Measurement of Diboson Production in Semileptonic Decay Modes and Anomalous Couplings

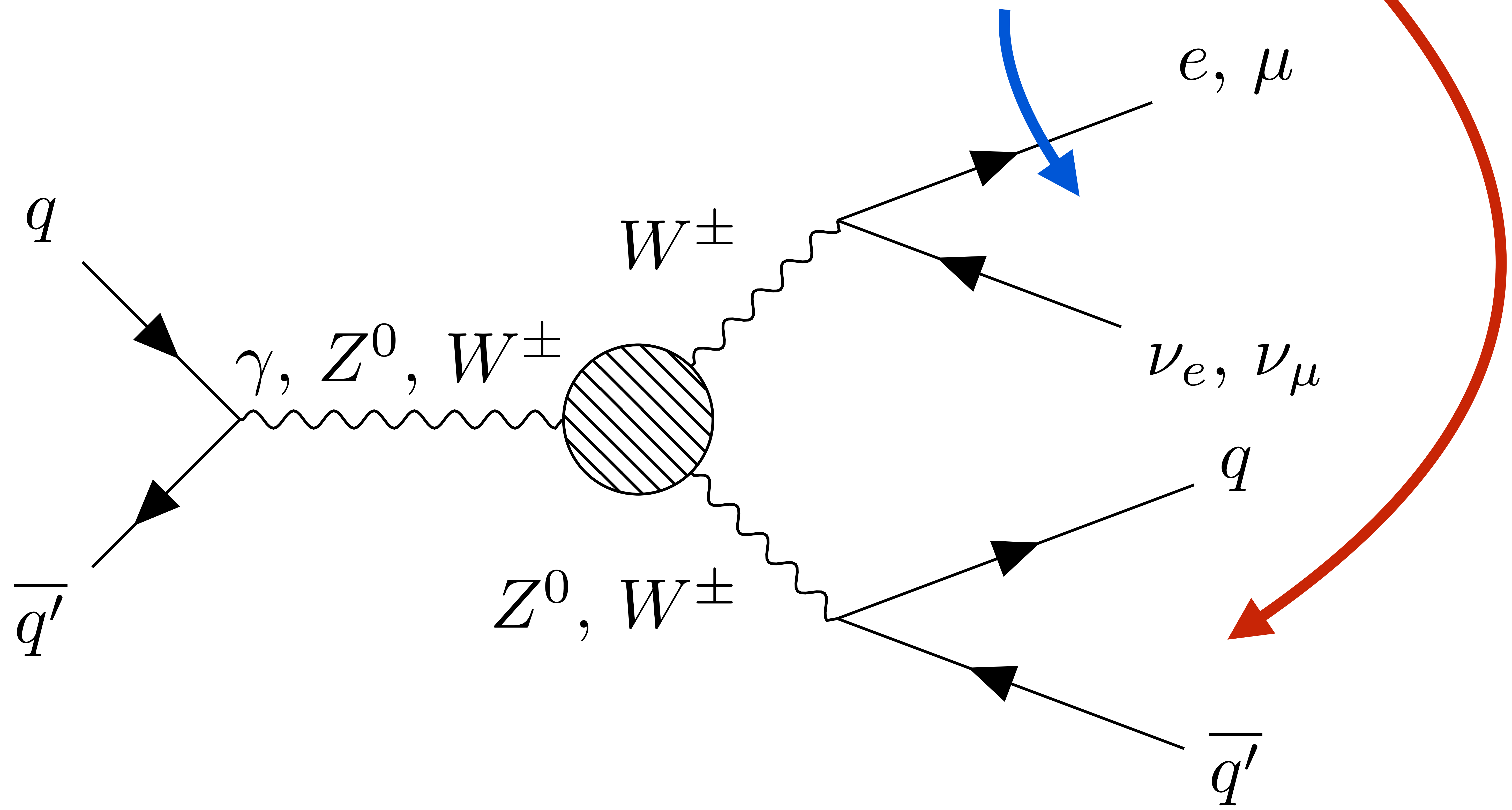
MULTI-BOSON INTERACTIONS 2019

Robin Aggleton
for the CMS & ATLAS Collaborations

Semileptonic:

Diboson final state with one V decay to quarks (→ jets),

and other V decay to final state with lepton (e, μ)

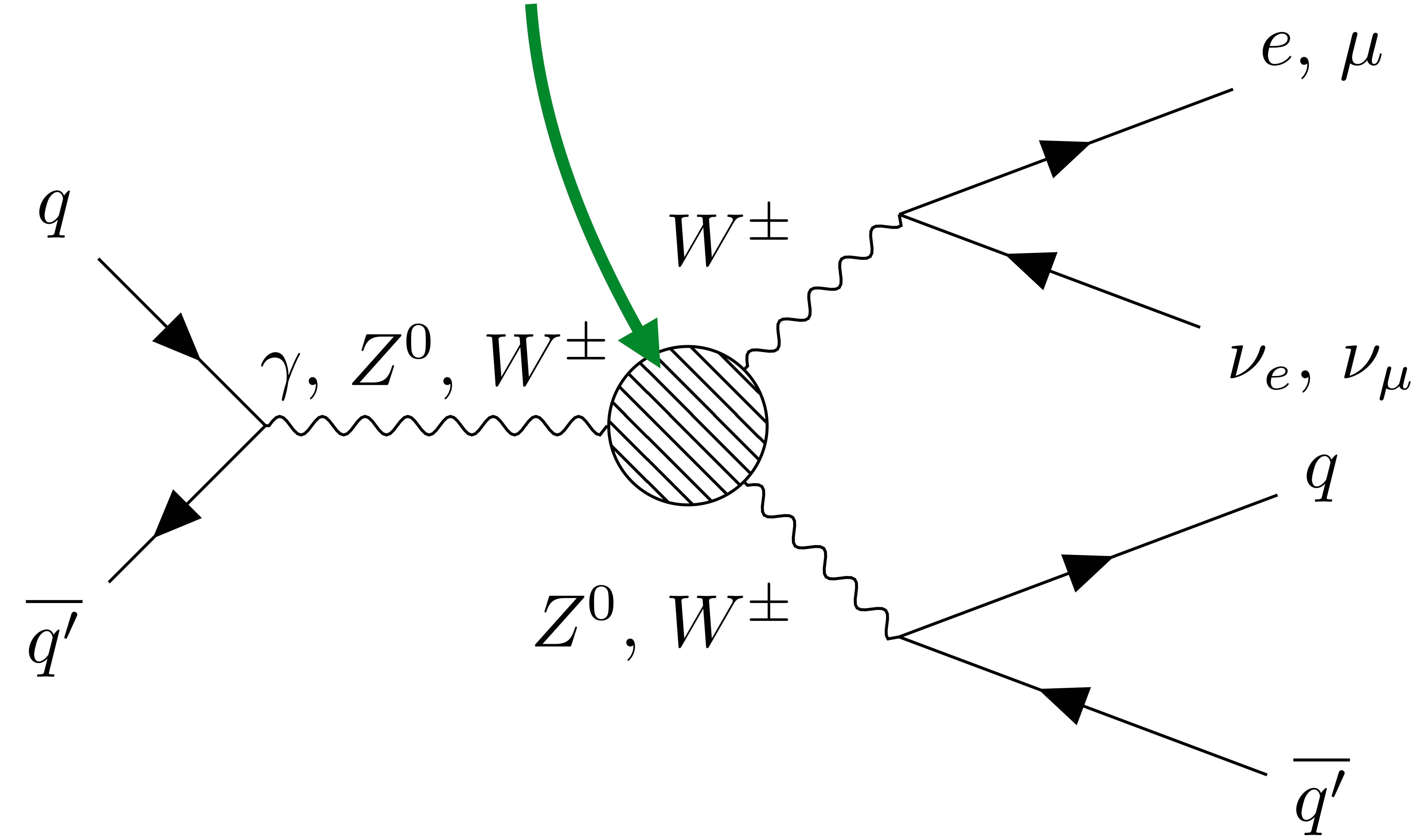


→ Can reconstruct WV state

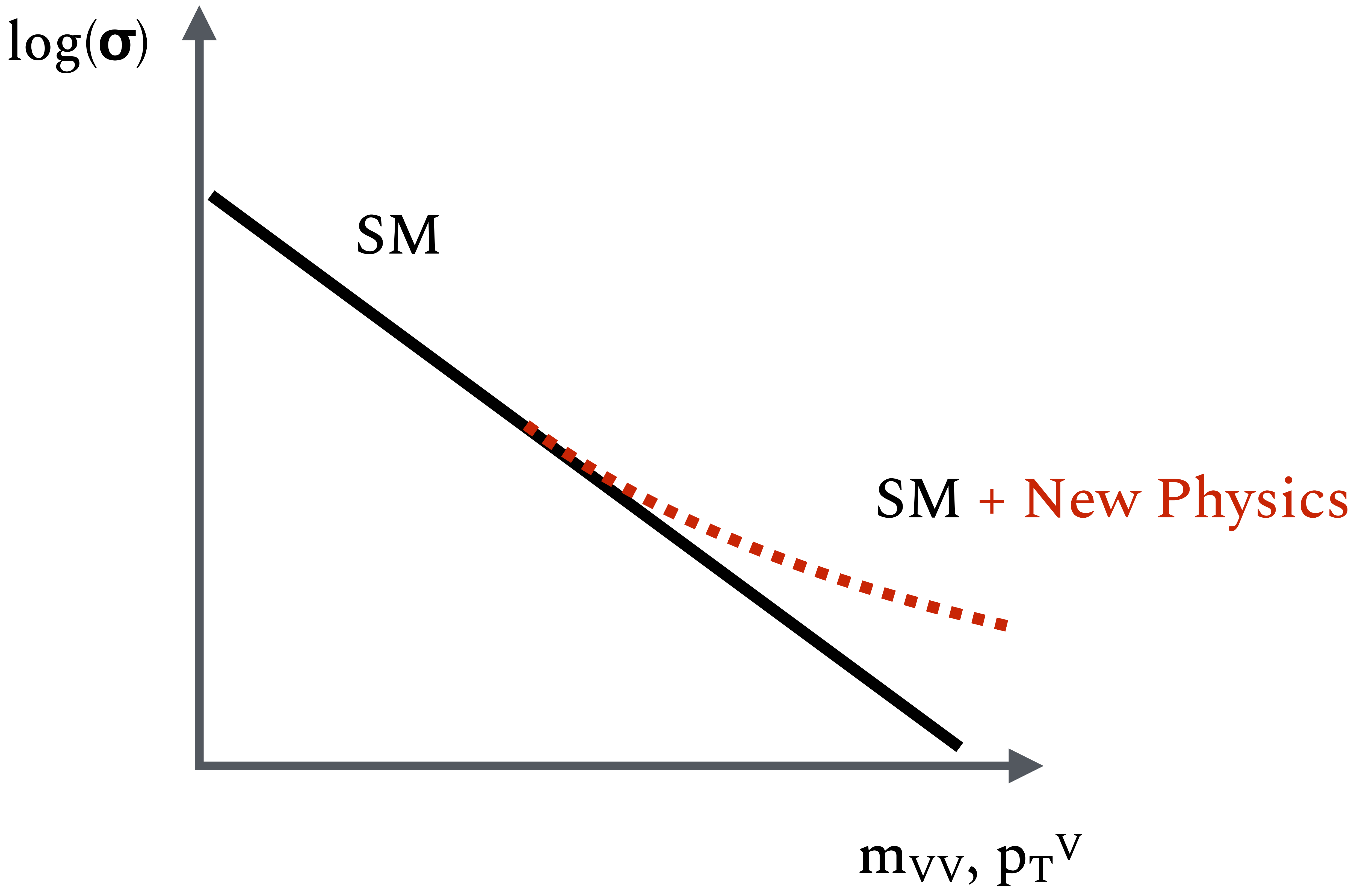
New Physics here?

Can directly probe the triboson coupling

- Anomalous Triple Gauge Coupling (aTGC)



New Physics visible in diboson mass spectrum & boson p_T as enhancement at larger values:



aTGC parametrization

How to describe new physics?

Phys. Rev. D 48 (1993) 2182

Ann. Phys. 335 (2013) 21

Use EFT parametrization

→ CP-conserving dimension-6 operators, each with a coefficient

$$\delta\mathcal{L} = \frac{c_{WWW}}{\Lambda^2} \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}\right] + \frac{c_W}{\Lambda^2}\left(D_\mu\Phi\right)^\dagger W^{\mu\nu}\left(D_\nu\Phi\right) + \frac{c_B}{\Lambda^2}\left(D_\mu\Phi\right)^\dagger B^{\mu\nu}\left(D_\nu\Phi\right)$$

Λ = new physics scale

Results in terms of scale coefficients, c_i/Λ^2 → $c_i = 0$ in SM, ≠ 0 in New Physics!

aTGC parametrization

Also interpret in terms of "LEP" / "Lagrangian" parametrization:

$$\mathcal{L} = ig_{WWV}\Big(g_1^V (W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho$$
$$+ig_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V \epsilon^{\mu\nu\rho\sigma}(W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma$$
$$+\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \Big)$$

Ann. Phys. 335 (2013) 21

LEP constraint: impose SU(2) × U(1) gauge invariance + low energy approx: 5 → 3 aTGCs hep-ph/9601233

Can express deviation from SM in terms of:

$\Delta g_1^Z = g_1^Z - 1$ $\Delta\kappa_Z = \kappa_Z - 1$ λ_Z

Others related by: $\lambda_Z = \lambda_\gamma, \quad \Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$

Variety of existing semileptonic diboson measurements:

(omitting VVjj & all-leptonic final states - covered in other talks)

D0

($\ell\nu jj + \ell\nu\ell\ell$)

Phys. Lett. B 718 (2012) 451

LEP [ALEPH, DELPHI, L3, OPAL]

(various final states)

Phys. Rept. 532 (2013) 119

CMS

@ 7 TeV ($\ell\nu jj$)

Eur. Phys. J. C 73 (2013) 2283

@ 8 TeV ($\ell\nu J$)

Phys. Lett. B 772 (2017) 21

@13 TeV (2015 data, $\ell\nu J$)

CMS-PAS-SMP-16-012

@13 TeV (2016 data, $\ell\nu J$) **NEW !!!**

1907.08354 (submitted to JHEP)

ATLAS

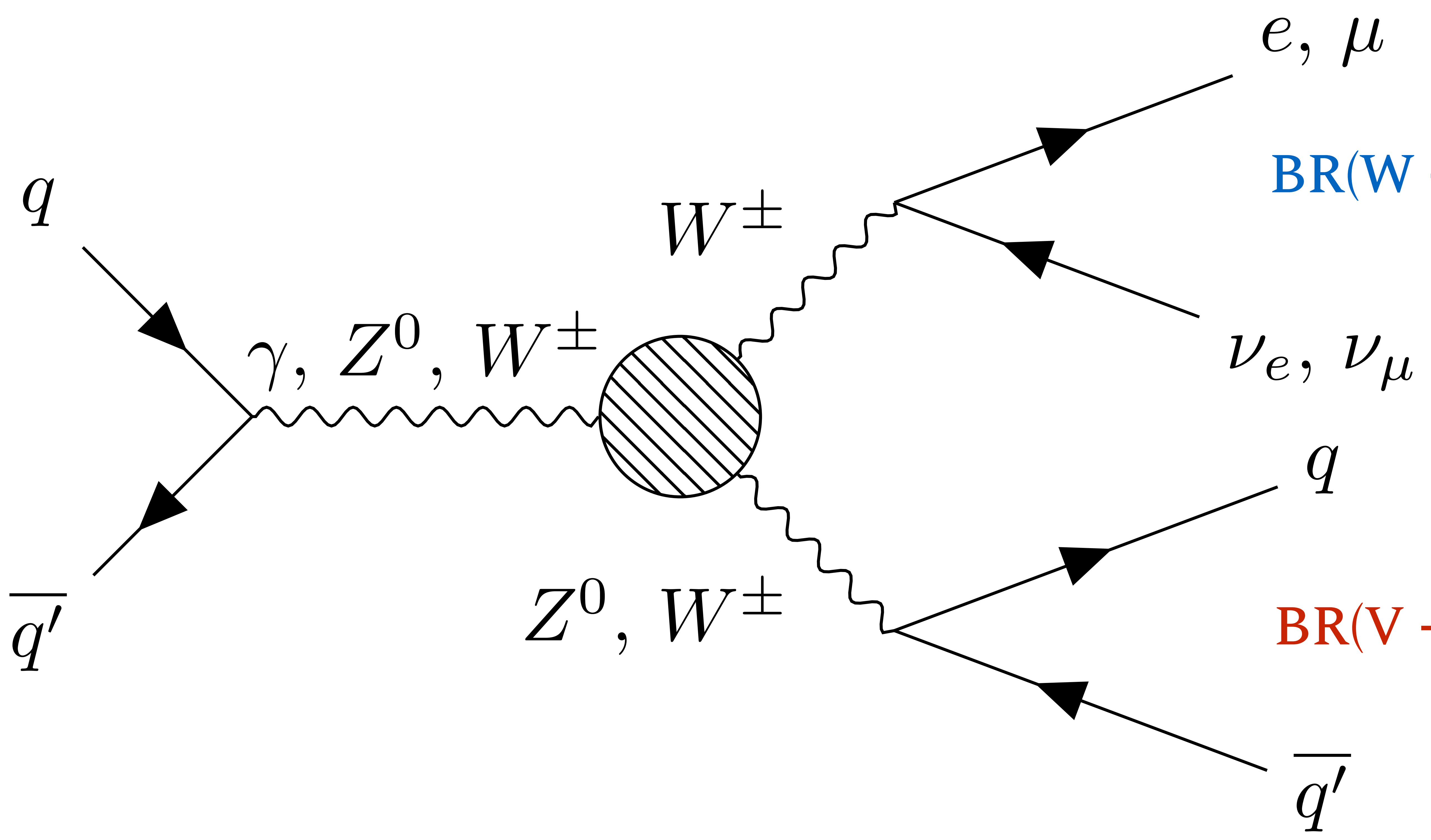
@ 7 TeV ($\ell\nu jj$)

JHEP 01 (2015) 049

@ 8 TeV ($\ell\nu jj + \ell\nu J$)

Eur. Phys. J. C 77 (2017) 563

Talk about these measurements today



BR(W → $\ell\nu$) ~ 20%

BR(V → qq) ~ 70%

V → qq significant!

But…

Leptons = nice, clean objects

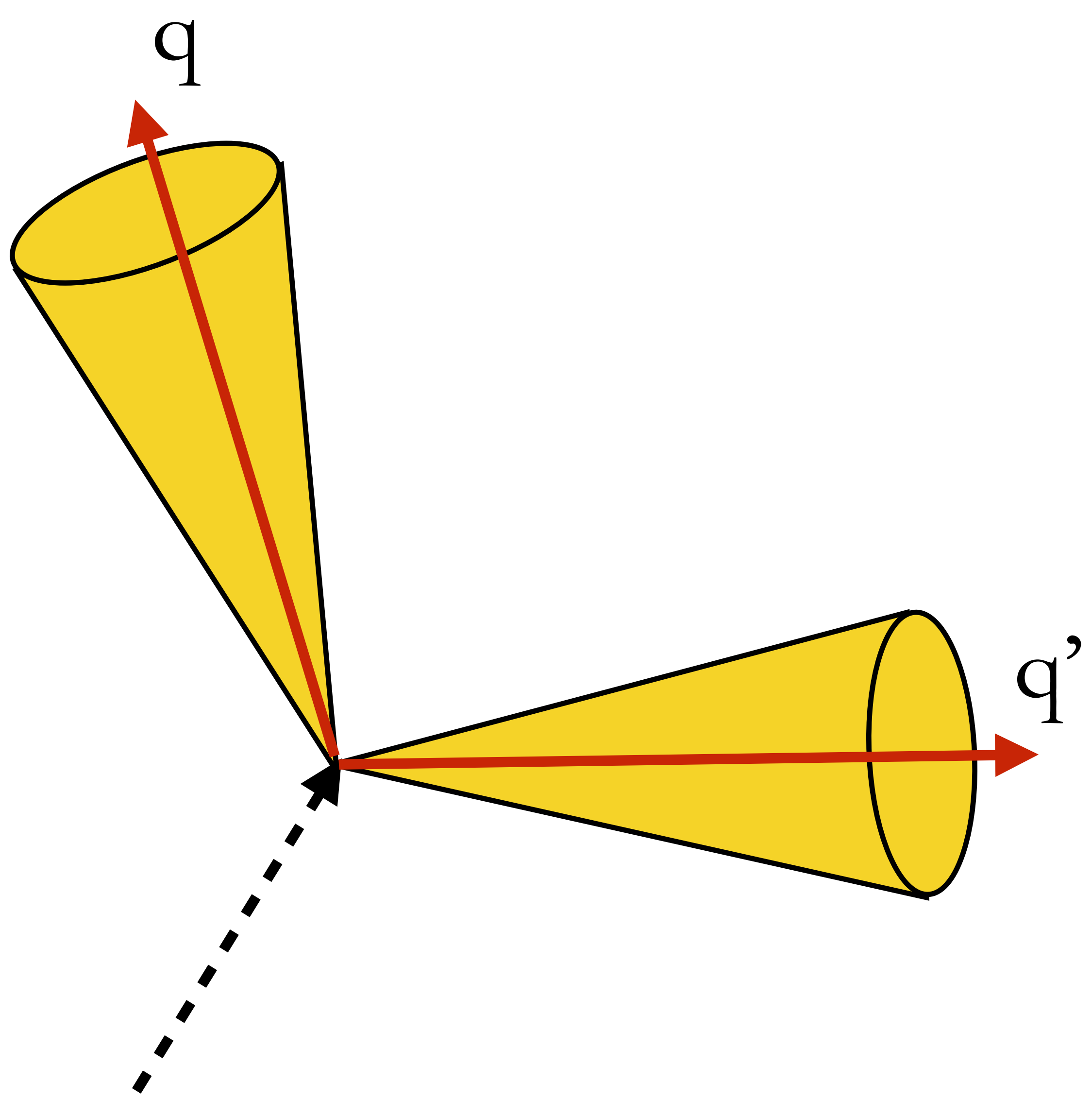
∴ Jets = tricky, messy objects?

Pileup 🤢

Single q/g initiated background jets 😱

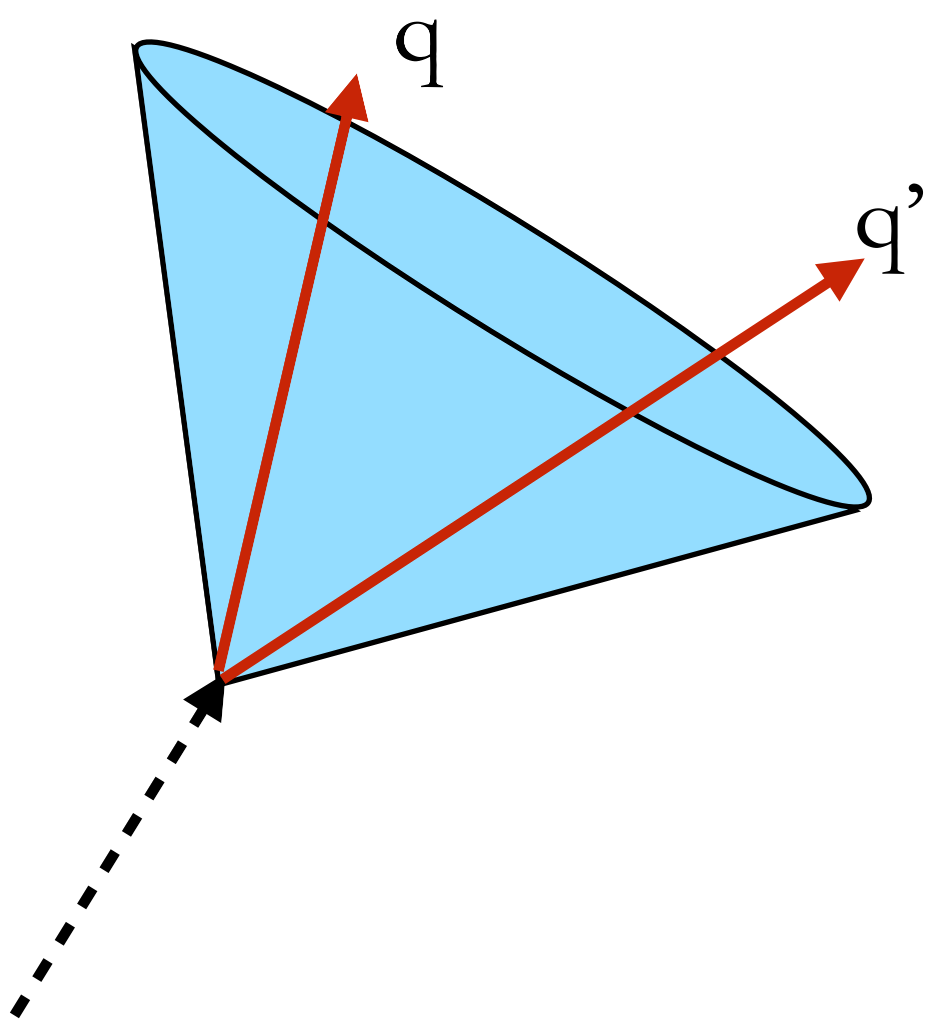
Or are they…

How to reconstruct hadronic V?



W/Z
$p_T \lesssim$ 200 GeV

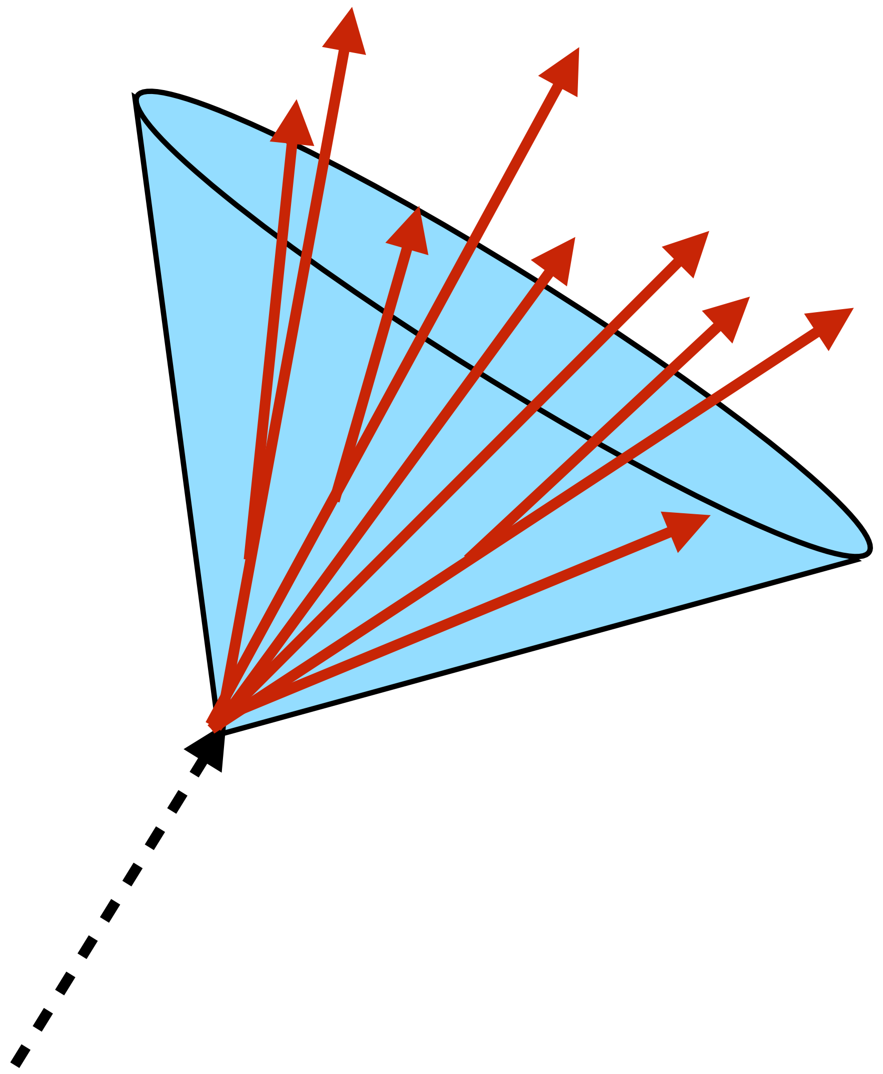
2 resolved
small-radius jets
(R = 0.4)



W/Z
$p_T \gtrsim$ 200 GeV

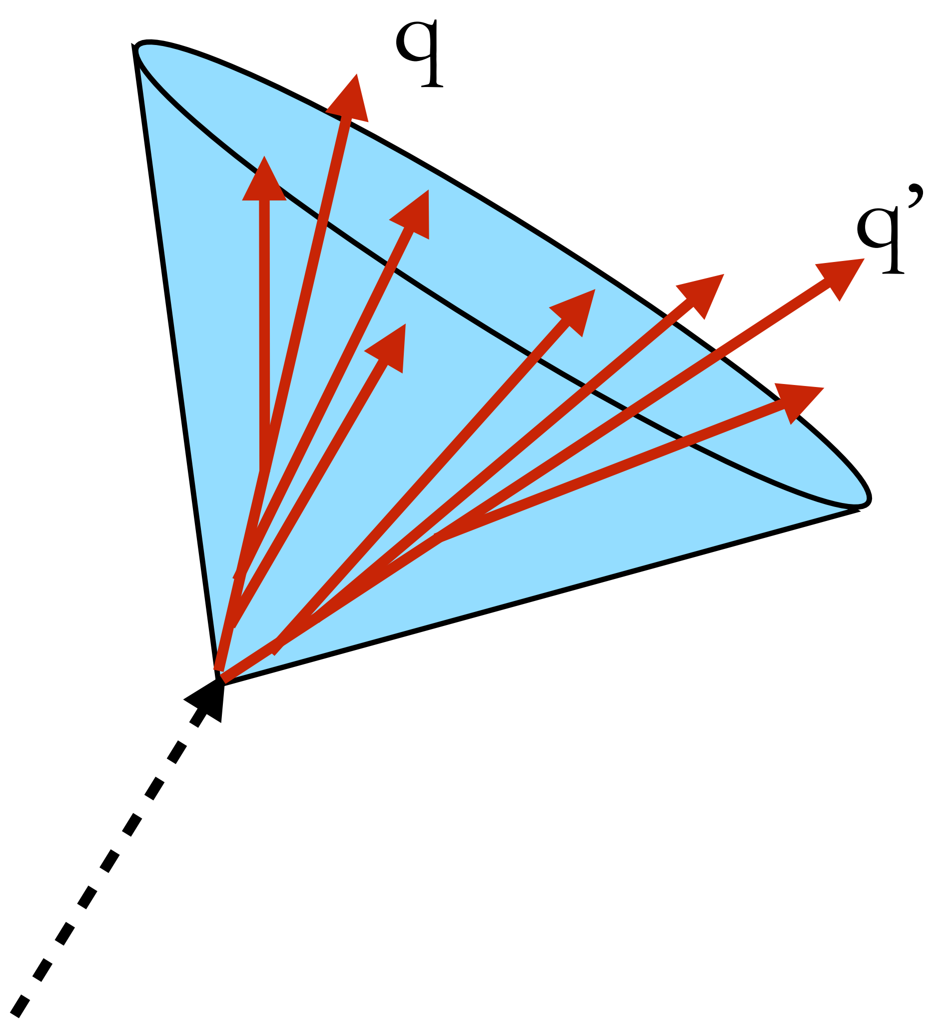
All decay products fall within 1
large-radius jet
(R = 0.8 for CMS, 1 for ATLAS)

How to distinguish QCD vs W/Z jets?



QCD
$p_T \gtrsim$ 200 GeV

→ use information from
jet constituents



W/Z
$p_T \gtrsim$ 200 GeV

All decay products fall within 1 large-radius jet
(R = 0.8 for CMS, 1 for ATLAS)

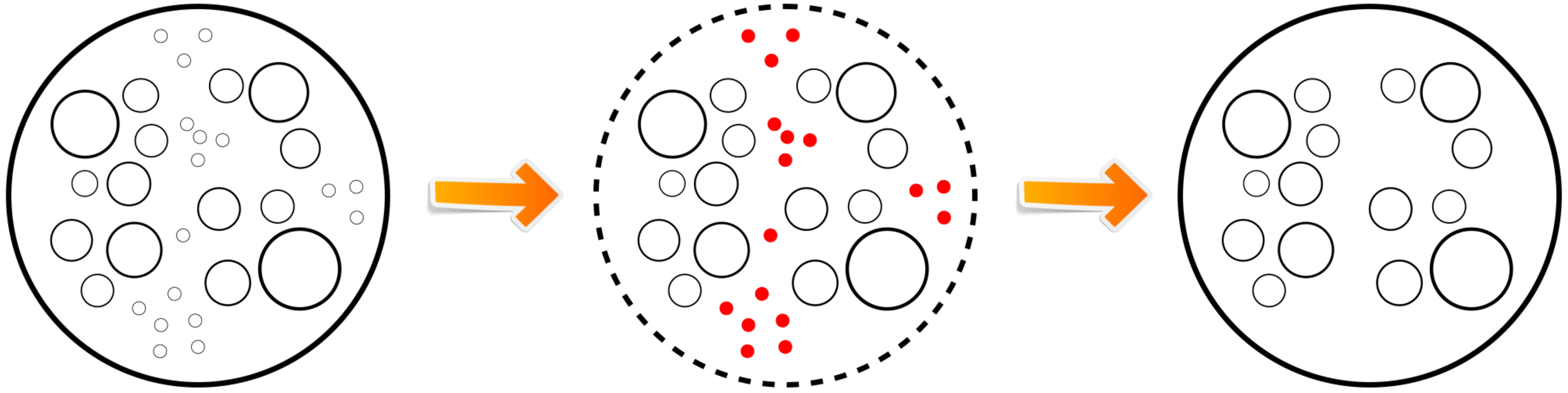
Grooming

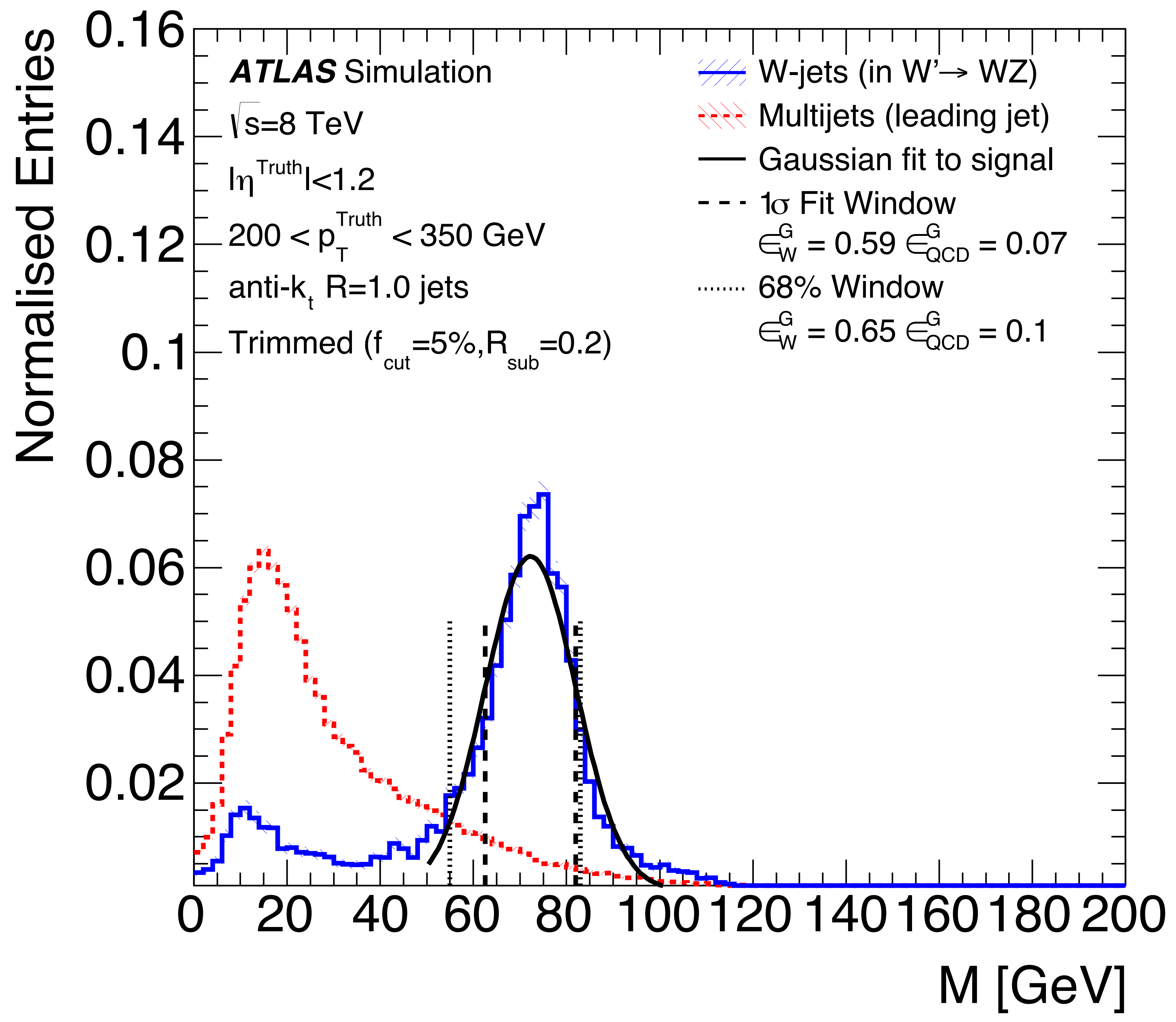
Remove soft/wide-angle radiation from jet (soft emissions, underlying event, pileup, ...)

→ would ruin jet mass resolution, etc

Compare *groomed* quantities (mass, # constituents, ...)

Variety of methods: trimming, soft drop, ...





Trimming: recluster with smaller radius (R=0.2),

drop subjets with too small p_T fraction (< 5%)

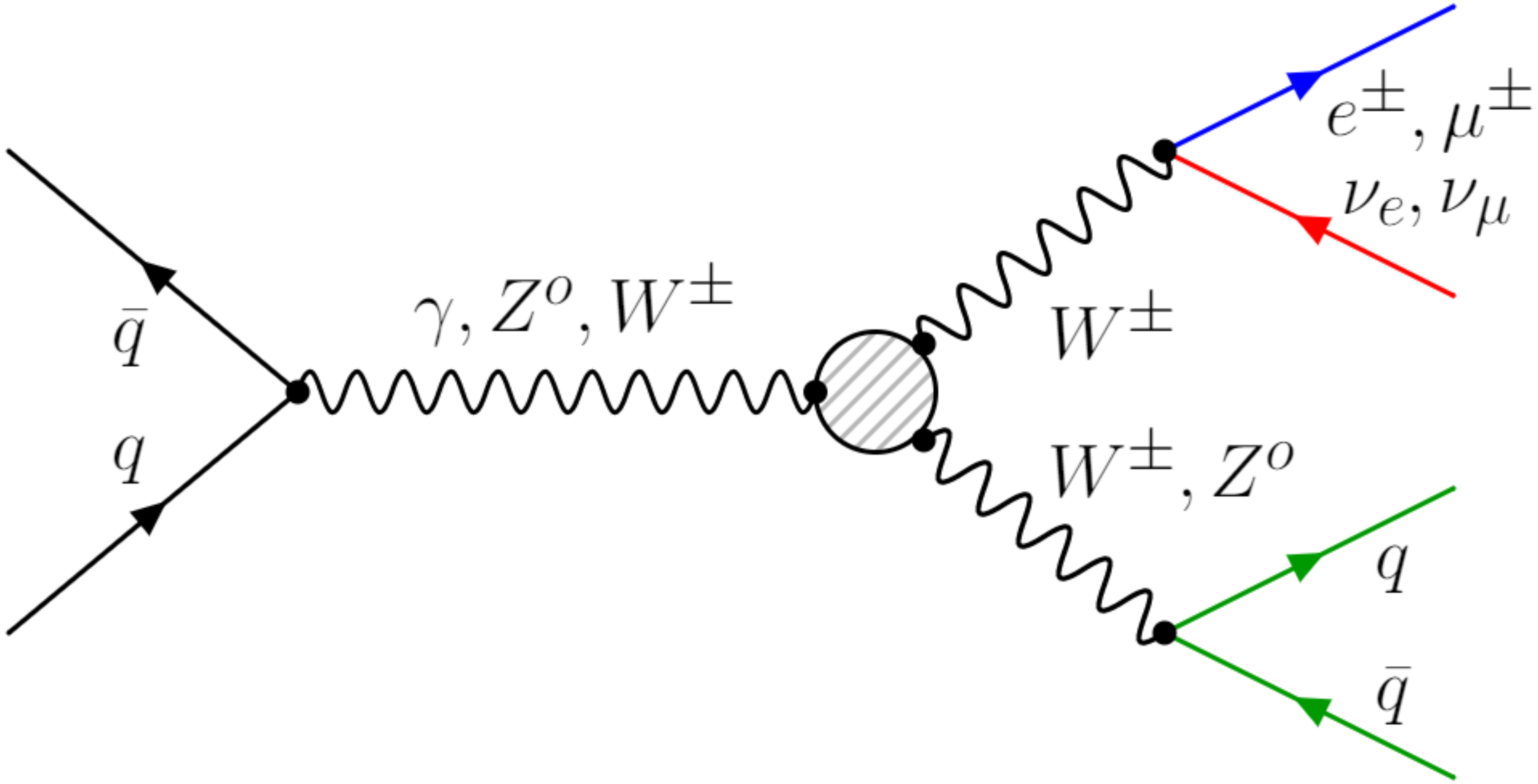
Eur. Phys. J. C 76 (2016) 154

ATLAS @ 8 TeV

ATLAS @ 8 TeV

Tackled both resolved & merged V→qq topologies

→ separate optimisations



Leptonic W reconstruction:

Exactly 1 electron or muon

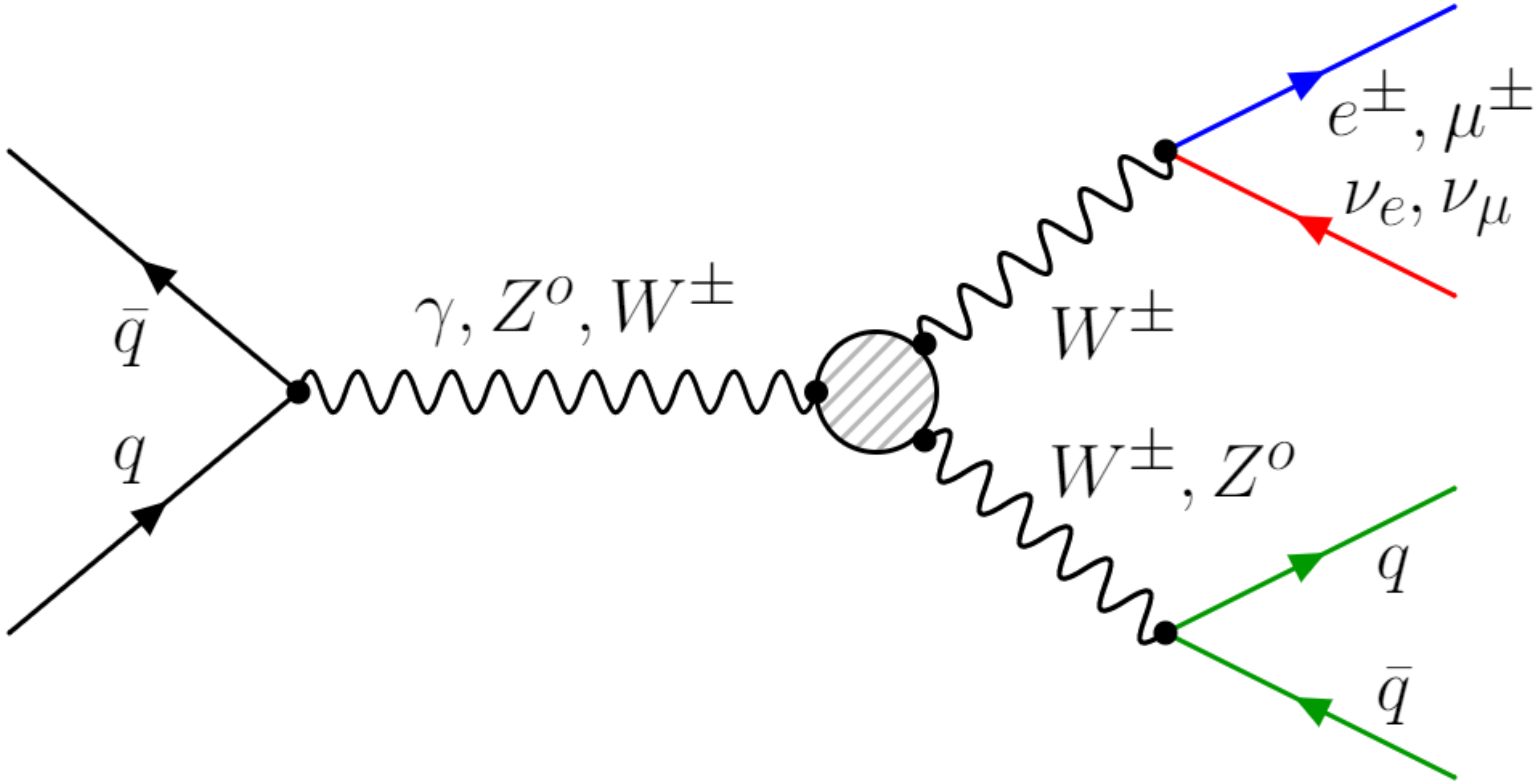
Missing transverse momentum

W_{lep} p_T > 100 GeV (jj only)

m_T > 40 GeV (jj only)

Data selected by electron or muon triggers

$\int L = 20.2\ fb^{-1}$



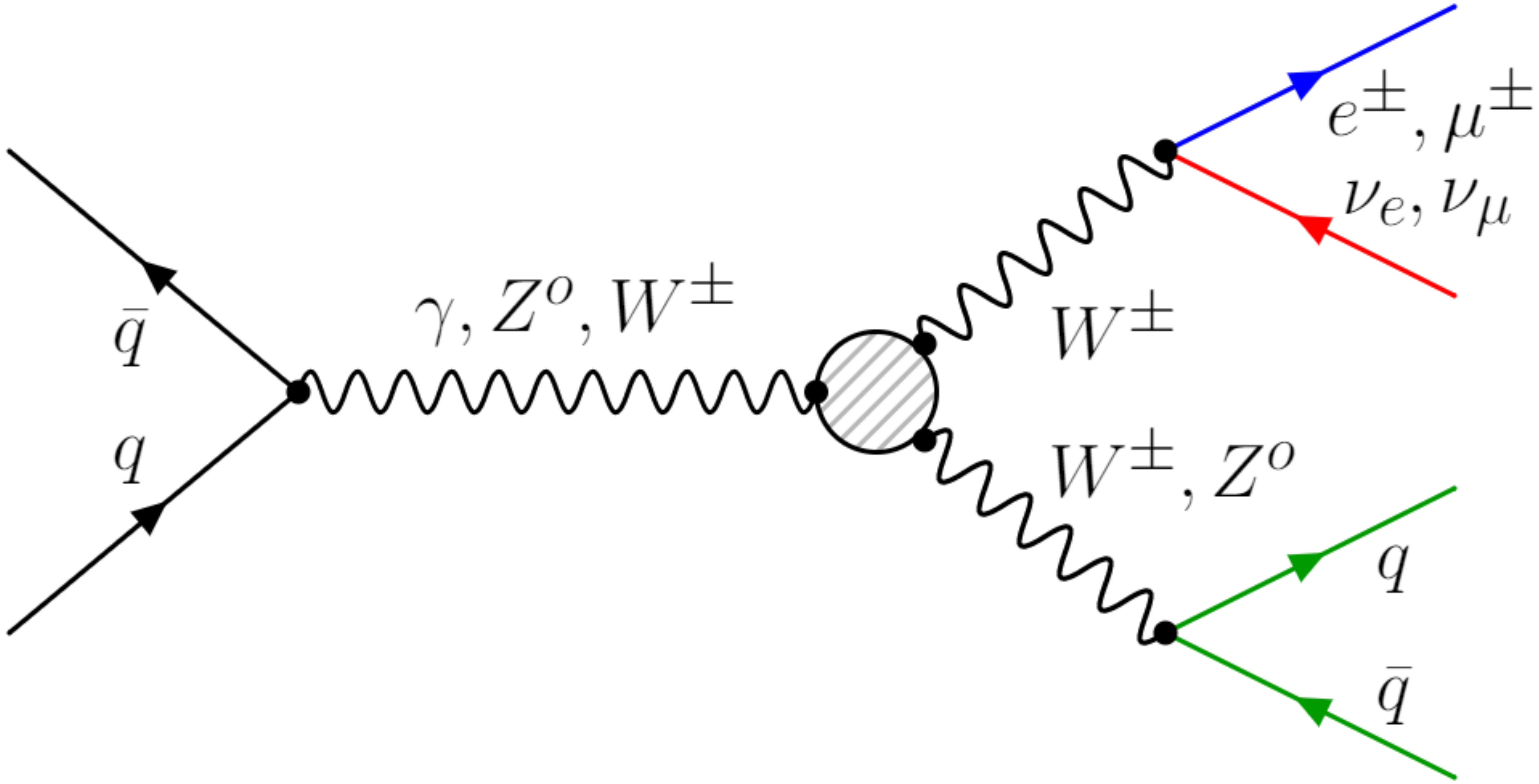
Hadronic V reconstruction:

2 small radius jets (jj) | 1 larger radius jet (J)

$\Delta\eta$(j,j) < 1.5 (jj)

p_T(jj) > 100 GeV | p_T(J) > 200 GeV

m_{jj} / trimmed mass $m_J \in$ [65, 95] GeV



Total WV reconstruction:

$\Delta\phi$(jet 1, p_T^{miss}) > 0.8 (jj)

ΔR(jet, lepton) > 0.4 (jj)

ΔR(jet, lepton) > 1 (J)

ATLAS @ 8 TeV

Major backgrounds

W + jets *(dominant background)*

$t\bar{t}$ *(has real W→ qq)*

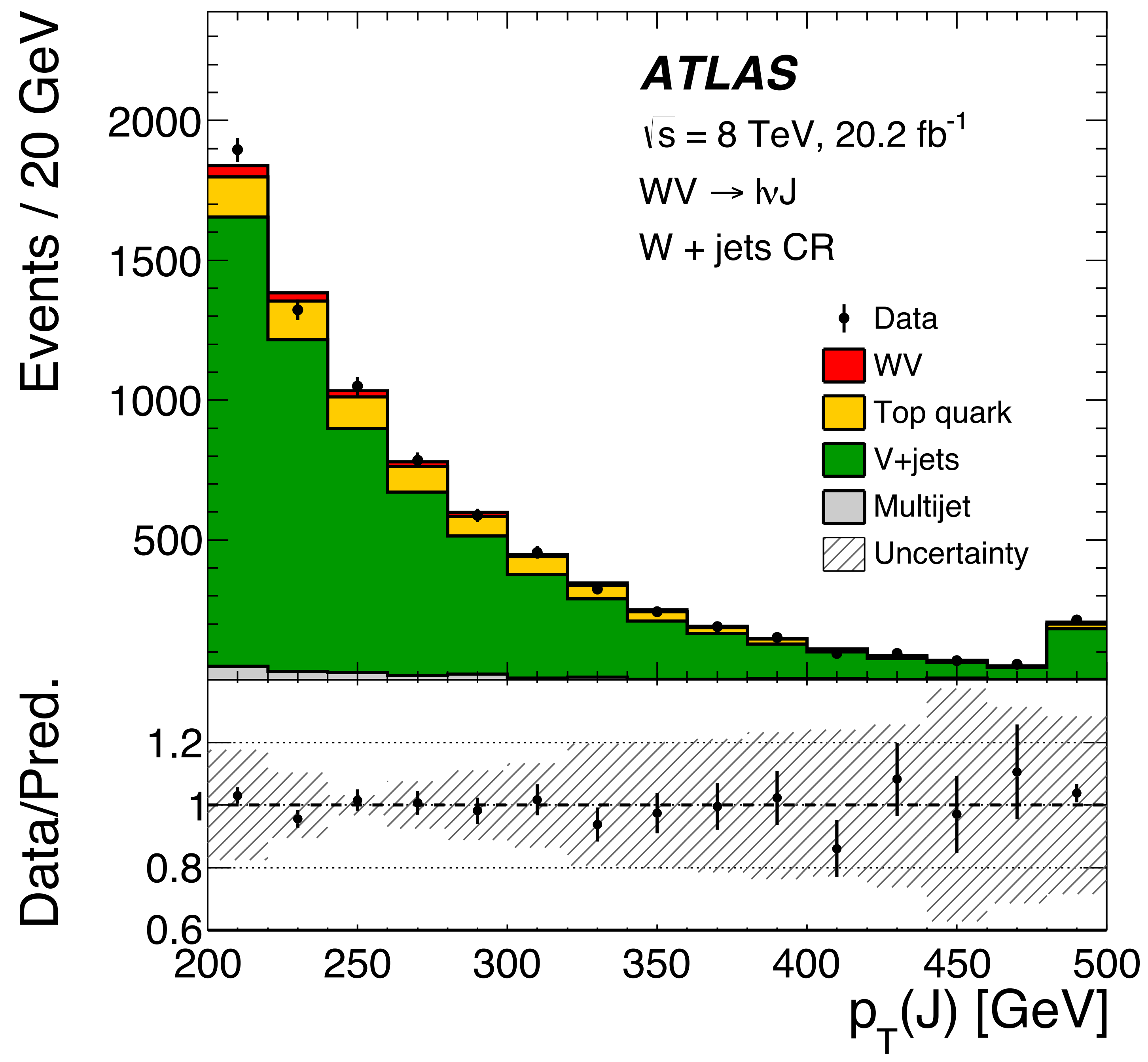
Minor backgrounds

Z + jets

QCD multijet *(mainly for electron channel)*

Single top quark

ZZ



→ Estimate from MC+data, use in binned Maximum-Likelihood fit of $p_T(jj)$ | $p_T(J)$

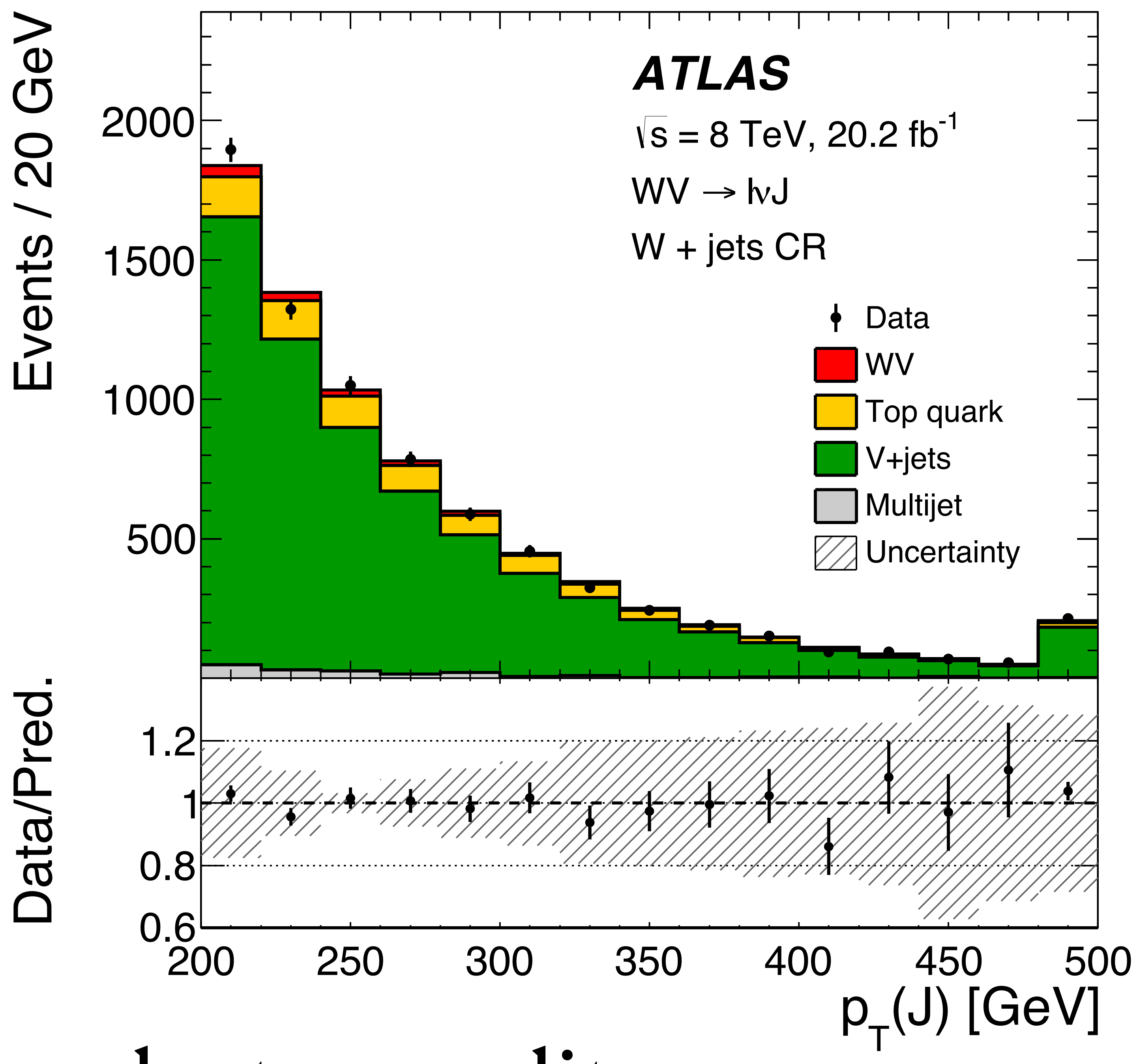
ATLAS @ 8 TeV: Backgrounds

V+jets:

MC, + data-driven corrections: use control region = signal region, but failing m_{jj} | m_J cut

$\ell\nu jj$: improve jet kinematics shapes: ~ 10% effect

$\ell\nu J$: determine overall normalisation factor (0.84)



Top-quark:

MC, compared to data using b-tagged jets.

Overall normalisation factor in $\ell\nu J$ channel (0.87)

Multijet:

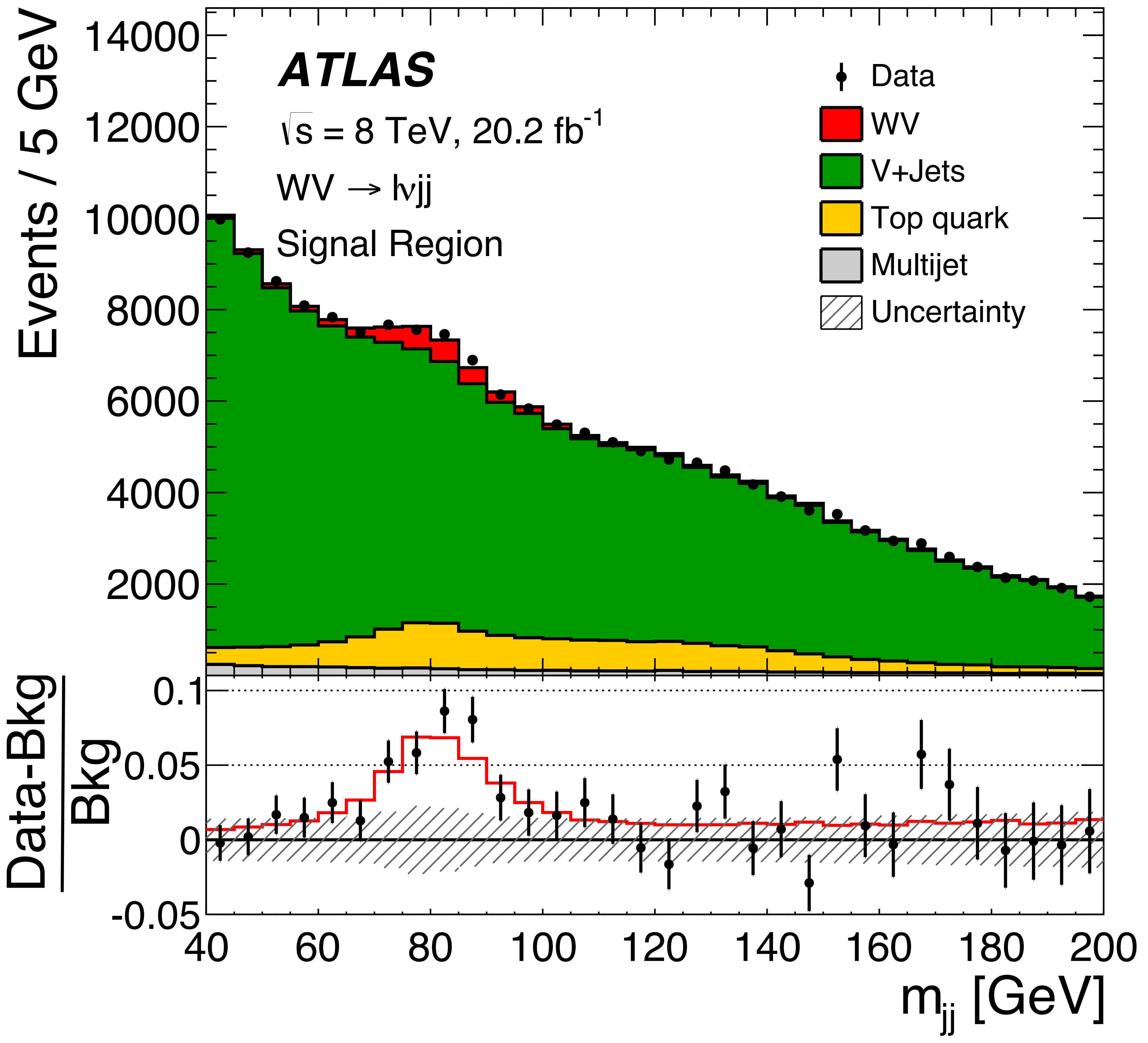
Kinematic shapes from data: use control region = signal region, but poorer lepton quality (→ more non-prompt & fake leptons)

Yield extrapolated from fit to p_T^{miss} in QCD enhanced-region

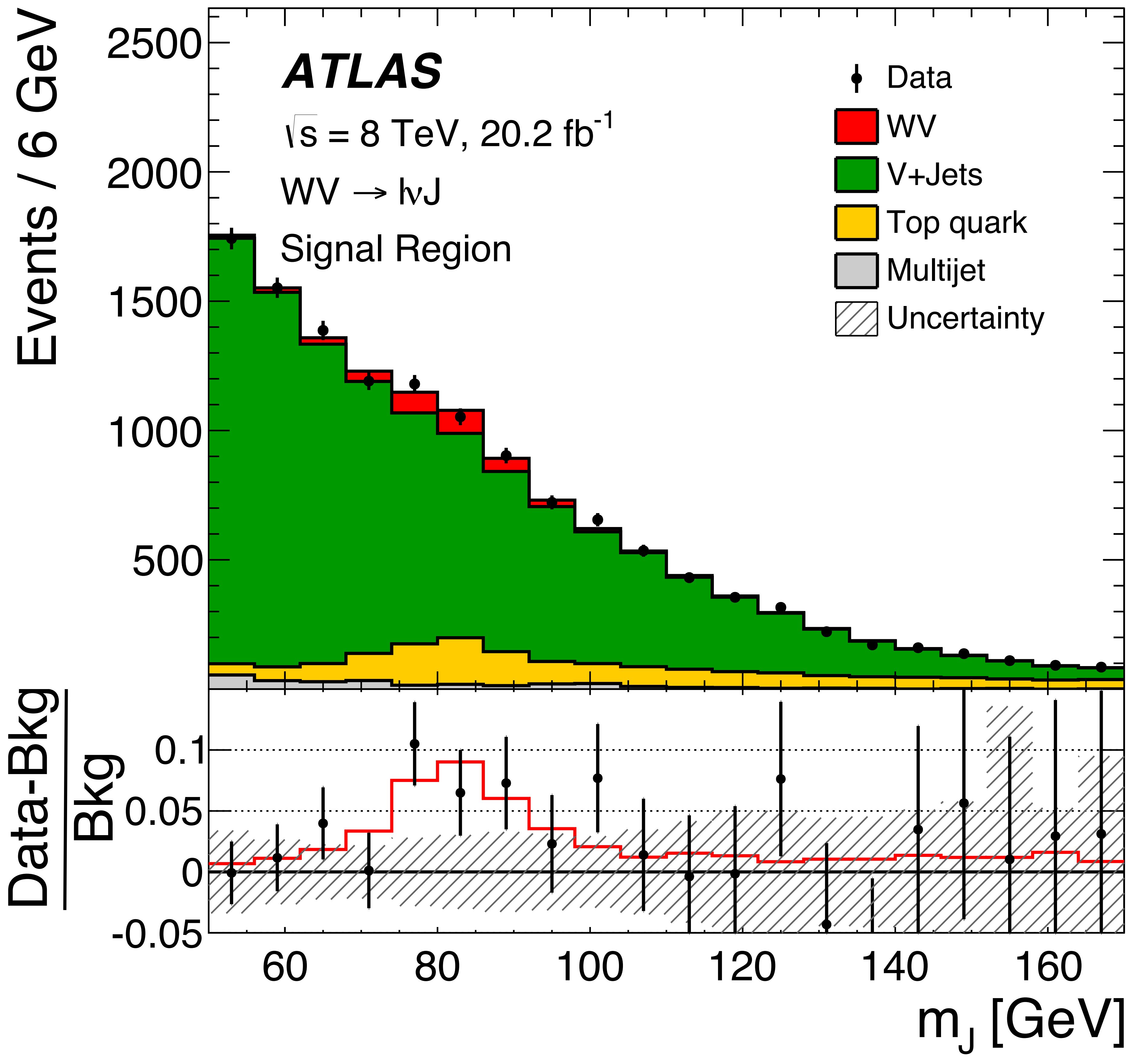
ATLAS @ 8 TeV

Reconstructed hadronic boson mass

Resolved jets (jj)



Merged jet (J)

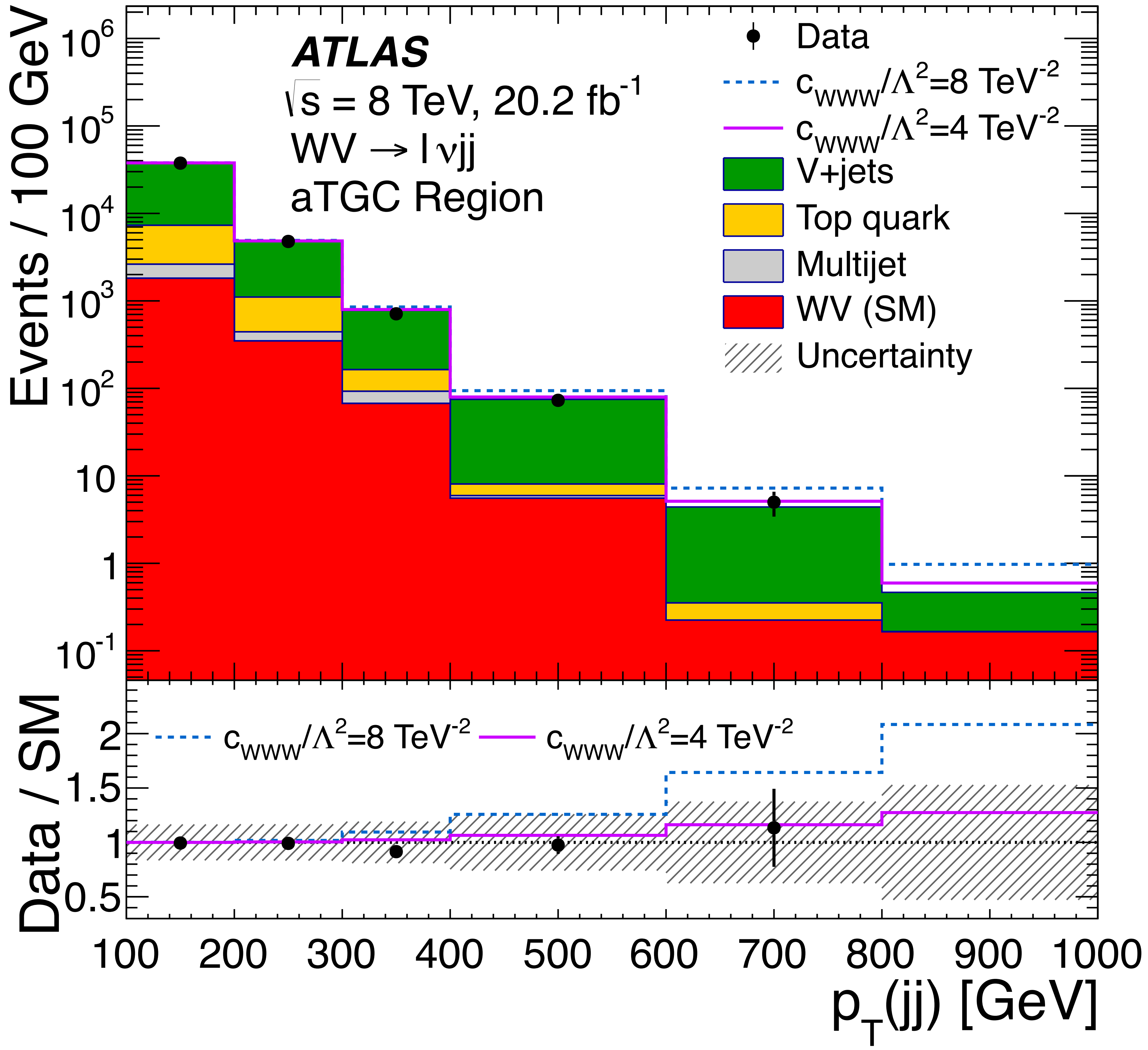


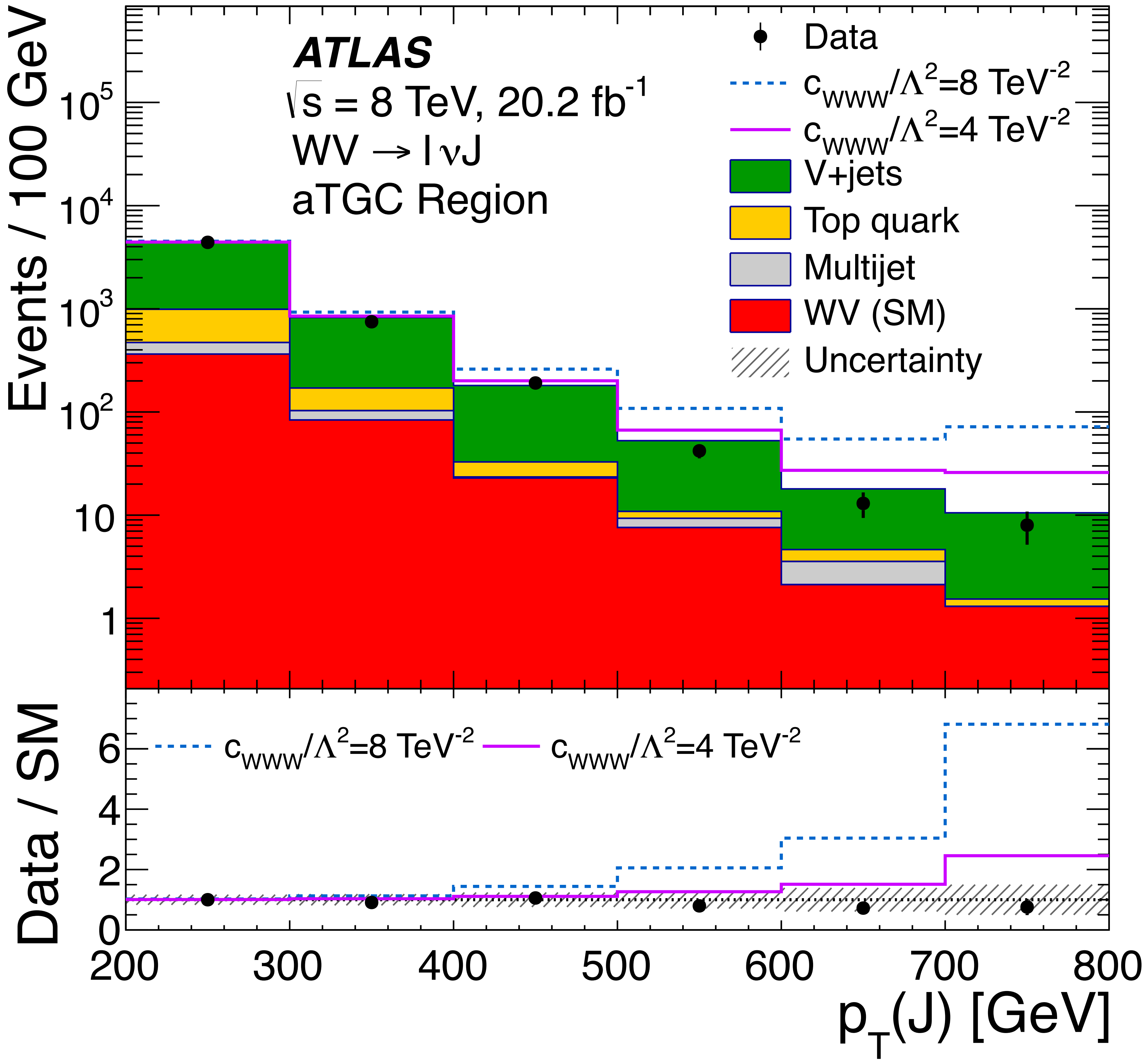
ATLAS @ 8 TeV

$\ell\nu jj$: Simultaneous fit to signal region + “sideband” region ($m_{jj} \in [40, 65]$ or $[95, 200]$ GeV)

$\ell\nu J$: Fit to signal region only

Largest systematic uncertainties from jet-related sources





ATLAS @ 8 TeV: 1D Limits

Derived 1D limits on aTGCs: separate limits for $\ell\nu$jj and $\ell\nu$J, assume all other aTGCs = 0

Parameter	Observed [TeV^{-2}]	Expected [TeV^{-2}]	Observed [TeV^{-2}]	Expected [TeV^{-2}]
	$WV \to \ell\nu$jj		$WV \to \ell\nu$J	
c_{WWW}/Λ^2	$[-5.3, 5.3]$	$[-6.4, 6.3]$	$[-3.1, 3.1]$	$[-3.6, 3.6]$
c_B/Λ^2	$[-36, 43]$	$[-45, 51]$	$[-19, 20]$	$[-22, 23]$
c_W/Λ^2	$[-6.4, 11]$	$[-8.7, 13]$	$[-5.1, 5.8]$	$[-6.0, 6.7]$

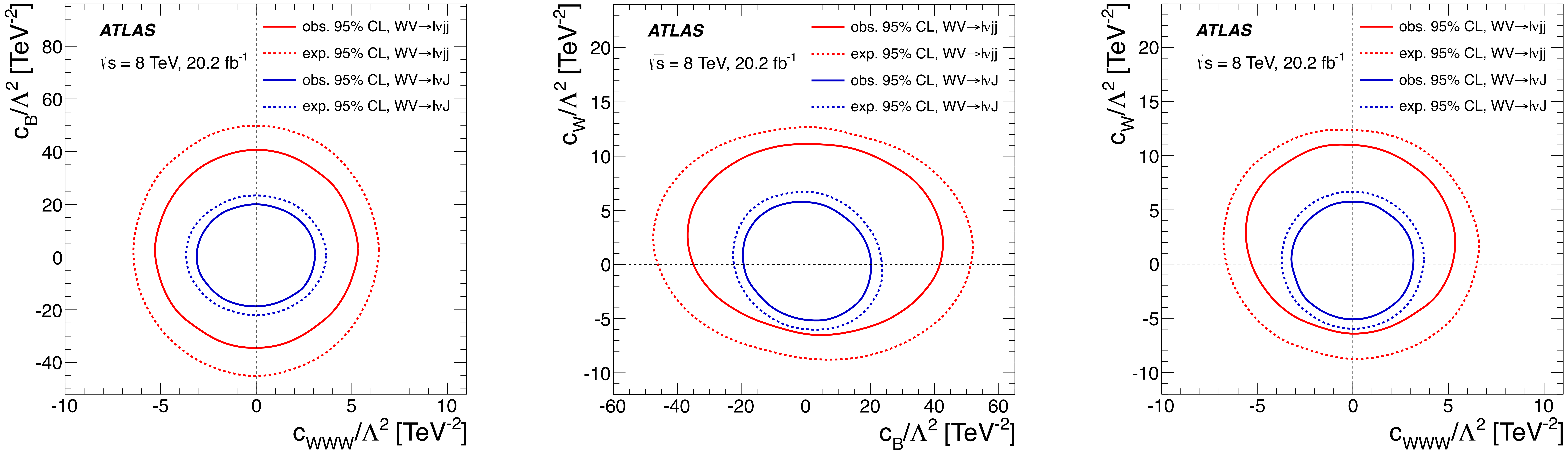
Parameter	Observed	Expected	Observed	Expected
	$WV \to \ell\nu$jj		$WV \to \ell\nu$J	
Δg_1^Z	$[-0.027, 0.045]$	$[-0.036, 0.051]$	$[-0.021, 0.024]$	$[-0.024, 0.027]$
$\Delta\kappa_\gamma$	$[-0.11, 0.13]$	$[-0.15, 0.16]$	$[-0.061, 0.064]$	$[-0.071, 0.075]$
$\lambda_Z = \lambda_\gamma$	$[-0.022, 0.022]$	$[-0.027, 0.026]$	$[-0.013, 0.013]$	$[-0.015, 0.015]$

Limits from $\ell\nu$J significantly stronger than those from $\ell\nu$jj

Also calculated limits varying cutoff scale - affects $\ell\nu$J more as probes larger m_{WV}

ATLAS @ 8 TeV: 2D Limits

Confidence regions for pairs of aTGCs: other aTGC = 0



CMS @ 13 TeV (2016 data)

Run II

Larger √s → opens up larger m_{WV} / p_T^V phase space

But larger instantaneous luminosity → larger pileup

New data, new tools:

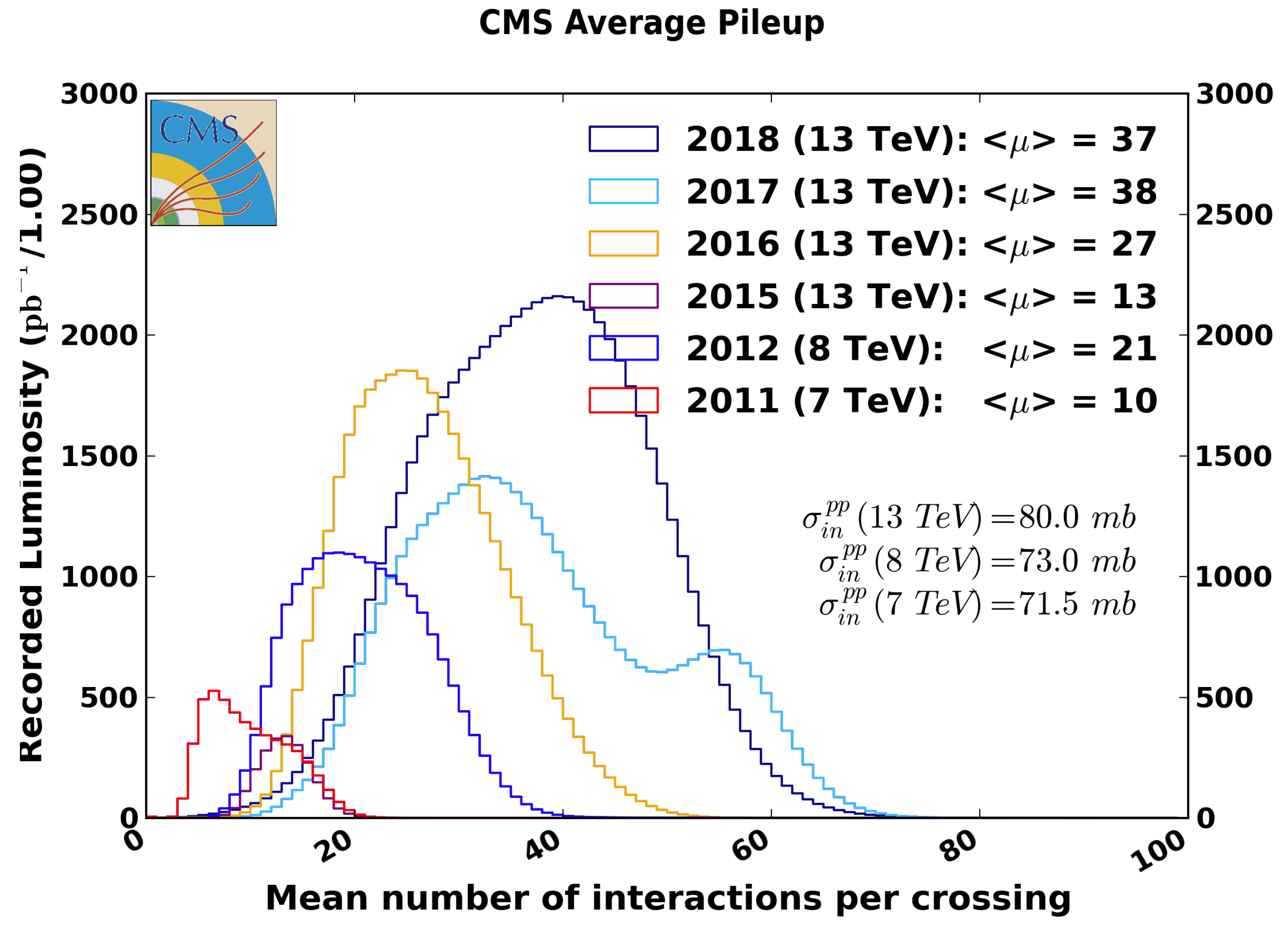
- better pileup rejection (PUPPI)

- better V jet vs QCD jet discrimination tools (Soft-drop, N-subjettiness)

Pileup

= other pp collisions happening simultaneously = extra particles you don't want!

CMS Luminosity Results

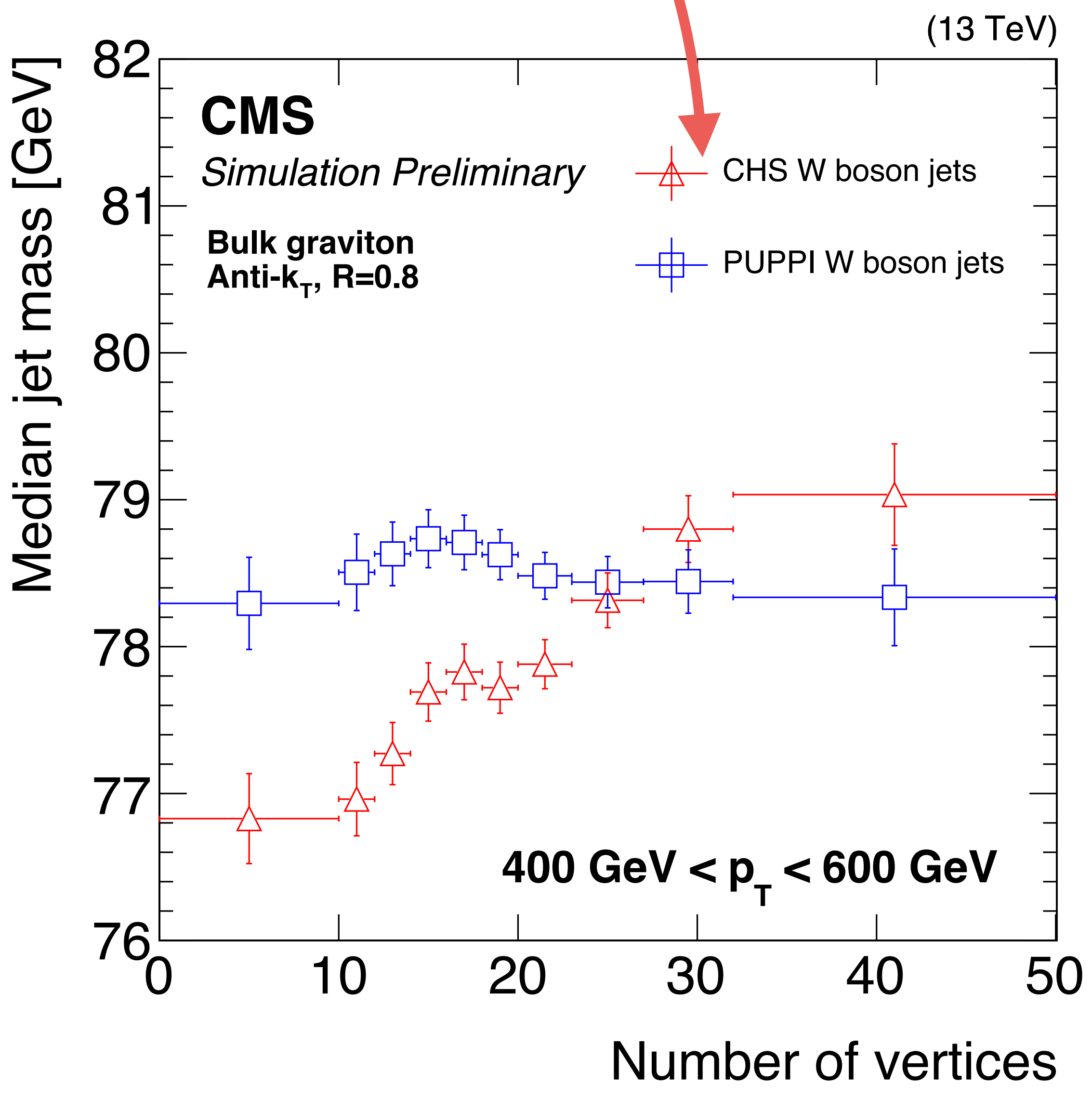


How to remove?

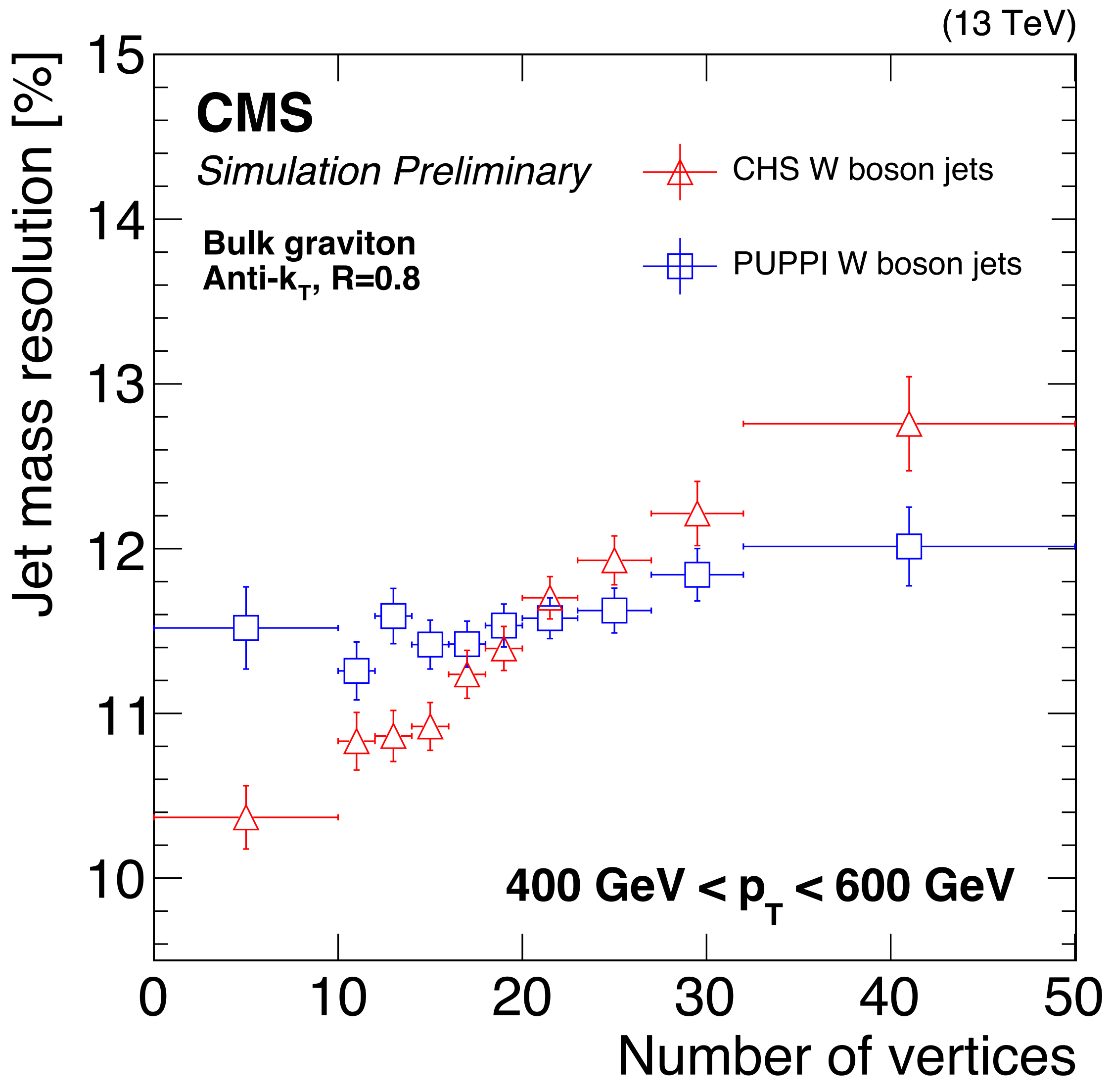
- Charged particles easy - use tracker to identify collision vertex
- Neutrals not as easy

Pileup Per Particle ID (PUPPI):

weight each particle based on probability from leading vertex



~ flat behaviour vs # vertices!



CMS-PAS-JME-18-001

JHEP 1410 (2014) 059

Grooming

Soft drop

Reclaster jet constituents with Cambridge-Aachen, then:

Break jet j into 2 subjets

If 2 subjets satisfy condition then j is final soft drop jet

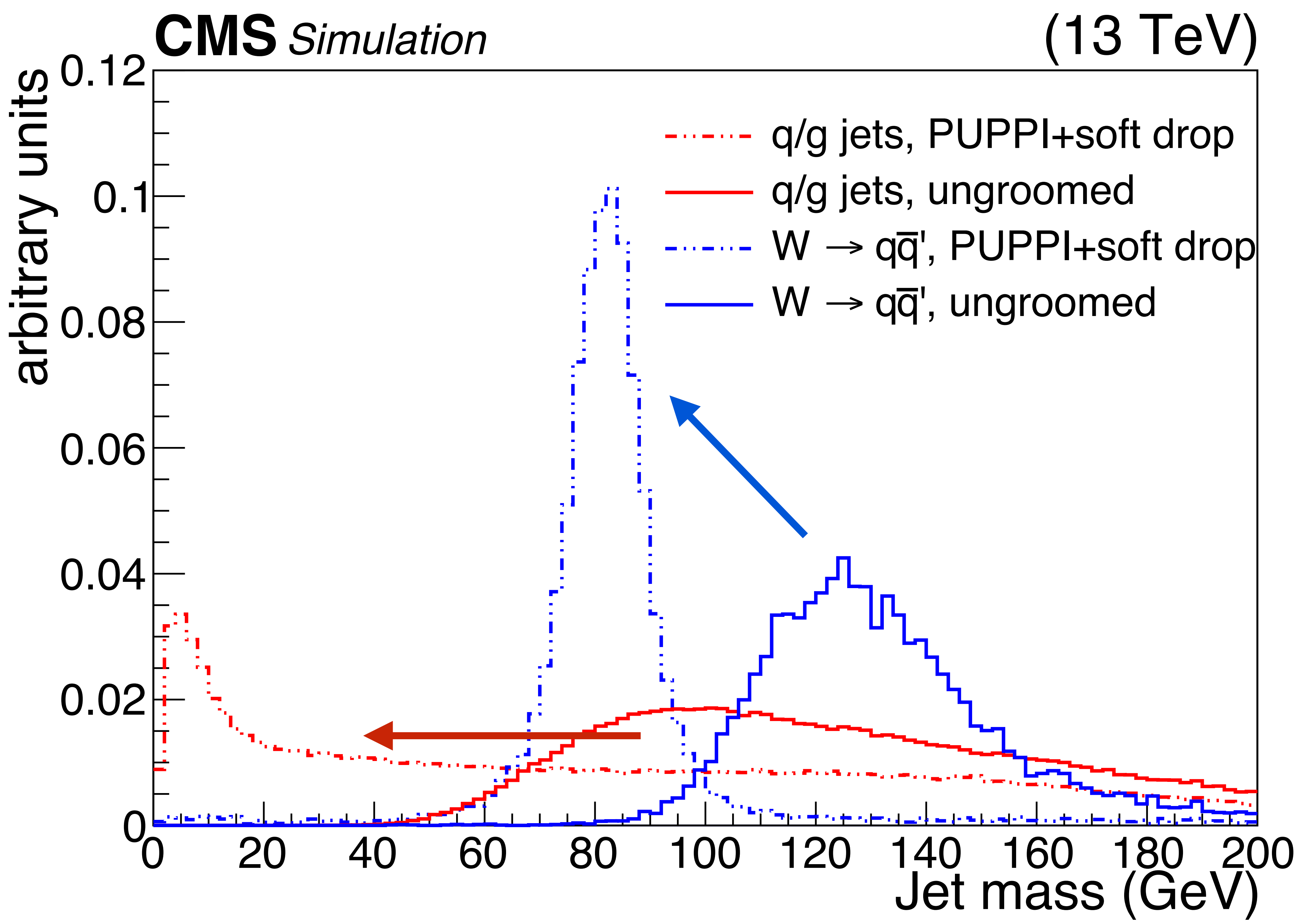
Otherwise j = subjet with larger p_T, repeat

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

CMS typically uses $\boldsymbol{\beta} = 0$, $z_{\mathrm{cut}} = 0.1$

Especially useful for **jet mass m_{SD}**: $m_{QCD} \rightarrow 0$,

whilst other objects peak at their mass m_X



Phys. Rev. D 97, 072006 (2018)

N-subjettiness

JHEP 1103 (2011) 015

τ_N: how "likely" is jet composed of N subjets?

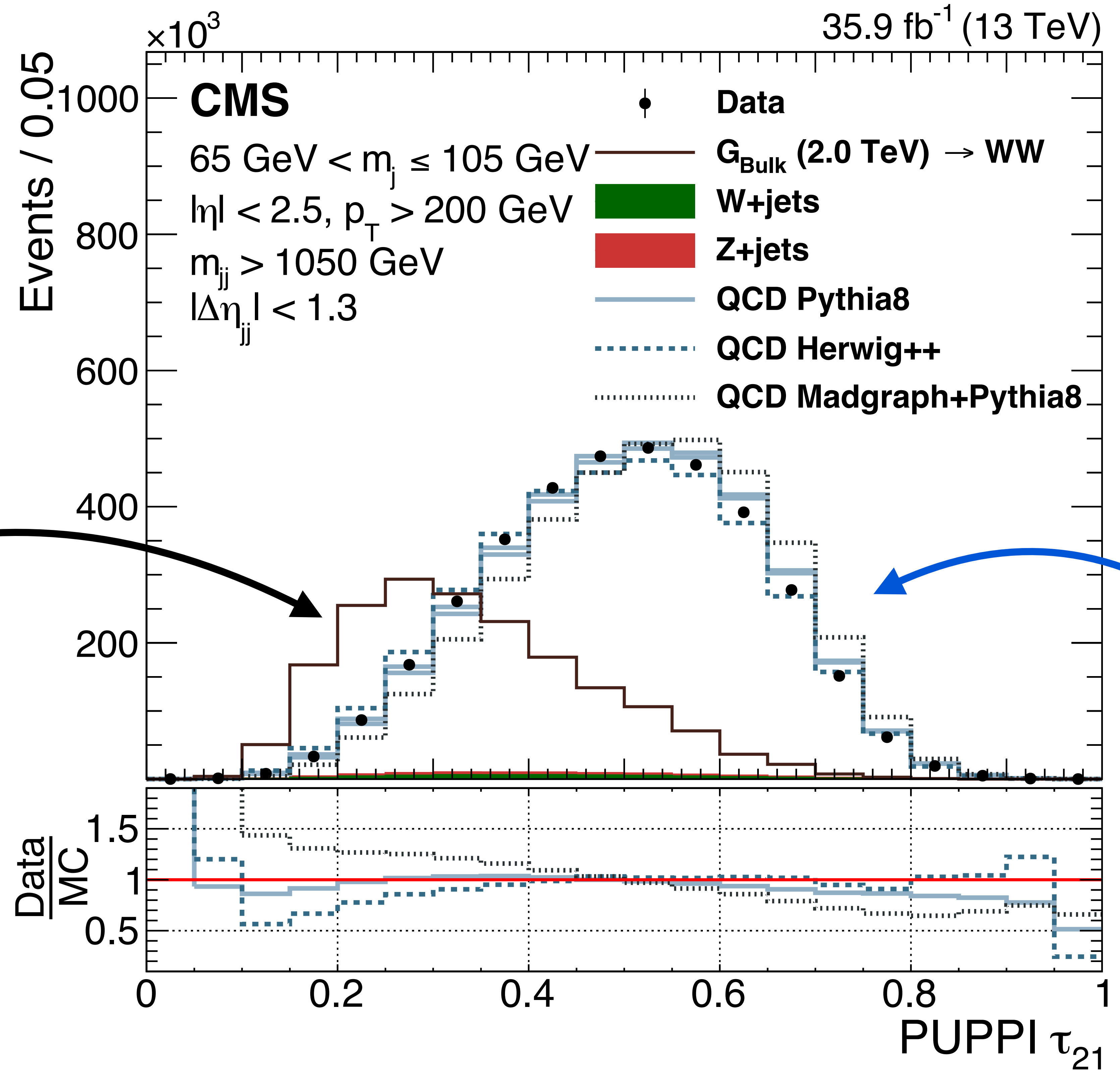
$\tau_N \to 0$ as radiation becomes aligned with N subjets

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}.$$

$$d_0 = \sum_k p_{T,k} R_0,$$

More powerful: $\tau_{21} = \tau_2 / \tau_1$

Boosted W jets: smaller τ_{21}



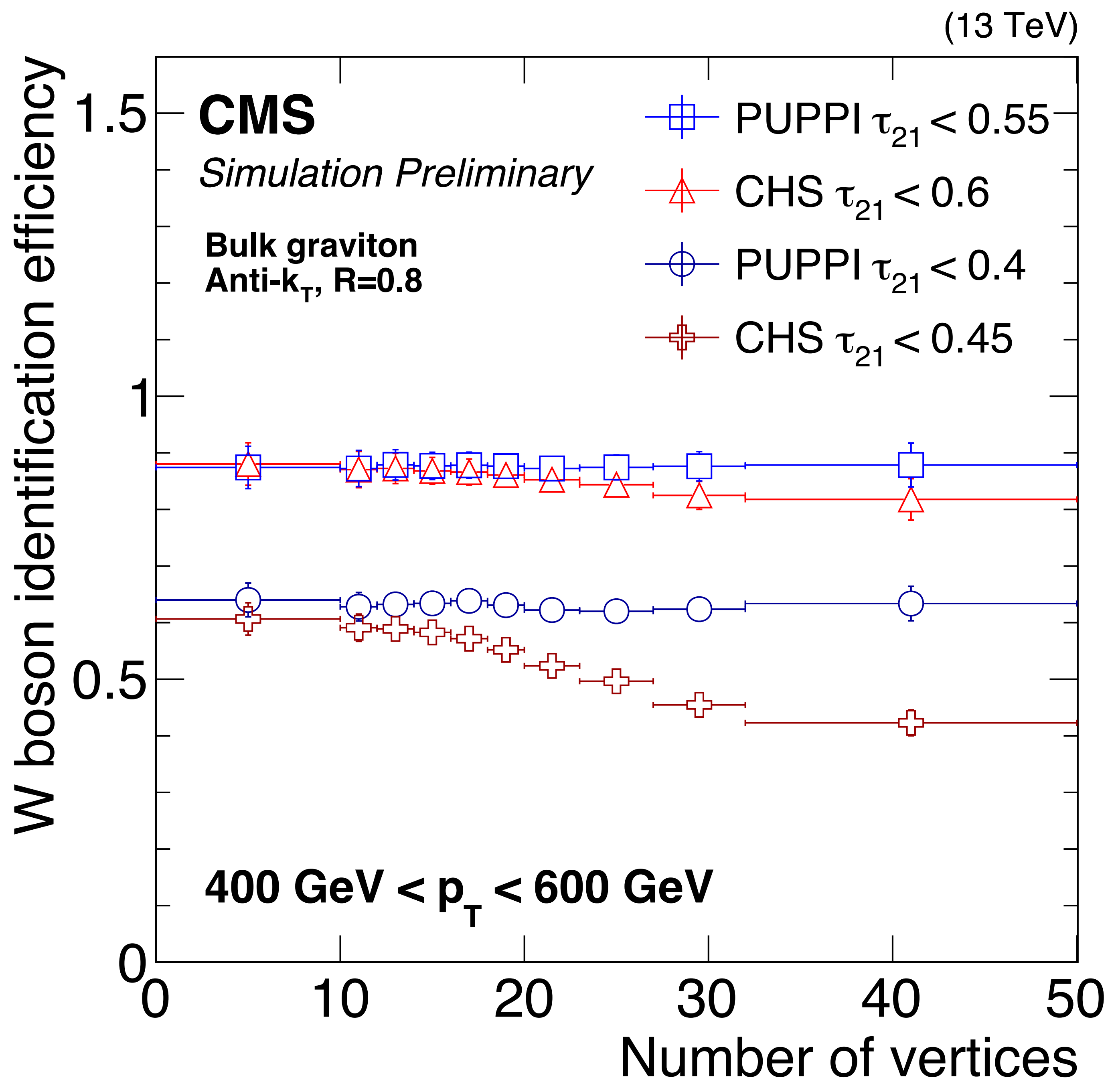
QCD jets: larger τ_{21}

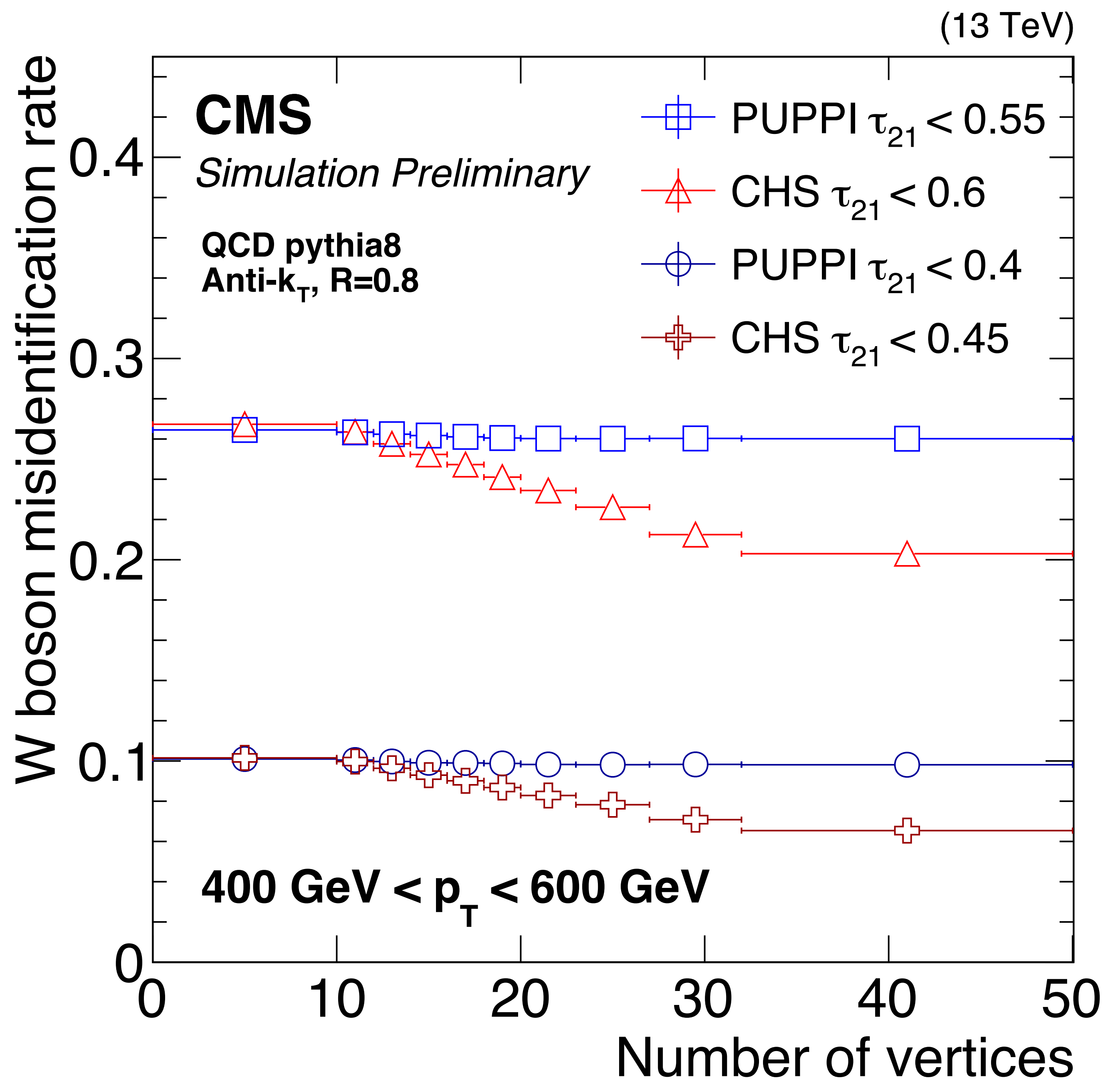
Phys. Rev. D 97, 072006 (2018)

PUPPI + Soft-drop + N-subjettiness

=

Powerful discrimination between W/Z jets & QCD jets in a pileup environment

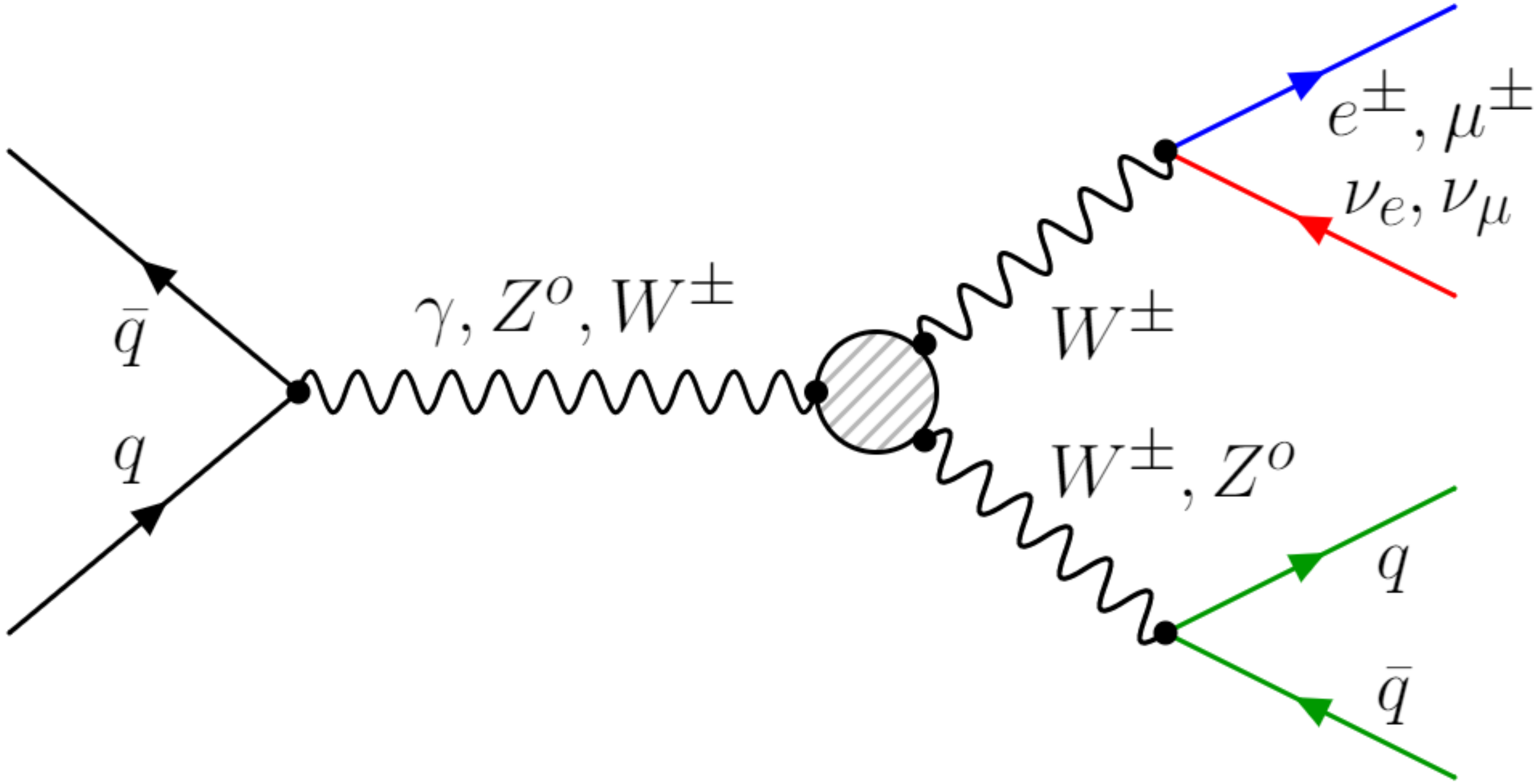




CMS-PAS-JME-18-001

CMS @ 13 TeV

Only consider **merged** V→qq topology



Leptonic W reconstruction:

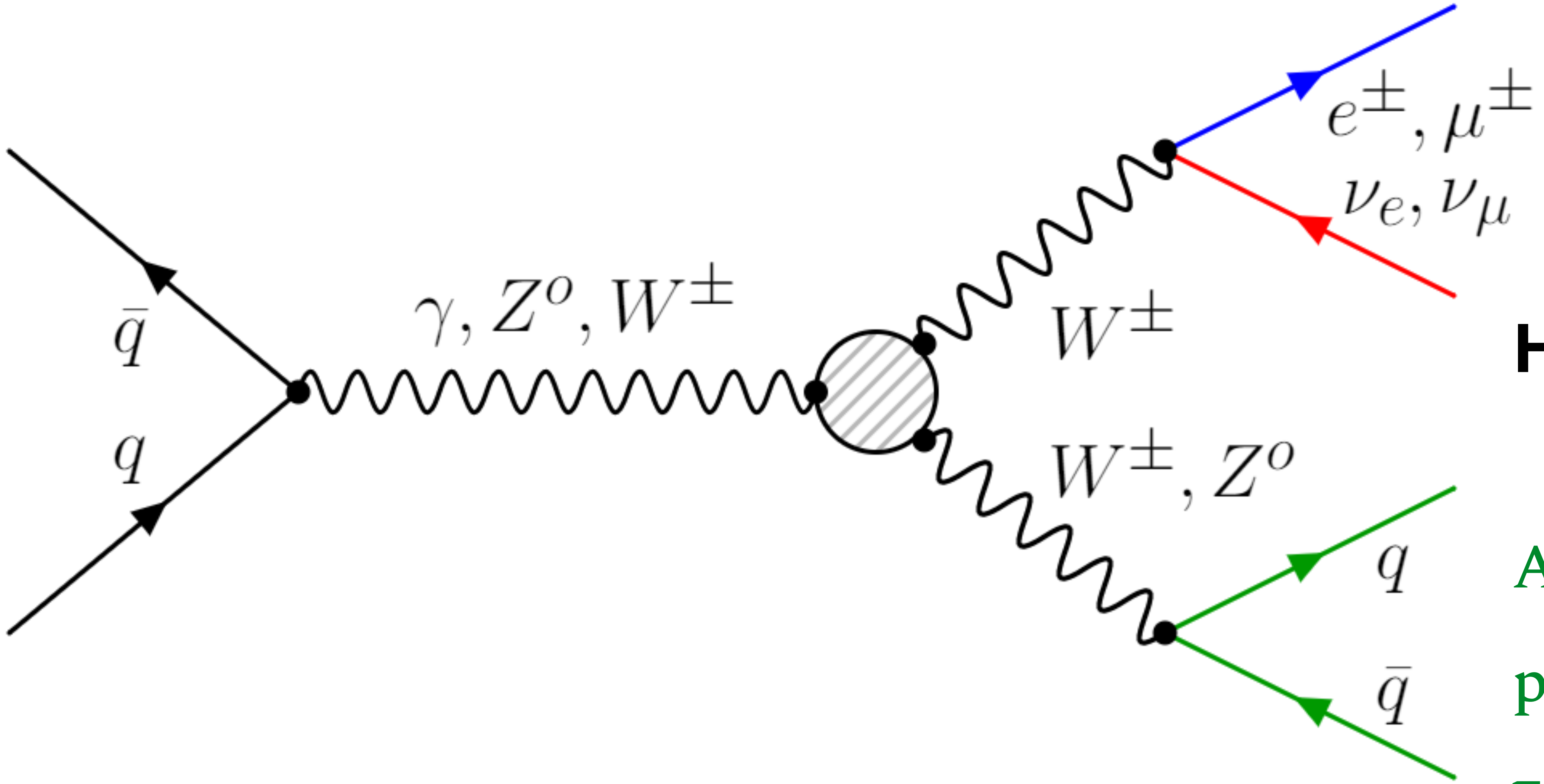
Exactly 1 electron or muon

Missing transverse momentum

W_{lep} p_T > 200 GeV

Data selected by electron or muon triggers

($\int L = 35.9\ fb^{-1}$)



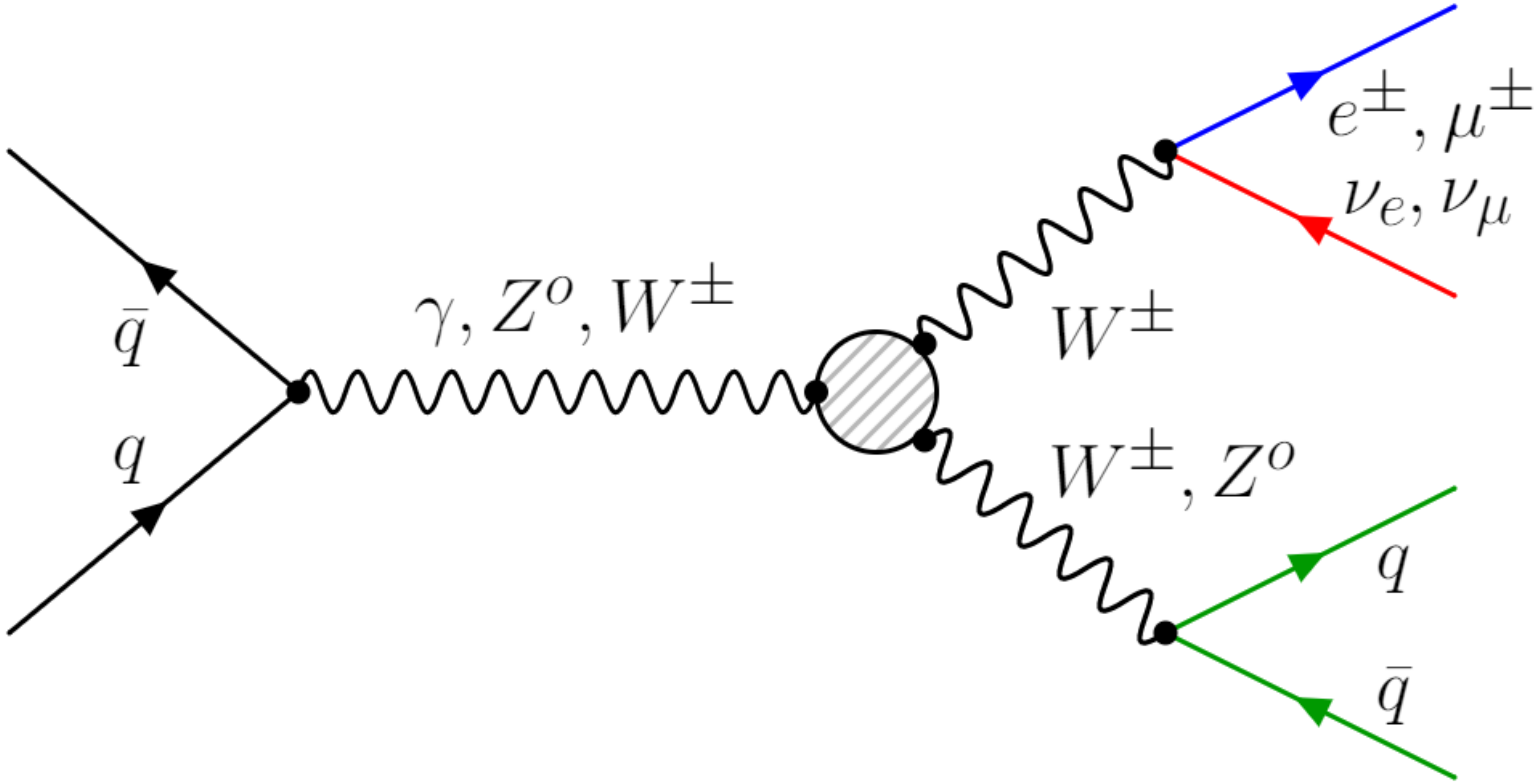
Hadronic V reconstruction:

At least 1 large-radius anti-k_T jet ($R = 0.8$)

$p_T > 200$ GeV

τ_{21} + PUPPI < 0.55

Jet mass (Soft Drop + PUPPI) $\in [40, 150]$ GeV



Total WV reconstruction:

Diboson invariant mass m_{WV} > 900 GeV

ΔR(jet, lepton) > $\pi/2$

$\Delta\phi$(jet, missing p_T) > 2

$\Delta\phi$(jet, W_{lep}) > 2

CMS @ 13 TeV: Backgrounds

Major backgrounds - estimate using data + MC

W + jets *(dominant background)*

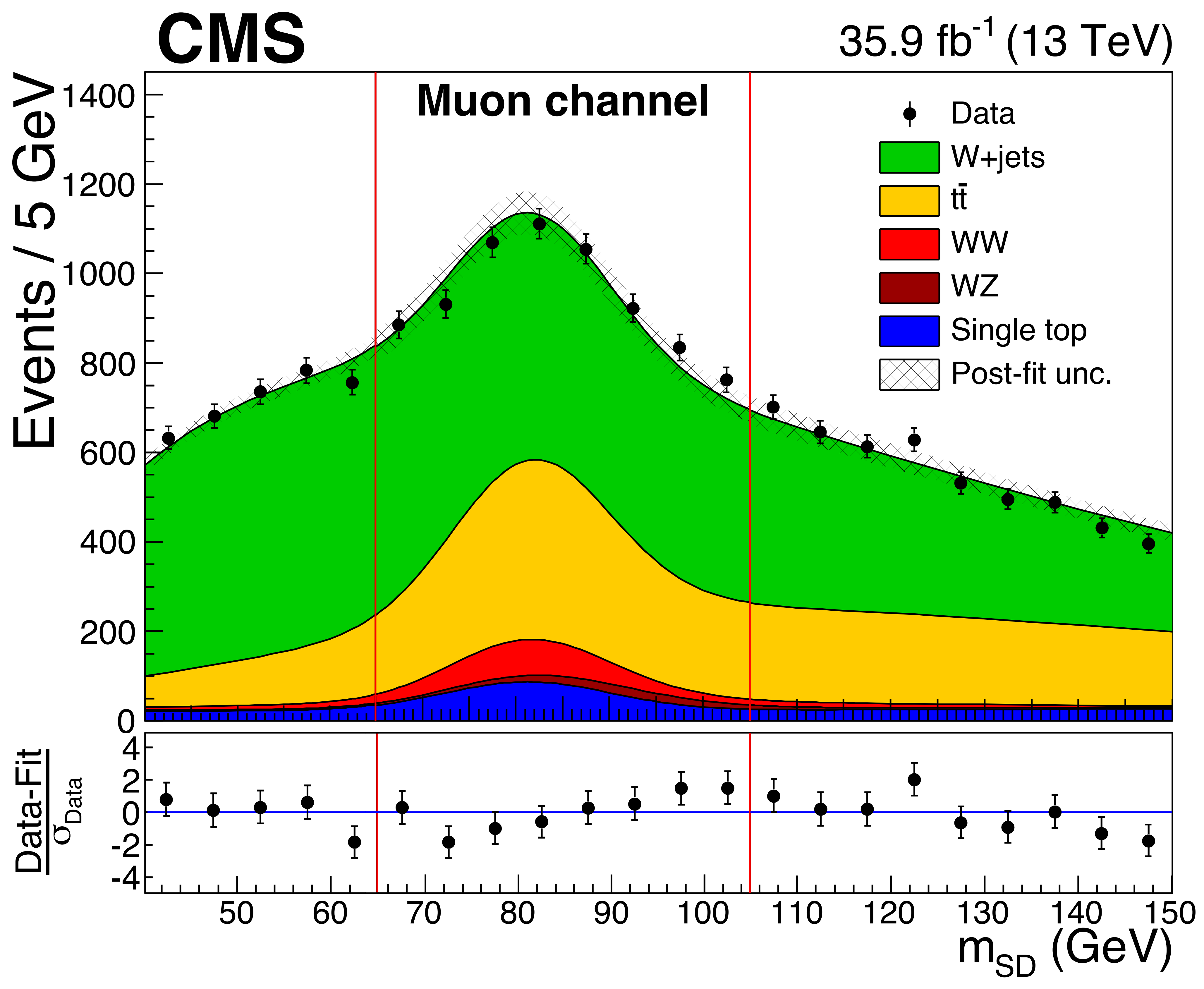
$t\bar{t}$

Minor backgrounds - estimate using only MC

Single top quark

SM diboson

(QCD mulitjet negligible, incorporated into W+jets shape)

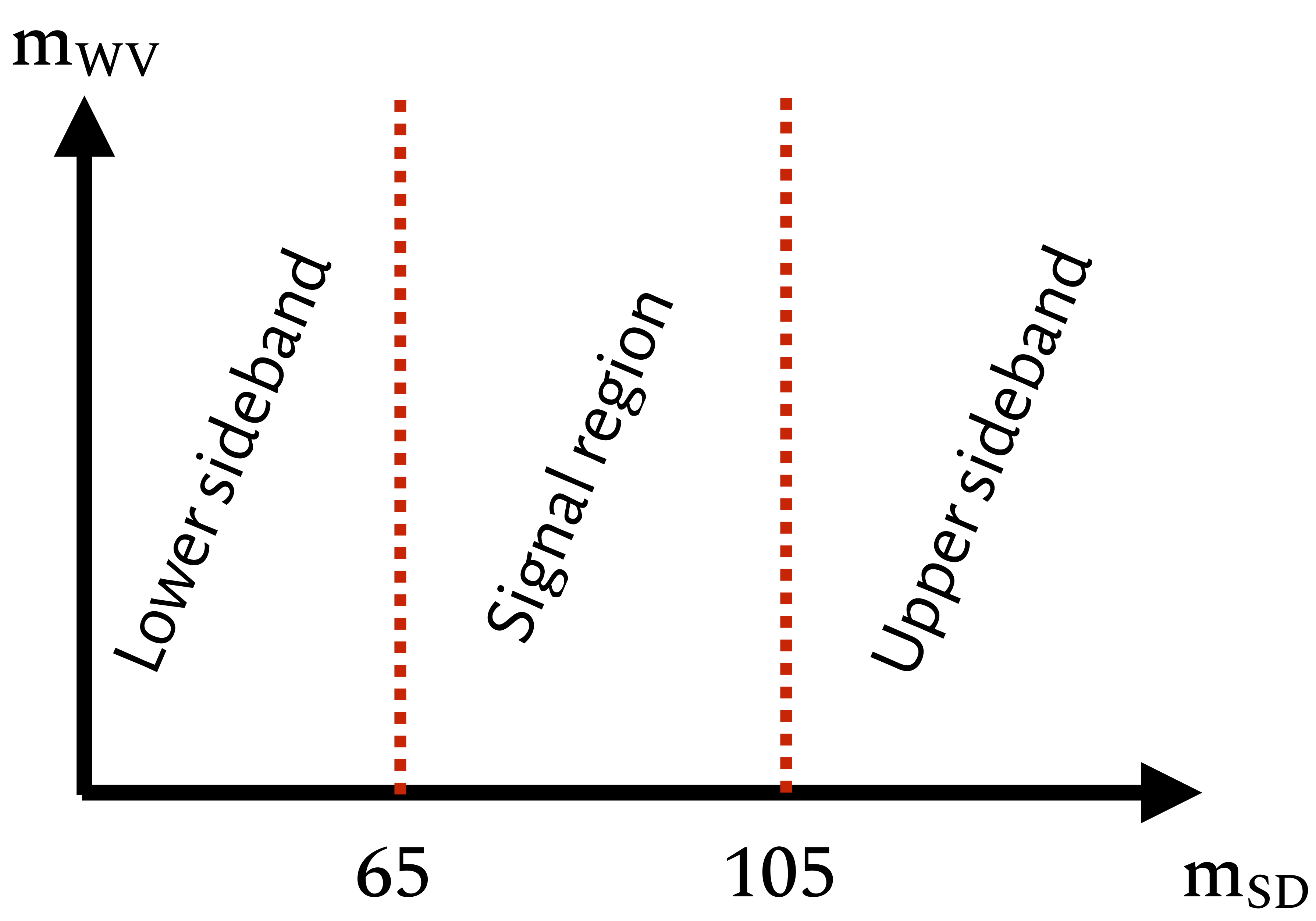


Jet mass (with soft drop) = m_{SD}

CMS @ 13 TeV: Analysis Strategy

Extract possible signal by 2D fit in (m_{WV}, m_{SD})

- Create template shapes for signal + backgrounds, then fit to data
- Not smooth kernel - divide m_{SD} into signal + "sideband" regions:
- Final simultaneous fit across **all** regions



m_{SD}: modelled by fitting to simulation

m_{WV}:

Signal: From MC, incorporating SM, aTGCs, and interference effects

Background:

W+jets: use data in W+jets-enriched region + MC → models correlation between m_{SD} and m_{WV}

Others: use shapes derived from MC

CMS @ 13 TeV: Signal Template

The m_{WV} shape can be modelled by **exponential decay**

+ aTGC effects → only has effect at larger m_{WV} (via Erf function)

Separate parts for:

- SM
- aTGC
- SM-aTGC interference effects
- aTGC-aTGC interference effects

$$F_{\mathrm{signal}}(m_{\mathrm{WV}}) = N_{\mathrm{SM}}\left(\mathrm{e}^{a_0 m_{\mathrm{WV}}} + \mathrm{e}^{a_{\mathrm{corr}} m_{\mathrm{WV}}}\right) + \sum_i \left(N_{c_i,1} c_i^2 \mathrm{e}^{a_{i,1} m_{\mathrm{WV}}} \left(\frac{1 + \mathrm{erf}[(m_{\mathrm{WV}} - a_{0,i})/a_{\mathrm{w},i}]}{2} \right) + N_{c_i,2} c_i \mathrm{e}^{a_{i,2} m_{\mathrm{WV}}} \right) + \sum_{i<j} \left(N_{c_i,c_j} c_i c_j \mathrm{e}^{a_{ij} m_{\mathrm{WV}}} \right),$$

"EWDim6" model used in MG5_aMC@NLO at NLO

→ each event weighted with different permutations of 0 & !=0 aTGCs

SM-only scenario normalised to NNLO cross-section

Phys. Rev. Lett. 113 (2014) 212001

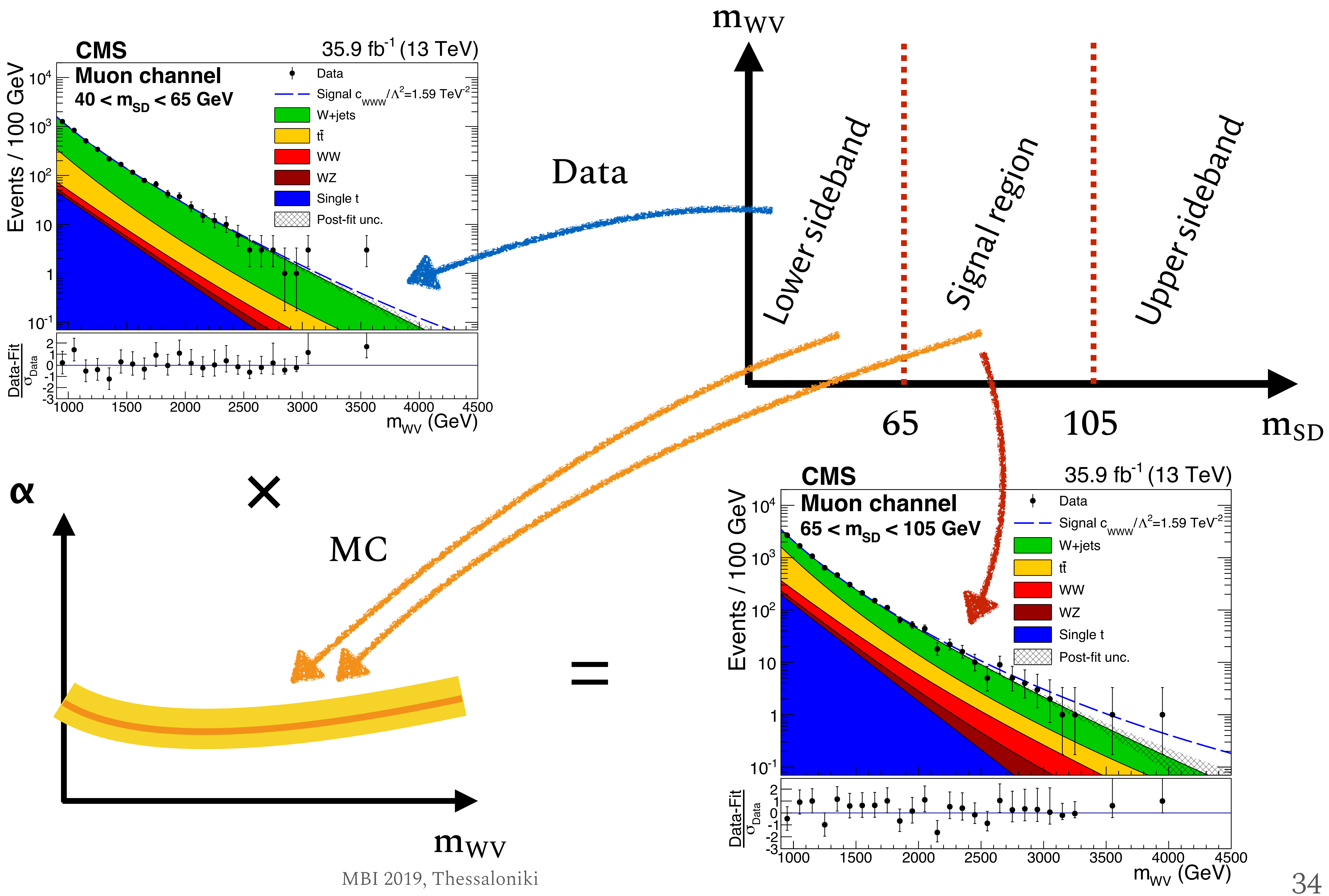
Phys. Lett. B 761 (2016) 179

CMS @ 13 TeV: W+jets template

W+jets background

Shape from data in sideband

× Transfer function from MC



CMS @ 13 TeV: Systematic Uncertainties

Normalisation uncertainties (pre-fit):

Uncertainty source	Electron channel $t\bar{t}$	Single t	WW	WZ	Muon channel $t\bar{t}$	Single t	WW	WZ
PDF	2.79	0.22	1.93	2.44	2.71	0.25	1.78	2.54
μ_R, μ_F	17.99	0.94	5.77	4.82	17.74	1.06	5.99	4.26
Luminosity	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Pileup	0.59	0.29	0.90	1.40	0.40	0.41	0.82	0.67
V tag	14	14	14	14	14	14	14	14
b tag	1.05	0.85	0.04	0.08	1.04	0.84	0.03	0.08
b mistag	0.04	0.05	0.02	0.04	0.05	0.05	0.03	0.04
Jet energy scale	4.41	4.94	4.26	2.44	3.54	2.97	3.75	2.50
Jet energy resolution	1.79	3.44	1.85	2.69	0.85	0.91	0.62	2.92
Lepton energy scale	0.80	1.45	1.53	0.94	0.68	1.14	1.72	1.19
Lepton energy resolution	0.26	1.22	0.11	0.21	0.02	0.27	0.14	0.33
Lepton ID	2.12	2.22	2.30	2.26	1.81	2.04	2.55	2.42
p_T^{miss}	0.91	1.50	1.01	0.64	0.59	0.99	0.24	0.17
Total	23.74	15.84	16.44	15.91	23.30	14.85	16.31	15.80

Scale & PDF only has large effect on $t\bar{t}$

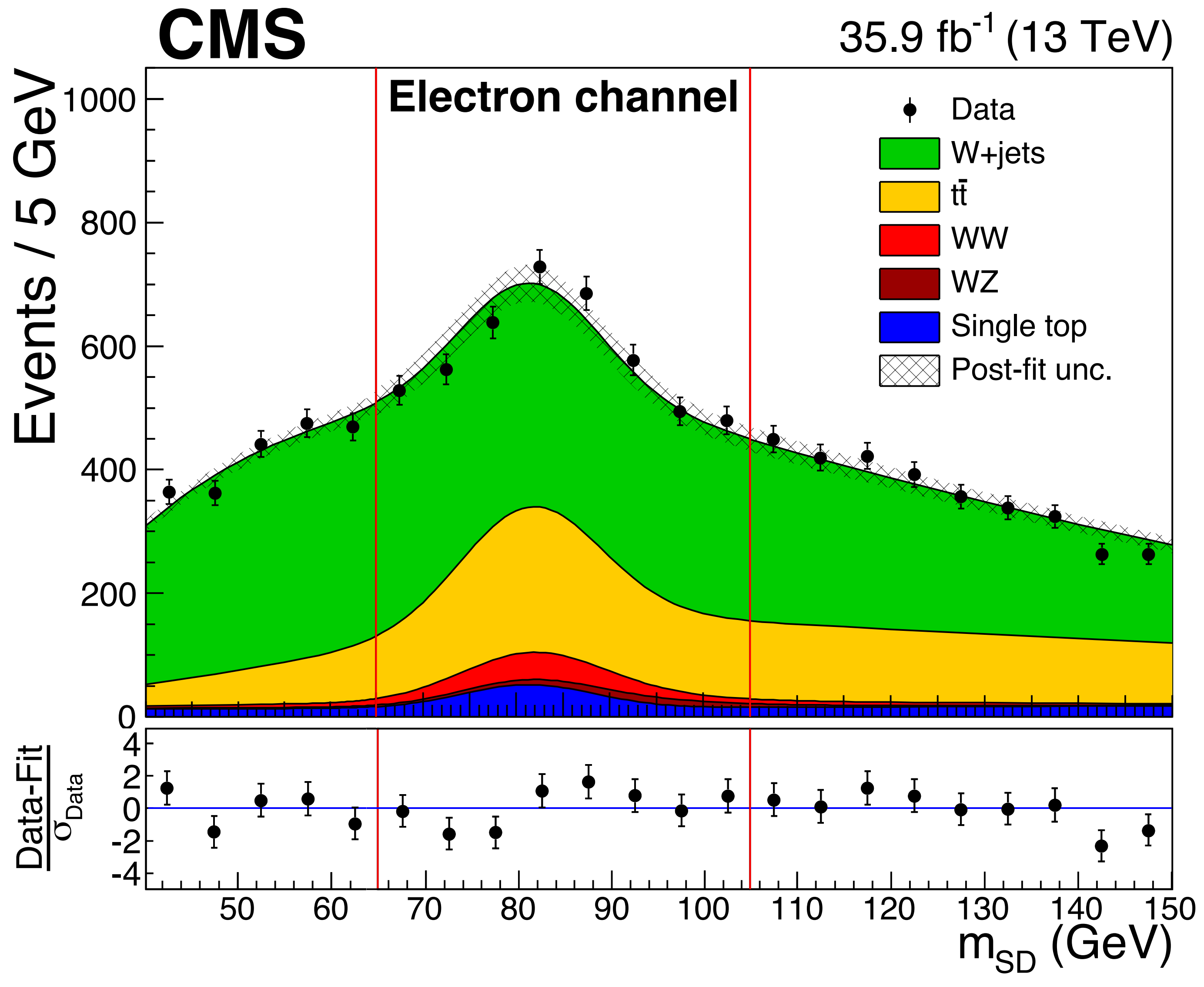
From V-tagging data:MC scale factor uncertainties

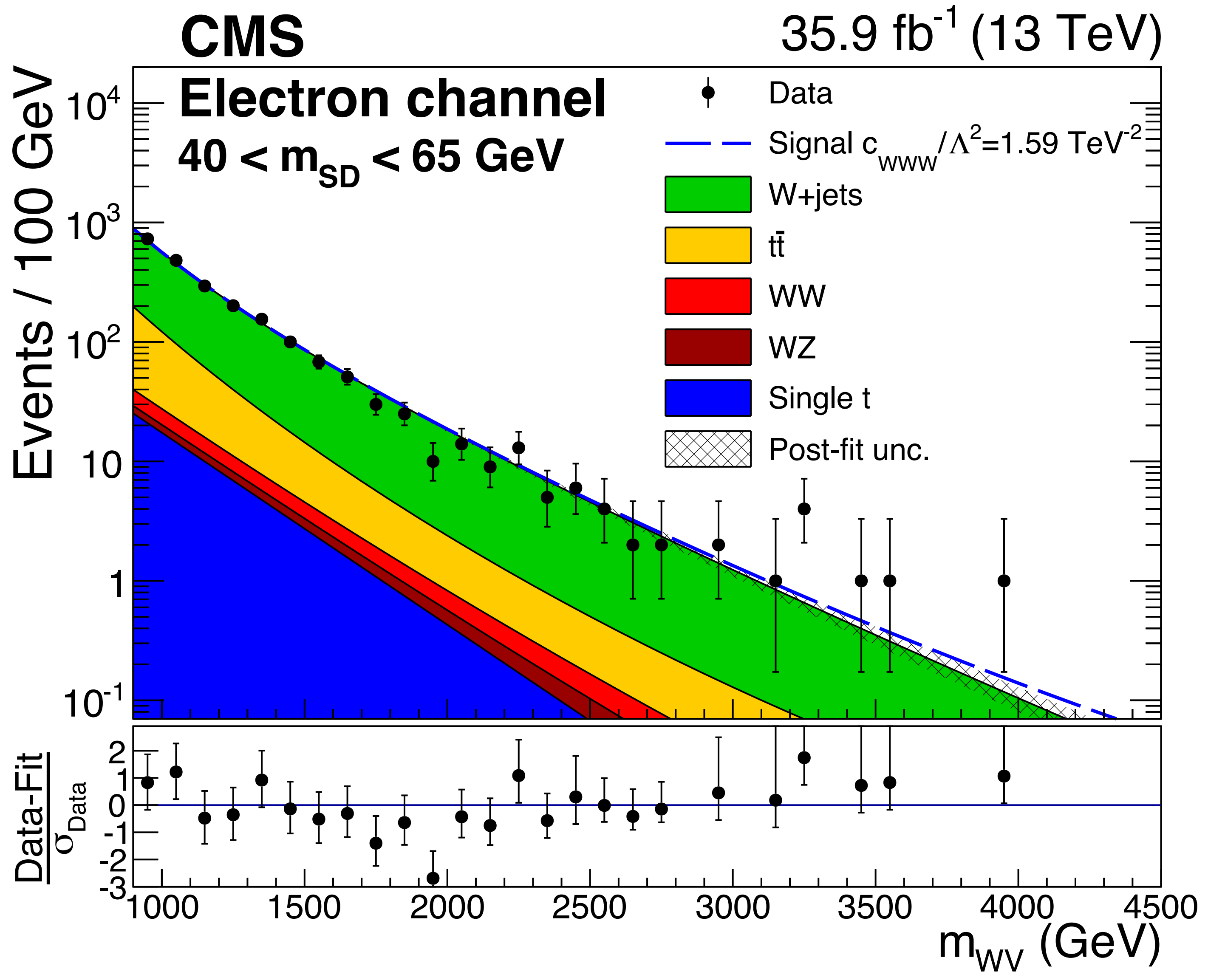
Also shape uncertainties from fit uncertainties + alternate fit models

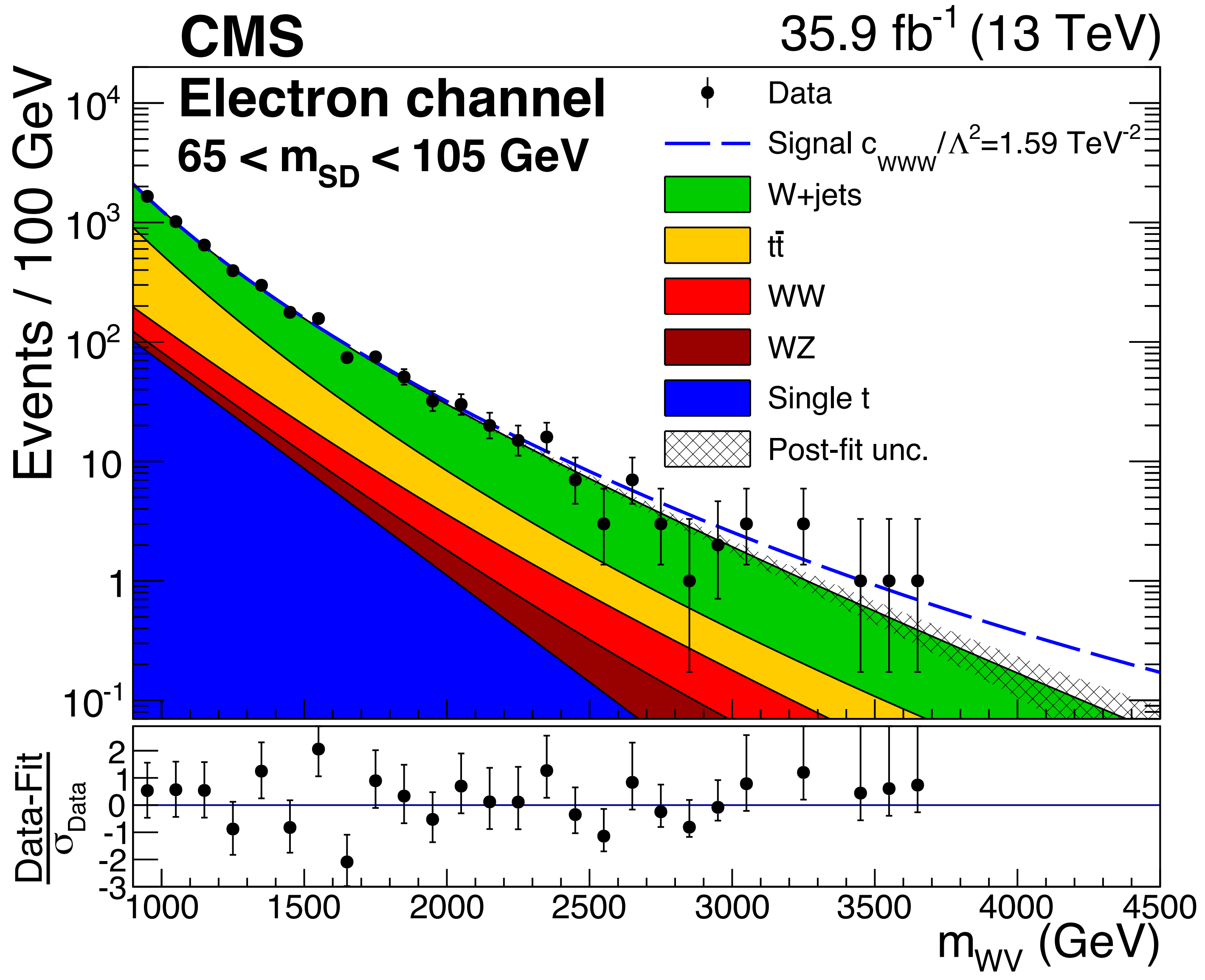
Signal shape uncertainty dominated by PDF & scale (μ_F, μ_R) effects

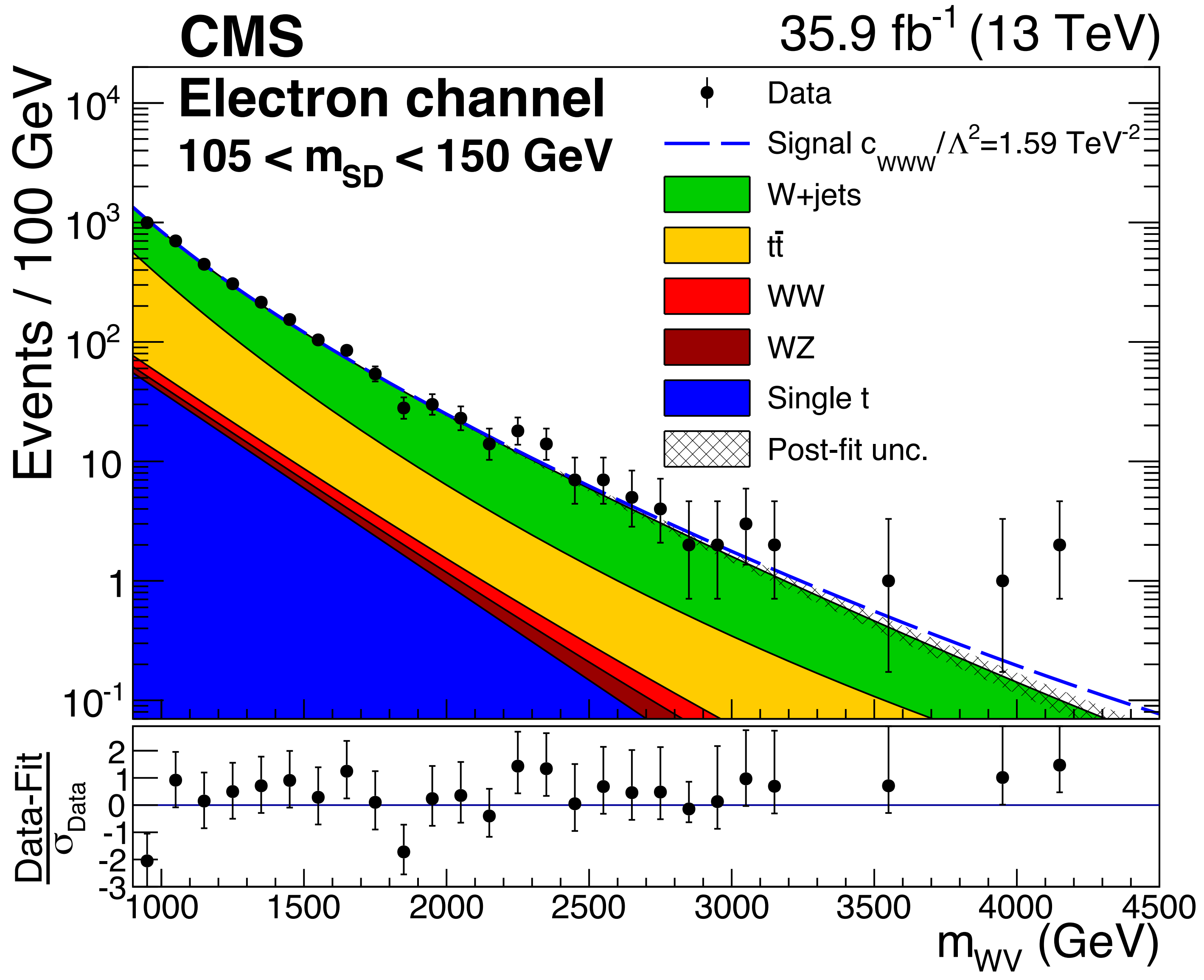
CMS @ 13 TeV: Final fits

Only electron channel shown here:









CMS @ 13 TeV: 1D Limits

Limits set on individual parameters: fix other aTGCs = 0

Do separately for each parametrisation

Big improvements on 8 TeV results!

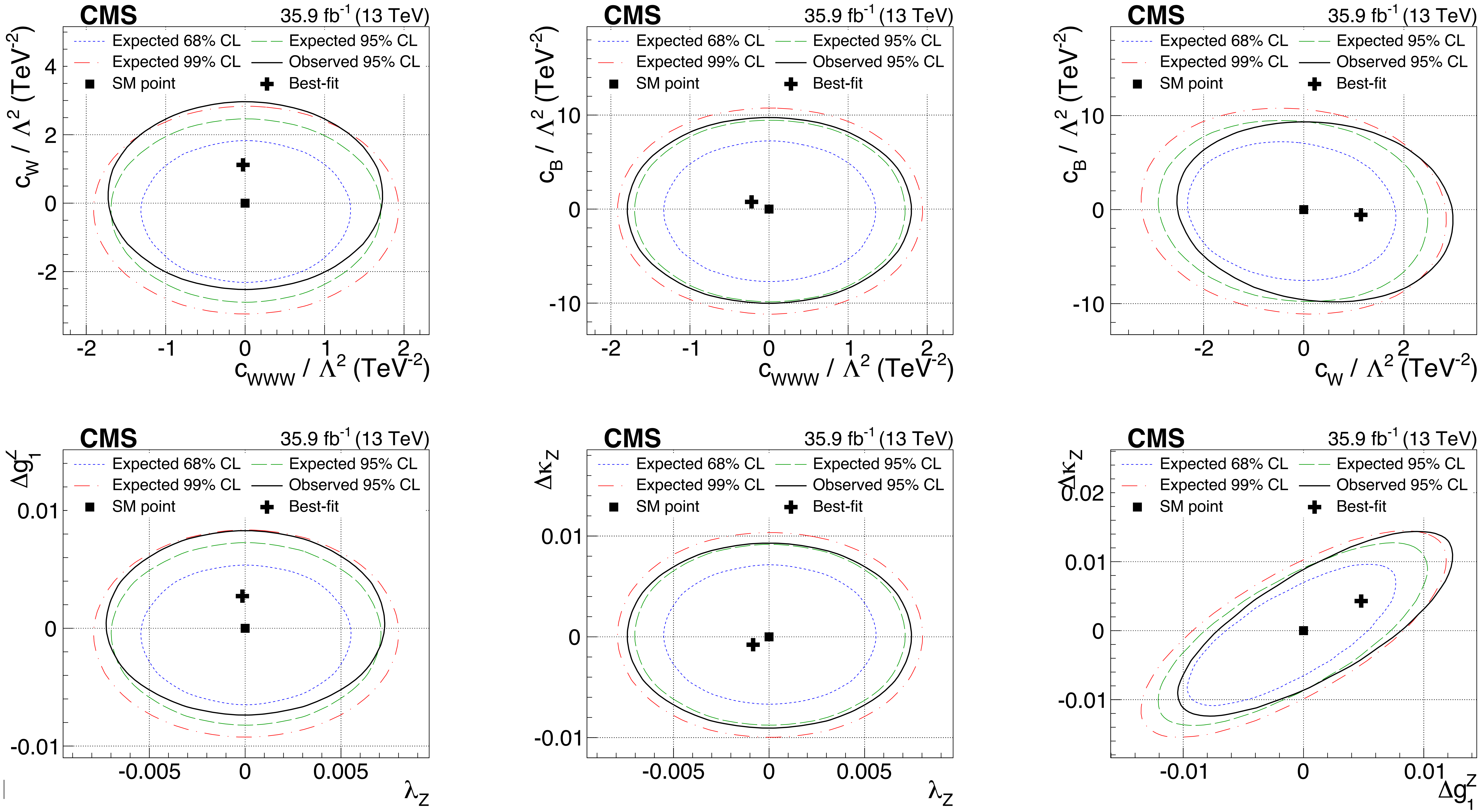
Parametrization	aTGC	Expected limit	Observed limit	Observed best-fit	CMS 8 TeV observed limit
EFT	$c_{\mathrm{WWW}}/\Lambda^2$ (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	-0.26	[-2.7, 2.7]
	c_{W}/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	1.21	[-2.0, 5.7]
	c_{B}/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	1.07	[-14, 17]
LEP	λ_{Z}	[-0.0060, 0.0061]	[-0.0065, 0.0066]	-0.0010	[-0.011, 0.011]
	Δg_1^{Z}	[-0.0070, 0.0061]	[-0.0061, 0.0074]	0.0027	[-0.009, 0.024]
	$\Delta\kappa_{\mathrm{Z}}$	[-0.0074, 0.0078]	[-0.0079, 0.0082]	-0.0010	[-0.018, 0.013]

CMS @ 13 TeV: 2D Limits

Also set 2D limits on pairs of aTGCS (fix other aTGC = 0)

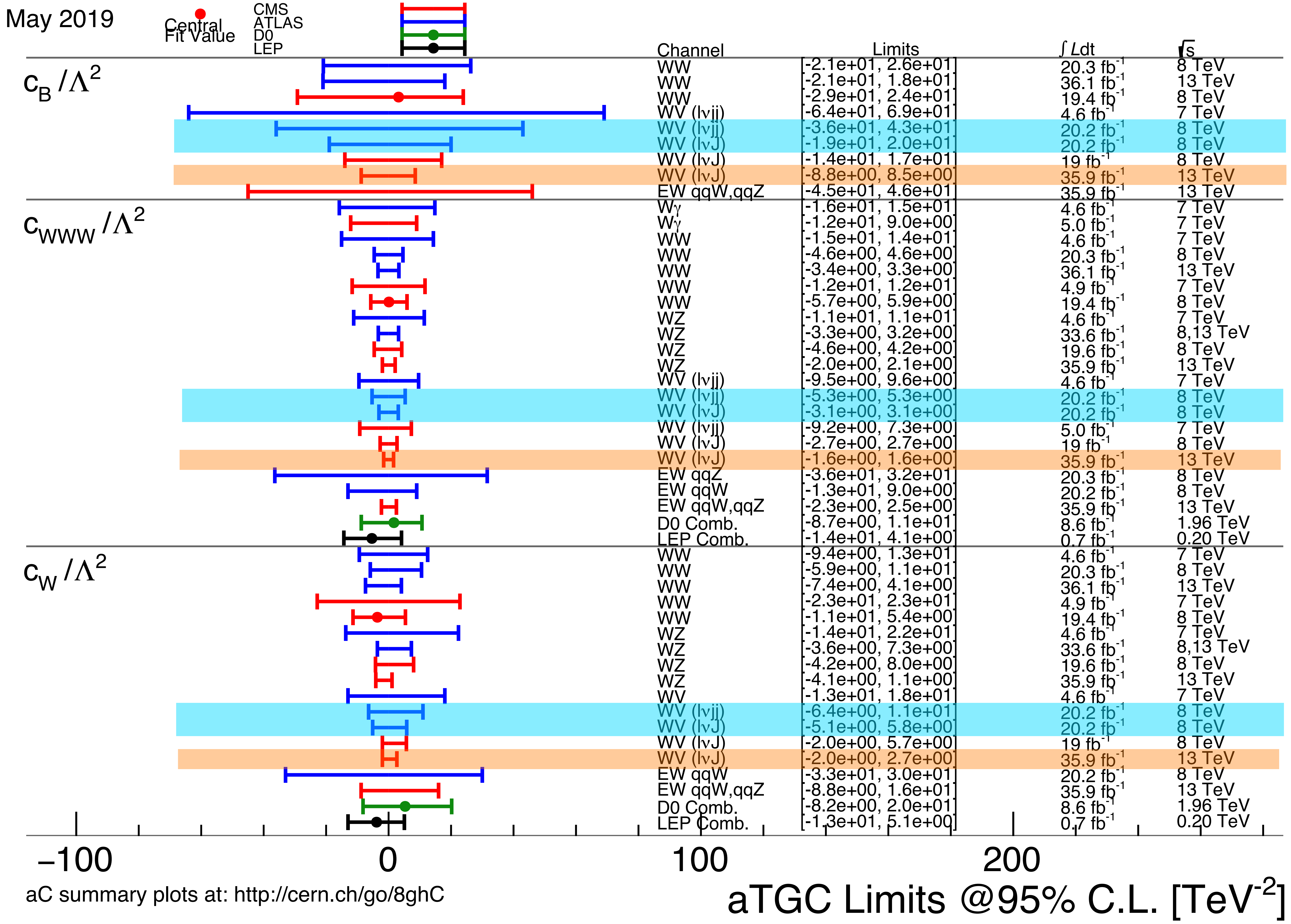
c_W, c_{WWW}, c_B basis:

λ_Z, Δg^Z_1, $\Delta\kappa_Z$ basis:



Comparison

Including all-leptonic & EWK searches



ATLAS result

CMS result

Strongest limits to date on all 3 aTGCs

LEP
Phys. Rept. 532 (2013) 119

D0
Phys. Lett. B 718 (2012) 451

CMS
Eur. Phys. J. C 73 (2013) 2283
Eur. Phys. J. C 73 (2013) 2610
Eur. Phys. J. C 77 (2017) 236
Phys. Lett. B 772 (2017) 21
Eur. Phys. J. C 78 (2018) 589
JHEP 04 (2019) 122
1903.04040 (Sub. to EPJC)

ATLAS
Eur. Phys. J. C 72 (2012) 2173
Phys. Rev. D 87 (2013) 112001
JHEP 04 (2014) 031
JHEP 01 (2015) 049
JHEP 09 (2016) 029
Phys. Rev. D 93 (2016) 092004
ATLAS-CONF-2016-043
Eur. Phys. J. C 77 (2017) 563
Eur. Phys. J. C 77 (2017) 474
1905.04242 (Sub. to EPJC)

Summary

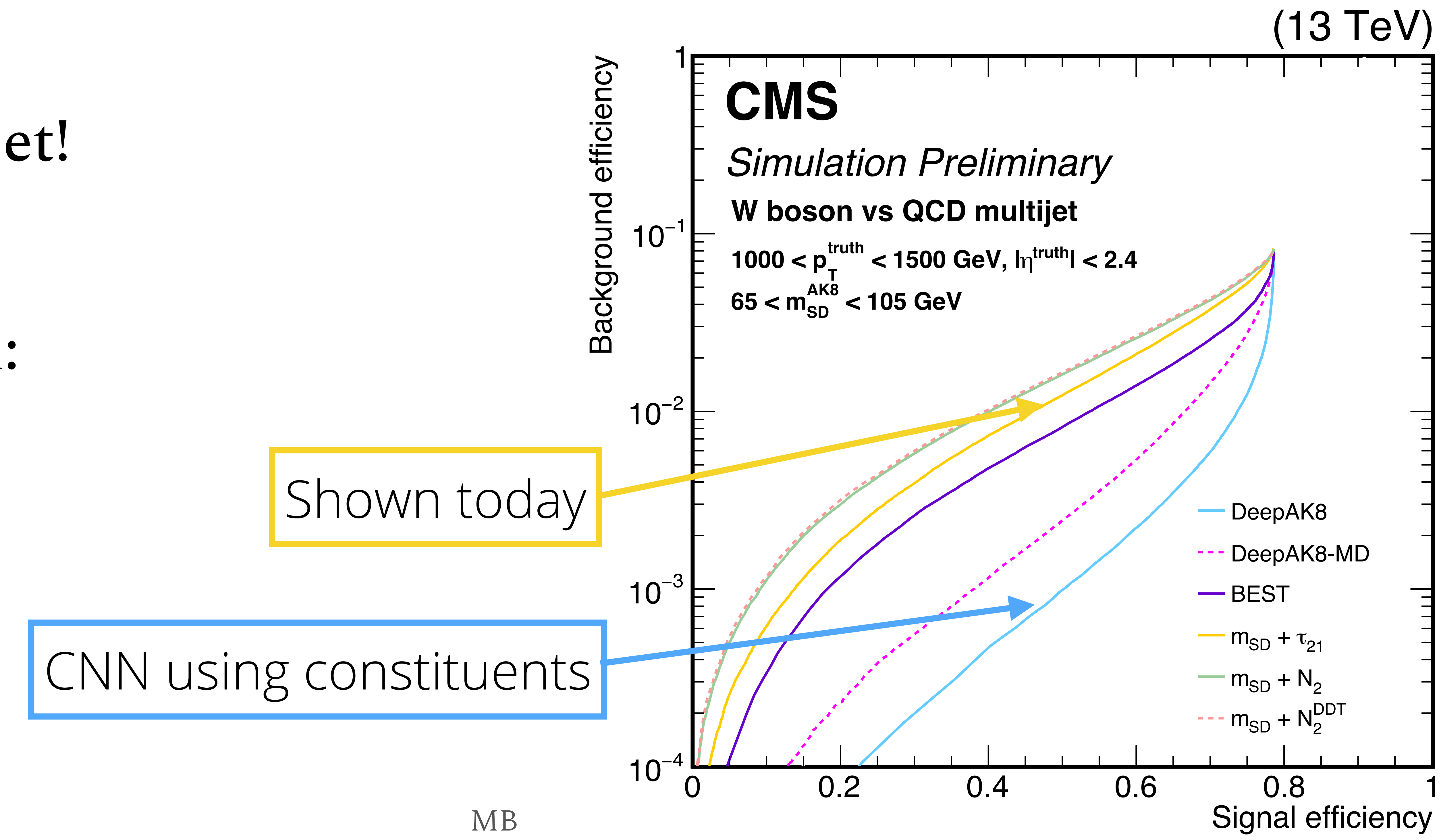
Latest result from CMS & ATLAS now include 13 TeV data from 2016

Limits on aTGCs driven by merged-jet channel

Large improvements in limits on aTGCs profiting from better V-tagging & larger √s

Still to do: full Run II dataset!

Better V-taggers developed:



CMS-PAS-JME-18-002

Backup

ATLAS backgrounds

	$WV \to \ell\nu jj$	$WV \to \ell\nu J$
Signal		
WW	2860 ± 110	542 ± 61
WZ	730 ± 30	128 ± 15
Total Expected Signal	3590 ± 140	670 ± 75
Background		
W + jets	136000 ± 8600	10500 ± 1300
Z + jets	2750 ± 340	245 ± 32
$t\bar{t}$	12980 ± 520	1130 ± 150
Single top-quark	3620 ± 150	249 ± 35
Multijet	3689 ± 60	313 ± 18
ZZ	14 ± 1	-
Total Expected Background	159000 ± 8600	12400 ± 1500
Total SM Expected	162600 ± 8700	13100 ± 1600
Observed	164502	12999
S/B (65 GeV $< m_{jj} <$ 95 GeV)	5.5%	10.1%
$S/\sqrt{B}$ (65 GeV $< m_{jj} <$ 95 GeV)	11.1	7.1

Table 1: Expected number of signal and background events in the $WV \to \ell\nu jj$ and $WV \to \ell\nu J$ signal regions, prior to performing the m_{jj} and m_J fits. The quoted uncertainties only include detector-related uncertainties and statistical uncertainties of the MC samples and control regions. The number of events observed in data is also shown. The signal predictions only correspond to qq'-initiated WV production.

ATLAS samples

Signal: NLO (QCD) MC@NLO v4.07 → H v6 + Jimmy. The W and Z bosons are generated on-shell by MC@NLO and decayed sub- sequently by Herwig.

Alternate signal: Powheg → Pythia8. Off-shell W and $Z/\gamma*$ decays are included; the $Z/\gamma*$ decays have a requirement of $m_{qq'} > 20$ GeV and $m_{ll} > 20$ GeV.

Alternate signal 2: Sherpa (LO @QCD + 3 partons) Off-shell *W* and Z/γ^* decays are included; the Z/γ^* decays have a requirement of m_{qq}>4GeV and m_{ll}> 4 GeV.

The W + jets and Z + jets backgrounds (collectively referred to as V + jets) are modelled at LO in QCD with Sherpa v1.4.1, with up to four additional final-state partons

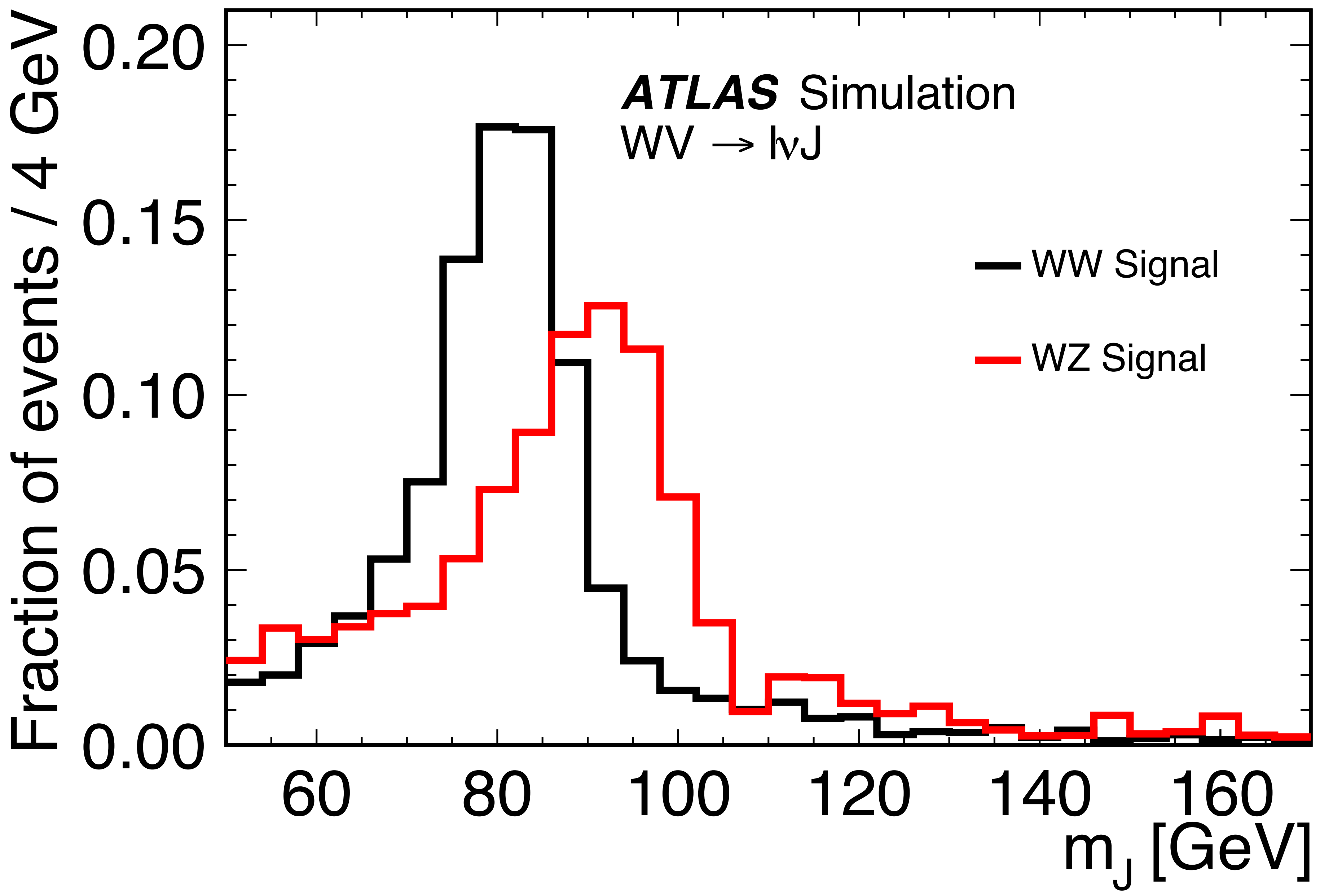
The MC samples for the $t\bar{t}$ and single-top-quark (t-channel, s-channel, and Wt) processes (collectively re- ferred to as top-quark processes) are generated with Powheg-Box

aTGC mapping

$$
\begin{aligned}
g_1^Z &= 1 + c_W \frac{m_Z^2}{2\Lambda^2} \\
\kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\
\kappa_Z &= 1 + (c_W - c_B \tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\
\lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2} \\
g_4^V &= g_5^V = 0 \\
\tilde{\kappa}_\gamma &= c_{\tilde{W}}\frac{m_W^2}{2\Lambda^2} \\
\tilde{\kappa}_Z &= -c_{\tilde{W}} \tan^2\theta_W \frac{m_W^2}{2\Lambda^2} \\
\tilde{\lambda}_\gamma &= \tilde{\lambda}_Z = c_{\tilde{W}WW}\frac{3g^2 m_W^2}{2\Lambda^2}
\end{aligned}
$$

Ann. Phys. 335 (2013) 21

ATLAS shapes



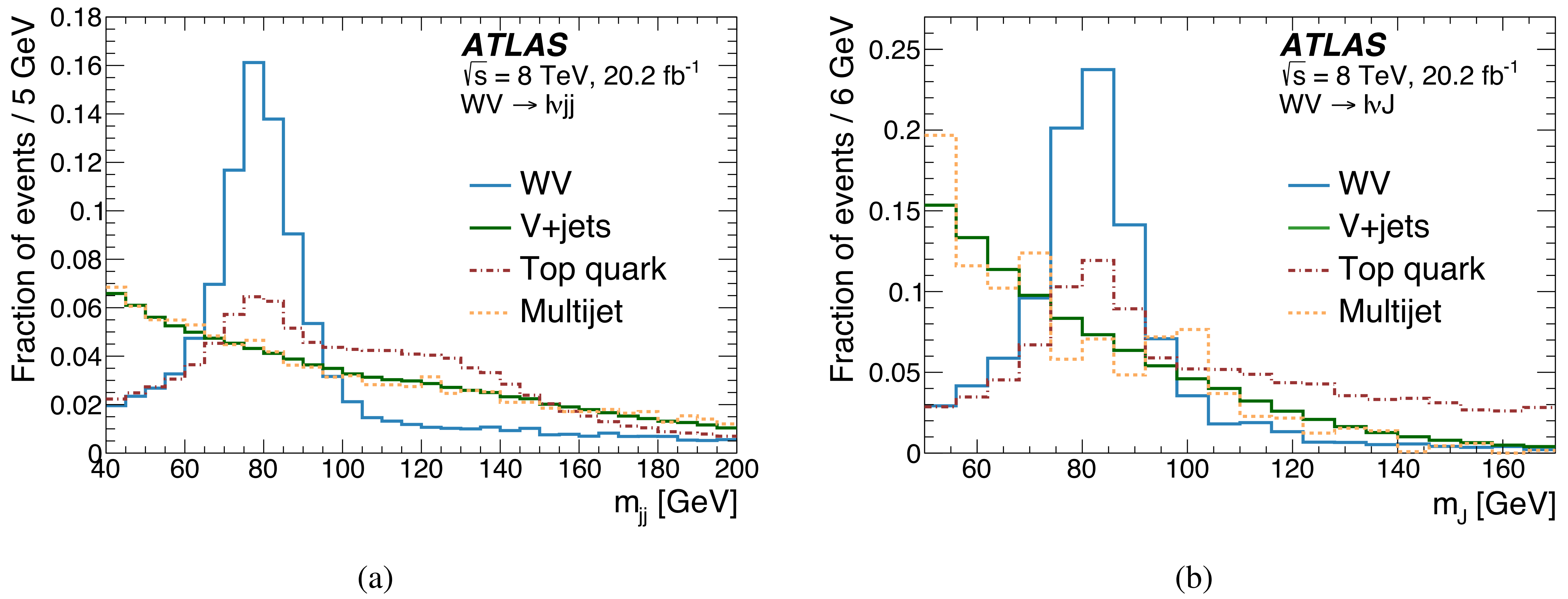


Figure 2: The shapes of (a) the predicted m_{jj} distributions in the $WV \to \ell\nu jj$ signal region and (b) the predicted m_J distributions in the $WV \to \ell\nu J$ signal region, for the signal (peaked near 80 GeV) and various background processes. The distributions are normalized to unity.

ATLAS systematics

Not all used in aTGC fit - normalisation & $p_T(V)$ ones used

Source of uncertainty	Relative uncertainty for σ_{fid}
Top-quark background modelling	13%
Signal modelling	12%
V + jets modelling	4%
Multijet background modelling	1%
Small-R jet energy/resolution	9%
Other experimental (leptons, pile-up)	4%
Luminosity	2%
MC statistics	9%
Data statistics	14%

Table 3: Breakdown of the uncertainties in the measured fiducial cross-section in the $WV \to \ell\nu$jj channel. Uncertainties smaller than 1% are omitted from the table.

Source of uncertainty	Relative uncertainty for σ_{fid}
V + jets modelling	60%
Top-quark background modelling	32%
Signal modelling	15%
Multijet background modelling	13%
Large-R jet energy/resolution	45%
Small-R jet energy/resolution	16%
Other experimental (leptons, pile-up)	3%
Luminosity	2%
MC statistics	19%
Data statistics	33%

Table 4: Breakdown of the uncertainties in the measured fiducial cross-section in the $WV \to \ell\nu$J channel. Uncertainties smaller than 1% are omitted from the table.

ATLAS @ 8 TeV: 1D Limits

Also extract limits with different cutoff parameters & ignoring LEP constraint

aTGC form factors to ensure unitarity:

$$\alpha \rightarrow \frac{\alpha}{\left(1 + \frac{\hat{s}}{\Lambda_{\mathrm{FF}}^2}\right)^2},$$

α = aTGC param

$\hat{s} = m_{WV}^2$

Λ_{FF}^2 = energy scale

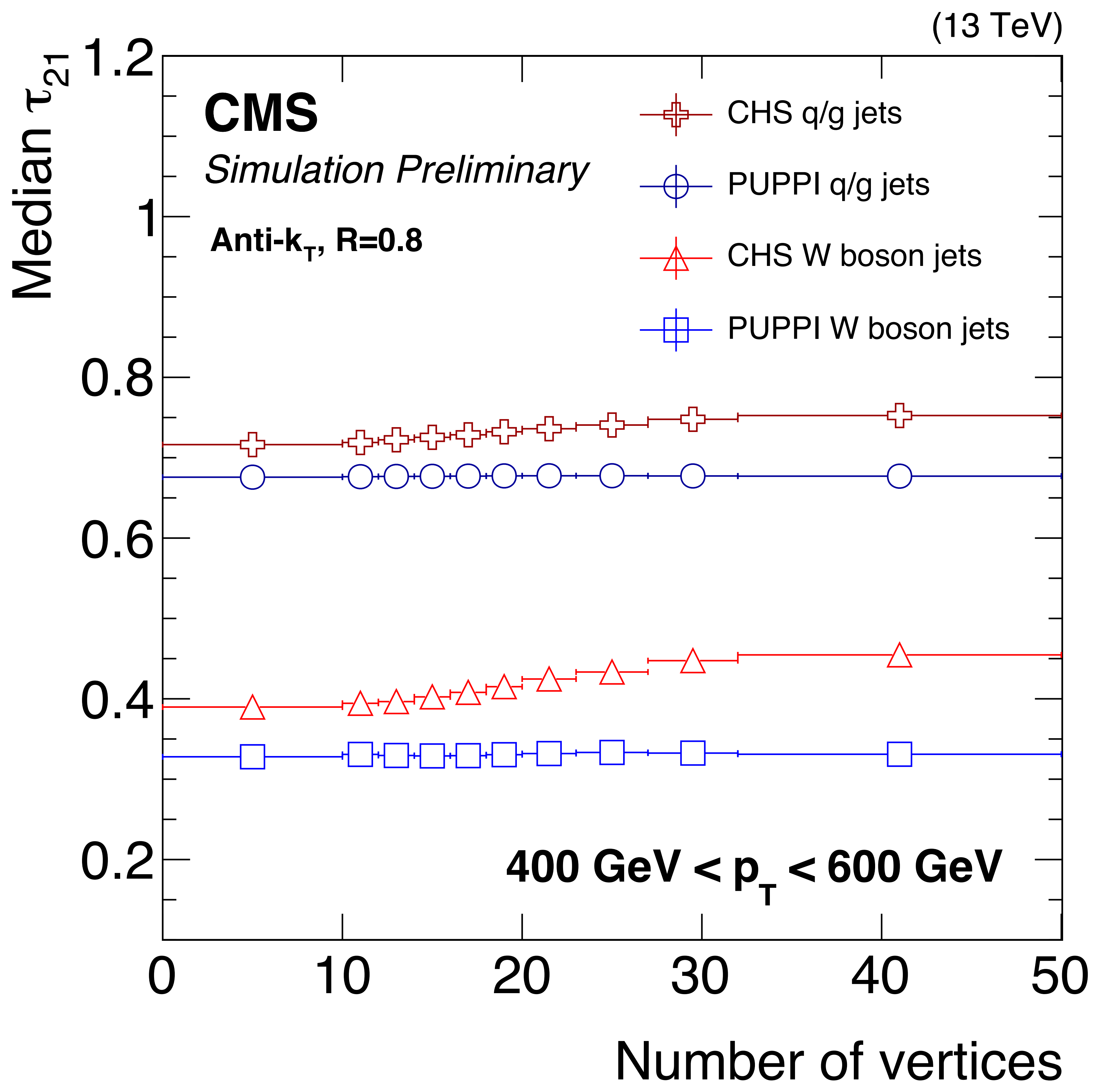
Form factor	Parameter	Observed $WV \to \ell\nu jj$	Expected $WV \to \ell\nu jj$	Observed $WV \to \ell\nu J$	Expected $WV \to \ell\nu J$
$\Lambda_{\mathrm{FF}} = \infty$	Δg_1^Z	$[-0.039, 0.059]$	$[-0.050, 0.066]$	$[-0.033, 0.036]$	$[-0.039, 0.042]$
	$\Delta\kappa_Z$	$[-0.045, 0.063]$	$[-0.060, 0.076]$	$[-0.028, 0.030]$	$[-0.033, 0.035]$
	λ_Z	$[-0.024, 0.024]$	$[-0.029, 0.029]$	$[-0.015, 0.015]$	$[-0.017, 0.017]$
	$\Delta\kappa_\gamma$	$[-0.099, 0.14]$	$[-0.13, 0.17]$	$[-0.058, 0.063]$	$[-0.067, 0.073]$
	λ_γ	$[-0.084, 0.084]$	$[-0.10, 0.10]$	$[-0.042, 0.041]$	$[-0.049, 0.049]$
$\Lambda_{\mathrm{FF}} = 5$ TeV	Δg_1^Z	$[-0.042, 0.064]$	$[-0.055, 0.073]$	$[-0.044, 0.048]$	$[-0.051, 0.054]$
	$\Delta\kappa_Z$	$[-0.047, 0.068]$	$[-0.064, 0.083]$	$[-0.037, 0.040]$	$[-0.043, 0.047]$
	λ_Z	$[-0.026, 0.026]$	$[-0.032, 0.032]$	$[-0.020, 0.019]$	$[-0.023, 0.022]$
	$\Delta\kappa_\gamma$	$[-0.10, 0.15]$	$[-0.14, 0.18]$	$[-0.077, 0.084]$	$[-0.089, 0.097]$
	λ_γ	$[-0.089, 0.089]$	$[-0.11, 0.11]$	$[-0.056, 0.056]$	$[-0.065, 0.065]$

→ Form factor scale has larger effect on $\ell\nu$J as probes larger p_T(V)

T21

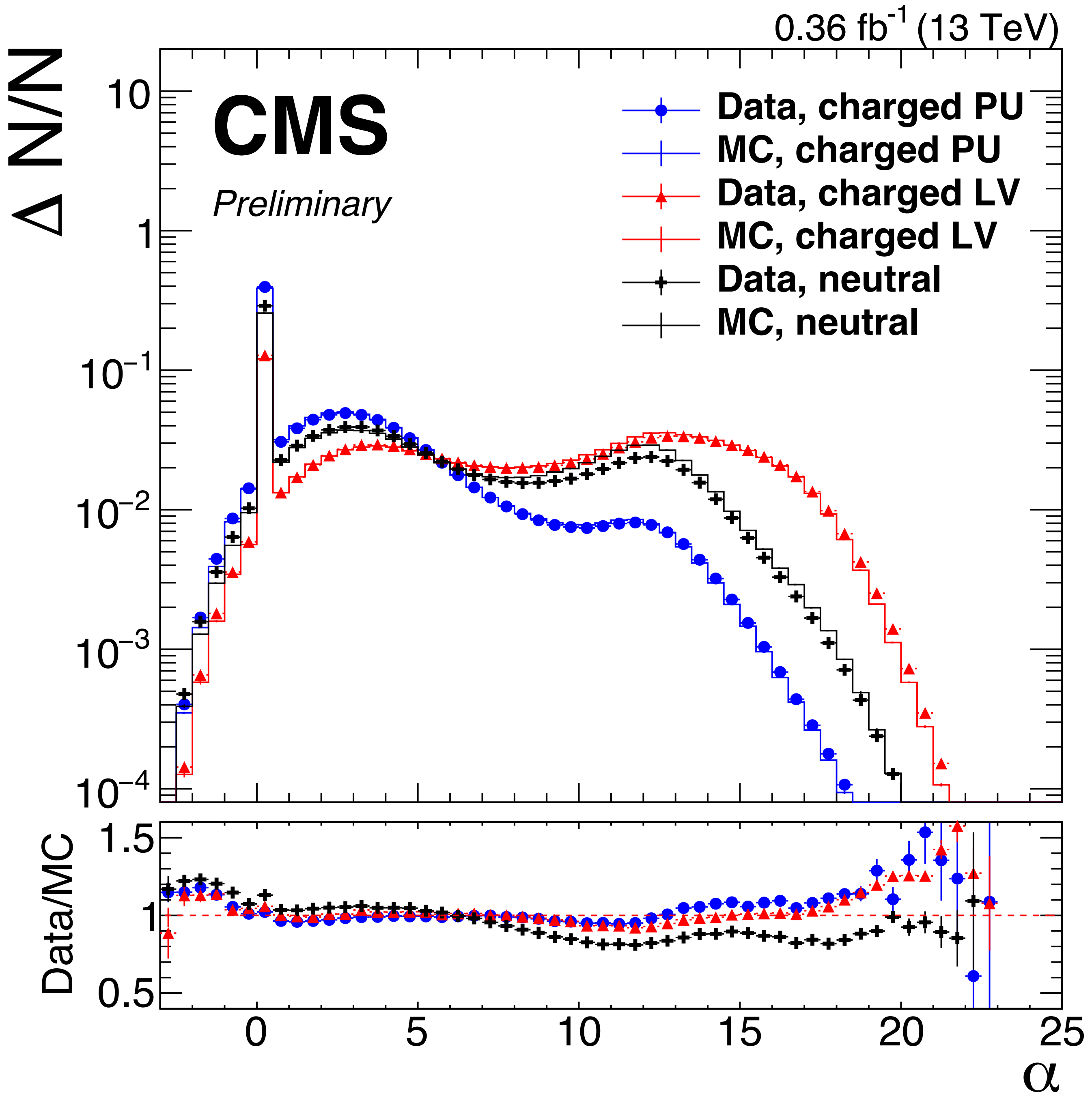
For CHS jets, shift in τ21 distribution to higher values for both signal & background

→ For given cut value, decrease in fake rate, but loses signal efficiency

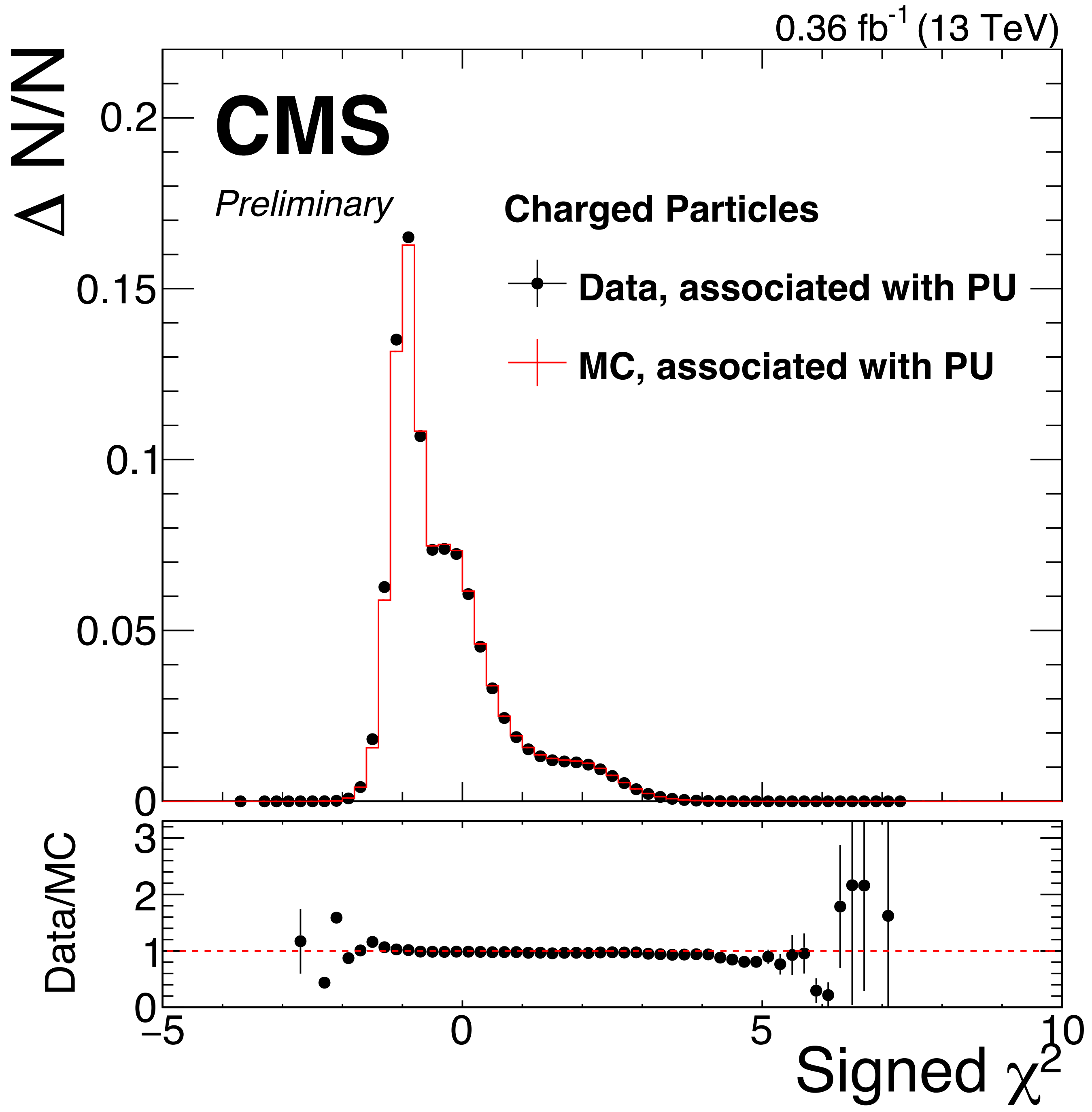


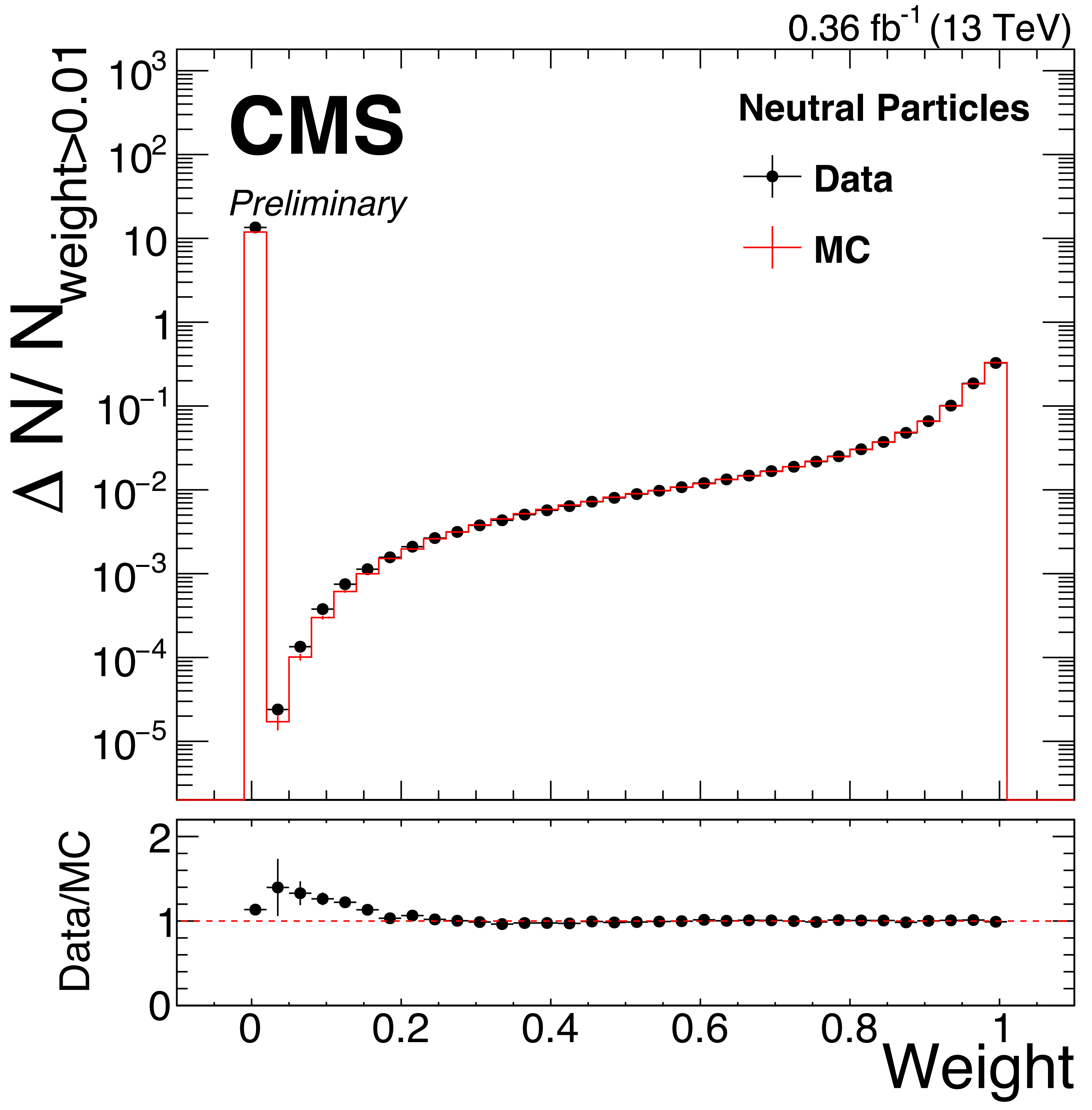
CMS-PAS-JME-18-001

PUPPI



CMS-PAS-JME-18-001





CMS samples

Signal: MADGRAPH5 aMC@NLO v2.4.2 at NLO in the strong coupling α_S, using the “EWDim6” model

Top quark: POWHEG. Normalized with Top++

W+jets: MG5_aMC@NLO at NLO. Normalized with NNLO from MCFM

All showered/hadronized with Pythia8

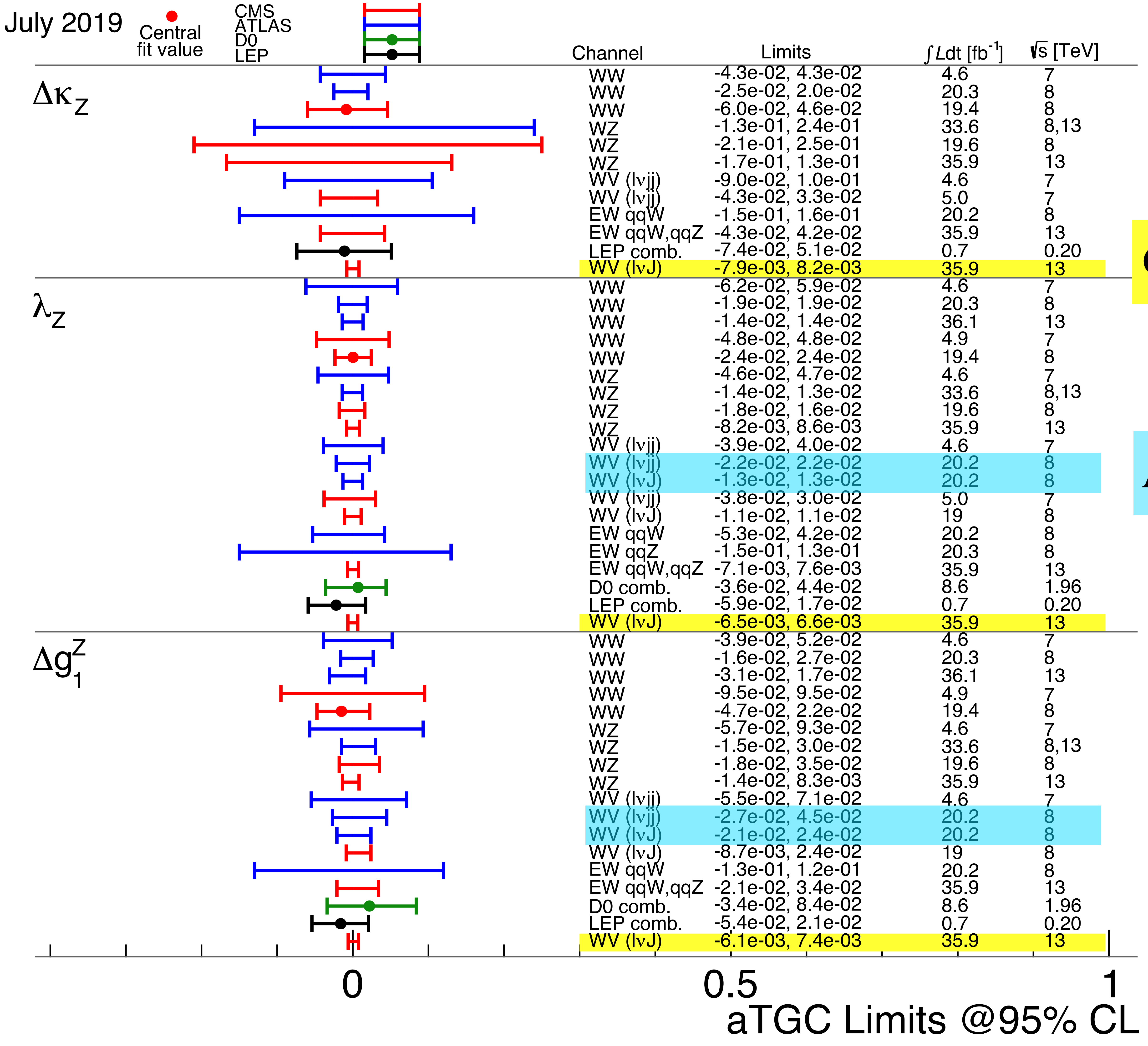
CMS yields

Table 1: Results of the signal extraction fits. The uncertainties in the pre-fit yields are their respective pre-fit constraints, whilst the uncertainties in the post-fit yields are the corresponding total post-fit uncertainties. Since the normalization of the W+jets contribution is allowed to vary freely in the fit, it does not have any corresponding pre-fit uncertainties.

	Electron channel			Muon channel		
	Pre-fit	Post-fit	Scale factor	Pre-fit	Post-fit	Scale factor
W+jets	2421	3036 ± 123	1.25	4319	4667 ± 182	1.08
$t\bar{t}$	1491 ± 324	1127 ± 119	0.76	2632 ± 570	1978 ± 202	0.75
Single t	271 ± 39	242 ± 26	0.89	509 ± 69	449 ± 43	0.88
Diboson	314 ± 314	267 ± 102	0.85	552 ± 552	465 ± 162	0.84
Total expected	4497	4672 ± 201	1.04	8012	7559 ± 319	0.94
Data		4691			7568	

Comparison

Including all-leptonic & EWK searches



CMS result

ATLAS result

Strongest limits to date on all 3 aTGCs

LEP

Phys. Rept. 532 (2013) 119

D0

Phys. Lett. B 718 (2012) 451

CMS

Eur. Phys. J. C 73 (2013) 2283
Eur. Phys. J. C 73 (2013) 2610
Eur. Phys. J. C 77 (2017) 236
Phys. Lett. B 772 (2017) 21
Eur. Phys. J. C 78 (2018) 589
JHEP 04 (2019) 122
1903.04040 (Sub. to EPJC)

ATLAS

Eur. Phys. J. C 72 (2012) 2173
Phys. Rev. D 87 (2013) 112001
JHEP 04 (2014) 031
JHEP 01 (2015) 049
JHEP 09 (2016) 029
Phys. Rev. D 93 (2016) 092004
ATLAS-CONF-2016-043
Eur. Phys. J. C 77 (2017) 563
Eur. Phys. J. C 77 (2017) 474
1905.04242 (Sub. to EPJC)