Colour as perceived by us ...
The Standard Model and strong force measurements

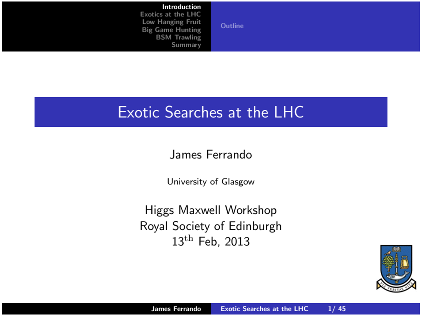
James Ferrando

Lancaster University

Higgs-Maxwell Workshop
Royal Society of Edinburgh
28th February 2024

Previously at Higgs-Maxwell ...

Last time I spoke here was about LHC Run 1 Searches and Run 2 prospects



Exotic Searches at the LHC

James Ferrando

University of Glasgow

Higgs Maxwell Workshop
Royal Society of Edinburgh
13$^{\text{th}}$ Feb, 2013

- Wide range of NP signatures explored
- Extremely strong constraints on many benchmark models
- Still no sign of new physics
- Plenty to explore in the 8 TeV data
- Need to look everywhere, surprises can always be lurking where you weren't expecting them...

Allison Pearson Talking offence is the new national sport

Peter Oborne Tony Blair has failed in the Middle East and should quit

Pep Guardiola Why he turned his back on England

The Daily Telegraph

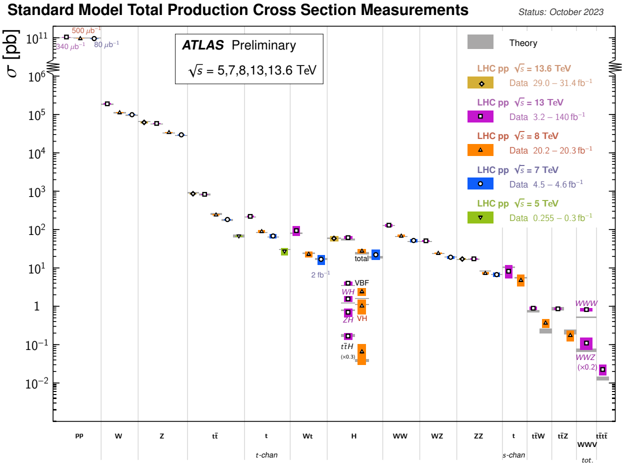
Horse meat in burgers for years

Crash helicopter 'was out of control'

Briton dies, many held, in al-Qaeda revenge raid

I was optimistic (and front page news at the time was rather different!)

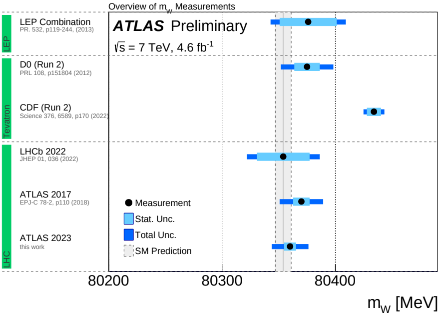
The SM at LHC Runs 1-3


Standard Model Total Production Cross Section Measurements

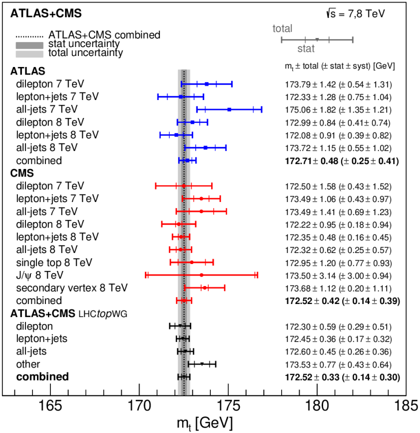
Status: October 2023

- Remarkable SM agreement for σ across many orders of magnitude
- Horribly good performance of the SM continues

Fundamental SM parameters: m_W, m_t

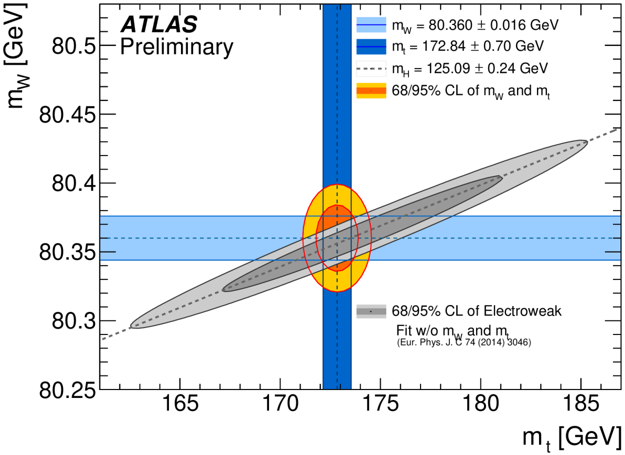


ATLAS-CONF-2023-004

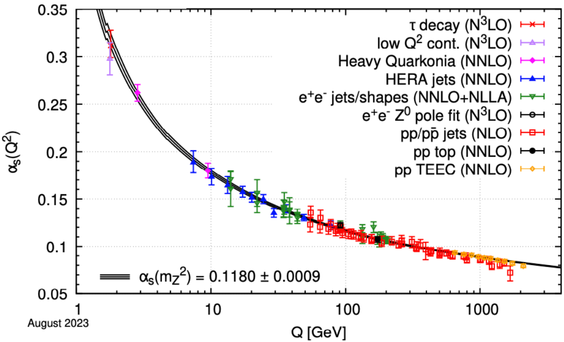


arXiv:2402.08713

Fundamental SM parameters: m_W, m_t, m_H



Fundamental SM parameters: α_S



averages per sub-field	unweighted	weighted	unweighted without subfield
τ decays & low Q^2	0.1173 ± 0.0017	0.1174 ± 0.0009	0.1177 ± 0.0013
$Q\bar{Q}$ bound states	0.1181 ± 0.0037	0.1177 ± 0.0011	0.1175 ± 0.0011
PDF fits	0.1161 ± 0.0022	0.1168 ± 0.0014	0.1179 ± 0.0011
e^+e^- jets & shapes	0.1189 ± 0.0037	0.1187 ± 0.0017	0.1174 ± 0.0011
hadron colliders	0.1168 ± 0.0027	0.1169 ± 0.0014	0.1177 ± 0.0011
electroweak	0.1203 ± 0.0028	0.1203 ± 0.0016	0.1171 ± 0.0011
PDG 2023 (without lattice)	0.1175 ± 0.0010	0.1178 ± 0.0005	n/a

PDG QCD Review: 2023 Update

Outline

This talk - focus on QCD measurements in collider experiments:

- Why make QCD measurements?
- What kinds of properties can we test?
- Some measurements...
- What is still to come?

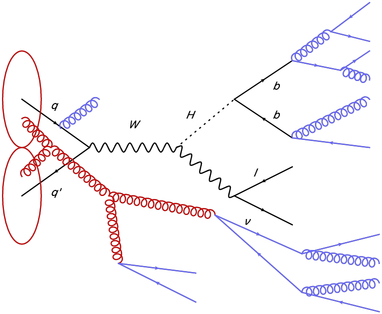
Why QCD measurements at colliders?

Why make QCD measurements: I

Because it's interesting!

- Proton Structure via Parton Distribution Functions (PDFs)
- Extra hard jets from higher-order perturbative terms
- Details of the parton shower
- Details of fragmentation and hadronisation
- Underlying event and multiple parton interactions

A very rich set of physics to explore



Why make QCD measurements: II

Because it's useful, Uncertainties on:

- Proton structure
- Parton shower
- Fragmentation and hadronisation

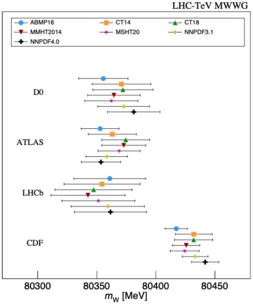
are significant for many searches and precision measurements at the LHC

Example I: *W*-Mass

ATLAS *W*-mass reanalysis[1] still has large uncertainties from QCD sources:

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

Study of compatibility of different m_W measurements[2] needed much work to ensure common QCD framework:



PDF set	All experiments (4 d.o.f.) m_W	σ_{PDF}	χ^2	$p(\chi^2, n)$
ABMP16	80392.7 ± 7.5	3.2	29	0.0008%
CT14	80393.0 ± 10.9	7.1	16	0.3%
CT18	80394.6 ± 11.5	7.7	15	0.5%
MMHT2014	80398.0 ± 9.2	5.8	17	0.2%
MSHT20	80395.1 ± 9.3	5.8	16	0.3%
NNPDF3.1	80403.0 ± 8.7	5.3	23	0.1%
NNPDF4.0	80403.1 ± 8.9	5.3	28	0.001%

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[1] ATLAS-CONF-2023-004

[2] LHC-TeV MWWG arXiv:2308.09417

Example II: Top-Mass

ATLAS Coll., JHEP 06 (2023) 019

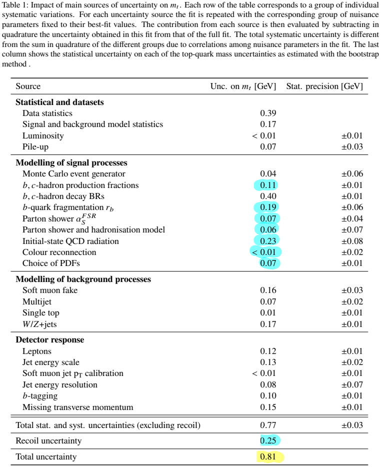
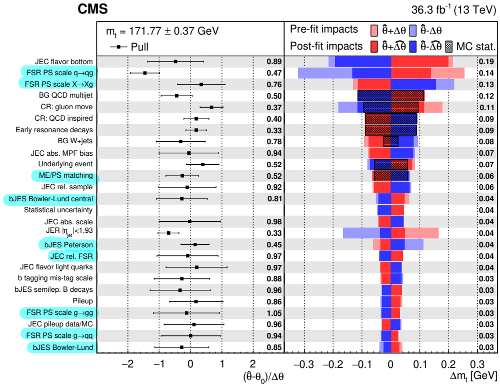


Table 1: Impact of main sources of uncertainty on m_t. Each row of the table corresponds to a group of individual systematic variations. For each uncertainty source the fit is repeated with the corresponding group of nuisance parameters fixed to their best-fit values. The contribution from each source is then evaluated by subtracting in quadrature the uncertainty obtained in this fit from that of the full fit. The total systematic uncertainty is different from the sum in quadrature of the different groups due to correlations among nuisance parameters in the fit. The last column shows the statistical uncertainty on each of the top-quark mass uncertainties as estimated with the bootstrap method .

Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Statistical and datasets		
Data statistics	0.39	
Signal and background model statistics	0.17	
Luminosity	< 0.01	±0.01
Pile-up	0.07	±0.03
Modelling of signal processes		
Monte Carlo event generator	0.04	±0.06
b, c-hadron production fractions	0.11	±0.01
b, c-hadron decay BRs	0.40	±0.01
b-quark fragmentation r_b	0.19	±0.06
Parton shower α_S^{FSR}	0.07	±0.04
Parton shower and hadronisation model	0.06	±0.07
Initial-state QCD radiation	0.23	±0.08
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.07	±0.01
Modelling of background processes		
Soft muon fake	0.16	±0.03
Multijet	0.07	±0.02
Single top	0.01	±0.01
W/Z+jets	0.17	±0.01
Detector response		
Leptons	0.12	±0.01
Jet energy scale	0.13	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.08	±0.07
b-tagging	0.10	±0.01
Missing transverse momentum	0.15	±0.01
Total stat. and syst. uncertainties (excluding recoil)	0.77	±0.03
Recoil uncertainty	0.25	
Total uncertainty	0.81	

CMS Coll, Eur. Phys. J. C 83 (2023) 963



What to measure

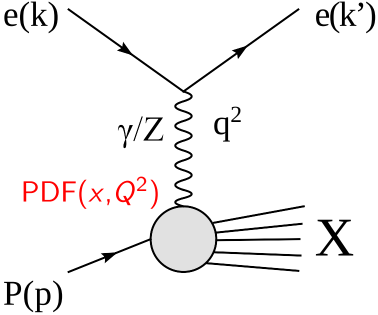
- **PDFs**
    - Differential cross sections in energy scale, and overall kinematics of the system
- α_S , e.g. in $N/N+1$ jet cross section ratios
- Parton shower/higher orders in
    - High jet multiplicity events
    - P_T **of vector bosons and/or** $t\bar{t}$
    - **(Sub)Structure of hadronic jets**
- Soft-QCD in the underlying event
- **Heavy quark fragmentation**
- Hadronisation using details of final state

Measurements

PDFs

Parametrise proton structure as Parton Distribution Functions (PDFs):

- Give probability of finding a parton of some type with fraction x of the proton's momentum when probing at a scale Q^2
- Can be measured: especially *ep* collisions (Deep Inelastic Scattering)
- QCD can predict how a PDF at a given x changes with Q^2 via DGLAP equations
- We expect the PDFs to be Universal:
  - Proton PDFs from *ep* data applicable in *pp* data
  - Extractions from Heavy Ion/Nuclear data need additional corrections



Two recent ATLAS experimental papers studied the effect of including LHC data in the PDF fits together with HERA *ep* data:

- Inclusive W/Z and V+jets JHEP 07 (2021) 223
- 'Global' fit Eur.Phys.J.C 82 (2022) 5, 438

Retain some of the advantages of HERA PDF2.0 (extraction purely from HERA data):

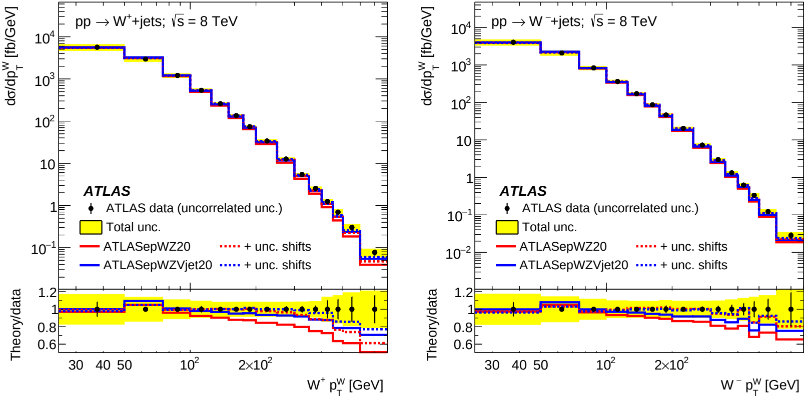
- ATLAS datasets also have well understood correlations between their systematic uncertainties
- Avoid nuclear corrections

LHC Data in the ATLAS 'Global' fit

Data set	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Decay channel	Observables entering the fit
Inclusive $W, Z/\gamma^*$	7	4.6	e, μ combined	η_ℓ (W), y_Z (Z)
Inclusive Z/γ^*	8	20.2	e, μ combined	$\cos\theta^*$ in bins of $y_{\ell\ell}$, $m_{\ell\ell}$
Inclusive W	8	20.2	μ	η_μ
$W^\pm$ + jets	8	20.2	e	p_T^W
Z + jets	8	20.2	e	$p_\mathrm{T}^\mathrm{jet}$ in bins of $\|y^\mathrm{jet}\|$
$t\bar{t}$	8	20.2	lepton + jets, dilepton	$m_{t\bar{t}}$, p_T^t, $y_{t\bar{t}}$
$t\bar{t}$	13	36	lepton + jets	$m_{t\bar{t}}$, p_T^t, y_t, $y_{t\bar{t}}^\mathrm{b}$
Inclusive isolated γ	8, 13	20.2, 3.2	-	E_T^γ in bins of η^γ
Inclusive jets	7, 8, 13	4.5, 20.2, 3.2	-	$p_\mathrm{T}^\mathrm{jet}$ in bins of $\|y^\mathrm{jet}\|$

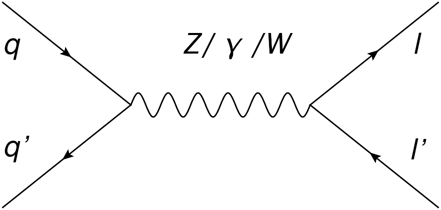
Correlated systematic uncertainties between the datasets are treated as nuisance parameters that generate shifts to the datasets

Example of shifts



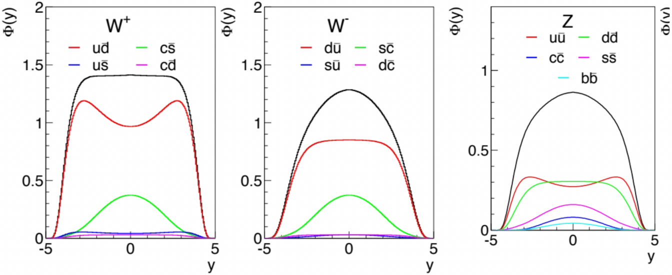
Example from the V+jets paper

Drell-Yan process I



- Simplest hard scattering process to calculate at the LHC
- Cross section an integral over: $q(x_1, Q)q(x_2, Q)\mathcal{M}(x, Q^2)\times$ LIPS.
  LIPS=Lorentz Invariant Phase Space
- Here $q(x, Q)$ are PDFs, if the boson is on shell then $Q^2 = M_V^2$
- At rest $(y = 0)$ $x_1 = x_2 = M_V/\sqrt{s}$
- if $x_1 > x_2$ then $|y| > 0$, sample higher and lower x at same Q^2
- Going very forward simultaneously samples higher and lower x

Drell-Yan process II

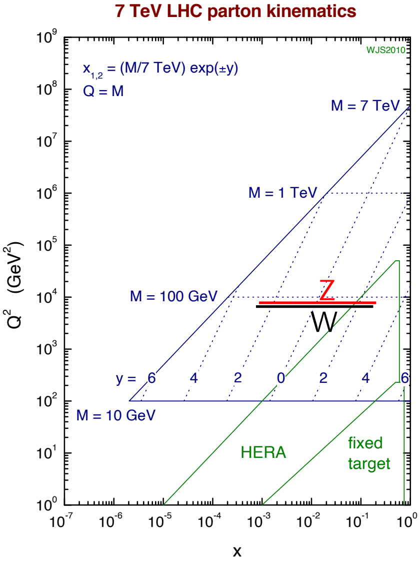


plots by S. Glazov, V. Radescu

Flavour sensitivity:

- Z boson sum pairs of all flavours $u\bar{u}, d\bar{d}$,....
- W^+ sums pairings of $+$ve charged (anti)quarks $(u\bar{d}), (u\bar{s})$, ...
- W^- sums pairings of -ve charged (anti)quarks $(d\bar{u}), (d\bar{c})$,...

W/Z Production , @ LHC



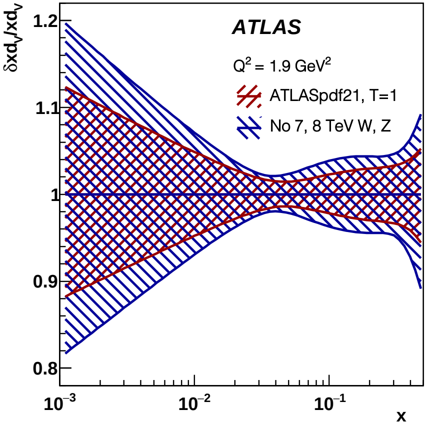
W/Z Production at the LHC

- Exploring a new range of parton kinematics
- Run I data: not only lower x than TeVatron, also lower x than HERA at central rapidity
- LHCb further extends measurement in x
- Inclusive W/Z essentially probes a horizontal band in x, Q^2 space
- 13 TeV data probes lower x for the same Q^2 as 7 TeV

Effect of including DY and W/Z data

Including the inclusive W/Z data:

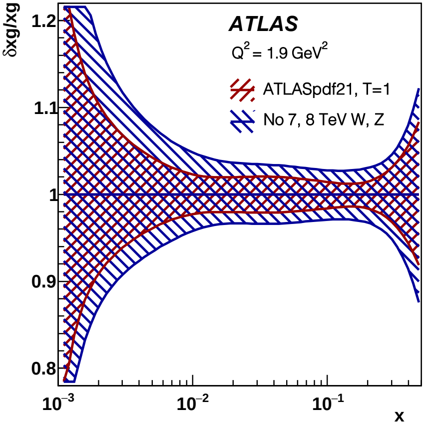
- reduced uncertainty on the down-valence distribution



Effect of including DY and W/Z data

Including the inclusive W/Z data:

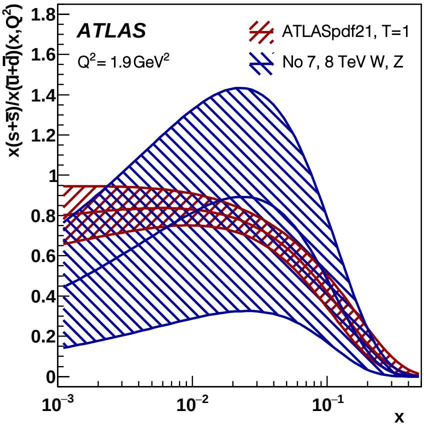
- reduced uncertainty on the down-valence distribution
- slightly reduced uncertainty on the gluon distribution



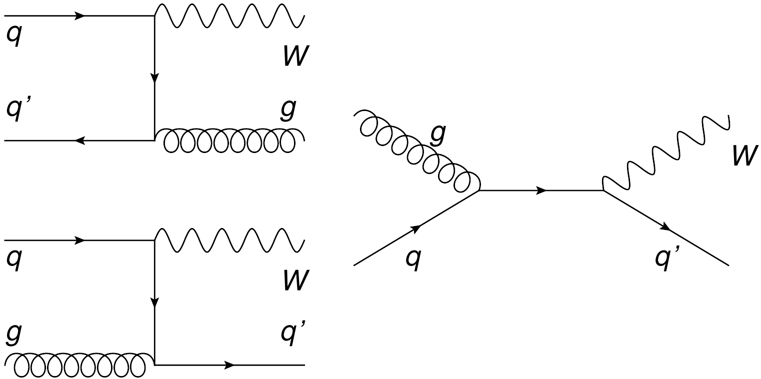
Effect of including DY and W/Z data

Including the inclusive W/Z data:

- reduced uncertainty on the down-valence distribution
- slightly reduced uncertainty on the gluon distribution
- much stronger constraint on the ratio of the s quark to the $\bar{u}$ and $\bar{d}$ quarks
- The value of this ratio had to be assumed for PDFs relying entirely on HERA data



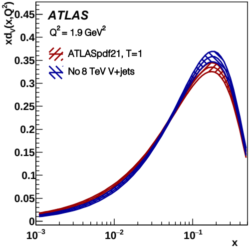
V+jets data

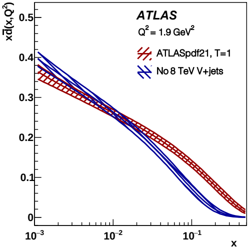


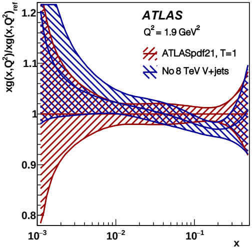
Aim of including V+jets:

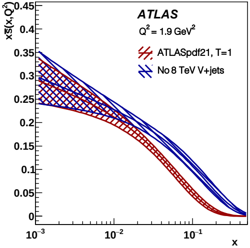
- probe higher Q^2,x
- more sensitivity to gluon

Effect of V+jets data



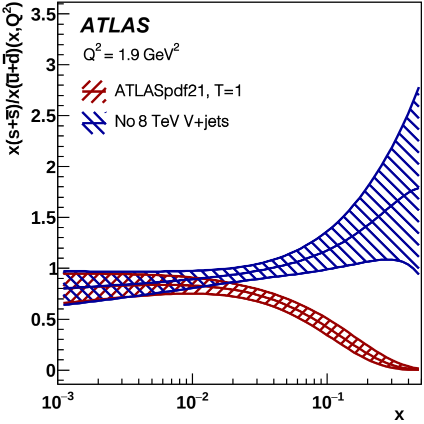






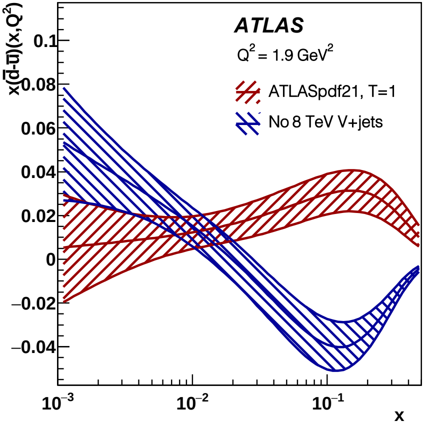
- changes the shape of quark distributions at higher-x
  - reduces $d_v, \bar{s}$ increases $\bar{d}$
- reduces the gluon at lower-x

Effect of V+jets data



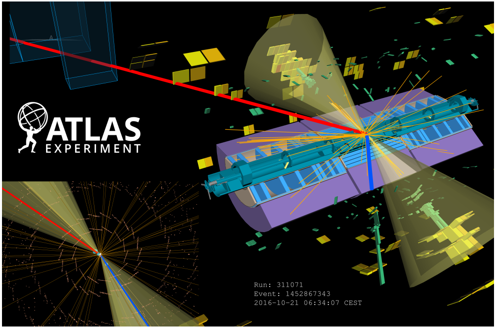
- Causes s to be suppressed relative to $\bar{d}$ and $\bar{u}$ at higher x - something preferred by CCFR/NuTev data from νN scattering

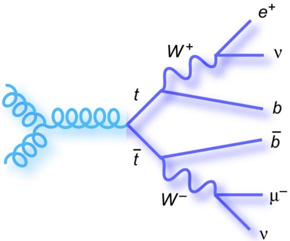
Effect of V+jets data

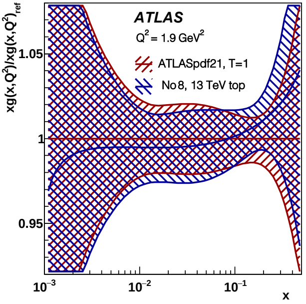


- Favours a positive $\bar{d} - \bar{u}$ - something preferred data frompN Drell-Yan data such as E907 Nature 590 (2021) 7847, 561-565.

Effect of including $t\bar{t}$ data

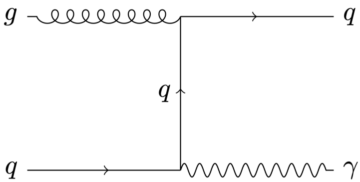


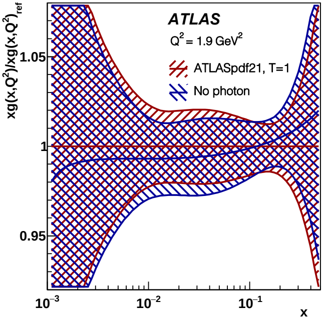


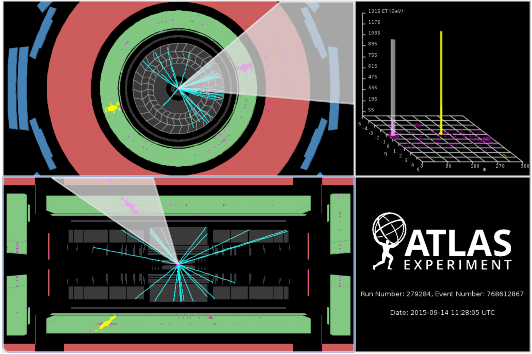


- The main effect is to reduce the mid-to-high-x gluon distribution
- Uncertainties at high-x are also reduced

Including Photons

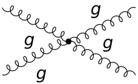






- Minimal effect from including the photon data

Including Jets



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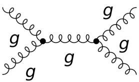

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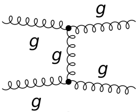

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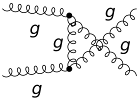

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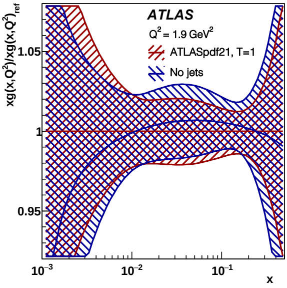
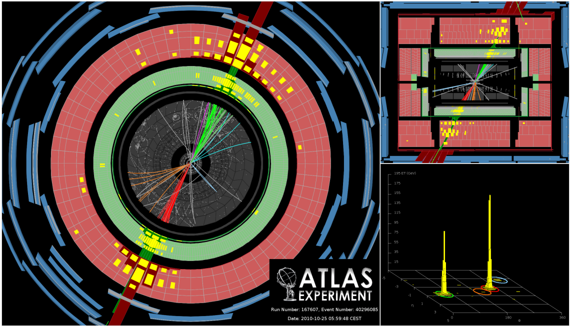
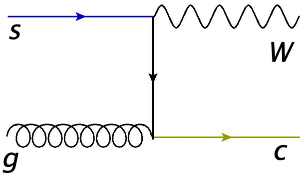


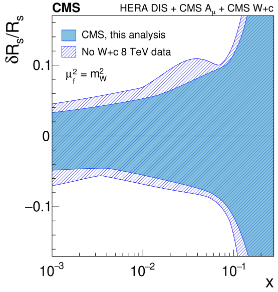


- Strong decrease in high-x gluon uncertainty

Looking at the strange quark with charm: W+c production

- $W+$ charm production includes production with strange quarks in the intial state
- The CMS collaboration measured this by identifying jets containing charm mesons in W production
- Studying the effect of including this data in PDF fits the CMS collaboration demonstrated that this data helps reduce the uncertainty on the strange quark distribution

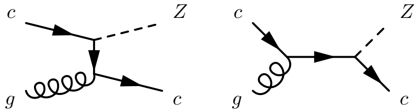


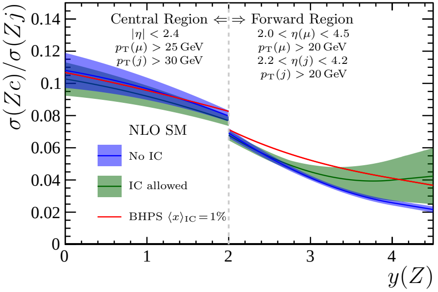


Eur. Phys. J. C 82 (2022) 1094

Bigger on the inside?
Intrinsic charm in the proton

- Possibility of *Intrinsic* charm (IC), a $|uudc\bar{c}\rangle$ component of the p wavefunction long debated
- separate from $g \to c\bar{c}$, should be shaped more like the valence quark distributions

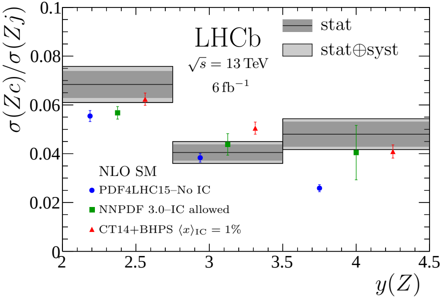




Phys.Rev.Lett. 128 (2022) 8, 082001

Bigger on the inside?
Intrinsic charm in the proton

- Possibility of *Intrinsic* charm (IC), a $|uudc\bar{c}\rangle$ component of the p wavefunction long debated
- separate from $g \to c\bar{c}$, should be shaped more like the valence quark distributions
- LHCb, with it's extremely forward coverage well-suited to explore this in $Z + c$ events
- measured the rate of $Z + c/Z$+jets and found that IC favoured by the data

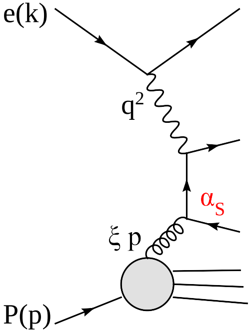


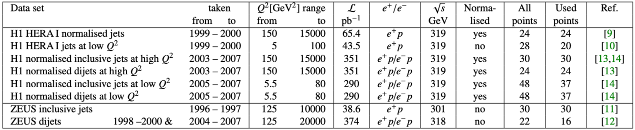
Phys.Rev.Lett. 128 (2022) 8, 082001

Measuring α_S - H1+ZEUS:

H1+ZEUS collaborations also recently explored the addition of new data to their PDF fits:

- Fits to inclusive DIS gave sensitivity to α_S - via scaling violations
- This strongly correlates the gluon with α_S
- Addition of jet cross sections adds an extra constraint on α_S
- Good for extracting α_S together with PDFs

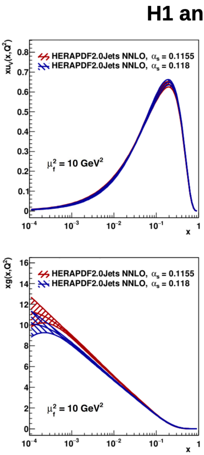


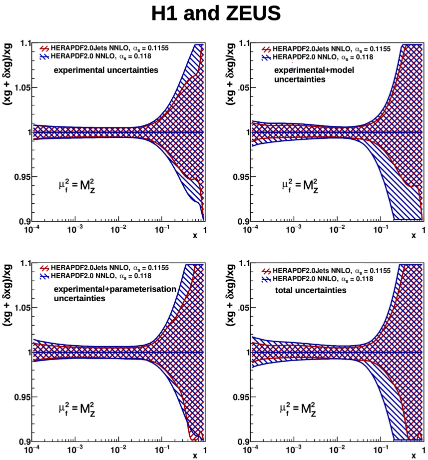


Data set	taken		Q^2[GeV^2] range		$\mathcal{L}$	e^+/e^-	$\sqrt{s}$	Norma-lised	All points	Used points	Ref.
	from	to	from	to	pb^{-1}		GeV				
H1 HERA I normalised jets	1999	2000	150	15000	65.4	e^+p	319	yes	24	24	[9]
H1 HERA I jets at low Q^2	1999	2000	5	100	43.5	e^+p	319	no	28	20	[10]
H1 normalised inclusive jets at high Q^2	2003	2007	150	15000	351	e^+p/e^-p	319	yes	30	30	[13,14]
H1 normalised dijets at high Q^2	2003	2007	150	15000	351	e^+p/e^-p	319	yes	24	24	[13]
H1 normalised inclusive jets at low Q^2	2005	2007	5.5	80	290	e^+p/e^-p	319	yes	48	37	[14]
H1 normalised dijets at low Q^2	2005	2007	5.5	80	290	e^+p/e^-p	319	yes	48	37	[14]
ZEUS inclusive jets	1996	1997	125	10000	38.6	e^+p	301	no	30	30	[11]
ZEUS dijets	1998 –2000 & 2004	2007	125	20000	374	e^+p/e^-p	318	no	22	16	[12]

Table 1: The jet-production data sets from H1 and ZEUS used for the HERAPDF2.0Jets NNLO fits. The term normalised indicates that these cross sections are normalised to the respective neutral current inclusive cross sections.

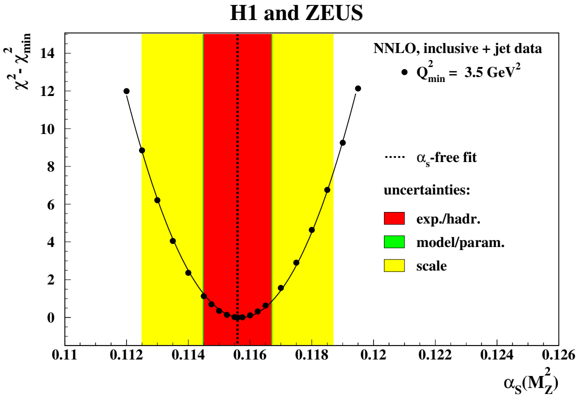
Measuring α_S - H1+ZEUS:





Clear change in slope and reduction in uncertainty of high-x gluon

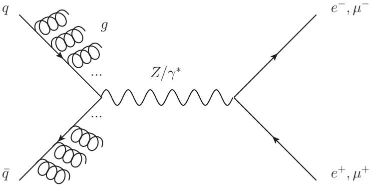
Measuring α_S - H1+ZEUS:

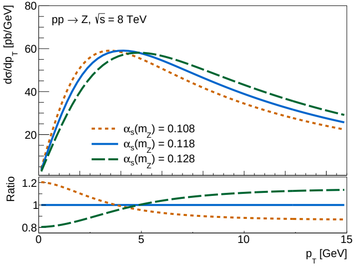


- Overall a precise experimental extraction achieved
- Dominated by NNLO scale uncertainty

$$\alpha_S = 0.1156 \pm 0.0011 \text{ (exp) } {}^{+0.0001}_{-0.0002} \text{ (model+ param.) } \pm 0.0029 \text{ (scale)}$$

Measuring α_S - ATLAS I





ATLAS published a new double-differential measurement of Z P_T and rapidity in full lepton phase space[a], using 8 TeV data

- The p_T distribution is highly sensitive to α_S
- Theory predictions available at N^3LO with N^4LL low-p_T resummation
- Allows a very high precision extraction[b] of α_S
- Methodology was demonstrated using TeVatron data in S. Camarda et al. Eur. Phys. J.C 84 (2024) 1, 39

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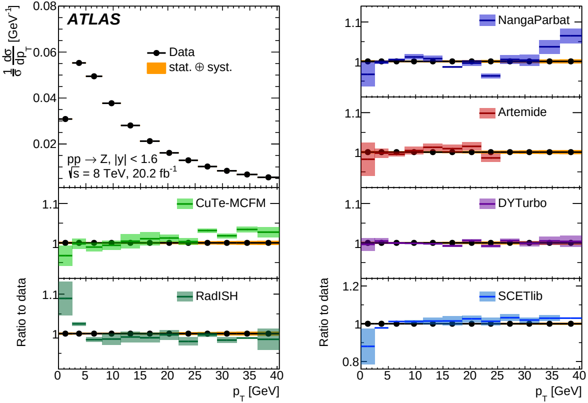
[a] arXiv:2309.09318

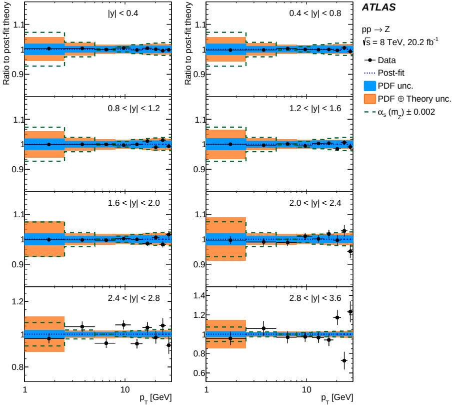
[b] arXiv:2309.12986

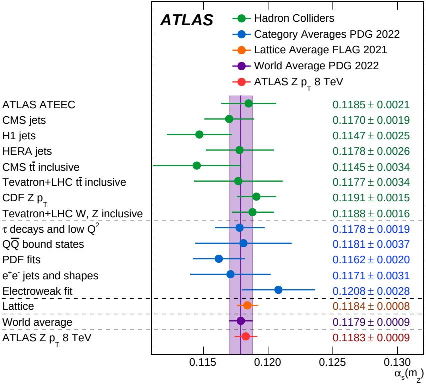
Measuring α_S - ATLAS II



DYTurbo (used for this extraction), is able to describe the p_T spectrum well

Measuring α_S - ATLAS III





The most precise single experimental determination of α_S

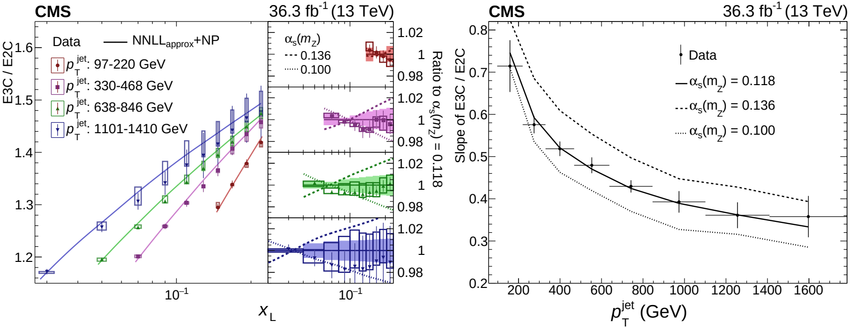
Jets

Alice, ATLAS, CMS have made many recent jet measurements, here I highlight:

- CMS α_S from jet substructure arXiv:2402.13864
- ATLAS Jet substructure in boosted top quark events arXiv:2312.03797
- CMS Lund plane:arXiv:2312.16343
- ATLAS Lund subjet multiplicities arXiv:2402.13052

α_S from jet substructure

Ratio of 2-particle to 3-particle Energy correlators inside jets is sensitive to α_S:

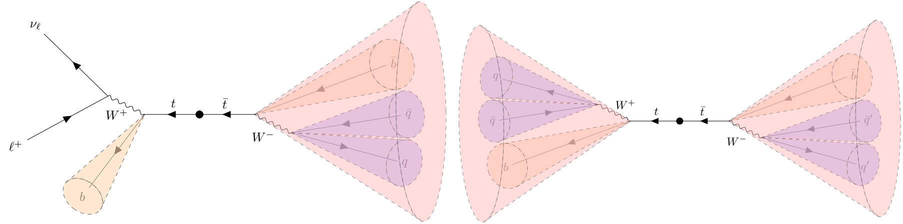


CMS have exploited this to extract :

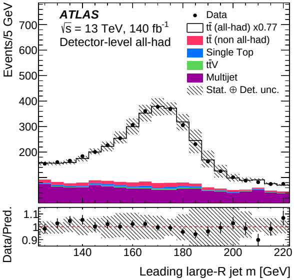
$\alpha_S(m_Z) = 0.1229^{+0.0014}_{-0.0012}$ (stat) $^{+0.0030}_{-0.0033}$ (theo) $^{+0.0023}_{-0.0036}$ (exp)

using the slope in the ratio as a function of the η, ϕ distance (x_L) between the pairs being considered.

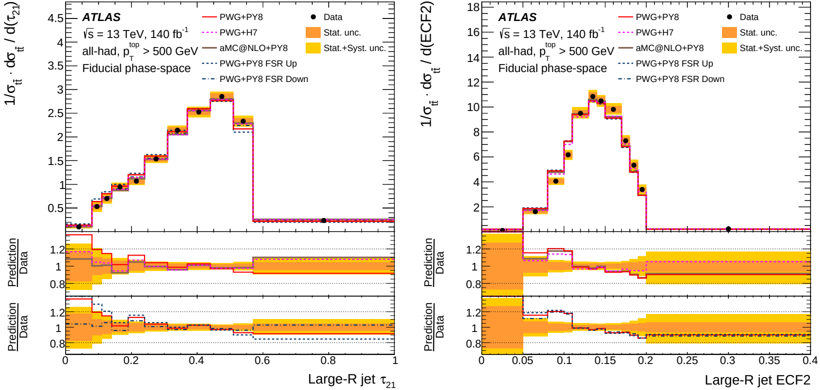
Boosted Top-quark Jets I



- high-p_T top-quarks can produce jets containing all the decay produces of the top
- such top jets are an interesting testing ground to study variables designed to distinguish jets with hard substructure from others
- ATLAS have studied this in $t\bar{t}$ events

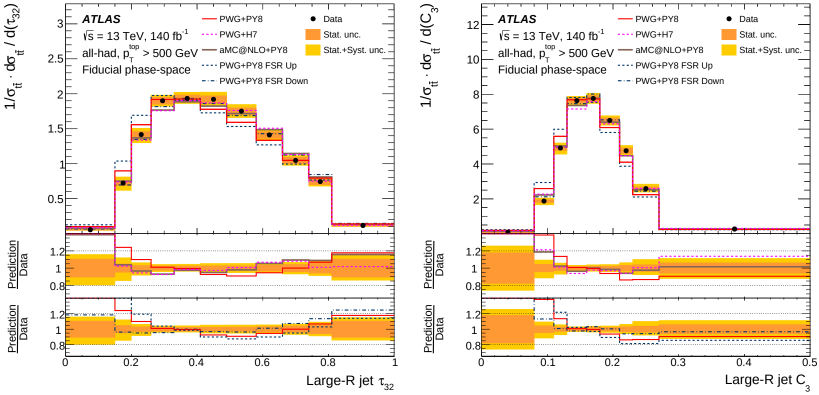


Boosted Top-quark Jets II



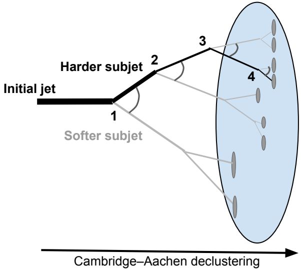
Variables designd to distinguish 2-prong like jets from 1 prong are generally well described

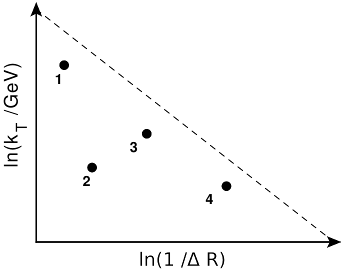
Boosted Top-quark Jets II

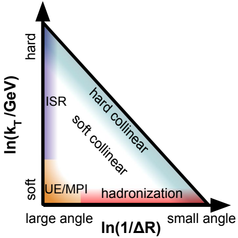


Variables designd to distinguish 3-prong like jets from 2 prong fare worse

The Lund Jet Plane

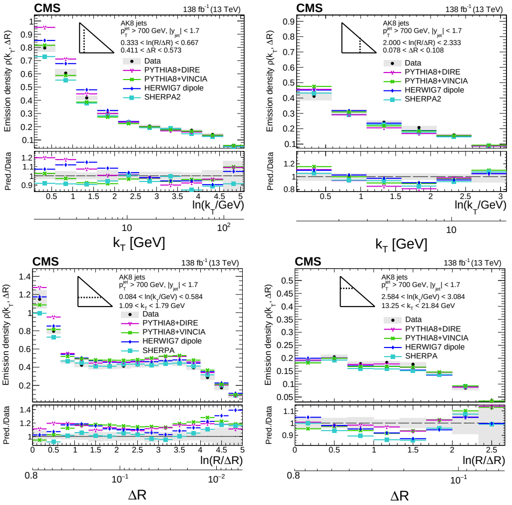






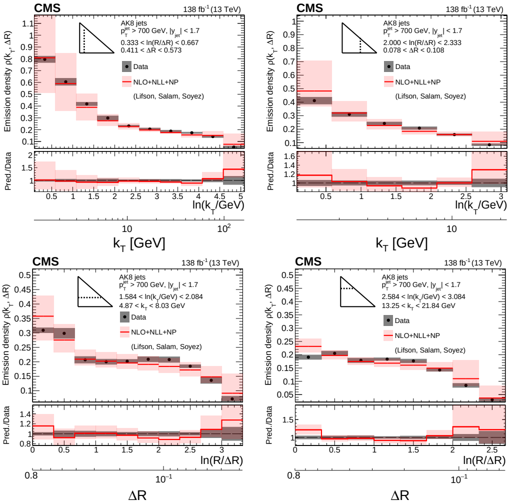
- recluster a jet
- follow splitting history
- identify jet ‘core’ and emissions
- assign emissions to the 2D plane
- different regions of the plane → different QCD physics

The Lund Jet Plane II



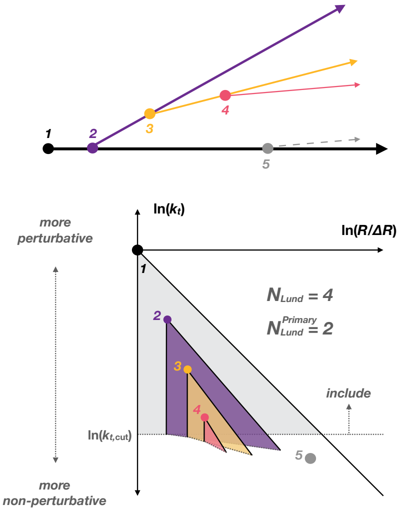
- Monte Carlo can do a reasonable job of describung the plane (Sherpa seems best)

The Lund Jet Plane II



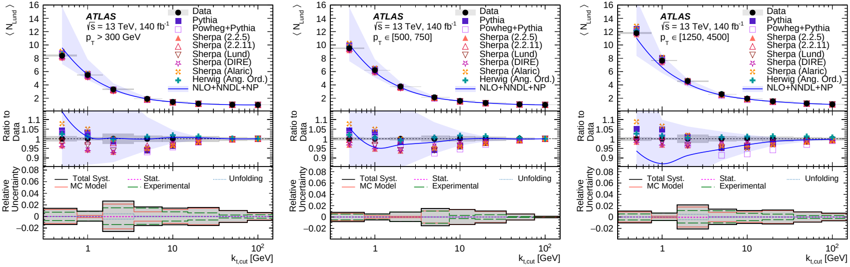
- Monte Carlo can do a reasonable job of describung the plane (Sherpa seems best)
- Analytical calculations also doing a good job

Lund Subjet multiplicities



- Lund Subjet multipicities offer even more information about events
- Here each emission is followed further, so long as it is above a certain p_T threshold
- total multiplicity above a given scale gives us more information about the shower (also sensitive to α_S)

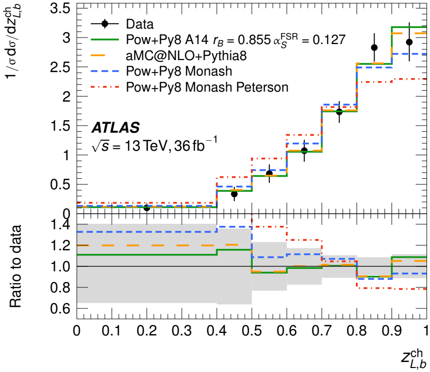
Lund Subjet multiplicities



Again MCs and analytical calculations doing well (though analytical calculation undershoots at higher p_T)

Heavy Flavour Fragmentation

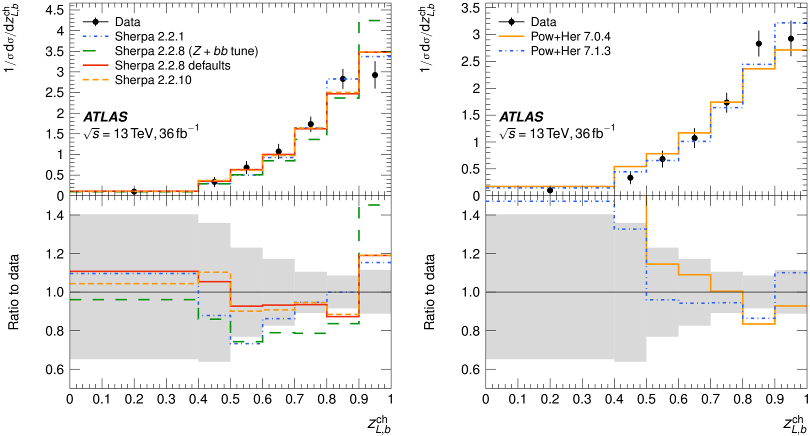
- Heavy flavour fragmentation is very important for measurements such as the top-quark mass
- Also important for flavour-tagging
    - Fraction of jet momentum carried by shifted vertex in *b*-jet is usually one of the best discriminating variables
- Relatively little data to constrain it



ATLAS studied b fragmentation in $t\bar{t}$ Phys. Rev. D 106 (2022) 032008

$Z^{ch}_{L,b}$ fraction of charged momentum parallel to the b-jet carried by b-proxy (shifted vertex)

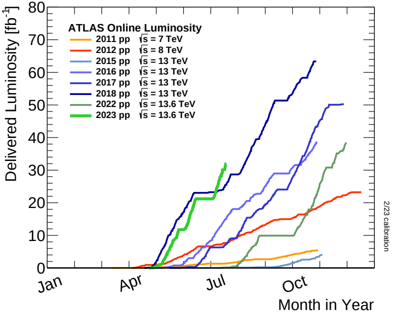
Heavy Flavour Fragmentation

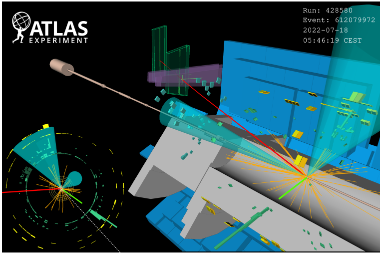


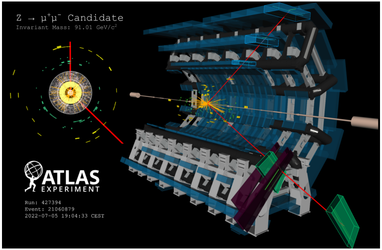
Clear that some MC tunes don't describe it well, but most doing a reasonable job

What Comes Next?

LHC Run 3 the story so far...



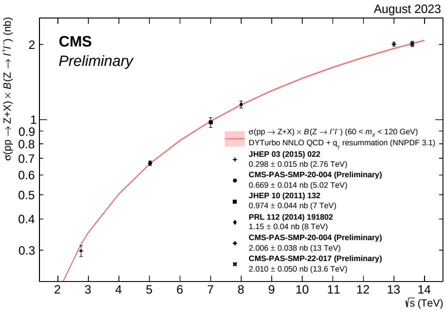




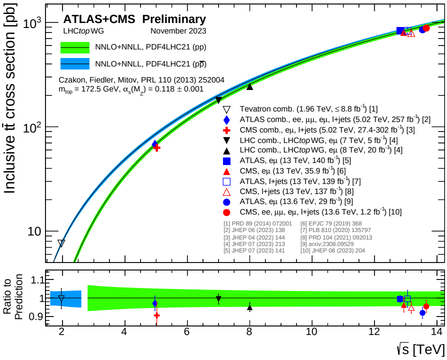
- LHC delivered around 70 fb^{-1} per experiment in 2022-2023
- Experiments are already starting to publish results with this data

First Run 3 Measurements

Atlas and CMS have already produced first Run 3 measurements of Z and $t\bar{t}$

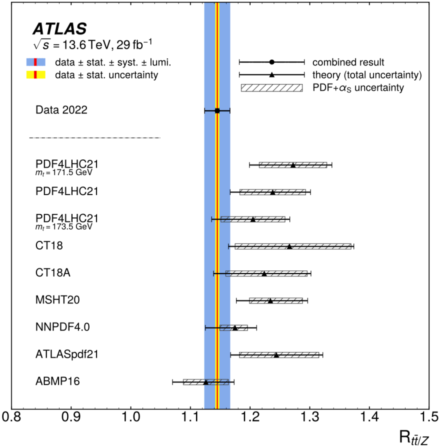


CMS-PAS-SMP-22-017



LHC Top WG summary

First Run 3 Measurements



- ATLAS also measured the $t\bar{t}/Z$ ratio (generally sensitive to PDFs)
- Value of the ratio is on the low side but still consistent with expectations from most PDFs

Phys. Lett. B 848 (2024) 138376

LHC Run 3 and Run 4

- In 2024-2025, the LHC is expected to deliver proton-proton collisions with an integrated luminosity of 190 fb-1.
- This represents an increase of around a factor of four in the Run 3 dataset
- Improvements from new experimental techniques continue to outpace mere statistical improvements
- Many theoretical developments helping us to understand QCD better
- Expect more jet measurements, with increasing precision amd more substructure measurements, including Lund plane

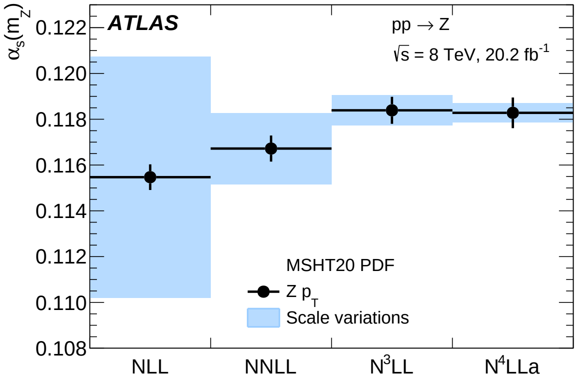
Summary

Summary

- It's a great time to be doing QCD measurements at the LHC:
  - huge datasets
  - Generators and calculations that are doing well at describing QCD prospects
  - LHC proving itself to be a machine for precision physics as well as discovery
- These measurements support other EW/Higgs/Top measurement and searches
- Many nice publications that I didn't have time to review here including:
  - LHCb measurements of A_i
  - Alice HF fragmentation and Lund jet plane work
  - CMS α_S from azimuthal correlations

Back-up

ATLAS α_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	
N^4LL approximation	±0.04	
Total	+0.91	−0.88

ATLASPDF Comparison to Sea quest data