Universität Hamburg
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FSP Erforschung von Universum und Materie

ATLAS EXPERIMENT

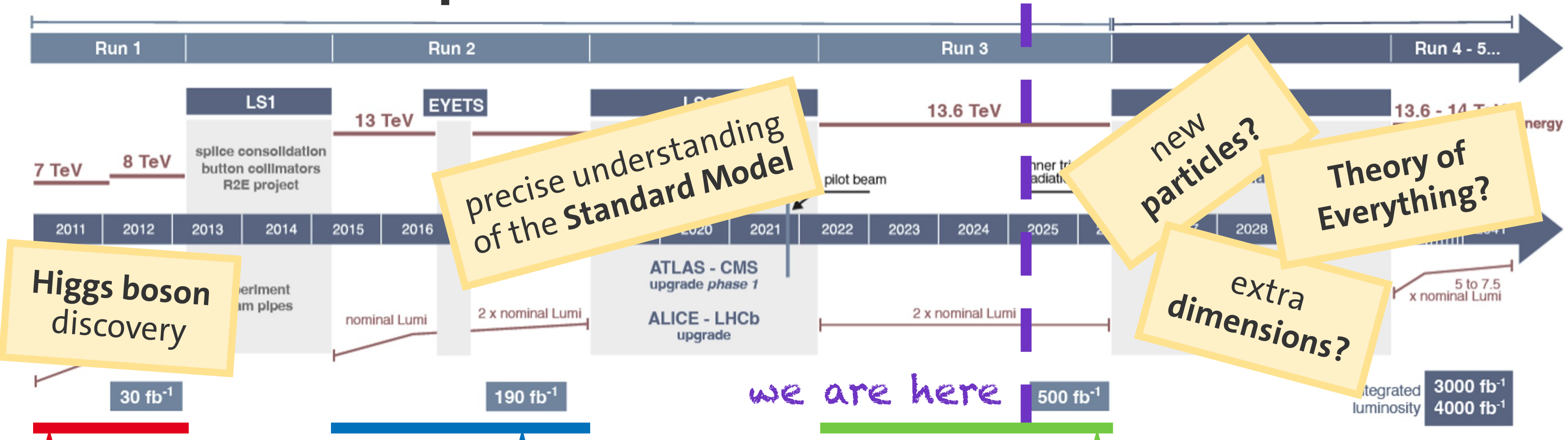
CMS

Highlights from Standard Model physics at the LHC in the precision era

DPG Spring Meeting | 3 April 2025 | Göttingen, Germany

Daniel Savoiu for the ATLAS and CMS collaborations

The LHC in the precision era & the road ahead



Run 1 2010–2013

first operation of a hadron collider at a multi-TeV center-of mass energy $\sqrt{s}$

Run 2 2015–2018

extensive array of measurements and new physics searches at $\sqrt{s}$ = 13 TeV

Run 3 2022–2026

energy & precision frontier at $\sqrt{s}$ = 13.6 TeV

◀ *Tevatron*: $\sqrt{s}$ = 1.96 TeV

High-Luminosity LHC ▶

The LHC in the precision era & the road ahead

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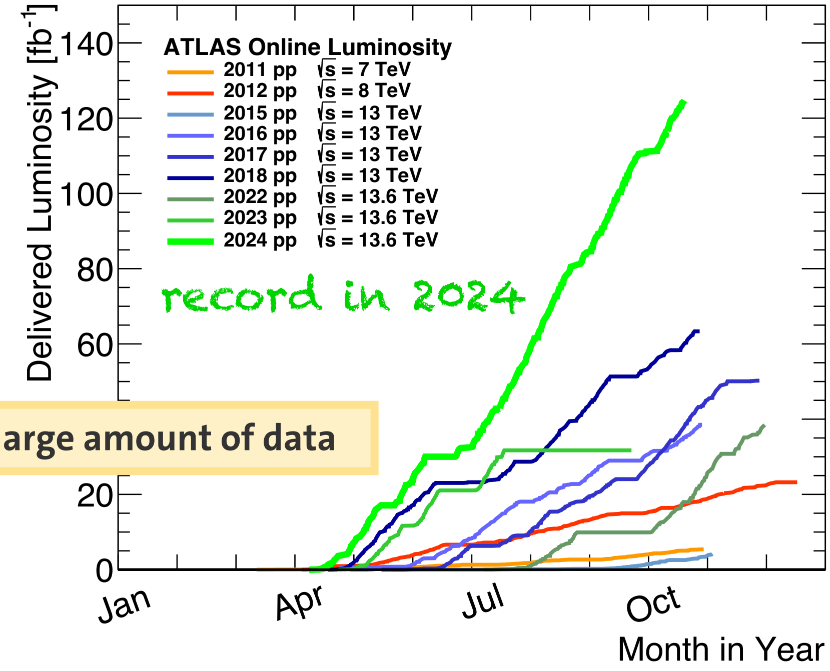
High-Luminosity LHC ▶

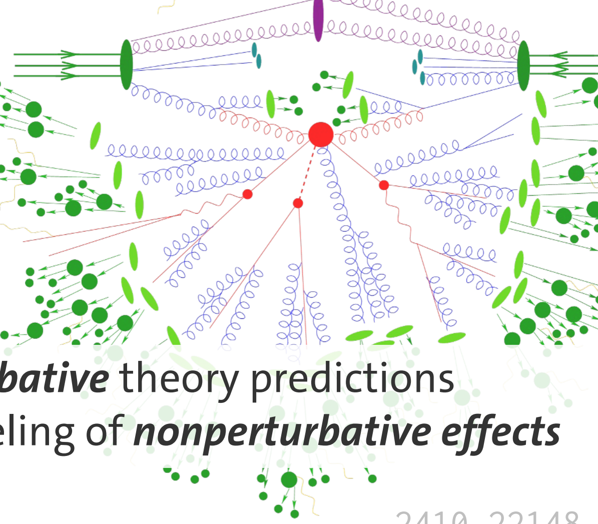
How do we get there?



large amount of data

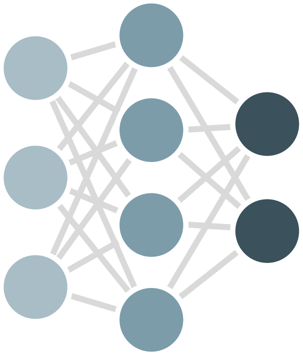
ca. **500 fb^{-1}** of collisions expected from the LHC by the end of Run 3

improved theoretical understanding



high energy: ***perturbative*** theory predictions
+ *low energy*: modeling of ***nonperturbative effects***

2410.22148
JHEP **12** (2024) 156



new technologies and improved approaches

better **detectors**,
reconstruction, **calibration**
& **analysis** methods

Outline

E. Schopf, Wed 11:30 (T 42.2)
M. Komm, Fri 12:00 (T 105.3)

1 Jets & Quantum Chromodynamics (QCD)

- Jet cross sections & other observables
- Parton distributions & strong coupling
- Jet substructure

+ Searches for new physics with **jets**

2 Electroweak measurements

- Vector boson production
- Lepton properties & electroweak SM parameters

+ Searches for new physics with **leptons & bosons**

Disclaimer #1
not covering Higgs boson or top quark, see dedicated talks

Disclaimer #2
cannot cover everything, presenting personal selection of results

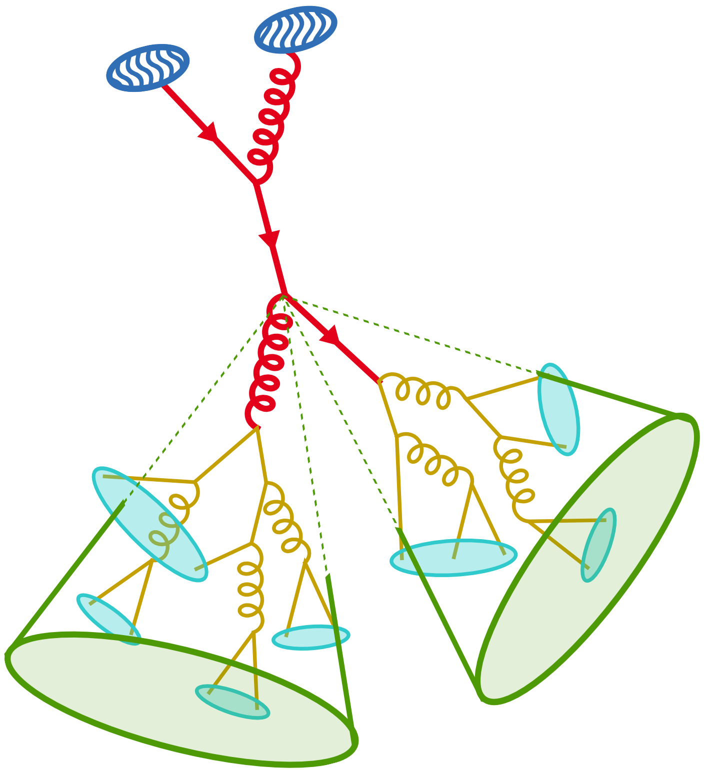
Disclaimer #3
both ***ATLAS*** and ***CMS*** have similar results on many topics, will sometimes show only one or the other

1

Jets & Quantum Chromodynamics (QCD)

Why study jets at the LHC?

jet = collimated stream of particles, experimental signature of color-charged particles (quarks, gluons)



Why study jets at the LHC?

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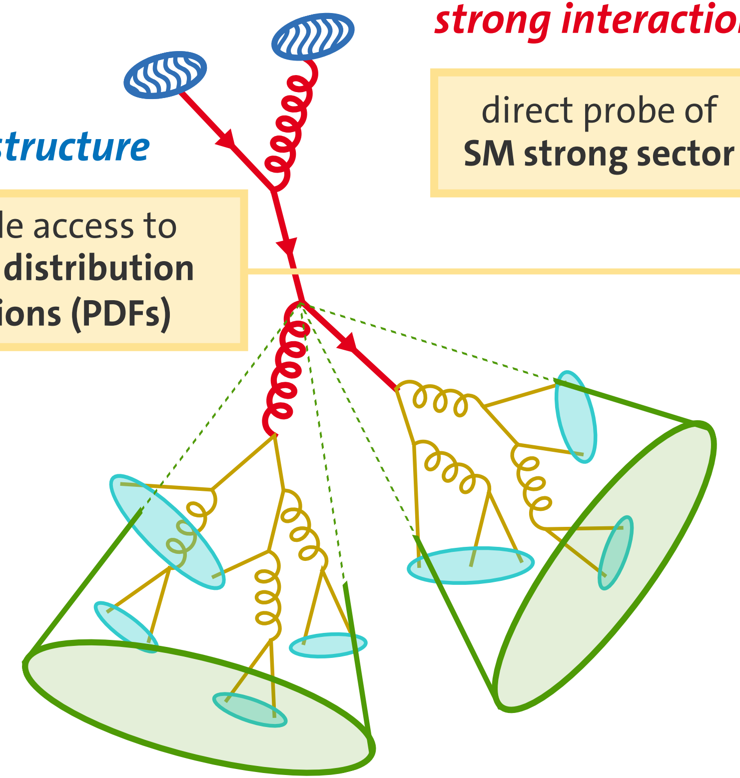
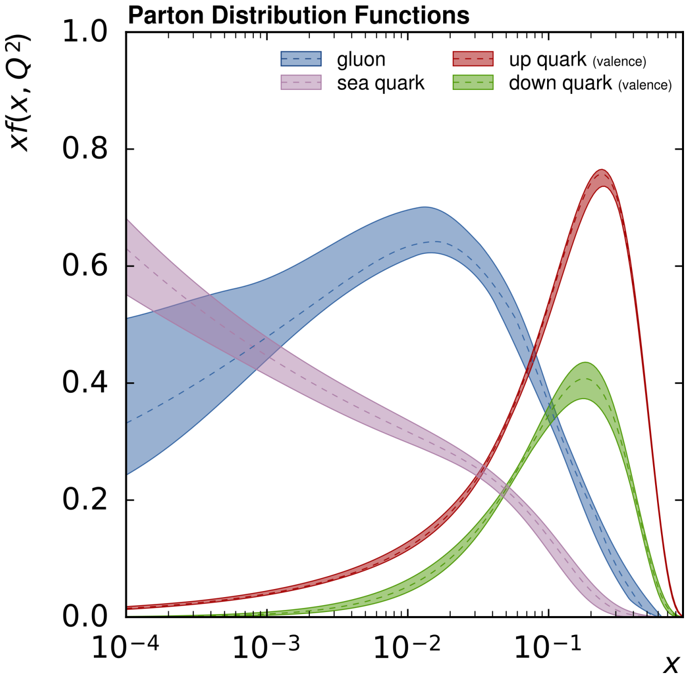
strong interaction → coupling strength α_s

proton structure

provide access to **parton distribution functions (PDFs)**

direct probe of **SM strong sector**





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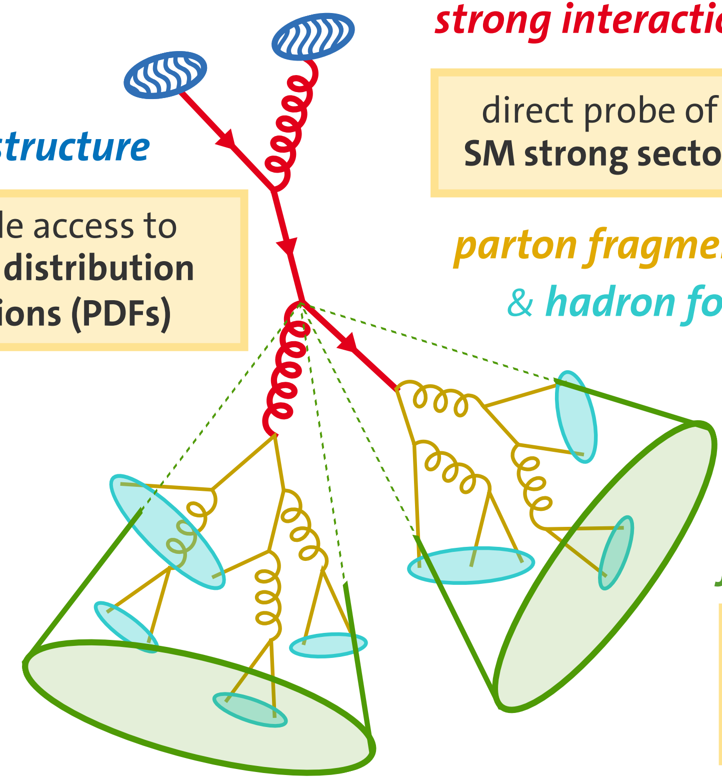


strong interaction → coupling strength α_s

direct probe of **SM strong sector**

proton structure

provide access to **parton distribution functions (PDFs)**

parton fragmentation & ***hadron formation*** } partly low-energy processes, challenging to model

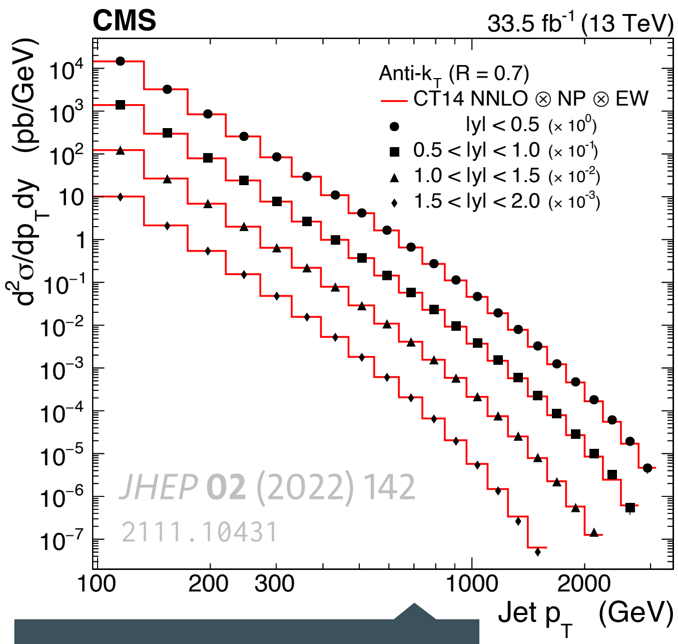
opportunities for improving **theoretical modeling**

jets → complex multiparticle states

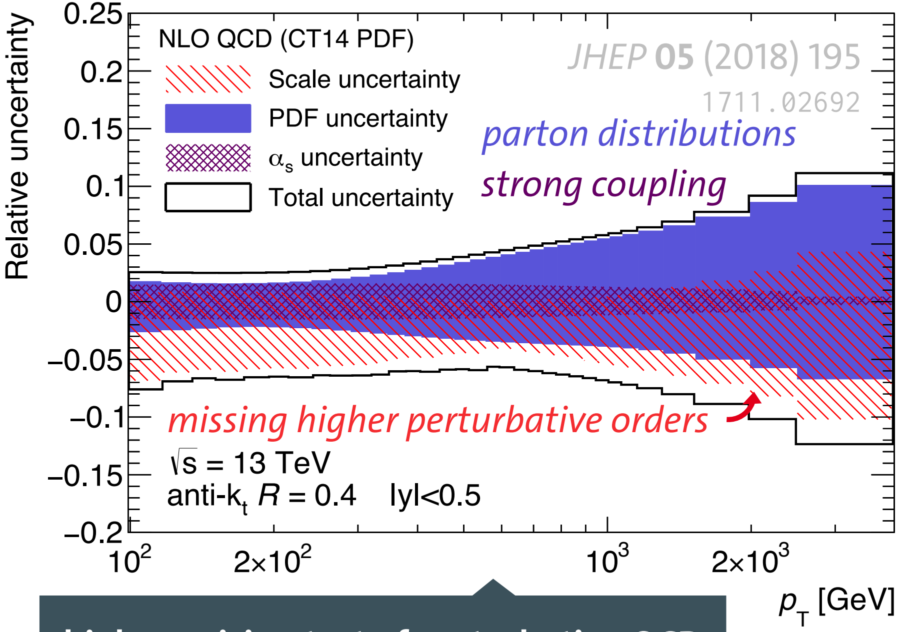
internal structure offers rich **information content**

Jet production – inclusive jet cross sections

highly precise differential measurements covering a large phase space



steeply falling spectra
spanning >7 orders of magnitude

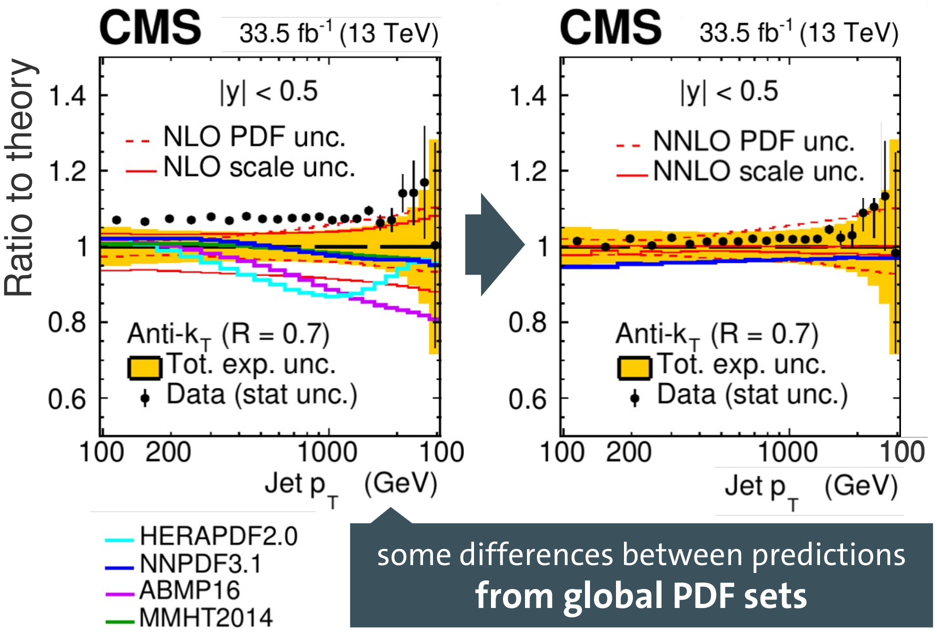


high-precision test of perturbative QCD
sensitive to many theoretical ingredients

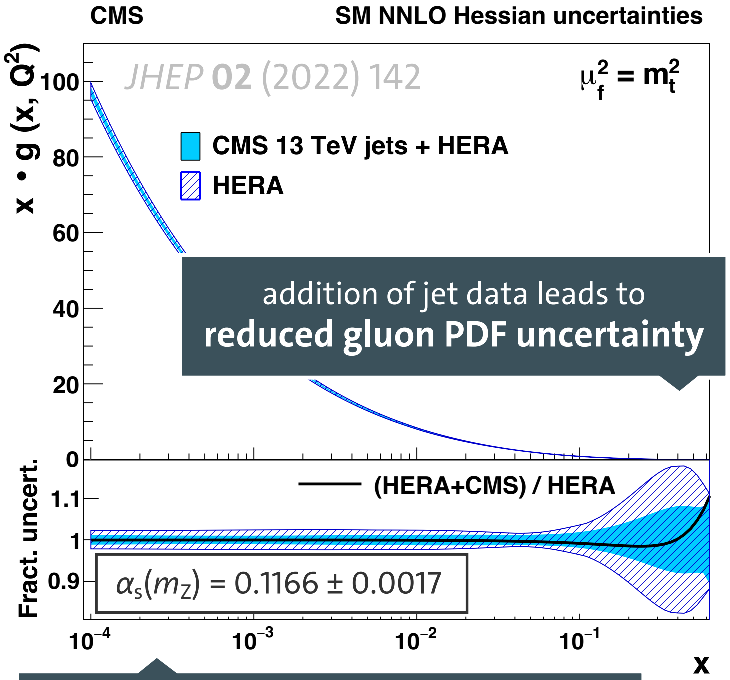
Jet production – constraints on PDFs & strong coupling

data provide precise constraints on fundamental theory components

state of the art: **next-to-next-to-leading order (NNLO)**
improved data description compared to NLO



some differences between predictions
from global PDF sets



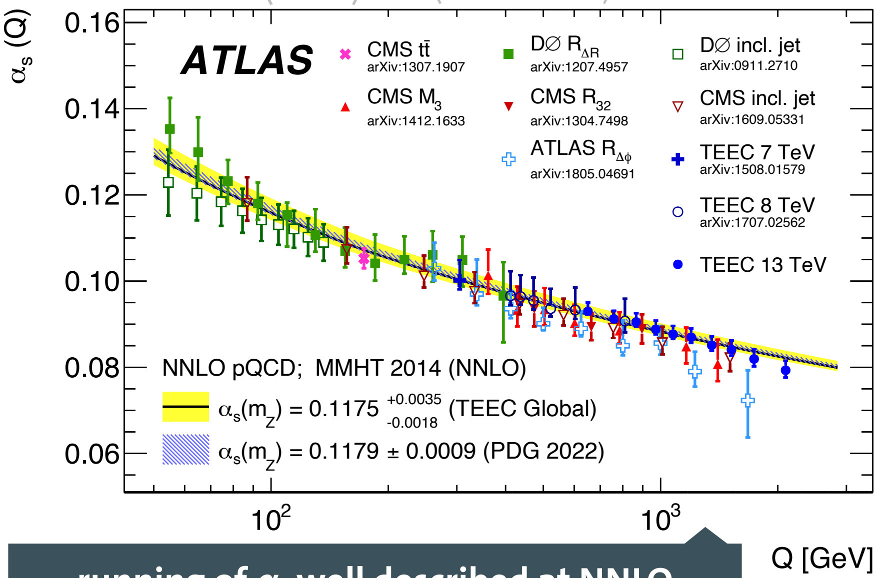
addition of jet data leads to
reduced gluon PDF uncertainty

simultaneous fit of *strong coupling*
most precise value obtained from jets

Strong coupling – α_s from jet measurements

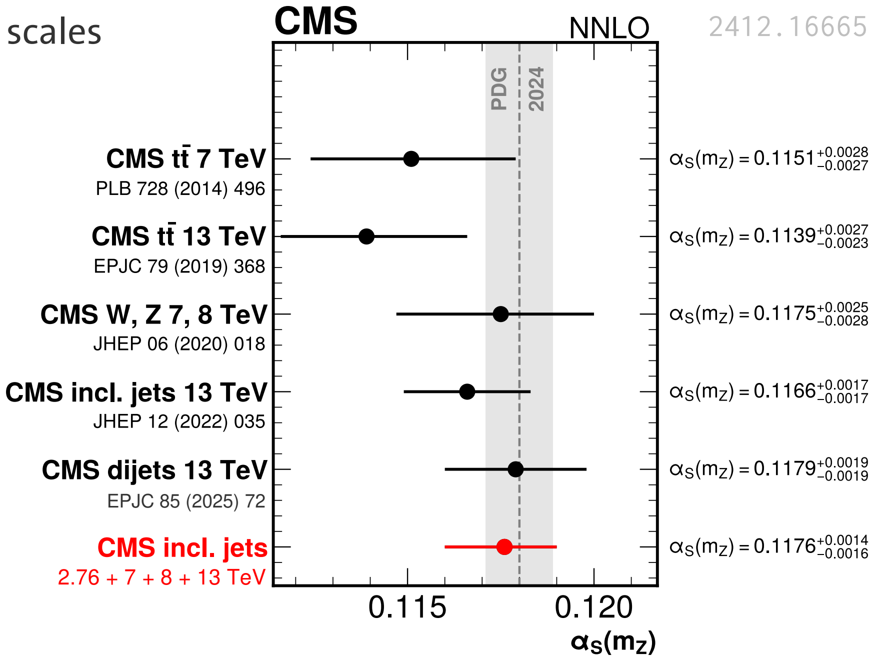
probe of perturbative QCD predictions at highest energy scales

JHEP **07** (2023) 85 (2301.09351)



running of α_s well described at NNLO
accessible by diverse measurements up to ≈2 TeV

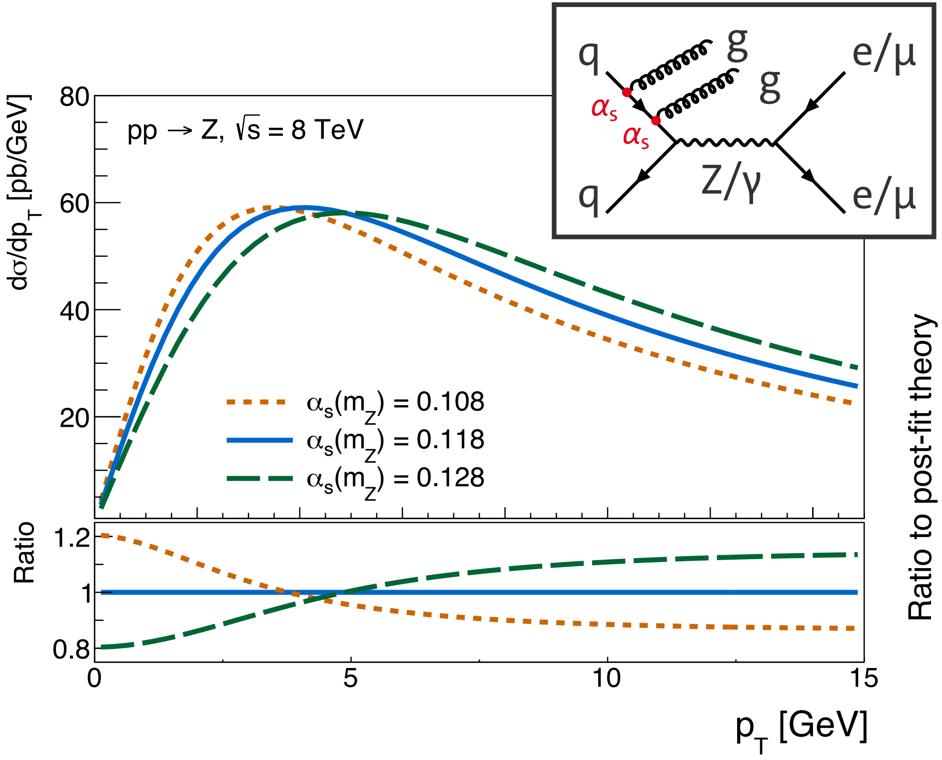
Submitted to *PLB*
2412.16665



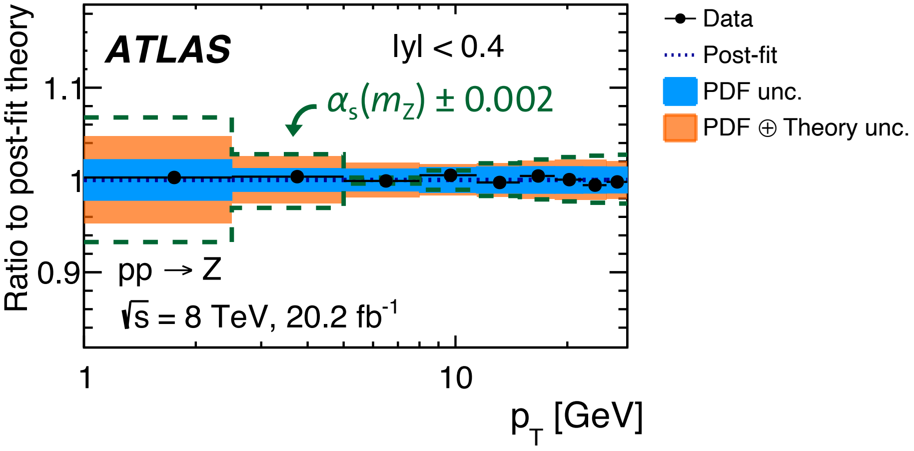
consistent results for $\alpha_s(m_Z)$
across observables & center-of-mass energies

Strong coupling – $\alpha_s(m_Z)$ from Z boson p_T

precise $\alpha_s(m_Z)$ determination from recoil of Z boson against radiation from initial-state partons

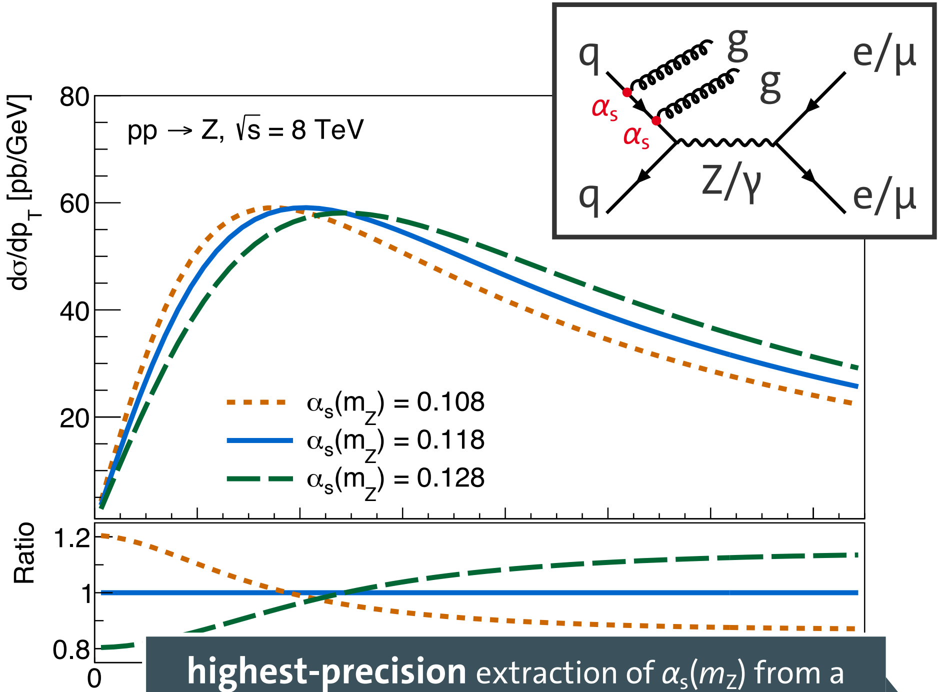


precise theory incorporating perturbative calculations at ***N³LO*** with ***N⁴LL*** resummation

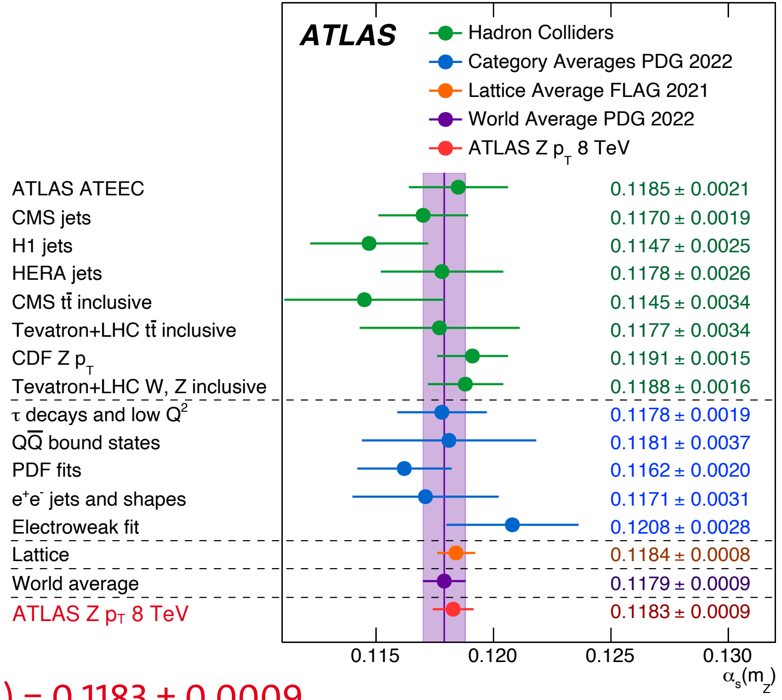


Strong coupling – $\alpha_s(m_Z)$ from Z boson p_T

precise $\alpha_s(m_Z)$ determination from recoil of Z boson against radiation from initial-state partons



highest-precision extraction of $\alpha_s(m_Z)$ from a single measurement

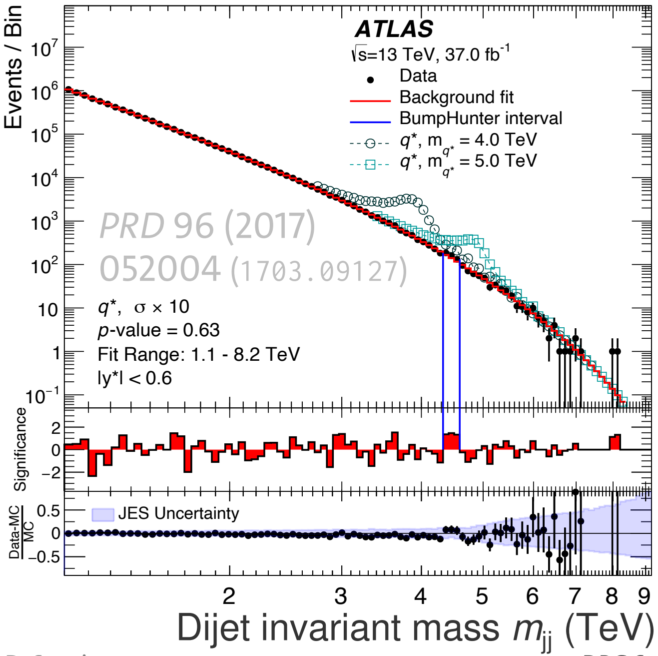


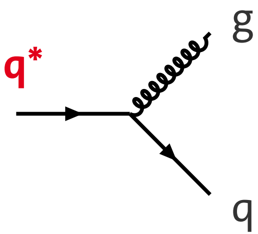
$\alpha_s(m_Z) = 0.1183 \pm 0.0009$

Finding new physics with jets

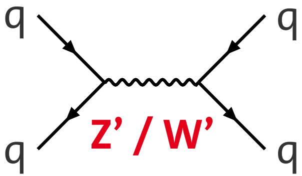
BSM models predict particles decaying to quarks & gluons

new heavy resonances appear as peaks
in dijet invariant mass spectrum



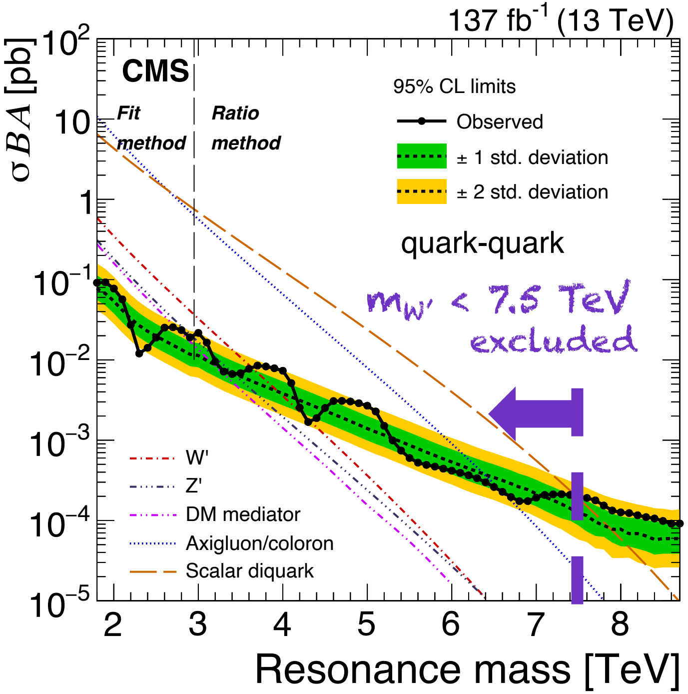


excited quark
in compositeness models



heavy vector bosons in
e.g. *Sequential Standard Model*

new data-driven background estimation
extends measurement range to higher masses

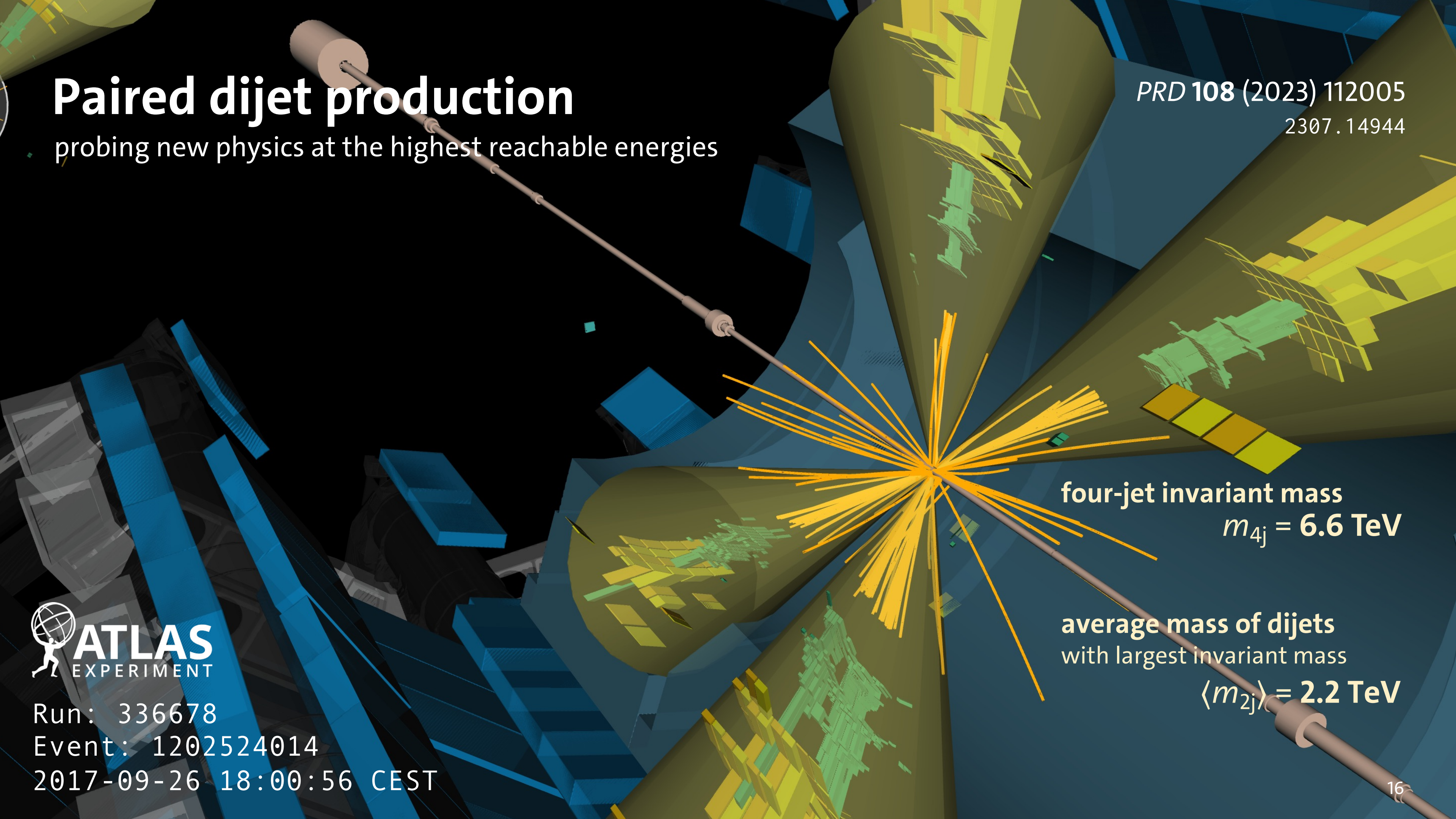


JHEP **05** (2020) 033
1911.03947

Paired dijet production

probing new physics at the highest reachable energies

PRD **108** (2023) 112005
2307.14944



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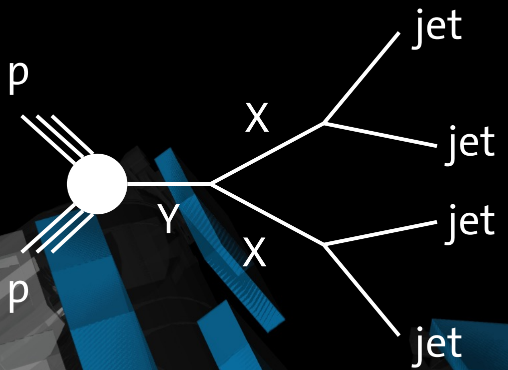
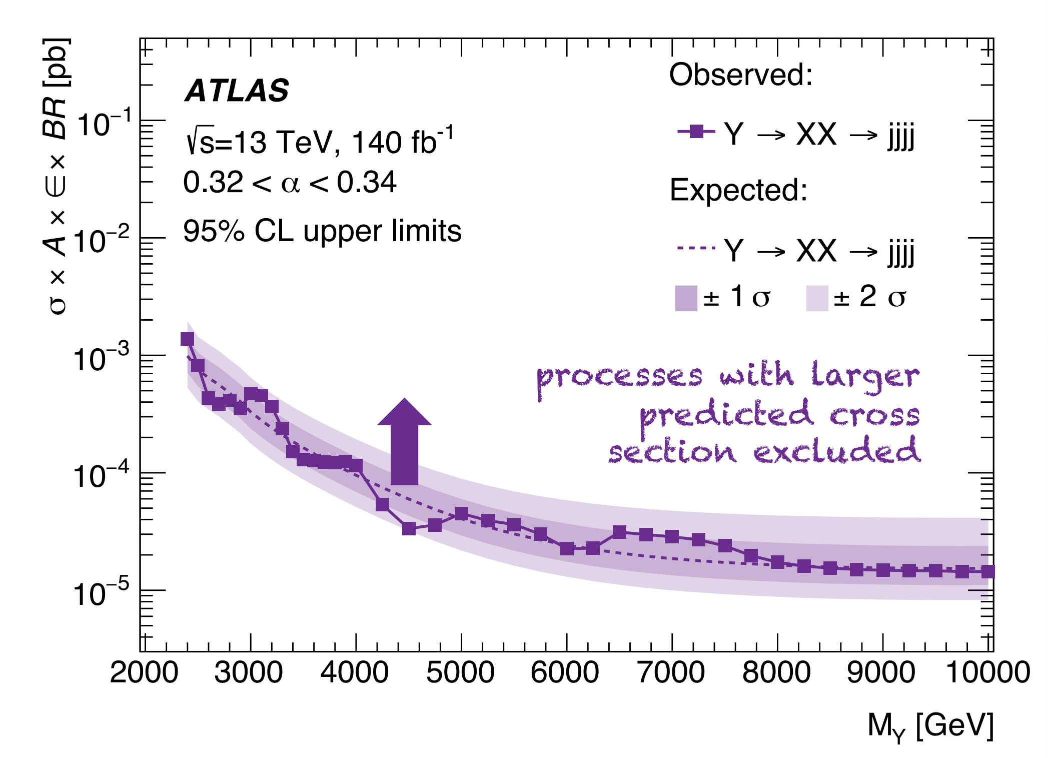
PRD **108** (2023) 112005
2307.14944



new heavy resonance Y
decaying to 4 jets via intermediate state X

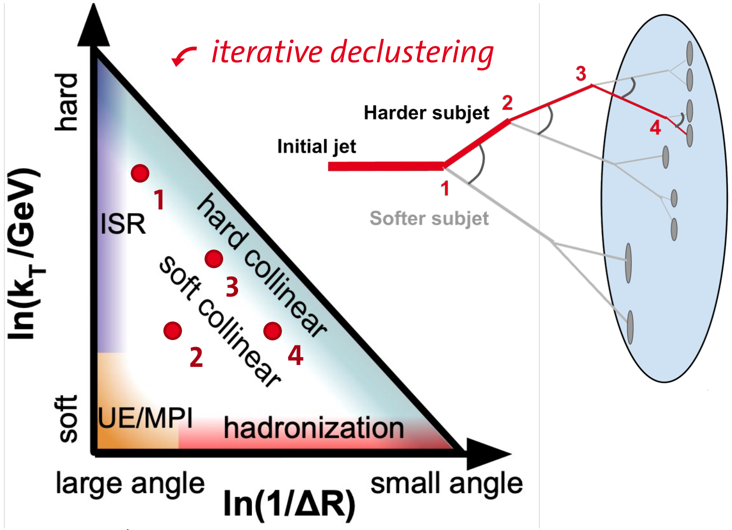


ATLAS EXPERIMENT

Run: 336678
Event: 1202524014
2017-09-26 18:00:56 CEST

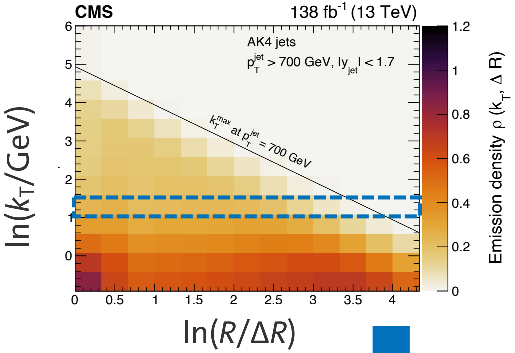
Jet substructure – looking inside jets with the *Lund jet plane*

2D representation of the phase space of emissions inside jets



separation of QCD regimes
soft region relies on tuned, partly nonperturbative Monte Carlo models

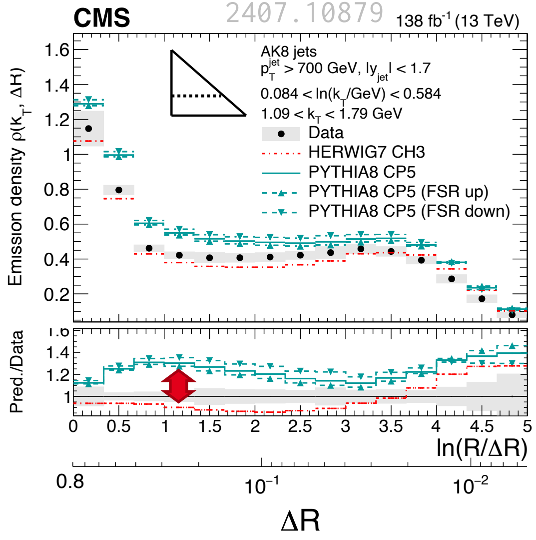
$$\frac{1}{N_{\text{jets}}}\frac{d^2 N_{\text{emissions}}}{d\ln(k_T)\, d\ln(R/\Delta R)}$$



k_T **slice**

measured emission density
reveals phase spaces where models can be improved

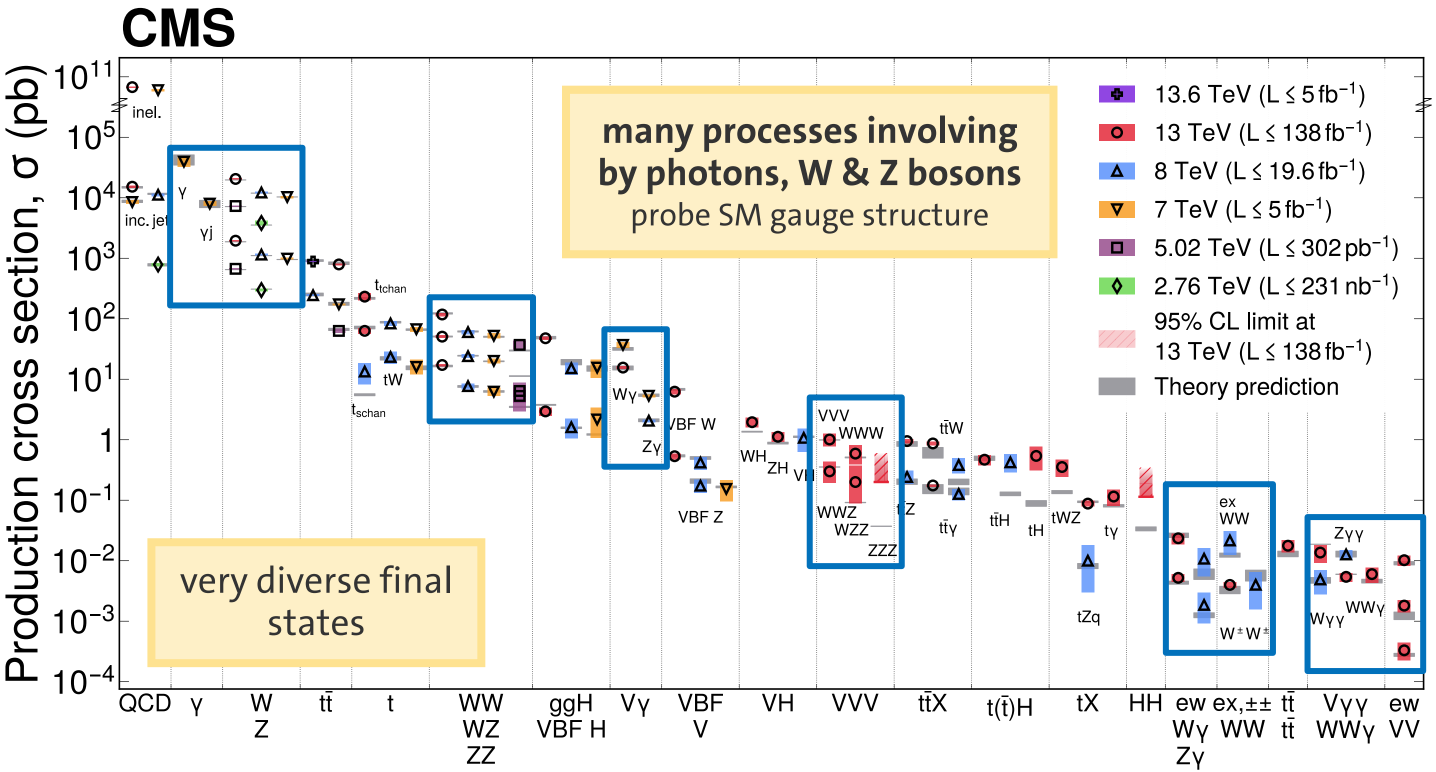
JHEP **05** (2024) 116
2407.10879



2

Electroweak measurements

Why measure electroweak processes?

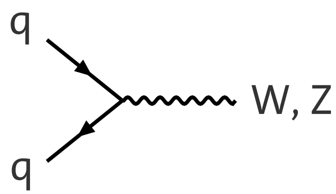


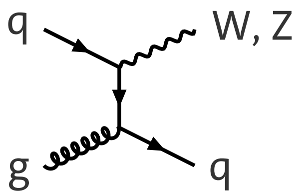
Accepted by
Physics Reports
2405.18661

traces of new phenomena in rare processes?

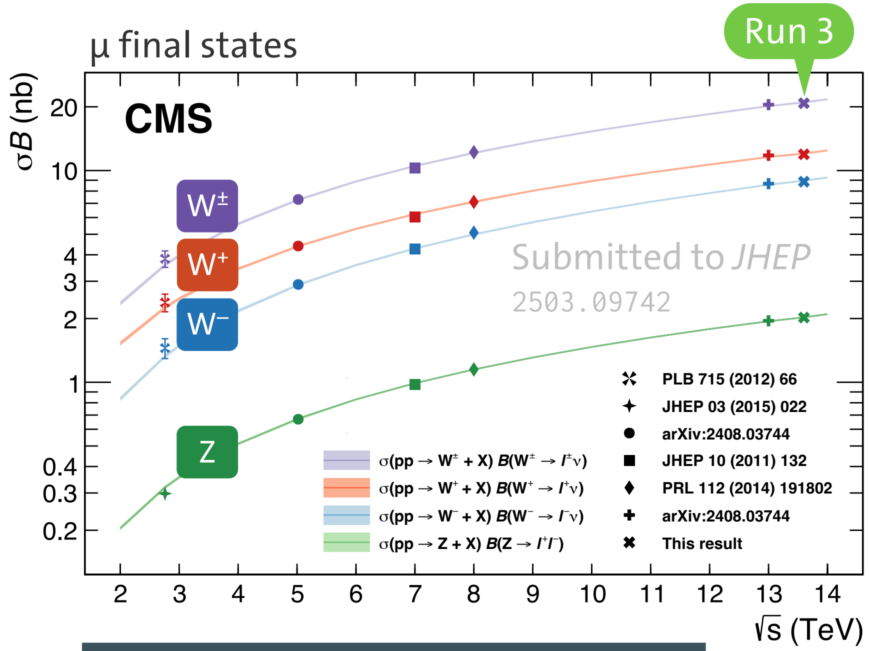
W & *Z* boson production

relatively high cross section, accessible in clean leptonic final states

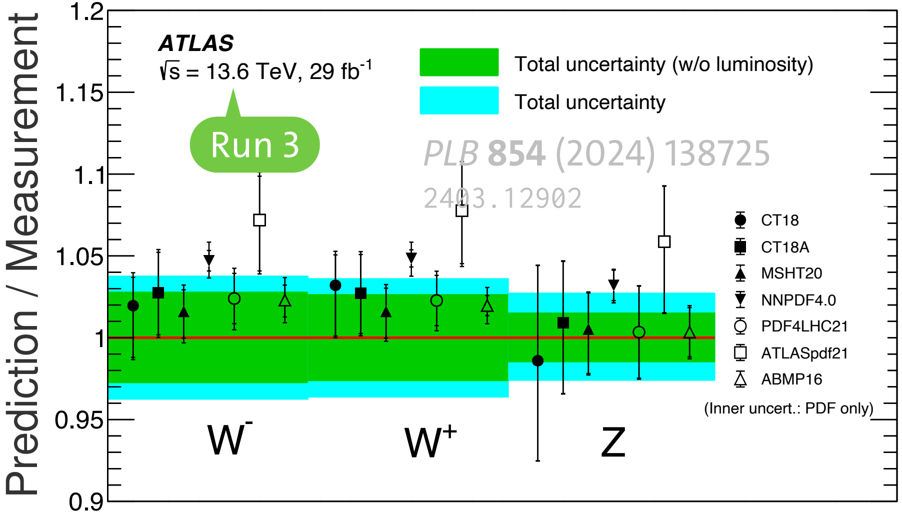




μ final states



μ + e final states



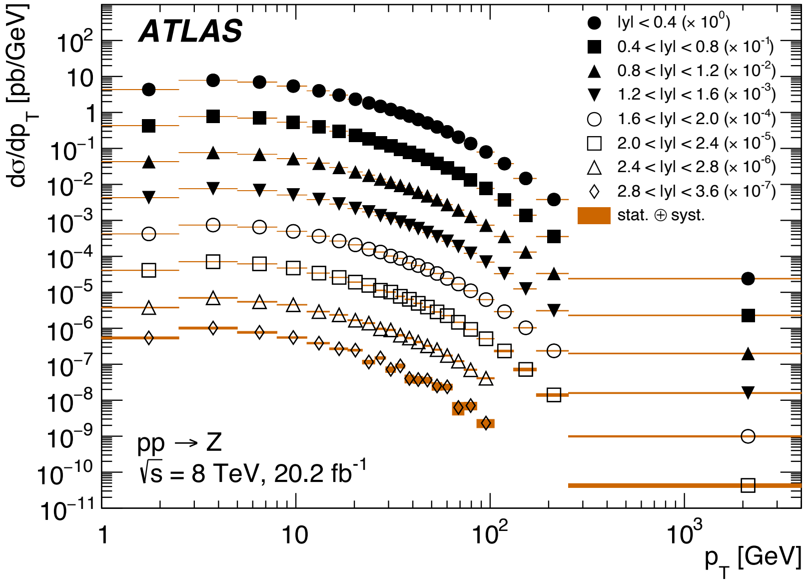
inclusive production cross sections
measured at new center-of-mass energy

well described by theory predictions
broad agreement among PDF sets

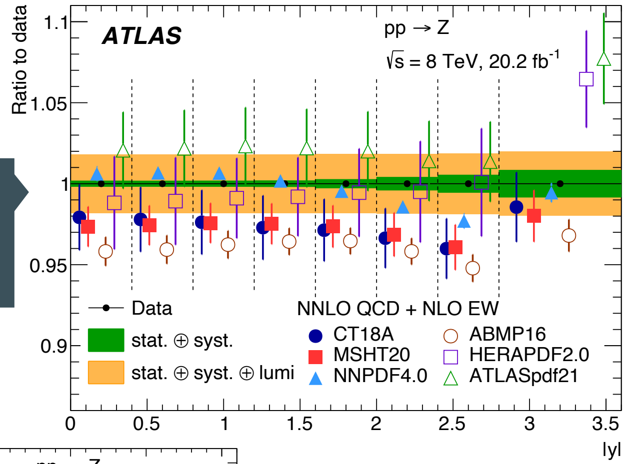
Z boson production – differential cross sections

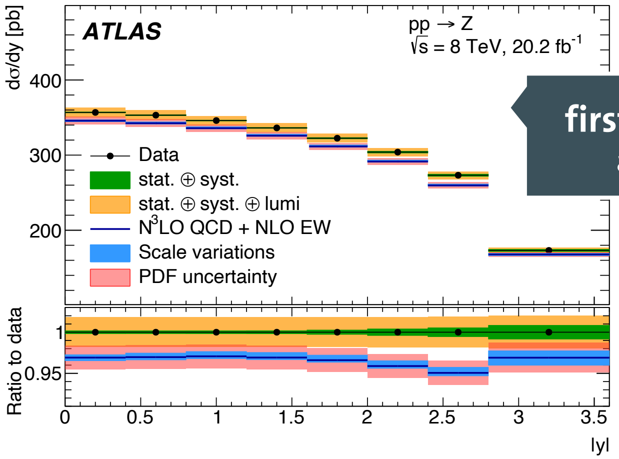
novel method for measurement in full phase space of decay leptons

extensive reach in *Z* boson kinematic properties



strong constraints on state-of-the art NNLO theory + PDFs



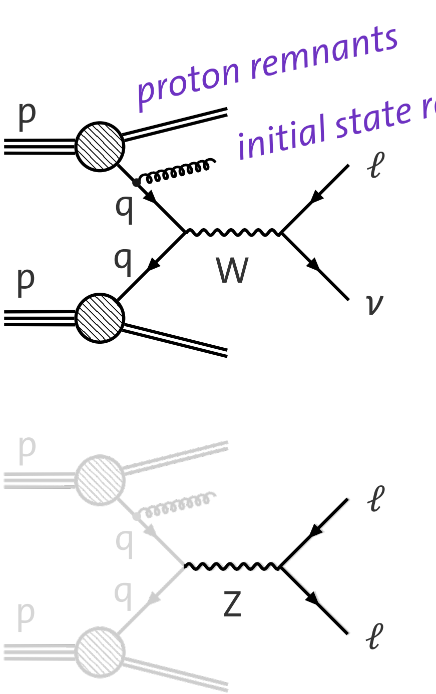


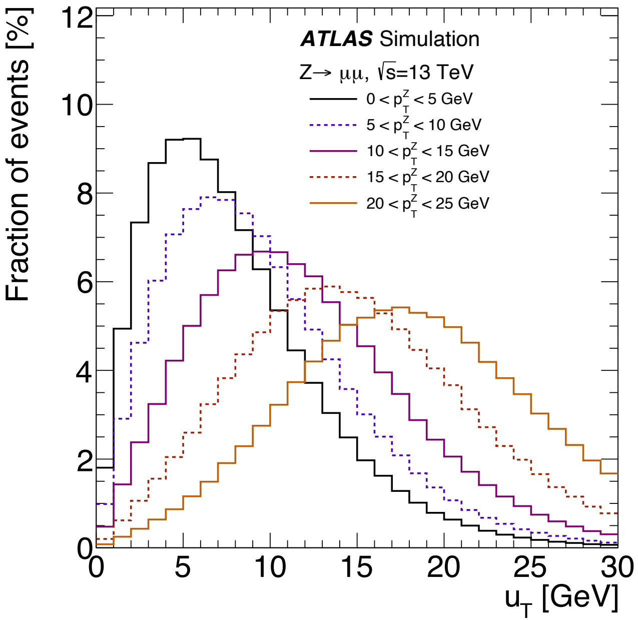
first comparison at N^{3}LO
agreement within 5%

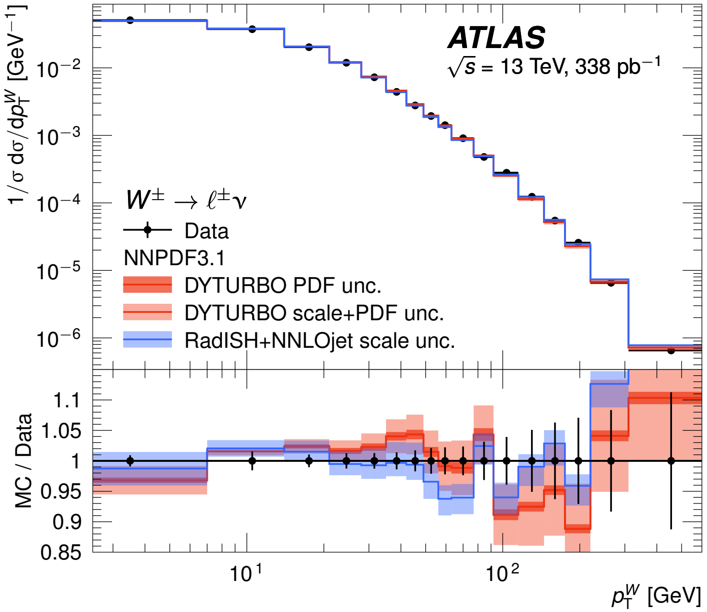
W boson production – calibration of hadronic recoil

EPJC **84** (2024) 1126
2404.06204

essential for measuring *W* boson properties







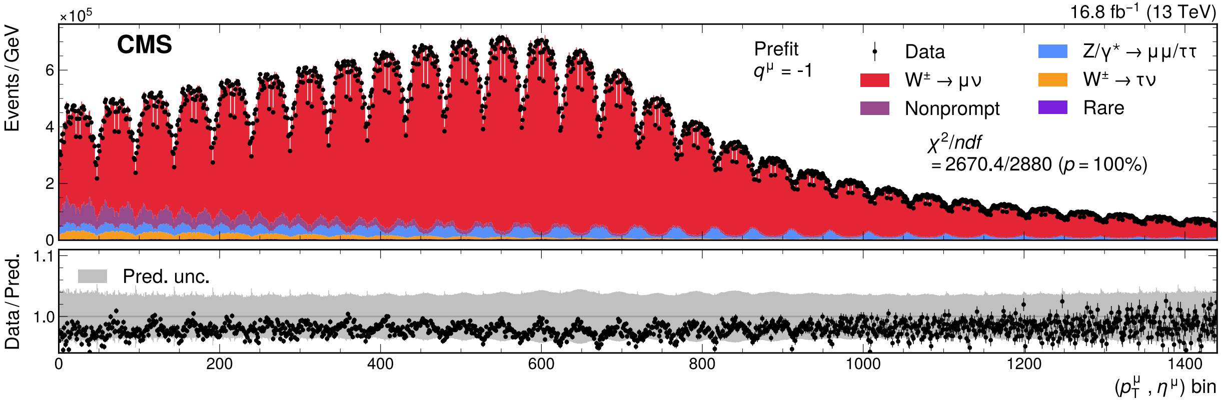
calibration of hadronic recoil u_T
using Z → μμ

W boson mass

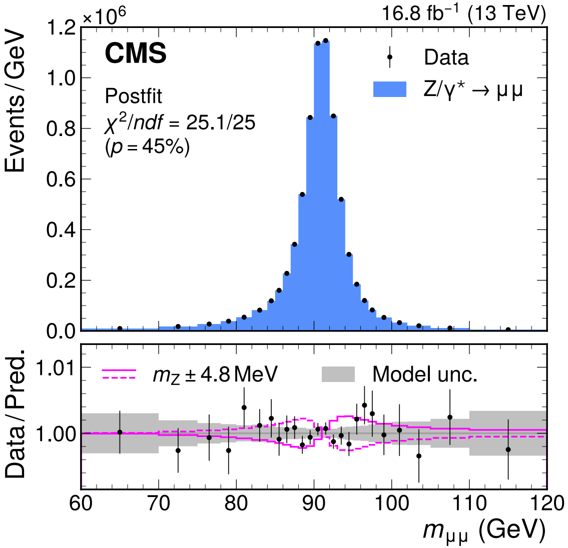
Submitted to *Nature*
2412.13872

fundamental SM parameter, new high-precision measurement from CMS

highly granular multidimensional fit of muon kinematics
incorporating all statistical & systematic effects



▲ ***"unrolled"*** *two-dimensional (p_T^{μ}, η^{μ}) distribution*



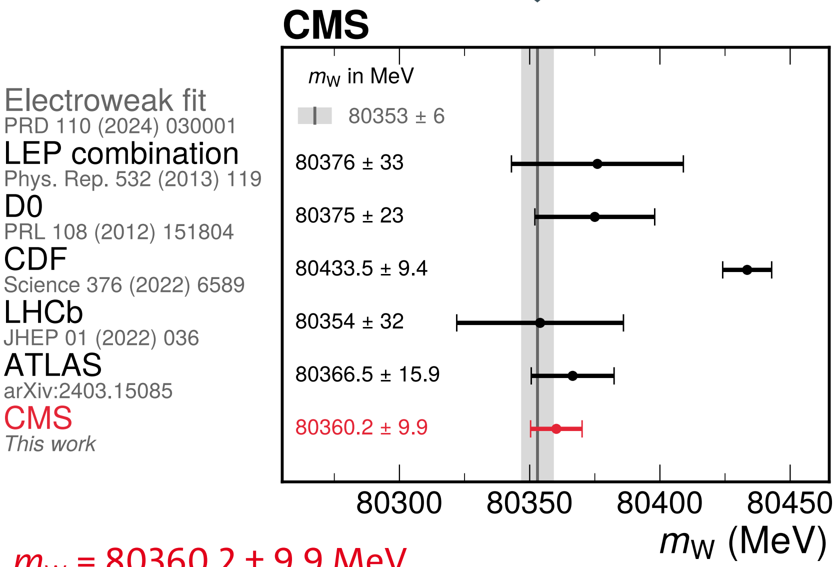
validated by W-like extraction of m_Z
using only one of the decay muons

$m_Z - m_Z^{(PDG)} = -2.2 \pm 4.8$ MeV

W boson mass

fundamental SM parameter, new high-precision measurement from CMS

most precise value obtained at the LHC
in agreement with SM expectation from EW fit



m_W = 80360.2 ± 9.9 MeV

highly controlled systematic uncertainties
thanks to improved analysis techniques

Source of uncertainty	Impact (MeV) in m_W
Muon momentum scale	4.8
Muon reco. efficiency	3.0
W and Z angular coeffs.	3.3
Higher-order EW	2.0
p_T^V modeling	2.0
PDF	4.4
Nonprompt-muon background	3.2
Integrated luminosity	0.1
MC sample size	1.5
Data sample size	2.4
Total uncertainty	9.9

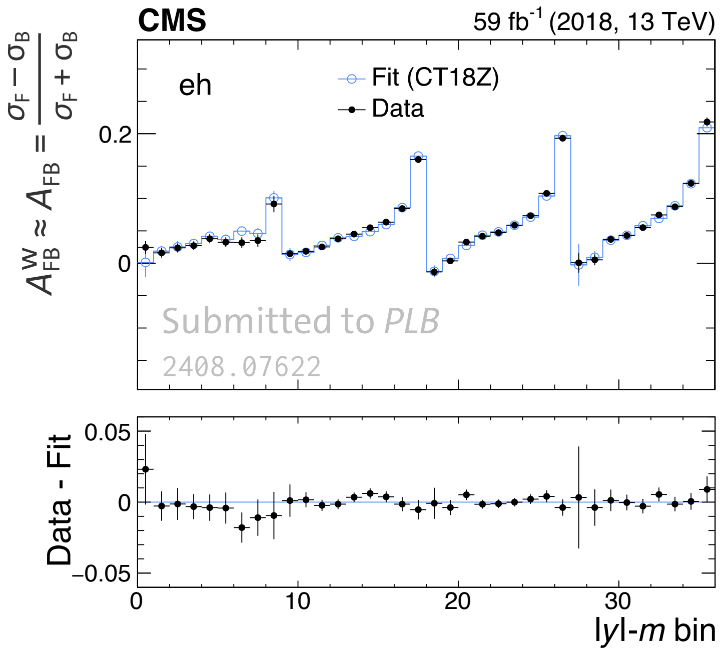
- custom **muon reconstruction** with improved track fitting, detector simulation & magnetic field modeling
- data-driven estimation of **backgrounds**
- simulation corrected for **higher-order effects**, including all-order resummation relevant at low p_T

Drell–Yan FB asymmetry & weak mixing angle

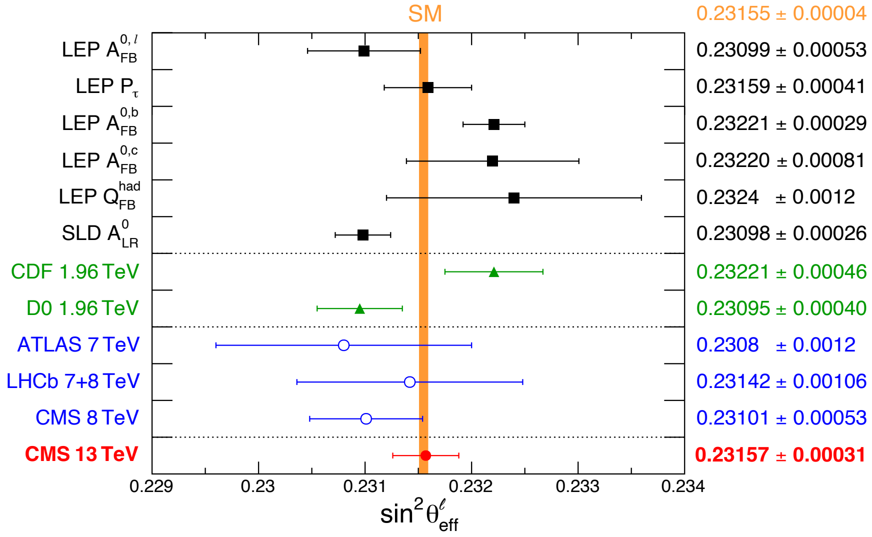
$$\sin^2 \vartheta_W = 1 - \frac{m_W^2}{m_Z^2}$$

key parameter of the SM, relates vector and axial-vector Z boson couplings to fermions

precise fit using forward-backward asymmetry variables
measured in di-electron and di-muon final states



(tree level) $\frac{v_f}{a_f} = 1 - 4\,|Q_f|\,\sin^2 \vartheta_W$ → $\sin^2 \vartheta^{\ell}_{\text{eff}}$ *(effective)*

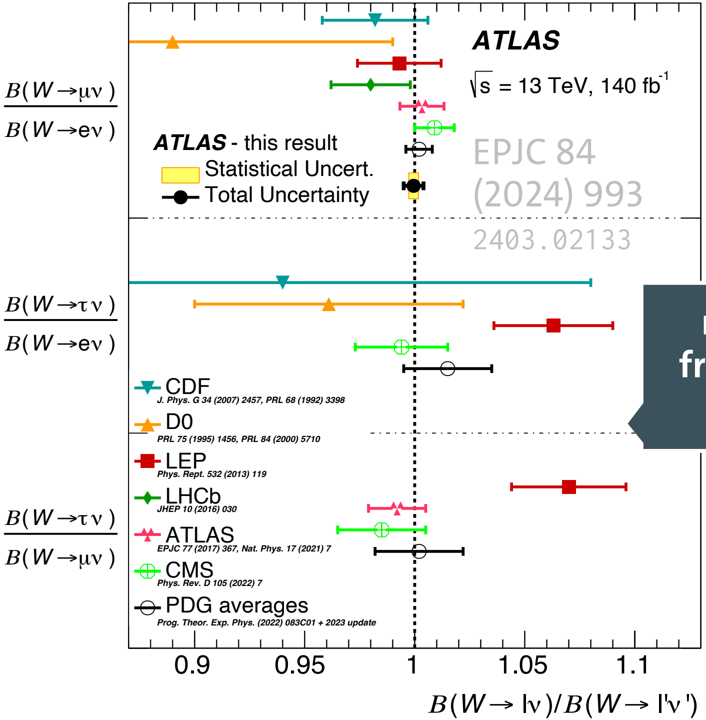


most precise value of $\sin^2 \vartheta^{\ell}_{\text{eff}}$
obtained at a hadron collider

Lepton universality in *W* decays

equal couplings to all leptons is important prediction of the SM

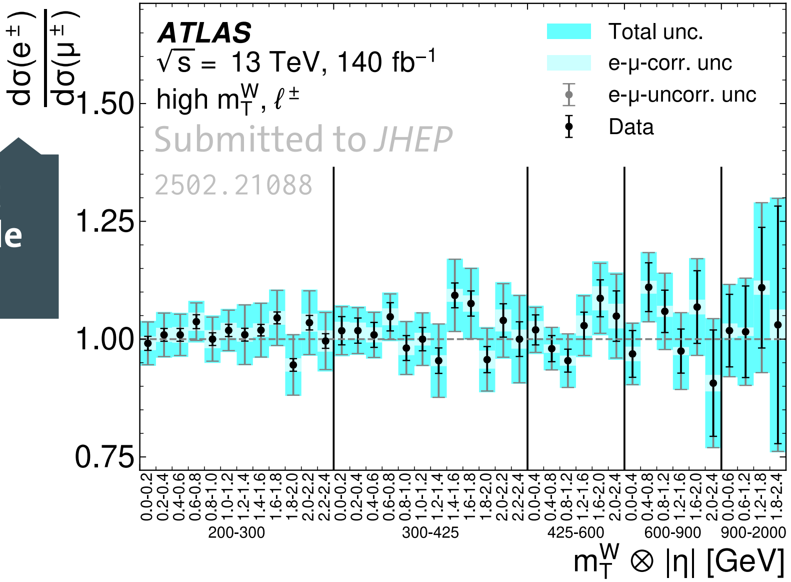
$$m_T{}^W = \sqrt{2 p_T{}^\ell p_T{}^\nu \,(1 - \cos\Delta\varphi(\ell, \nu))}$$



ratio of branching fractions compatible with unity

2D measurement in transverse mass $m_T{}^W \times |\eta|$

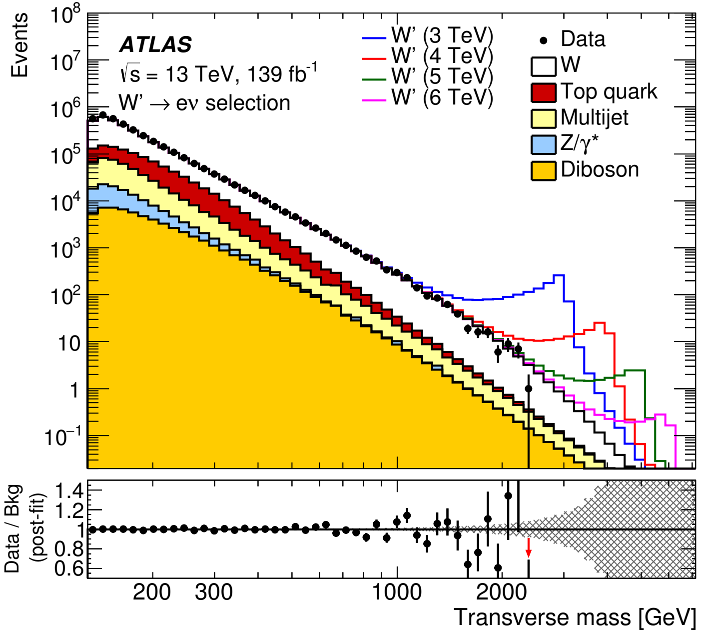
total experimental precision of 3% at low $m_T{}^W$

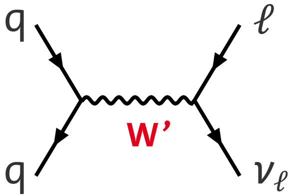


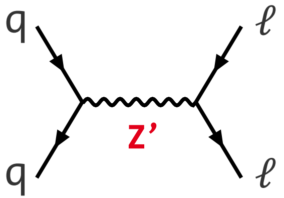
Resonances – searches with leptons

high sensitivity thanks to clean final states and low background

BSM resonances appear as bumps on
on dilepton / transverse mass spectra

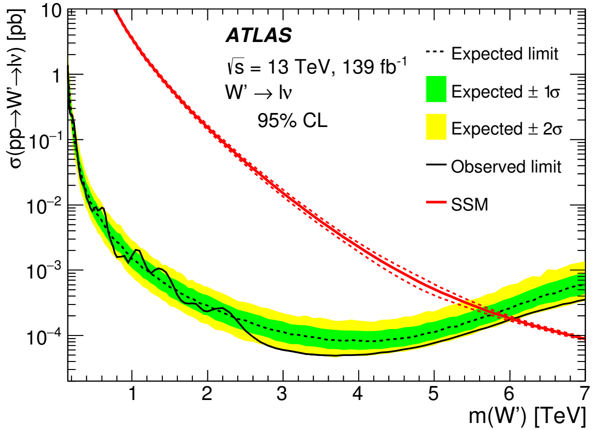


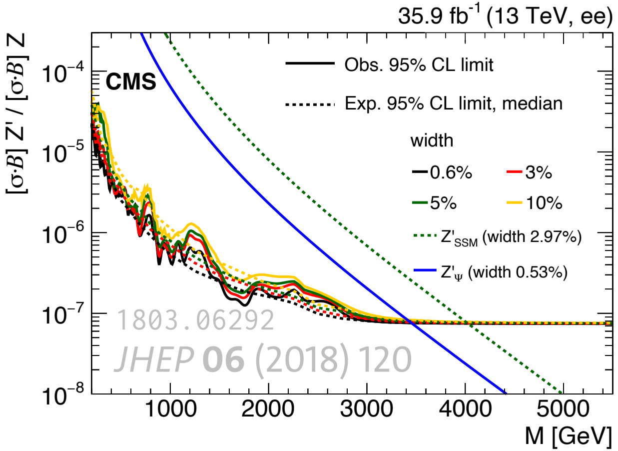




upper limits on cross section
set for several models

PRD **100** (2019) 052013 (1906.05609)

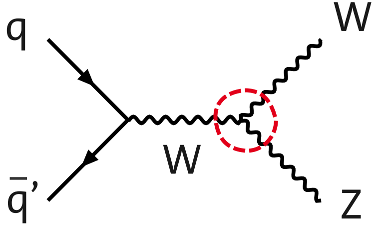




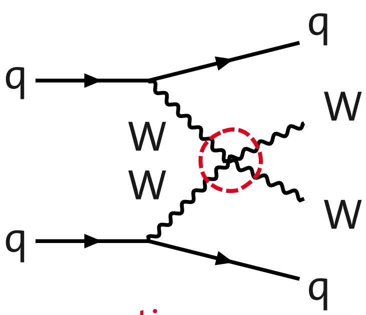
1803.06292
JHEP **06** (2018) 120

Diboson production

sensitive probe of SM gauge structure



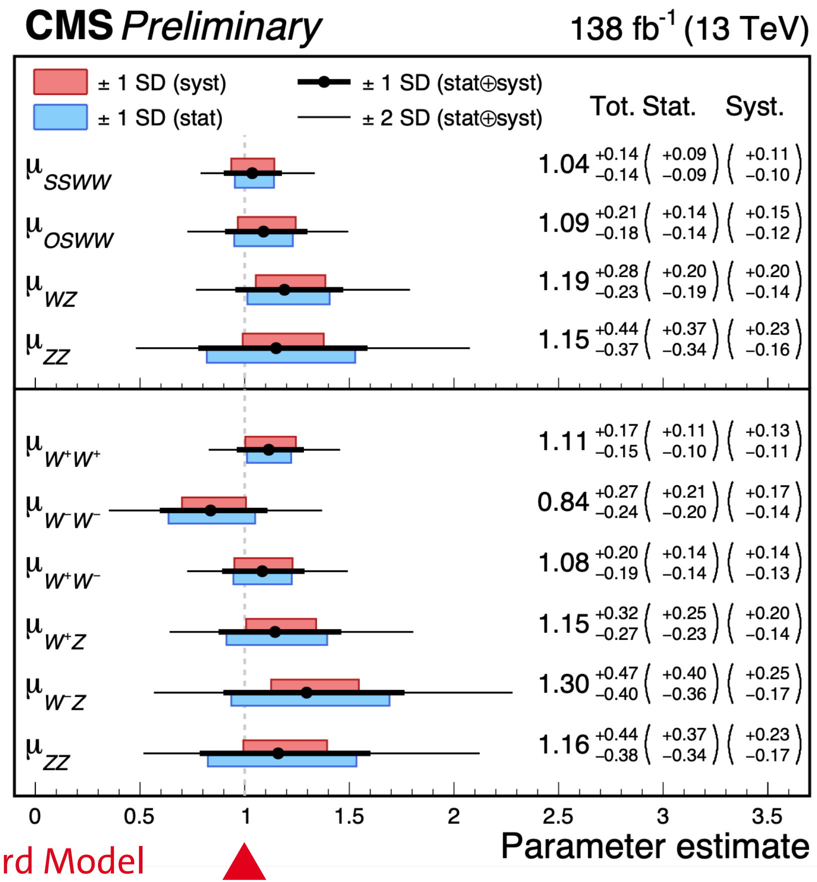
triple gauge coupling (TGC)



quartic gauge coupling (QGC)

combination of different diboson final states
all observations consistent with SM gauge couplings

CMS-PAS-SMP-24-013

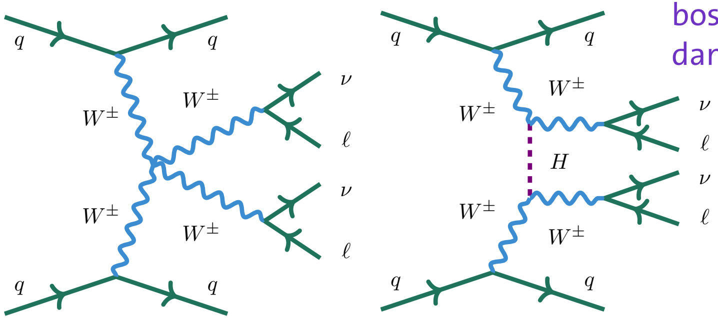


Standard Model

Same-sign WW production – first evidence for longitudinally polarized W_L

vector boson scattering as a probe of electroweak symmetry breaking

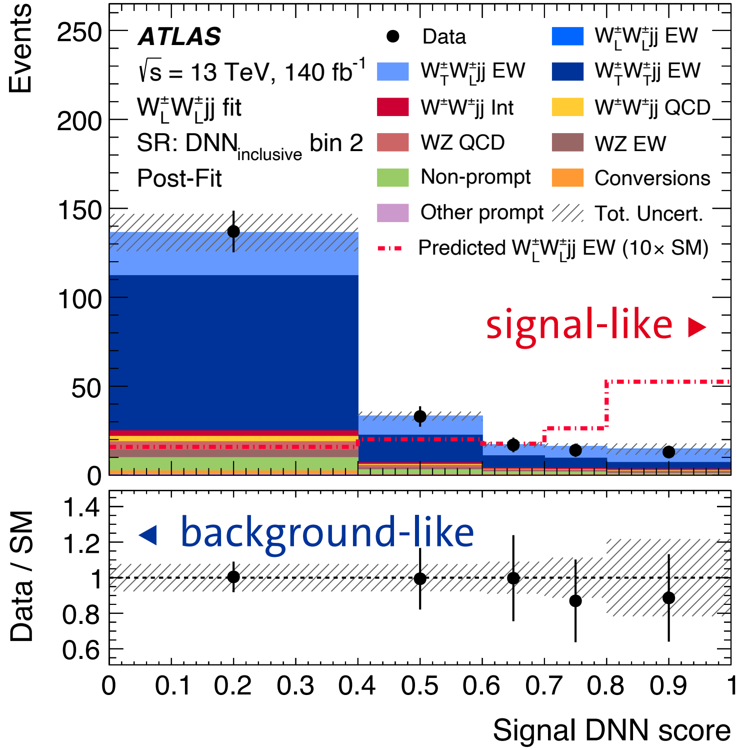
W_L crucial for finite scattering amplitudes
in vector boson scattering (VBS) processes



contribution from Higgs boson coupling to W_L dampens amplitude

machine learning to separate W_L contribution
using three deep neural networks for signal extraction

significance: 3.3 standard deviations



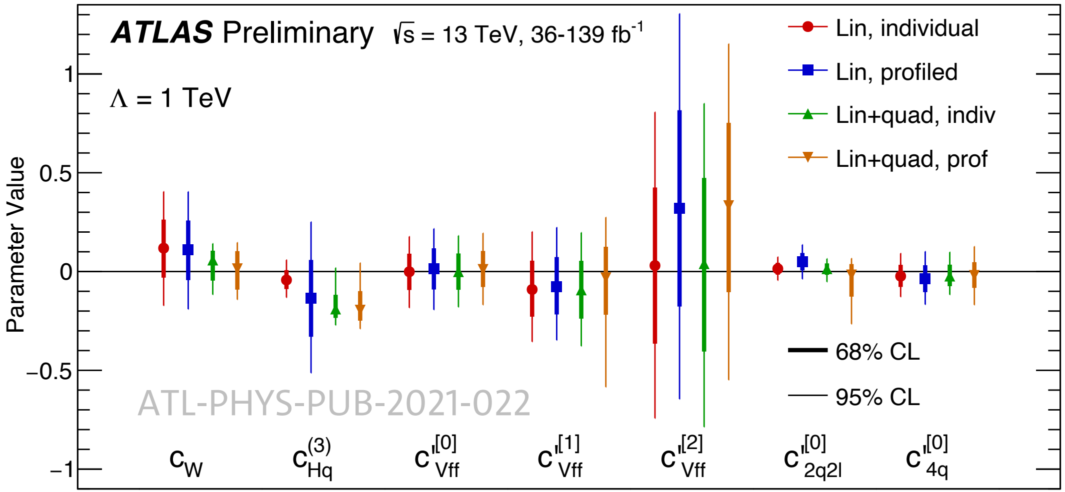
Probing new physics – going beyond the SM with *Effective Field Theory*

parameterize contributions from new phenomena via additional terms in Lagrangian

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots$$

$c_i^{(n)}$ are *Wilson* coefficients
quantify contribution from higher-dimensional operators

potential energy scale for new physics ($\Lambda \approx 1$ TeV)



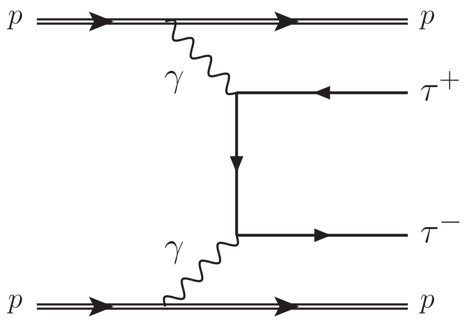
◀ **constraints on various *Wilson* coefficients**
from fit to data from multiple processes

WW, WZ, Z $\rightarrow \ell\ell$

no deviation from SM observed
Wilson coefficients compatible with zero

LHC as a photon collider

high-energy photons radiating from protons as a precise probe of Quantum Electrodynamics (QED)



pure QED production of tau lepton pairs
observed for the first time in proton-proton collisions

RPP **87** (2024) 107801

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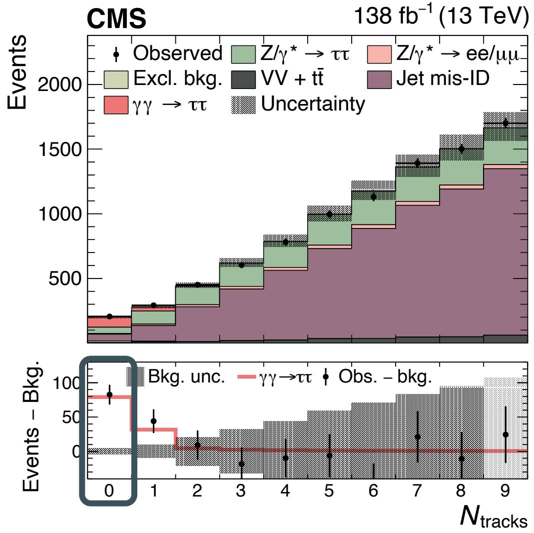
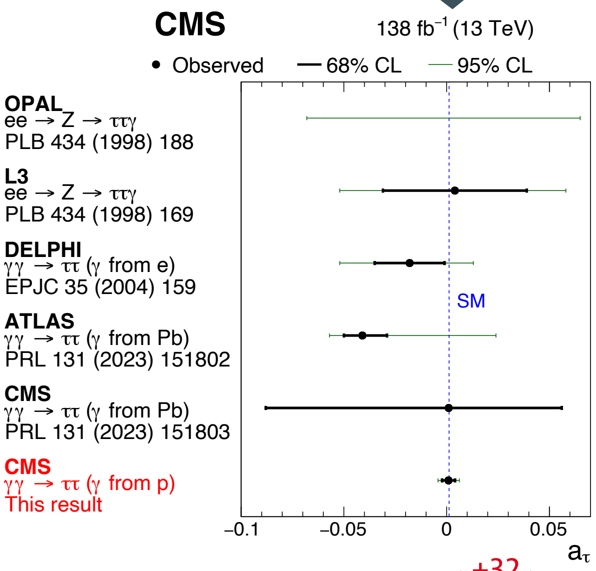


accurate modeling of track multiplicity
enhances sensitivity to γγ→ττ process

most stringent constraints to date on
anomalous τ magnetic moment



$a_\tau = 0.0009\,\left(^{+32}_{-31}\right)$

Summary

- **ATLAS** & **CMS** have an extensive and varied program of Standard Model measurements, demonstrating the unprecedented level of **experimental precision** reachable at the LHC
- **QCD** & **electroweak** measurements are crucial for refining our understanding of the **Standard Model**, and provide a constraining baseline in the search for **new phenomena**
- much of the improvement is due to a deeper understanding of **systematic effects**, an improved **theoretical modeling** and more **sophisticated analysis techniques**

many more results that I could not cover here
check out the experiment result pages for more

Thank you for your attention!