Electroweak and QCD aspects in V+jets in CMS

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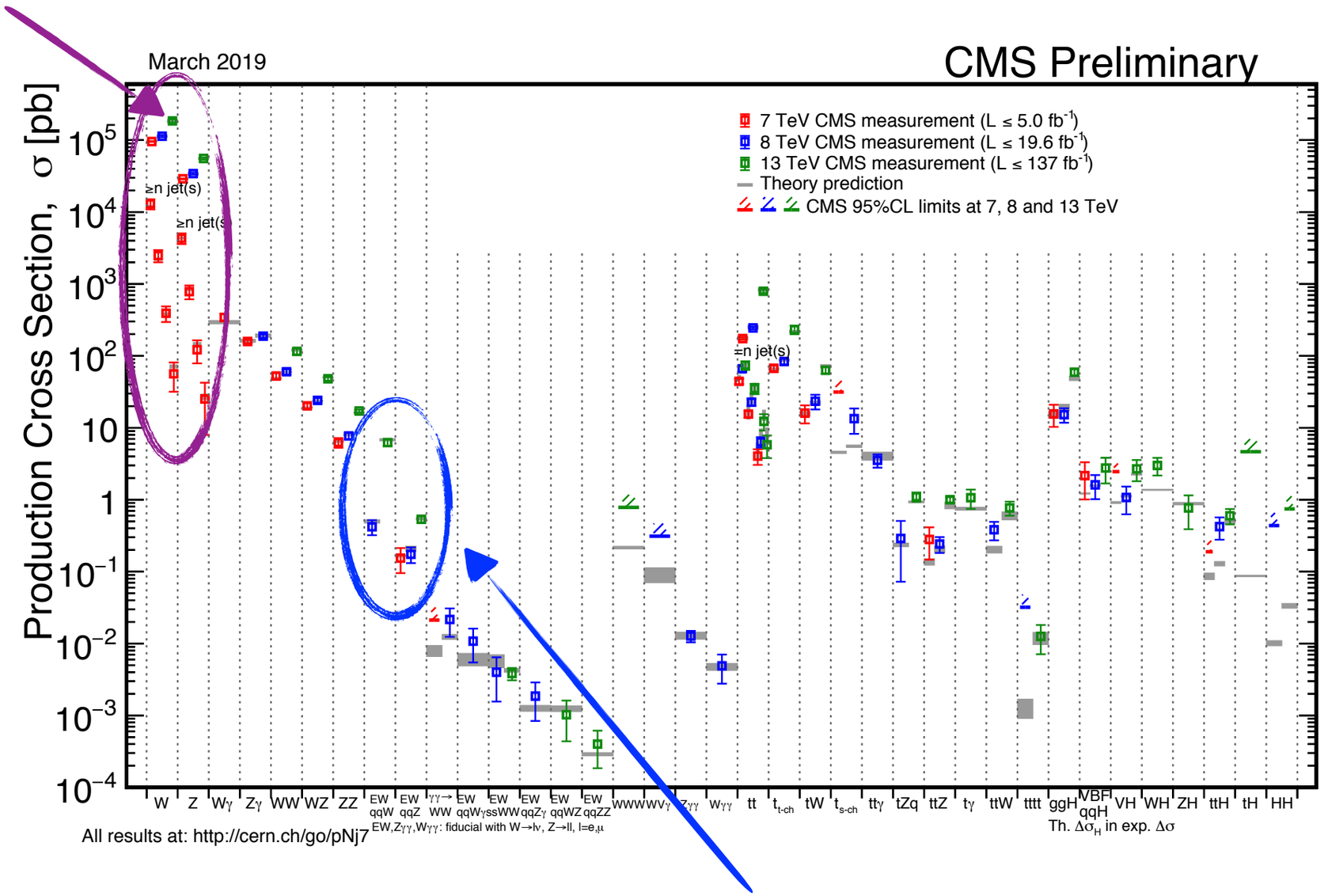
On behalf of the CMS Collaboration

Overview

- Study of associated production of vector bosons and jets (V+jets) excellent test of QCD predictions.



- Electroweak-initiated V+jets (VBF W/Z) processes important probe of VBF processes.

Outline

- Differential (QCD) V+jets:
  - Stringent tests of perturbative QCD, Monte Carlo simulations.
  - Important background for many SM and BSM measurements/searches → crucial to measure with high precision.

W+jets:
Phys. Rev. D 96 (2017) 072005

Z+jets:
Eur. Phys. J. C 78 (2018) 965

- Electroweak (EW) V+jets:
  - Critical background for VBF Higgs searches/measurements.
  - Precision probe of modeling of VBF processes.
  - Test of soft QCD rapidity gap modeling.
  - Constraints on anomalous trilinear gauge couplings.

VBF Z:
Eur. Phys. J. C 78 (2018) 589

VBF W:
arXiv:1903.04040, submitted to EPJC

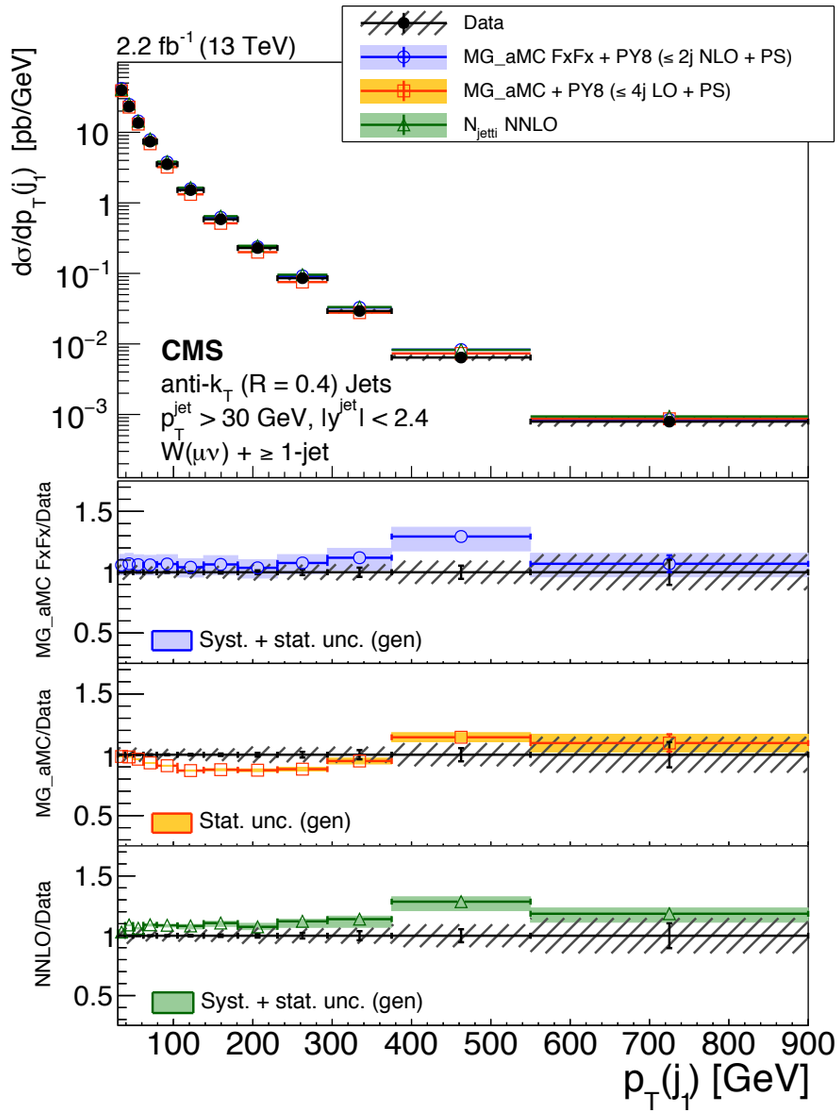
(QCD) W(μν)+jets

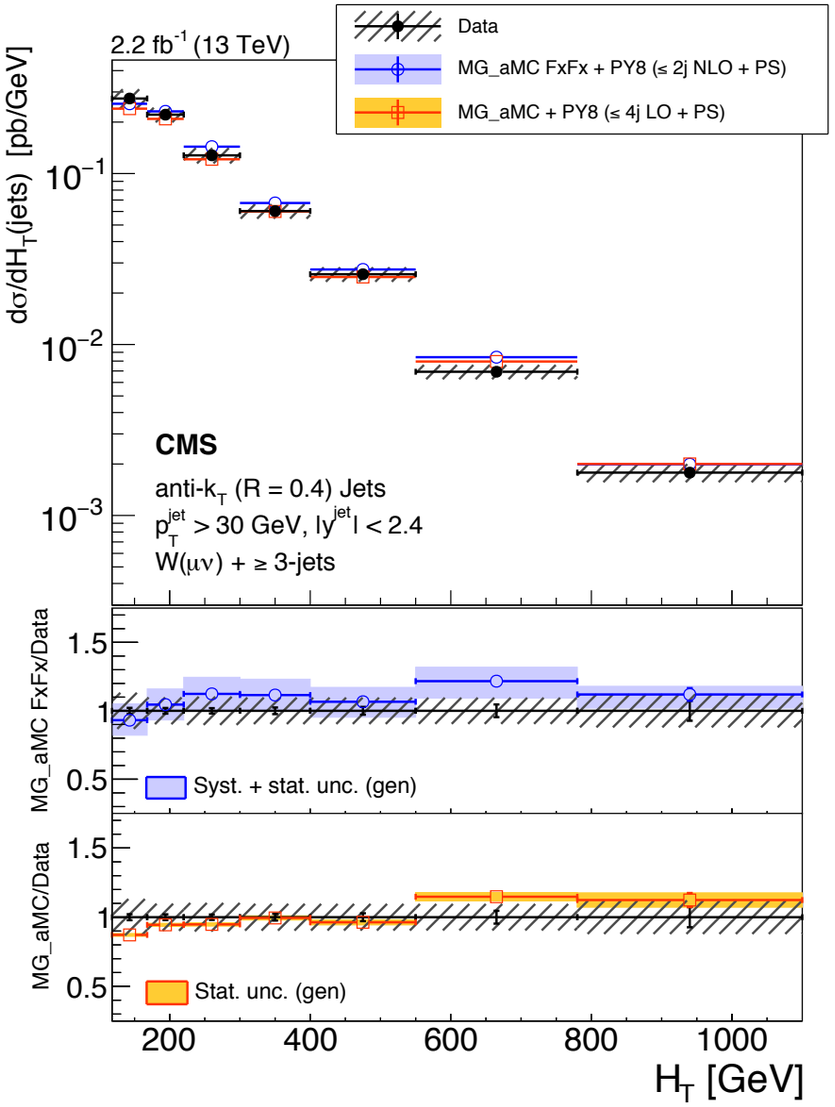
Event selection:

- μ with p_T > 25 GeV, $|\eta_\mu| < 2.4$
- $p_{T\,jet}$ > 30 GeV, $|\eta_{jet}| < 2.4$
- $m_T(W)$ > 50 GeV

Backgrounds:

- tt dominant, contamination increasing with N_{jet}.
- QCD multijet. (data-driven).





Iterative d'Agostini unfolding

- Compared to predictions: LO(≤4j) and NLO(≤2j) MadGraph5_aMC@NLO; NNLO for one jet
- Measured : excl./incl. jet multiplicities, jet p_T, jet η, and H_T up to ≥ 3 jets
- Good agreement with predictions, but overall LO MadGraph5_aMC@NLO slightly underestimates data on the low-p_T observables

Phys. Rev. D 96 (2017) 072005

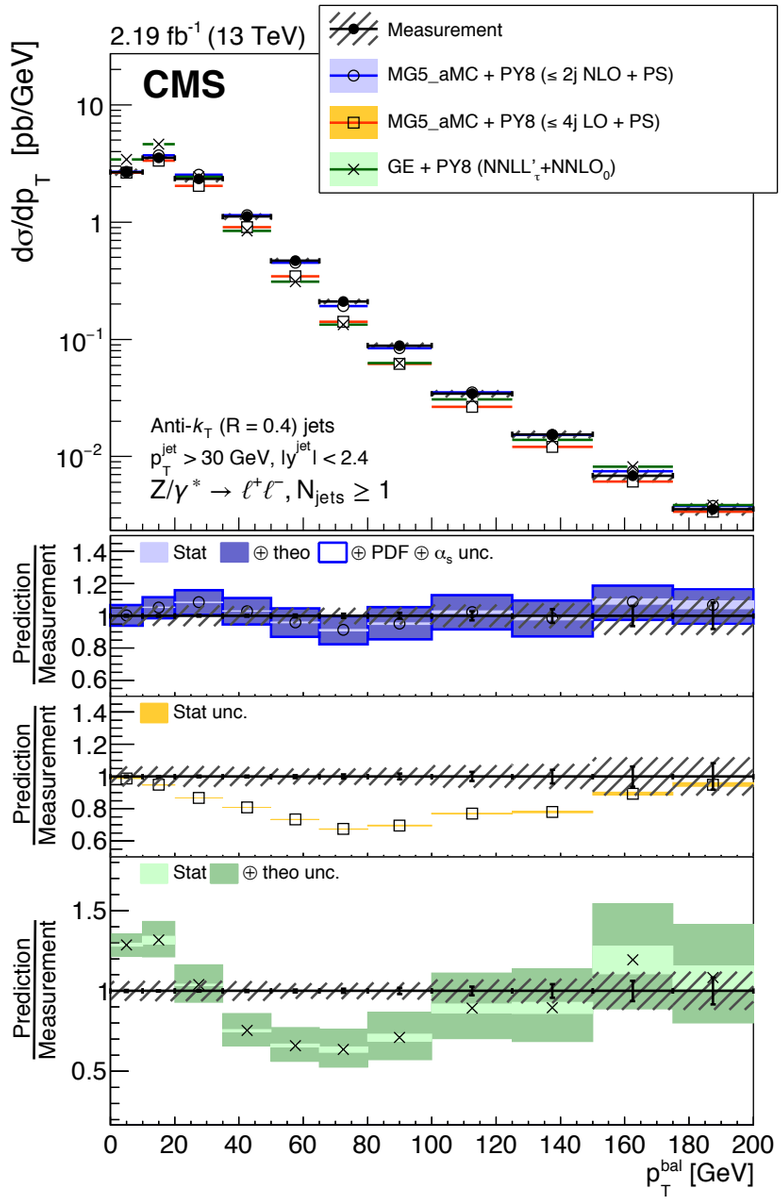
(QCD) Z+jets

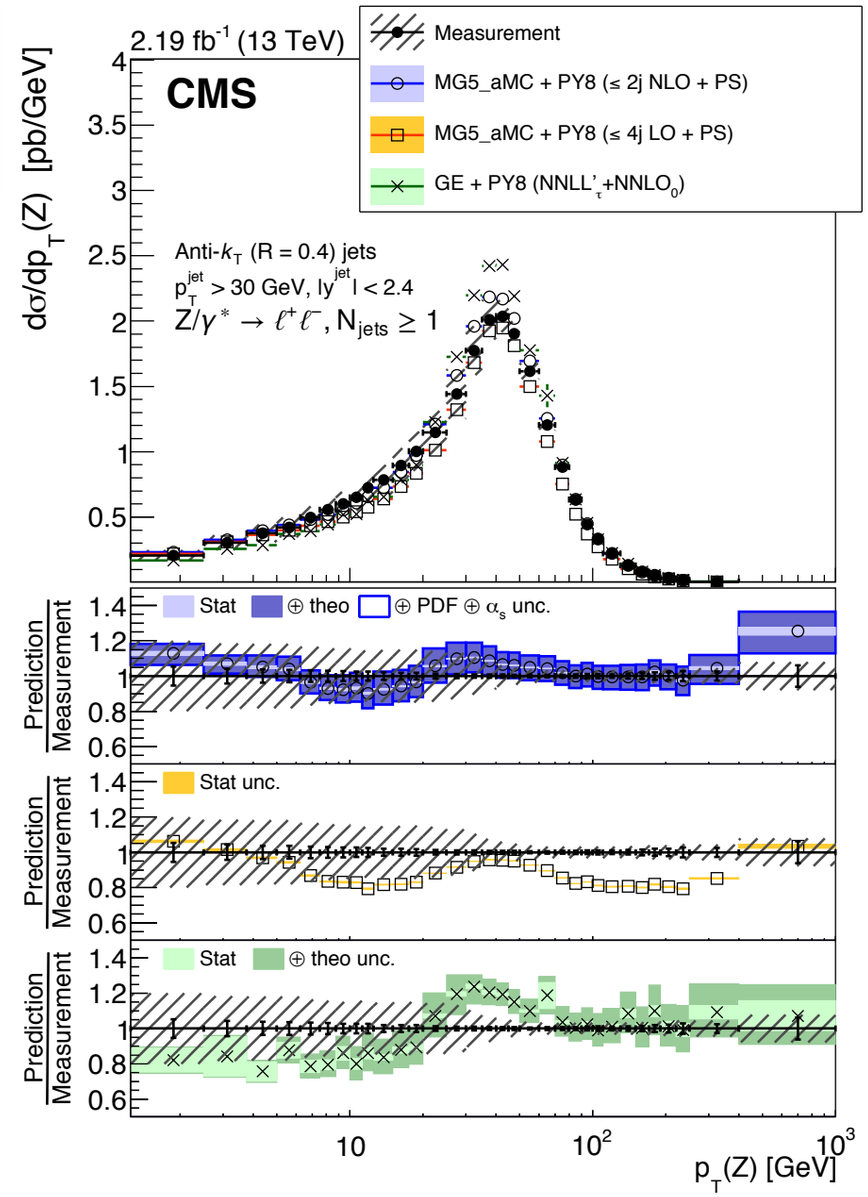
Event selection:

- 2 e/μ with p_T > 20 GeV, $|\eta_l|$ < 2.4
- $p_{T\,jet}$ > 30 GeV, $|\eta_{jet}|$ < 2.4
- $|m(\ell\ell) - m(Z)|$ < 20 GeV

Backgrounds:

- tt dominant at large jet multiplicities (~15%).
- Z→ττ subtracted.





Iterative d'Agostini unfolding

- Compared to predictions: LO(≤4j) and NLO(≤2j) MadGraph5_aMC@NLO; NNLO + NNLL GENEVA; NNLO fixed order for one jet
- Measured : jet multiplicities, $p_T(Z)$, p_T balance, jet p_T, jet η, and H_T up to ≥ 3 jets
- Good agreement with predictions with NLO, significant discrepancies with LO for leading jet kinematics. NNLL'$_\tau$ + NNLO$_0$ does not describe well p_T balance (sensitive to additional jets).

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EW Z+jets

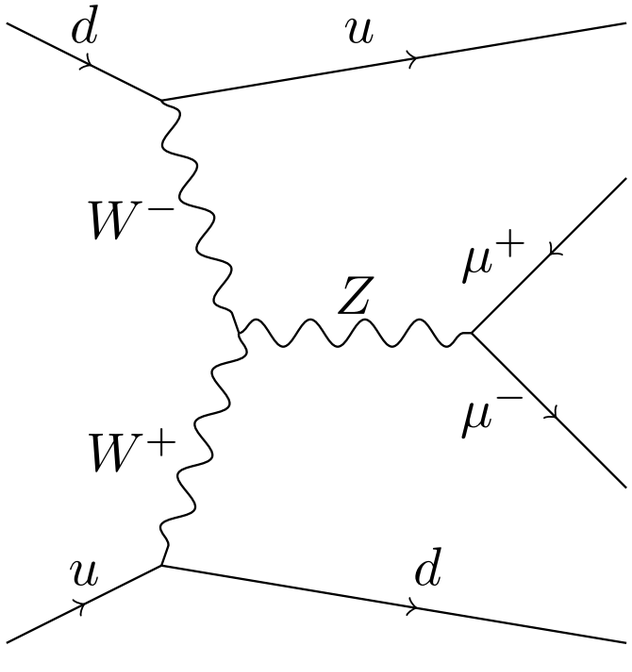
Signal defined as: $\ell\ell jj$ final state with m(jj) > 120 GeV, $p_T(j)$ > 25 GeV, m($\ell\ell$) > 50 GeV.

$$\sigma_{LO}(EW\,\ell\ell jj) = 543^{+7}_{-9}\,(\text{QCD scale}) \pm 22\,(\text{PDF})\ \text{fb}$$

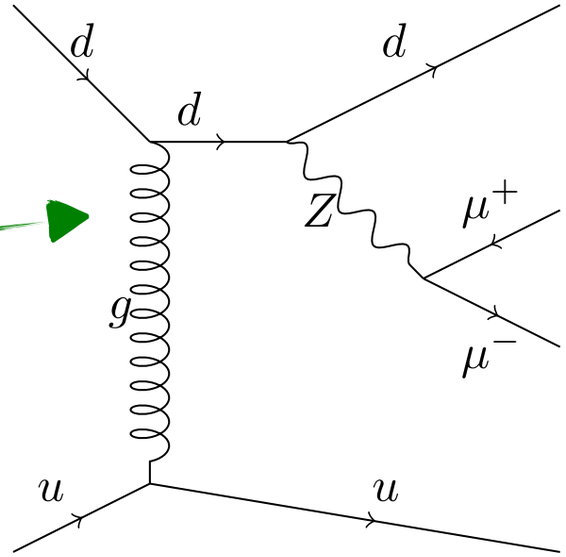
Event selection:

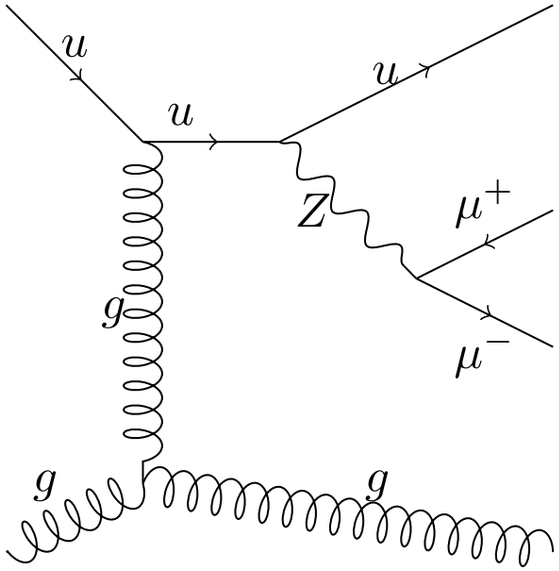
- Two OS e/μ: p_T > 30 (20) GeV, |η| < 2.4, |m($\ell\ell$) - m(Z)| < 15 GeV
- At least two jets with p_T > 50 (30) GeV, |η| < 4.7
- M(jj) > 200 GeV

VBF Z signal



Drell-Yan background





- Drell-Yan background dominant background.
- Interference between signal and DY background (~3% impact), generated with MG5_amc.

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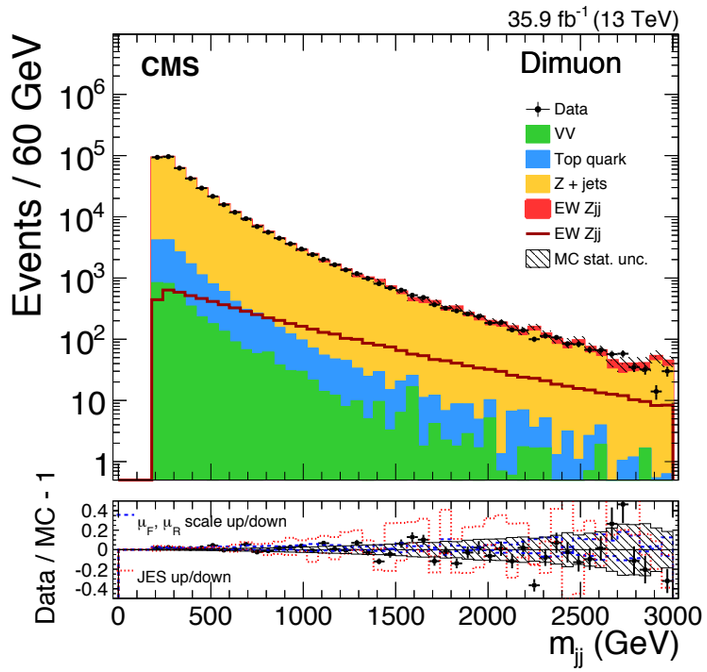
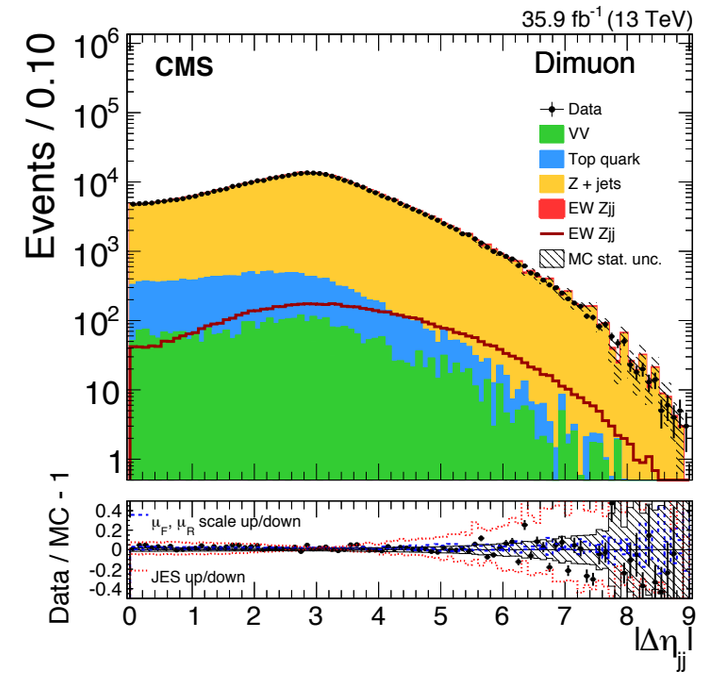
Signal vs. background discrimination

BDT trained to separate S from B.

S/BG separation :

- m(jj), Δη(jj)
- qgl(1st/2nd jets)
- p_T(jj)
- R(p_T^{hard}), z^*_{ll}

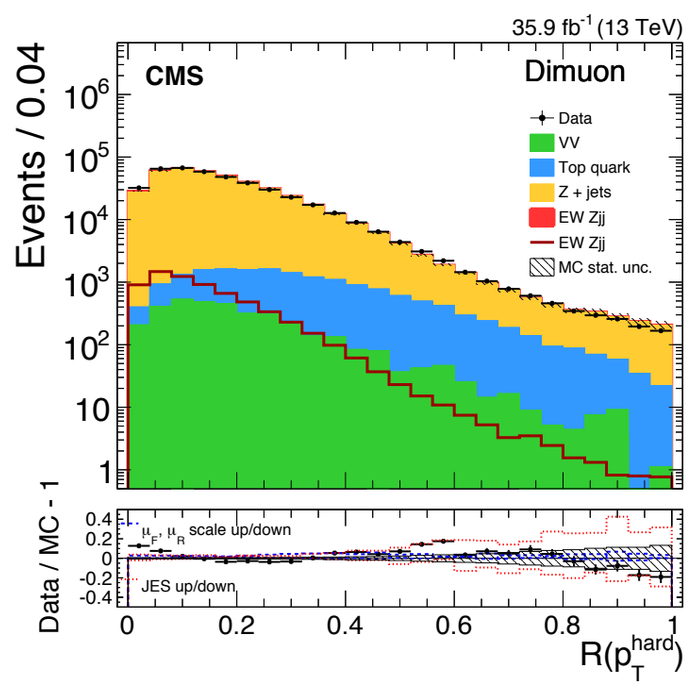


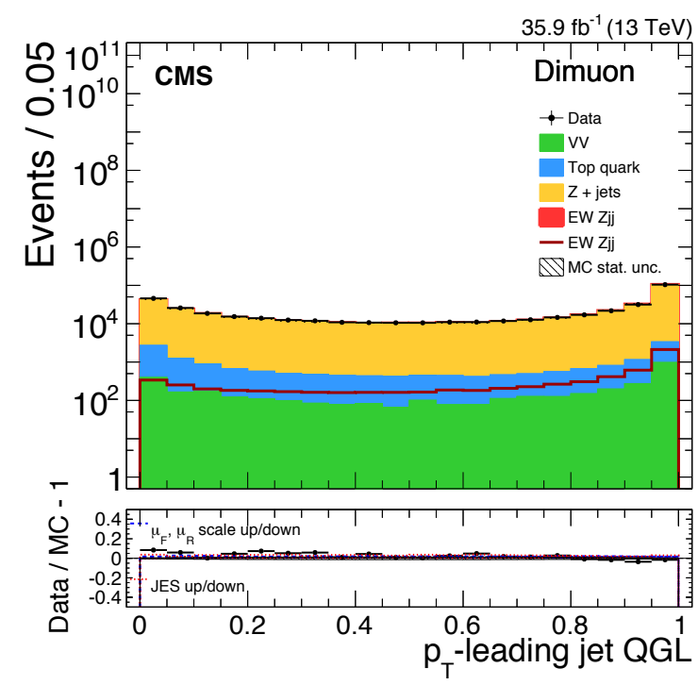


$$y^* = y(Z) - \frac{y(j_1) + y(j_2)}{2}$$

$$z^* = \frac{y^*}{\Delta y_{jj}}$$

$$R(p_T^{hard}) = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2) + \vec{p}_T(Z)|}{p_T(j_1) + p_T(j_1) + p_T(Z)}$$





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Cross section measurement

- Binned maximum-likelihood fit to BDT score.
- Measurement dominated by systematic uncertainties.
  - Primarily jet energy scale and signal theory uncertainties.
- In good agreement with LO prediction within uncertainties.

10% precision

Z→ee

$$\sigma(EW\,\ell\ell jj) = 554 \pm 34\,(stat.) \pm 70\,(syst.)\ \text{fb}$$

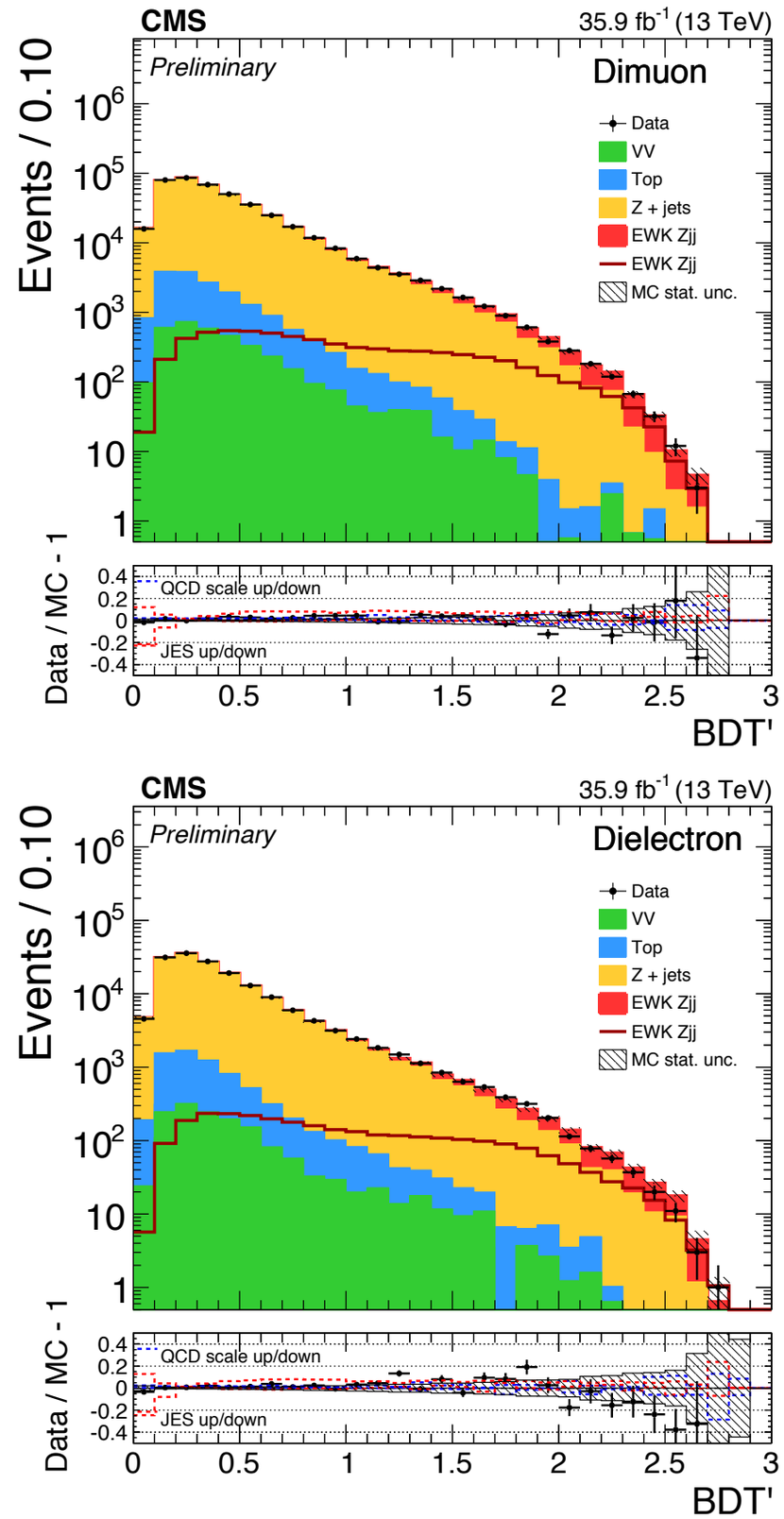
Z→μμ

$$\sigma(EW\,\ell\ell jj) = 540 \pm 23\,(stat.) \pm 56\,(syst.)\ \text{fb}$$

combined:

$$\sigma(EW\,\ell\ell jj) = 552 \pm 19\,(stat.) \pm 55\,(syst.)\ \text{fb}$$

$$\sigma_{LO}(EW\,\ell\ell jj) = 543^{+7}_{-9}\,(\text{QCD scale}) \pm 22\,(\text{PDF})\ \text{fb}$$



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Gap activity studies

- Signal-enriched sample selected with BDT > 0.92 ⇒ S/B ~ 1.
- Study additional hadronic activity in region between VBF jets.
  - Suppressed for EW VBF signal.
- Consider additional jets with p_T > 15 GeV jets in the gap (first bin are events with no additional jets).
- Use track-only "soft activity" jets (pileup-resistant) to probe lower in p_T (bottom row).

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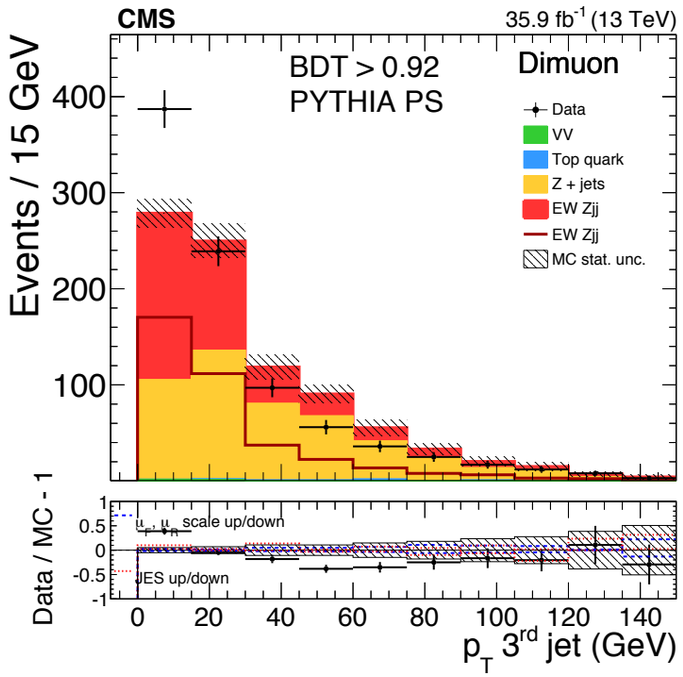
PYTHIA



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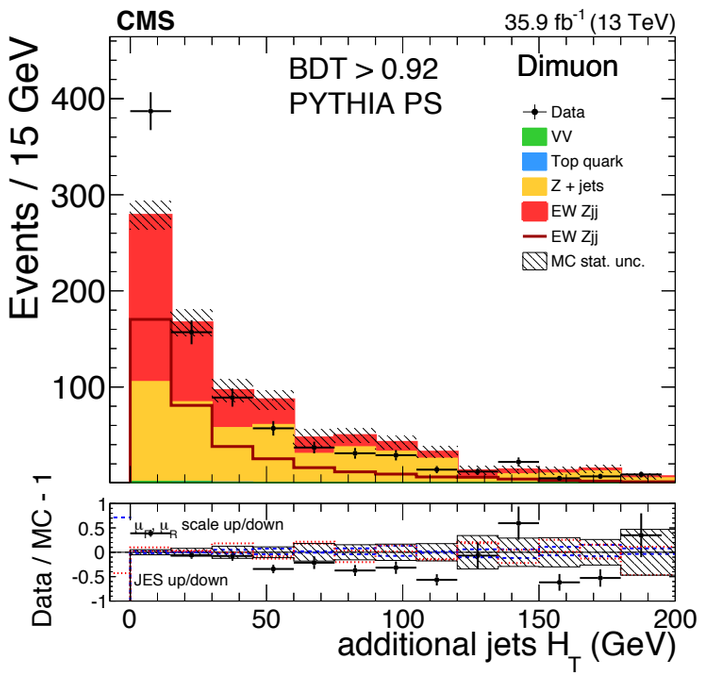

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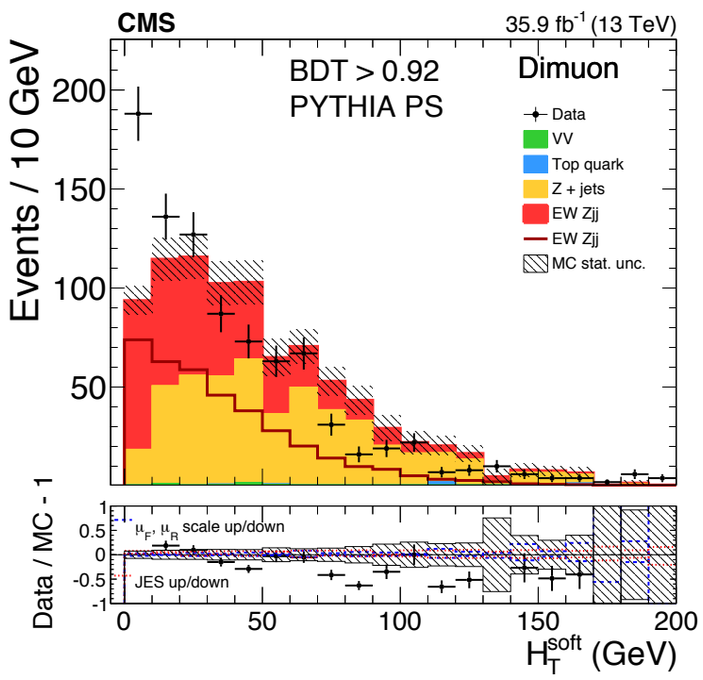
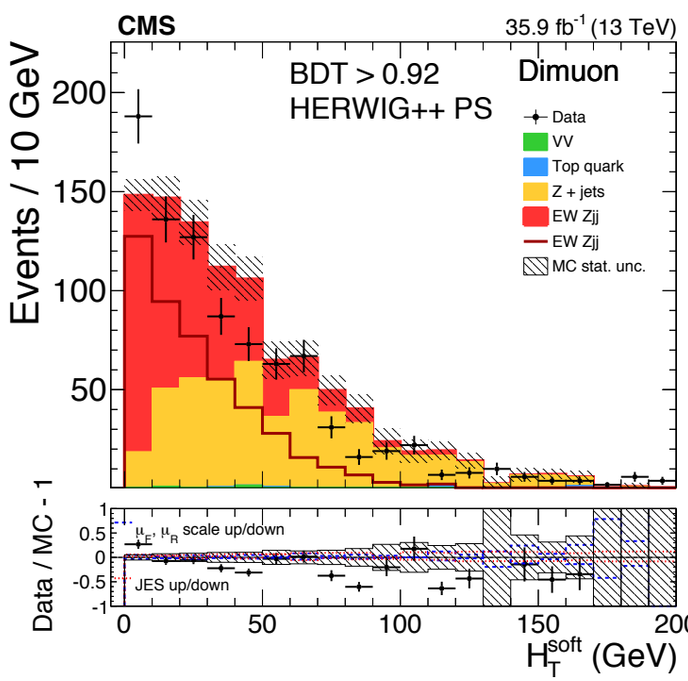
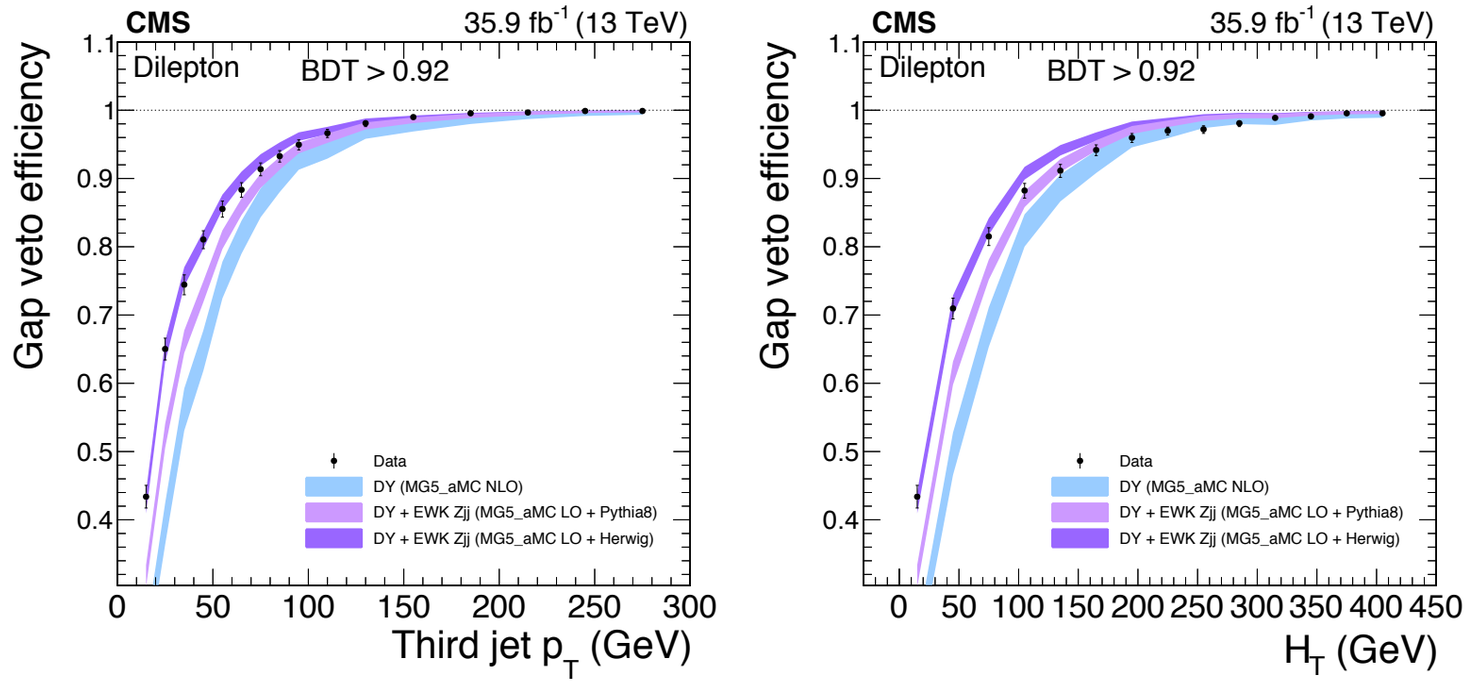


HERWIG

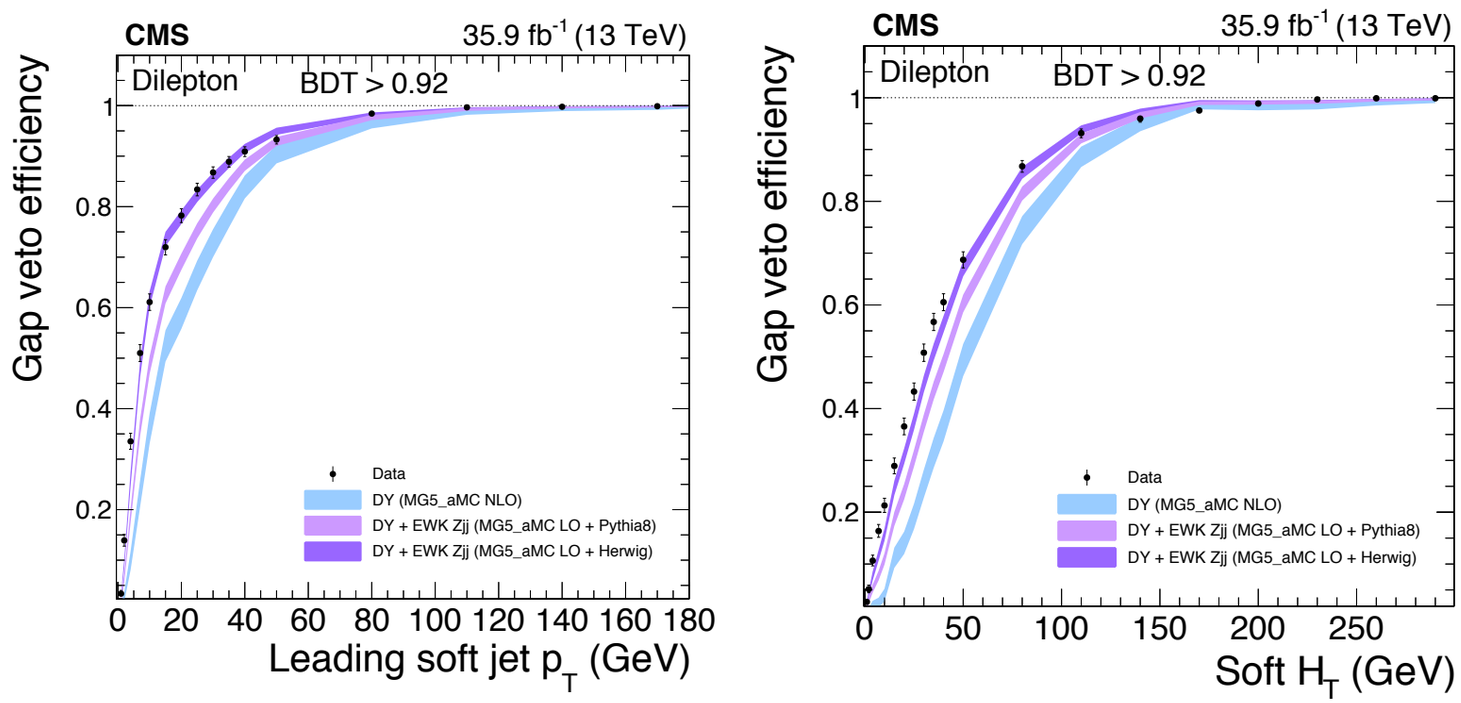


Gap activity veto efficiencies

- Consider fraction of events without jet activity in rapidity gap above a given threshold.
  - Efficiency of potential veto to enhance in VBF signals.
- Quantitive measure of reliability of simulation in modeling soft hadronic activity in VBF-enriched region.



track-jet observables (probe lower p_T)



Data prefer signal model with HERWIG PS at low gap activity.

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EW W+jets

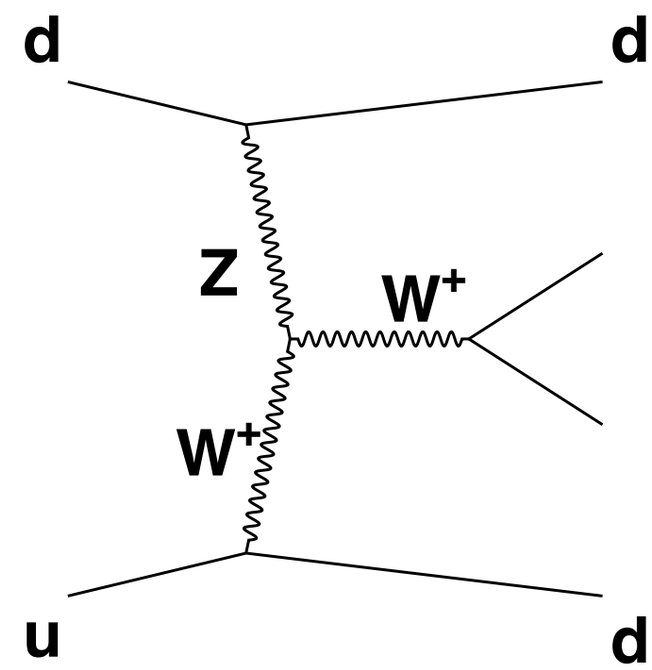
Signal defined as: ℓνjj final state with m(jj) > 120 GeV, p_T(j) > 25 GeV

$$\sigma_{LO}(EW\,\ell\nu jj) = 6.81^{+0.03}_{-0.06}\,(\text{QCD scale}) \pm 0.26\,(\text{PDF})\,\text{pb}$$

Event selection:

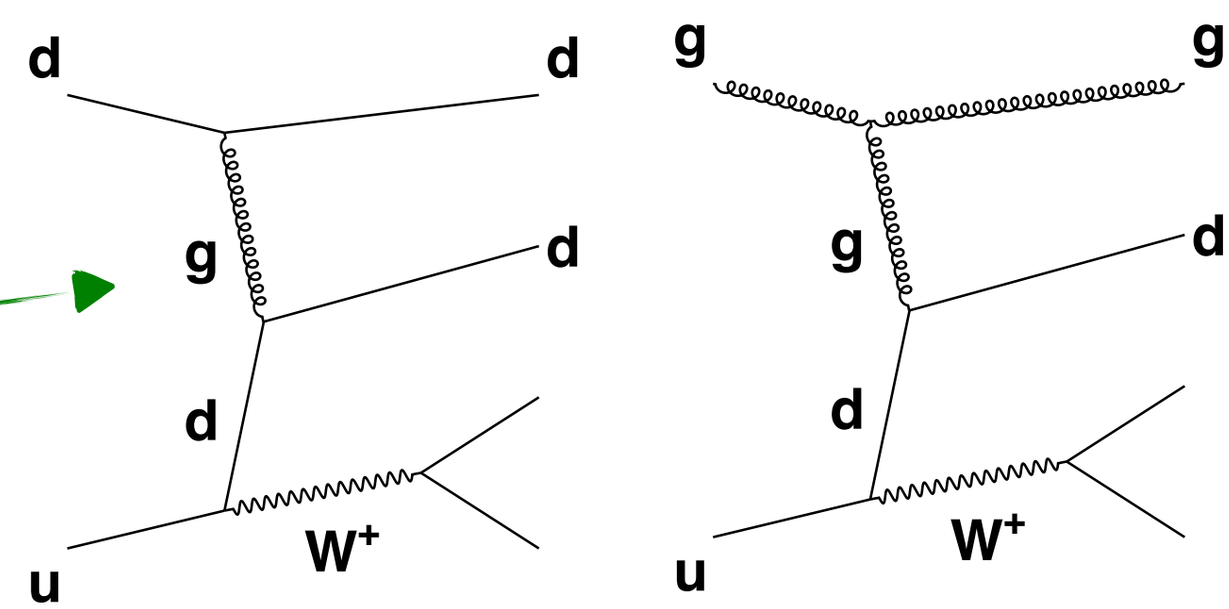
- One e (μ) with p_T > 30 (25) GeV, |η| < 2.4
- $\vec{p}_T^{\,miss}$ > 40 (20) GeV, m_T(W) > 40 GeV
- At least two jets with p_T > 50 (30) GeV, |η| < 4.7
- m(jj) > 200 GeV, R(p_T) < 0.2

VBF W signal



- QCD W+jets dominant background, but significant contributions as well from top and QCD multijet.

QCD W+jets background

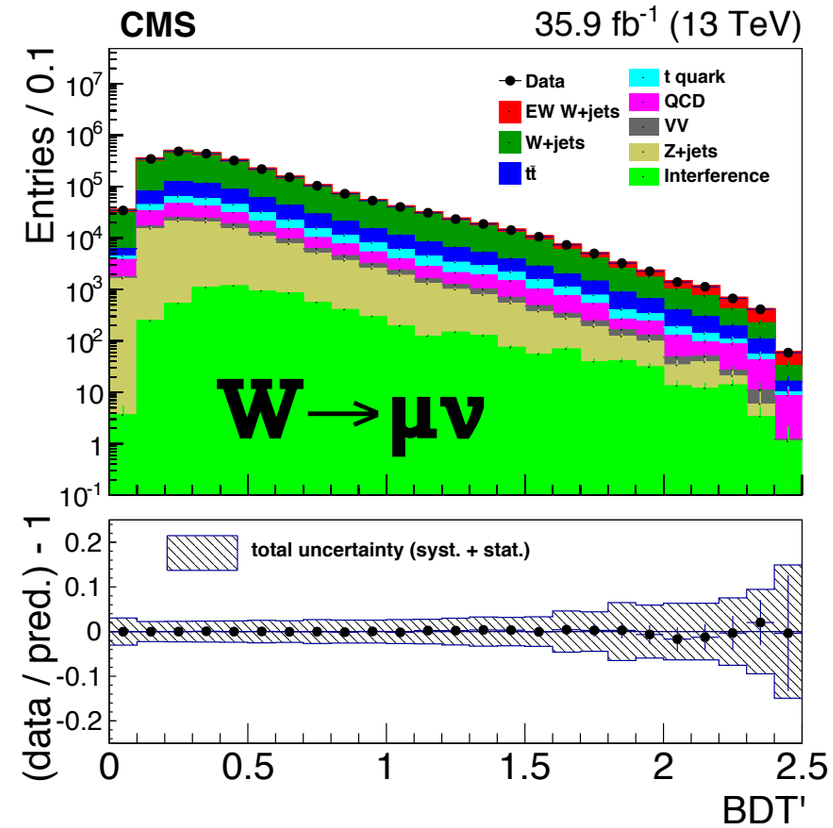


- Interference between signal and W+jets background (~3% impact), generated with MG5_amc.

arXiv:1903.04040, submitted to EPJC

Cross section measurement

- Factor ~10 more statistics than VBF Z.
- Measurement entirely systematics-dominated.
- In good agreement with LO prediction within uncertainties.



W→eν

$$\sigma(EW\,\ell\nu jj) = 6.22 \pm 0.12\,(stat.) \pm 0.74\,(syst.)\,\text{pb}$$

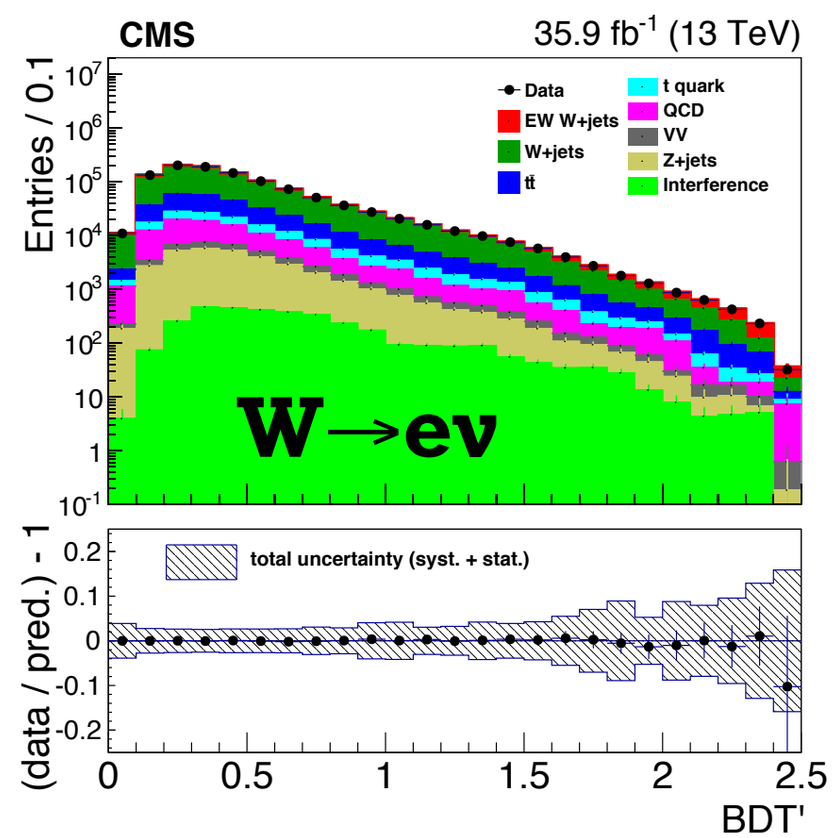
W→μν

$$\sigma(EW\,\ell\nu jj) = 6.27 \pm 0.19\,(stat.) \pm 0.80\,(syst.)\,\text{pb}$$

combined:

$$\sigma(EW\,\ell\nu jj) = 6.23 \pm 0.12\,(stat.) \pm 0.61\,(syst.)\,\text{pb}$$

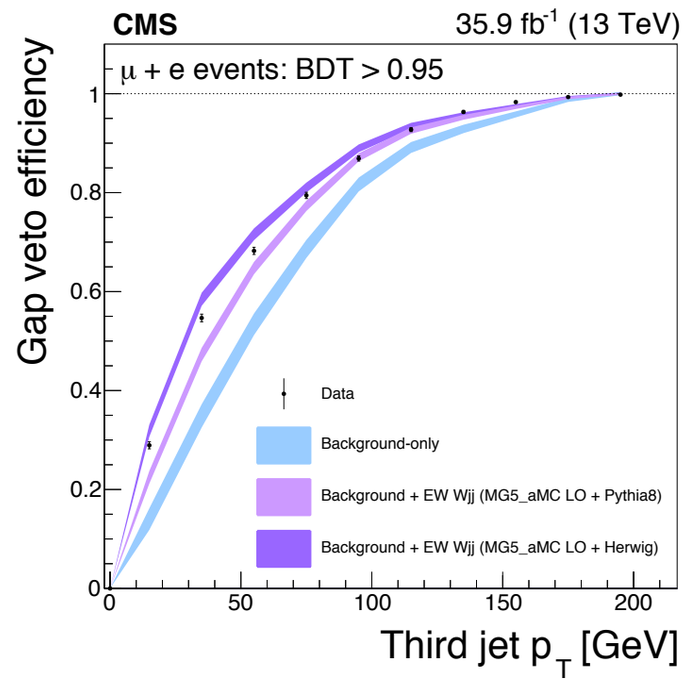
$$\sigma_{LO}(EW\,\ell\nu jj) = 6.81^{+0.03}_{-0.06}\,(\text{QCD scale}) \pm 0.26\,(\text{PDF})\,\text{pb}$$

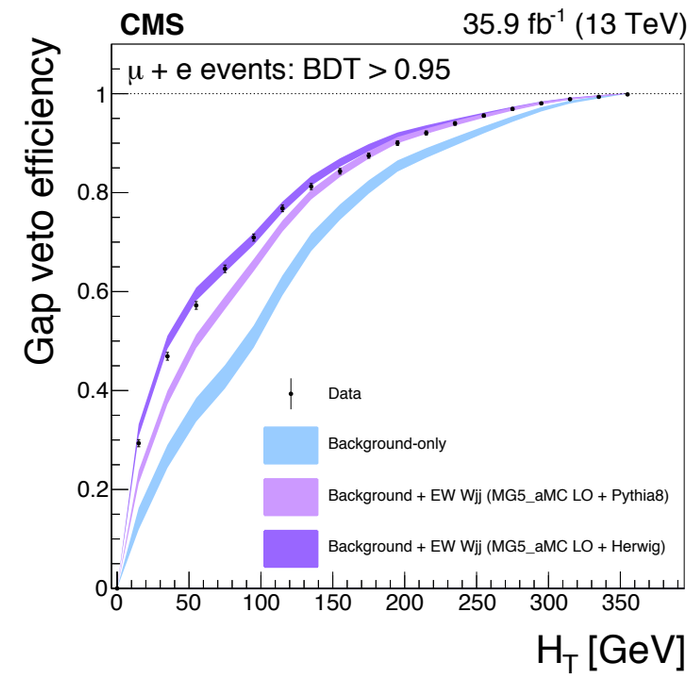


arXiv:1903.04040, submitted to EPJC

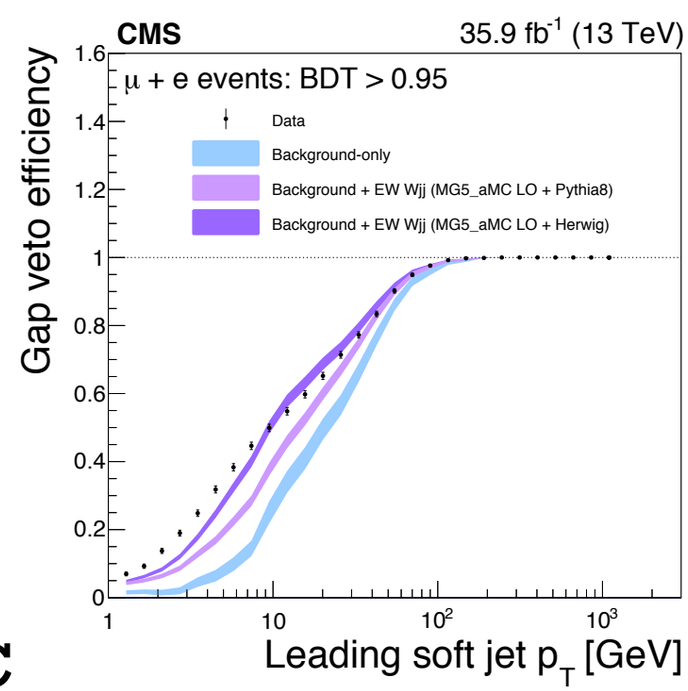
Gap activity veto efficiencies

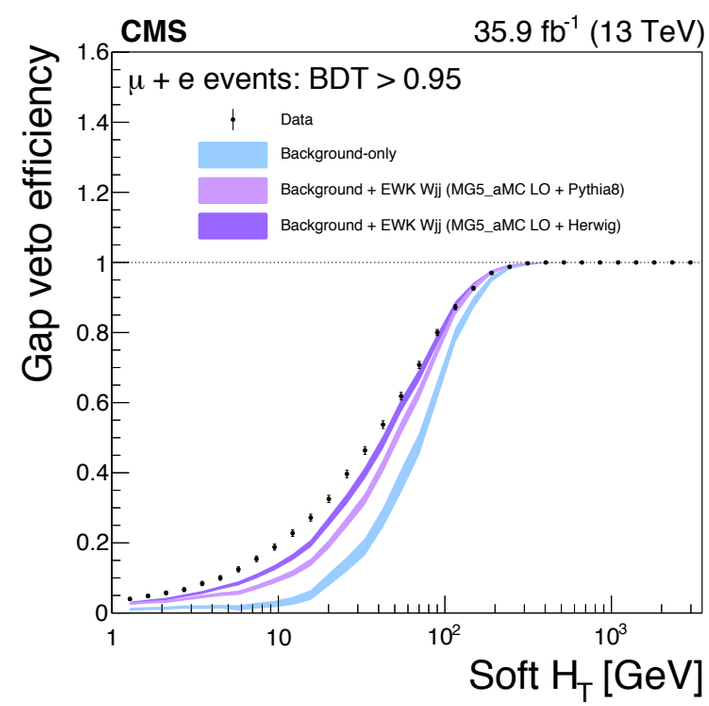
- Require BDT > 0.95 to achieve S/B ~ 1.
- Consider same set of gap activity observables as in VBF Z.
- Higher statistics with respect to VBF Z allows probing more granularly at low p_T.





track-jet observables (probe lower p_T)

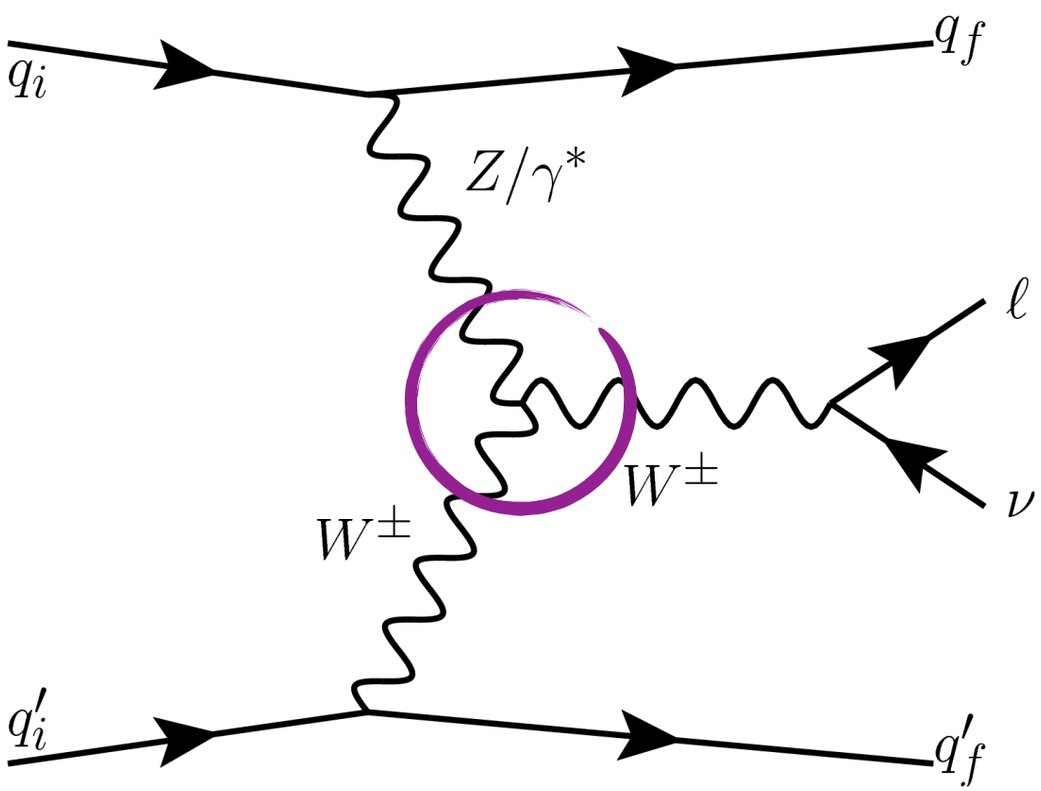




Consistent with VBF Z: data prefer signal model with HERWIG PS at low gap activity.

arXiv:1903.04040, submitted to EPJC

Anomalous trilinear gauge couplings



- Anomalous trilinear gauge couplings (aTGC's) can be constrained via measurement of diboson and VBF W/Z production.
  - Particularly in high-energy tails of kinematic distributions.

$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho},$$

$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} W_{\mu\nu} (D^{\nu}\Phi),$$

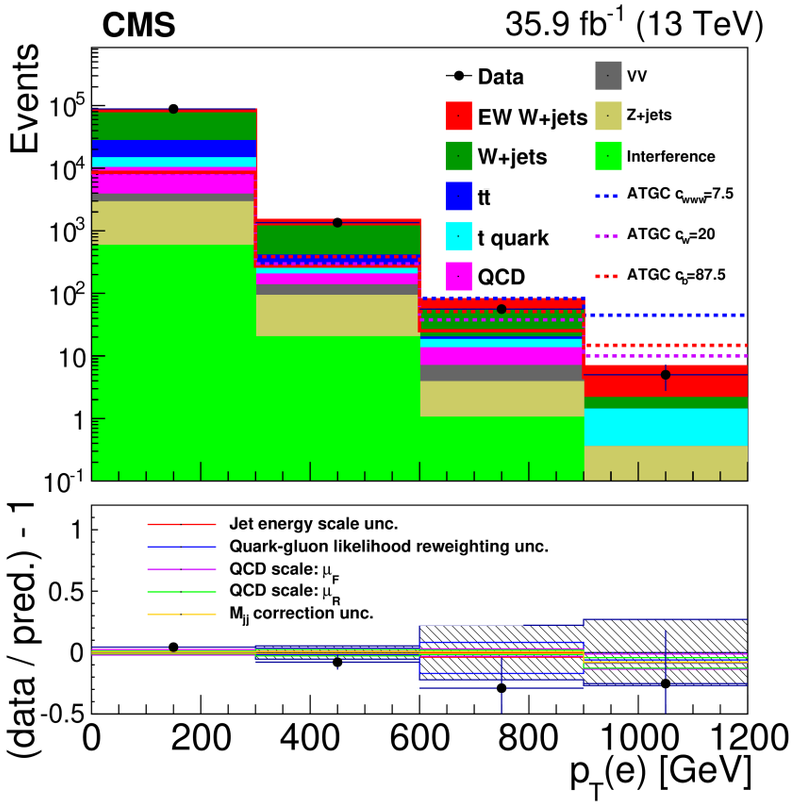
$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} B_{\mu\nu} (D^{\nu}\Phi)$$

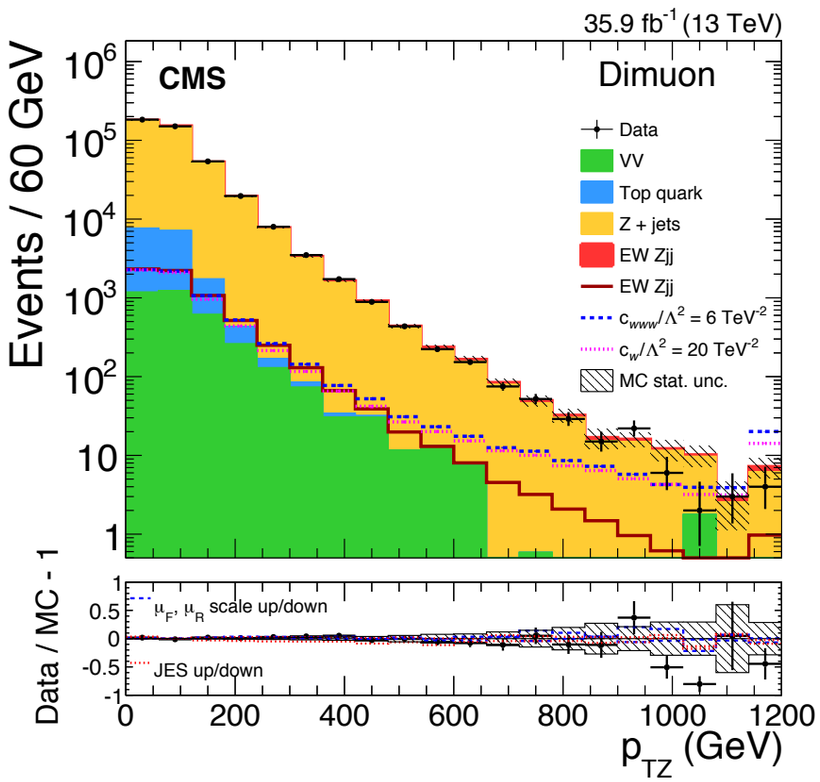
- Consider experimentally clean $p_T(Z)$ and $p_T(\ell)$ distributions to limit systematic uncertainties.

Constraints on aTGC's

- Combined fit of $p_T(Z)$ from VBF Z and $p_T(\ell)$ from VBF W.
- Constraint in VBF W channel improved by 20-25% by requiring BDT > 0.5 in preselection.

Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	$[-2.3, 2.4]$	$[-1.8, 2.0]$
c_W/Λ^2	$[-11, 14]$	$[-5.8, 10.0]$
c_B/Λ^2	$[-61, 61]$	$[-43, 45]$





Most stringent limit to date on c_{WWW}.

arXiv:1903.04040, submitted to EPJC

Summary

- Extensive unfolded measurements of jet kinematics for W/Z+jets performed at 13 TeV.
  - Generally good agreement between data and NLO predictions.

- Measurements of electroweak-initiated (VBF) W/Z processes at 13 TeV.
  - Cross sections measured with 10% precision.
  - Quantitive measure of modeling of VBF processes in region with high VBF purity.
  - Most stringent constraints to date on some anomalous trilinear gauge couplings.

Thank you!

Additional Material

Gap activity studies: VBF W

- Signal-enriched sample selected with BDT > 0.95 ⇒ S/B ~ 1.
- Study additional hadronic activity in region between VBF jets.
  - Suppressed for EW VBF signal.
- Consider additional jets with p_T > 15 GeV jets in the gap (first bin are events with no additional jets).
- Use track-only "soft activity" jets (pileup-resistant) to probe lower in p_T (bottom row).

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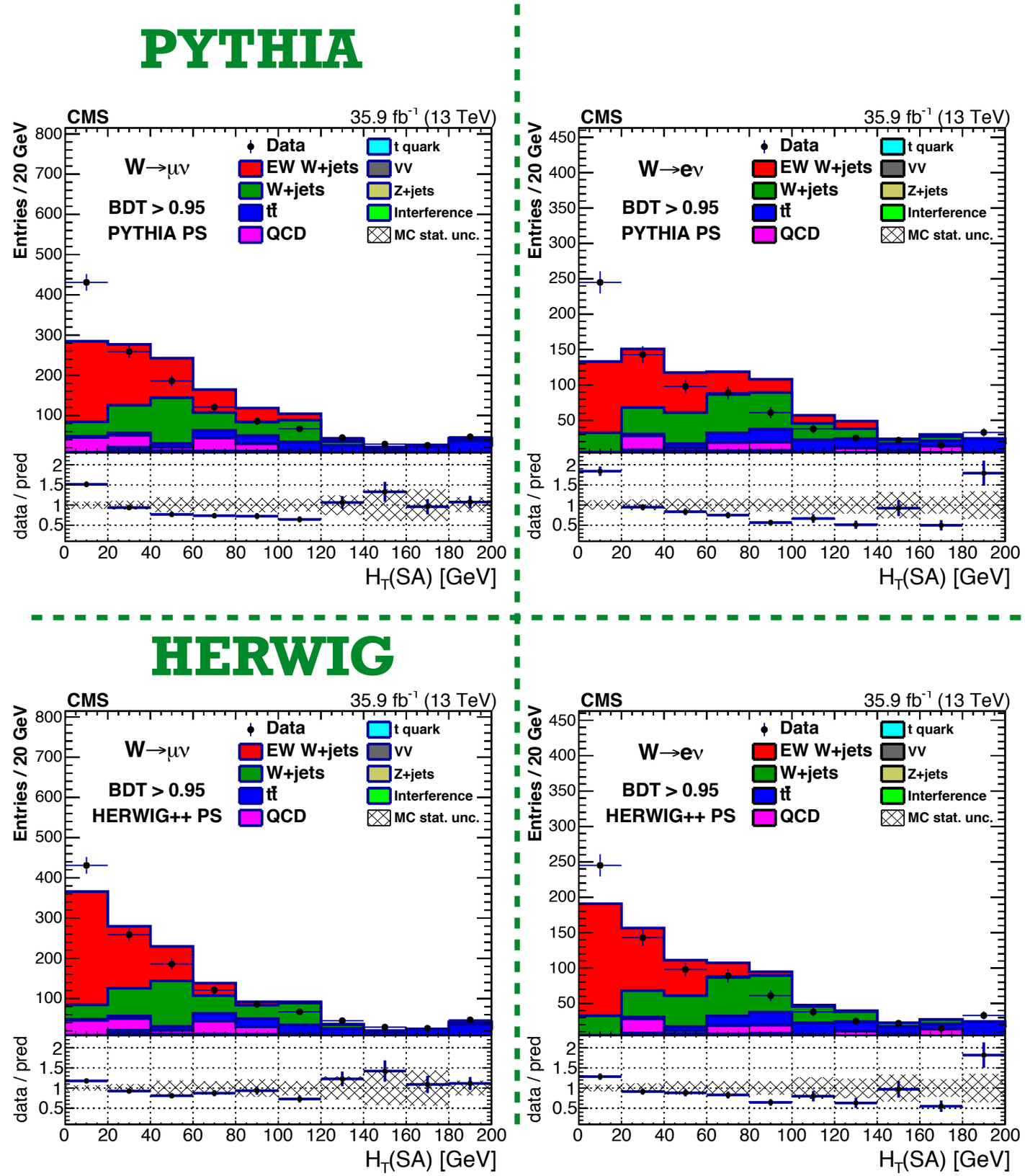
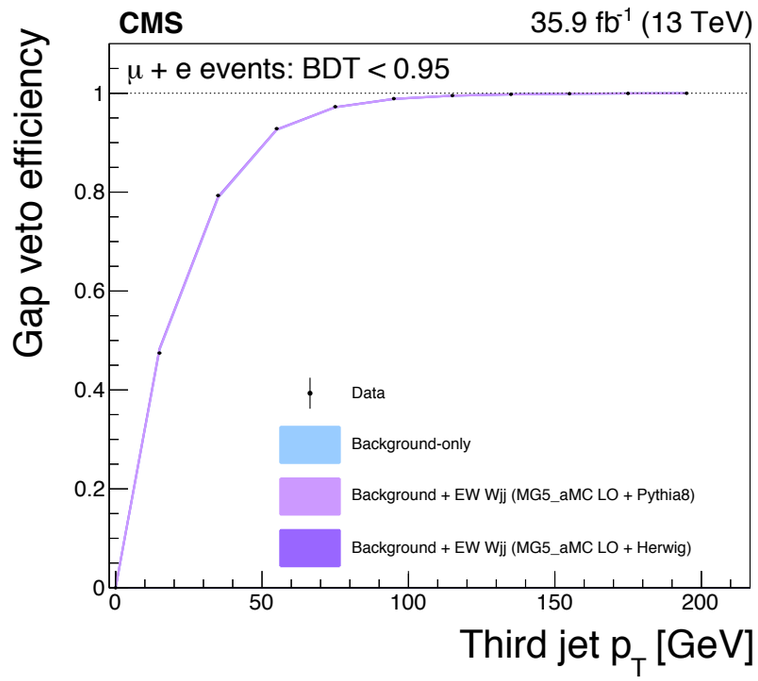
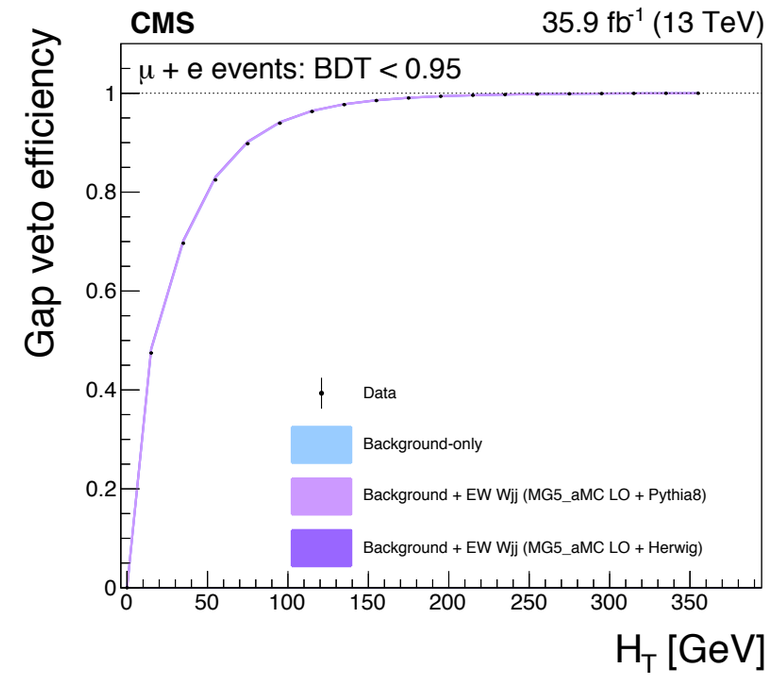


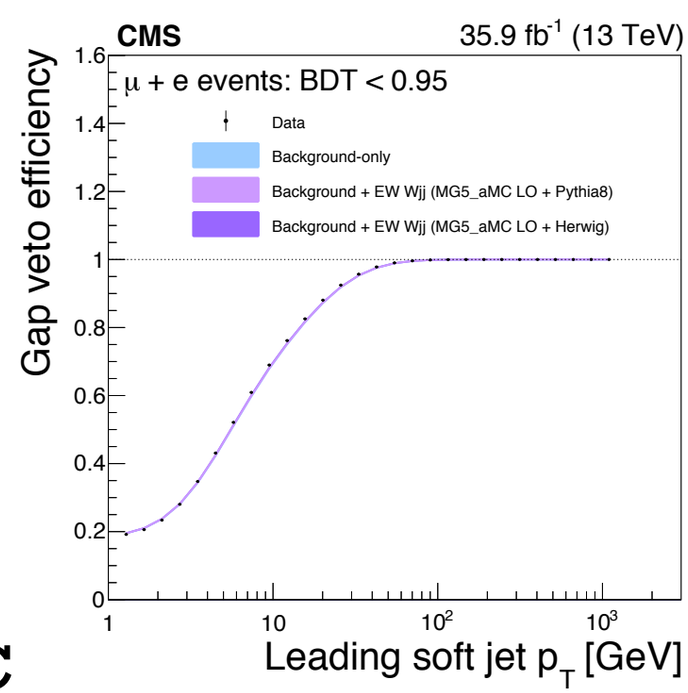
Gap activity veto efficiencies: validation

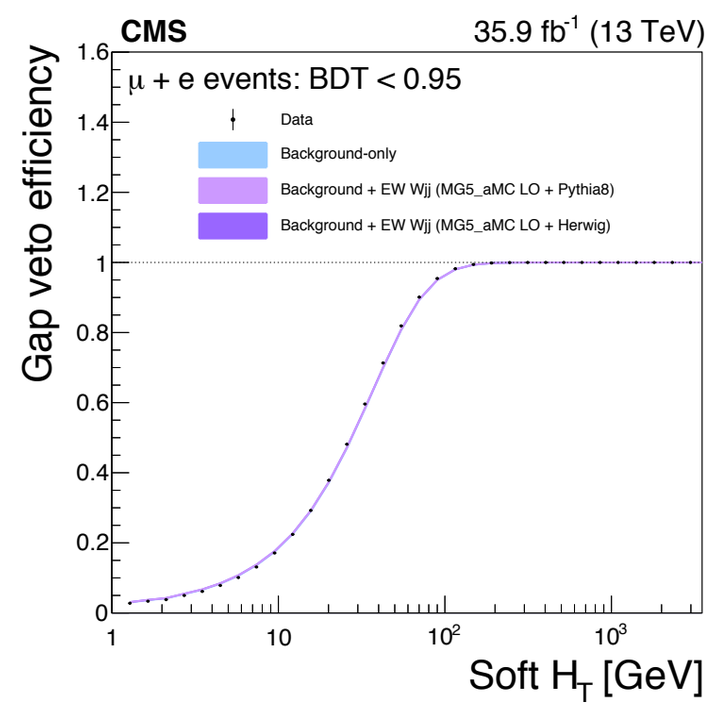
- Require BDT < 0.95 to deplete signal.
- Simulation models well the background throughout the full spectrum of the observables.





track-jet observables (probe lower p_T)





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