W boson production in association with jets at CMS

On behalf of the CMS Collaboration

Kadir Ocalan, Necmettin Erbakan University

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Overview

- Measurements of W boson + jets production rates and properties in proton-proton collisions at the LHC are important for:
  - testing pQCD predictions at the highest jet transverse momentum and jet multiplicities
  - tuning MC generators and theoretical calculations
  - probing strange, heavy flavor, and gluon content in the proton
  - providing inputs to constrain parton distribution functions
  - modeling backgrounds to rare SM (Higgs, single top) and beyond SM (SUSY, dark matter) signatures
- W + jets measurements at CMS:
  - W boson is identified reconstructed via their leptonic decays ($W \rightarrow l\nu$, $l=e,\mu$)
  - Leptons and jets are reconstructed using the Particle Flow algorithm, and an anti-kt clustering algorithm for jets with R= 0.5 (0.4) at 8 TeV (13 TeV)
  - Events containing an isolated lepton and jets are corrected for data-to-simulation discrepancies in lepton selection, jet energy scale (JES) and resolution (JER) calibration, pileup, and flavor tagging
  - Measured cross sections are unfolded to particle level for detector effects and compared to LO, NLO (+ PS) predictions from MCs, and NLO, NNLO fixed-order calculations where available

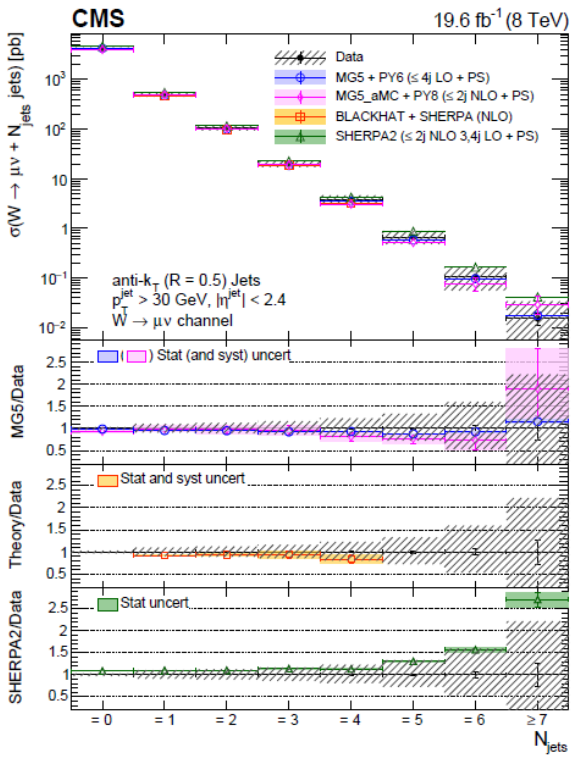
Outline

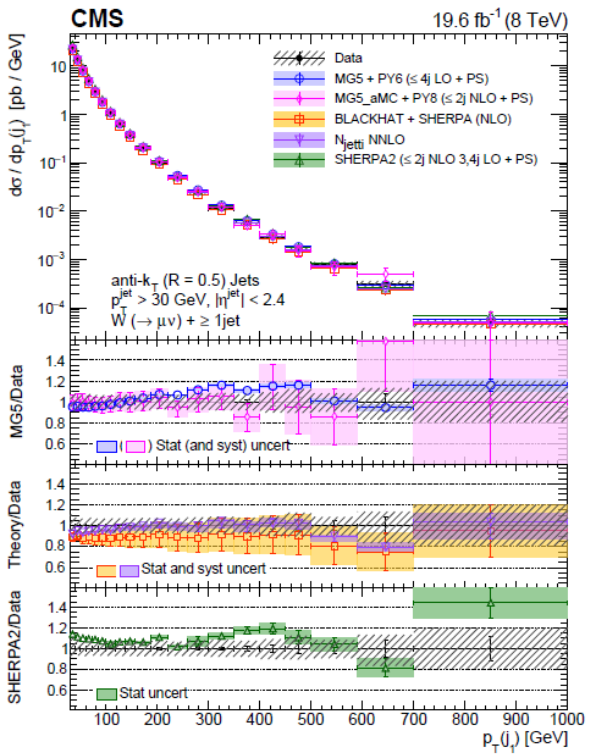
- Presented here the recent CMS W + jets results based on 8 TeV (2012, $L \leq 19.8\ fb^{-1}$) and 13 TeV (2015, $L = 2.5\ fb^{-1}$) pp collisions data

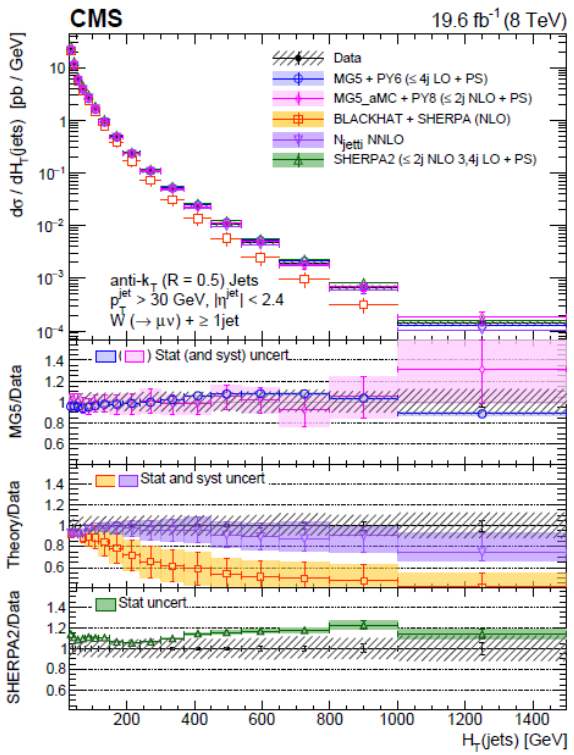
  - ✓ W + jets differential cross sections at 8 TeV (arXiv:1610.04222, accepted by PRD)
  - ✓ W + jets differential cross sections at 13 TeV (CMS-PAS-SMP-16-005)
  - ✓ W + 2 b jets cross section at 8 TeV (arXiv:1608.07561, accepted by EPJC)
  - ✓ EW production of W + 2 forward jets at 8 TeV (JHEP 11 (2016) 147)

W + jets at 8 TeV

- Differential cross sections in muon channel up to 7 jets and inclusive 4 jets on observables
- Several predictions by multileg (N)LO + PS, fixed-order NLO, and fixed-order NNLO for W + ≥ 1 jet
- NLO theory calculations up to 4 partons. NP effects are accounted for fixed-order calculations



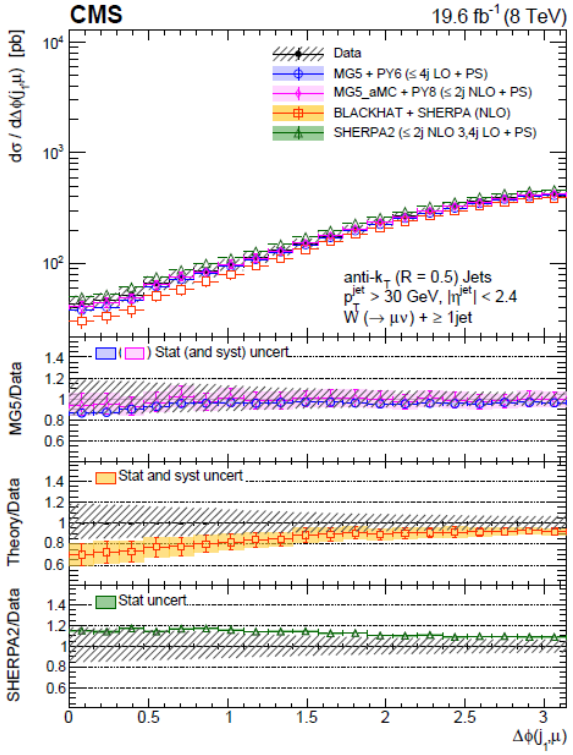


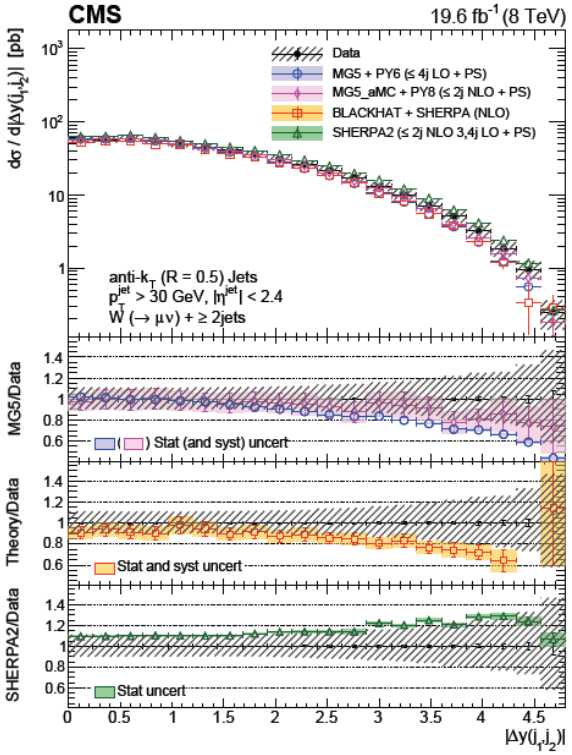


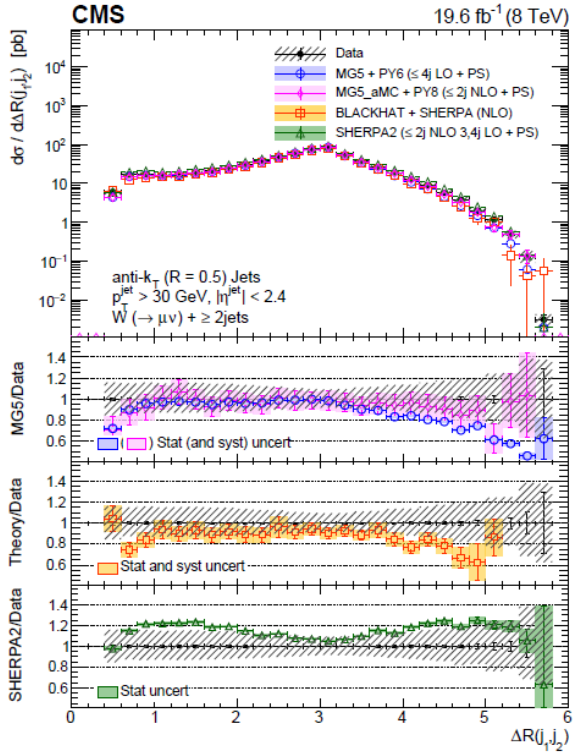
- ✓ **Measured ranges extend up to 1 TeV on the first-leading jet p_T and 1.5 TeV on H_T for $N_{jets} \geq 1$**
- ✓ **Good data description by MG5_aMC FxFx (NLO up to two jets) and N_{jetti} NNLO predictions**

W + jets angular correlations at 8 TeV

- The large amount of 8 TeV data motivates for a more detailed study of angular correlation variables
- Testing the accuracy of modeling on angular variables by MC generators and NLO calculation



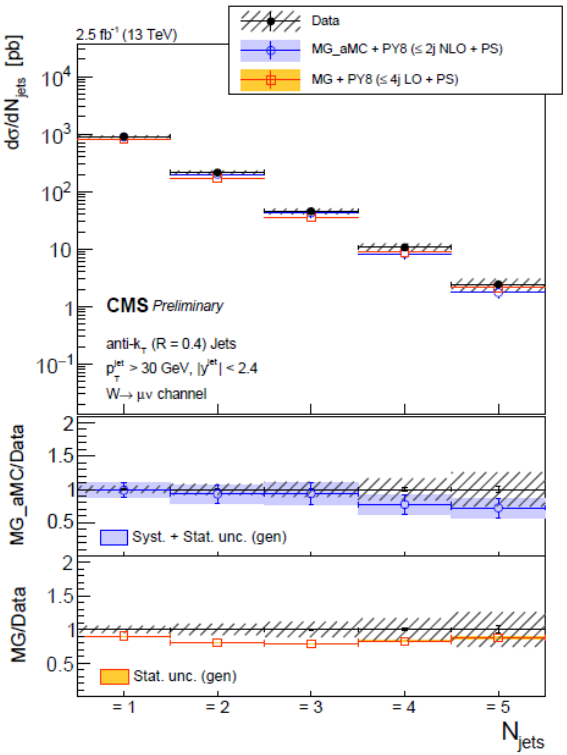


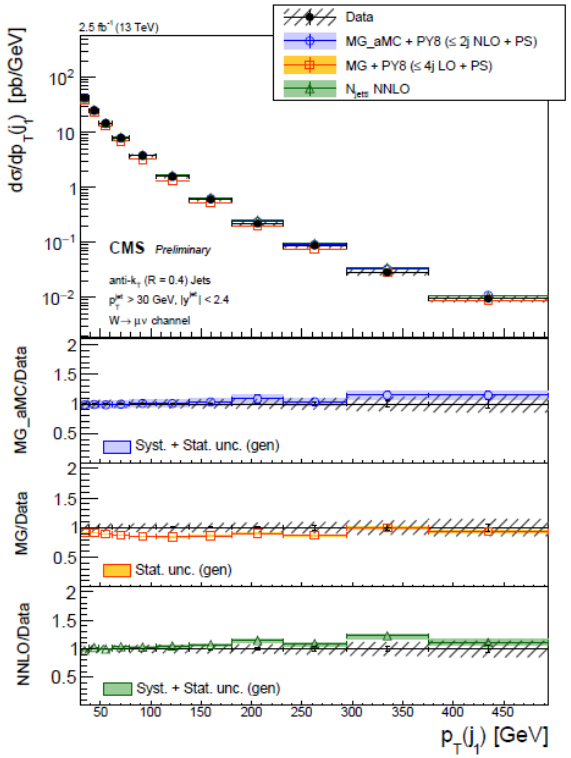


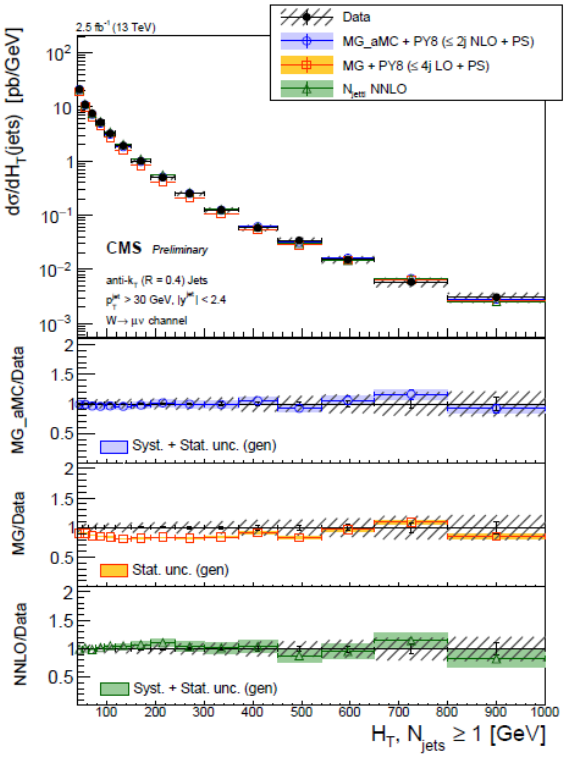
- ✓ **Overall, best description of data by MG5_aMC FxFx merged NLO**
- ✓ **Fixed-order NLO shows some more deviations from data at low Δϕ between muon and jets and at high Δy between jets. Sherpa 2 shows higher trend over almost the entire ranges**
- ✓ **More distributions (dijet, average N_{jets}, and correlations) are in back-up**

W + jets at 13 TeV

- First results of the W + jets differential cross sections measurement available on 2015 data
- Data comparison to MG5 tree level + PS, MG5_aMC merged NLO + PS, and N_{jetti} NNLO predictions







- ✓ **MG5_aMC merged NLO agrees well with data up to 5 jets on jet multiplicity**
- ✓ **Remarkable agreement with data on jet p_T and H_T by NLO and fixed-order N_{jetti} NNLO W + ≥ 1 jet**

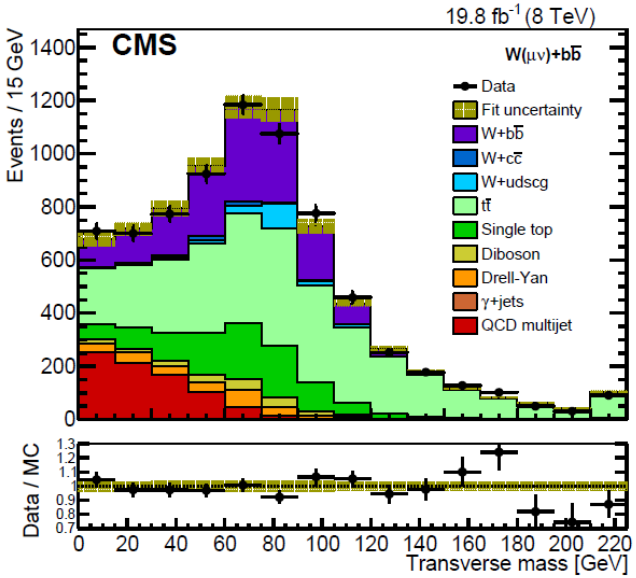
W + heavy flavor (HF) jets

- Challenging analyses but are of paramount importance
- Tests of pQCD. Background processes to Higgs and BSM searches
- Sensitivity to probe strange and heavy quark (b, c) content in the proton
- b quark flavor content of the PDFs: 4 flavor vs 5 flavor schemes

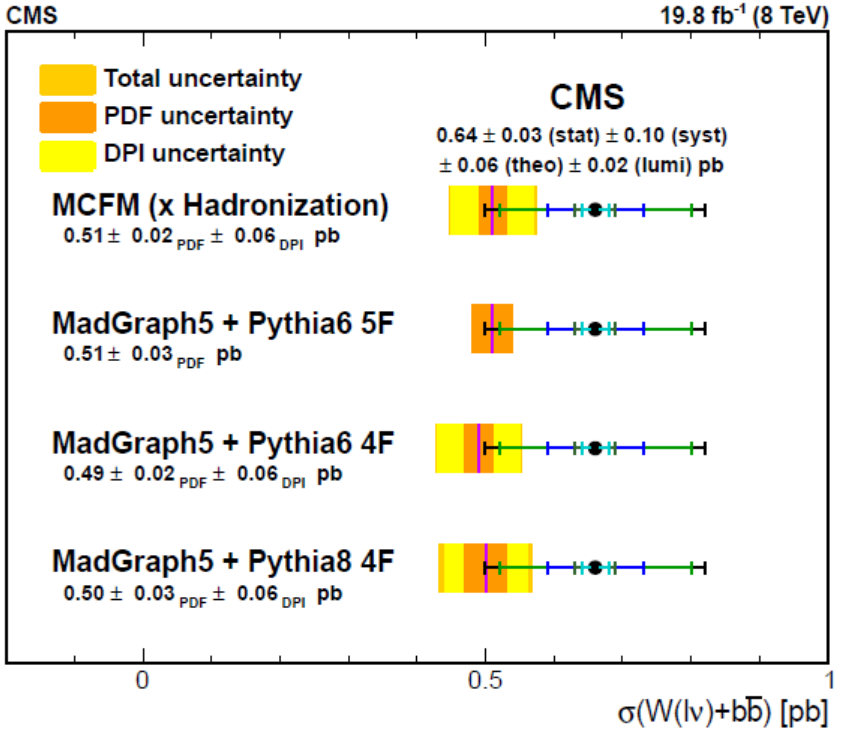
- HF jets are identified with CMS Combined Secondary Vertex (CSV) algorithm
- Exploiting long-lifetime and relatively large masses of b hadrons (e.g. secondary vertex and large impact parameter) using multivariate analysis techniques

W + 2b jets at 8 TeV

- Measurement of the cross section for W(e/μ+ν) with exactly 2 b jets, background to SM Higgs production (VH, H → $b\bar{b}$)
- Theoretical predictions by MCFM NLO, MG5 + PYTHIA 6 / PYTHIA 8 in 4FS / 5FS approaches
  - MCFM is corrected for hadronization with a correction obtained from MG5 + PYTHIA 6
  - MCFM and MG5 + PYTHIA 6/8 using 4FS do not account for the $b\bar{b}$ system from DPI, that is estimated with MG5 + PYTHIA 8



✓ **The simulation is tuned to better describe the tt̄ control samples and used to extract the signal yield in the signal region (back-up)**

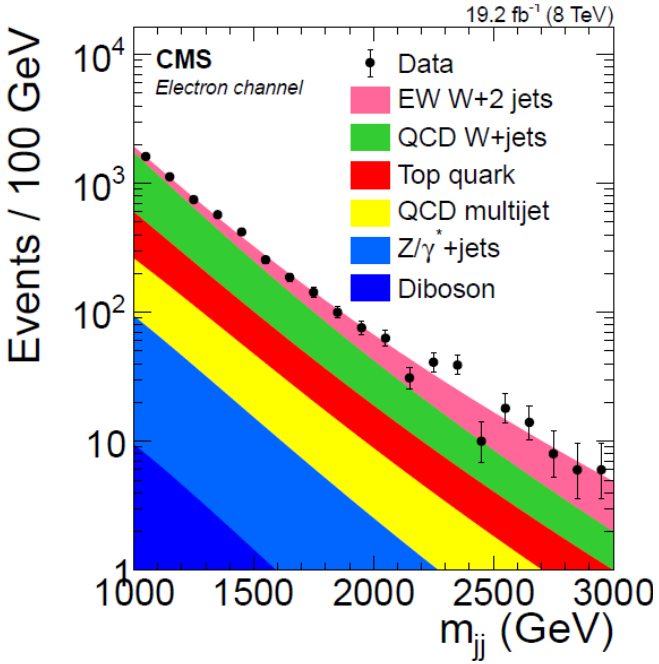


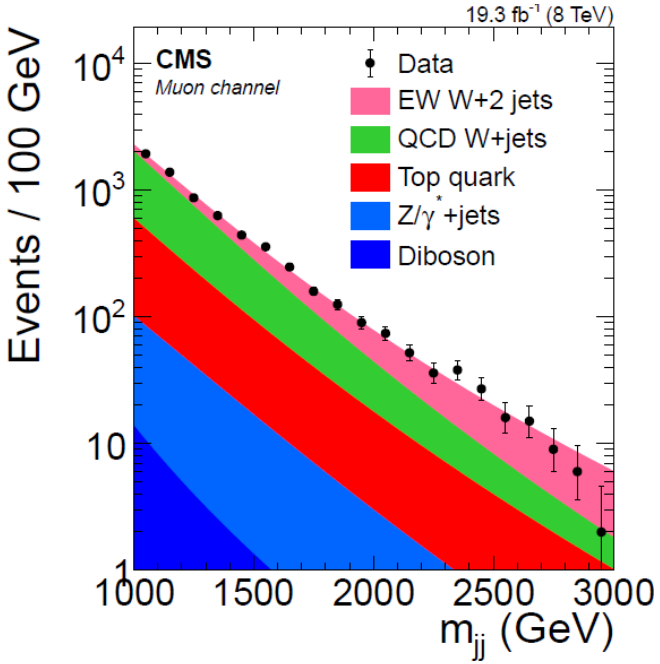
✓ **Predictions agree with each other and are consistent with CMS data within their uncertainties**

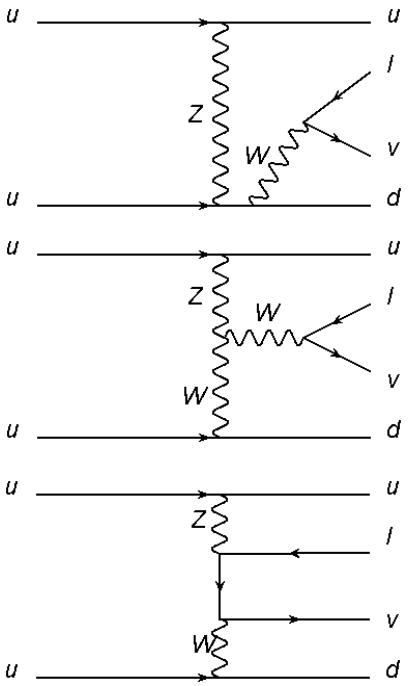
✓ **Important test of pQCD with heavy flavors: 4FS (b massive) and 5FS (b massless)**

EW production of W + 2 jets at 8 TeV

- This is the first cross section measurement for this process
- Probes Triple Gauge Couplings and background to Higgs production in VBF channel
- W(e/μ+ν) plus two forwards jets with $|\eta| < 4.7$ and $m_{jj} > 1000$ GeV
- BDT used to separate signal and background (QCD W + jets)
- Signal extracted via fits to $m_{j1,j2}$







✓ **Measured cross section in agreement with SM LO prediction by MG5_aMC + PYTHIA 6**

$$\sigma(W \to l\nu + 2\ \text{jets}, l = e, \mu) = 0.42 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.01\,(\text{lumi})\ \text{pb}$$

$$\sigma_{\text{SM LO}}(W \to l\nu + 2\ \text{jets}, l = e, \mu) = 0.50 \pm 0.02\,(\text{scale}) \pm 0.02\,(\text{PDF})\ \text{pb}$$

Conclusion

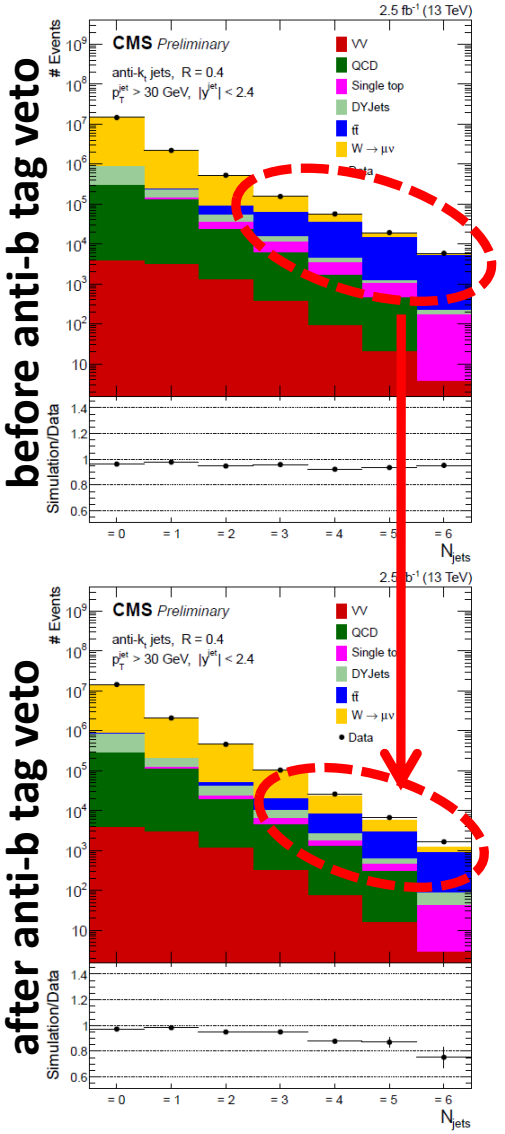
- CMS has provided unique precision tests for pQCD effects on production of W boson in association with jets (including HF jets) using the large pp collisions data
- Differential cross sections are measured over several orders of magnitude as a function of numerous variables probing wider kinematic regimes (TeV-scale jets!)
- Different predictions including LO, NLO ME + PS, fixed-order NLO and NNLO (x NP) have been scrutinized with data
- Best description of unfolded data with NLO ME + PS and fixed-order N_{jetti} NNLO
- Measured fiducial cross sections for W + bb and EW W + 2 jets processes are in agreement with the SM predictions
- Many more CMS results are still to come with unprecedented kinematic reach and more precise description of LHC Run II data on V + jets including heavy flavors!

Thank you

Back-up slides

QCD W + jets analyses

- Measurements with higher statistical precisions (σ_{W+jets} ~ 10 x σ_{Z+jets})
- Probe wider kinematic regimes on several variables sensitive to higher-order processes
- Large backgrounds of QCD multijet and top pair production
  - Estimate QCD background from data (by requiring non-isolated muon selection in the M_T variable)
  - Top rejection at higher jet multiplicity bins using anti-b tag selection
  - Suppress contribution from Drell-Yan background by vetoing extra leptons
- Measured cross sections are in fiducial phase space of W(e/μ+ν)+jets
  - Detector acceptance of $|\eta| < 2.1$ (~2.4) for leptons and $|\eta$ (or y)$| < 2.4$ (< 4.7 forward) for jets
  - Reconstruction of isolated leptons and jets typically with $p_T > 25$ - 30 GeV
  - Identify escaping neutrino using E_T^{miss}, use an M_T(W) selection for rejection of non-W final states
- Data distributions are unfolded for detector effects to the fiducial phase space at particle level
- Compare unfolded data to available MC generators and to fixed-order calculations (after correction for non-perturbative (NP) effects such as hadronization and MPI)



Top rejection in SMP-PAS-16-005

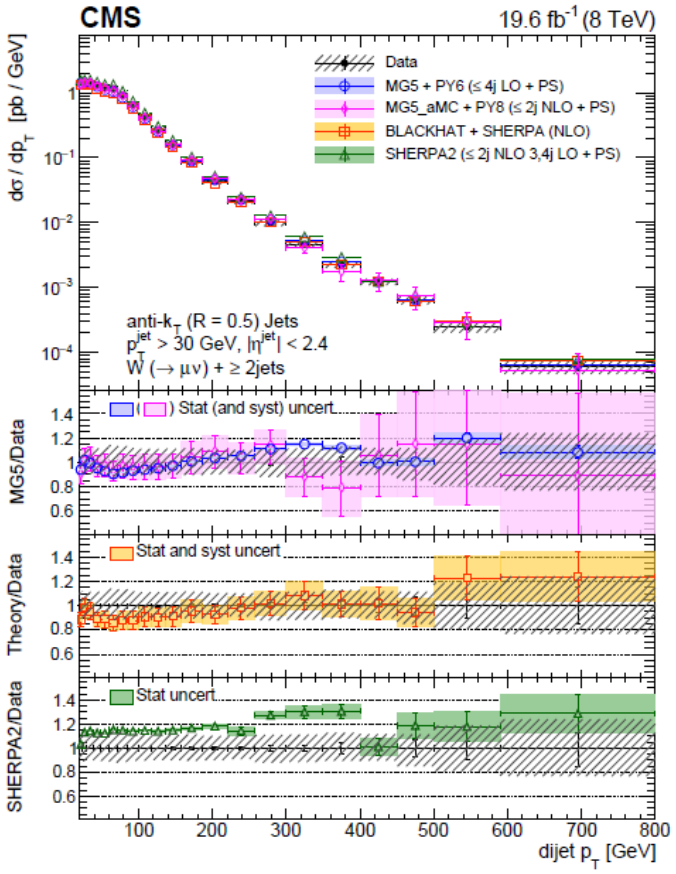
Summary of theoretical predictions

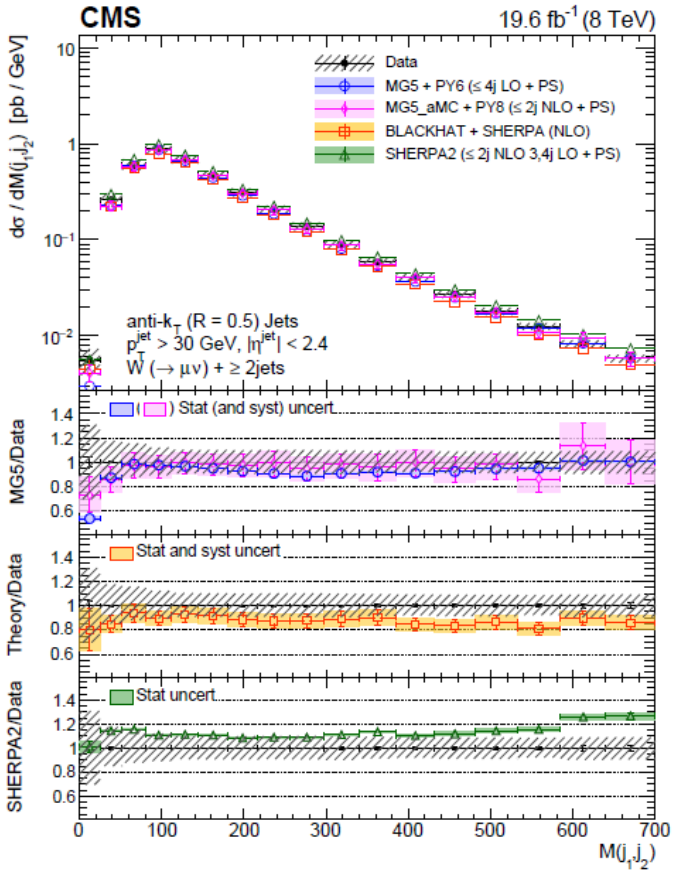
- **W + jets at 8 TeV / *13 TeV***
  - *MADGRAPH 5 + PYTHIA 6 using CTEQ6L1 PDF, ME + PS merged with kt-MLM*
  - *MADGRAPH 5_AMC@NLO + PYTHIA 8 using FxFx merging scheme, ME computation up to 2 jets at NLO accuracy, ME using NNPDF3.0 and PS using NNPDF2.3*
  - SHERPA 2 (+ BLACKHAT) NLO up to 2 partons and using CT10 PDF, ME + PS merged with MEPS@NLO
  - BLACKHAT + SHERPA, fixed-order NLO up to 4 jets, using CT10 PDF
  - *N_{jetti} NNLO for W + ≥ 1 jet (Phys. Rev. Lett. 115, 062002) using CT14 NNLO PDF*
- **W + bb at 8 TeV**
  - MADGRAPH 5 + PYTHIA 6 in 5FS using CTEQ6L PDF
  - MADGRAPH 5 + PYTHIA 6 / PYTHIA 8 in 4FS using NNLO PDF, corrected for DPI
  - MCFM NLO using MSTW2008 PDF, corrected for hadronization and DPI effects
- **W + 2 forward jets at 8 TeV**
  - MADGRAPH 5_AMC@NLO + PYTHIA 6 at LO, using CTEQ6L1 PDF

- Total cross section for MADGRAPH 5 tree level LO is normalized to the NNLO cross section computed with FEWZ
- Non-perturbative corrections are applied to fixed-order calculations to bring them in line with measurements
- Z2* (CUETP8M1) tune is used in PYTHIA 6 (PYTHIA 8) consistently in analyses

W + dijet at 8 TeV

- Dependence of the measured cross sections on the dijet transverse momentum and invariant mass that are sensitive to the presence of physics beyond the SM in dijet final states

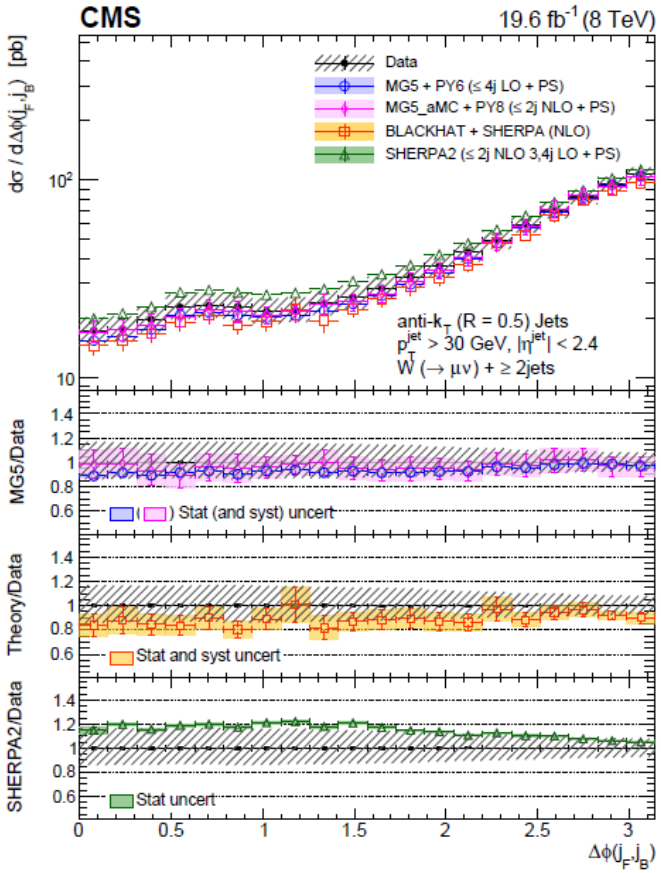


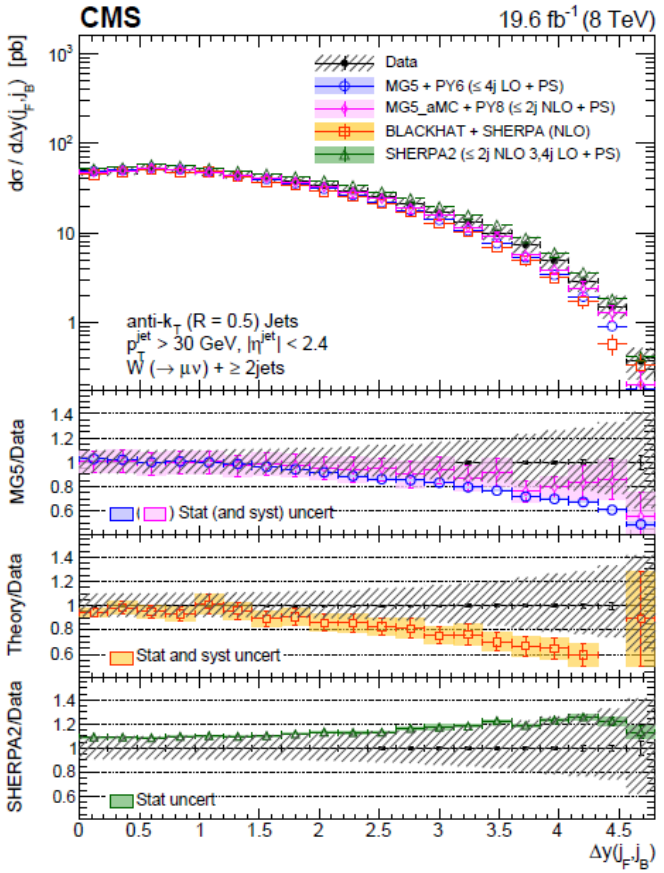


✓ **For dijet p_T and $M_{j1,j2}$, different generators give similar prediction, apart from Sherpa 2**

W + jets at 8 TeV: $\Delta\phi(j_F, j_B)$ and $\Delta y(j_F, j_B)$

- $\Delta\phi(j_F, j_B)$: A sensitive test of modeling of higher-order corrections in theoretical calculations
- $\Delta y(j_F, j_B)$: A test of wide-angle parton radiation and ME + PS matching schemes

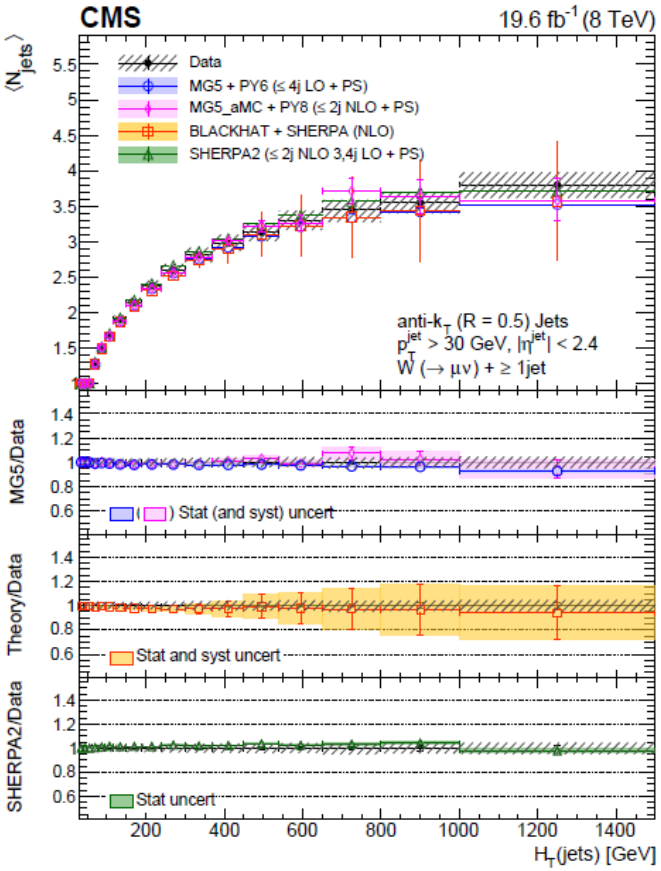


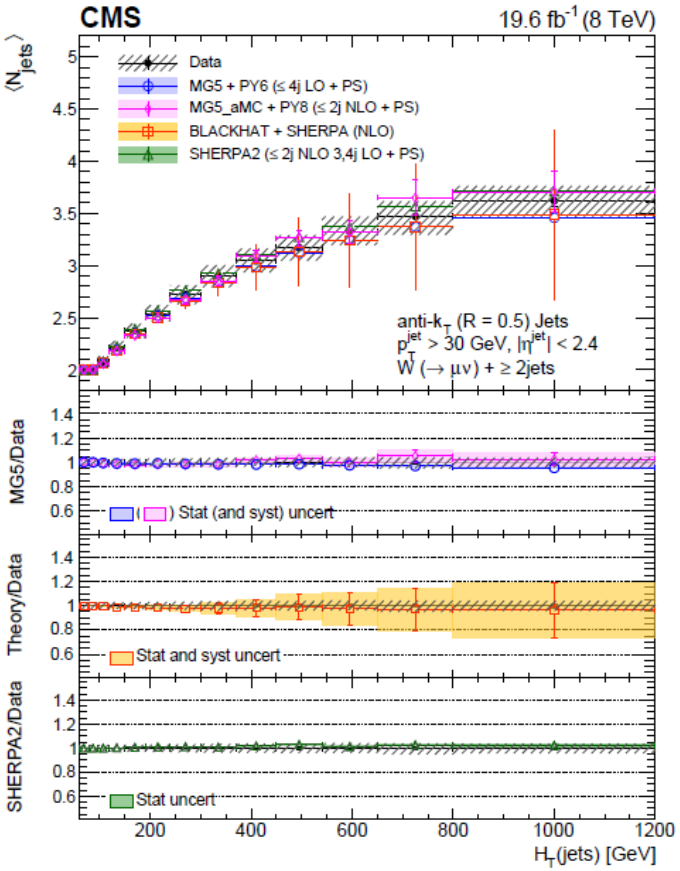


✓ **Predictions tend to undershoot data at high rapidity separation of jets, except Sherpa 2**

W + jets at 8 TeV: Average number of jets <N_{jets}>

- Sensitivity to the effects of the higher-order processes

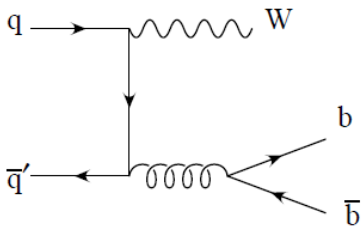


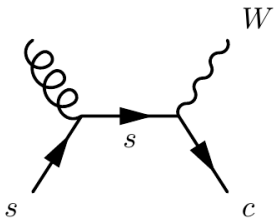


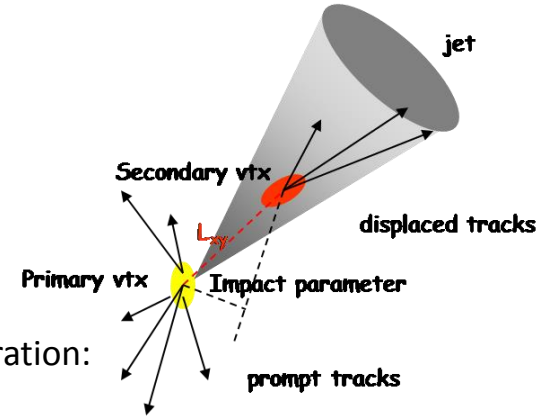
✓ **Excellent description of data over the entire ranges of H_T for N_{jets} ≥ 1 (2) jet left (right)**

W + HF measurements

- Measurements of the W + HF (b, c) jets processes are crucial for the understanding of SM Higgs, single top, and searches for new physics
- W + b is sensitive to gluon splitting and intrinsic-b PDF
- W + c is sensitive to strange PDF and gluon splitting





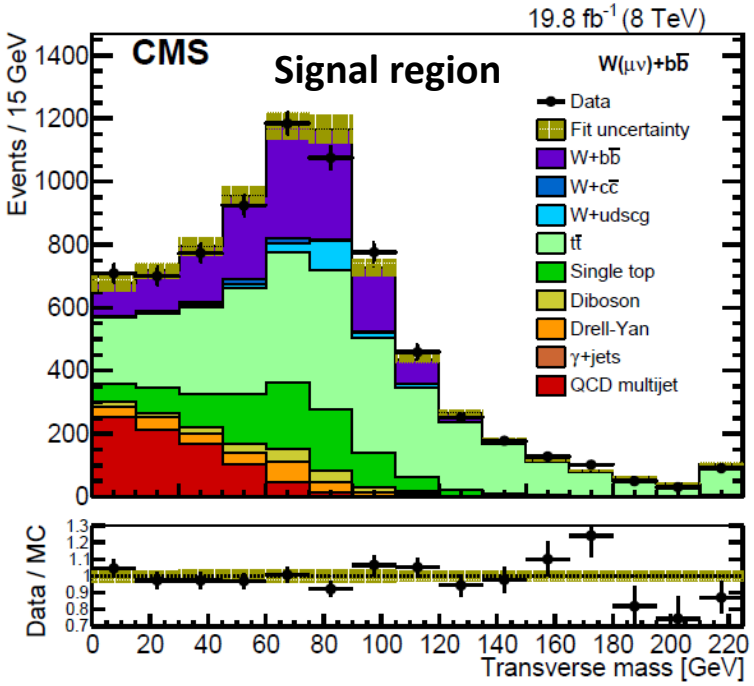


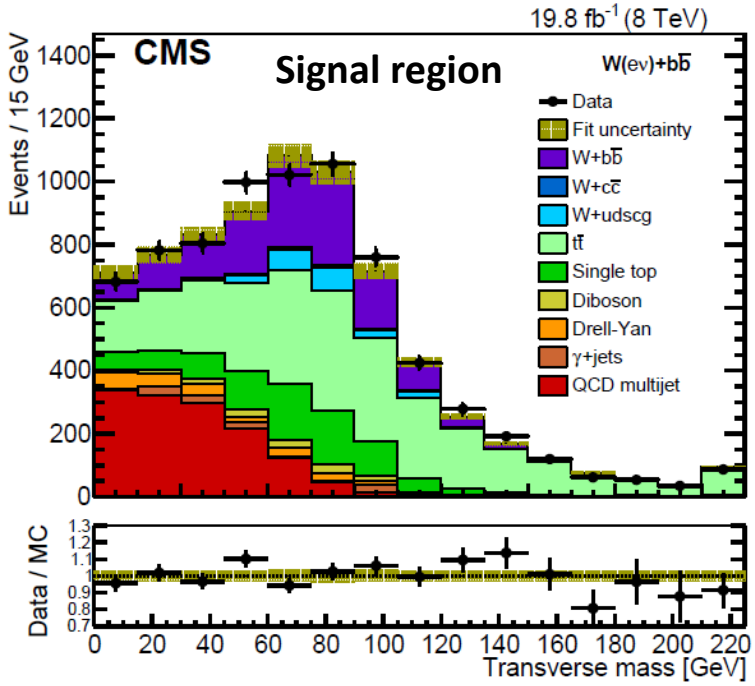
- Rely on displaced vertex reconstruction (HF jet tagging) and bottom/charm separation:
  - Signature of a b hadron decay is a displaced vertex:
    - Long lifetime of B hadrons ($c\tau$ ~450μm) + boost
    - B hadrons travel L_{xy} ~ 3mm before decaying with large charged track multiplicity
    - improved tagging performance from combining several inputs (displaced vertex, lifetime, jet kinematics) with multivariate algos
  - c-jets and b-jets separation achieved by explicit reconstruction of D mesons or statistical discriminants
- Background levels are higher than for V + light jets channels. Added model uncertainties include choice of flavor scheme (FS), quark masses, etc.
- Signal extraction based on fit to distributions sensitive to jet flavor (see next page)
- CMS tests different b-initiated processes along with predictions:
  - 4 flavors number scheme (4FS): massive b-quark generated through gluon splitting
  - 5 flavors number scheme (5FS): massless b-quark generated in the initial state by DGLAB evolution

(see talk by E. Barberis in APS 2017 April Meeting)

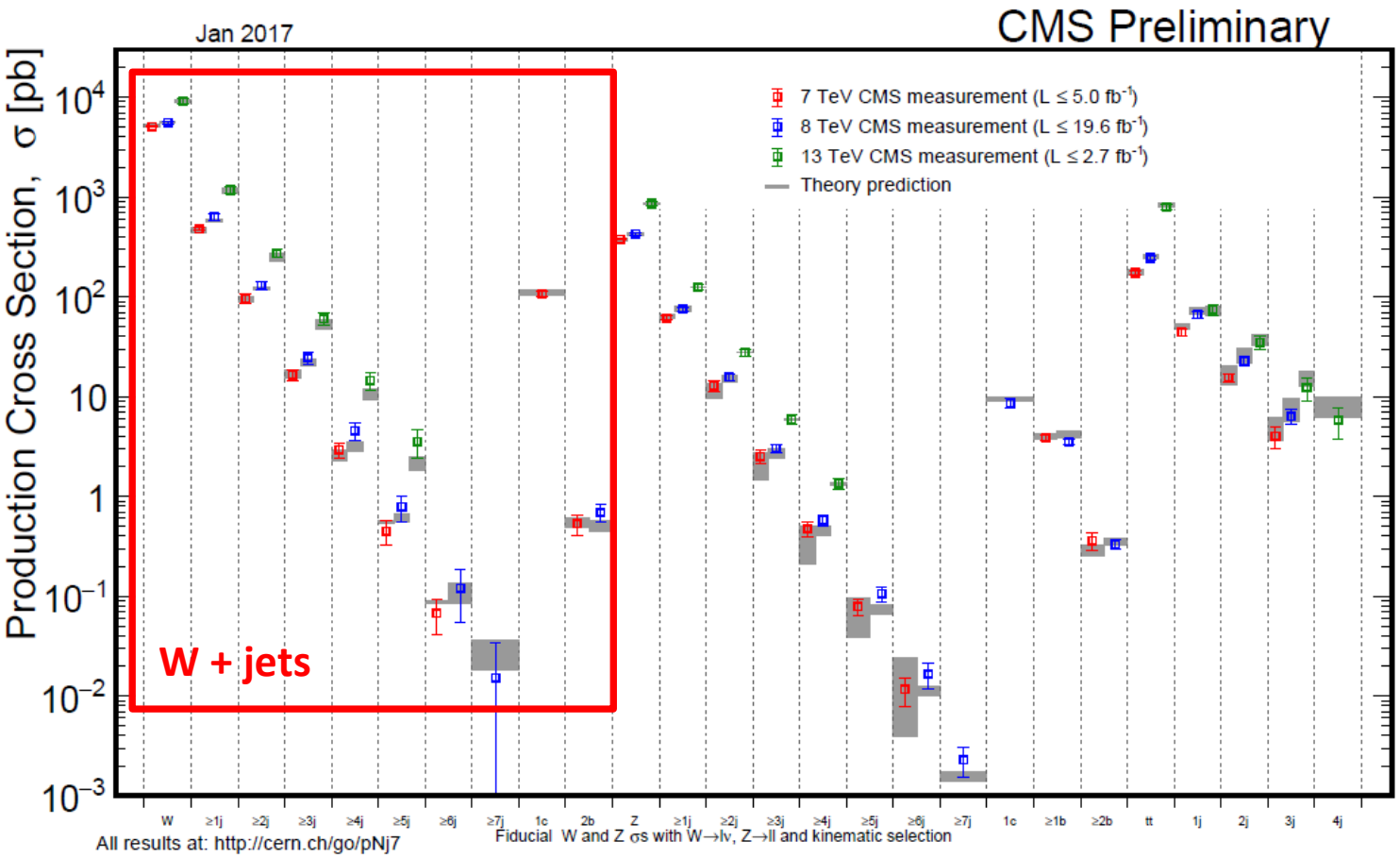
W + bb

- Production of W(→lν, l = μ, e) + $b\bar{b}$, signal region: $p_T(l) > 30$ GeV and $|\eta(l)| < 2.1$, exactly two b–tagged jets with $p_T(b) > 25$ GeV and $|\eta(b)| < 2.4$, veto on other jets
- Likelihood fit to $M_T(W)$ in two $t\bar{t}$ control regions: fit in $t\bar{t}$-multijet to estimate b tagging efficiency scale factors and in $t\bar{t}$-multilepton to adjust for JES in simulation
- Then, extract W+$b\bar{b}$ event yield by fitting in the signal region in two lepton channels





Snapshot of SM V + jets cross sections at CMS



✓ **CMS W + jets measurements at 7 TeV, 8 TeV, and 13 TeV spanning many orders of magnitude in cross section up to higher jet multiplicities**