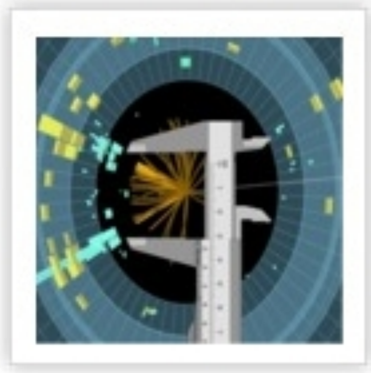
Precision Standard Model measurements at the LHC

lessons learned and future prospects



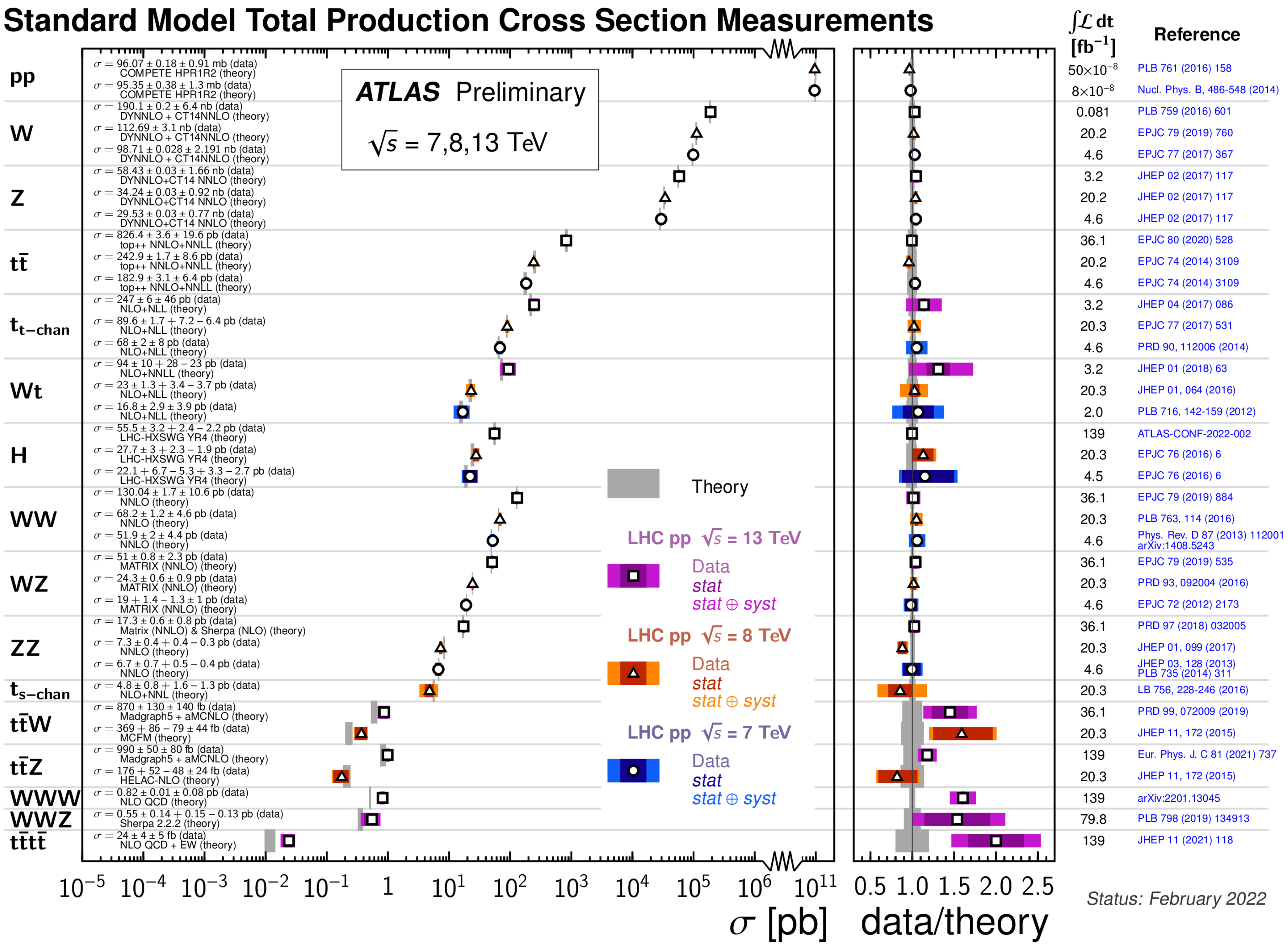
Paolo Azzurri – INFN Pisa

Benasque 2023 workshop

The LHC Precision Program Oct 1-7, 2023

Intro

- LHC data provide the opportunity to carry out a staggering extent of diverse verifications of the Standard Model predictions, covering processes with assorted final states and spanning several orders of magnitude in cross-section
- Standard Model (precision) measurements also offer the opportunity for a comprehensive and unbiased search for new physics effects
- Precision measurements are dominated by systematic uncertainties, experimental and theoretical. Optimal measurements can/should balance/trade statistical fluctuations with systematics to improve the results.



precision measurements mostly from inclusive & high rate processes

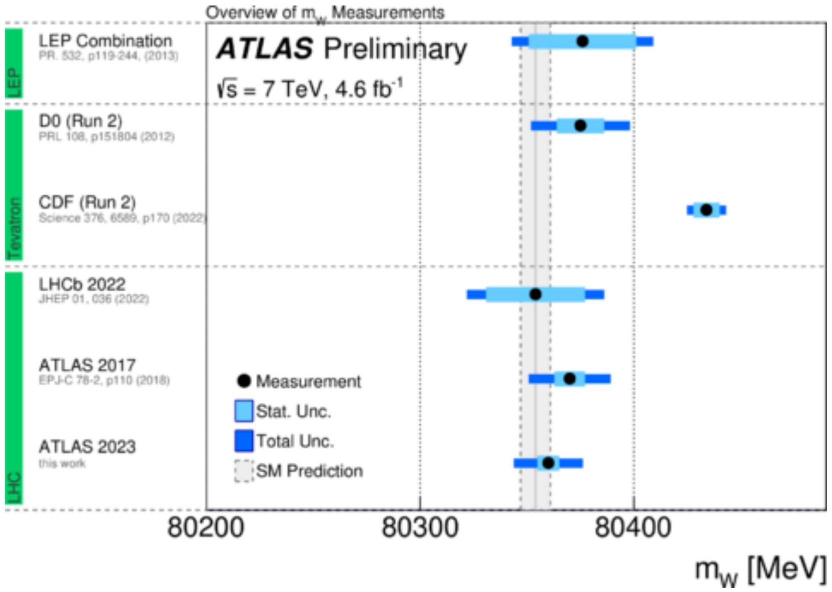
10^{-4} precision : m_W

[Science 376 (2022) 6589](#)

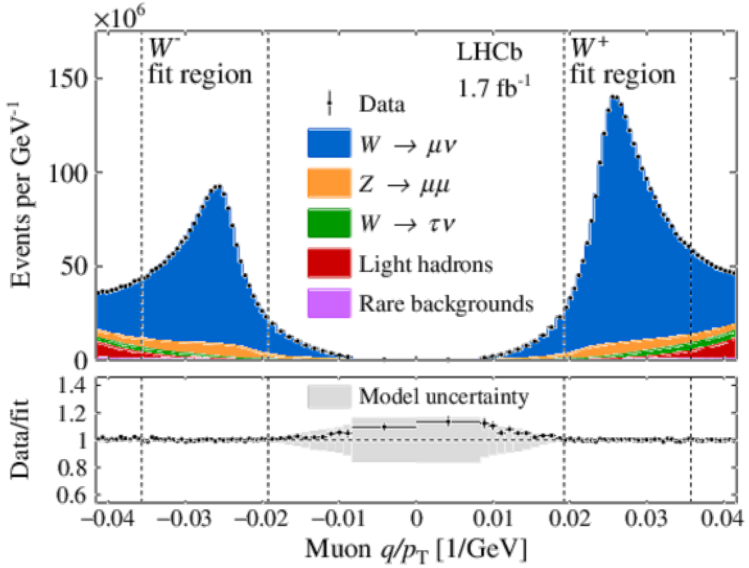
[arXiv:2109.01113](#)

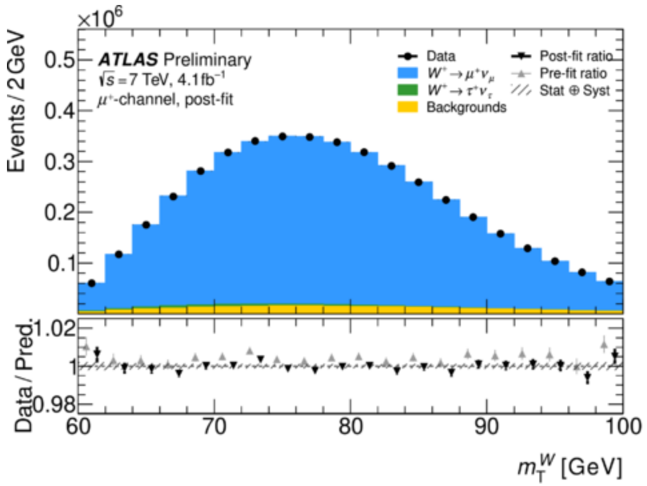
[arXiv:1701.07240v2](#)

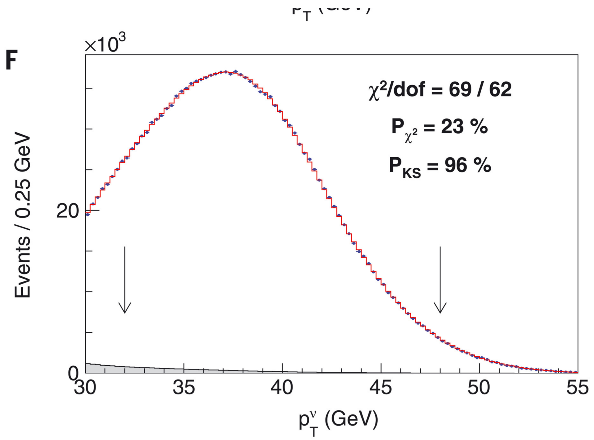
[ATLAS-CONF-2023-004](#)



Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

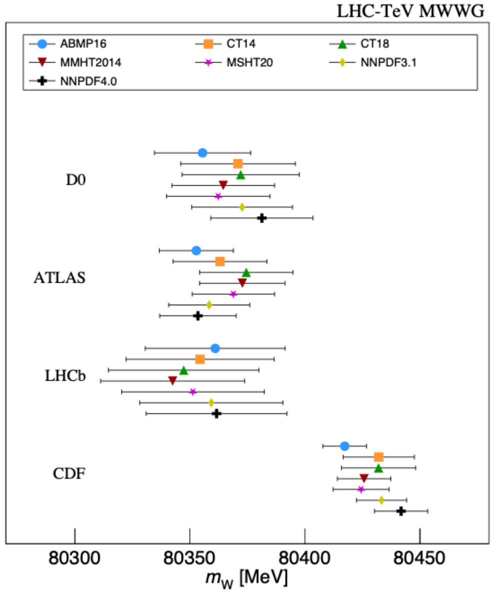


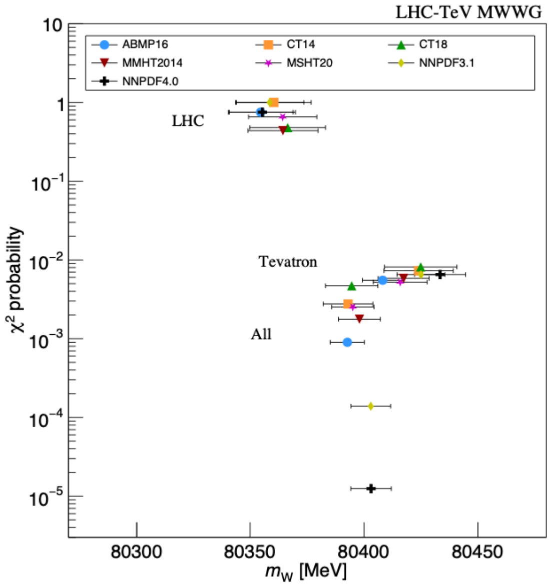




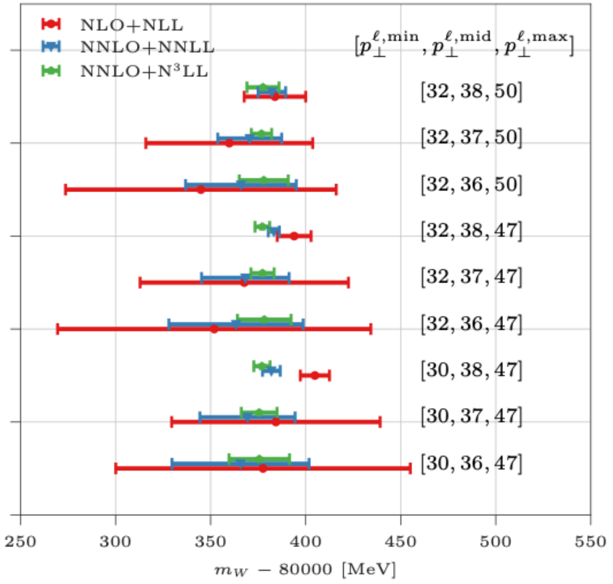
Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

10^{-4} precision : m_W





Different choices for Theory modeling and their uncertainties
Compatibility and combinations arXiv:2308.09417



measure m_W with a single observable arXiv:2308.15993

jacobian asymmetry

$$\mathcal{A}_{p_t^\ell}(p^\ell_{t,\min}, p^\ell_{t,\mathrm{mid}}, p^\ell_{t,\max}) = \frac{L-U}{L+U}$$

more data should allow less model dependence
CERN-THESIS-2021-271 Asymow ERC *theory agnostic* m_W

$$\frac{d\sigma}{d\Phi} \propto BW(Q) \times \frac{d^2\sigma}{dy\, dq_T} \cdot (1 + \varepsilon_{UL}(y, q_T)) \times (1 + \cos\theta^2 + \sum A_i \cdot (1 + \varepsilon_i(y, q_T)) \times P_i(\theta, \varphi))$$

DY pT

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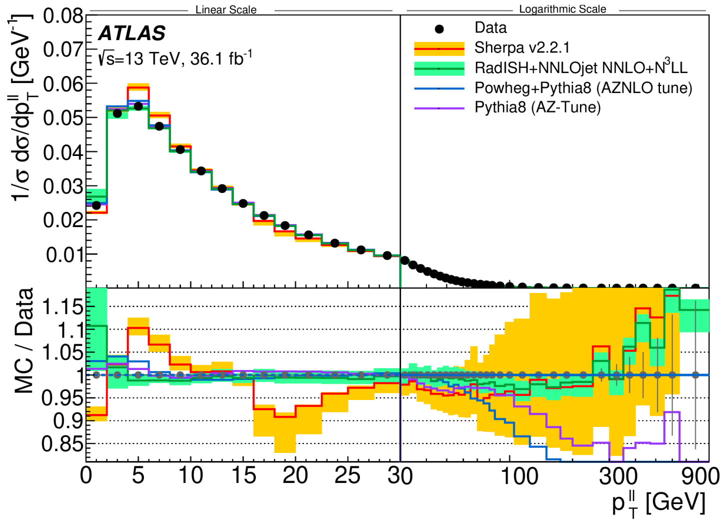
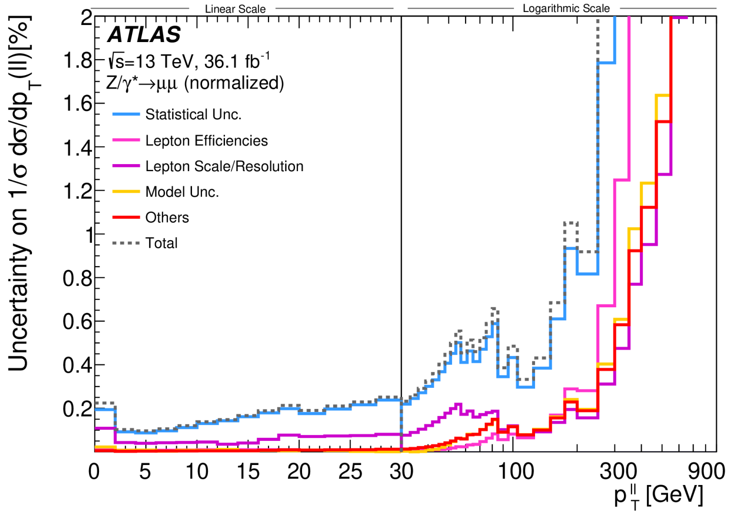
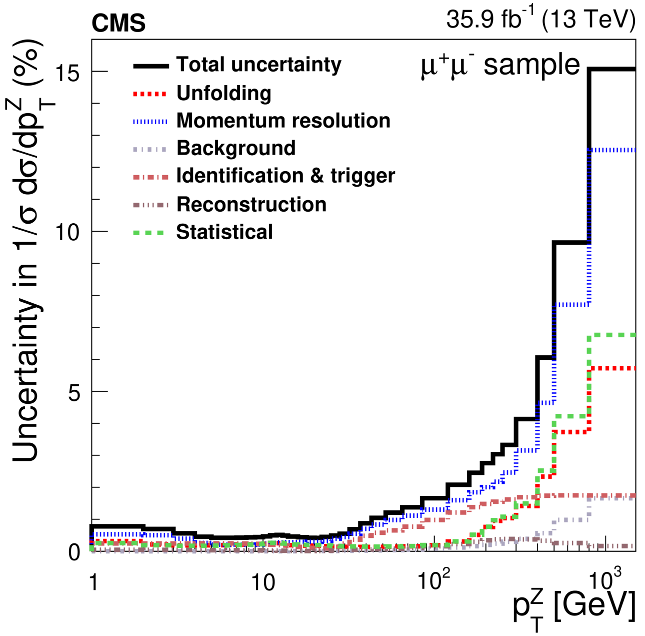
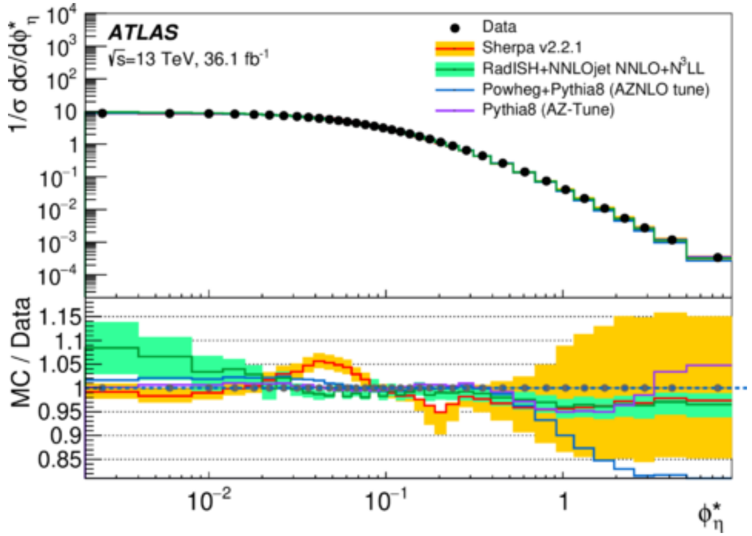
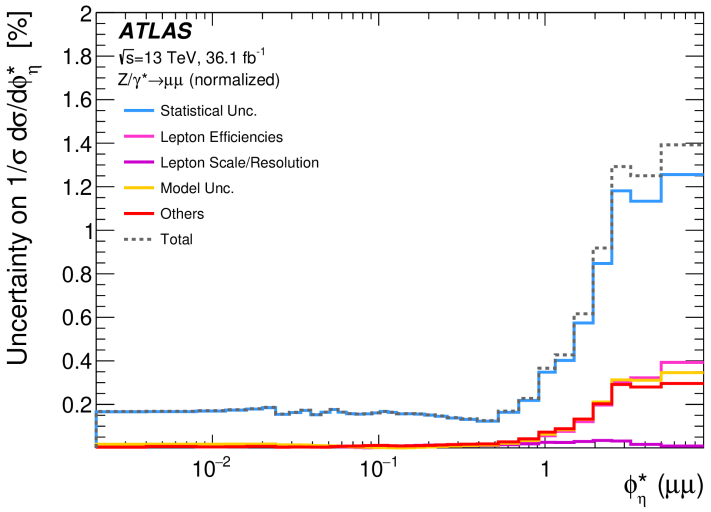
JHEP 12 (2019) 061

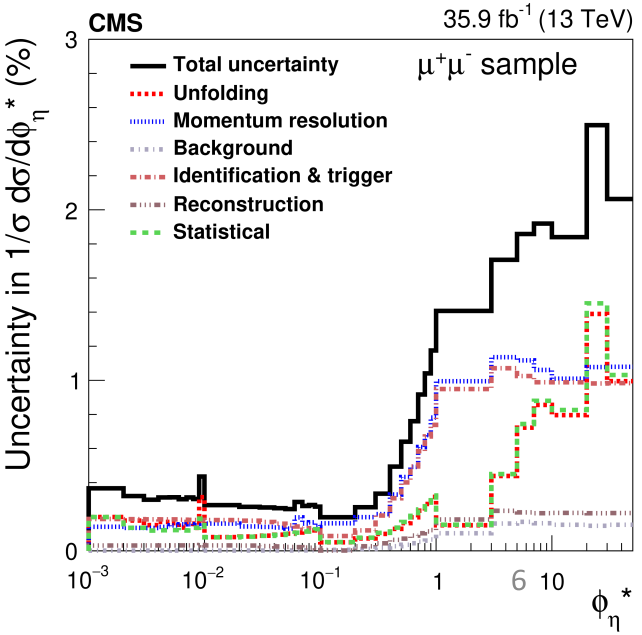








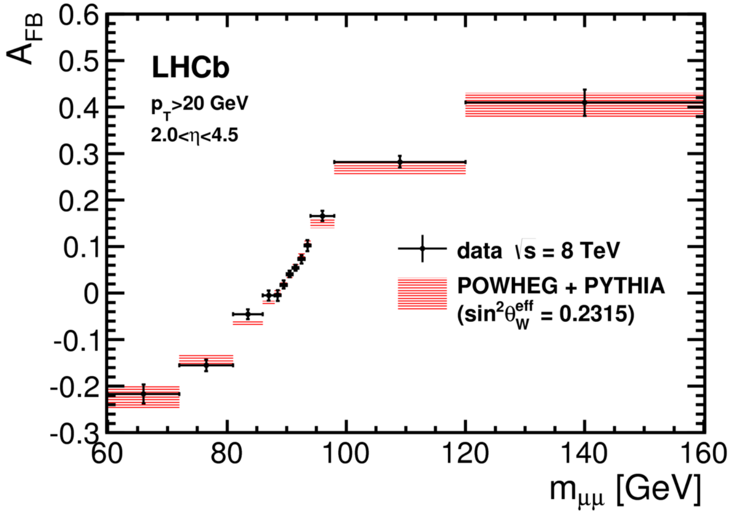




10^{-3} precision : $\sin\theta_W$

ATLAS: JHEP 1509 (2015) 49 4.8/fb @7TeV
LHCb:JHEP 1511 (2015) 190 1/fb+2/fb @7+8 TeV
CMS: arXiv:1806.00863 20/fb @8TeV
ATLAS-CONF-2018-037 20/fb @8TeV
(electron pairs with one electron in the forward region)

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC}+\mu\mu_{CC}$	$ee_{CC}+\mu\mu_{CC}+ee_{CF}$
Total	65	59	42	48	34
Stat.	47	39	29	30	21
Syst.	45	44	31	37	27
	Uncertainties in measurements				
PDF (meas.)	7	7	7	7	4
p_T^Z modelling	< 1	< 1	1	< 1	< 1
Lepton scale	5	4	6	3	3
Lepton resolution	3	1	3	1	2
Lepton efficiency	1	1	1	1	1
Electron charge misidentification	< 1	0	< 1	< 1	< 1
Muon sagitta bias	0	4	0	2	1
Background	1	1	1	1	1
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	36	37	21	32	22
QCD scales	5	5	9	4	6
EW corrections	3	3	3	3	3



effective leptonic weak mixing

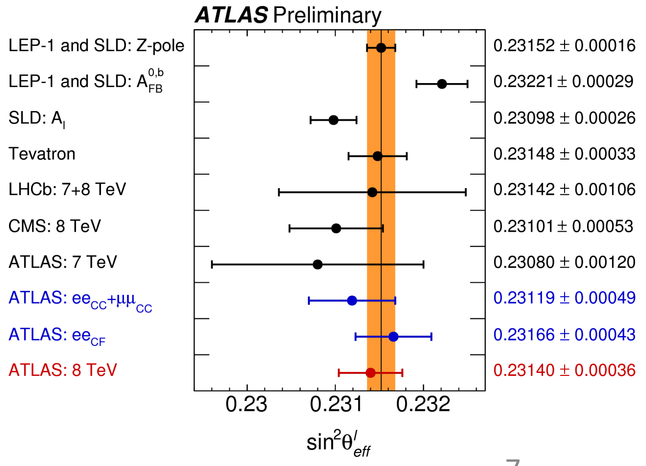
large PDF syst uncertainties can be reduced

- constraining in situ (off peak)
- fitting also angular coefficients (m_{ll}, y_ll)

impact of exp systematics are much smaller

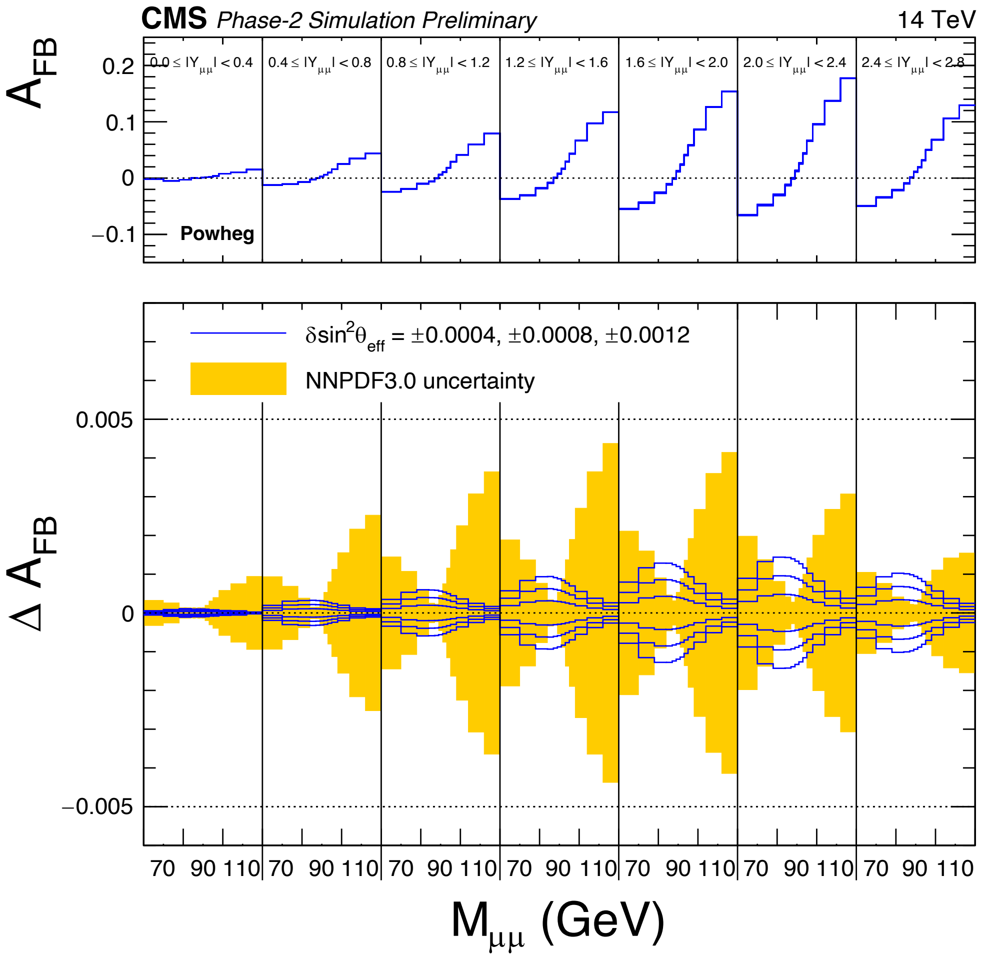
LHCb high rapidity yields less A^{FB} dilution

LEP+SLD still 2-3x better



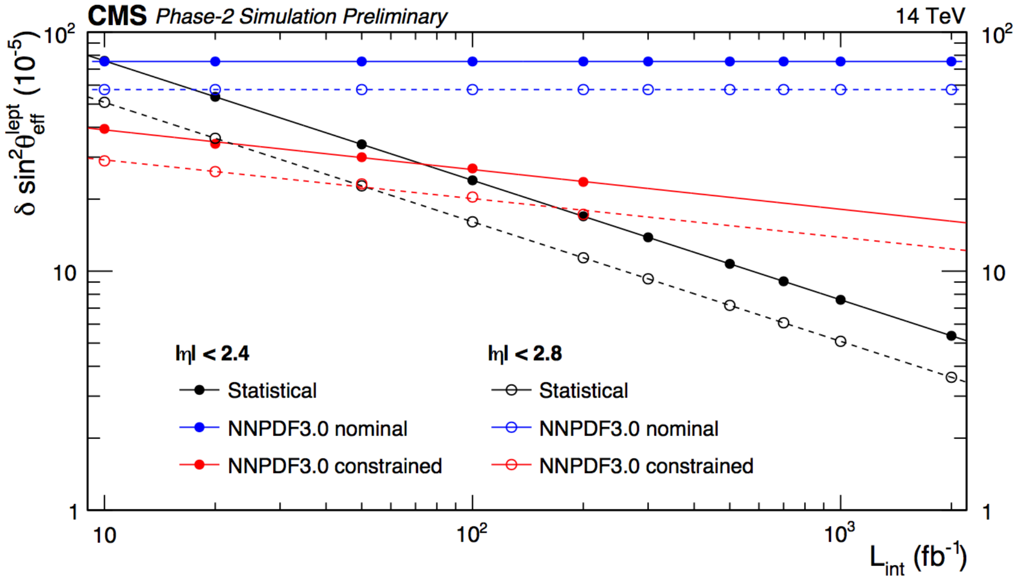
10^{-3} precision : $\sin\theta_W$

[CMS-PAS-FTR-17-001]



L_{int} (fb^{-1})	$\delta_{stat}[10^{-5}]$ $\lvert\eta\rvert < 2.4$	$\delta_{stat}[10^{-5}]$ $\lvert\eta\rvert < 2.8$	$\delta^{nominal}_{nnpdf3.0}[10^{-5}]$ $\lvert\eta\rvert < 2.4$	$\delta^{nominal}_{nnpdf3.0}[10^{-5}]$ $\lvert\eta\rvert < 2.8$	$\delta^{constrained}_{nnpdf3.0}[10^{-5}]$ $\lvert\eta\rvert < 2.4$	$\delta^{constrained}_{nnpdf3.0}[10^{-5}]$ $\lvert\eta\rvert < 2.8$
10	76	51	75	57	39	29
100	24	16	75	57	27	20
500	11	7	75	57	20	16
1000	8	5	75	57	18	14
3000	4	3	75	57	15	12
19	43		49		27	
19 (from [1])	44		54		32	

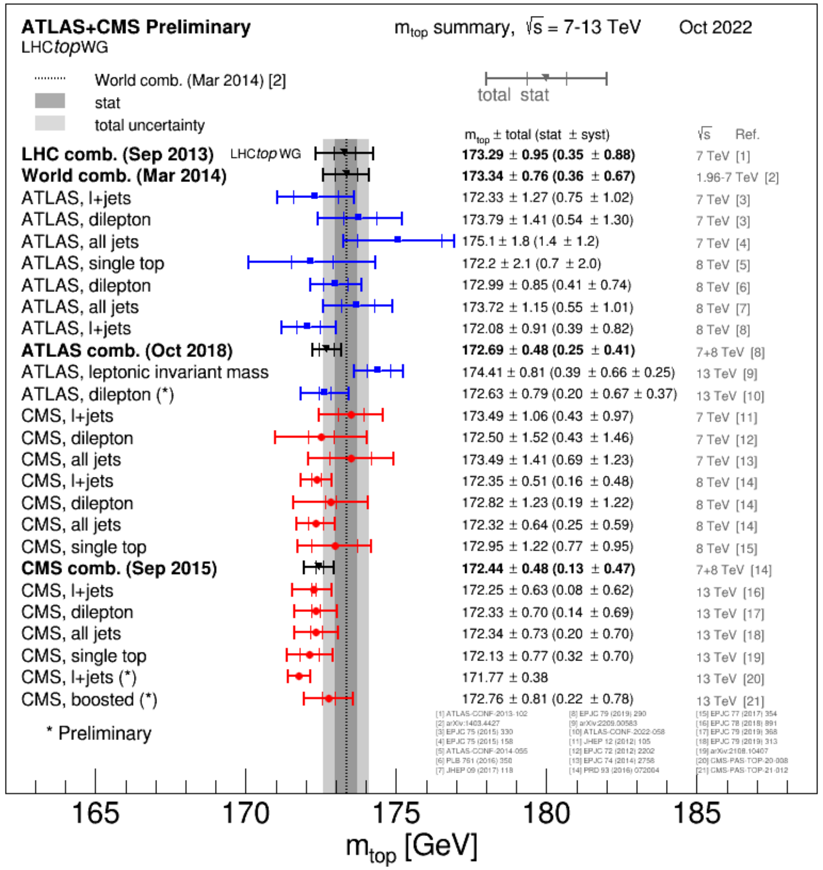
reach LEP+SLD precision with 1/ab (and improve with 3/ab)

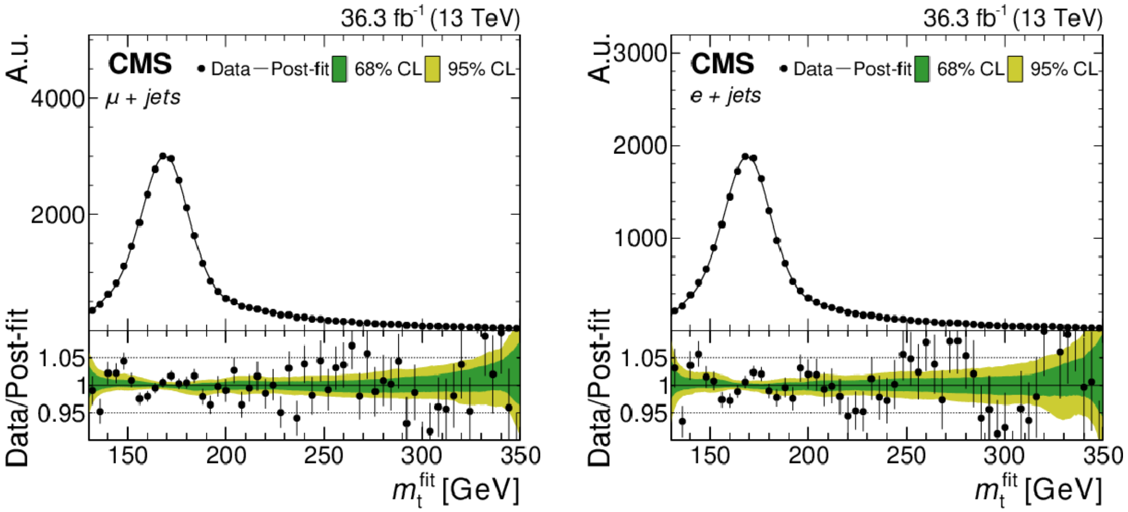


10^{-3} precision : top quark mass

Latest CMS arXiv:2302.01967

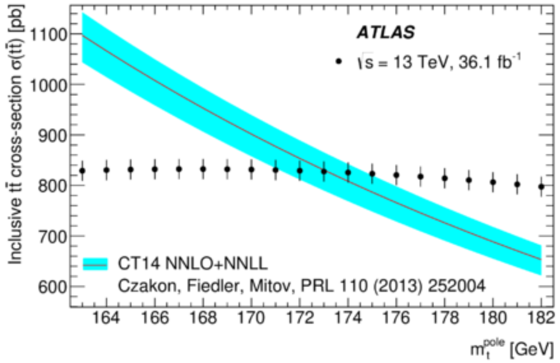
Direct reconstruction





5-D likelihood ⇒ $\mathbf{m_t=171.77 \pm 0.37}$ **GeV**

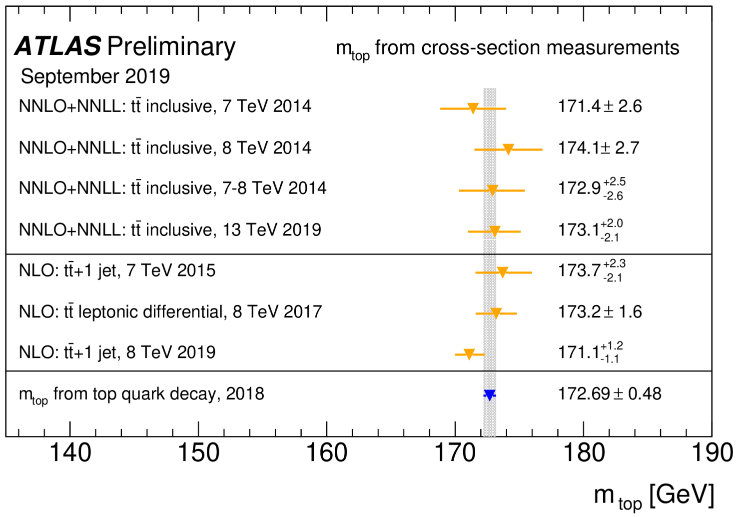
Complementary extraction of pole m_t from (differential) σ_{tt}



	δm_t [GeV] previous *2D*	*2D*	*5D*
Experimental uncertainties			
Method calibration	0.05	0.02	0.02
JEC	0.18	0.32	0.16
– Intercalibration	0.04	0.10	0.04
– MPFInSitu	0.07	0.15	0.07
– Uncorrelated	0.16	0.21	0.10
Jet energy resolution	0.12	0.12	0.05
b tagging	0.03	0.01	0.03
Lepton SFs and mom. scale		0.00	0.03
Pileup	0.05	0.00	0.03
Background	0.02	0.12	0.15
Modeling uncertainties			
JEC flavor	0.39	0.30	0.20
b-jet modeling	0.12	0.15	0.11
PDF	0.02	0.00	0.01
Ren. and fact. scales	0.01	0.03	0.02
ME/PS matching	0.07	0.06	0.07
ISR PS scale	0.07	0.01	0.01
FSR PS scale	0.13	0.37	0.21
Top quark p_T	0.01	0.06	0.00
Underlying event	0.07	0.09	0.04
Early resonance decays	0.07	0.13	0.09
CR modeling	0.31	0.15	0.15
Statistical	0.08	0.05	0.04
Total	0.63	0.52	0.37

large reductions of JES & JER impacts

top quark mass



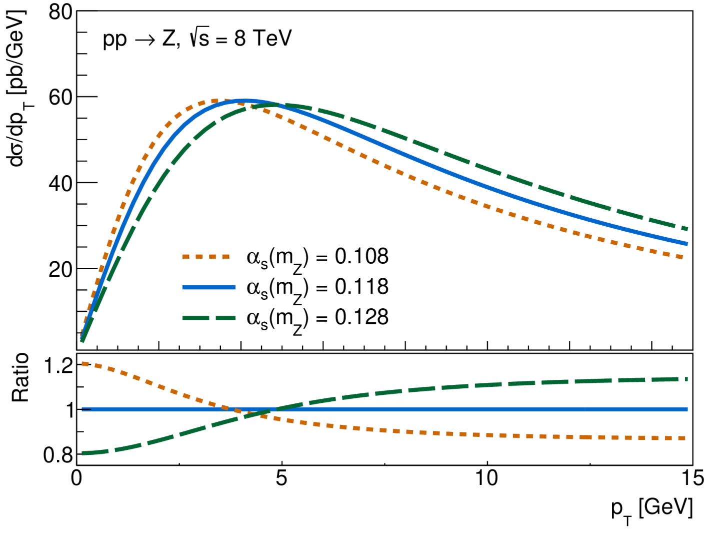
(CMS) JHEP 02 (2022) 142 :
simultaneous fit of inclusive jets and differential tt to extract PDFs, α_S / m_t :

$$\alpha_S(m_Z) = 0.1187 \pm 0.0016\,(\text{fit}) \pm 0.0005\,(\text{model}) \pm 0.0023\,(\text{scale}) \pm 0.0018\,(\text{param.})$$

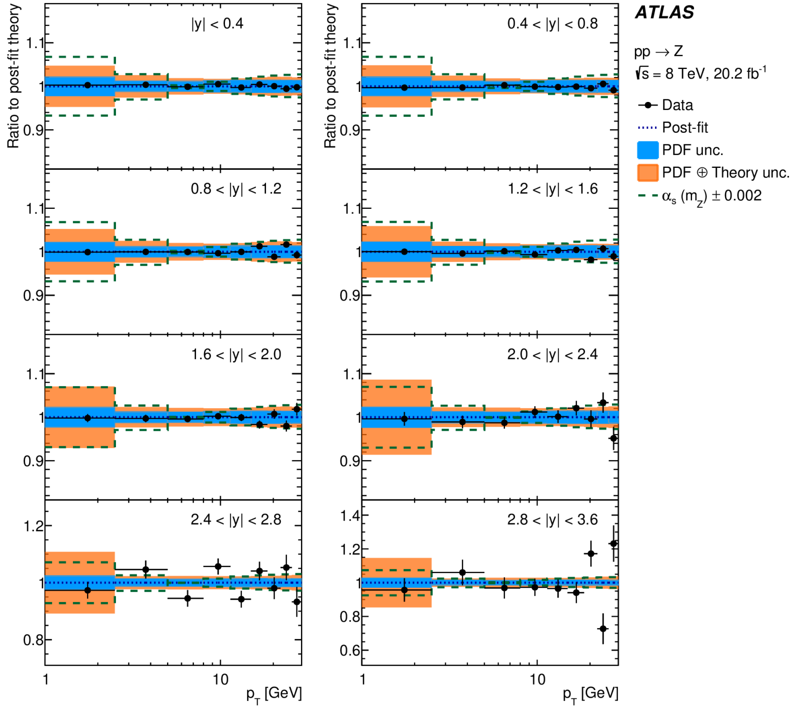
$$m_t^{\text{pole}} = 170.4 \pm 0.6\,(\text{fit}) \pm 0.1\,(\text{model}) \pm 0.1\,(\text{scale}) \pm 0.2\,(\text{param.})\,\text{GeV}$$

arXiv:2309.12986

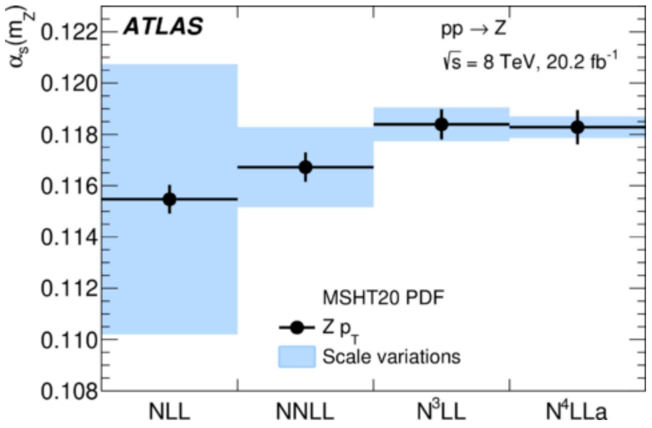
10^{-2} precision : $\boldsymbol{\alpha}_S$

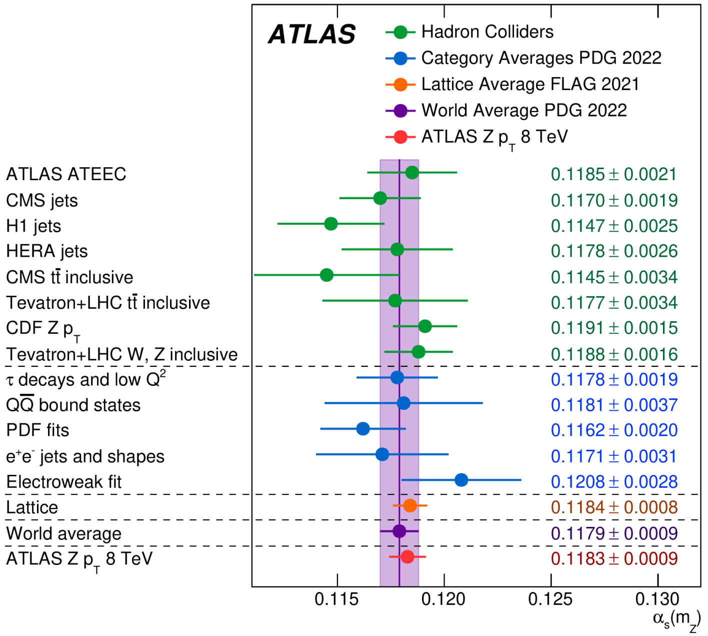


Experimental uncertainty	± 0.44	
PDF uncertainty	± 0.51	
Scale variation uncertainties	± 0.42	
Matching to fixed order	0	-0.08
Non-perturbative model	$+0.12$	-0.20
Flavour model	$+0.40$	-0.29
QED ISR	± 0.14	
$\mathrm{N}^4\mathrm{LL}$ approximation	± 0.04	
Total	$+0.91$	-0.88



units of 10^{-3}.





10^{-2} precision : $\boldsymbol{\alpha}_S$

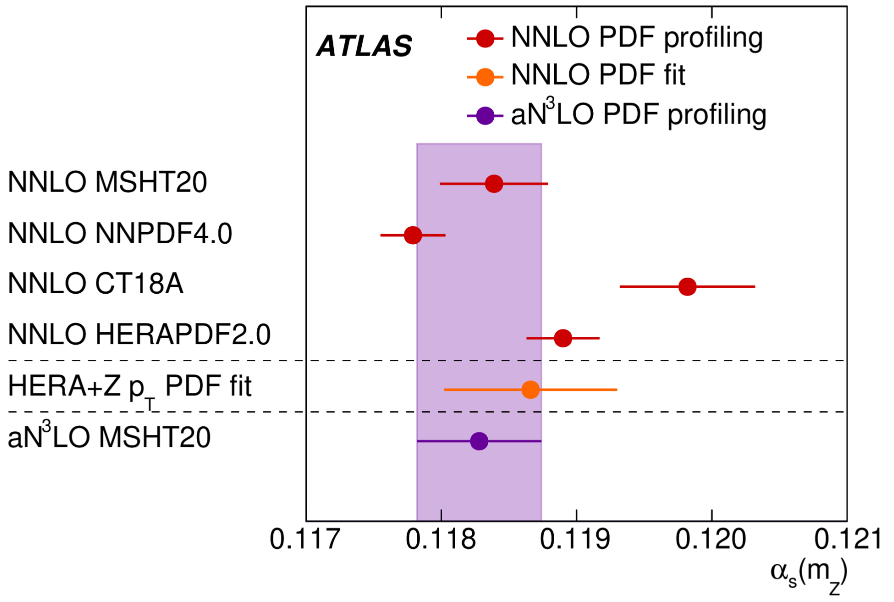
NP QCD form factor

$$S_{\rm NP}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}^2}{Q_0^2}\right]$$

$$g_j(b) = \frac{g\,b^2}{\sqrt{1+\lambda b^2}} + \text{sign}(q)\left(1-\exp\left[-|q|\,b^4\right]\right)$$

$$g_K(b) = g_0\left(1-\exp\left[-\frac{C_F\alpha_s(b_0/b_*)b^2}{\pi g_0\, b_{\rm lim}^2}\right]\right),$$

g and *q* are fitted from data
other parameters varied to assess
envelope of syst uncertainty



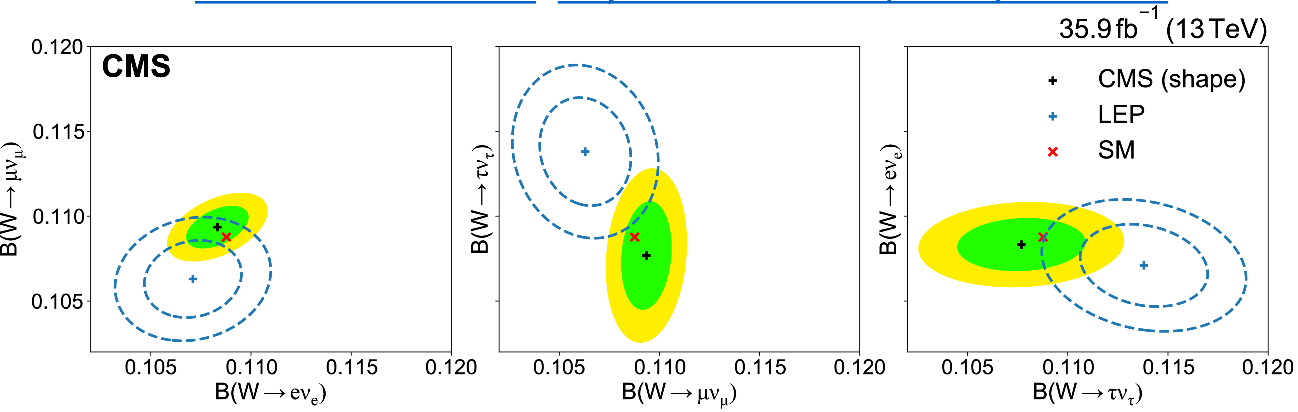
compare with most recent CMS-PAS-SMP-22-005
$\boldsymbol{\alpha}_S$ form jet azimuthal correlations

PDF set	$\alpha_S(M_Z)$	Exp.	NP	PDF	EW	Scale	$\chi^2/n_{\rm dof}$
ABMP16	0.1197	0.0008	0.0007	0.0007	0.0002	$^{+0.0043}_{-0.0042}$	16/16
CT18	0.1159	0.0013	0.0009	0.0014	0.0002	$^{+0.0099}_{-0.0067}$	19/16
MSHT20	0.1166	0.0013	0.0008	0.0010	0.0003	$^{+0.0112}_{-0.0063}$	17/16
NNPDF3.1	0.1177	0.0013	0.0011	0.0010	0.0003	$^{+0.0114}_{-0.0068}$	20/16

here NP uncertainties from envelope of MC gen showers & tunes

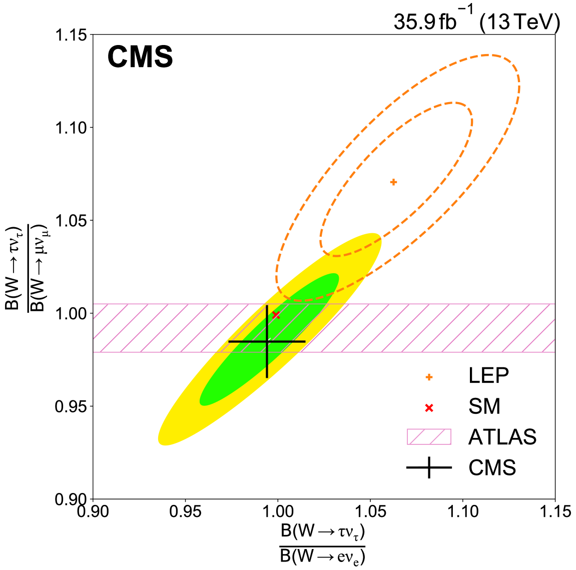
W decay measurements

CMS SMP-18-011 *Phys. Rev. D 105 (2022) 072008*



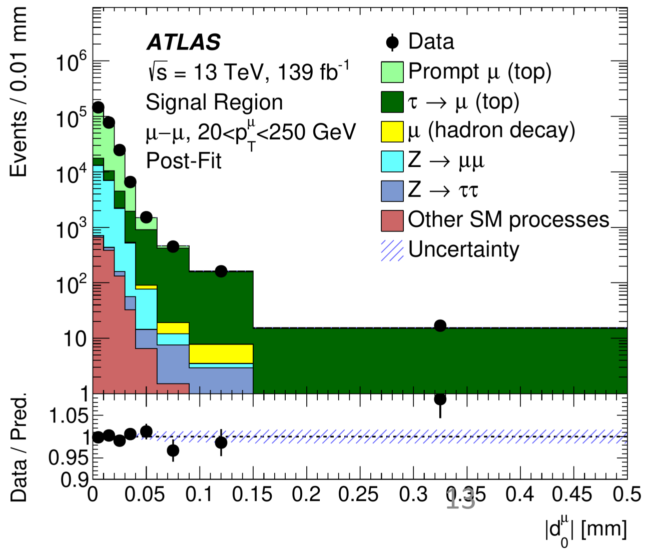
	CMS	LEP
$\mathcal{B}(W \to e\bar{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\bar{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\bar{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to q\bar{q}')$	$(67.46 \pm 0.04 \pm 0.28)\%$	—
Assuming LFU		
$\mathcal{B}(W \to \ell\bar{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to q\bar{q}')$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

$\alpha_S(m_W^2)$	$\lvert V_{cs}\rvert$	$\sum_{ij}\lvert V_{ij}\rvert^2$
0.095 ± 0.033	0.967 ± 0.011	1.984 ± 0.021 height



	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—	—	—	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	—	—	—
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—	—	—	—

ATLAS Nature Phys. 17 (2021) 813



W decay measurements

	$W \to e\bar{\nu}_e$	$W \to \mu\bar{\nu}_\mu$	$W \to \tau\bar{\nu}_\tau$	$W \to q\bar{q}'$
Pileup	20	6	11	14
Luminosity	5	14	5	7
JES/JER	3–17	5–21	4–11	4–21
b tagging	<1–19	<1–25	<1–5	<1–17
tW normalization	35	43	27	46
WW normalization	8	9	5	9
WW p_T	1–2	1–2	<1–5	<1–4
W+jets normalization	<1–6	<1–7	<1–13	<1–10
γ+jets normalization	1	2	5	4
WZ, ZZ normalization	<1	1	<1	<1
$t\bar{t}$ production:				
QCD scale	32	47	25	45
top quark p_T	16	24	7	18
ISR	10	16	37	37
FSR	3	4	9	5
PDF	4	5	3	4
α_S	5	5	3	6
PYTHIA 8 UE tune	1	5	7	7
hdamp parameter	3	3	2	4
Drell–Yan background:				
QCD scale	2–24	10–27	5–20	8–30
PDF	3	5	2	4
QCD multijet background:				
$e\mu$	5	12	12	6
eh	3–4	11–17	6–7	6–10
μh	10–11	10–13	5–13	2–3
$e\tau_h$	<1–5	<1–8	<1–9	<1–7
$\mu\tau_h$	<1–12	<1–10	<1–9	<1–10
emeasurement:				
Reconstruction efficiency	50	13	3	15
Identification efficiency	<1–14	1–8	<1–10	<1–5
Trigger (prefiring)	29	2	1	9
Trigger	<1–27	<1–4	<1–13	<1–9
Energy scale	7	6	<1	4
μ measurement:				
Reconstruction efficiency	<1–2	<1–5	<1–6	<1–6
Trigger	8	26	3	7
Energy scale	1	<1	3	2
τ_h measurement:				
Reconstruction efficiency	2–14	7–17	21–46	14–24
Energy scale	9	5	14	6
Jet misidentification	1–14	<1–10	1–24	<1–10
emisidentification	<1	<1	2	1
$\tau \to e, \mu, h$	<1	<1	<1–2	<1–1

[CMS SMP-18-011](#)

[Phys. Rev. D 105 (2022) 072008](#)

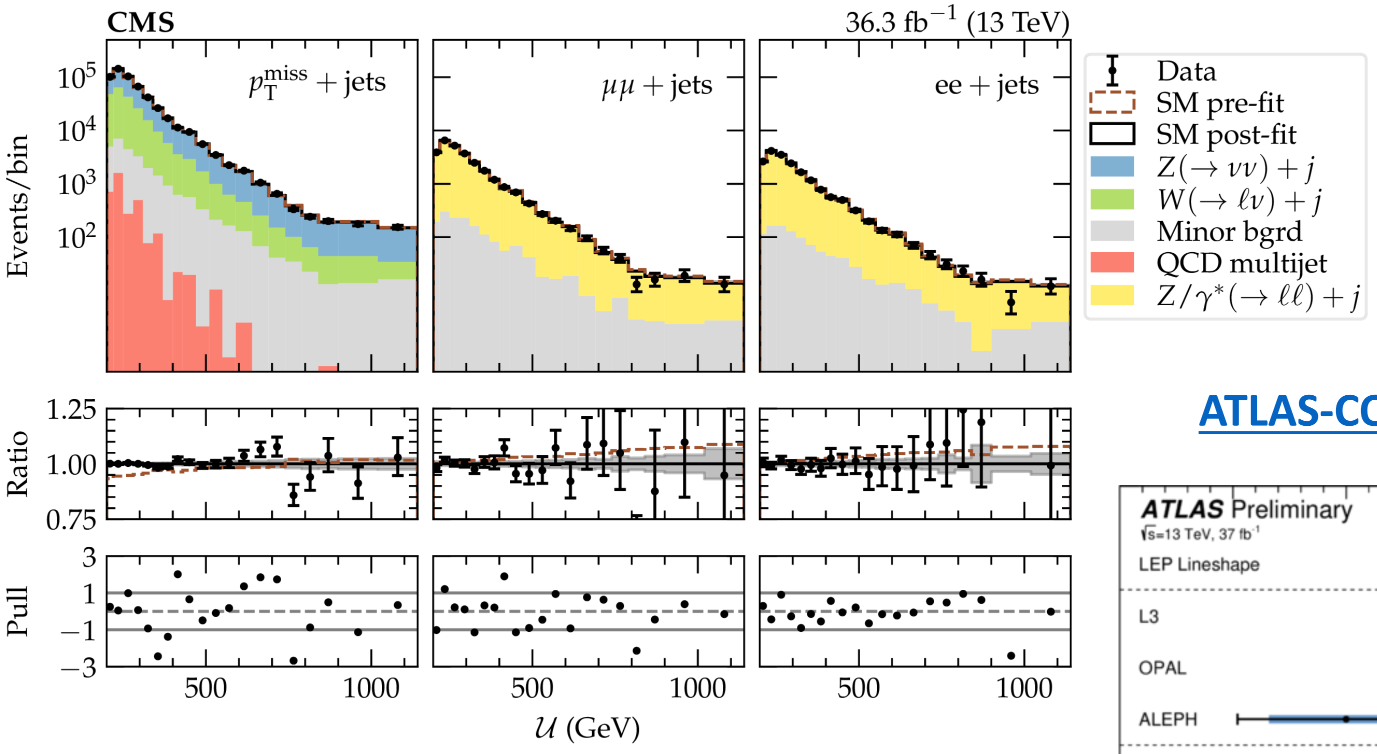
<table>
<tr><th></th><th>$N_j = 0$</th><th>$N_j = 1$</th><th>$N_j = 2$</th><th>$N_j = 3$</th><th>$N_j \geq 4$</th></tr>
<tr><td>$N_b = 0$</td><td>$e\tau_h$, $\mu\tau_h$, $e\mu$</td><td>$e\tau_h$, $\mu\tau_h$, $e\mu$</td><td colspan="3">$e\tau_h$, $\mu\tau_h$ $e\mu$</td></tr>
<tr><td rowspan="3">$N_b = 1$</td><td rowspan="3"></td><td rowspan="2">$e\tau_h$, $\mu\tau_h$, $e\mu$</td><td>$e\tau_h$, $\mu\tau_h$</td><td colspan="2">$e\tau_h$, $\mu\tau_h$</td></tr>
<tr><td colspan="3">ee, $\mu\mu$, $e\mu$</td></tr>
<tr><td colspan="3"></td><td>eh, μh</td></tr>
<tr><td rowspan="3">$N_b \geq 2$</td><td rowspan="3" colspan="2"></td><td>$e\tau_h$, $\mu\tau_h$</td><td colspan="2">$e\tau_h$, $\mu\tau_h$</td></tr>
<tr><td colspan="3">ee, $\mu\mu$, $e\mu$</td></tr>
<tr><td colspan="2"></td><td>eh, μh</td></tr>
</table>

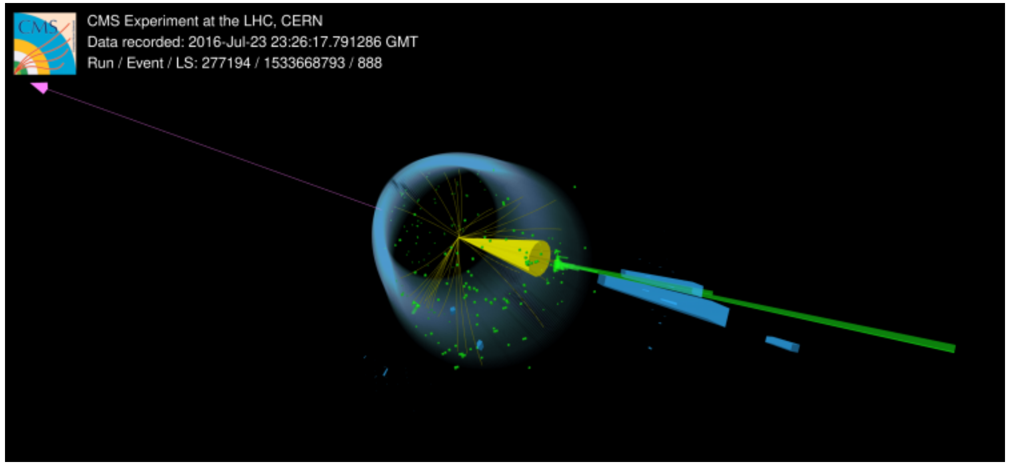
Source	**Impact on $R(\tau/\mu)$**
Prompt d_0^μ templates	0.0038
$\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
$\mu_{(had.)}$ normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
$\mu_{(had.)}$ parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

[ATLAS Nature Phys. 17 (2021) 813](#)

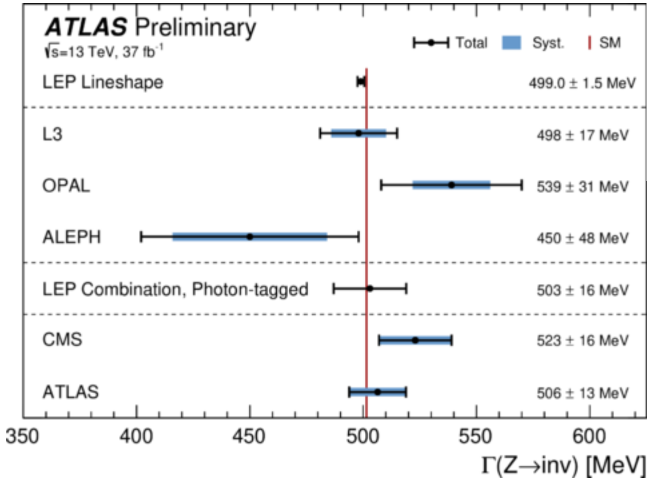
invisible Z width

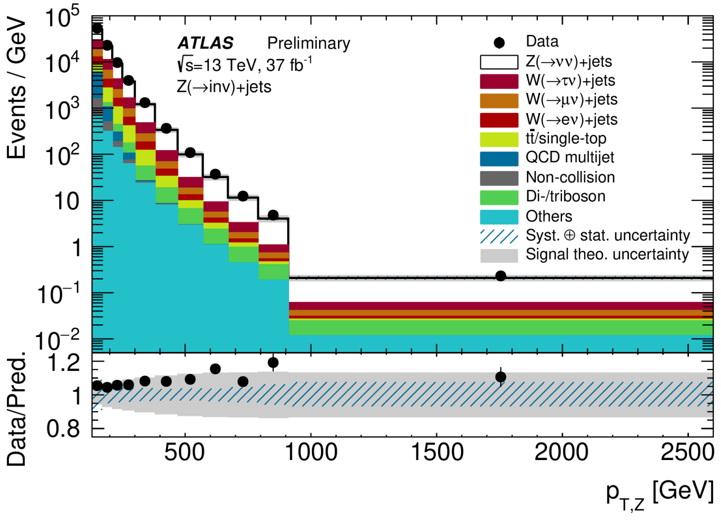
CMS   Phys. Lett. B 842 (2023) 137563





ATLAS-CONF-2023-053





$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z\text{+jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z\text{+jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

Γ_Z^{inv} **direct** determinations
(LEP single-γ is more direct)

invisible Z width

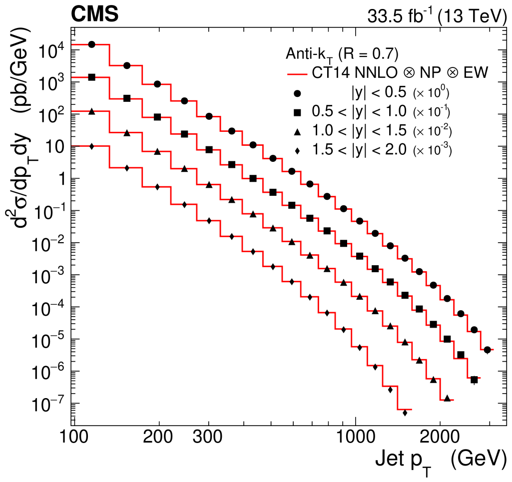
ATLAS-CONF-2023-053

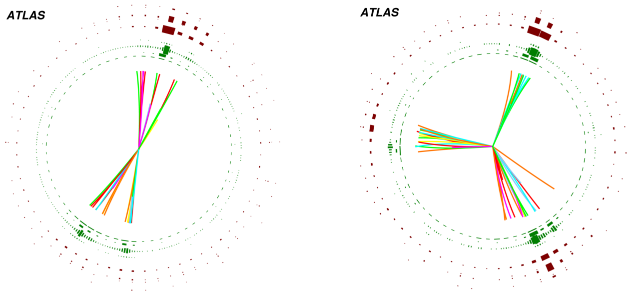
CMS Phys. Lett. B 842 (2023) 137563

Source of systematic uncertainty	Uncertainty (%)
Muon identification efficiency (syst.)	2.1
Jet energy scale	1.8–1.9
Electron identification efficiency (syst.)	1.6
Electron identification efficiency (stat.)	1.0
Pileup	0.9–1.0
Electron trigger efficiency	0.7
τ_h veto efficiency	0.6–0.7
p_T^{miss} trigger efficiency (jets plus p_T^{miss} region)	0.7
p_T^{miss} trigger efficiency ($Z/\gamma^* \to \mu\mu$ region)	0.6
Boson p_T dependence of QCD corrections	0.5
Jet energy resolution	0.3–0.5
p_T^{miss} trigger efficiency (μ+jets region)	0.4
Muon identification efficiency (stat.)	0.3
Electron reconstruction efficiency (syst.)	0.3
Boson p_T dependence of EW corrections	0.3
PDFs	0.2
Renormalization/factorization scale	0.2
Electron reconstruction efficiency (stat.)	0.2
Overall	3.2

Systematic Uncertainty	Impact on $\Gamma(Z \to \text{inv})$ in [MeV]	in [%]
Muon efficiency	7.4	1.5
Renormalisation & factorisation scales	5.9	1.2
Electron efficiency	4.9	1.0
Detector correction	4.4	0.9
QCD multijet	3.2	0.6
E_T^{miss}	2.4	0.5
$Z(\to \mu\mu)$+jets mis. id. lepton estimate	1.9	0.4
Jet energy resolution	1.6	0.3
$W(\to \ell\nu)$+jets normalisation	1.5	0.3
Pile-up reweighting	1.5	0.3
Non-collision background estimate	1.3	0.3
Jet energy scale	1.3	0.3
γ^*-correction	1.0	0.2
$Z(\to ee)$+jets mis. id. lepton estimate	1.0	0.2
Luminosity	1.0	0.2
Parton distribution functions + α_s	0.7	0.1
$\Gamma(Z \to \ell\ell)$ [5,9]	0.5	0.1
Tau energy scale	0.4	0.1
Muon momentum scale	0.3	0.1
$W(\to \ell\nu)$+jets mis. id. lepton estimate	0.3	0.1
(Forward) jet vertex tagging	0.2	< 0.1
Top subtraction scheme	0.2	< 0.1
Electron energy scale	0.1	< 0.1
Systematical	12	2.4
Statistical	2	0.4
Total	13	2.5

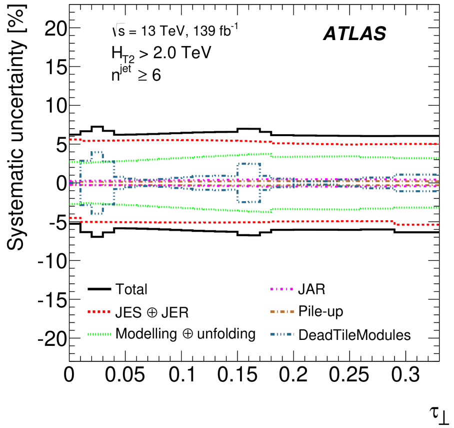
jets

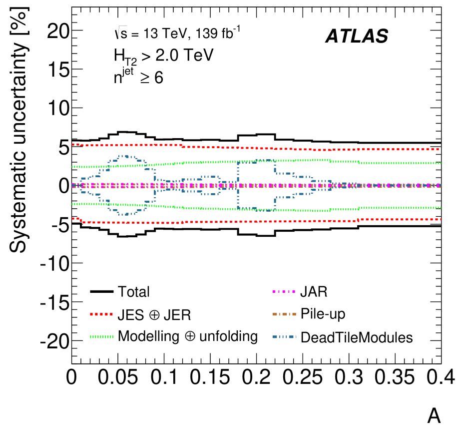




event shapes (multijets)

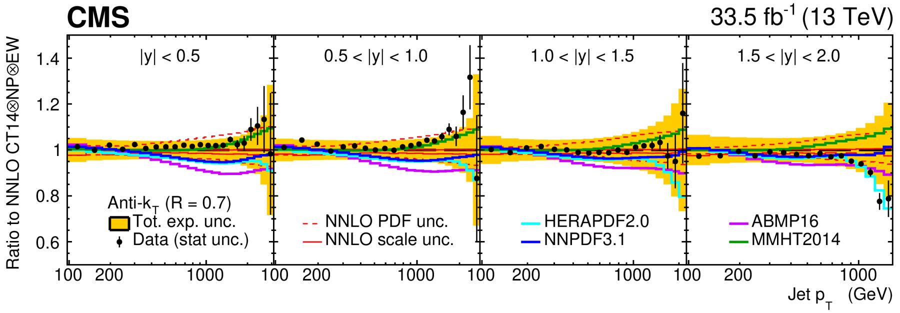
ATLAS *JHEP 01 (2021) 188*

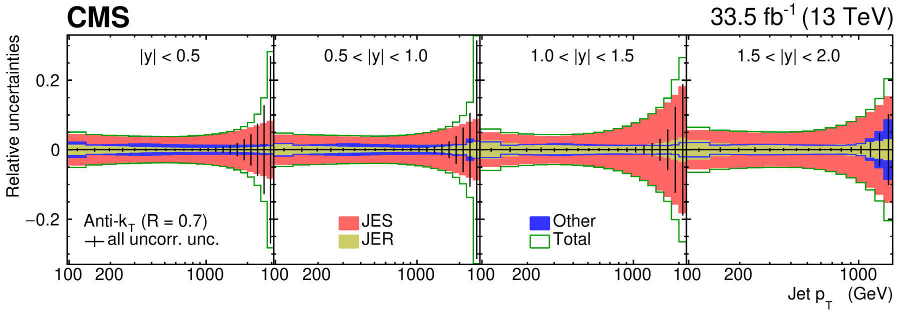


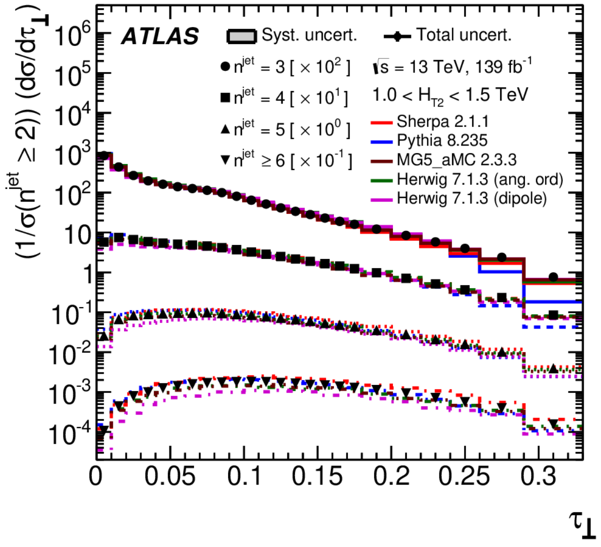


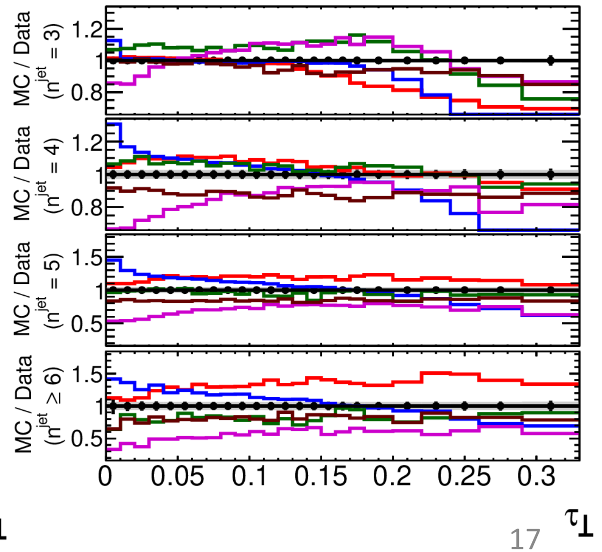
double differential inclusive jets

CMS : [JHEP 02 (2022) 142](#) :



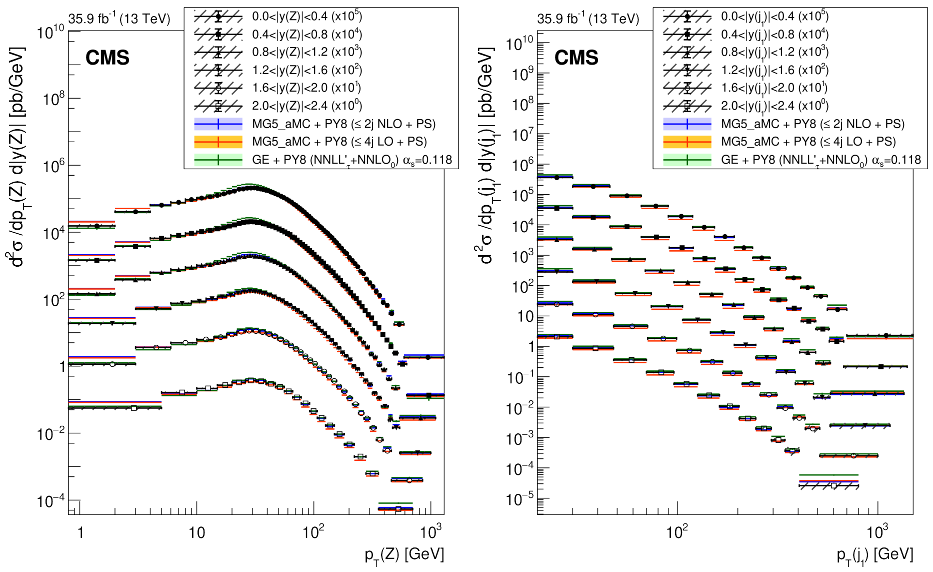




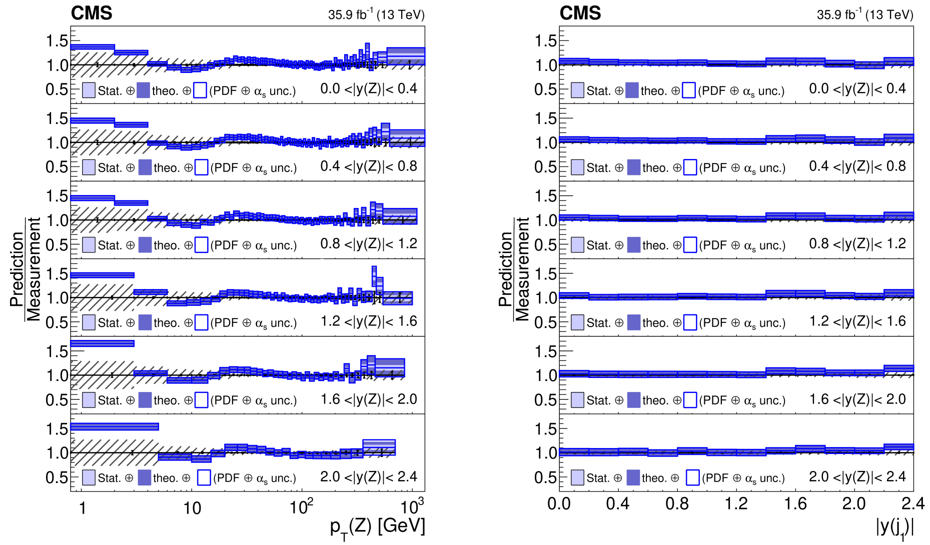


V + jets

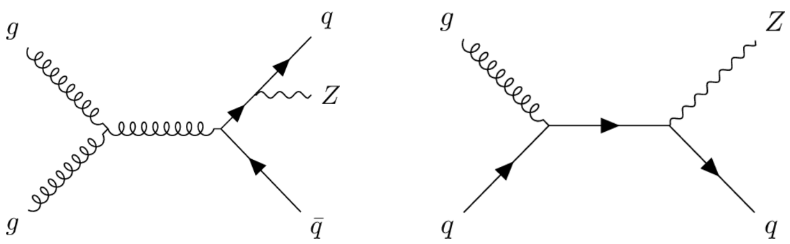
exhaustive multi-differential measurements

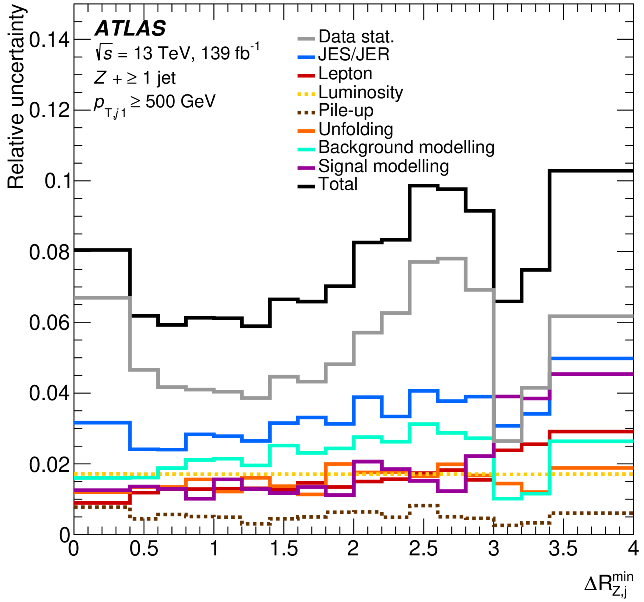


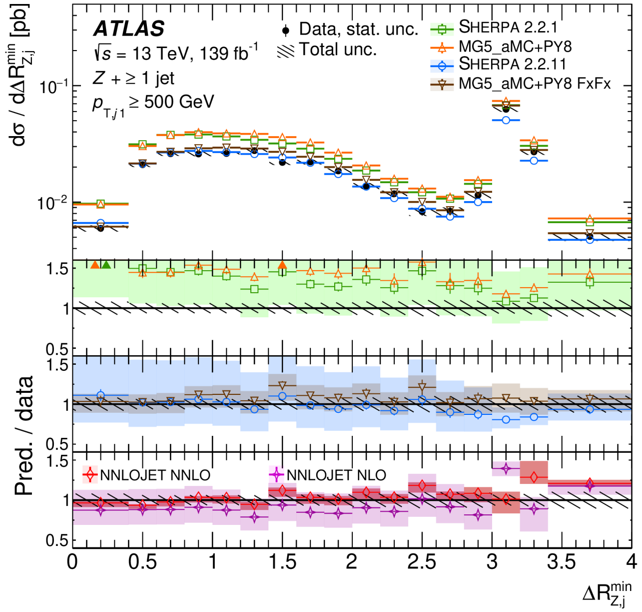
[Phys. Rev. D 108 (2023) 052004]()



ATLAS Z+ high pT jets

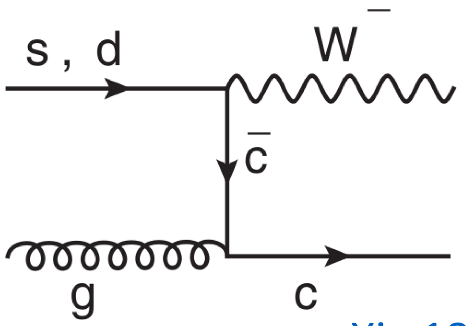




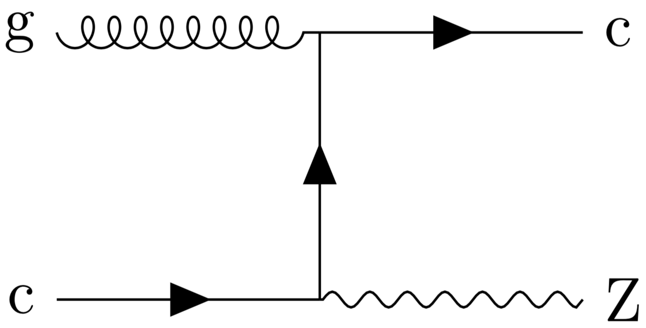


integrated unc

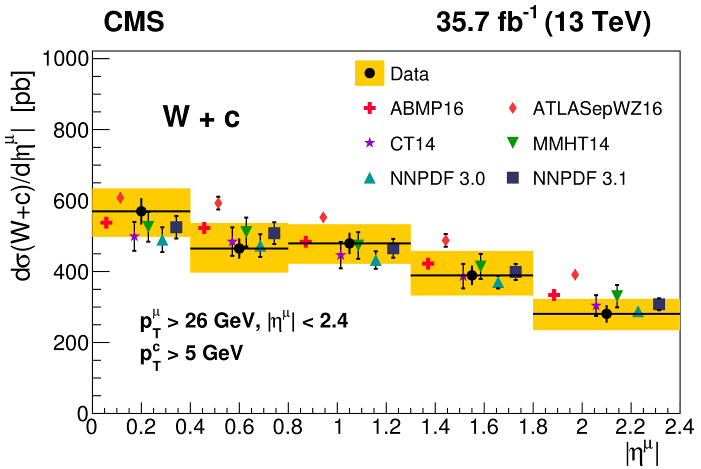
Uncertainty source [%]	*Inclusive*	*High-p_T*	*Collinear*	*Back-to-back*	*High-S_T*
JES/JER	2.6	3.2	2.8	3.6	2.8
Lepton	0.9	1.6	1.4	2.0	1.1
Luminosity	1.7	1.7	1.7	1.7	1.7
Pile-up	0.1	0.4	0.4	0.4	0.4
Unfolding	0.5	1.0	1.1	1.4	0.8
Background modelling	0.5	2.0	2.0	1.9	1.7
Signal modelling	0.5	1.2	1.1	1.1	1.1
Total syst. uncertainty	3.4	4.8	4.4	5.3	4.2
Data stat. uncertainty	0.1	2.1	2.9	2.7	1.2
Total uncertainty	3.4	5.3	5.3	5.9	4.4

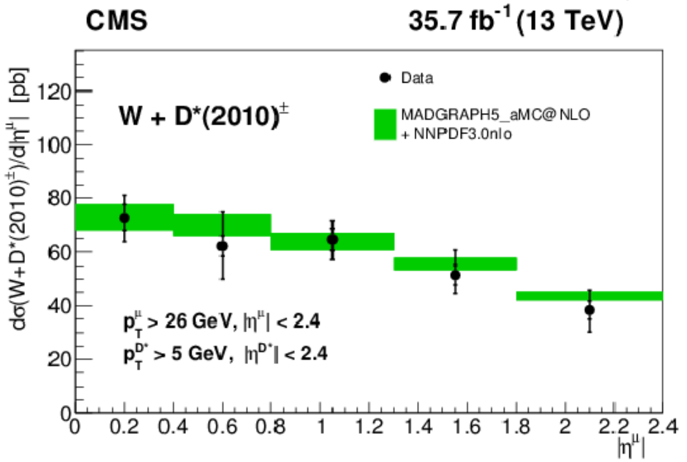


V + charm

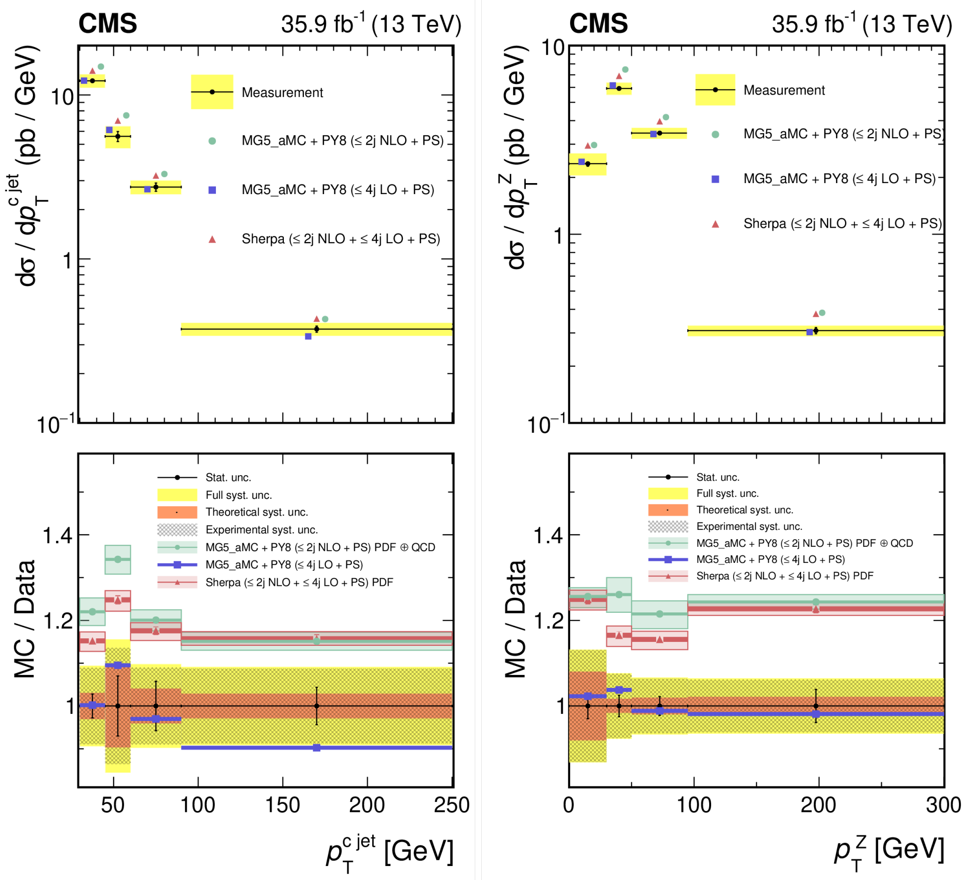


arXiv:1811.10021 + arXiv:2308.02285

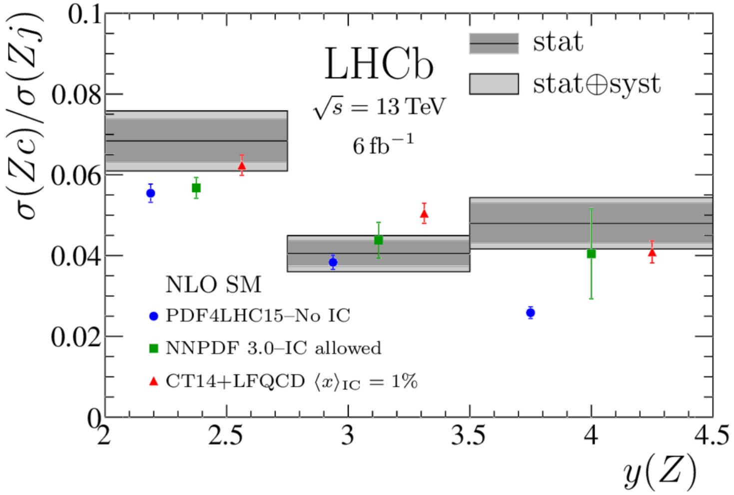




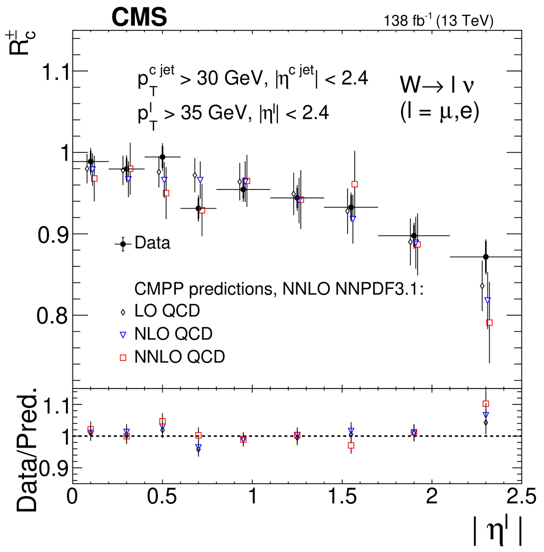
Z+c arXiv:2012.04119



Would be interesting to use full lumi for Z+c **exploring more IC scenarios** (forward rapidity ?)

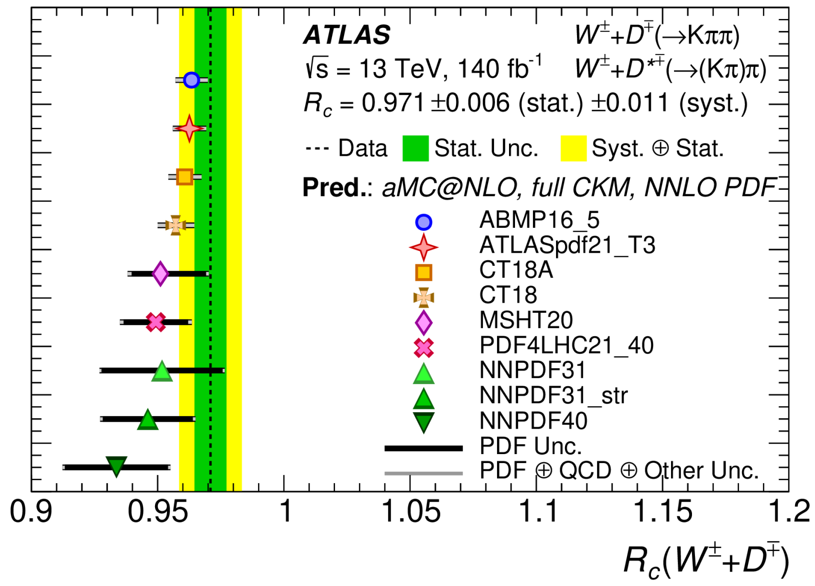


arXiv:2109.08084



W + charm

OS-SS bkg subctraction



W+c CMS :[arXiv:2308.02285]

syst related to charm-tagging

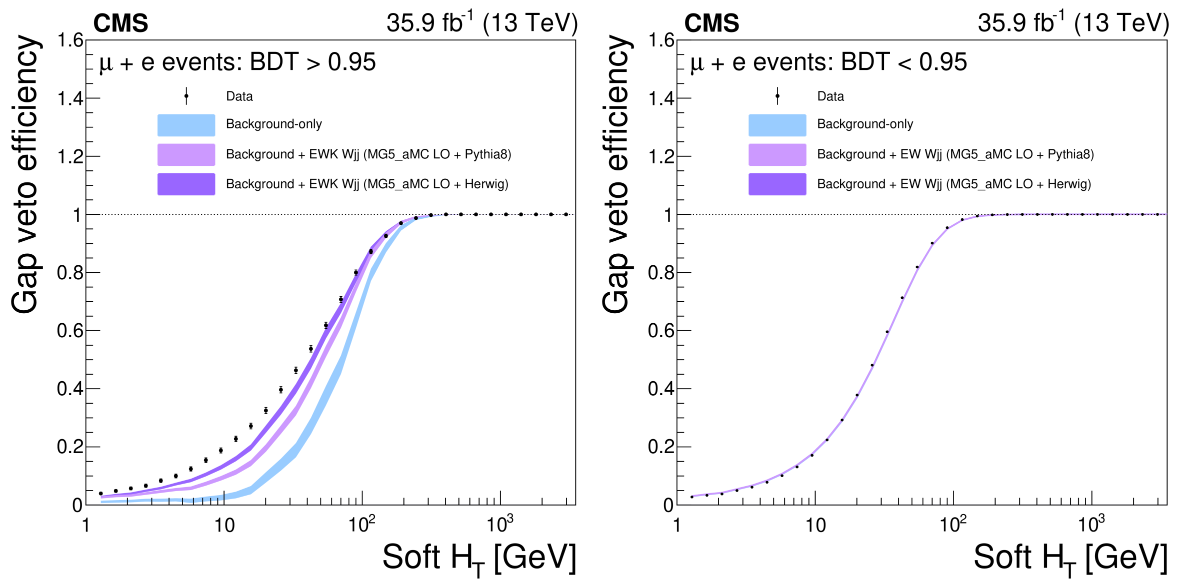
W+D ATLAS : ***Phys. Rev. D 108 (2023) 032012***

	SL $W \to e\nu$	SL $W \to \mu\nu$	SV $W \to e\nu$	SV $W \to \mu\nu$
Source	Uncertainty [%]			
Isolated lepton identification	1.6	0.9	1.6	0.9
Jet energy scale and resolution	2.0	2.0	1.0	1.0
Muon in jet identification	3.0	3.0	—	—
SV reconstruction	—	—	3.7	3.7
Charm fragmentation and decay	2.6	2.6	2.4	2.4
PDF in MC samples	1.0	1.0	1.0	1.0
Stat. uncert. selection efficiency	0.9	1.2	0.9	0.8
Background contributions	0.6	0.9	1.3	1.3
Integrated luminosity	1.6	1.6	1.6	1.6
Total	5.2	5.1	5.4	5.2

	D^+ channel			D^{*+} channel		
Uncertainty [%]	$\sigma_{fid}^{OS-SS}(W^-+D^+)$	$\sigma_{fid}^{OS-SS}(W^++D^-)$	$R_c^{\pm}(D^+)$	$\sigma_{fid}^{OS-SS}(W^-+D^{*+})$	$\sigma_{fid}^{OS-SS}(W^++D^{*-})$	$R_c^{\pm}(D^{*+})$
SV reconstruction	3.0	2.9	0.5	2.3	2.3	0.4
Jets and E_T^{miss}	1.7	1.9	0.2	1.5	1.5	0.4
Luminosity	0.8	0.8	0.0	0.8	0.8	0.0
Muon reconstruction	0.6	0.7	0.3	0.7	0.7	0.3
Electron reconstruction	0.2	0.2	0.0	0.2	0.2	0.0
Multijet background	0.2	0.2	0.1	0.1	0.1	0.1
Signal modeling	2.1	2.1	0.1	1.2	1.2	0.0
Signal branching ratio	1.6	1.6	0.0	1.1	1.1	0.0
Background modeling	1.1	1.2	0.3	1.3	1.3	0.5
Finite size of MC samples	1.2	1.2	1.1	1.4	1.4	1.3
Data statistical uncertainty	0.5	0.5	0.7	0.7	0.7	1.0
Total	4.6	4.6	1.4	3.7	3.7	1.7

precision in parton showers : rapidity gap

PS is now the leading systematic uncertainty source for VBF & VBS measurements



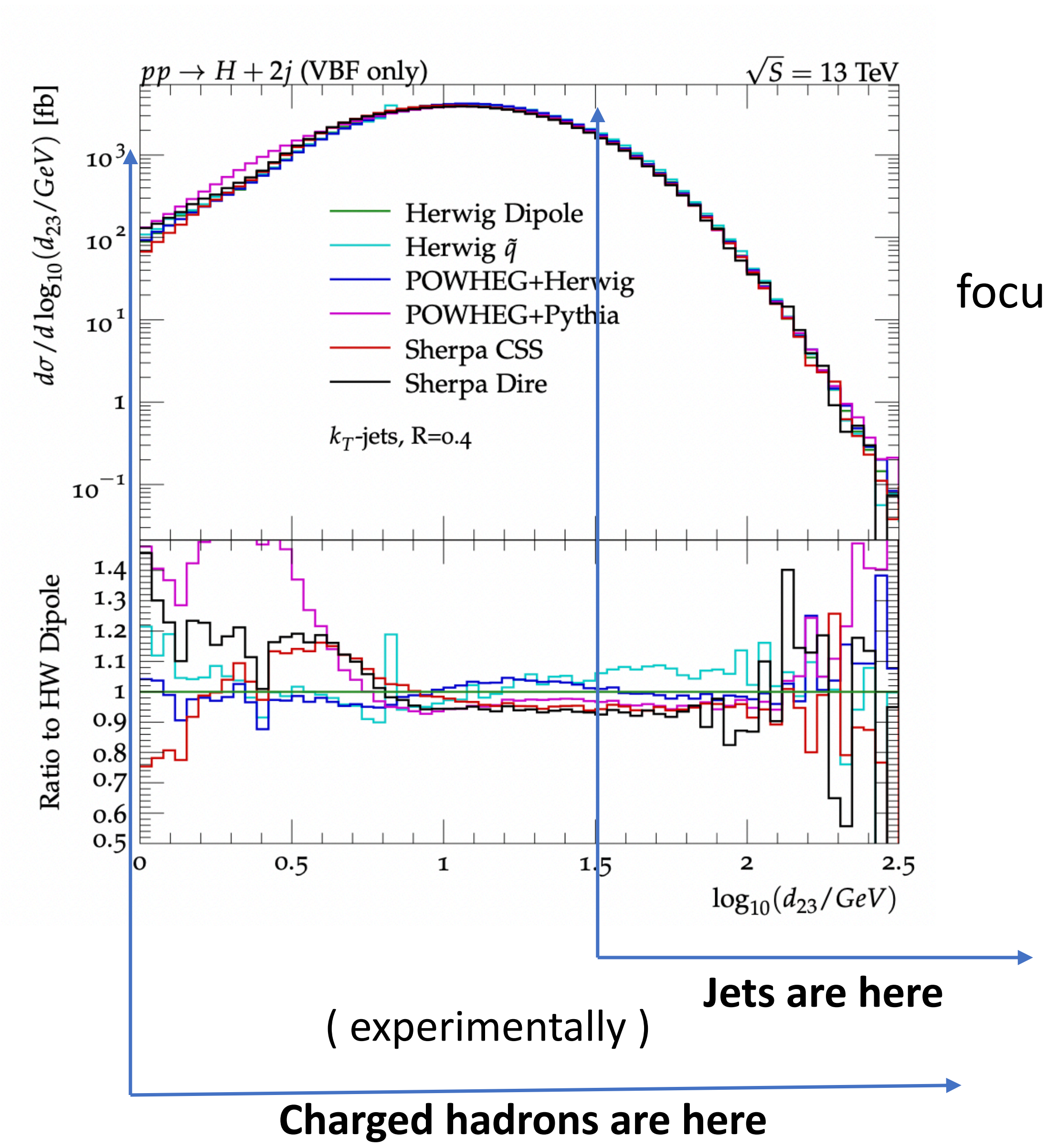
VBF Z & W events relatively large productions offer the opportunity to **measure and test rap gap activity** predictions.

Very **relevant for VBF Higgs and VBS** analyses that often make (in)direct use of the rap gap signal properties

can test & show results with several other model (pythia **dipole** recoil …)

2105.11399

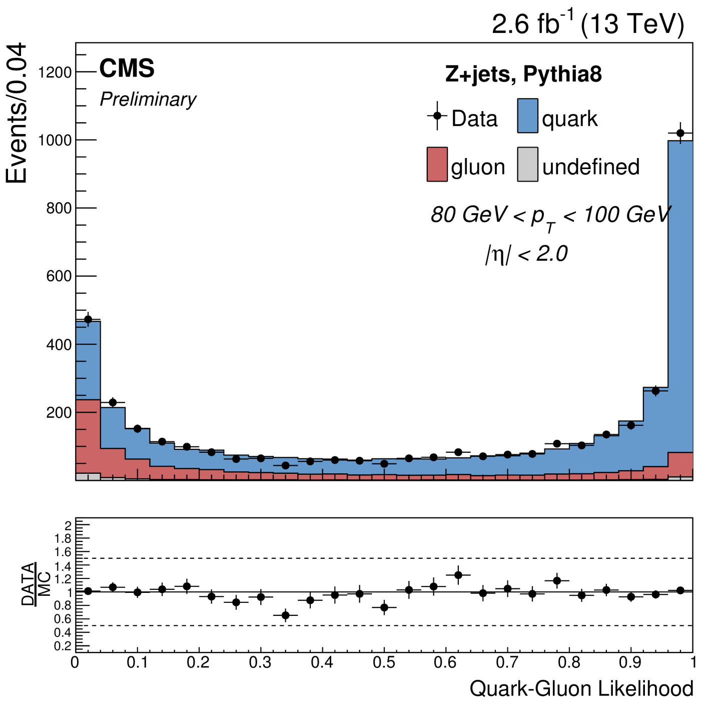
precision in parton showers



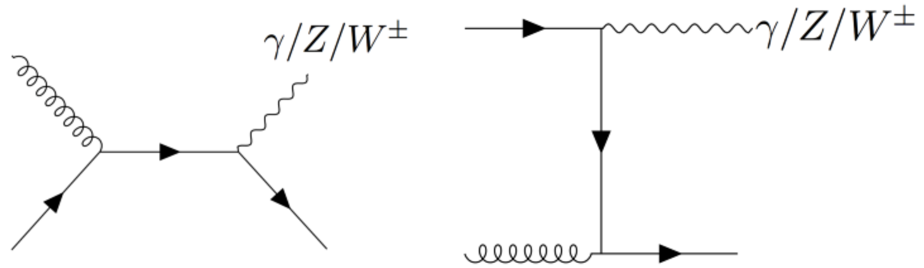
focus on the individual hadrons for precise observations

Future developments ?
Retuning with more information (particle id)
Higher-order precision in PSs
How reliable is LEP Z→qq data for fragmentation ?

quark and gluon jets



potentially interesting phenomenology of q/g-jets fractions in different (pT,y) kinematic regions to be explored



Interplay of gluon-jet fractions in pp→ dijet and V+jet would have important impact on Gluon PDF determinations

CMS JME-13-002 JME-16-003

possible measurements and procedures to be defined with theorists (Predictions/results depend on jet clustering radius)

ATLAS ATL-PHYS-PUB-2017-017
Eur. Phys. J. C (2014) 74:
arXiv:2308.00716

quark and gluon jets

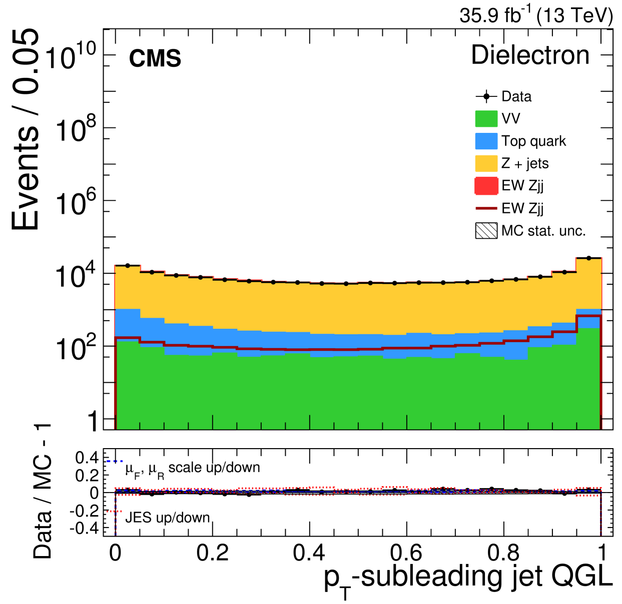
for signal/background separation
VBF/VBS tagging & W/Z→qq

What is a Quark Jet?

From lunch/dinner discussions

Les Houches 2015
arXiv:1605.04692

Ill-Defined ↓ Well-Defined	What people sometimes think we mean ↑ What we mean	
Quark as noun		A quark parton
		A Born-level quark parton
		The initiating quark parton in a final state shower
		An eikonal line with baryon number 1/3 and carrying triplet color charge
		A quark operator appearing in a hard matrix element in the context of a factorization theorem
Quark as adjective		A parton-level jet object that has been quark-tagged using a soft-safe flavored jet algorithm (automatically collinear safe if you sum constituent flavors)
		A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)

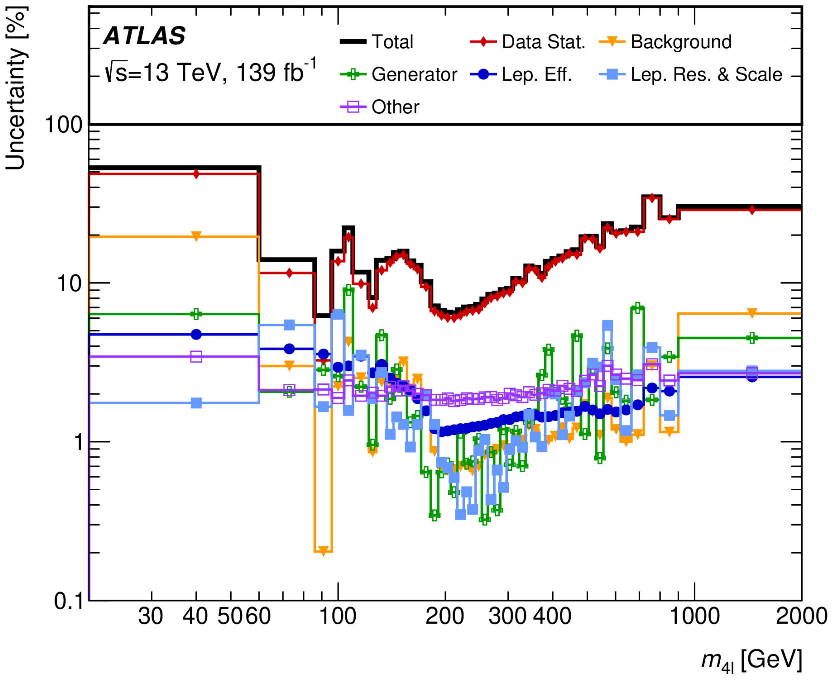


Eur. Phys. J. C 78 (2018) 589

Multibosons

CMS-PAS-SMP-19-007 : **4l/2l ratios** exploited to cancel exp syst in the Z peak region : improved $B(Z\rightarrow 4\ell)$
$B(Z\rightarrow 4\ell) = 4.67 \pm 0.11\ (stat) \pm 0.10\ (sys)) \times 10^{-6}$

differential 4-leptons



JHEP 07 (2021) 005

ATLAS

	Region				
	Full	$Z \rightarrow 4\ell$	$H \rightarrow 4\ell$	Off-shell ZZ	On-shell ZZ
Measured fiducial cross-section [fb]	88.9 ±1.1 (stat.) ±2.3 (syst.) ±1.5 (lumi.) ±3.0 (total)	22.1 ±0.7 (stat.) ±1.1 (syst.) ±0.4 (lumi.) ±1.3 (total)	4.76 ±0.29 (stat.) ±0.18 (syst.) ±0.08 (lumi.) ±0.35 (total)	12.4 ±0.5 (stat.) ±0.6 (syst.) ±0.2 (lumi.) ±0.8 (total)	49.3 ±0.8 (stat.) ±0.8 (syst.) ±0.8 (lumi.) ±1.3 (total)
Sherpa	86±5	23.6±1.5	4.57±0.21	11.5±0.7	46.0±2.9
Powheg + Pythia8	83±5	21.2±1.3	4.38±0.20	10.7±0.7	46.4±3.0

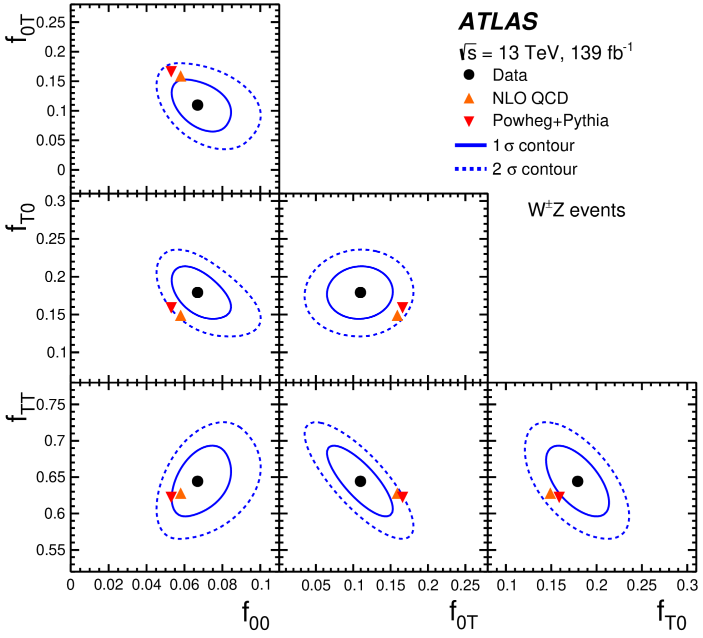
CMS

uncertainties on total cross section

Uncertainty	Range of values
Lepton efficiency	2–5%
Trigger efficiency	1–2%
Background	0.6–1.3%
Pileup	1%
μ_R, μ_F	1%
PDF	1%
NNLO/NLO corrections	1%
Integrated luminosity	2.5% (2016), 2.3% (2017), 2.5% (2018)

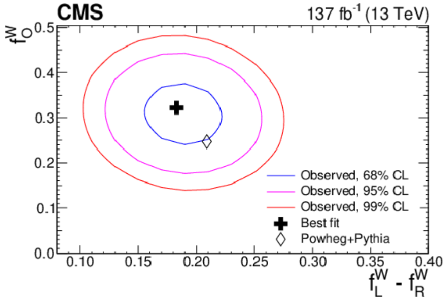
EPJC 81 (2021) 200

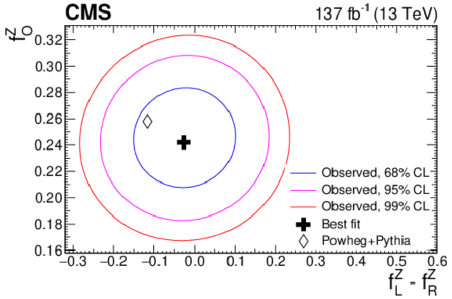
Multibosons



ATLAS WZ polarization **arXiv:2211.09435**

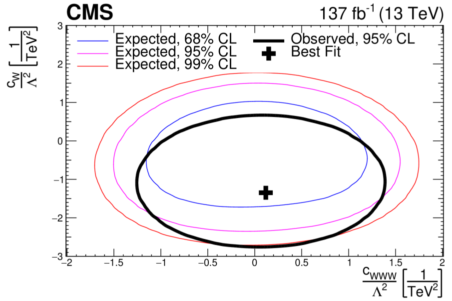
	f_{00}	$f_{0\mathrm{T}}$	f_{T0}	f_{TT}
Relative uncertainty [%]				
e energy scale and id. efficiency	0.34	0.6	0.8	0.31
μ energy scale and id. efficiency	0.8	0.23	0.23	0.13
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	3.3	1.3	1.2	0.4
Pile-up	0.6	0.17	0.4	0.15
Misidentified lepton background	2.3	1.6	0.8	0.26
ZZ background	0.9	0.17	0.32	0.07
Other backgrounds	3.0	1.6	1.3	0.4
Parton Distribution Function	0.5	1.8	0.09	0.5
QCD scale	0.19	8	0.9	2.0
Modelling	9	4	2.9	1.2
Total systematic uncertainty	14	15	8	4
Luminosity	0.35	0.24	0.15	0.05
Statistical uncertainty	13	10	12	3.0
Total	19	18	14	5

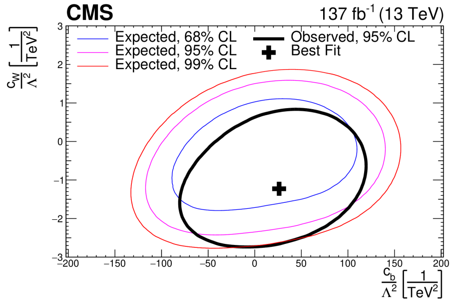


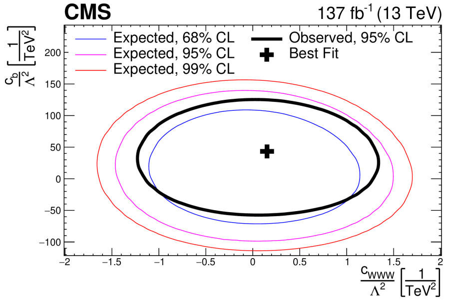


CMS WZ *JHEP 07 (2022) 032*

Source	Combined	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Electron efficiency	0.6	3.2	1.8	0.9	—
Muon efficiency	1.2	—	0.5	1.0	1.5
Electron energy scale	0.1	0.3	0.1	0.1	0.0
Muon energy scale	0.1	0.0	0.0	0.1	0.1
Trigger efficiency	0.7	0.7	0.8	0.7	0.7
Jet energy scale	0.9	0.8	0.7	1.0	0.9
b tagging	1.6	1.8	1.7	1.8	1.6
Pileup	0.9	1.0	1.2	0.8	0.7
ISR	0.2	0.2	0.2	0.2	0.2
Nonprompt normalization	0.6	0.7	0.8	0.6	0.7
Nonprompt shape	1.0	1.2	1.0	0.9	0.9
VVV normalization	0.5	0.6	0.5	0.5	0.5
VH normalization	0.2	0.1	0.2	0.2	0.2
WZ EWK normalization	0.2	0.2	0.2	0.2	0.2
ZZ normalization	0.3	0.3	0.3	0.3	0.3
t$\bar{t}$Z normalization	0.3	0.4	0.4	0.4	0.3
tZq normalization	0.4	0.4	0.4	0.4	0.4
Xγ normalization	0.2	0.5	0.1	0.5	0.1
Total systematic uncertainties	2.8	4.3	3.7	3.0	3.0
Integrated luminosity	2.1	2.2	2.2	2.1	2.1
Statistical uncertainty	1.5	5.0	3.4	2.5	2.0
PDF+scale	0.9	0.9	0.9	0.9	0.9







rich variety of relevant syst impacts

precision EFT

Summary

- Systematic uncertainties are dominating LHC precision measurements
- *Results have surprisingly surpassed expectations* in many directions implementing new ideas, analysis methodologies and event reconstruction
  - improved S/B benefits on both stat and syst impacts
- Correlations of syst uncertainties need to be treated with care
- Choices for theory modeling and their uncertainties play a crucial role in many precision results
- Keep on being creative and use new ideas to get the best from the Run3 and HL statistics