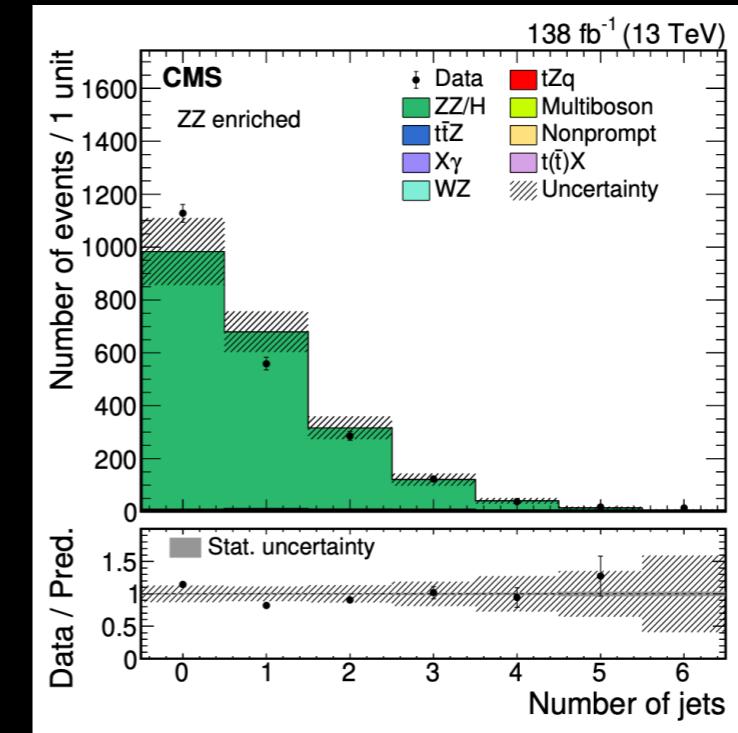
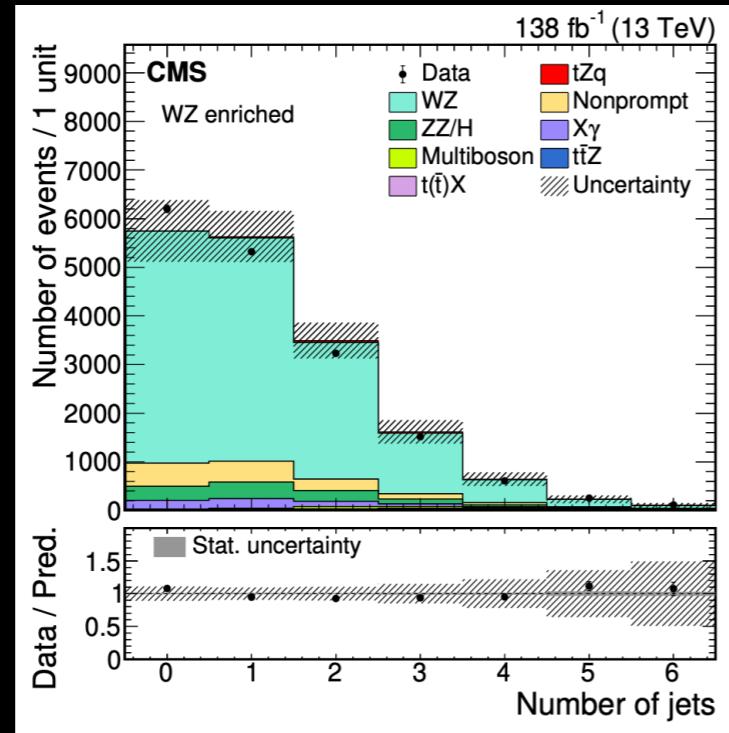


$t(\bar{t}) + Z + q$

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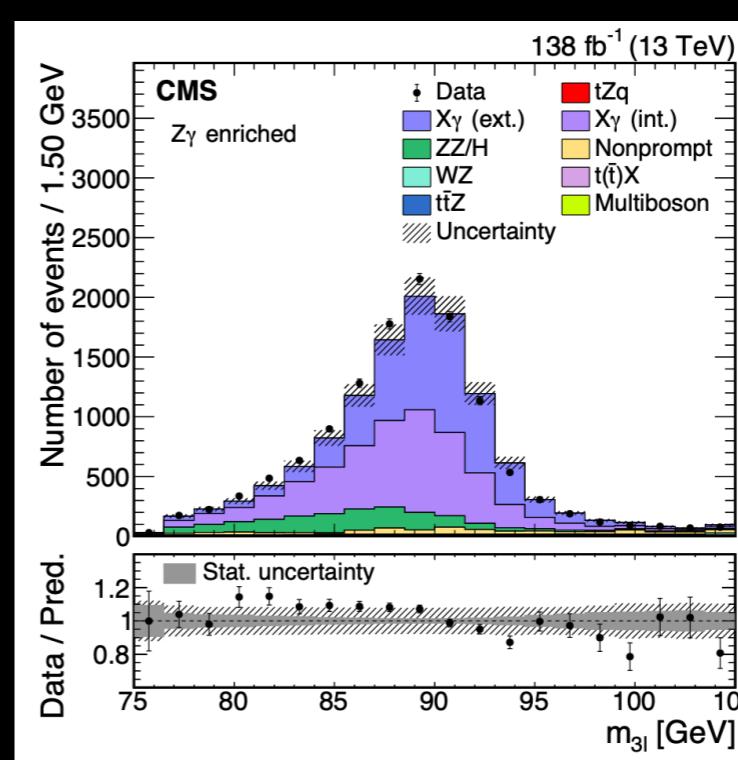
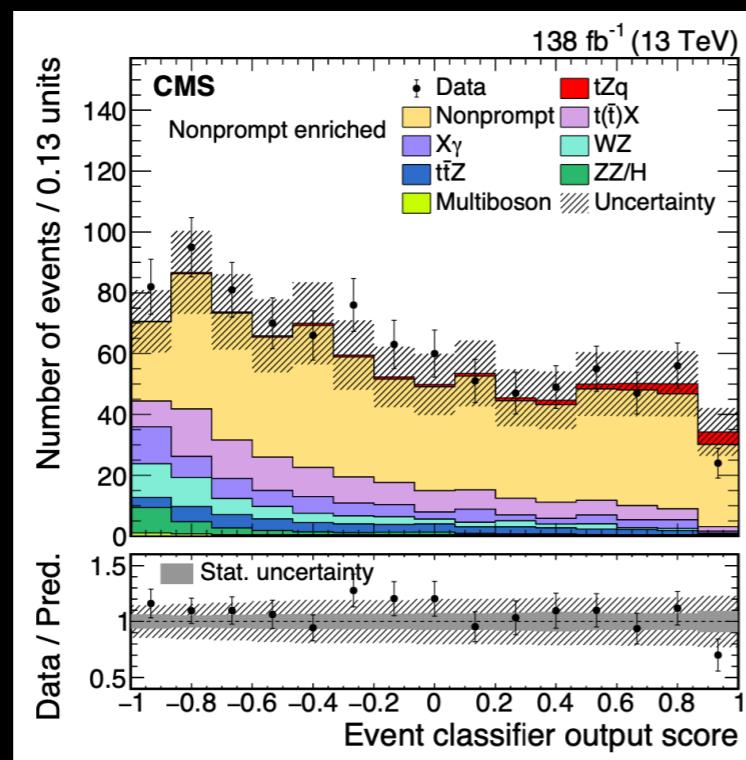
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- **WZ:** veto b-tagged jets, $E_T^{\text{miss}} > 50 \text{ GeV}$



- **ZZ:** four-lepton CR with both lepton pairs are on Z

- **Nonprompt:** $N(j) = 2$ or 3 , $N(b) = 1$, no on-Z lepton pair



- **Z γ :** trilepton CR with $|m(\ell\ell\ell) - m_Z| < 15 \text{ GeV}$