

# Transverse momentum dependent PDF and use in MC generators for boosted $W/Z$ + jet

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# Motivation for measurement of W/Z production in the high $p_T$

W/Z as the SM 'standard candles'

## Test of SM at the extreme kinetic region

- Sensitive to higher order correction

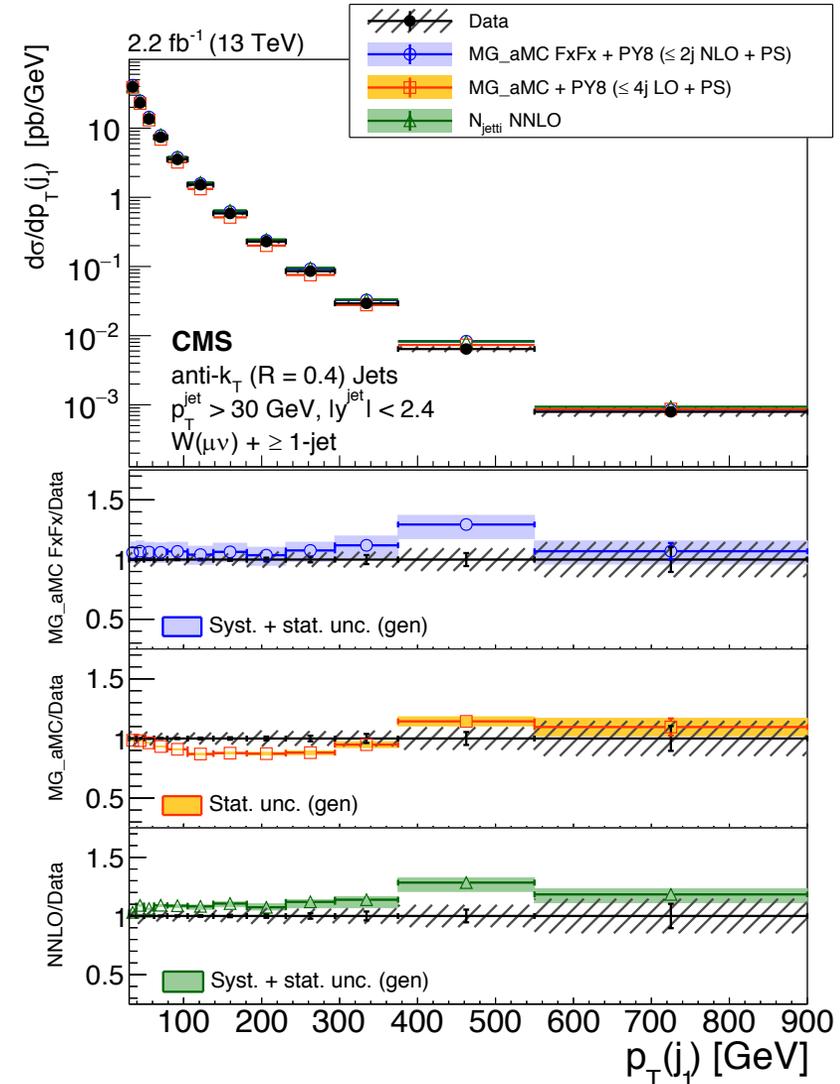
## Goal

- Inclusive cross-section of W/Z up to TeV scale
- Azimuthal correlation of W/Z with additional jet

## Where are we so far?

- Golden channels (leptonic decay) are not suitable for high  $p_T$  measurements = not so good resolution
- Lets try different decay channel?
  - Hadronic decay channel (B.R. ~70%)

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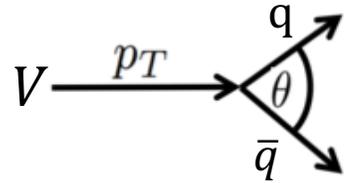


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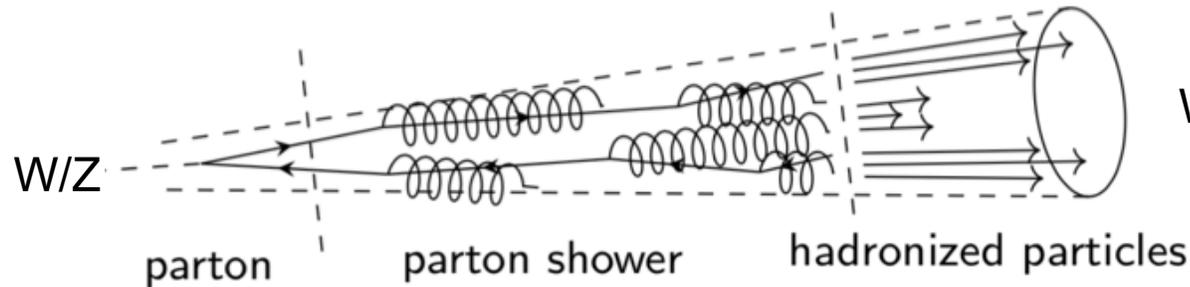
## Hadronic decay of high $p_T$ W/Z

- Decay products are boosted into large cone size jet

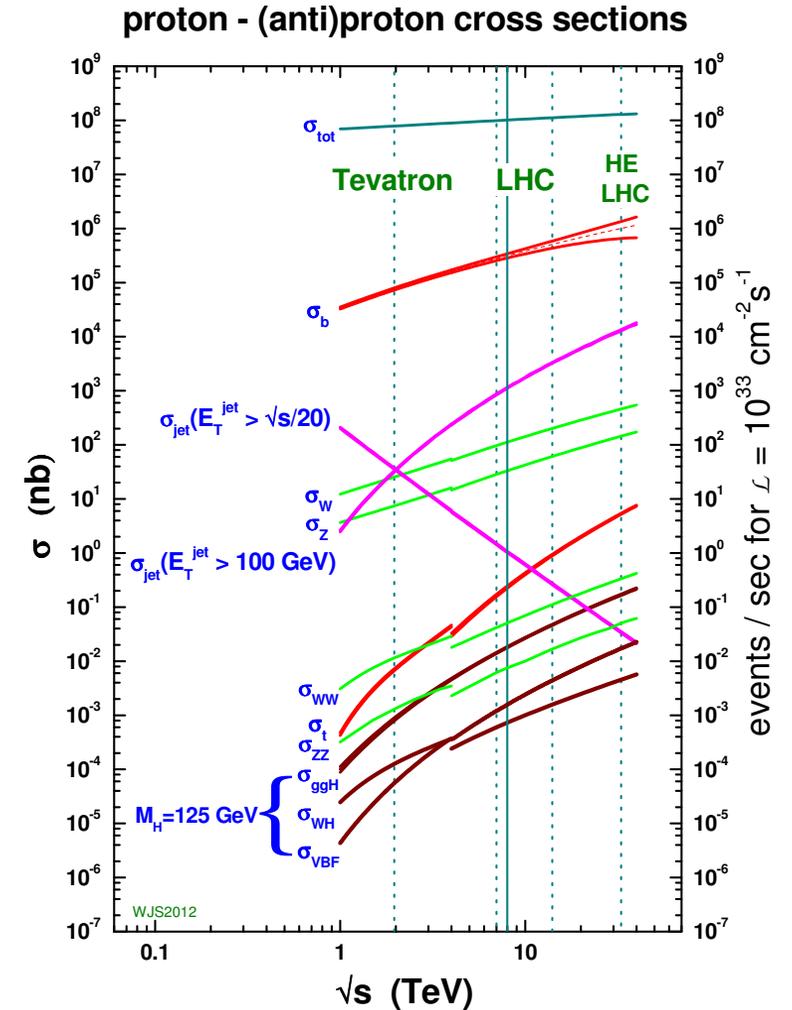


$$\Delta R \approx \theta \approx 2 \frac{m_V}{p_T}$$

- Jet substructure provides powerful handles to suppress QCD jets



- Boosted objects are also tools for BSM searches



# Boosted objects in LHC and its identification

## High $p_T$ $W$ , $Z$ , Higgs and top

### How to remove QCD background?

#### Jet substructure

- Traditional cut-based approach
- Many new variables for tagging

Observable	Variable	Used for
Calibrated jet kinematics	$p_T, m^{\text{comb}}$	top, $W$
Energy correlation ratios	$e_3, C_2, D_2$	top, $W$
$N$ -subjettiness	$\tau_1, \tau_2, \tau_{21}$	top, $W$
	$\tau_3, \tau_{32}$	top
Fox–Wolfram moment	$R_2^{\text{FW}}$	$W$
Splitting measures	$z_{\text{cut}}$	$W$
	$\sqrt{d_{12}}$	top, $W$
	$\sqrt{d_{23}}$	top
Planar flow	$\mathcal{P}$	$W$
Angularity	$a_3$	$W$
Aplanarity	$A$	$W$

### Machine learning technique

- ML + jet physics
- Better performance
- Can be used simultaneously for several types of boosted objects
- Example of new developments in CMS:
  - Boosted Event Shape Tagger: CMS-DP-2017-027
  - Deep double-b/c tagger: CMS-DP-2018-033
  - DeepAK8: CMS-DP-2017-049
  - Etc.

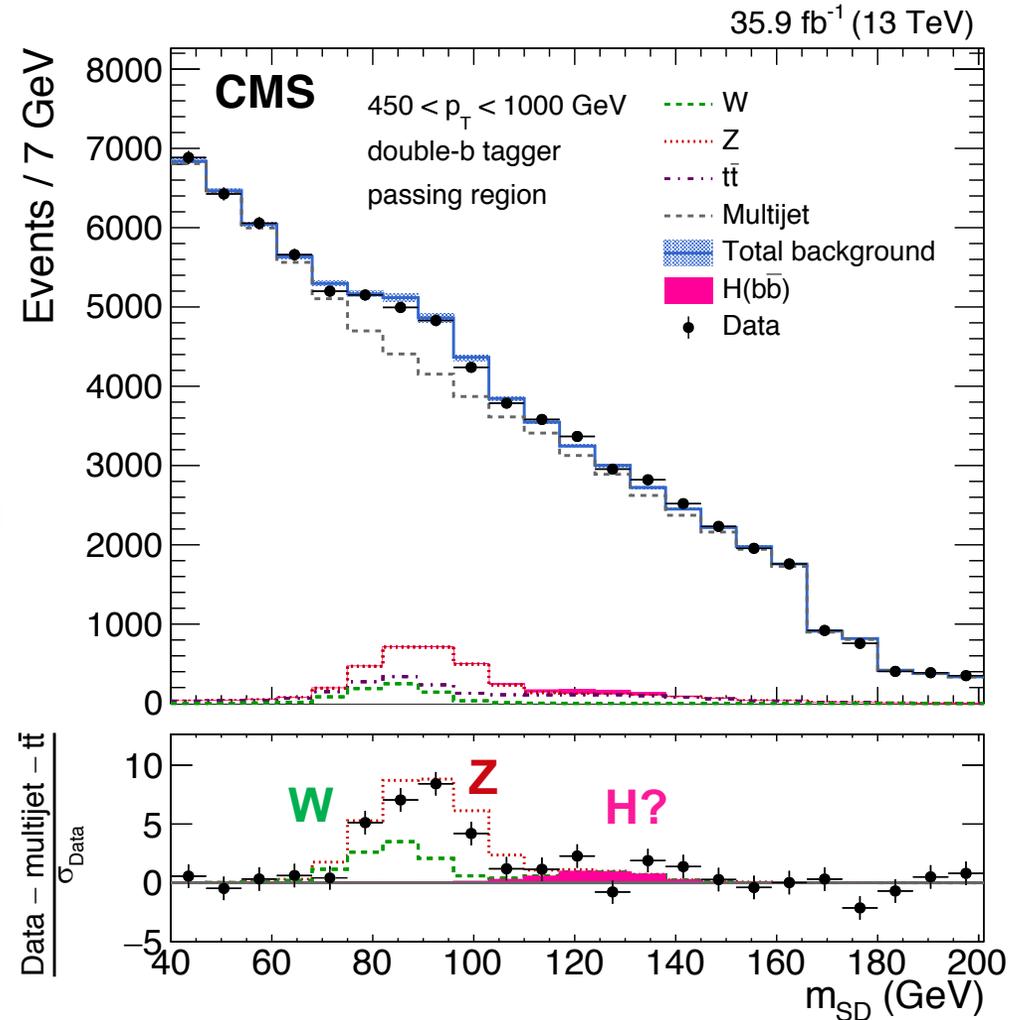
# Jet substructure for identification of boosted bosons

W/Z as the SM 'standard candles'

PRL 120, 071802 (2018)

## Boosted Higgs(bb)

- Production mechanism: gluon fusion
- B.R.  $\sim 56\%$
- Boosted W/Z as a proof of principle
- ECF & double-b tagging
- Data driven method for background description
- Boosted W/Z are observed
- Z(bb):  $5.1\sigma$  ; Higgs(bb):  $1.5\sigma$



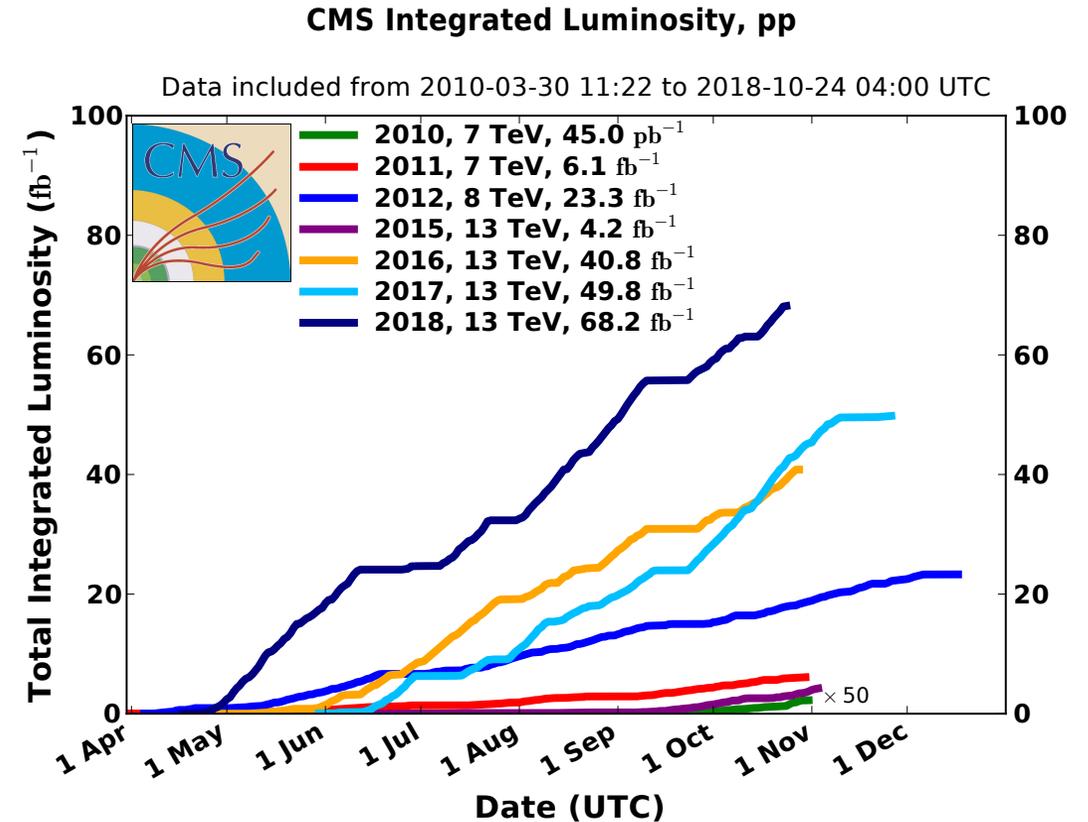
# LHC Run2 & Measurement of W/Z production in the high $p_T$

## Boosted W/Z

### LHC Run2 has just ended

- LHC delivered to CMS:  $> 150 \text{ fb}^{-1}$
- Differential measurement of inclusive cross-section of W/Z in hadronic decay channel up to TeV scale is underway

Lets look at MC predictions, what we can expect



# Theoretical prediction for hadronic decay of boosted Z + jet

## Overview of used MC generator

### MC generators:

- Powheg + Pythia
    - NLO matrix element
    - Parton shower by Pythia
    - CUETP8M1 Pythia8 tune
  - Powheg + Cascade-lhe
    - NLO matrix element
- Cascade-lhe:
- Add  $k_T$  to each parton as function of  $x$  and  $\mu$  according to TMD
  - Apply initial and final state shower according to TMD

### Generated process: $pp \rightarrow Z + \text{jet}$

- $\sqrt{s} = 13\text{TeV}$
- Z - hadronic decay
- $p_T(Z) > 400\text{ GeV}$
- Jets are reconstructed by anti- $k_T$  algorithms
- $R=0.8$

### PDFs:

- Powheg: HERA PDF 2.0, NLO, LHAPDF ID: 61100
- Cascade-lhe: PB-NLO-2018-Set1, PB-NLO-2018-Set2

# Theoretical prediction for hadronic decay of boosted Z + jet

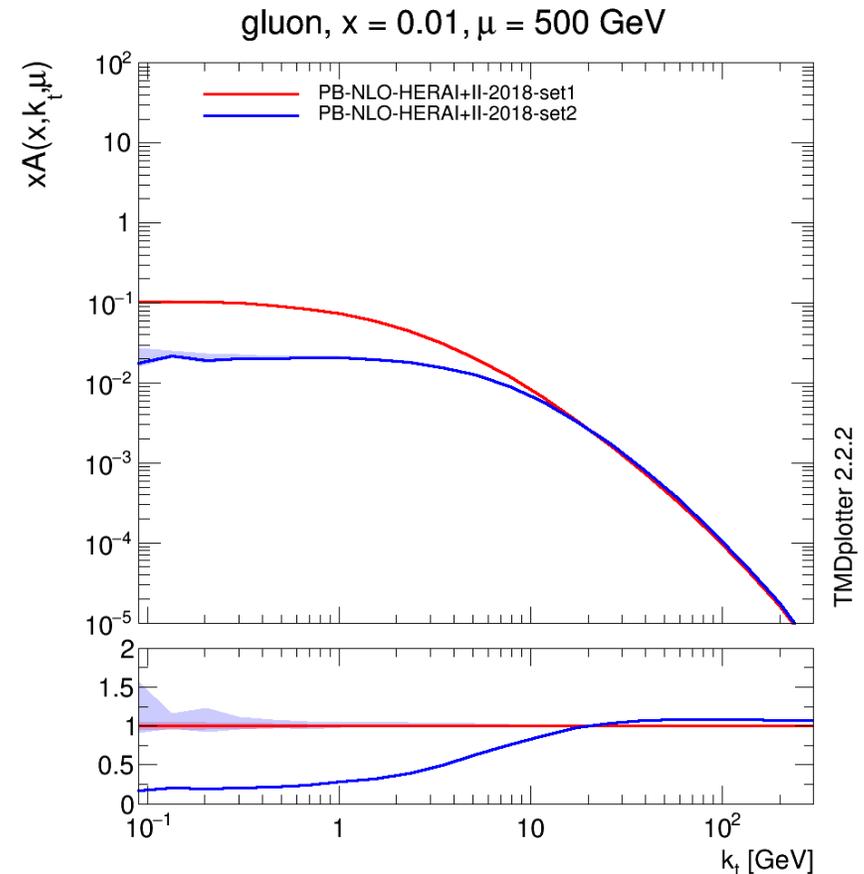
## Overview of used MC generator

### What do we want to study?

- Can we see effect of TMDs?
  - Powheg+Pythia vs Powheg+Cascade-lhe
  - Two sets of TMDs[1] will be used:
    - PB-NLO-2018-Set1, PB-NLO-2018-Set2
    - Available in TMDLIB, TMDPlotter
    - Include model and experimental uncertainties

### Main observables in our study

- $\Delta\phi$  between Z and additional jet
- $\phi^*$  for Z and additional jet



### References:

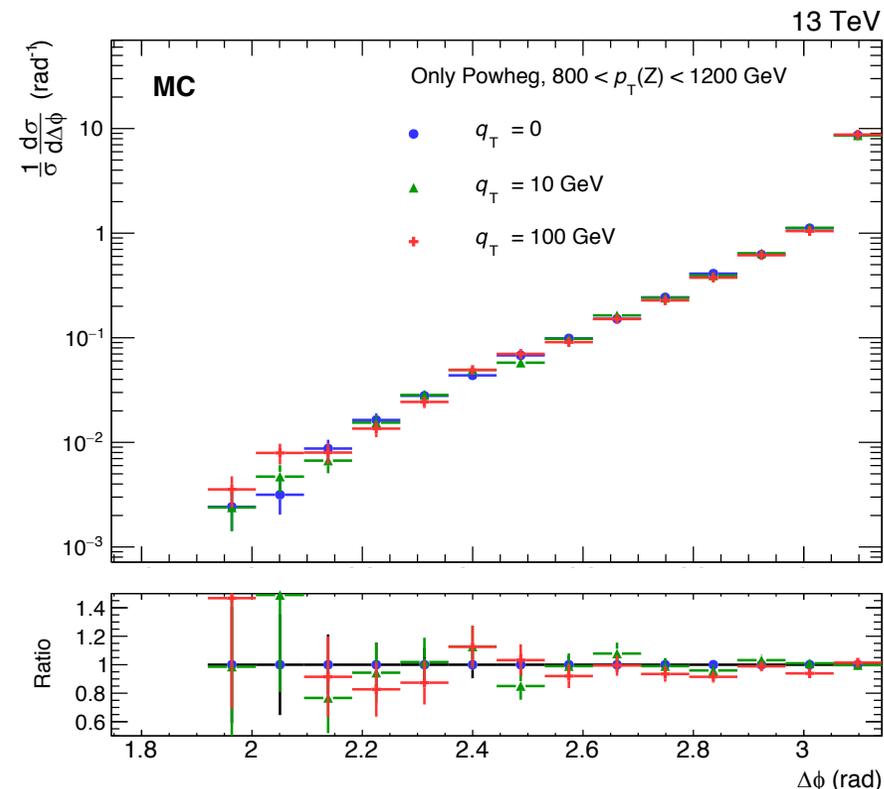
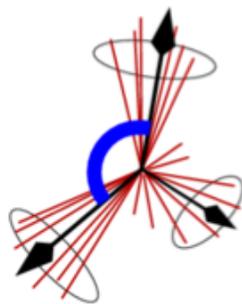
[1] Bermudez Martinez, A., Connor, P., Hautmann, F., Jung, H., Lelek, A., Radescu, V., and Zlebcik, R. (2018): Collinear and TMD parton densities from fits to precision DIS measurements in the parton branching method, arXiv:1804.11152

# Theoretical prediction for hadronic decay of boosted Z + jet

## Motivation

### Azimuthal correlation without initial and final state shower:

- $2 \rightarrow 2$ :
  - Partonic final state are back-to-back, e.i.  $\Delta\phi = \pi$
- $2 \rightarrow 3$ :
  - Partonic final state needed to get the tail
  - $q_T$  cut (ptsqmin) applied to allow for contribution from PS and TMDs

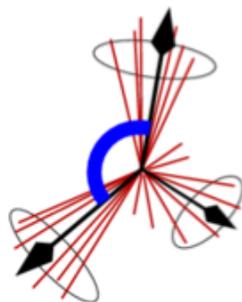


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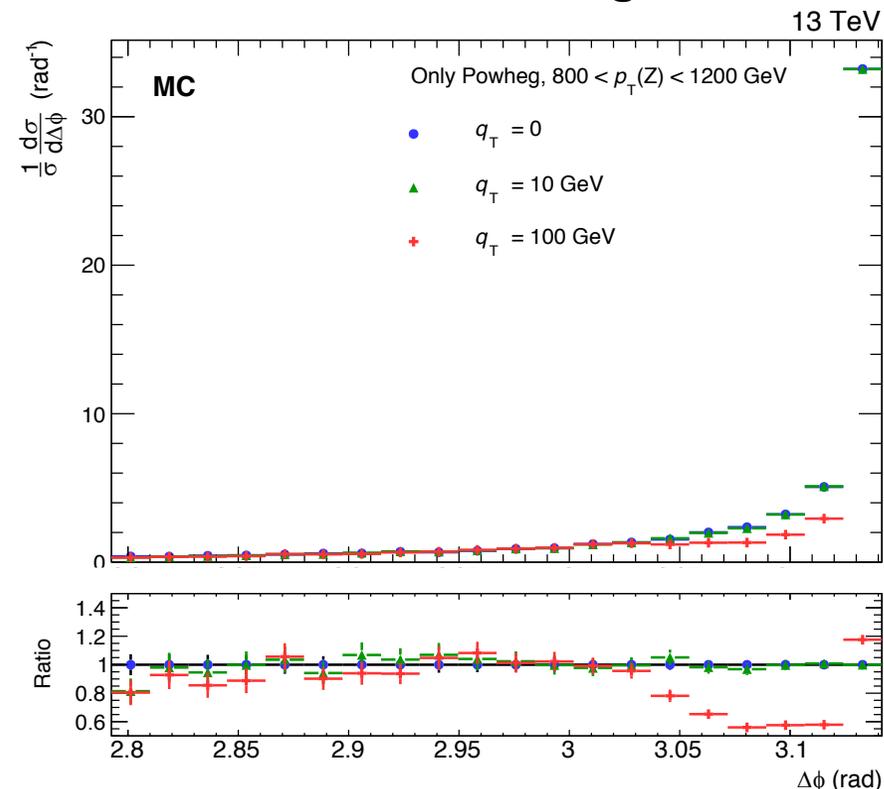
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### Back-to-back region



# Theoretical prediction for hadronic decay of boosted Z + jet

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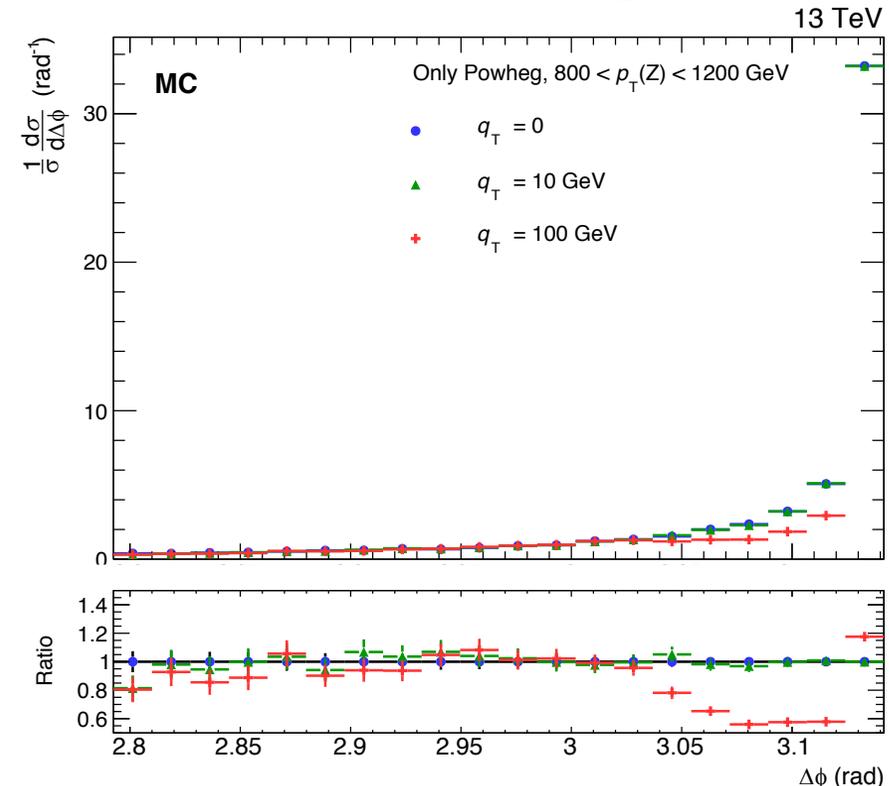
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### In our study:

- Initial/Final state shower with/without TMDs ?
- Since W/Z is colorless, is there difference for Z+jet vs dijet?

### Back-to-back region

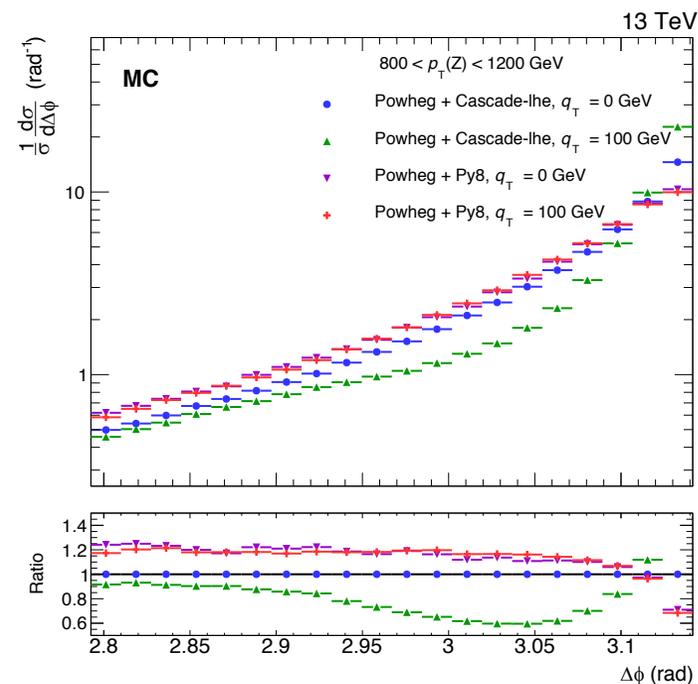
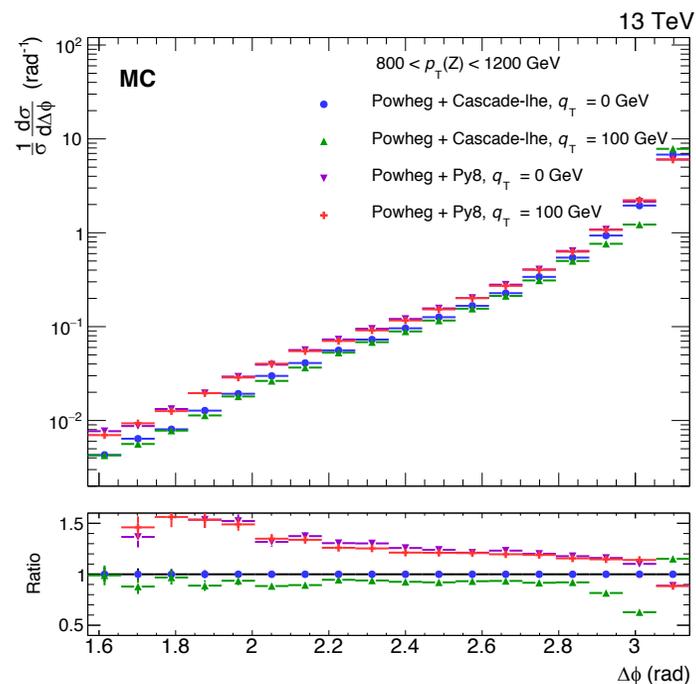


# Theoretical prediction for hadronic decay of boosted Z + jet

## Results

### Azimuthal correlation between boosted Z and jet

- Powheg+Cascade-lhe vs Powheg+Pythia8
- Precision predictions for the back-to-back region with the TMDs (with full uncertainties)
- Visible effect of TMDs

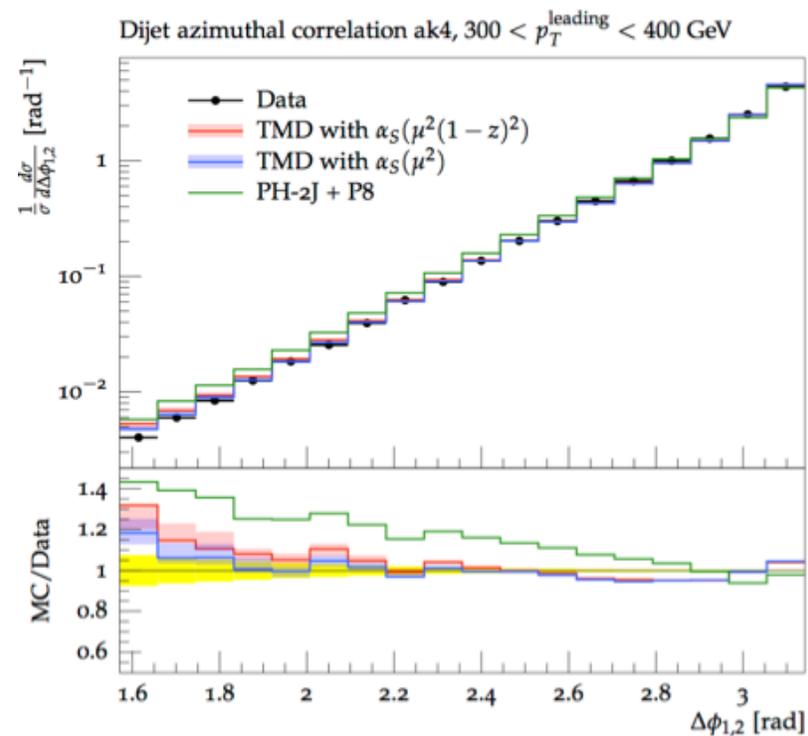
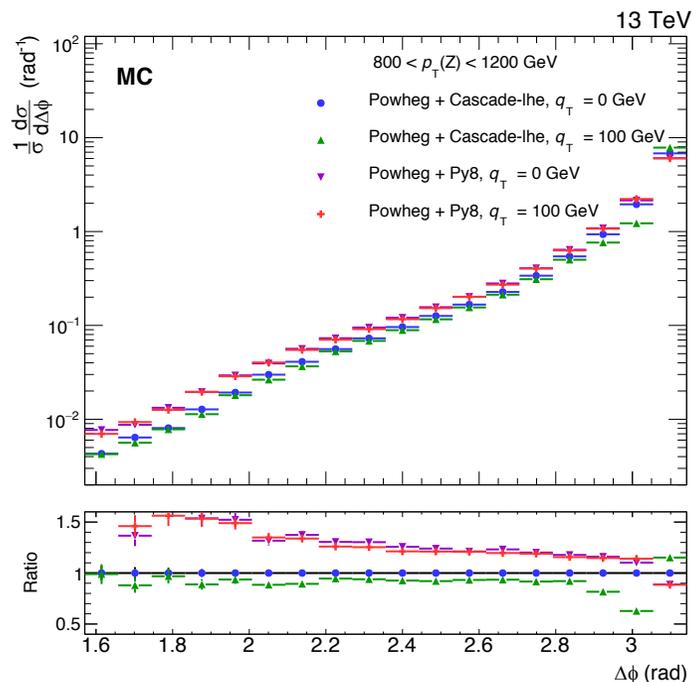


# Theoretical prediction for hadronic decay of boosted Z + jet

## Results

### Azimuthal correlation between boosted Z and jet

- Visible effect of TMDs
- Similar behavior observed for dijet events



# Theoretical prediction for hadronic decay of boosted Z + jet

## Results

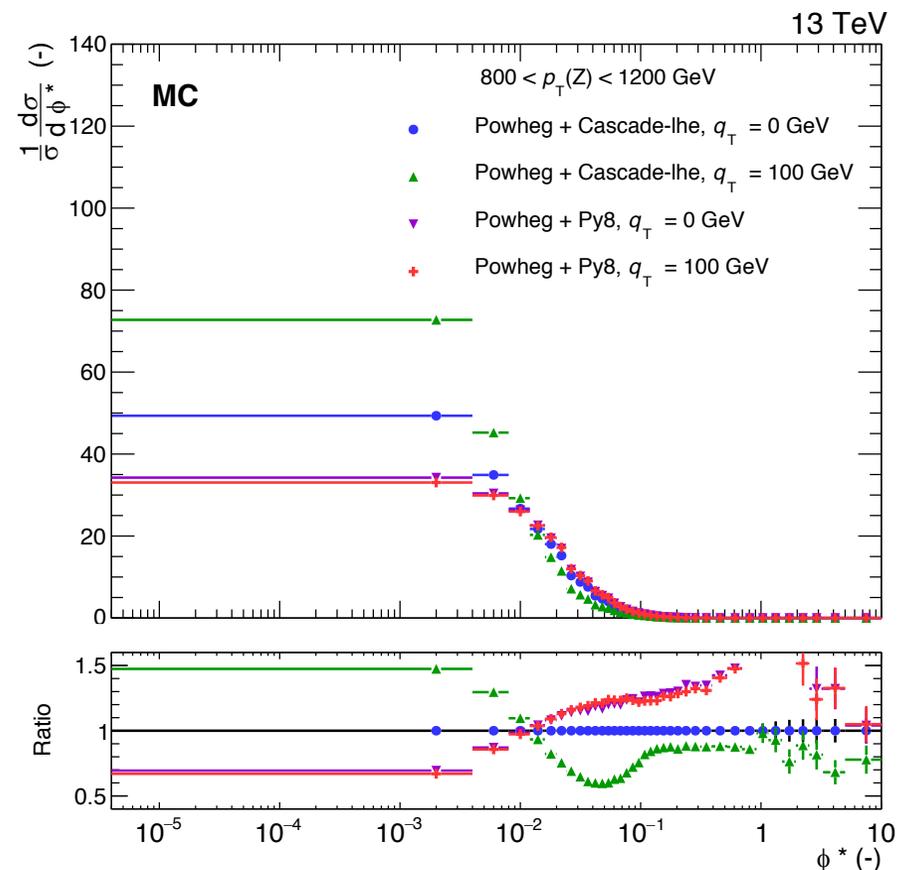
### $\phi^*$ variables

- In analogy to Drell-Yan production, when two leptons are in the back to back configuration

- $$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \sin(\theta_\eta^*),$$

where  $\cos(\theta_\eta^*) = \tanh[(\eta^- - \eta^+)/2]$

- Also this variable is sensitive to TMDs

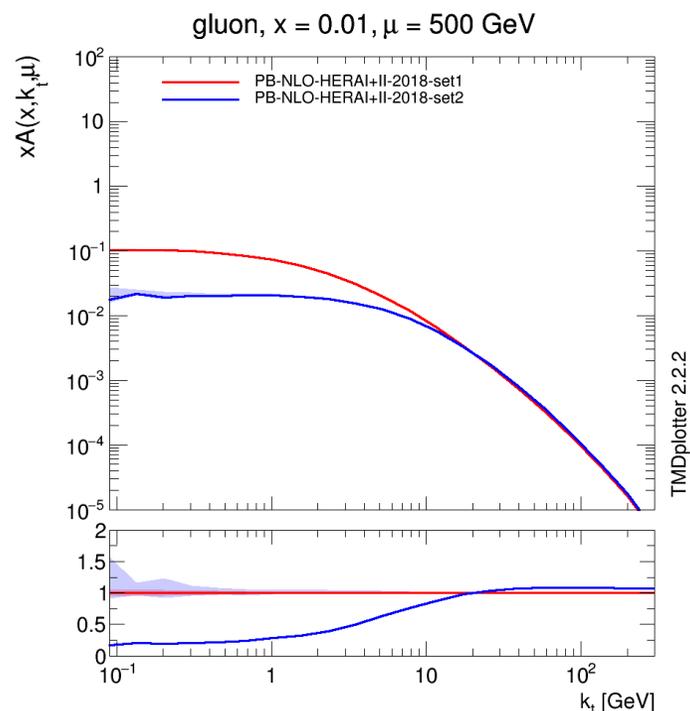


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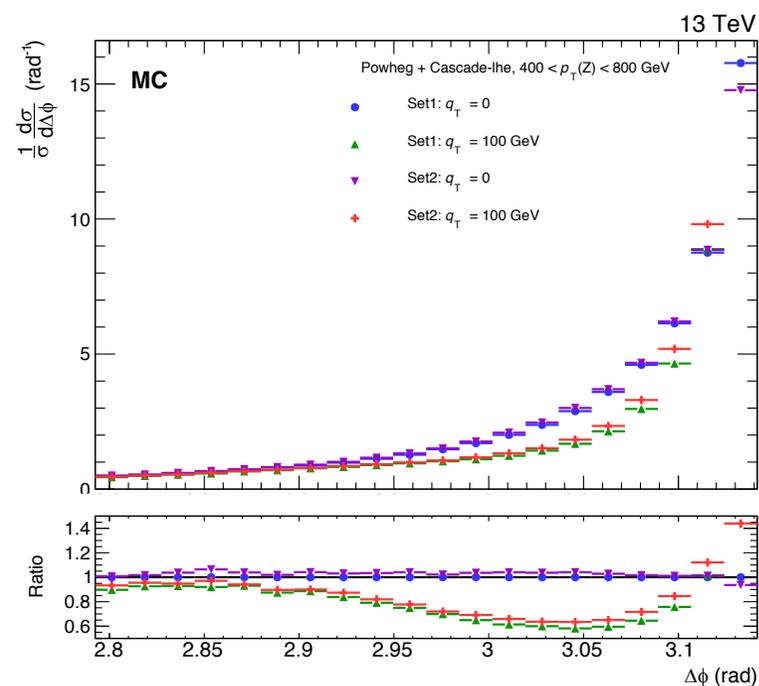
## Results

### Cascade with 2 sets of TMDs[1]:

- PB-NLO-2018-Set1, PB-NLO-2018-Set2



- Small difference between two sets is present



### References:

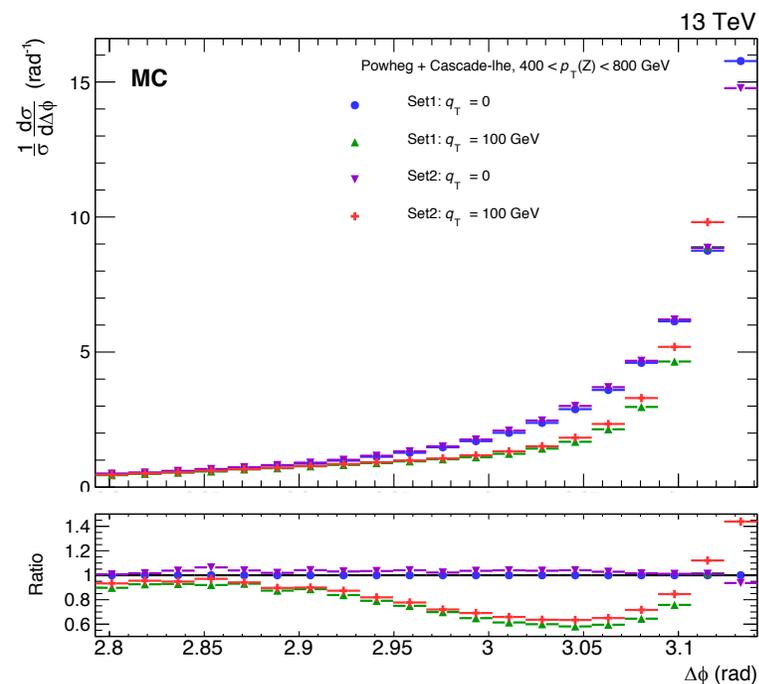
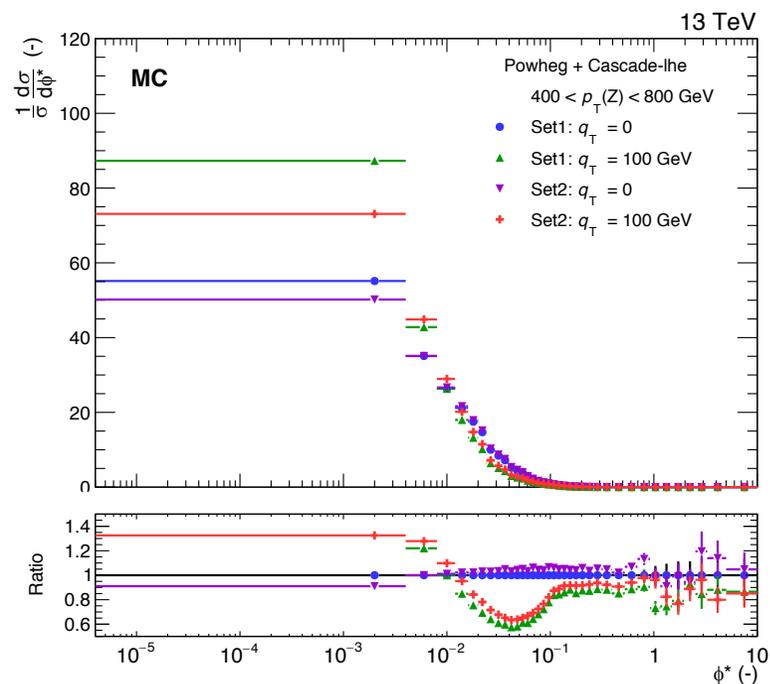
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# Theoretical prediction for hadronic decay of boosted Z + jet

## Results

### Cascade with 2 sets of TMDs[1]:

- PB-NLO-2018-Set1, PB-NLO-2018-Set2
- Difference between two sets is observed



### References:

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# Summary & Outlook

## Transverse momentum dependent PDF and use in MC generators for boosted W/Z + jet

### High $p_T$ W/Z as the SM 'standard candles'

- Jet substructure technique can help to reach TeV scale by boosted regime of W/Z
- Theoretical prediction for boosted Z+ jet was discussed: Powheg+Py8 vs Powheg+Cascade-lhe
  - Precision predictions for the back-to-back region with the TMDs (with full uncertainties)
  - Two sets of TMDs were used

# Summary & Outlook

## Transverse momentum dependent PDF and use in MC generators for boosted W/Z + jet

### High $p_T$ W/Z as the SM 'standard candles'

- Jet substructure technique and ML can help to reach TeV scale with hadronic decay of W/Z bosons
- Theoretical prediction for boosted Z+ jet was discussed: Powheg+Py8 vs Powheg+Cascade-lhe
  - Precision predictions for the back-to-back region with the TMDs (with full uncertainties)
  - Two sets of TMDs were used

**Thank you for your attention!**