Electroweak results and precision tests of the Standard Model

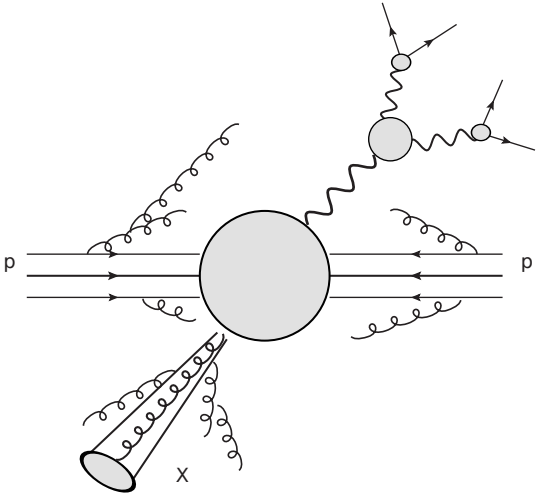
Jan Kretzschmar, University of Liverpool

12.7.2022

The Standard Model & Open Questions

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

The Standard Model & Open Questions



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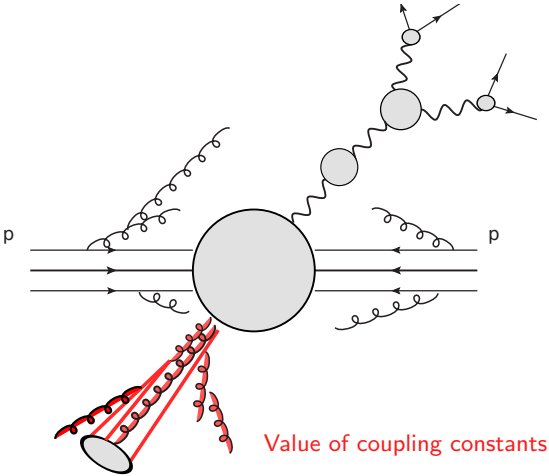
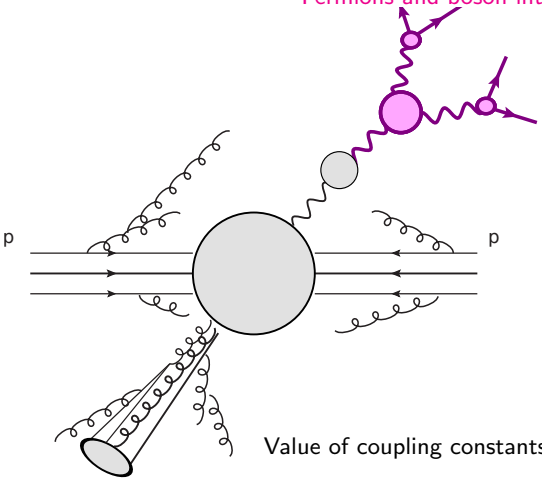


Value of coupling constants, e.g. α_S

The Standard Model & Open Questions

Fermions and boson interactions and self-interactions



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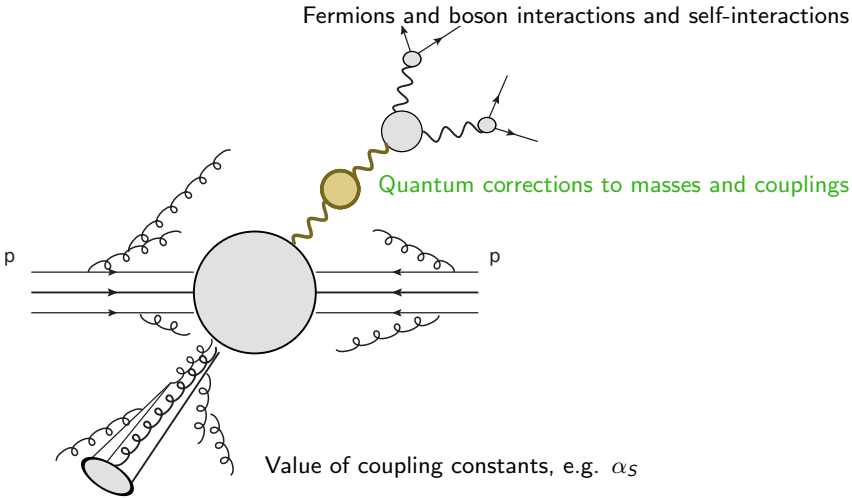

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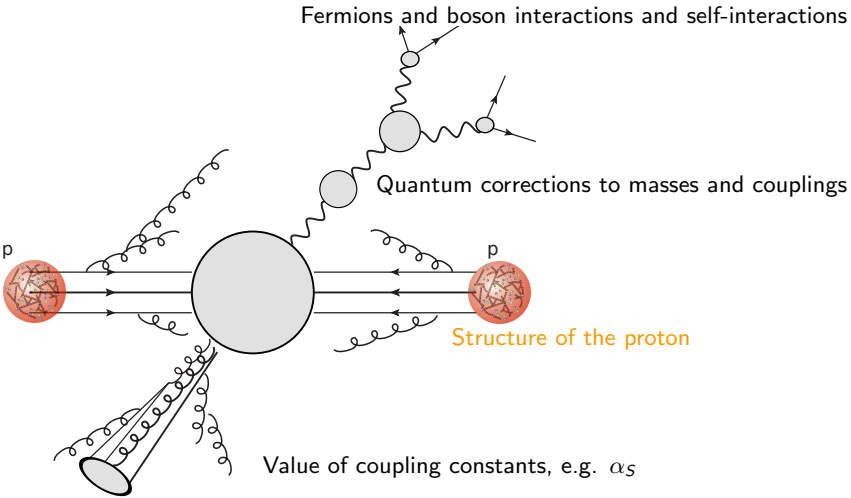

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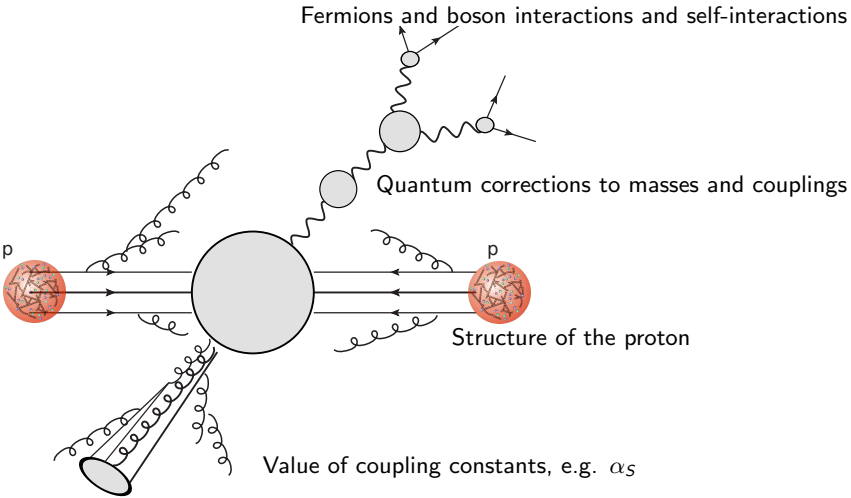
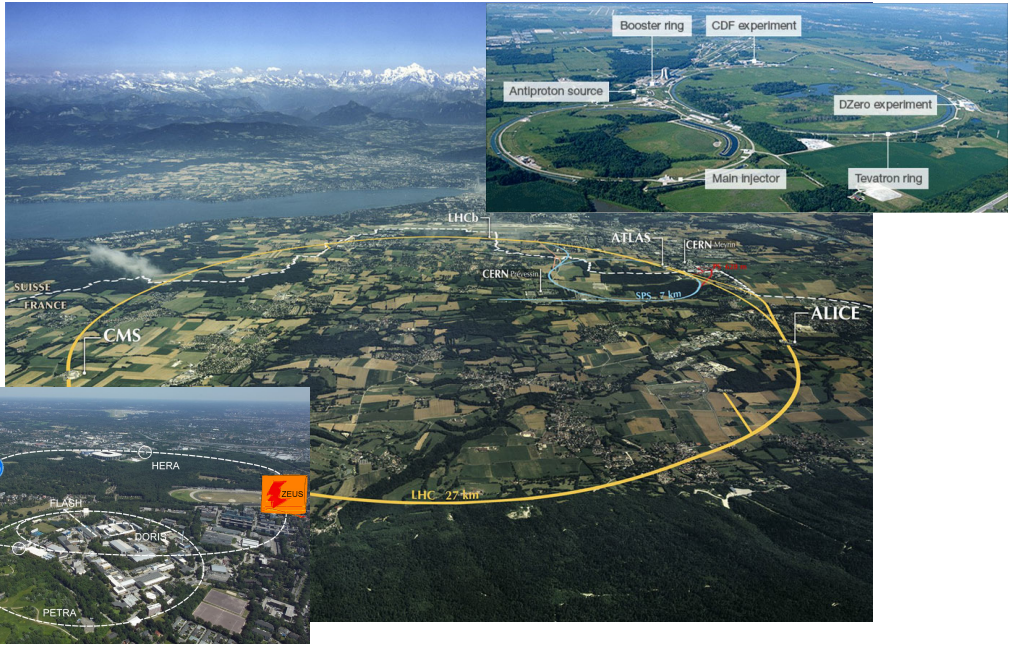
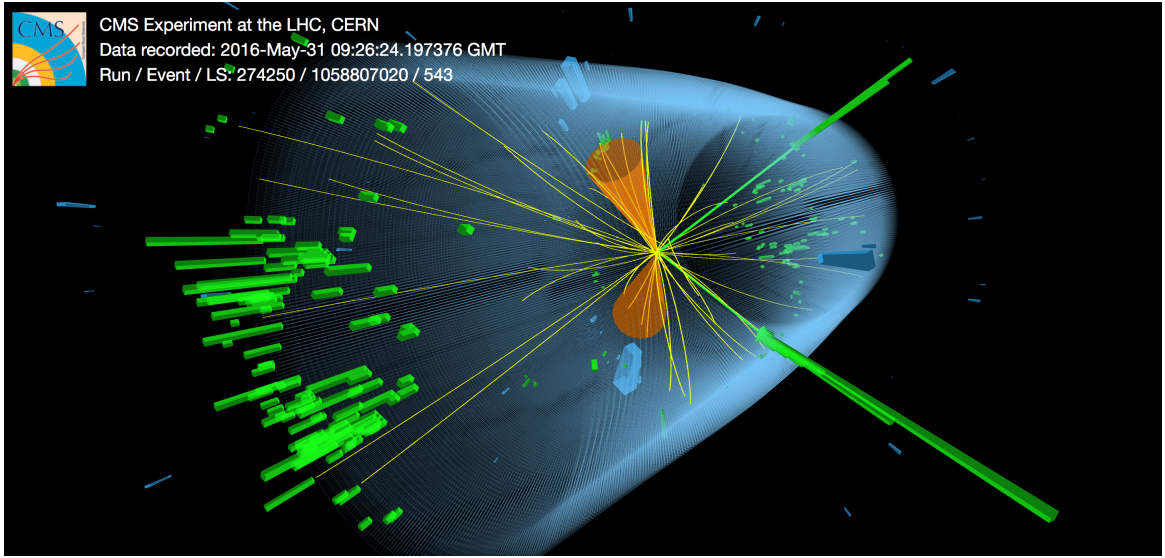


- Hadron collider experiments continue to extract extraordinary results through ingenious data analyses
- Interpretation needs precise theory – progress in field of higher-order QCD and EW calculations put to use

Colliders


Booster ring
CDF experiment
Antiproton source
DZero experiment
Main Injector
Tevatron ring
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km
HERA
ZEUS
FLASH
DORIS
PETRA

QCD studies and the top-quark

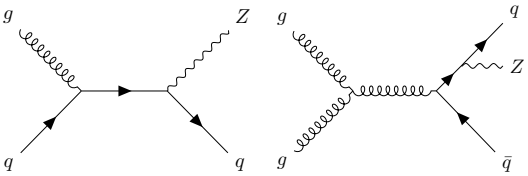


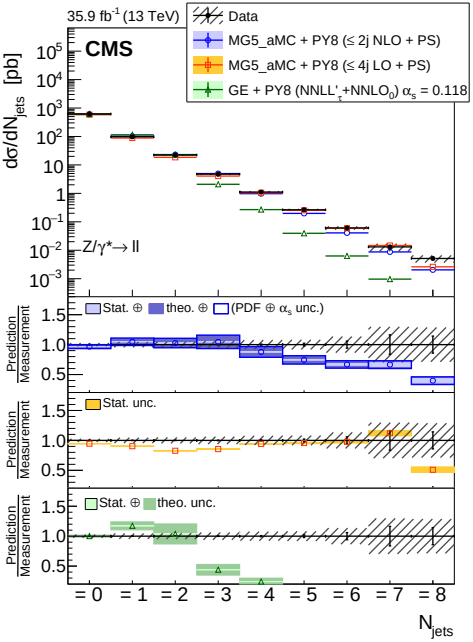
$Z(ee)$+2 jets

$Z(\ell\ell)$+jets

arXiv:2205.02597 (ATLAS), arXiv:2205.02872 (CMS)

- High-precision measurements over wide range: up to 8 jets and jets beyond 1 TeV
- Critical testbed for QCD calculations:
  - new multijet-merged MC simulations (MadGraph FxFx and Sherpa 2.2.11) agree generally well with data
  - Highest precision given by NNLO fixed-order calculations, in agreement with data
- Validation of background predictions and signal simulation for current and future analyses





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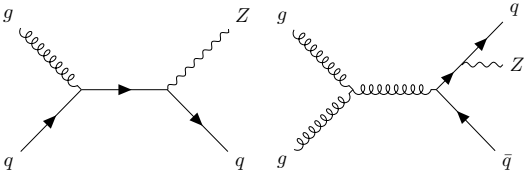
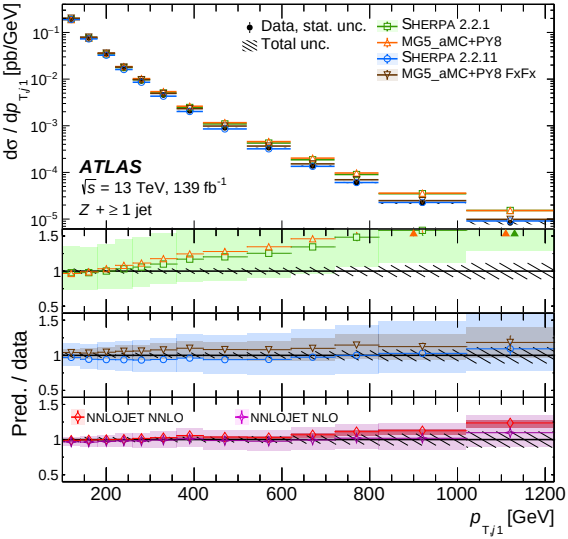
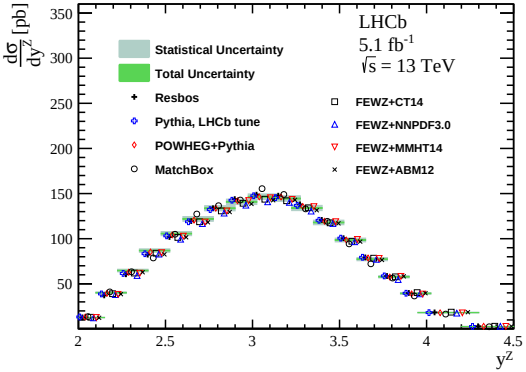


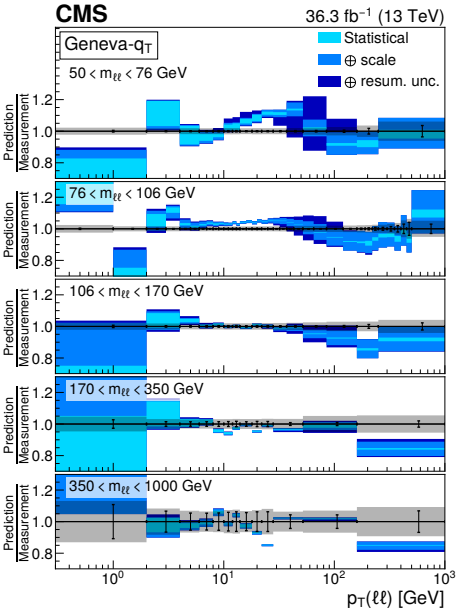


$Z(\ell\ell)$ off-peak and forward

arXiv:2205.04897 (CMS) , arXiv:2112.07458 (LHCb)

- New CMS result off Z-peak, test modern NNLO MCs (MiNNLOPS and Geneva)
- LHCb performs unique forward-rapidity measurement
- Constrain PDFs and develop MCs with impact on e.g. W-boson mass measurement

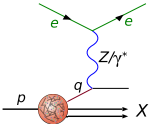


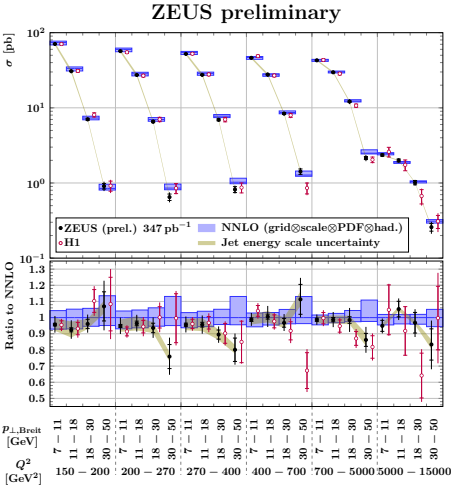


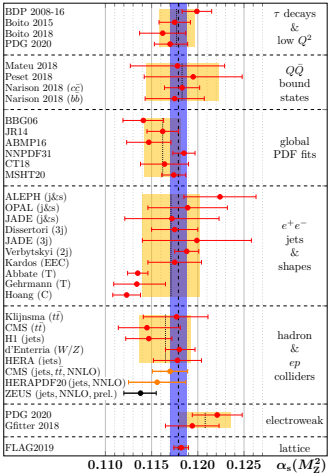
Jet production in DIS at HERA

arXiv:2112.01120 (H1+ZEUS), ZEUS-prel-22-001

- HERA DIS data ($ep \to eX$) important to determine proton PDFs
- Adding ep jet data improves gluon uncertainty $\to$ HERAPDF2.0JetsNNLO
- ... and allows to measure
  $\alpha_S(m_Z) = 0.1138 \pm 0.0014(\mathrm{exp})^{+0.0004}_{-0.0008}(\mathrm{model})^{+0.0008}_{-0.0007}(\mathrm{scale})$:







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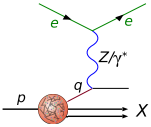
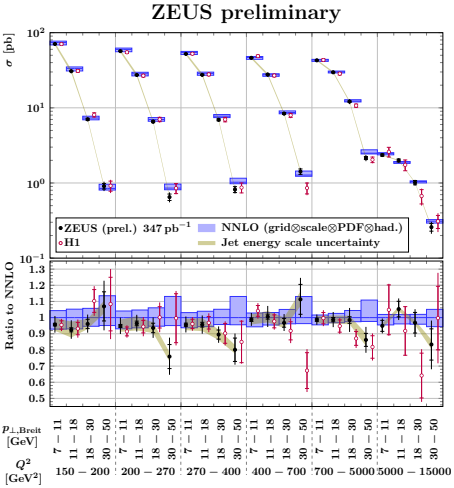
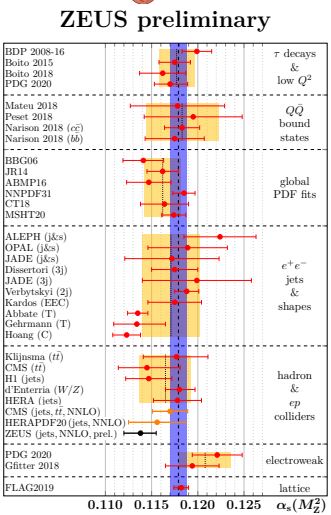




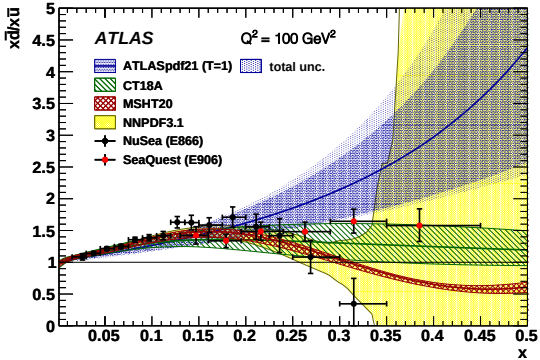


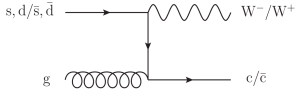
See also S. Camarda ($p_{T,Z}$@N^{3}LO+N^{3}LL) and D. Boito (τ decays)

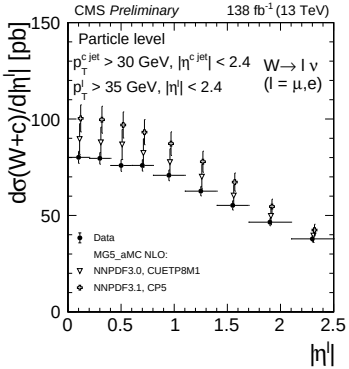
Impact of LHC data on PDFs

EPJC 82 (2022) 438 (ATLAS), CMS-PAS-SMP-21-005

- LHC data an important source of information on PDFs
- New CMS $W + c$ result sheds light on strange density: most precise result to date; start to constrain $s - \bar{s}$ asymmetry through ratio $W^+ + \bar{c}/W^- + c$
- New ATLASpdf21 with diverse ATLAS data: constrain high-x $\bar{d}/\bar{u}$ ratio, in agreement with recent fixed-target SeaQuest Drell–Yan data



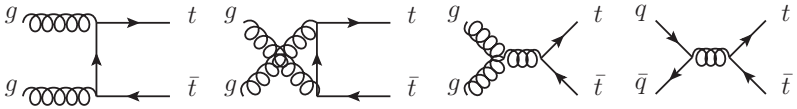




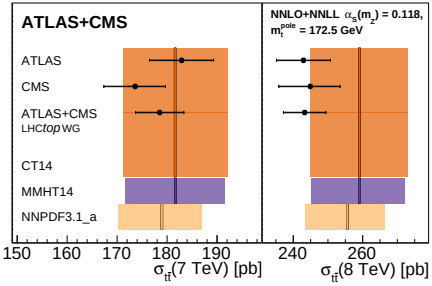
PDF set	$R_c^{\pm}$	Δ_{PDF}	Δ_{scales}	Δ_{α_s}	Total uncert.
MMHT14	0.935	$^{+0.021}_{-0.014}$	$^{+0.0}_{-0.006}$	± 0.004	$^{+0.021}_{-0.016}$
CT18	0.955	± 0.003	± 0.003	± 0.001	± 0.004
CT18Z	0.958	± 0.003	± 0.001	± 0.001	± 0.003
ABMP16	0.964	± 0.002	± 0.001	± 0.001	± 0.002
NNPDF3.0	0.935	± 0.017	± 0.001	± 0.001	± 0.017
NNPDF3.1	0.939	± 0.020	± 0.001	± 0.001	± 0.020
CMS	$0.950 \pm 0.005\,(\text{stat}) \pm 0.010\,(\text{syst})$				

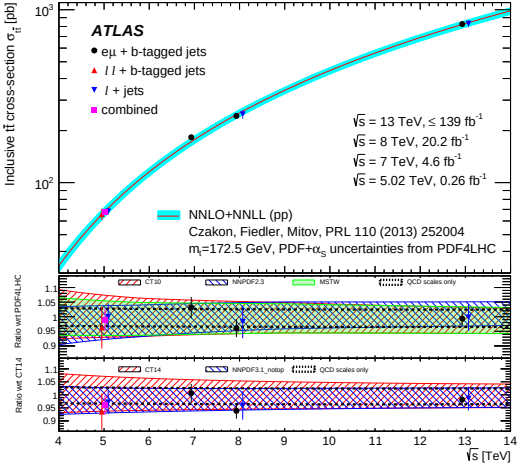
Top-quark pair production

arXiv:2207.01354 (ATLAS) , arXiv:2112.09114 (CMS) , arXiv:2205.13830 (ATLAS & CMS)



- Important QCD benchmark and gluon constraint
- New ATLAS measurement of $\sigma(t\bar{t})$ at $\sqrt{s} = 5.02$ TeV: 3.9% precision
- New ATLAS+CMS combinations of $\sigma(t\bar{t})$ at $\sqrt{s} = 7$ TeV and 8 TeV: 2.5% precision

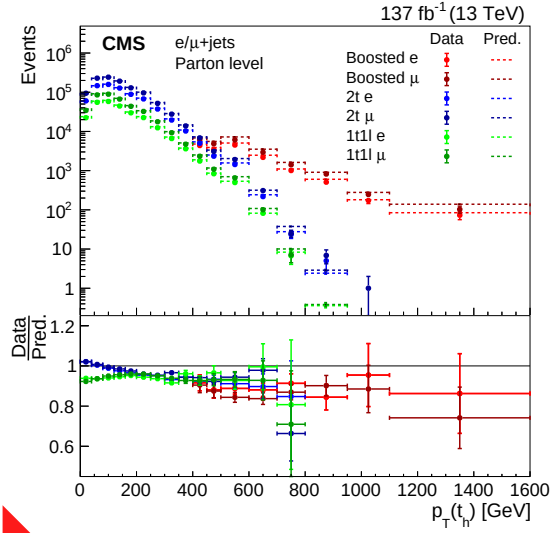


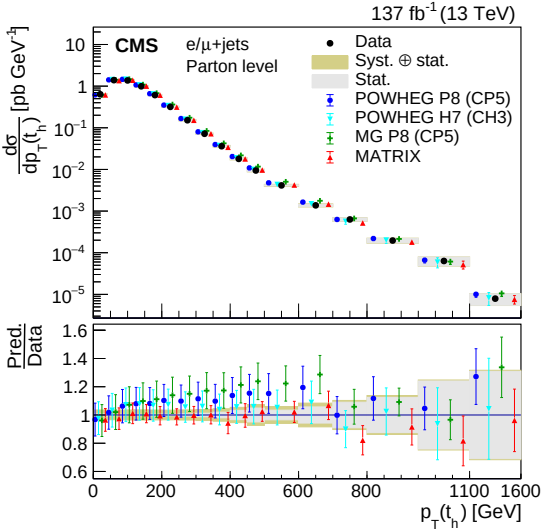


Differential $t\bar{t}$

arXiv:2205.02817 (ATLAS), JHEP 06 (2022) 063 (ATLAS), CMS-PAS-TOP-20-006, PRD 104 (2021) 092013 (CMS)

- Precise measurements using reconstruction with resolved and "merged" objects – well into the TeV range
- Compatible with SM predictions, specifically NNLO predictions (and often more precise than theory)
- Data used to constraint anomalous top-quark interactions $C_{tq}^{(8)}$ and C_{tG}





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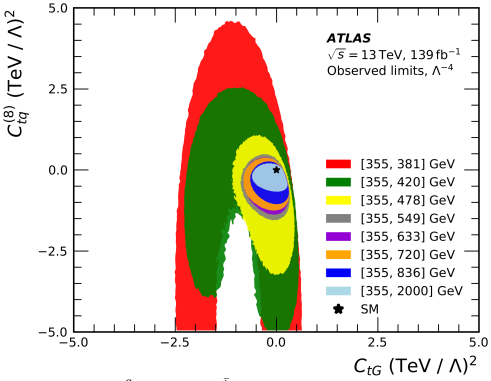
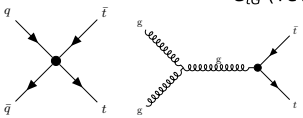
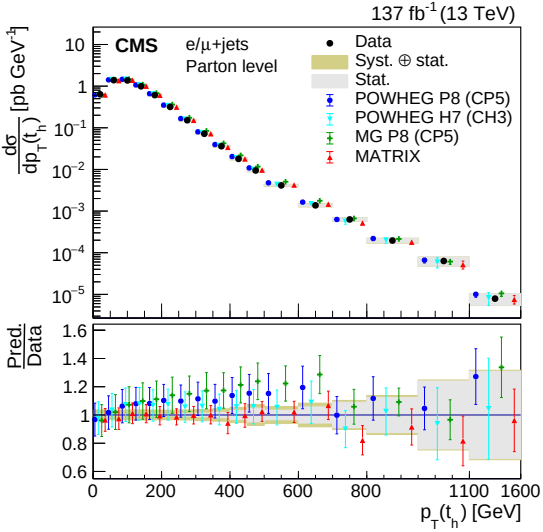
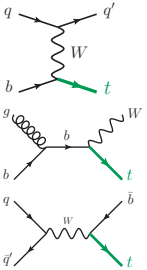


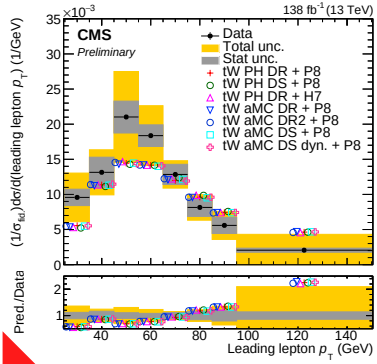


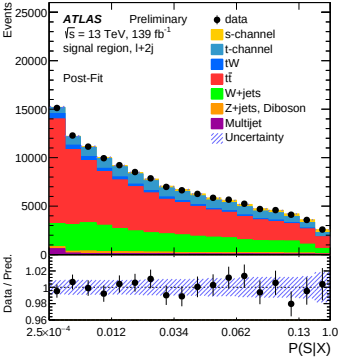


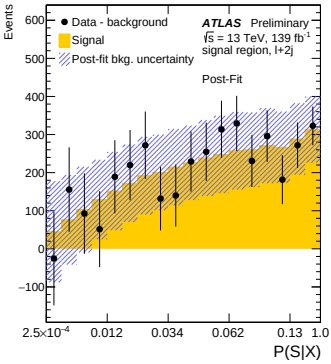
Single top production

- New CMS Wt result: $\sigma = 79.2 \pm 0.8(\mathrm{stat})^{+7.0}_{-7.2}\mathrm{syst} \pm 1.1(\mathrm{lumi})$ pb
  - Consistent with SM prediction
  - Robust against procedure to remove "overlap" with $t\bar{t}$
- New ATLAS s-channel result: $\sigma = 8.2^{+3.5}_{-2.9}$ pb
  - using Matrix Element Method to obtain 3.3σ evidence for this challenging channel, a first at 13 TeV

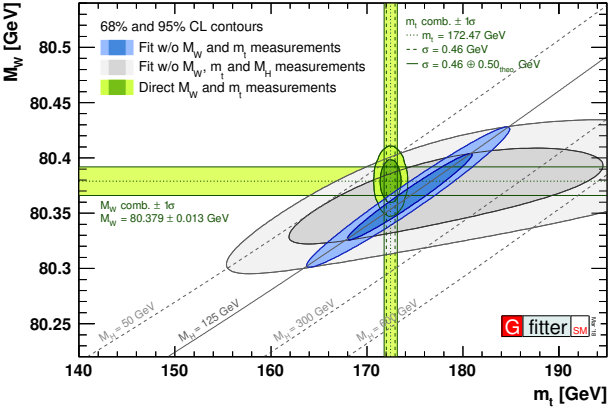


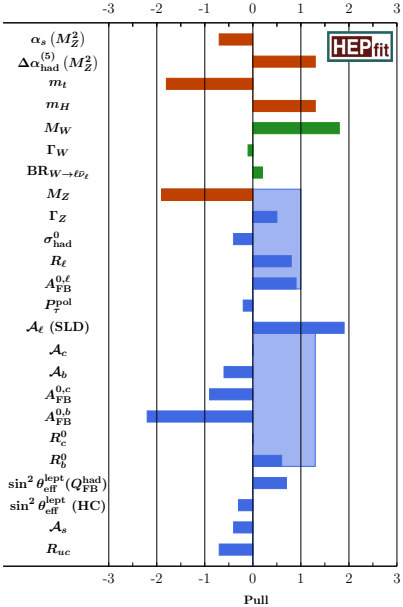






Precision Observables



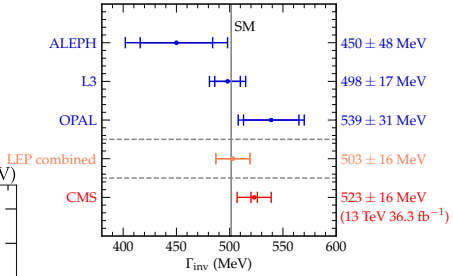


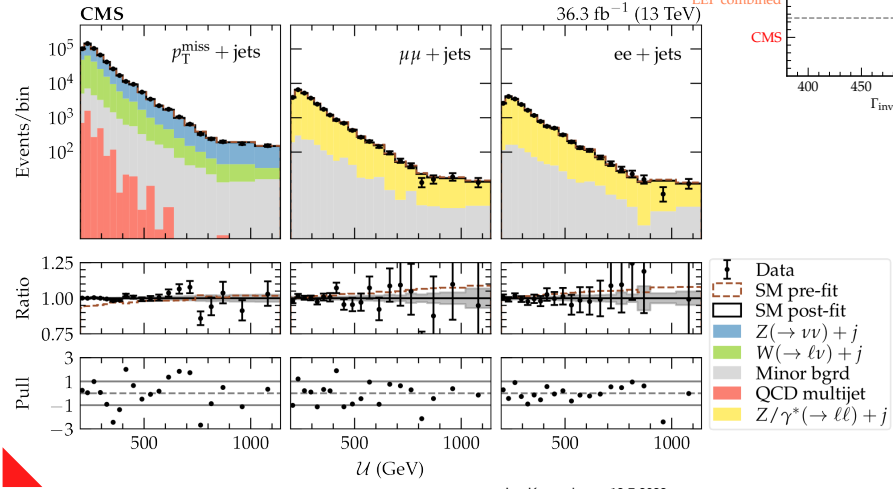
EPJC 78 (2018) 675 , arXiv:2112.07274

$\Gamma(Z \to \nu\nu)$

arXiv:2206.07110 (CMS)

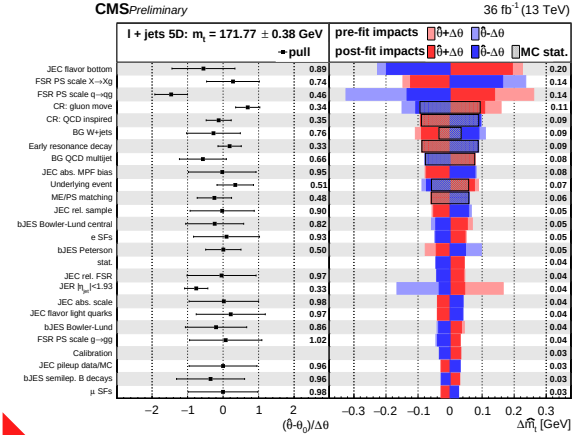
- Invisible width of Z boson constrained by LEP lineshape measurement to ± 1.5 MeV, however "direct" measurement via ISR much less precise
- New CMS result extracts $\Gamma(Z \to \nu\nu)$ from ratio $\sigma(p_T^{\text{miss}} + \text{jets})/\sigma(\ell\ell + \text{jets})$ to ± 16 MeV

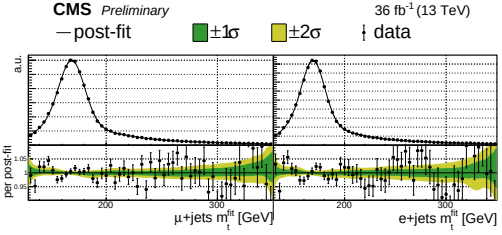


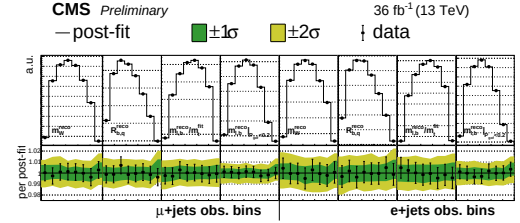


Top quark mass

- Full profile-likelihood fit using 5 input distributions
- All modelling variations performed inside Pohweg+Pythia8 (PDFs, QCD scales in ME, ME/PS matching, 32 decorrelated ISR/FSR PS scales, colour reconnection, underlying event tune parameters, top p_T)
- Final result of $m_{\mathrm{top}} = 171.77 \pm 0.38$ GeV (stat. error of ± 0.04 GeV)
- Best single measurement to date, several strongly constrained systematics







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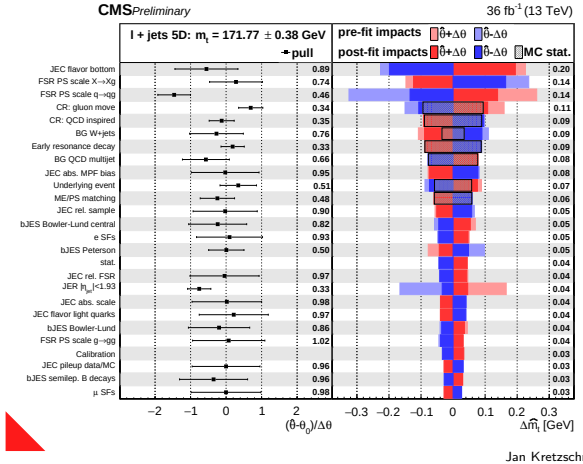
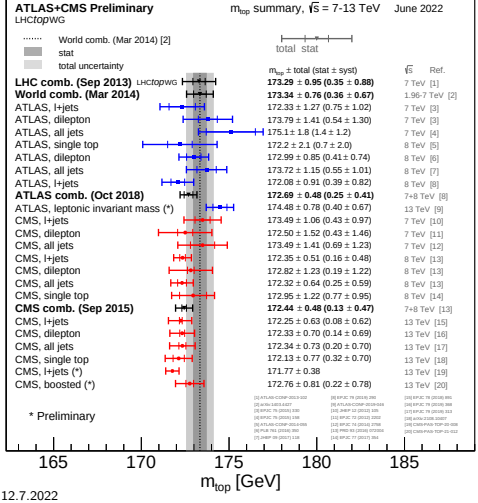
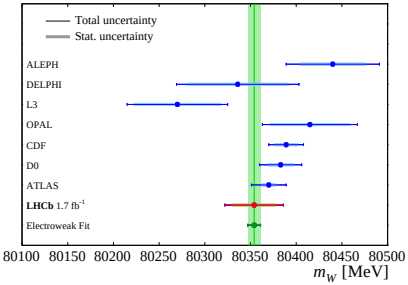


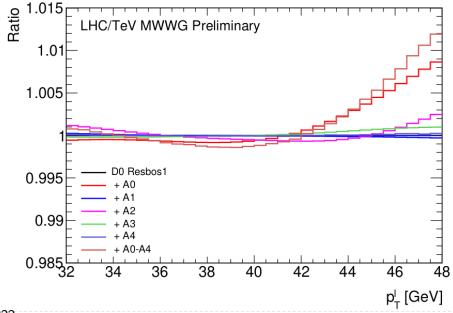


W-boson mass

- Key observable in the SM EW fit: predicted from other parameters $m_W = 80\,355 \pm 6$ MeV
- Already **pre-2022** best measurements from hadron colliders:
  - TeVatron $p\bar{p}$: D0 (± 23 MeV) and CDF (± 19 MeV)
  - LHC pp: ATLAS (± 19 MeV) and LHCb (± 32 MeV)
- Extreme demands on detector understanding
- Notoriously hard to control theory modelling to "compensate" for the unmeasured neutrino in $W \to \ell\nu$
- Ongoing LHC/TeVatron Electroweak WG effort towards combination – understand theoretical correlations between measurements: prime examples PDFs and lepton angular correlations (A_i)
  - E.g. description of W A_i in legacy Resbos codes not ideal, motivates of $\mathcal{O}(10\,\mathrm{MeV})$
  - Recent LHCb measurement of A_i in $Z \to \ell\ell$

Status before 2022





W-boson mass

- Key observable in the SM EW fit: predicted from other parameters $m_W = 80\,355 \pm 6$ MeV
- Already **pre-2022** best measurements from hadron colliders:
  - TeVatron $p\bar{p}$: D0 ($\pm$23 MeV) and CDF ($\pm$19 MeV)
  - LHC pp: ATLAS ($\pm$19 MeV) and LHCb ($\pm$32 MeV)
- Extreme demands on detector understanding
- Notoriously hard to control theory modelling to "compensate" for the unmeasured neutrino in $W \to \ell\nu$
- Ongoing LHC/TeVatron Electroweak WG effort towards combination – understand theoretical correlations between measurements: prime examples PDFs and lepton angular correlations (A_i)
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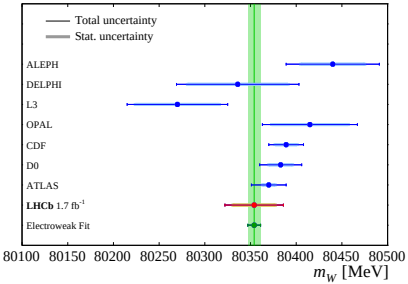
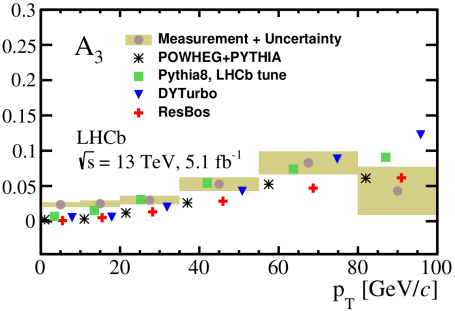
Status before 2022

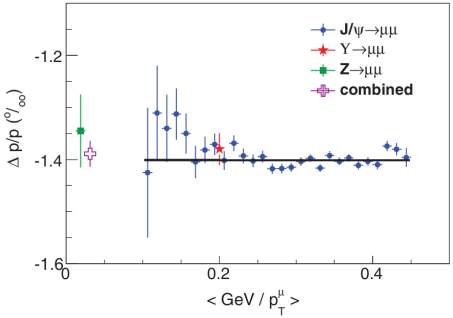


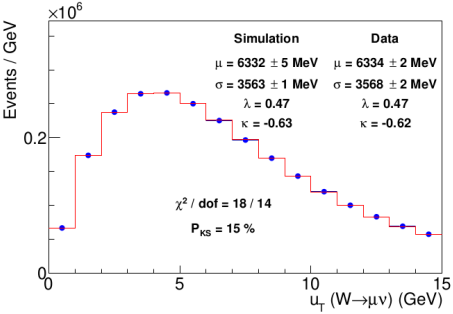


CDF W-boson mass

Science 376, no.6589, 170 (2022)

- Muons calibrated using high-statistics $J/\psi \to \mu\mu$ sample and transferred to electrons via E/p
- Measurement of Z-boson mass: $M_Z = 91\,192.0 \pm 6.4(\mathrm{stat}) \pm 4.0(\mathrm{syst})$ MeV in agreement with LEP
- W and Z boson production and decay simulated using RESBOS, $p_T(Z)$ spectrum tuned to Z data and validated on W
- Fit to m_T, p_T^ℓ and p_T^ν for $W \to e\nu$ and $W \to \mu\nu$





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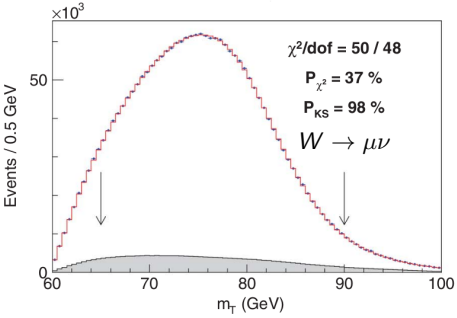

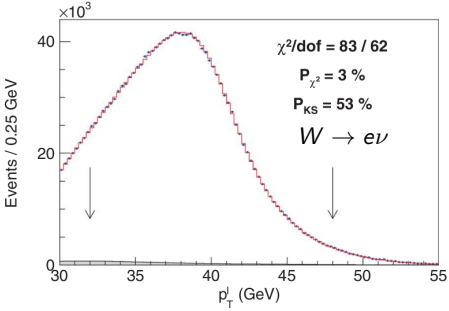

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- Muons calibrated using high-statistics $J/\psi \to \mu\mu$ sample and transferred to electrons via E/p
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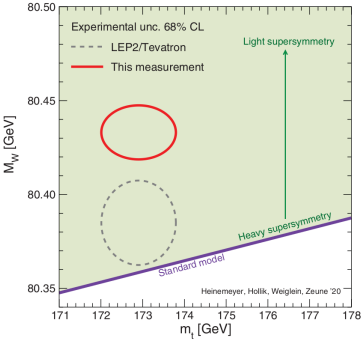
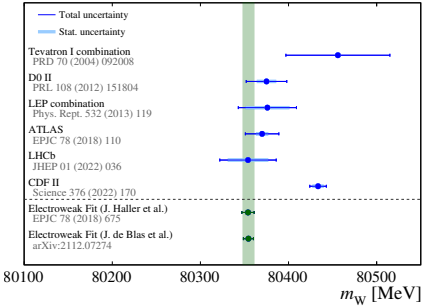
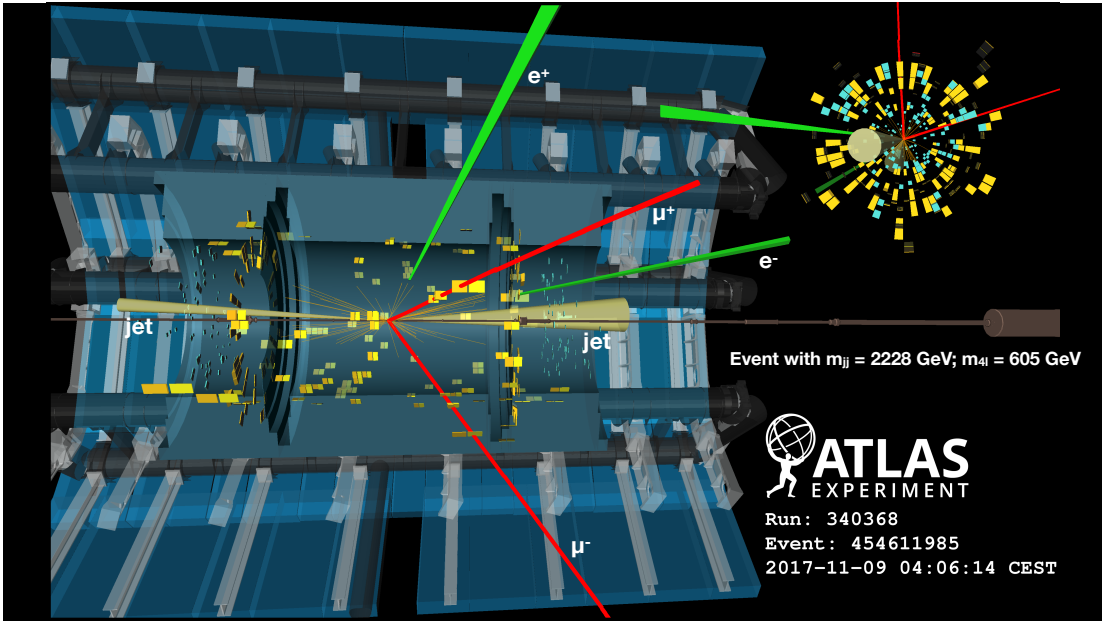
- W and Z boson production and decay simulated using RESBOS, $p_T(Z)$ spectrum tuned to Z data and validated on W
- Fit to m_T, p_T^ℓ and p_T^ν for $W \to e\nu$ and $W \to \mu\nu$
- Measurement of W-boson mass: $M_W = 80\,433.5 \pm 6.4(\mathrm{stat}) \pm 6.9(\mathrm{syst})$ MeV
  - Factor 2 better precision than any previous result
  - 7σ away from the SM EW fit prediction!

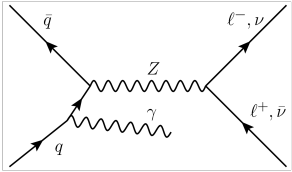




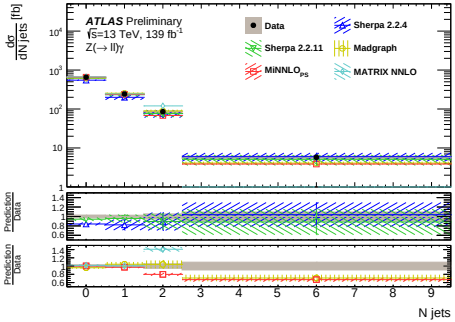
Multiboson interactions

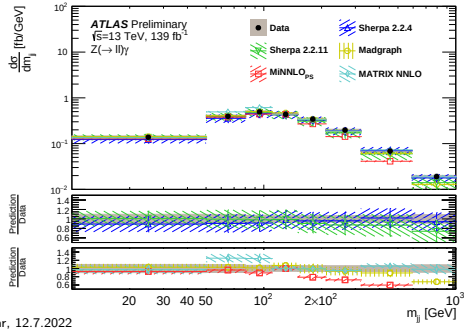


$Z\gamma$+jets



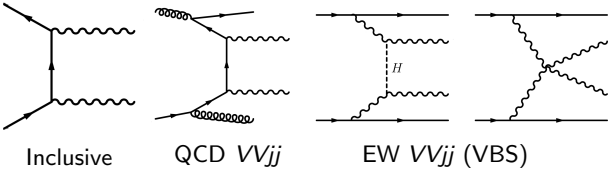
- New: ATLAS $Z(\ell\ell)\gamma$ + jets selection enriched in ISR photon production
- High statistics, high-precision channel to study additional QCD radiation in multiboson environment: 4-10% uncertainties
- Compared to state-of-the art (N)LO multijet-merged and NNLO predictions from Sherpa, MadGraph+Pythia, Powheg MiNNLOPS, MATRIX: good description of data in wide range

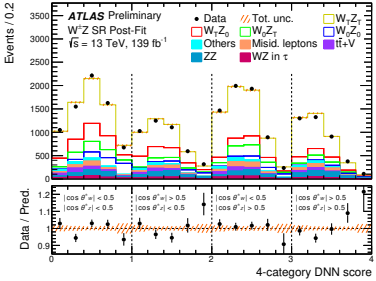




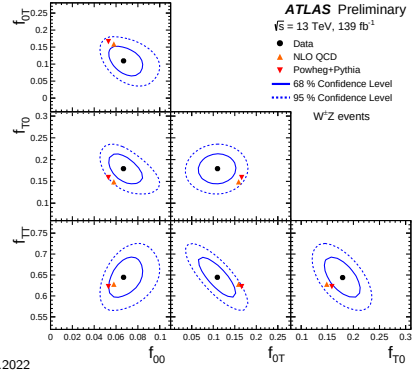
$WZ(\ell\nu\ell\ell)$ polarisation

ATLAS-CONF-2022-053, arXiv:2110.11231 (CMS)



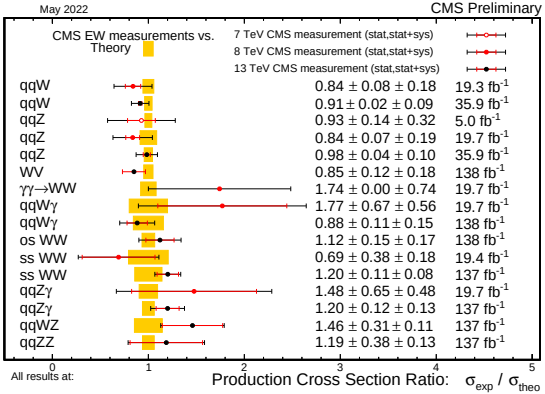


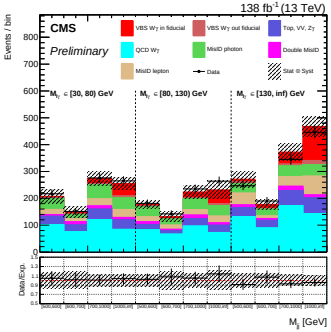
- Electroweak *VVjj* production can proceed in transverse (T) or longitudinal (0) polarisation states
- Longitudinal (00) component intertwined with Higgs mechanism & probes VBS unitarization: long term goal for the HL-LHC
  - currently measurements focus on polarisation or VBS
- New: first measurement of joint polarisation states in inclusive *WZ* production by ATLAS using DNN reconstruction techniques – observation of double-longitudinal component with $> 7\sigma$

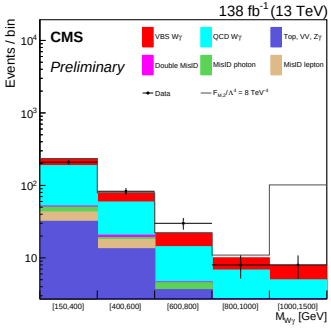


VBS $W(\ell\nu)\gamma$

- Growing list of observed electroweak $VVjj$ production
- New: CMS observation of VBS $W\gamma jj$ with $> 6\sigma$
- Selection of $W(\ell\nu)$ balanced by a high-mass m_{jj} dijet system with large rapidity gap, complex background
- Good agreement with SM: differential cross sections, limits on anomalous quartic couplings



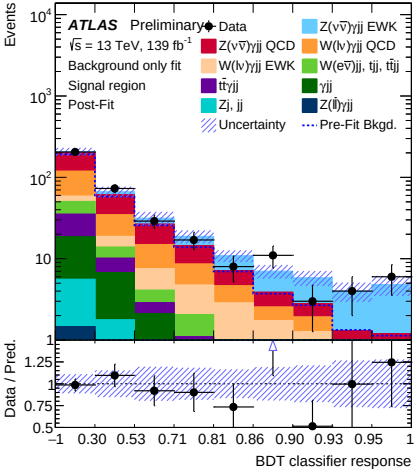


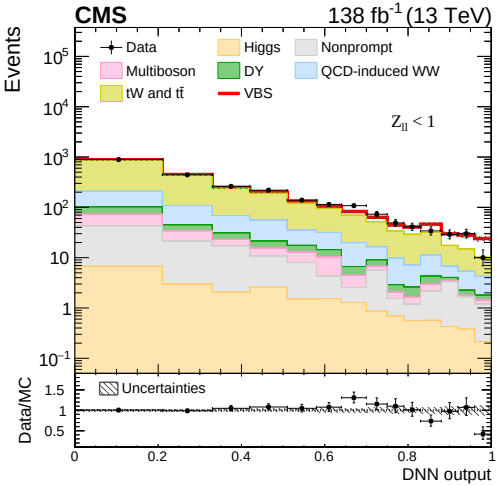


VBS $Z(\nu\nu)\gamma$ and $W^+W^-(\ell\nu\ell\nu)$

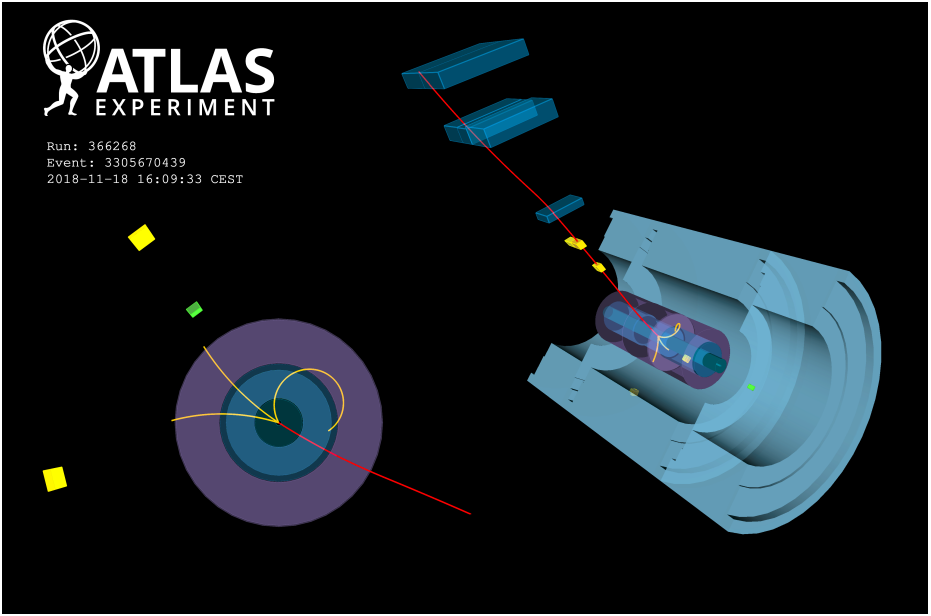
STDM-2018-59 (ATLAS) arXiv:2109.00925 (ATLAS), arXiv:2205.05711 (CMS)

- Many VBS analyses use MVA techniques: input variables on the dijet system, the central system as well as their correlations; background general challenge
- New: ATLAS study of VBS $Z(\nu\nu)\gamma jj$ with $p_T^\gamma > 150\,\mathrm{GeV}$, good agreement with SM, aQGC limits derived; combined with prior lower p_T^γ study: 6.3σ observation
- New: CMS observation of opposite-charge VBS W^+W^- at 5.6σ





Exclusive Production



$\mathrm{PbPb} \to \mathrm{Pb}(\gamma\gamma \to \tau\tau)\mathrm{Pb}$

arXiv:2204.13478

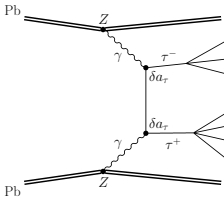
Exclusive $\mathrm{PbPb} \to \mathrm{Pb}(\gamma\gamma \to \tau\tau)\mathrm{Pb}$

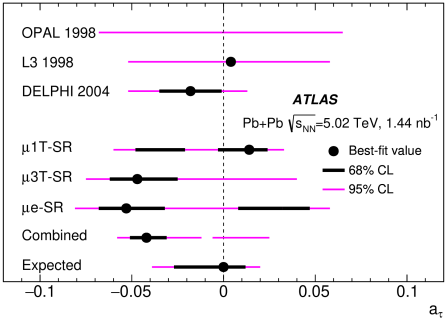
arXiv:2206.05192 (CMS) , arXiv:2204.13478 (ATLAS)

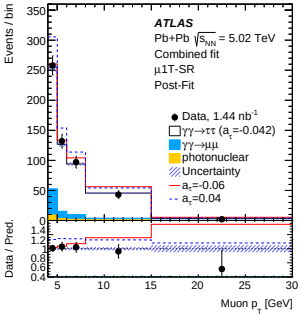
- Photon-induced di-tau production sensitive to anomalous magnetic moment a_τ:

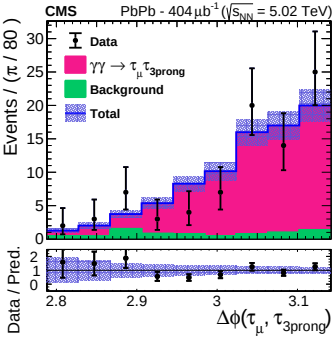
$$a_\ell = \frac{g_\ell - 2}{2} = \frac{\alpha}{2\pi} + \ldots \approx 0.0012$$

- New results by ATLAS + CMS using LHC HI collisions observe clearly exclusive $\tau\tau$ production; τs reconstructed with low p_T muon, hadronic 1/3-prongs or electrons
- Current limits on a_τ similar to prior LEP results, statistically limited





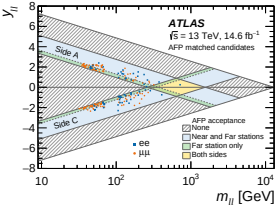


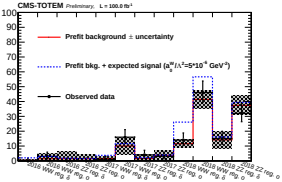


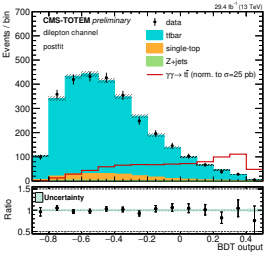
Exclusive production in *pp*

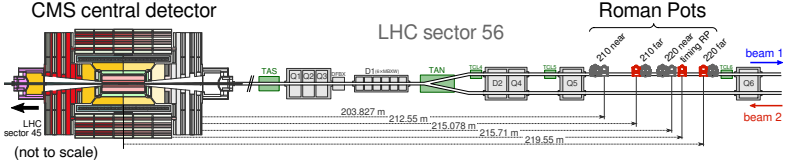
CMS-PAS-TOP-21-007 , CMS-PAS-SMP-21-014 , PRL 125 (2020) 261801 (ATLAS)

- Both CMS and ATLAS have Run 2 data with forward proton spectrometers (CT-PPS / AFP): unique way of detecting exclusive production with intact forward protons
- ATLAS: first measurement of tagged of $\gamma\gamma \to \ell\ell$
- New: CMS search for $\gamma\gamma \to p(WW)p$ and $\gamma\gamma \to p(ZZ)p$ with hadronic, boosted $V \to J$ – no signal (as expected), sensitivity for anomalous effects at high mass
- New: CMS search for exclusive $p(t\bar{t})p$: $\sigma < 0.59$ pb



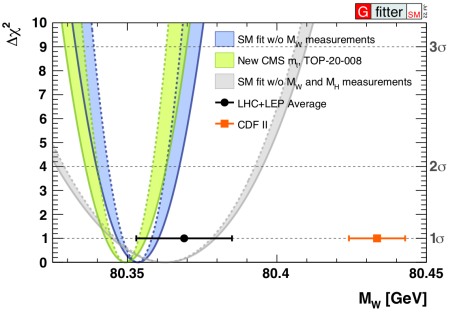


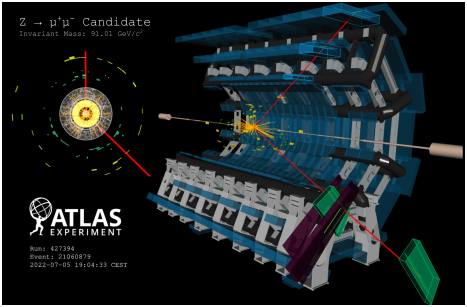




Conclusions

- Experiments continue to extract extraordinary results, especially from the rich LHC Run 2 data
  - Precise, differential measurements over wide kinematic ranges
  - Exciting new result on the top-quark mass and W-boson mass – call to experimental collaborations for more work
  - Multiboson studies with many "fundamental firsts"
  - Exclusive reactions
- Interpretation often limited by theory – push towards higher-order predictions and use of data constraints
- LHC Run 3 data will give further opportunities





Backup

June 26, 2022

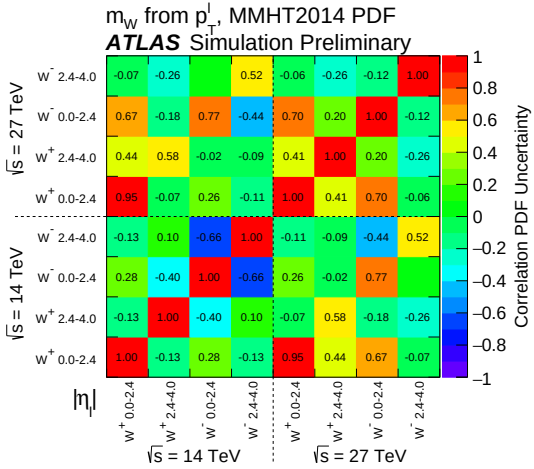
In 2012, D0 published a measurement of the W boson mass using 5.3 fb^{-1} of Tevatron data (Phys. Rev. Lett. **108**, 151804 (2012)), with a subsequent longer description (Phys. Rev. D **89**, 012005 (2014)). This measurement, $\mathbf{m_W = 80{,}375 \pm 23}$ **MeV**, remains the official D0 result.

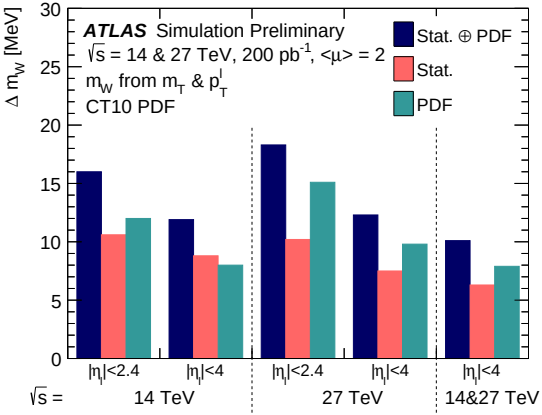
A study of the remaining approximately 5 fb^{-1} of data taken between 2009 and 2011 showed that the deterioration of the detector due to radiation damage effects, combined with the higher pileup owing to the increased instantaneous luminosity, precludes a further precision measurement of the W boson mass.

Correction	$\delta m_W^{\mathrm{QCD}}$ [MeV]					
	p_{T}^W-constrained			No constraint		
	p_{T}^{ℓ}	m_{T}	p_{T}^{ν}	p_{T}^{ℓ}	m_{T}	p_{T}^{ν}
Invariant mass	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Rapidity	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
A_0	7.6	10.0	15.8	16.0	12.6	19.5
A_1	-2.4	-1.9	-1.8	-1.2	-1.6	-1.4
A_2	-3.0	-2.6	2.9	-4.2	-3.0	2.3
A_3	2.9	1.6	-0.5	3.5	1.8	-0.2
A_4	2.4	-0.1	-0.5	0.1	-0.7	-1.0
$A_0 - A_4$	7.6	7.0	16.0	14.1	9.1	18.9
Total	7.6	7.0	16.0	14.1	9.1	18.9
ResBos2	7.3±1.1	8.4±1.0	16.6±1.2	13.9±1.1	10.3±1.0	19.8±1.2
Non-closure	-0.3±1.1	1.4±1.0	0.6±1.2	-0.2±1.1	1.2±1.0	0.9±1.2

Table 5: Effect of reweighting the angular coefficients in the D0 ResBos1 events to those of ResBos2, as well as a direct fit of ResBos1 to ResBos2. Good closure is observed.

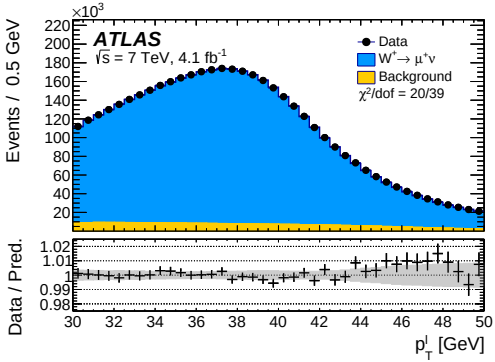
W-boson mass

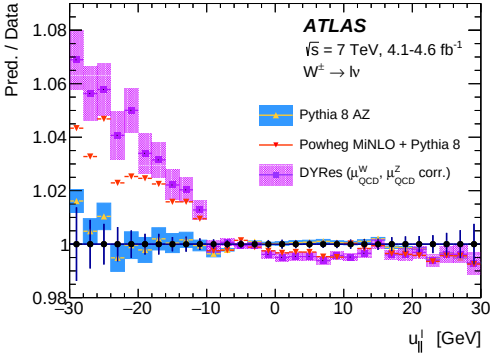

m_W from p_T^l, MMHT2014 PDF
ATLAS Simulation Preliminary
$\sqrt{s}$ = 27 TeV
$\sqrt{s}$ = 14 TeV
W^- 2.4-4.0
W^- 0.0-2.4
W^+ 2.4-4.0
W^+ 0.0-2.4
-0.07 -0.26 0.52 -0.06 -0.26 -0.12 1.00
0.67 -0.18 0.77 -0.44 0.70 0.20 1.00 -0.12
0.44 0.58 -0.02 -0.09 0.41 1.00 0.20 -0.26
0.95 -0.07 0.26 -0.11 1.00 0.41 0.70 -0.06
-0.13 0.10 -0.66 1.00 -0.11 -0.09 -0.44 0.52
0.28 -0.40 1.00 -0.66 0.26 -0.02 0.77
-0.13 1.00 -0.40 0.10 -0.07 0.58 -0.18 -0.26
1.00 -0.13 0.28 -0.13 0.95 0.44 0.67 -0.07
$|\eta_l|$
$\sqrt{s}$ = 14 TeV
$\sqrt{s}$ = 27 TeV
Correlation PDF Uncertainty
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1


ATLAS Simulation Preliminary
$\sqrt{s}$ = 14 & 27 TeV, 200 pb^{-1}, <μ> = 2
m_W from m_T & p_T^l
CT10 PDF
Stat. ⊕ PDF
Stat.
PDF
Δm_W [MeV]
30
25
20
15
10
5
0
$|\eta_l|$<2.4
$|\eta_l|$<4
$|\eta_l|$<2.4
$|\eta_l|$<4
$|\eta_l|$<4
$\sqrt{s}$ =
14 TeV
27 TeV
14&27 TeV

ATLAS Measurement of m_W

[EPJC 78 (2018) 110, ATL-PHYS-PUB-2018-004]



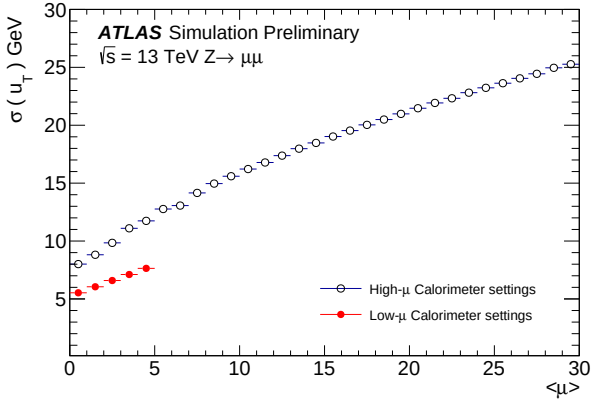


	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
W^+	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4
W^-	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4
$W^\pm$	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

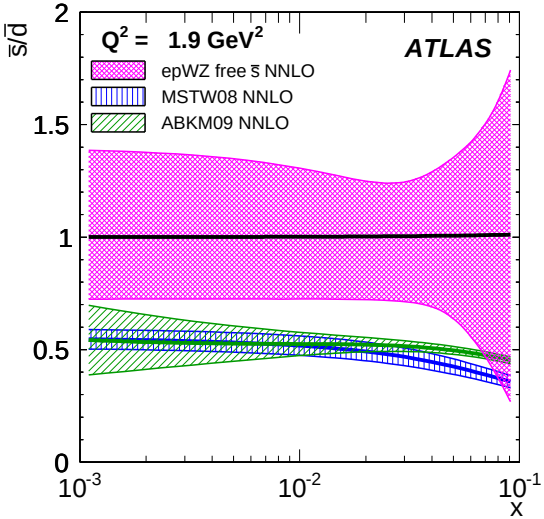
[MeV]

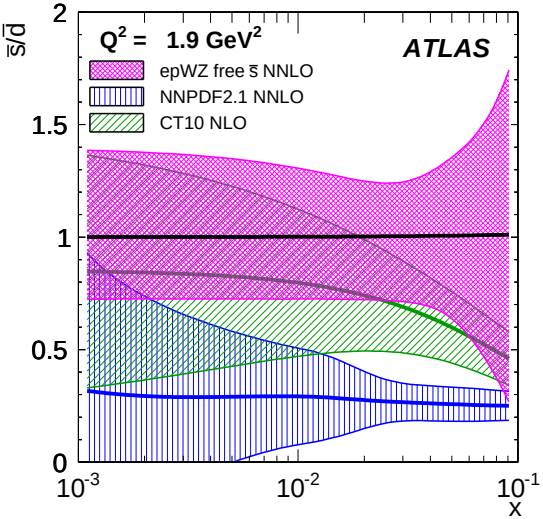
W low-$p_{T,W}$ spectrum

[ATL-PHYS-PUB-2017-021]



Strange History





Strange History