Prospects for a measurement of the **W boson mass in the all-jets final state** at hadron colliders

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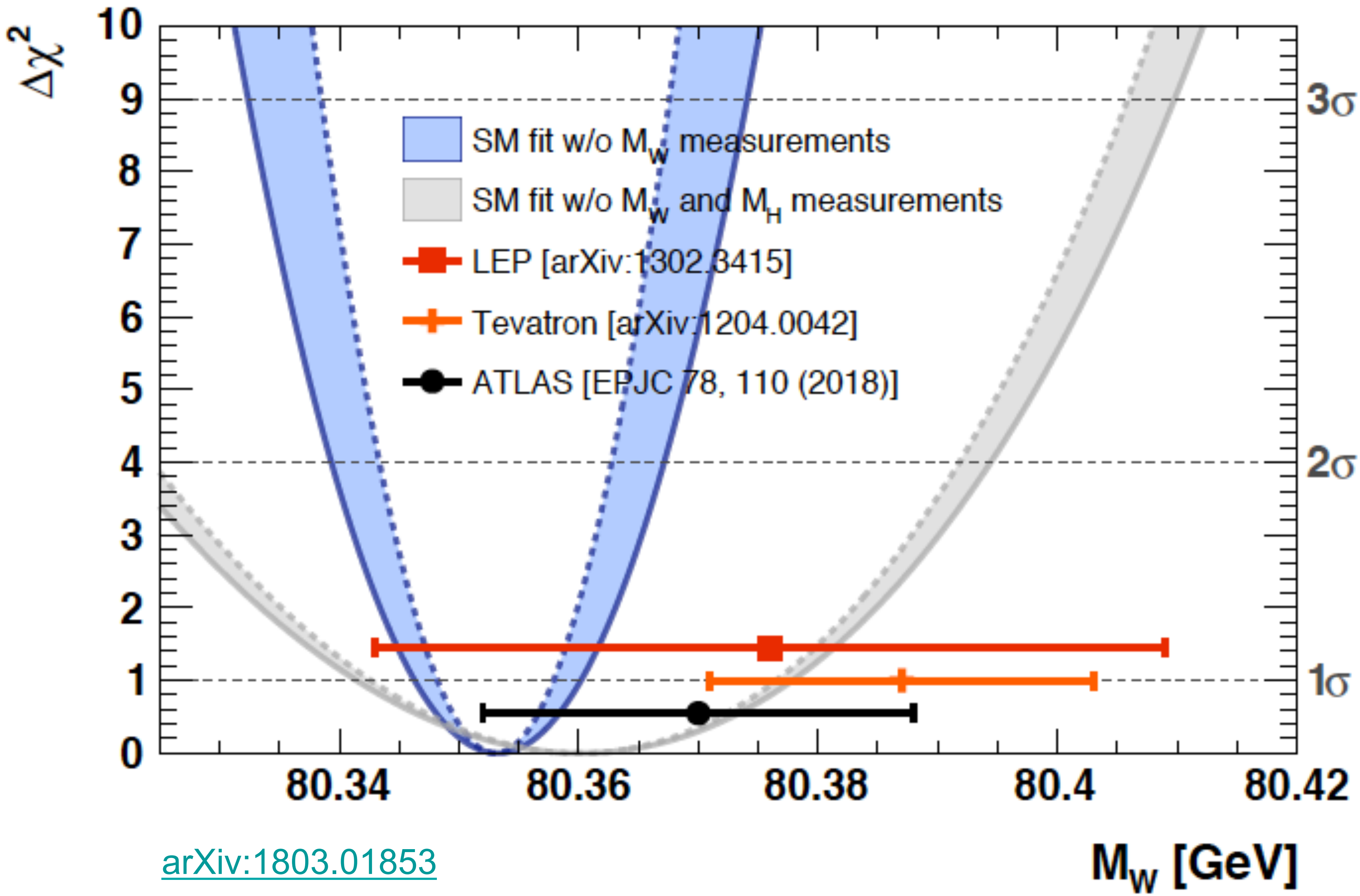
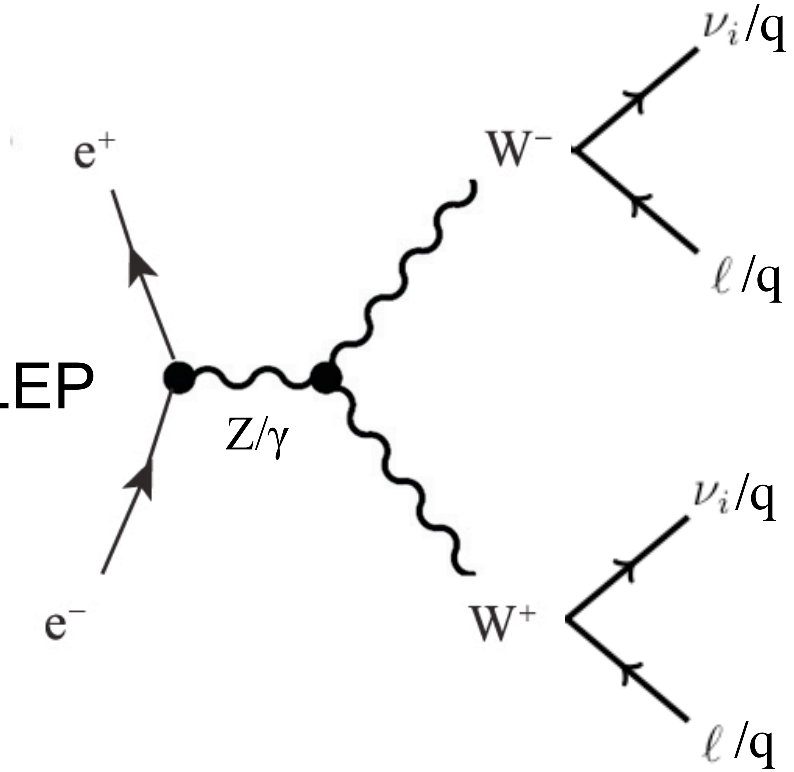
W mass measurements



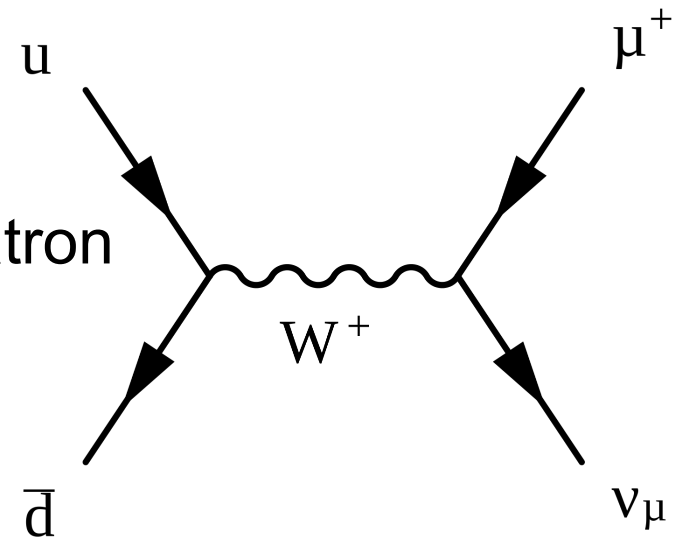
arXiv:1803.01853

Previous measurements

LEP



Tevatron
LHC

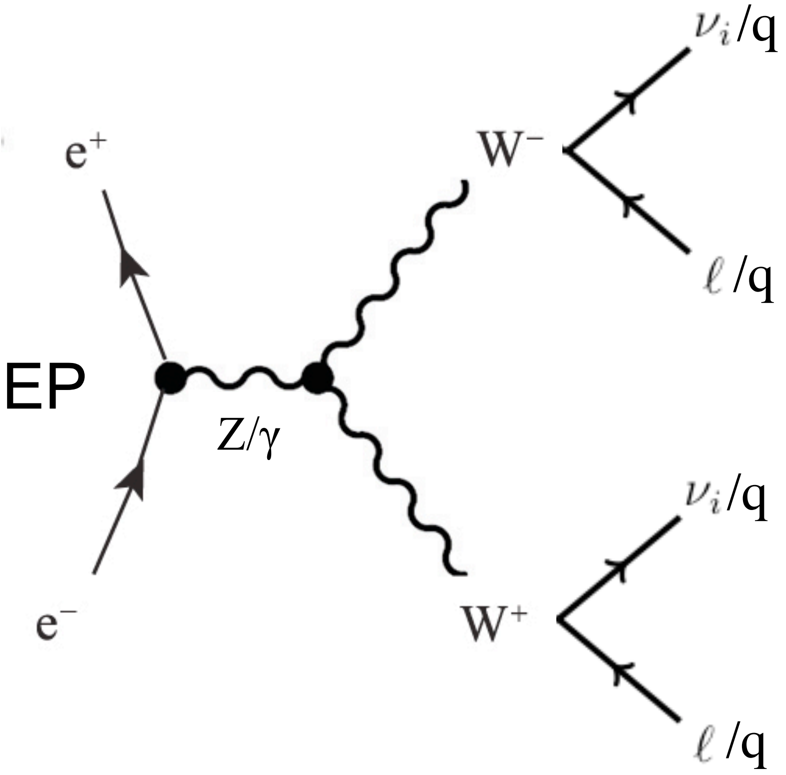


ALEPH (Eur.Phys.J.C47:309-335,2006):
lvqq: ± 54 (stat) ± 25 (syst) MeV
qqqq: ± 70 (stat) ± 28 (syst) ± 28 (FSI) MeV

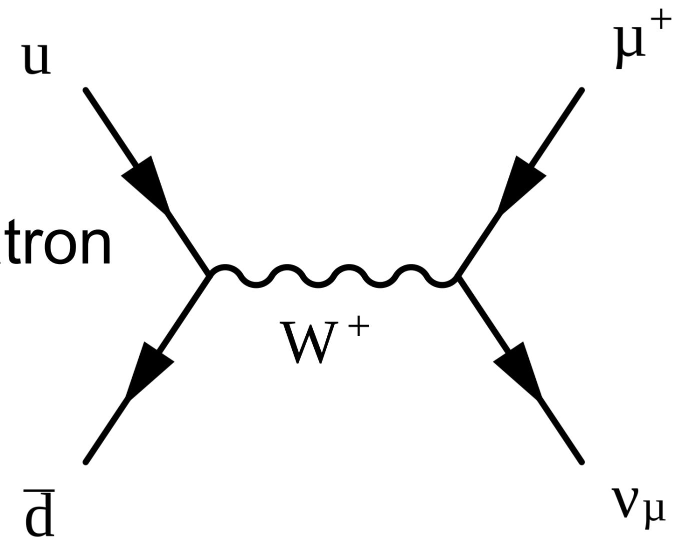
ATLAS (Eur. Phys. J. C 78 (2018) 110):
lv: ± 7 (stat) ± 11 (exp. syst.) ± 14 (mod. syst.) MeV

The all-jets final state

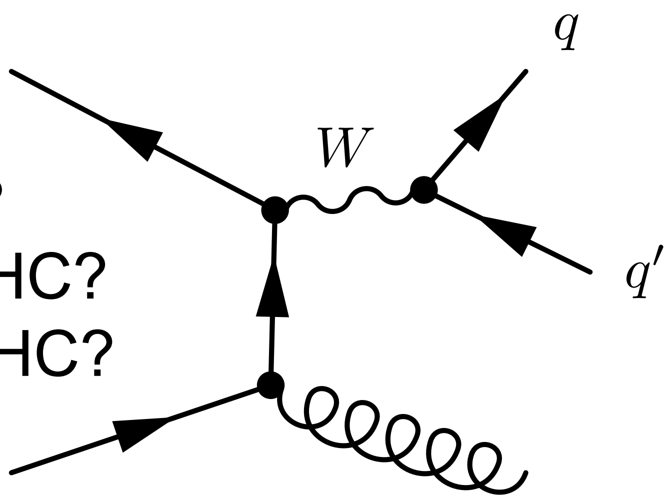
LEP

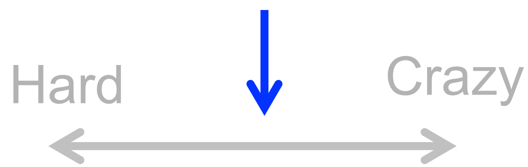


Tevatron
LHC



LHC?
HL-LHC?
HE-LHC?

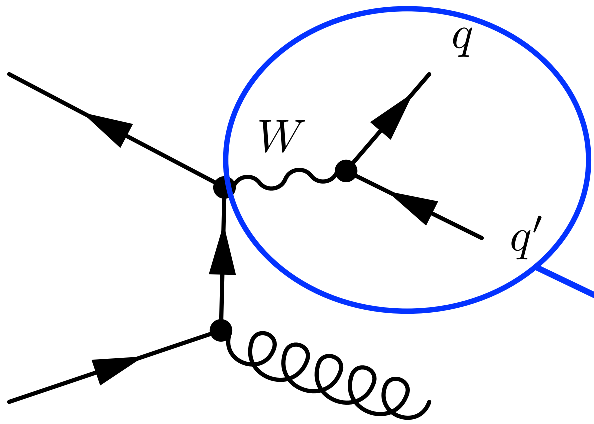


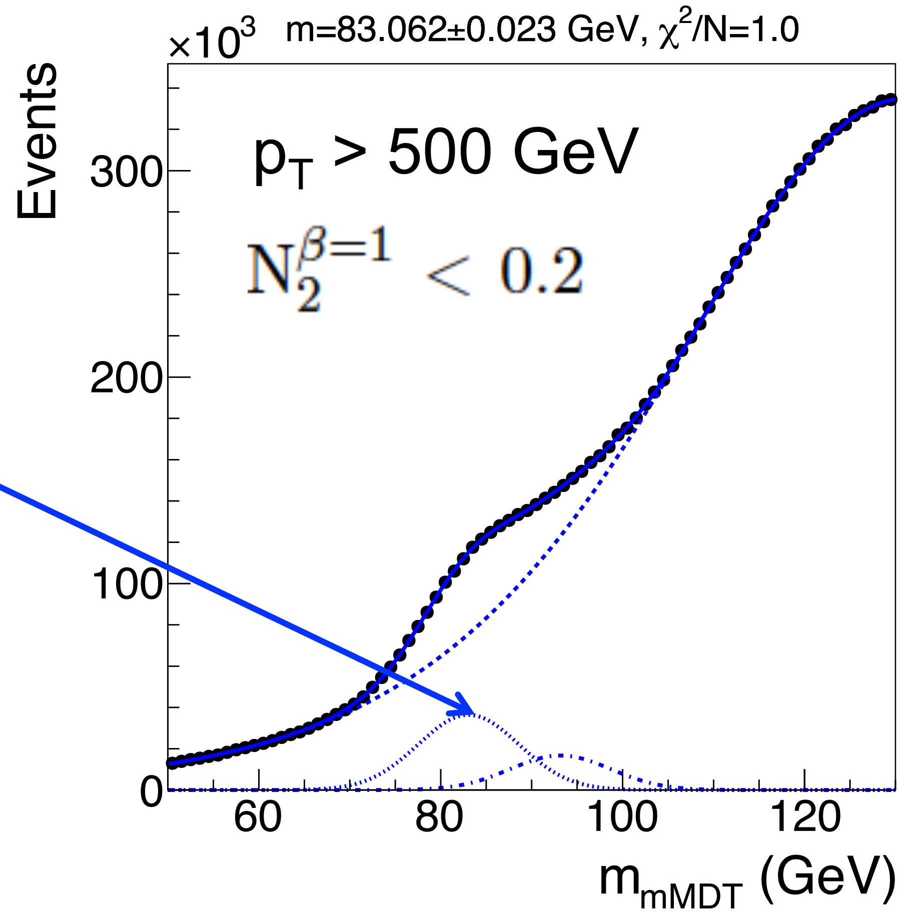


Outline

- Method
  - Signal and background
  - Choice of tagger
  - Extraction of W and Z mass peak
- Statistical uncertainty
  - Where LHC stands now
  - Trigger strategy
- Systematic uncertainties
  - Experimental uncertainties
  - Perturbative effects
  - Non-perturbative effects
    - Where MC generators stand now
    - Constraining non-perturbative effects
- Discussion

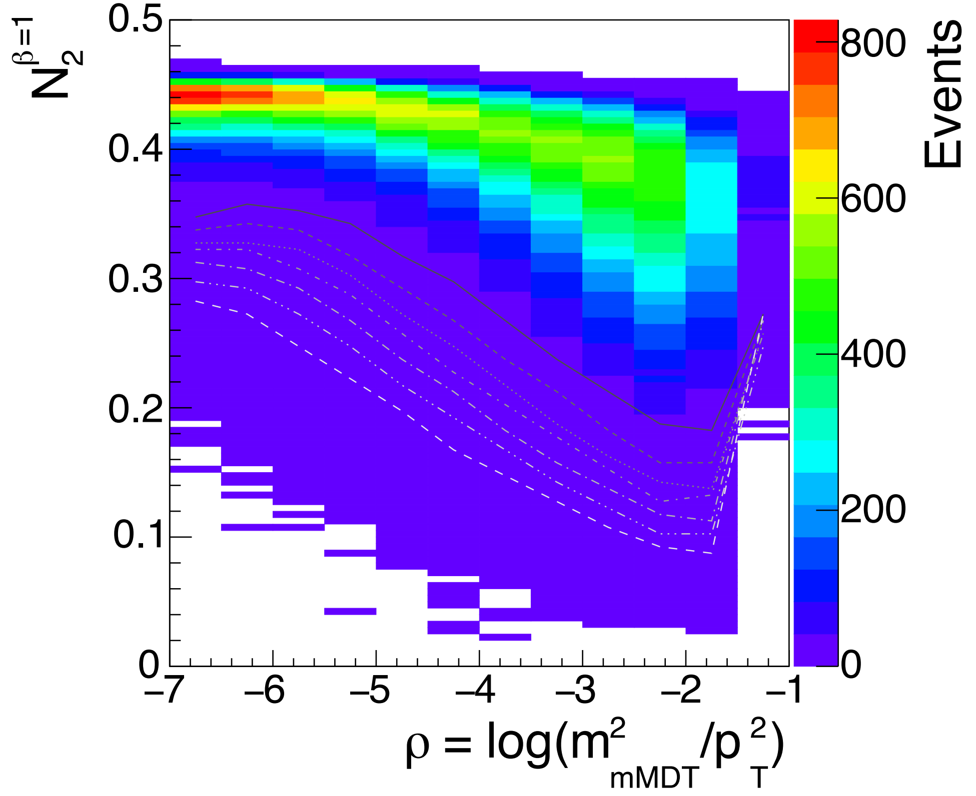
Signal and background

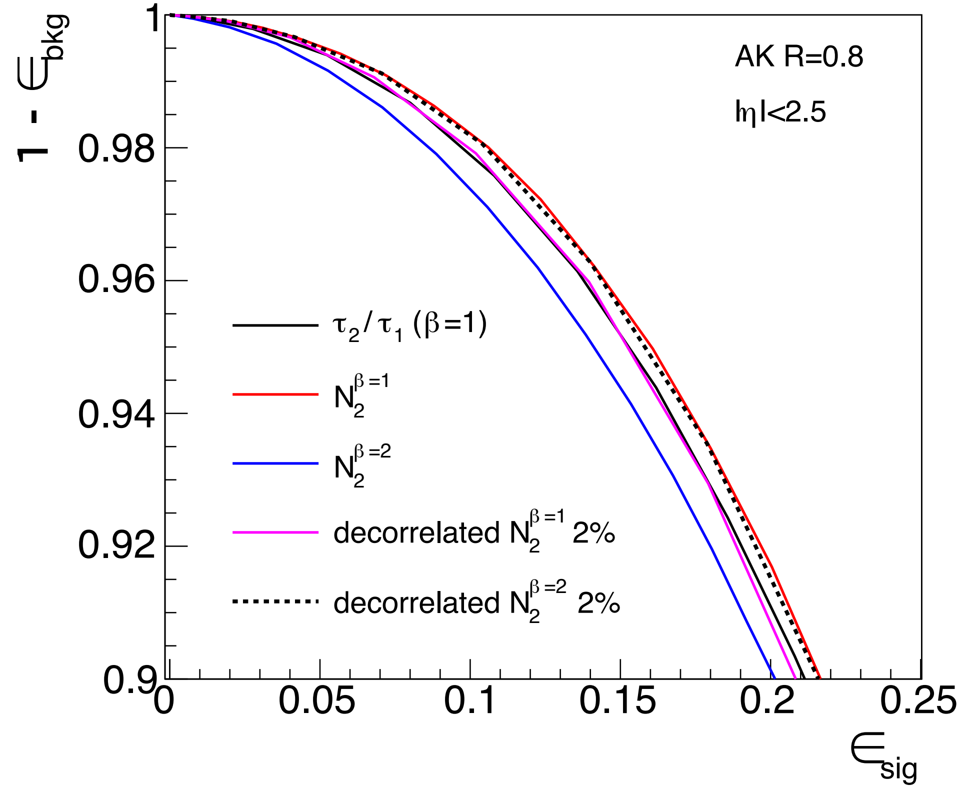




- W+jets, Z+jets, QCD multijets, top quark production
- Madgraph + simple detector simulation tuned to current jet substructure performance of ATLAS/CMS detectors
- Pseudo-data corresponding to HL-LHC luminosity

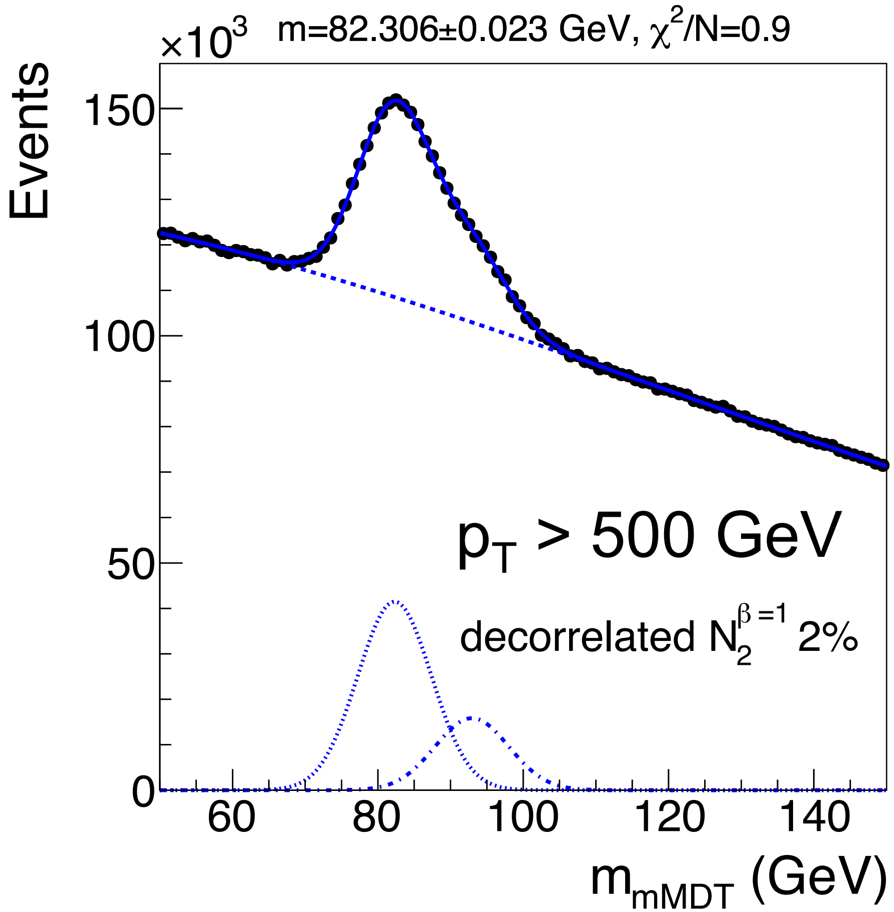
Choice of tagger

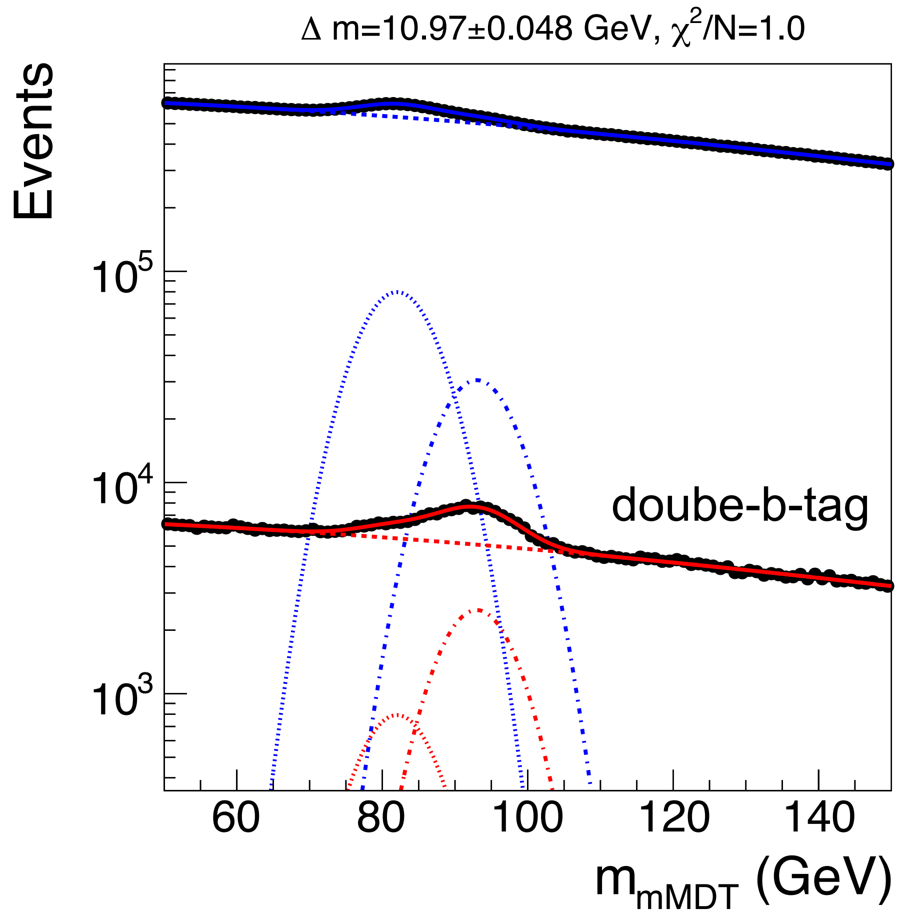




- Flatten background by de-correlating jet substructure selection from jet mass
- Small effect on signal efficiency, but better control of background estimate

Extraction of W and Z mass peaks





- Enriched sample of Z-bosons with double-b-tagger
- Measure m_Z-m_W such that many experimental systematic uncertainties cancel out

Statistical uncertainty

- Assuming current detector performance and triggers

- Statistical precision for m_W:

	Selection	Int. luminosity	σ_{m_W} [MeV]
LHC	decorrelated $N_2^{\beta=1}$1%, $p_T > 500$ GeV	300/fb	75
HL-LHC	decorrelated $N_2^{\beta=1}$1%, $p_T > 500$ GeV	3000/fb	23

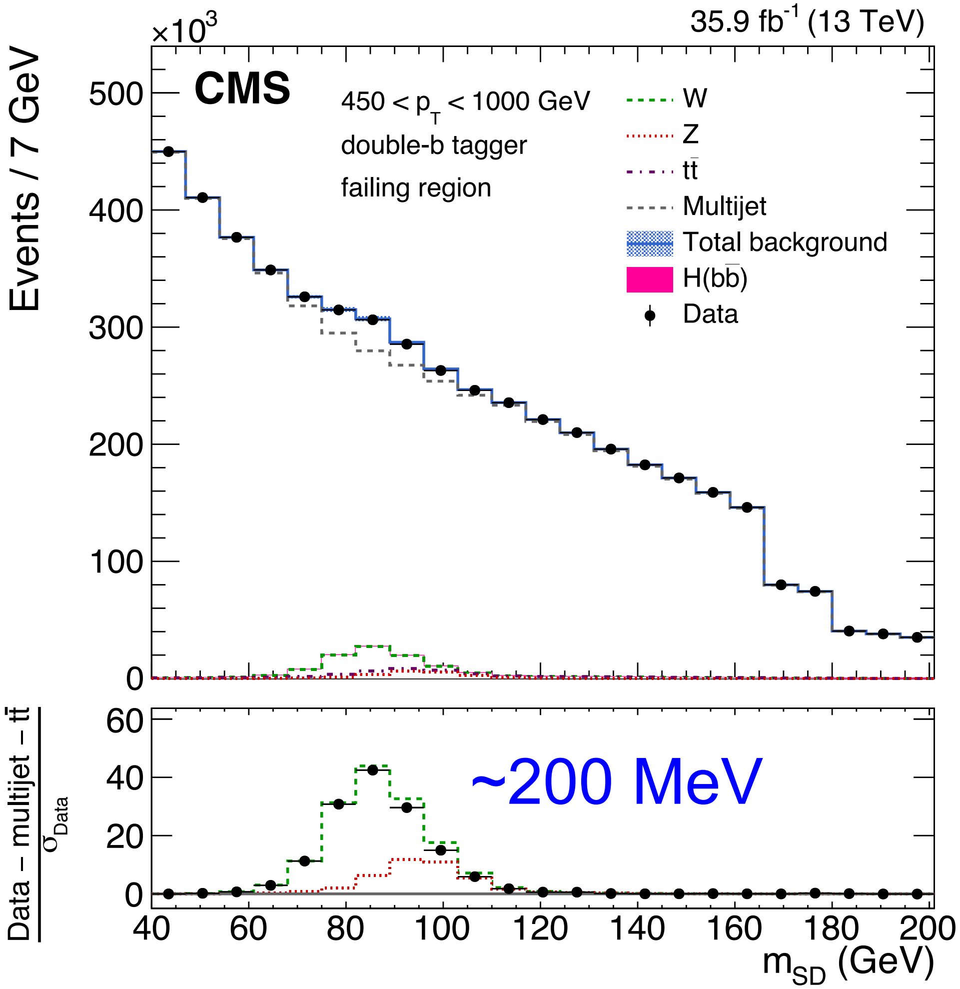
- Statistical precision for m_Z-m_W:

	Selection	Int. luminosity	σ_{m_W} [MeV]
LHC	decorrelated $N_2^{\beta=1}$2%, $p_T > 500$ GeV	300/fb	171
HL-LHC	decorrelated $N_2^{\beta=1}$5%, $p_T > 500$ GeV	3000/fb	48

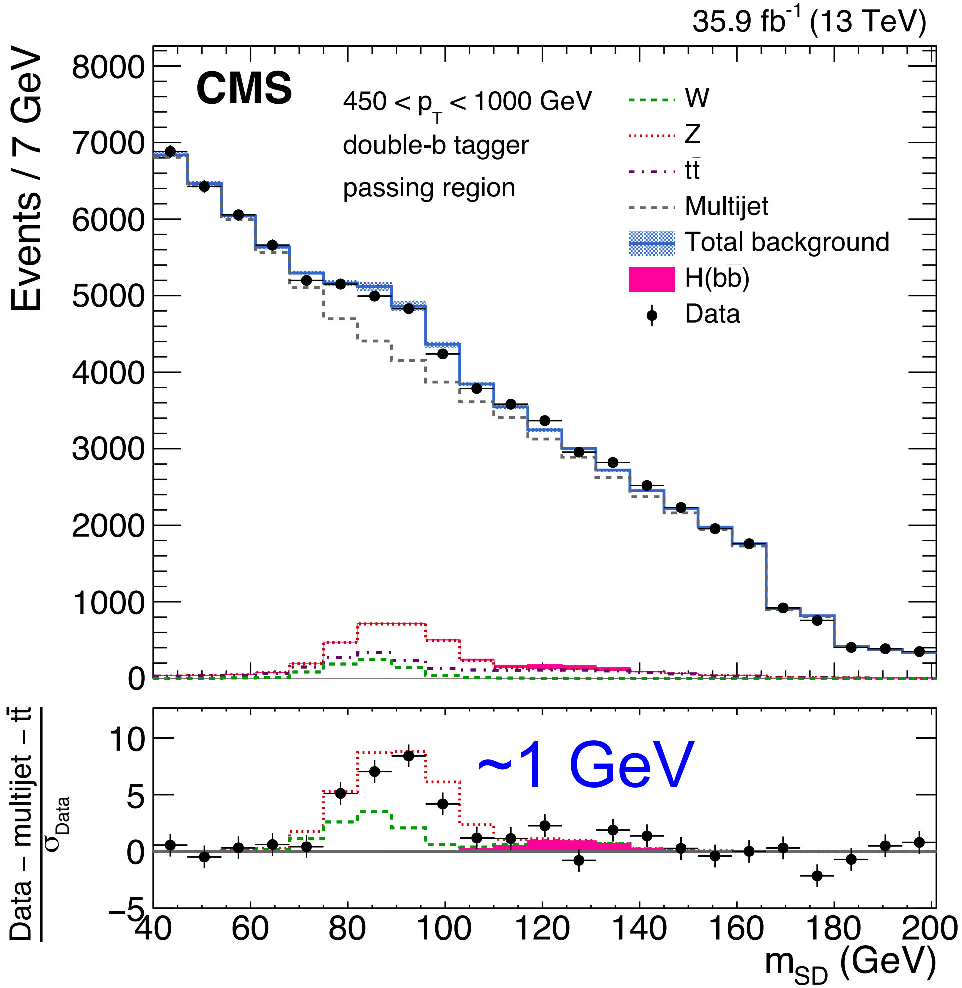
  - Limited by cross section of Z→bb

Where LHC stands now

double-b-tag fails



double-b-tagged



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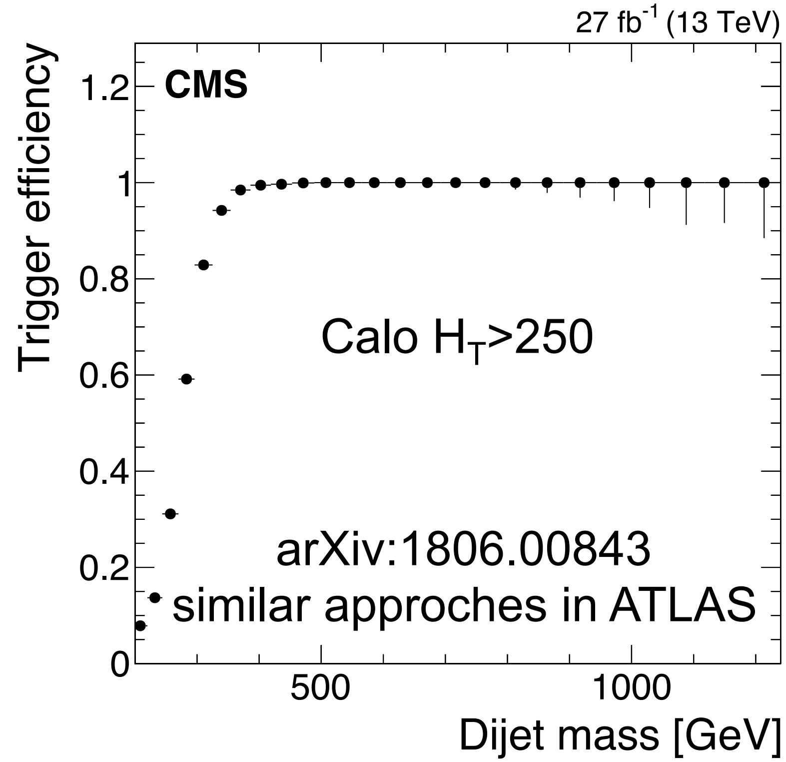
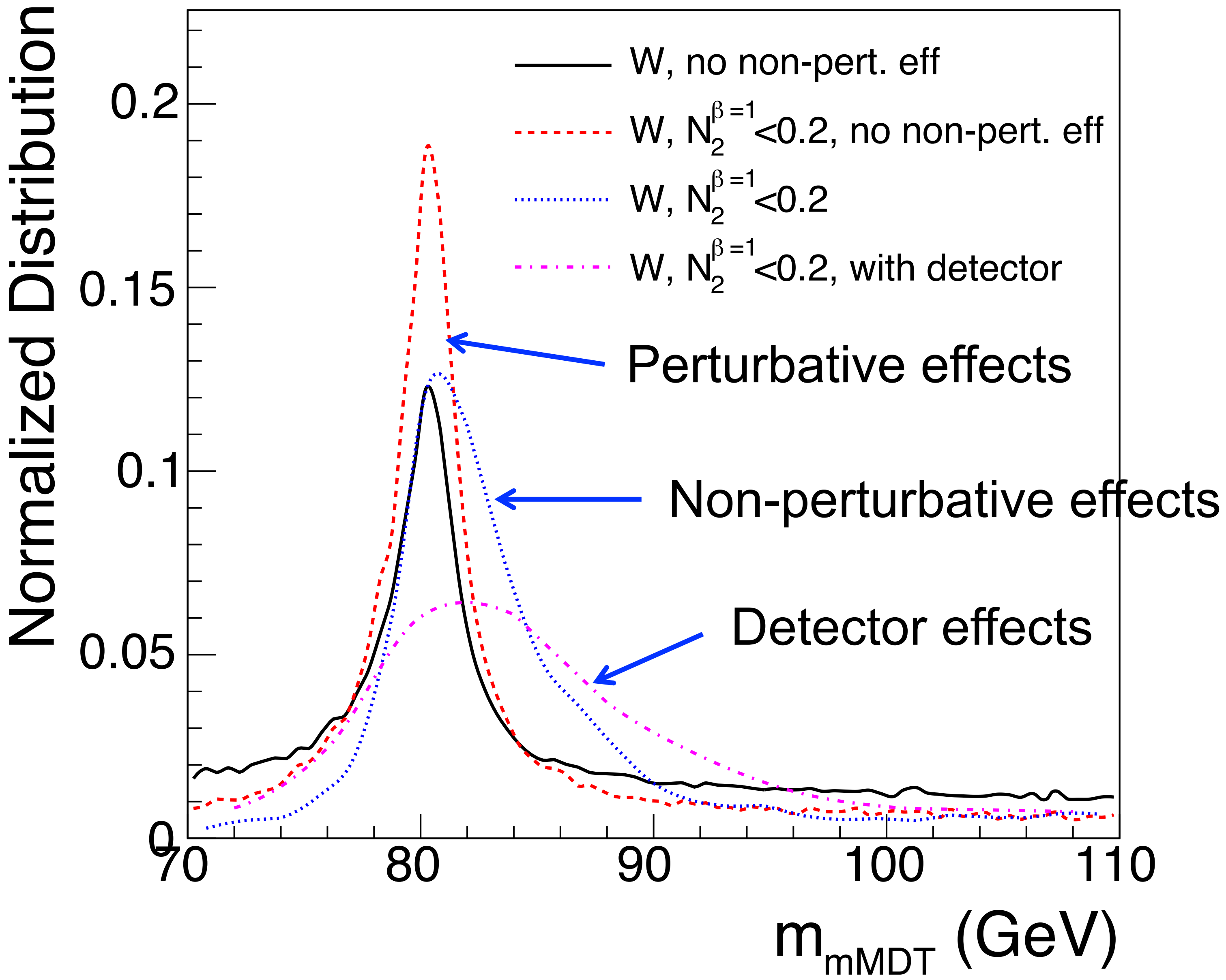
Trigger strategy

- Current trigger threshold for at ATLAS/CMS p_T>~500 GeV
- Alternative approaches storing lower size events at higher rates allows going to p_T>~200 GeV
- Assume substructure evaluated at L1+HLT trigger level at HL-LHC



Strategy	Selection	Int. luminosity	σ_{m_W} [MeV]
measure m_W	decorrelated $N_2^{\beta=1}$1%, $p_T > 500$ GeV	3000/fb	23
measure m_W	decorrelated $N_2^{\beta=1}$1%, $p_T > 400$ GeV	3000/fb	21
measure m_W	decorrelated $N_2^{\beta=1}$2%, $p_T > 300$ GeV	3000/fb	13
measure $m_Z - m_W$	decorrelated $N_2^{\beta=1}$5%, $p_T > 500$ GeV	3000/fb	48
measure $m_Z - m_W$	decorrelated $N_2^{\beta=1}$5%, $p_T > 400$ GeV	3000/fb	40
measure $m_Z - m_W$	decorrelated $N_2^{\beta=1}$5%, $p_T > 300$ GeV	3000/fb	32

Systematic uncertainties



Experimental uncertainties

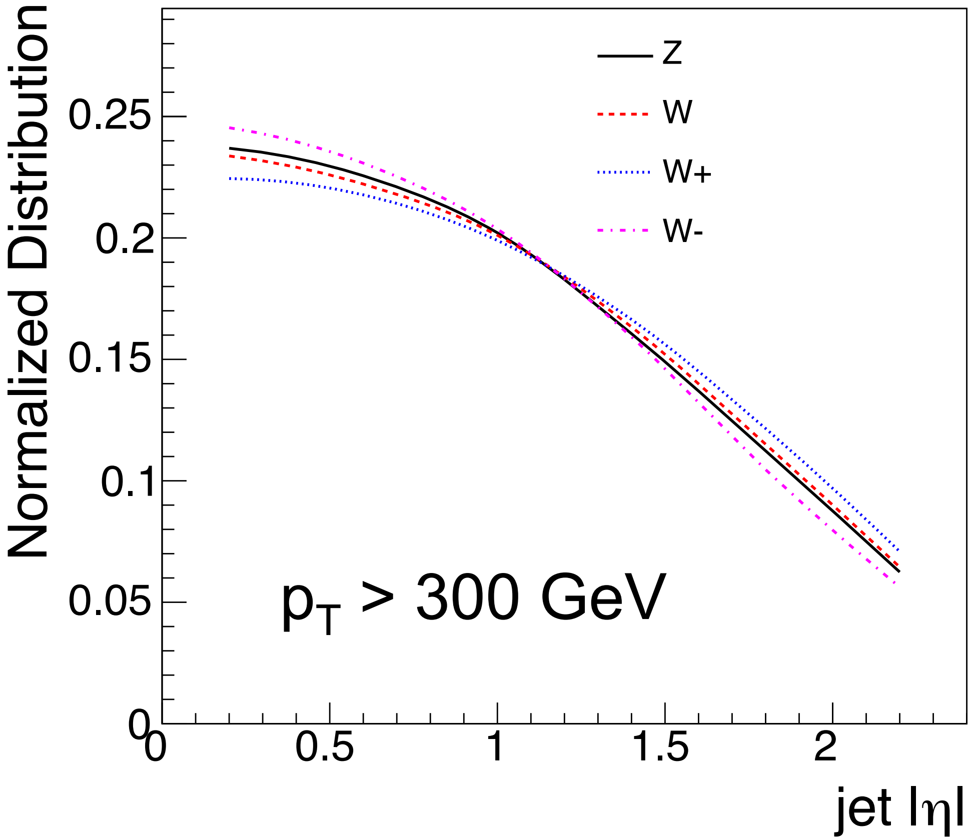
- Assume particle-flow reconstruction, evaluating systematic effects separately on charge particles, photons (and π^0) and neutral hadrons

- Estimate precision of energy scale calibration needed to achieve uncertainty on m_W less than 10 MeV

Quantity	Effect	Understanding needed for σ_{m_W}=10 MeV	Typical precision nowadays
m_W	Charged particle energy scale	0.03%	0.05%
m_W	Photon (and π^0) energy scale	0.06%	0.1%
m_W	Neutral hadron energy scale	0.1%	1%
m_W	200 pileup interactions	1.4%	1%

- These uncertainties cancel when measuring m_Z-m_W
  - Residual effects from hadronization model affecting W→qq vs. Z→bb jet response (discussed later)

Perturbative effects



Effect	Size of effect	Understanding needed for σ_{m_W}=10 MeV
NLO QCD	4 MeV	✓
NLO EW	1 MeV	✓
NLO PDF	1 MeV	✓
$N_2^{\beta=1} < 0.2$ selection	200 MeV	5%

- Prediction of W boson kinematics not a limiting factor in all-jets final state
- Need prediction at 5% level of how much substructure selection changes the W mass

Non-perturbative effects

- Disabling non-perturbative effects (MPI and hadronization in Pythia8) to estimate of size of effect on both m_W and m_Z-m_W
  - 10 times smaller for m_Z-m_W than for m_W

- Comparing Z→qq vs. Z→bb mass peaks to estimate size of hadronization effects on m_Z-m_W

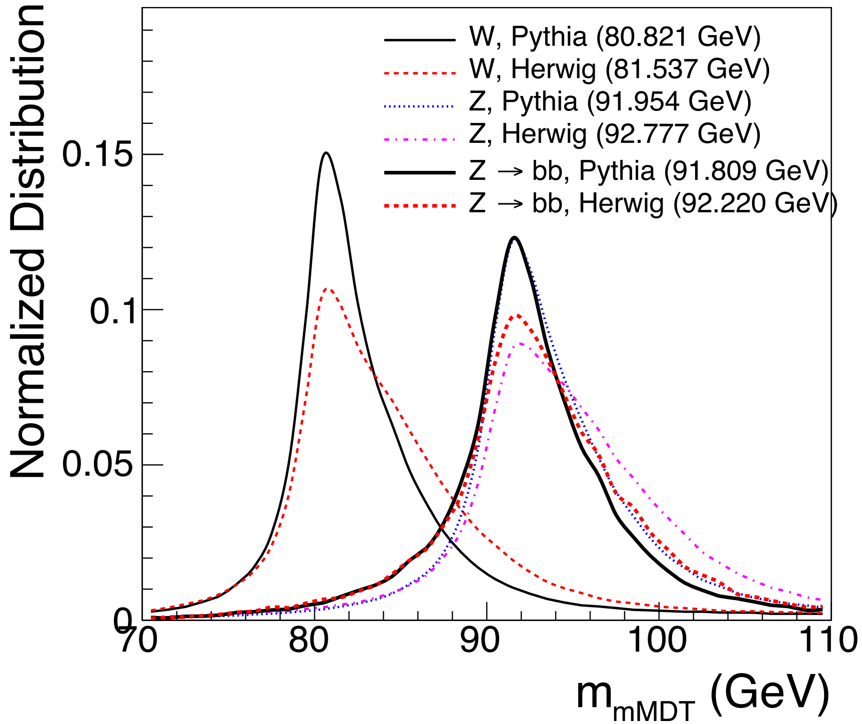
p_T > 300 GeV

Quantity	Effect	Size of effect	Understanding needed for σ_{m_W}=10 MeV
m_W	non-pert. corrections	1100 MeV	0.9%
m_W	$W \to q\bar{q}'$ vs. $W \to c\bar{s}$	80 MeV	13%

Quantity	Effect	Size of effect	Understanding needed for σ_{m_W}=10 MeV
$m_Z - m_W$	non-pert. corrections	110 MeV	9%
m_Z	$Z \to q\bar{q}$ vs. $Z \to b\bar{b}$	140 MeV	7%

Where MC generators stand now

- Estimate current understanding of convolution of perturbative and non-perturbative effects by comparing Pythia8 and Herwig++
- Depends on grooming algorithm and substructure selection



p_T > 300 GeV

Quantity	Effect	Size of effect
m_W	non-pert. corrections	1100 MeV
m_W	$W \to q\bar{q}'$ vs. $W \to c\bar{s}$	80 MeV

m_W^P / m_W^H ~ 200-1000 MeV

Quantity	Effect	Size of effect
$m_Z - m_W$	non-pert. corrections	110 MeV
m_Z	$Z \to q\bar{q}$ vs. $Z \to b\bar{b}$	140 MeV

$(m_Z^P - m_W^P)/(m_Z^H - m_W^H)$ ~ 50-500 MeV

$(m_Z^P - m_{Z\to bb}^P)/(m_Z^H - m_{Z\to bb}^H)$ ~ 50-500 MeV

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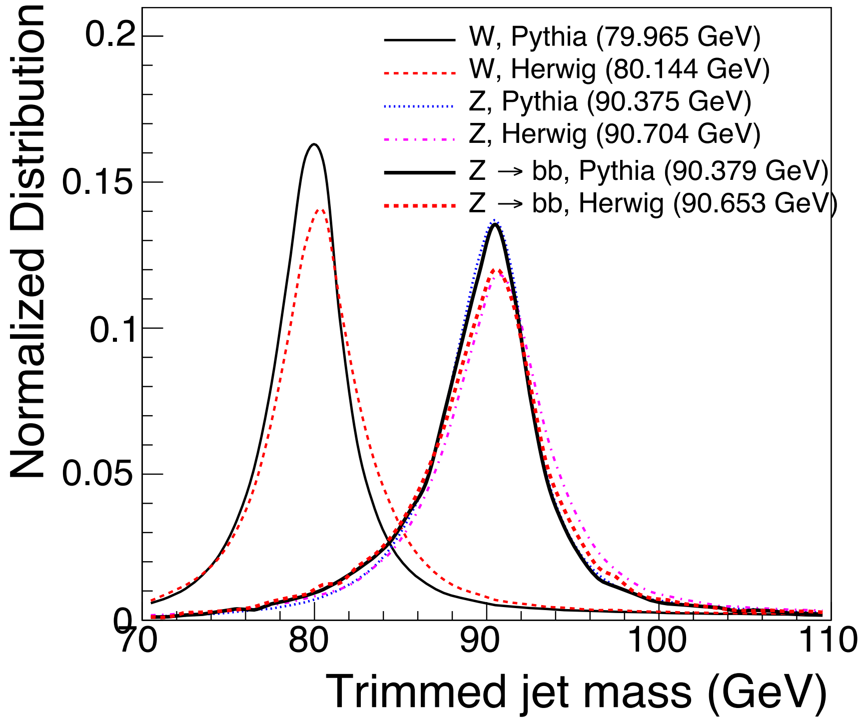

$p_T > 300$ GeV

Quantity	Effect	Size of effect
m_W	non-pert. corrections	1100 MeV
m_W	$W \to q\bar{q}'$ vs. $W \to c\bar{s}$	80 MeV

$m_W^P / m_W^H \sim 200\text{-}1000$ MeV

Quantity	Effect	Size of effect
$m_Z - m_W$	non-pert. corrections	110 MeV
m_Z	$Z \to q\bar{q}$ vs. $Z \to b\bar{b}$	140 MeV

$(m_Z^P - m_W^P)/(m_Z^H - m_W^H) \sim 50\text{-}500$ MeV

$(m_Z^P - m_{Z\to bb}^P)/(m_Z^H - m_{Z\to bb}^H) \sim 50\text{-}500$ MeV

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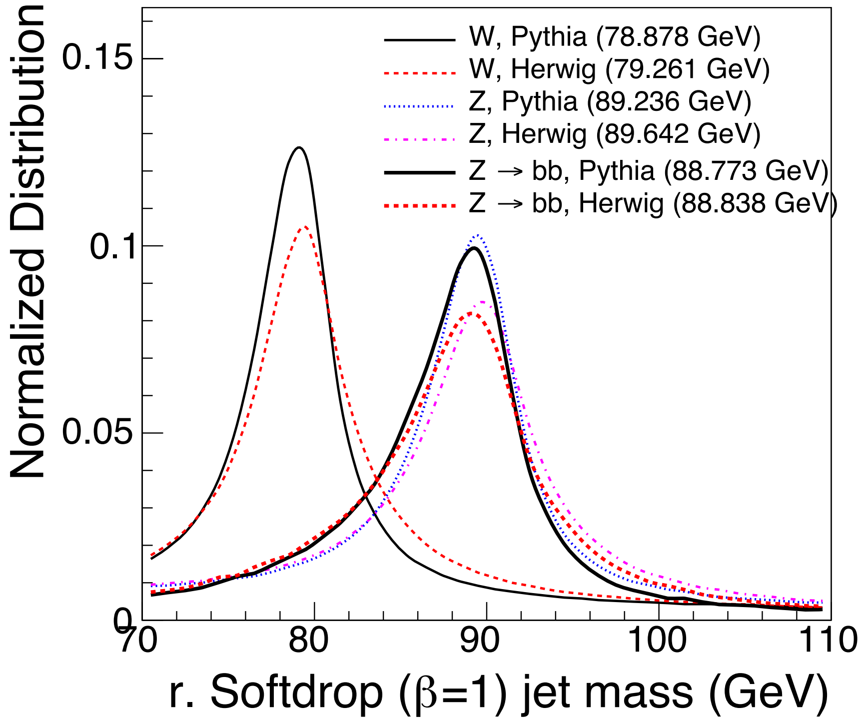

p_T > 300 GeV

Quantity	Effect	Size of effect
m_W	non-pert. corrections	1100 MeV
m_W	$W \to q\bar{q}'$ vs. $W \to c\bar{s}$	80 MeV

m_W^P / m_W^H ~ 200-1000 MeV

Quantity	Effect	Size of effect
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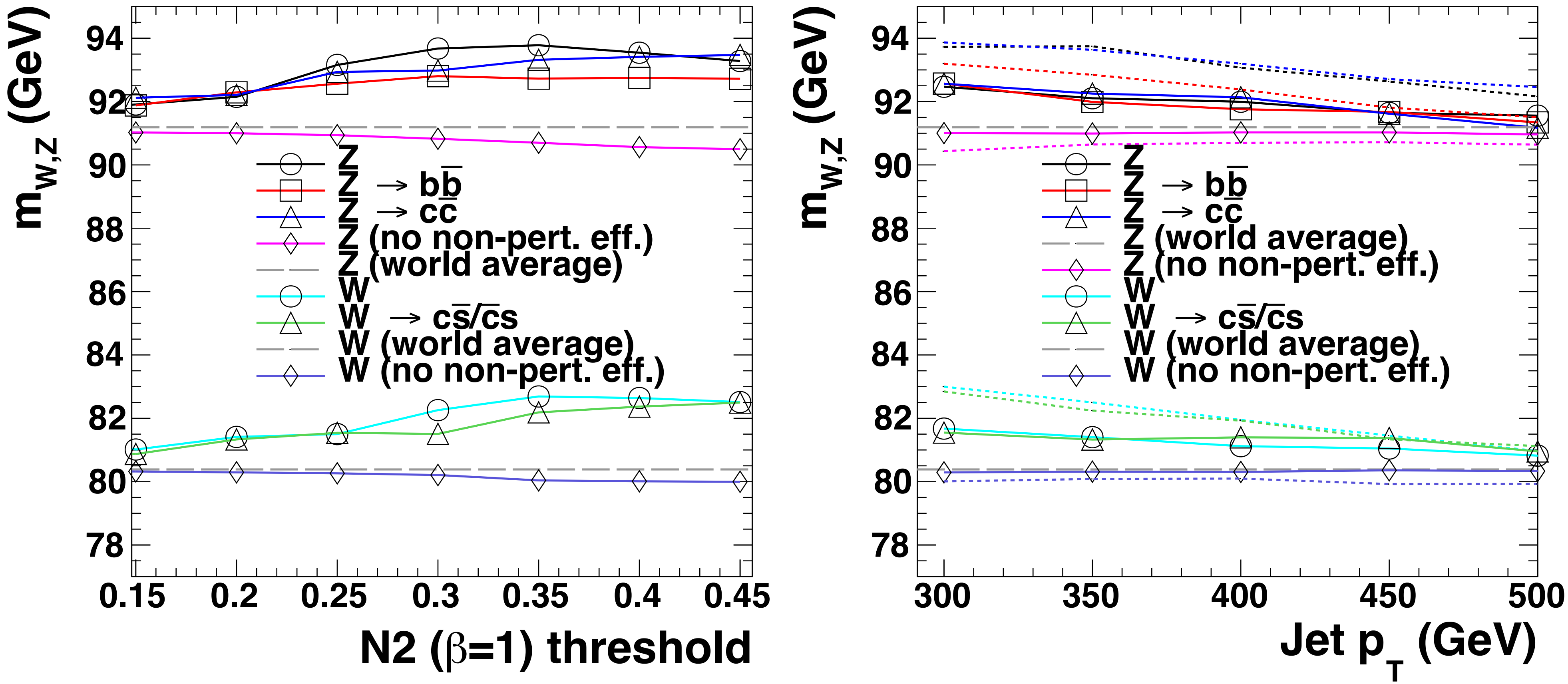
m_Z	$Z \to q\bar{q}$ vs. $Z \to b\bar{b}$	140 MeV

$(m_Z^P - m_W^P)/(m_Z^H - m_W^H)$ ~ 50-500 MeV

$(m_Z^P - m_{Z\to bb}^P)/(m_Z^H - m_{Z\to bb}^H)$ ~ 50-500 MeV

Constraining non-perturbative effects



- Non-perturbative effects strongly reduced by substructure selection and at high jet p_T
- Pythia-Herwig difference for m_Z-m_W reduced to 10-50 MeV with p_T>500 GeV
- Differential measurement of m_Z-m_W vs. p_T and substructure promising to contrain non-perturbative effects

Discussion

- The leading theoretical task will be an extraction of non-perturbative corrections, either from other data or self-consistently with mass measurement itself
  - W boson groomed N_2 and groomed mass (a color singlet)
    - Groomed D_2 Larkoski, Moult, Neill (1708.06760, 1710.00014), Moult, Nachman, Neill (1710.06859)
    - Groomed top quark mass Hoang et al. (1708.02586)
  - A statement on universality of the non-perturbative corrections for hadronic W and Z decays

- Measurement of m_W peak interesting in itself, since it can help to better understand hadronization of boosted W/Z bosons, supporting searches

- HE-LHC would allow access to even higher p_T with less non-perturbative effects

Conclusions

- Compared to lν final state, all-jets final state could avoid experimental systematic uncertainties related to measurement of missing E_T and theoretical uncertainties related to m_T
- Measurement of the mass difference between the W and Z bosons more feasible than the W mass itself
- New trigger strategies needed to reach statistical uncertainty of 30 MeV with 3000/fb HL-LHC data
- Measurement limited by the understanding of non-perturbative contributions to the invariant masses of W→qq and Z→bb
  - Significant improvement required to reach below 100 MeV precision, e.g. by differential measurement of m_Z-m_W vs. p_T and substructure
  - This measurement points to a number of theoretical issues which deserve further thought, and whose resolution would have wider applicability in a number of jet substructure measurements