Associated production of V + jets @ LHC

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QCD@LHC
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Introduction

- Measurements of σ(pp→V+jets) provide tests the EW & pQCD predictions. **Results sensitive to hard scattering process & associated soft QCD radiation**

- Allows better understanding of proton structure.

- Background to some SM processes and in searches

- Used extensively as control samples in V+HF analysis to measure/calibrate mistag rate.

Analysis strategy:

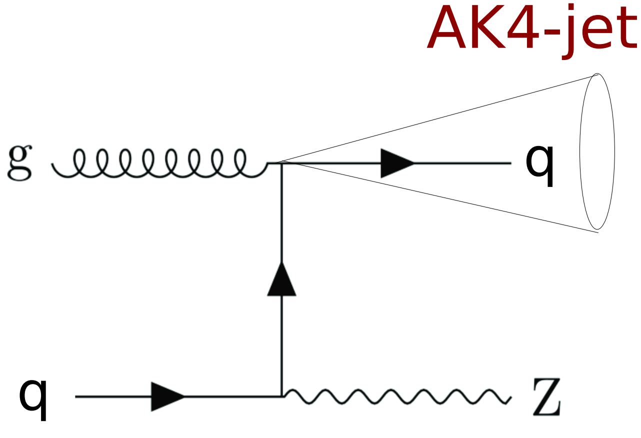
- Standard $Z \to l^+ l^-$
  - Isolated leptons with $p_T(l)>20$ (26) GeV and $|\eta(l)|<2.4$ from Z
  - Dilepton invariant mass: [71,111] GeV

- Standard $W^+ \to l^+ \nu$ (+c.c.)
  - Isolated lepton with $p_T(l)>30/35$ GeV for μ/e and $|\eta(l)|<2.4$
  - W transverse mass > 20 GeV

At large p_T usually accompanied by an associated hadronic recoil collimated into one or more jets

- jet selection:
  - anti-k_T jet: p_T^{jet} >30 GeV & $|\eta^{jet}|<2.5$

Analyses using a cone of radius of 0.4 :

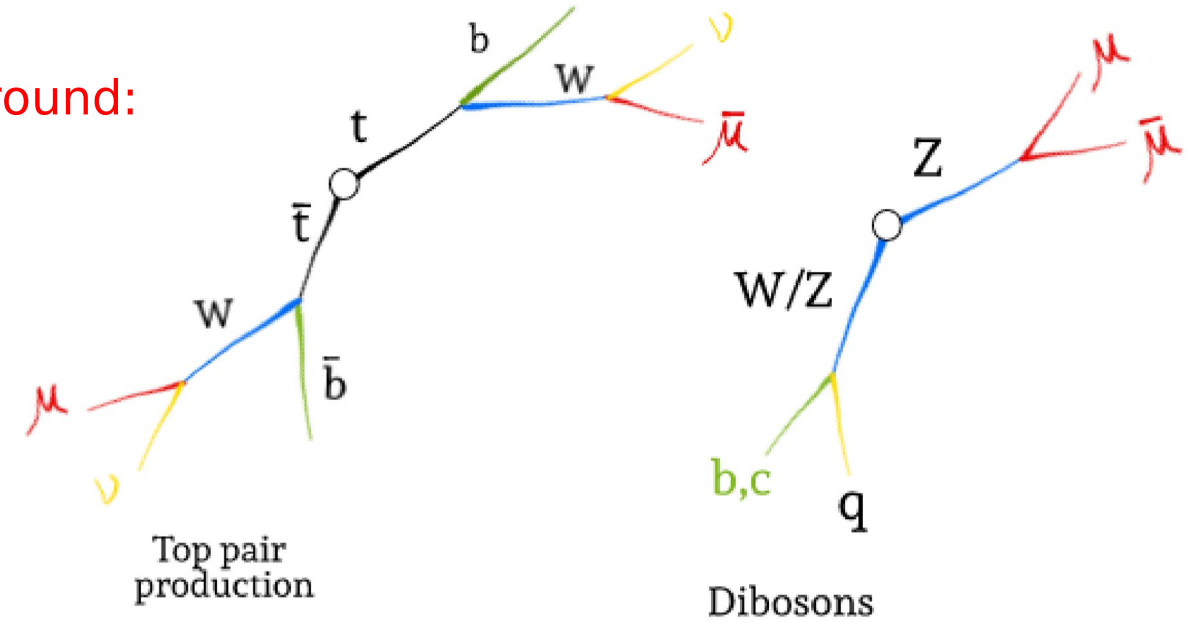


Samples:

DATA: 2016-2018 13 TeV (138 fb^{-1} for CMS , 139 fb^{-1} for ATLAS)

Signal: gen. V+jets MADGRAPH + PYTHIA or SHERPA or GENEVA
(MG5)

Main background:



Contributions from $t\bar{t}$ (from simulations or from data (*) for Z analysis) and dibosons.

(*) It is advisable to use control samples to test normalization and or shape dependence with a data sample (high momentum e,mu pair) or just use this sample to model the background

Probing the kinematic properties of V bosons

Measured observables

- Z and W boson tranverse momentum: W/Z p_T
- Azimuthal correlation between Z and leading jet
- 24 different observables as input of a machine

  learning method : OmniFold

Azimuthal correlations (CMS)

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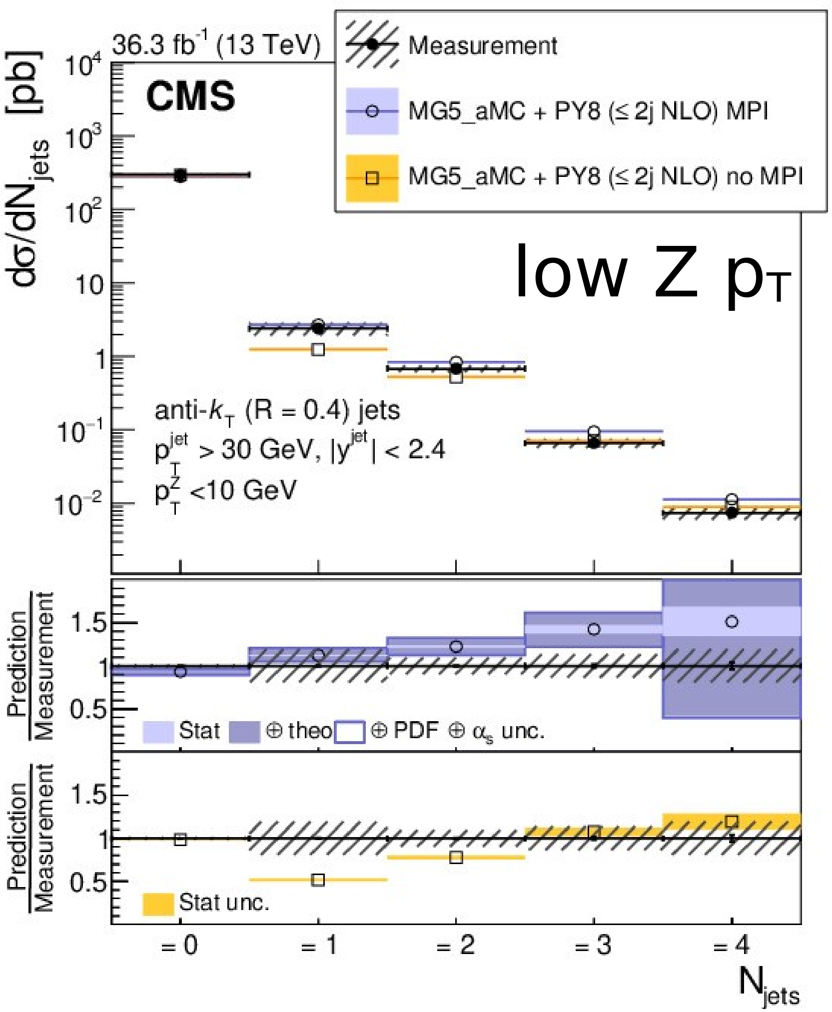
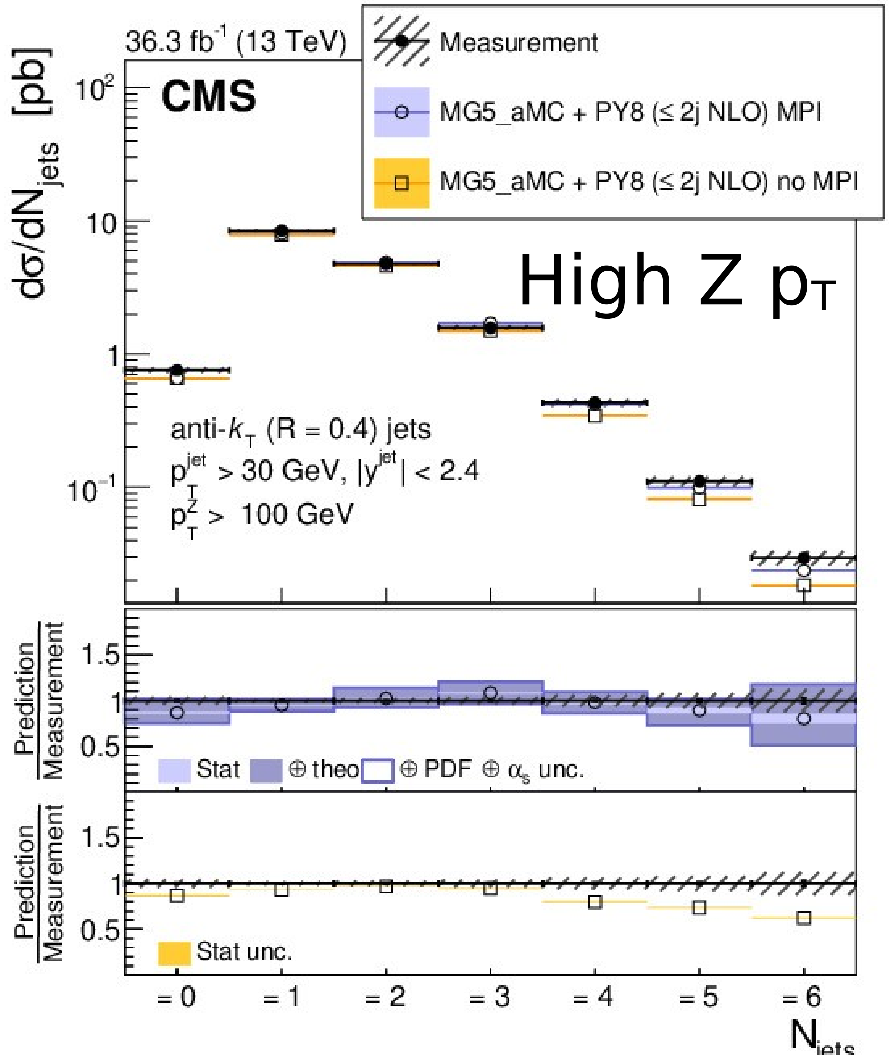
Jet Multiplicity in 3 different regions of $p_T(Z)$: <10, 30-50, >100 GeV

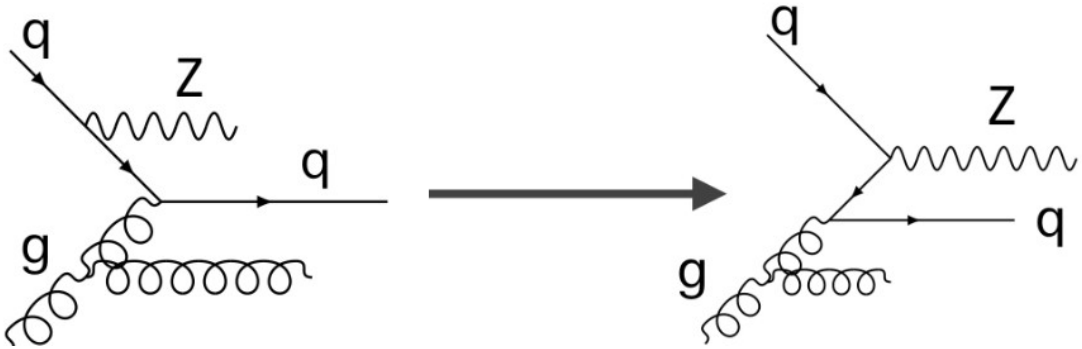




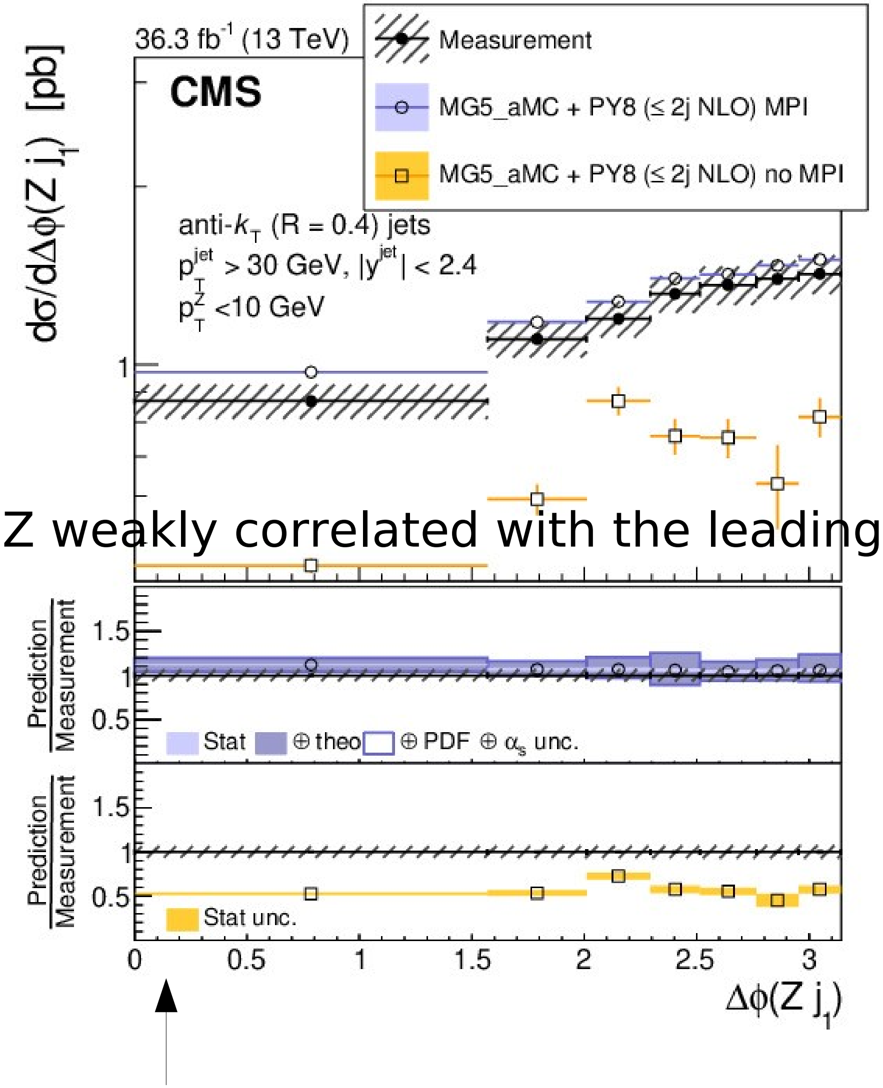
At low Z p_T, additional jets must balance the leading jet of p_T > 30 GeV.
At large Z p_T the Z boson is expected to balance the p_T of the leading jet.

About azimuthal correlations

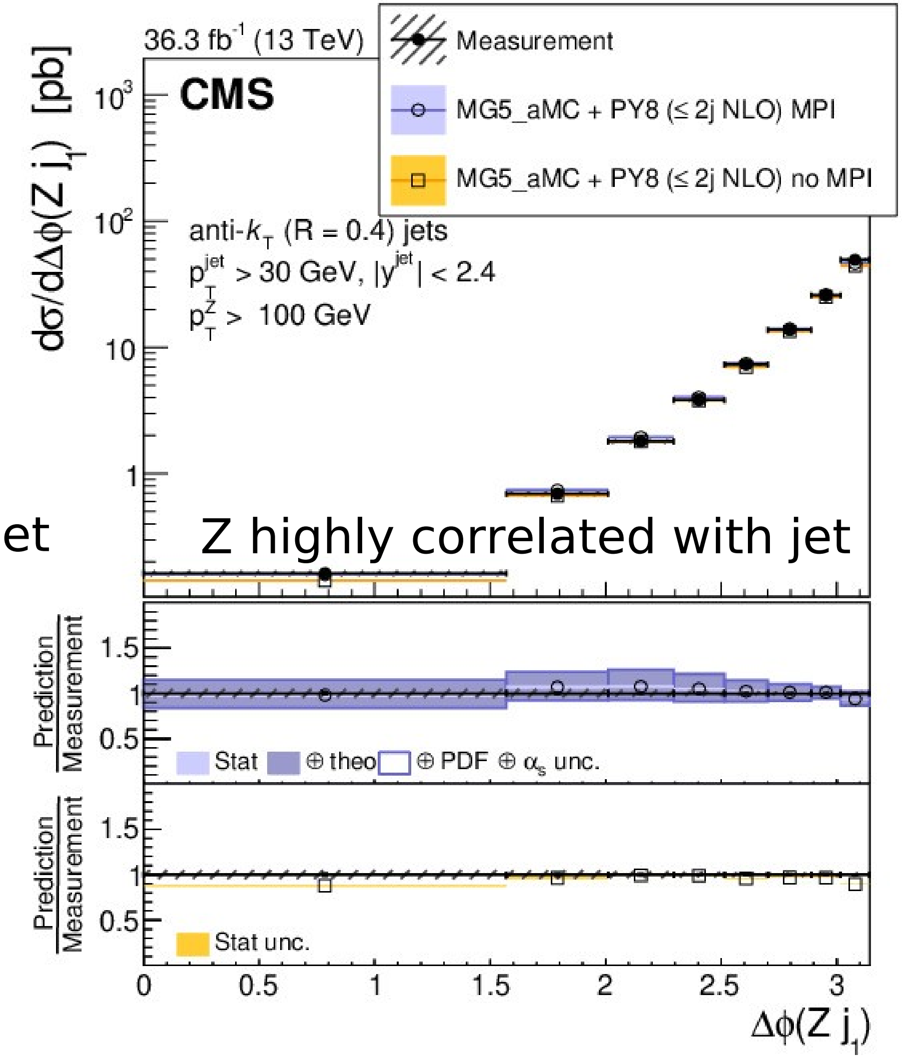
- Z bosons is a purely electroweak (EW) process but corrections from QCD play an increasingly important role as Z p_T increases
- At low Z p_T, the jet production is the dominant process, and the Z boson appears as a higher order EW correction.



- At high Z p_T, Z+jet production is dominant with significant corrections coming from QCD processes.



Z weakly correlated with the leading jet



Z highly correlated with jet

- MPI contributes about 40% at low Z p_T
- The prediction of MG5 AMC+PY8 (≤ 2j NLO) including MPI decribes the measurements

(ATLAS)

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Z + high p_T jets

- First ever Z + high-p_T jets measurement using 139 fb^{-1} of Run 2.

- Measurements unfolded to fiducial phase space.

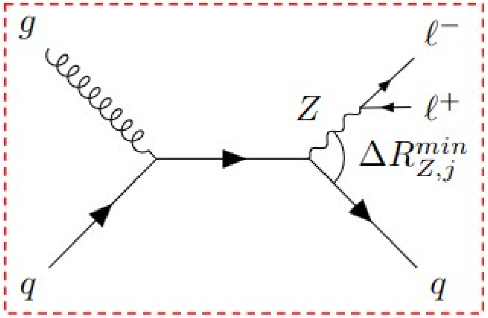
- High-p_T jet and Z phase spaces sensitive to NLO QCD and EW corrections.

Event Selection

Z + high p_T jets (ATLAS)

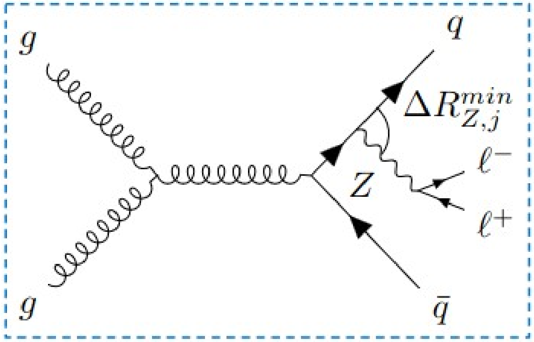
- Standard $Z \rightarrow l^+l^-$
- p_T jets > 100 GeV

- *High-p_T* region defined with: $p_T(j_1) \geq 500$ GeV.
- Use $\Delta R^{min}_{Z,jet} = \sqrt{\Delta y^2 + \Delta\phi^2}$ to study enhanced topologies:
  → **Back-to-back** Z + 1 jet hard-scatter.
  → **Collinear** *Z* boson emission.



Back-to-back Z+1 jet

$\Delta R^{min}_{Z,jet} \geq 2.0$

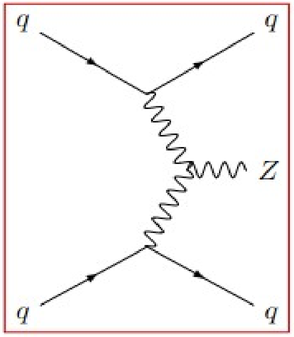


Collinear Z + 2 jets

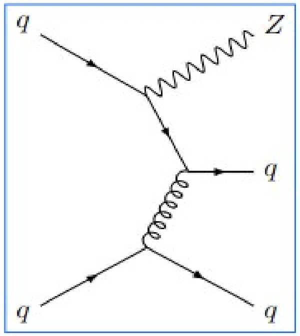
$\Delta R^{min}_{Z,jet} \leq 1.4$

Background

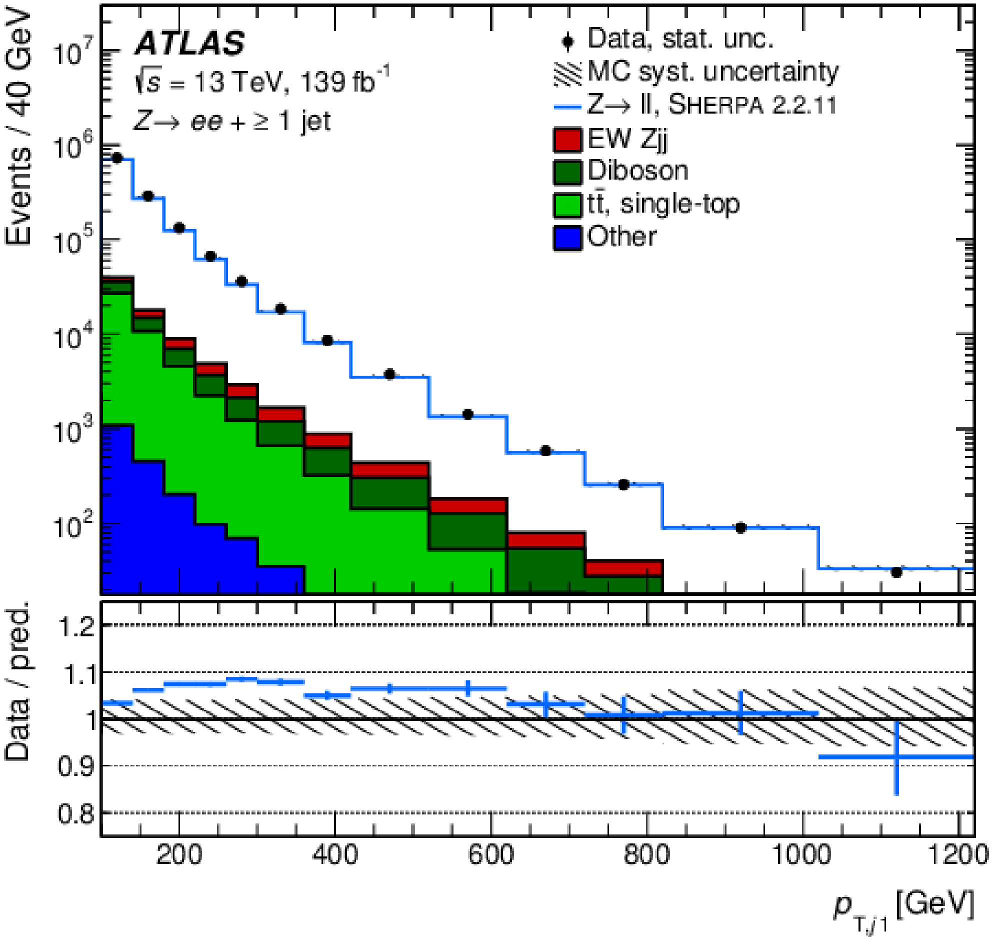
- EW produced Z + 2 jets treated as background



EW Z + 2 jets



Strong Z + 2 jets



- Monte-Carlo generators to model diboson and EW Z + 2 jets

- Data-driven method to estimate tt̄ background using eμ control region

Dominant backgrounds:

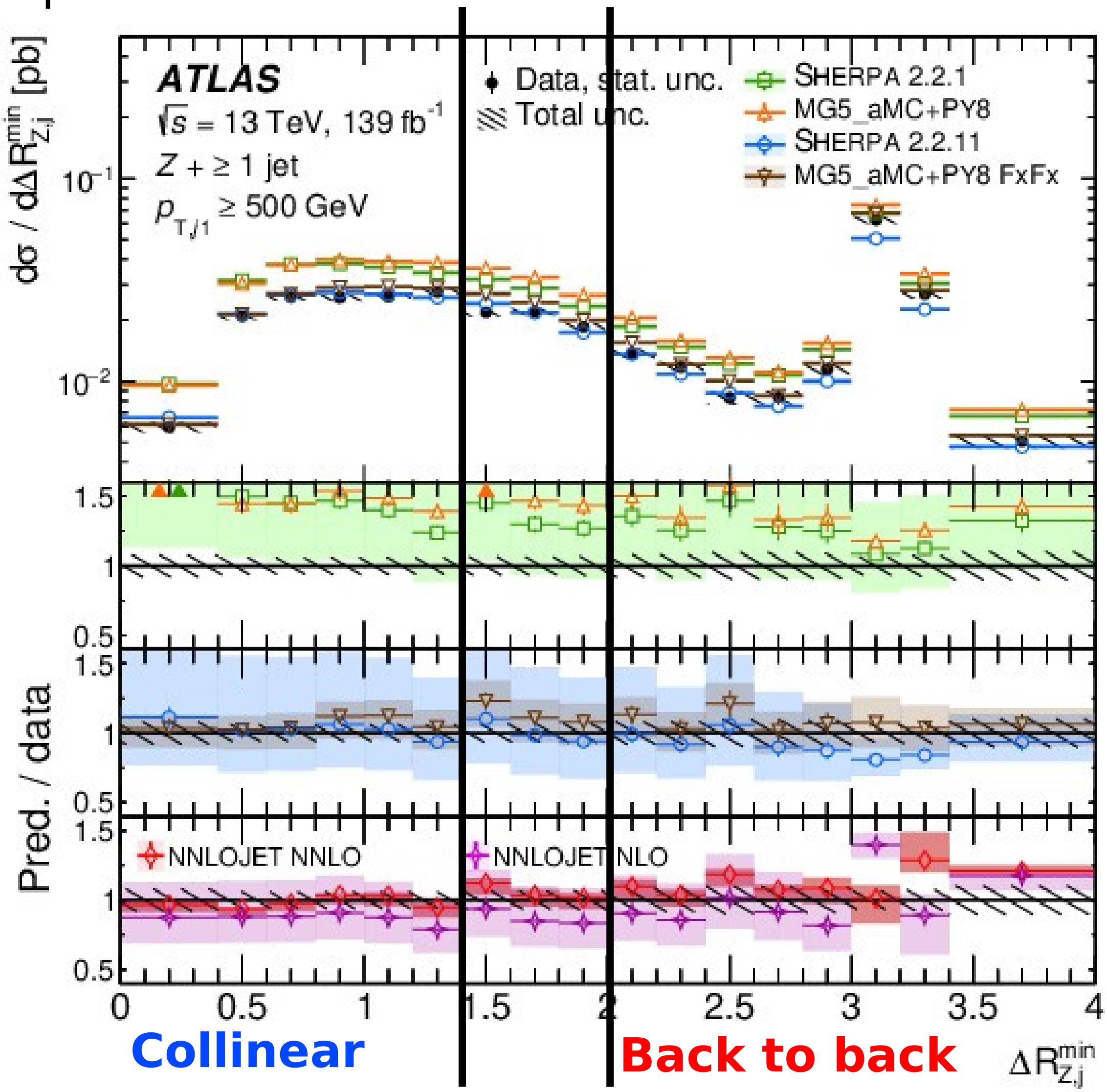
→ tt̄ 2-6 %

→ Diboson 2-5%

→ EW Z + 2 jets 1-5%

Results (ATLAS)

- Fiducial cross sections compared against theoretical predictions and fixed-order calculations from NNLOjet.



Only Sherpa2.2.11 includes NLO virtual EW corrections.

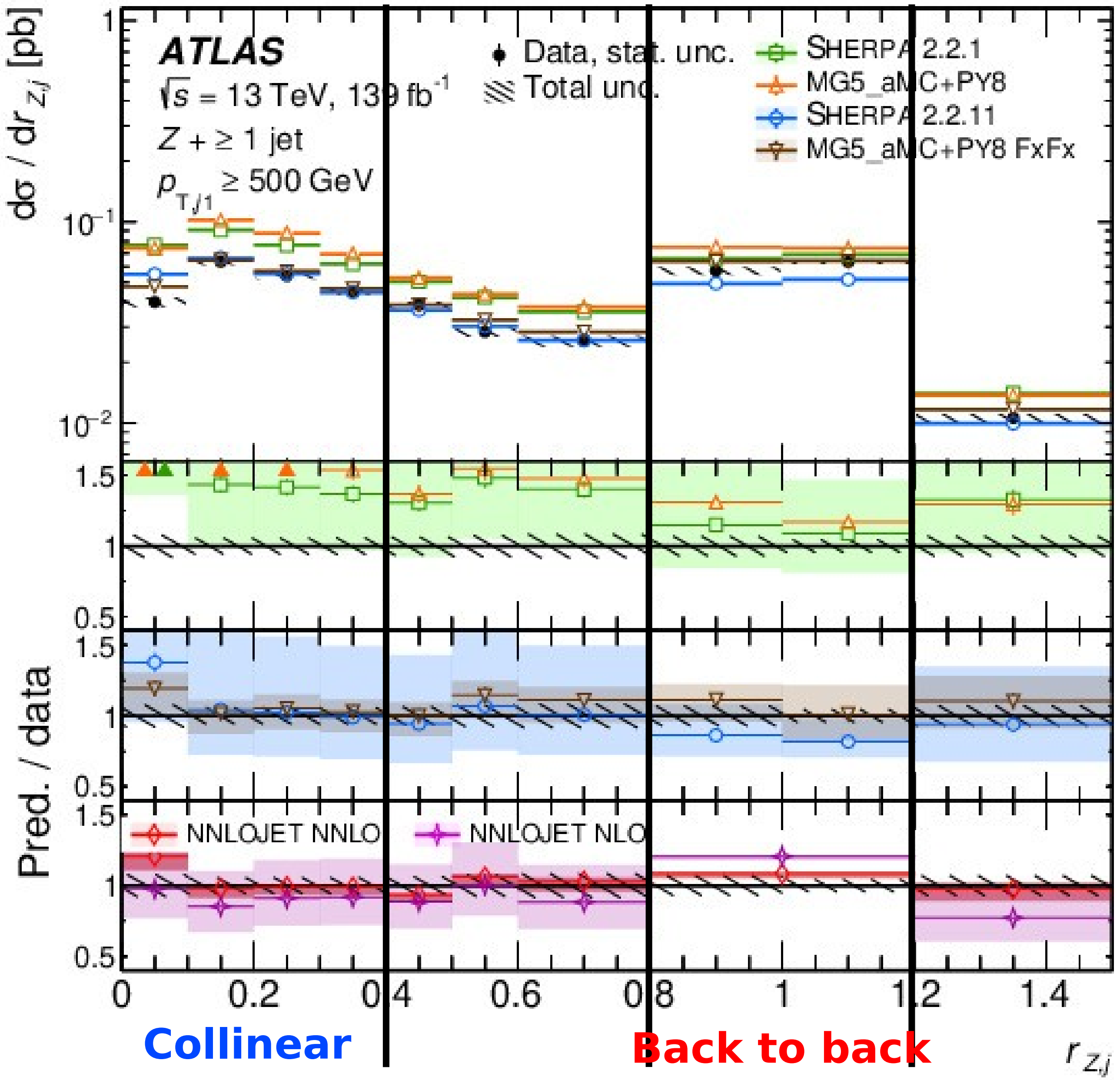
Low $\Delta r^{min}_{Z,jet}$ populated by collinear events

- Back-to-back events in peak at $\Delta r^{min}_{Z,jet} = \pi$.
- All predictions consistent with data within errors.

Results

Collinear emissions have large effect in high-pT region.

(ATLAS)



Sherpa2.2.1 and MG5_aMC+Py8 overestimate events of collinear Z emission

- Back-to-back events generally well modelled
- MG5_aMC+Py8 FxFx very precise & describes data in full range of distributions.
- NLO virtual EW corrections have 10% - 20% impact

- QCD scale uncertainties very large: several 10s of %.

(ATLAS)

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Z + jets with OMNIFOLD

- Z + jets measurement using 139 fb^{-1} of Run 2.

- $Z \to \mu^+\mu^-$ $p_T(\mu) > 25$ GeV , $|\mu| < 2.5$, $m(Z) \in (81, 101)$ GeV, and $p_T(Z) > 200$ GeV

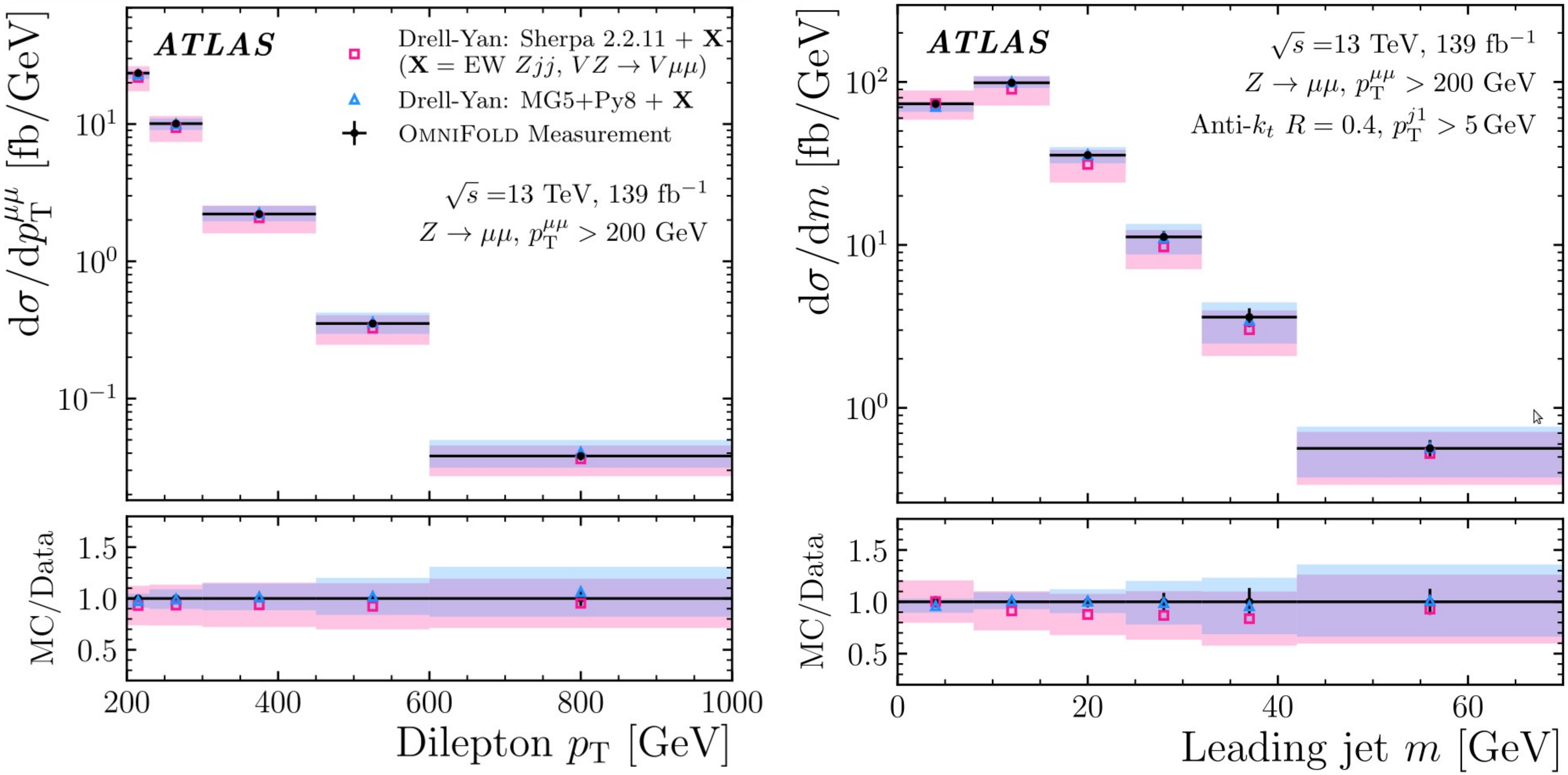
- 24 measured observables as input (ML method), p_T (Z), η (Z), kin. variables of muons and two leading jets, masses of jets, Charged hadron multiplicities, jet-subtructure

- Top backgrounds small (0.2%) and treated as syst. unc.

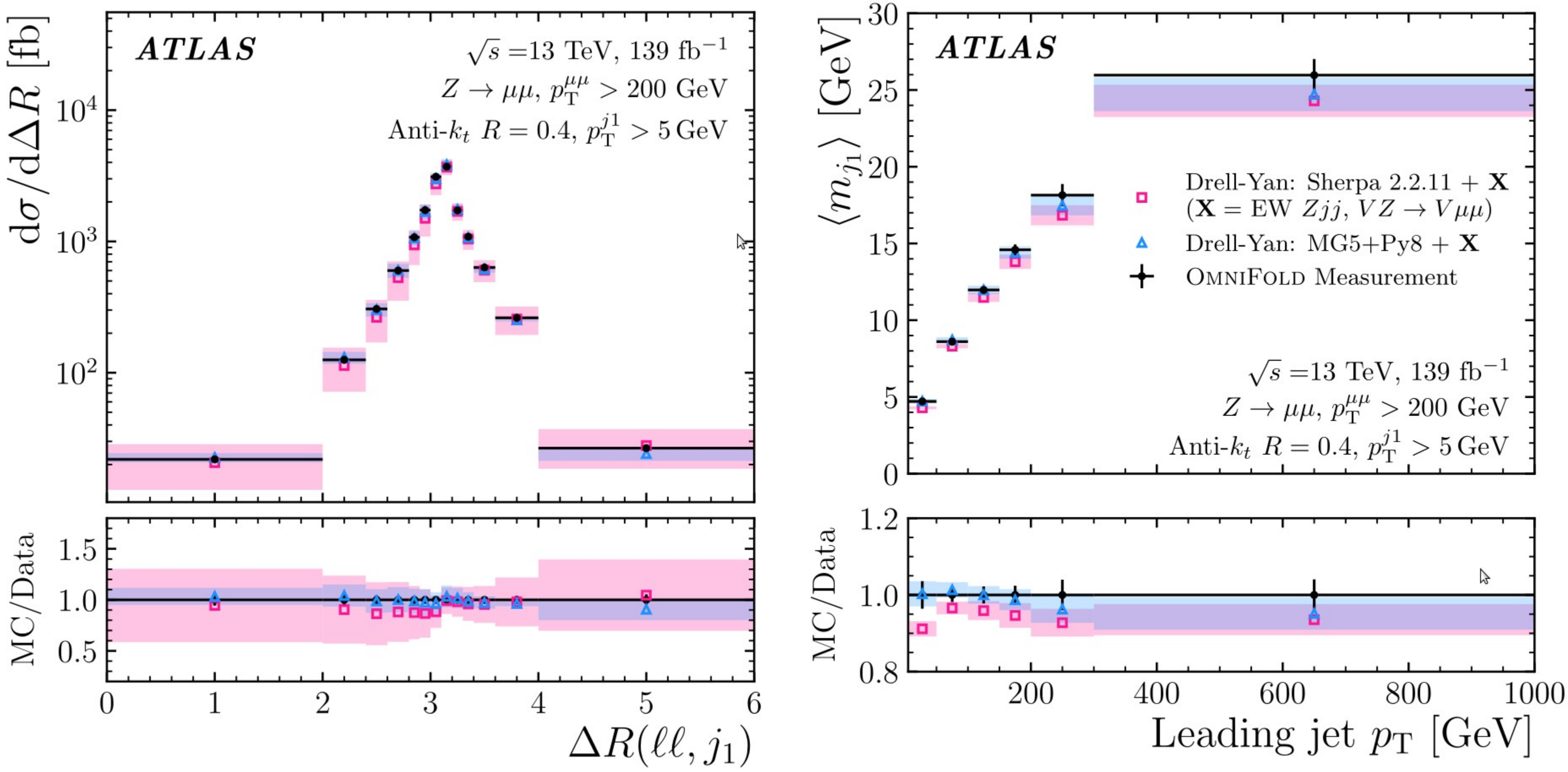
- Unbinned differential cross section $L\,\sigma_{\text{fid}}\,\varepsilon\,/\,f_{\text{fid}} = n_{\text{data}}$,

Results (ATLAS)

Presented differentially on any of the 24 variables or combinations



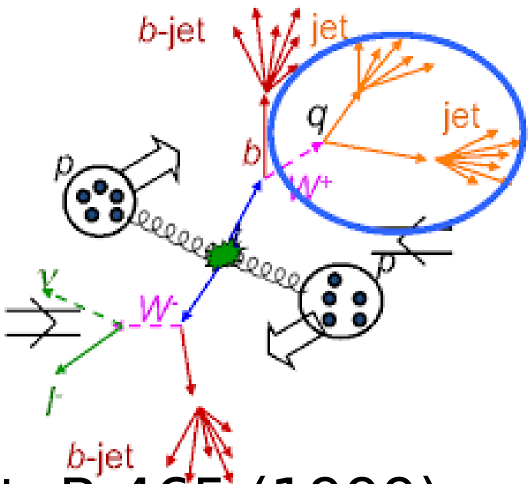
- Experimental precision better than theory
- Overall MG5 better than Sherpa



- Experimental precision better than prediction
- Overall MG5 better than Sherpa
- Method: Unbinned analysis with potential for future prospects

Measurement of B(W→cq)/B(W→qq’) [R_c^W] (CMS)

CMS-PAS-SMP-23-009



Motivation of selection:

- CKM unitarity test
- PDG value: $R_c^W = 0.49 \pm 0.04$
- Measurements at LEP : ALEPH : Phys. Lett. B 465 (1999) 349; OPAL: Phys. Lett. B 490 (2000) 71-86
- First time in LHC: $t\bar{t}$ sample offers a good sample of W bosons for a high precision study.
- Semileptonic has one W boson decaying leptonically, providing a lepton for the trigger and another one decaying hadronically, enabling the goal measurement
- Charm tagging and its systematics are key to conduct the measurement

Selection

• Lepton + jets: W boson decay selection + 4 jets with $p_T > 25$ GeV

• Two identified as b-jets (misid rate 1% for light, efficiency of identification of 70%)

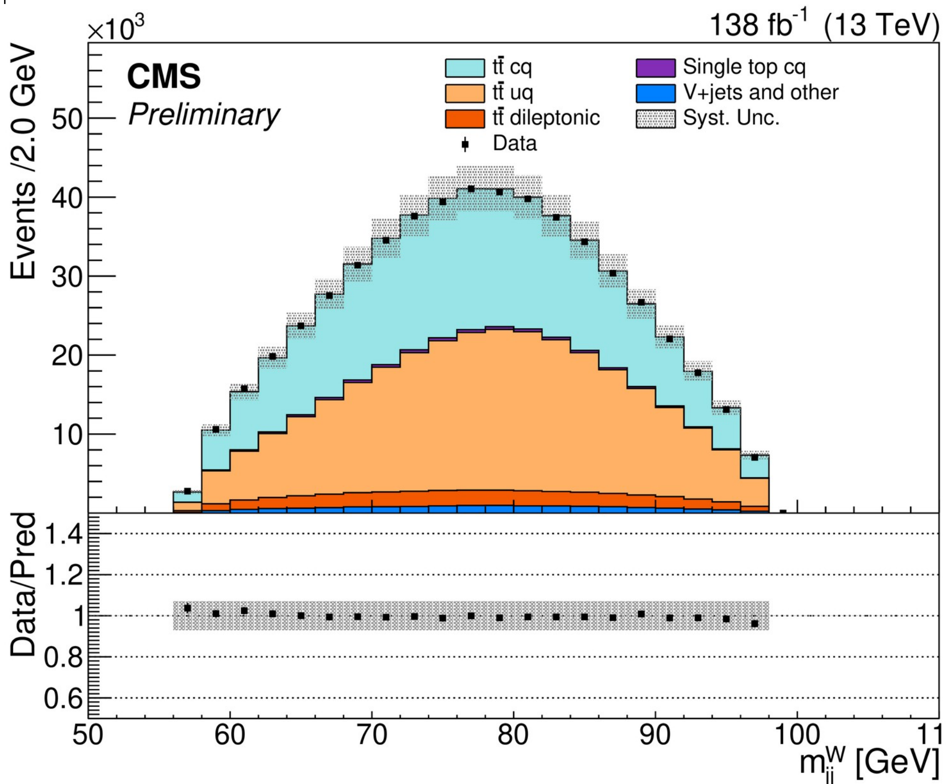
• Compatibility of the 4 jet configuration with the $t\bar{t}$ semileptonic signal process to improve up to 81% the correct pair of jet from the W hadronic decay

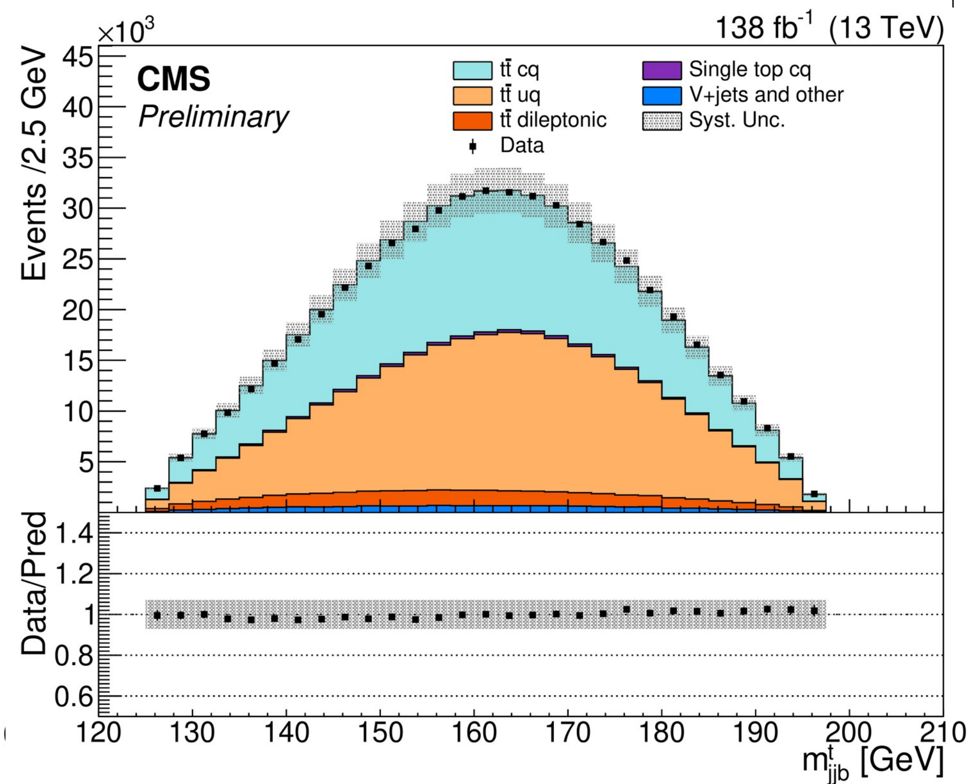
	Cumulative efficiency
Single muon/electron trigger	35.6%
1 high-p_T muon/electron and 4 jets	17.5%
p_T^{miss} and m_T	12.8%
2 b-tagged jets medium WP	6.0%
Kinematic reconstruction	2.2%

After $t\bar{t}$ selection

The data sample selected with the criteria described above consists of ~ 1 M events. According to the simulation, the data sample is composed of :

45% semileptonic $t\bar{t}$ events with W → cq,
45% semileptonic $t\bar{t}$ with W → uq,
6% dileptonic tt, 3% single top, and 1% V + jets

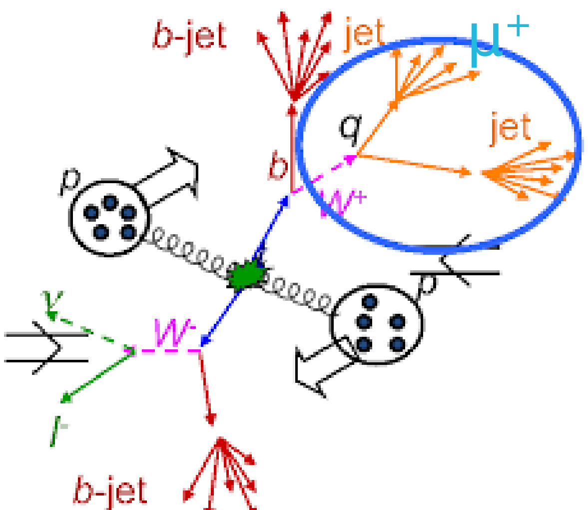




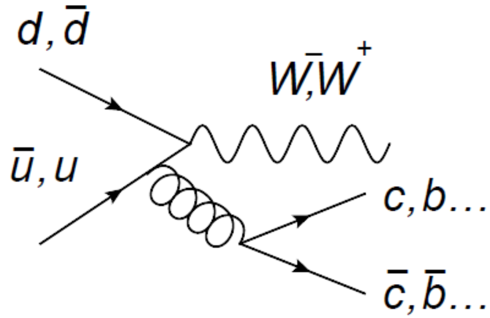
Grey band represents the pre-fit systematic uncertainties

Charm tagging

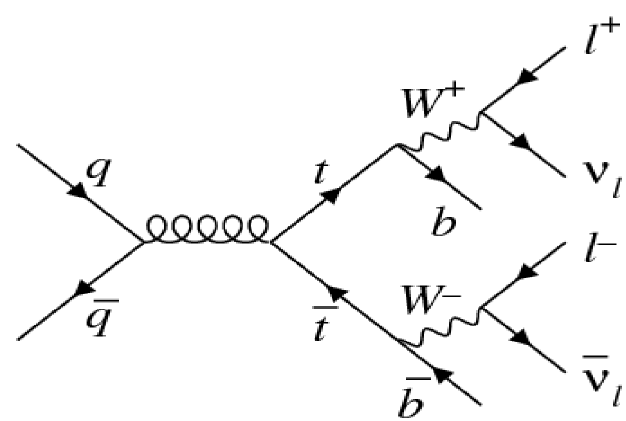
- Muon inside a jet
- Used in many analysis (see next talk for example) in the context of V+c
- Strategy of the analysis:
    - Signal is OS, most of the background 50% OS & 50 % SS
    - Model the charge symmetric background with data : use SS data sample to model the background under the OS sample



OS event



Bckg: 50% OS, 50% SS



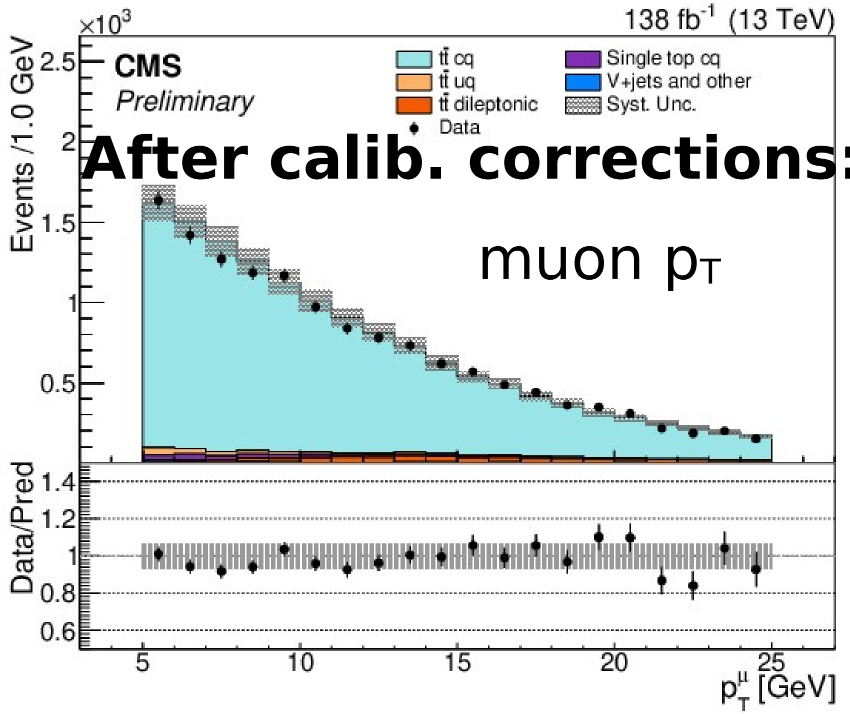
Muon calibration

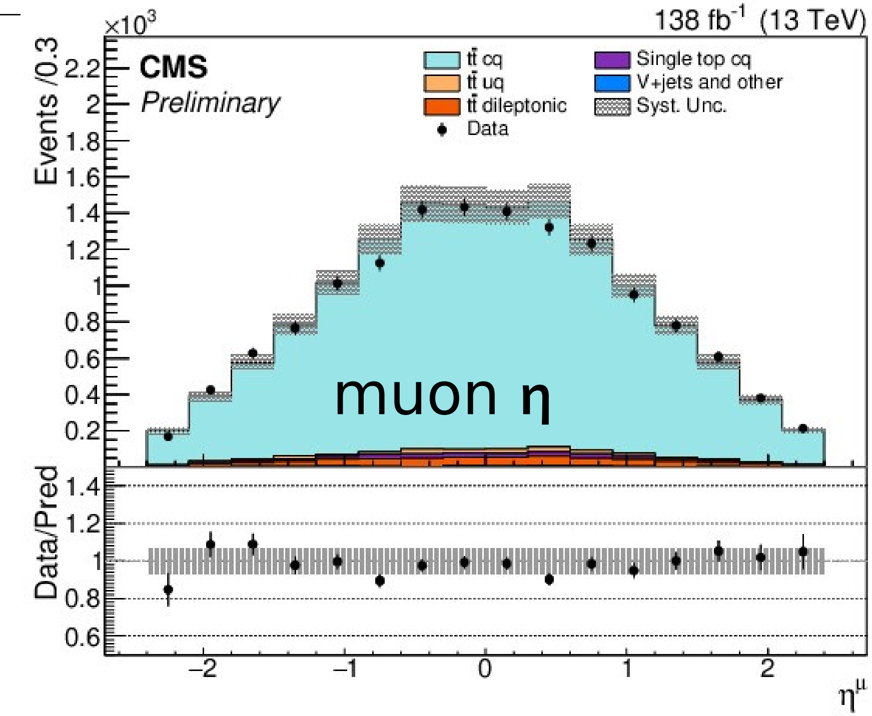
We need to make sure muon production rate is well simulated.

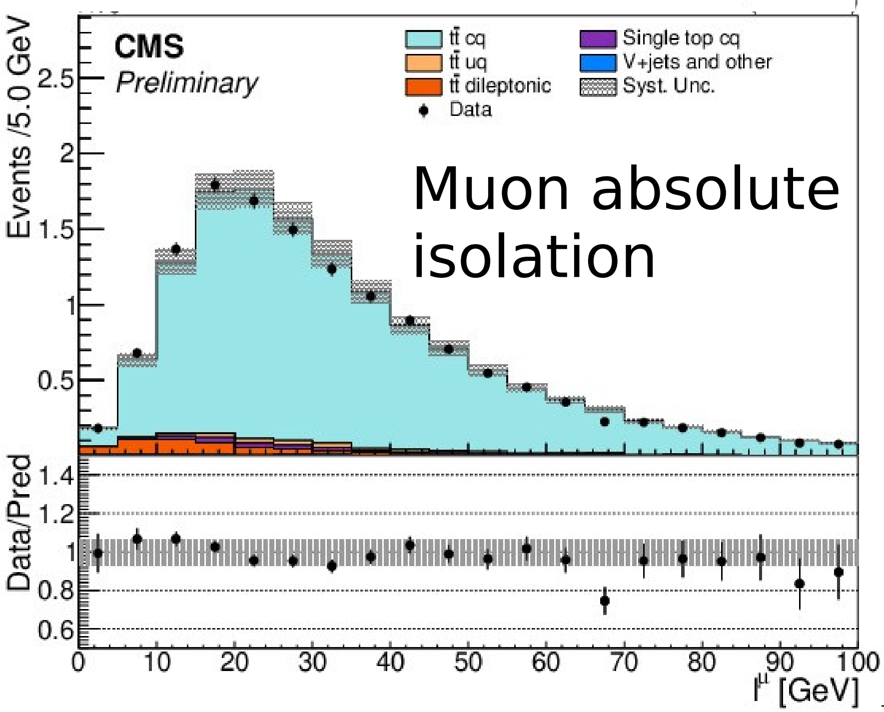
- Check muon rate in simulation compared to data
    - FF ($c \rightarrow D_h$) [from Eur. Phys. J. C 76 (2016) 397]
    - BR ($D_h \rightarrow \mu + X$) [from PDG]

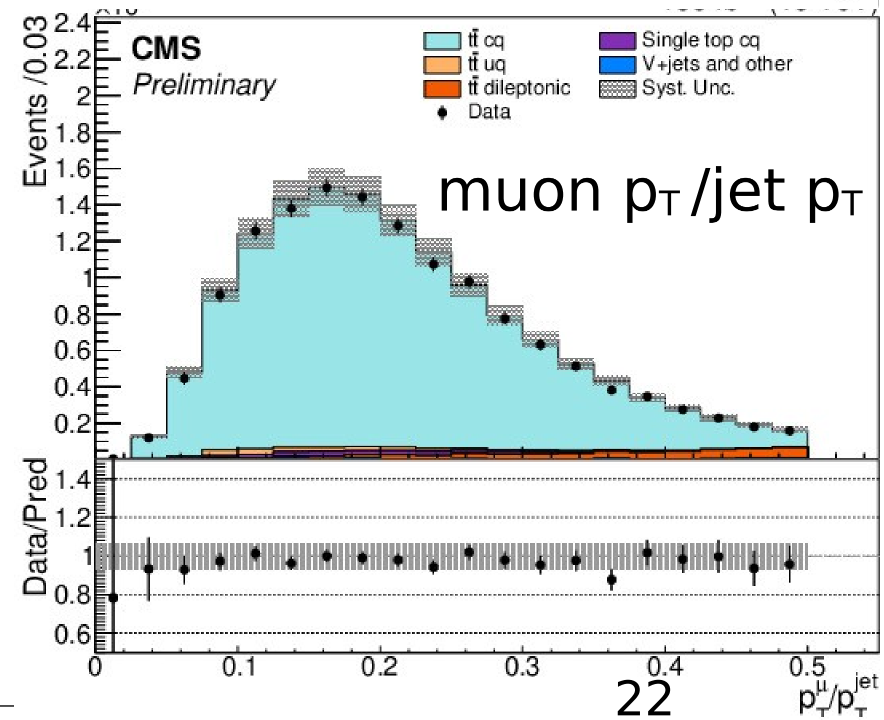
- Check muon reconstruction efficiency with data with a sample of muons in b-jets (from $t\bar{t}$)

After calib. corrections:









Fit

- Four channels
  - Two for the type of isolated leptons:
    - e
    - **μ**
  - Two for tagging:
    - No charm tag category
    - Charm tag

Global normalization free on the fit
Relative no charm tag vs charm tag contribution free too

Systematics

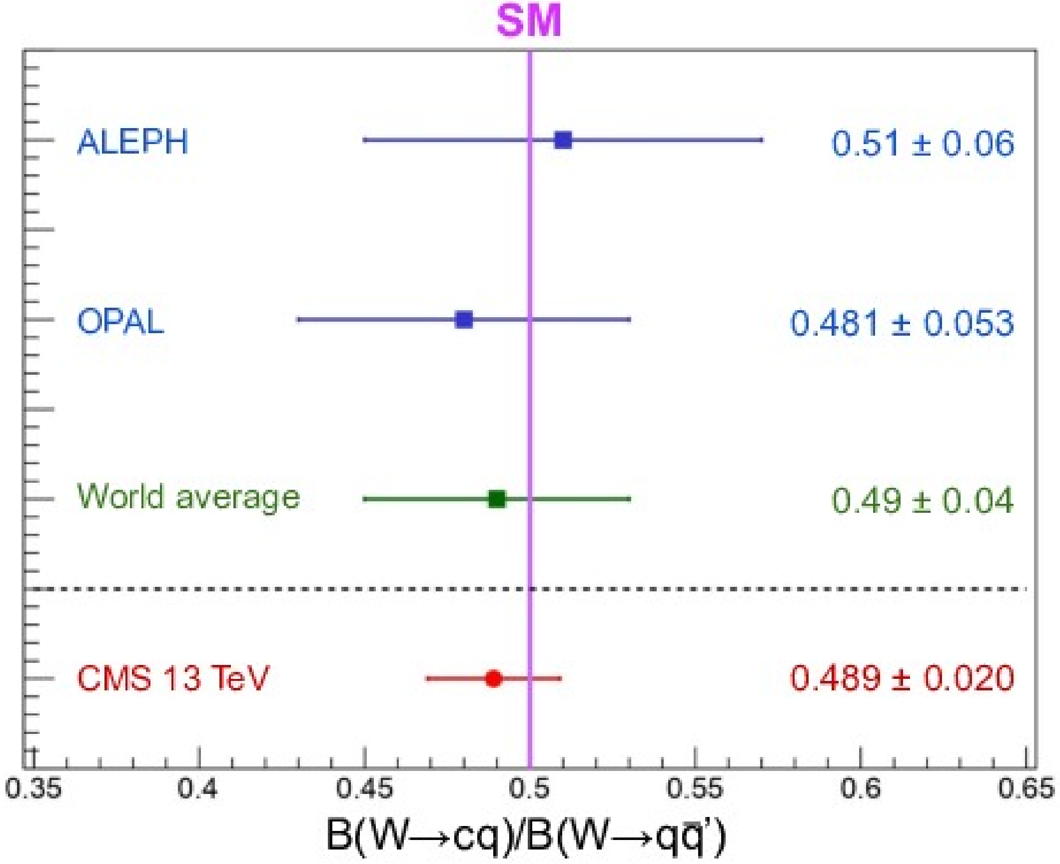
	No charm tag	Charm tag	Impact on R_c^W
Charm tagging: muon identification	—	2.7	2.6
Charm tagging: muon rate in simulation	—	2.2	2.1
Parton shower final state radiation	4.0	6.0	1.9
Jet energy scale	4.0	4.0	0.6
SS data statistical uncertainty	—	1.6	0.5
Charm fragmentation modeling	—	0.4	0.3
Jet energy resolution	1.0	1.0	0.3
b tagging	2.5	2.5	0.2
MC background normalization	5.0	5.0	0.1
Integrated luminosity	1.6	1.6	0.1
Total			3.9

Result

R_c^W = 0.489 ± 0.005 (stat) ± 0.019 (syst) = 0.489 ± 0.020

Compatible with SM prediction

Uncertainty twice as precise as the world average value



Conclusions

Broad range of Standard Model Electroweak and QCD physics results with 13 TeV and 13.6 (on the way) data deepen and challenge our understanding of Electroweak interactions and their theoretical modeling.

There has been a lot of improvement in the last decades and there is more to come from both , theoretical and experimental results

Era of precision physics: Increasingly more precise and complex SM measurements now dominate on dedicate direct searches in probing for new physics.

The full set of Standard Model results is available at
http://cms-results.web.cern.ch/cms-results/public-results/publications/
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Back up

Kinematic reconstruction

Compatibility of the 4 jet configuration with the signal process :

$$\chi^2 = \frac{1}{1-\hat{\rho}^2}\left[\frac{(X_W - \hat{m}^W_{jj})^2}{\hat{\sigma}^2_{m^W_{jj}}} + \frac{(X_t - \hat{m}^t_{jjb})^2}{\hat{\sigma}^2_{m^t_{jjb}}} - \frac{2\hat{\rho}(X_W - \hat{m}^W_{jj})(X_t - \hat{m}^t_{jjb})}{\hat{\sigma}_{m^W_{jj}}\,\hat{\sigma}_{m^t_{jjb}}}\right]$$

- Invariant mass of the isolated lepton and the b jet for the two possible combinations < 150 GeV

- Use W boson and top quark mass constraints to perform a χ^2 test evaluating the compatibility of the various permutations of jets with the expectation from the simulation (discard if p-value in the χ^2 test < 0.2 to improve up to 88% the correct pair of jet from the W hadronic decay)

Muon reconstruction calibration

- Charm tagging based on muons .

- muon-in-jet ε^{rec} & ε^{id} in simulation calibrated in data with a sample of muons in b-jets (from $t\bar{t}$)

- Purest and most similar sample to calibrate our signal.

- Differences in particle density around the muon taken into account calculating corrections differential in I^{μ} (μ abs. Isolation). The less isolated the muon is, the larger the correction that ranges from 0.85 to 1.

- Included a 1% systematics to take into account residual systematics associated to the calculation of the corrections (small contribution of decays-in-flight muons, residual differences between beauty and charm, ...) .

Two parameter fit

Measurement with combine

- Two free parameter fit:
  - rate modifier for (W->cq + W->uq) rate: r_{Wqq}
  - rate modifier for W->cq rate (anticorrelated with W->uq rate): r

$$[W \to cq + W \to uq] \propto r_{Wqq}$$

$$R_c^W = r/2$$

$$W \to cq \ \propto \ r_{Wqq} \cdot (r/2)$$
$$W \to uq \ \propto r_{Wqq} \cdot (1 - r/2)$$