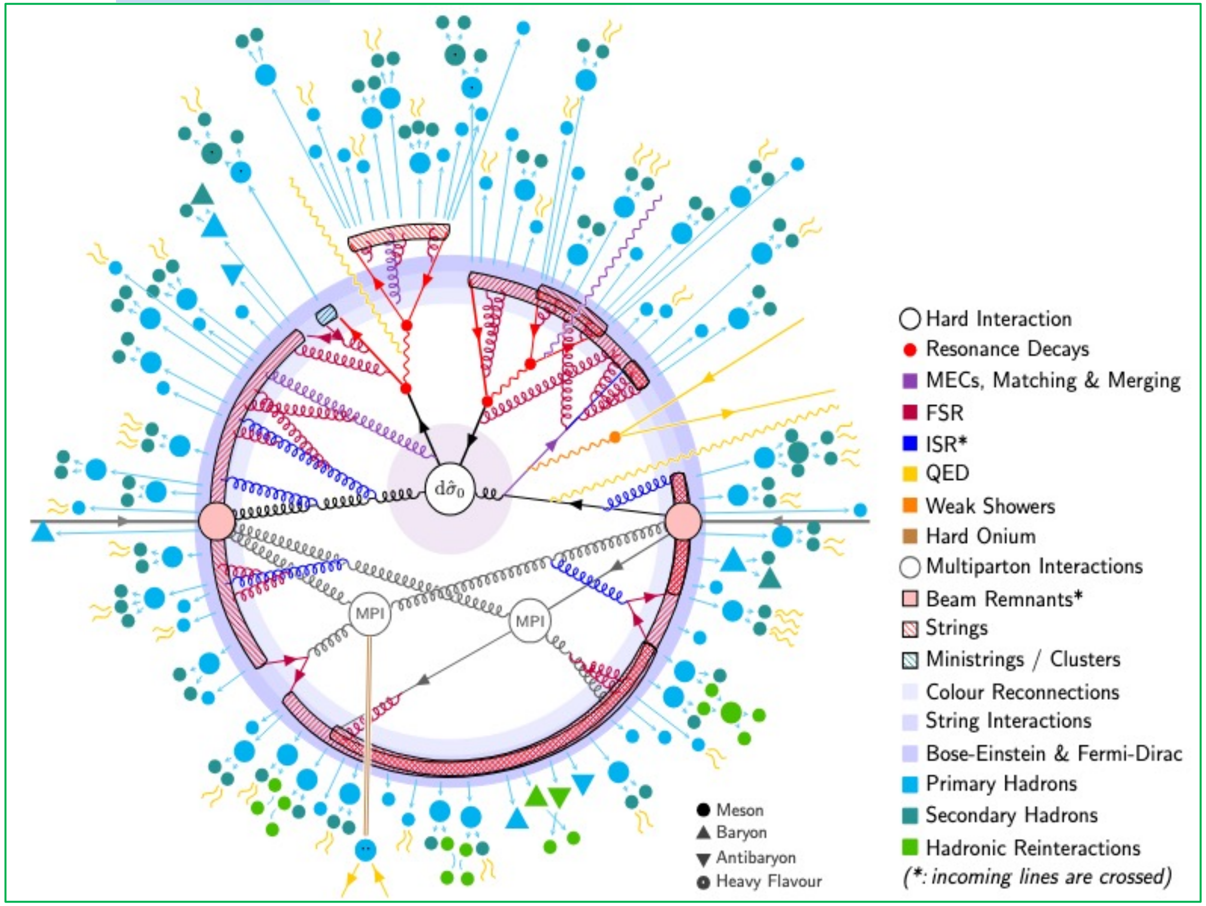
Exploring QCD and Heavy Flavor Physics at ATLAS

Kunihiro Nagano

Lake Louise Winter Institute (LLWI) 2026
3/March/2026, Lake Louise, Calgary, Canada

LHC – a QCD machine

Pythia 8.3

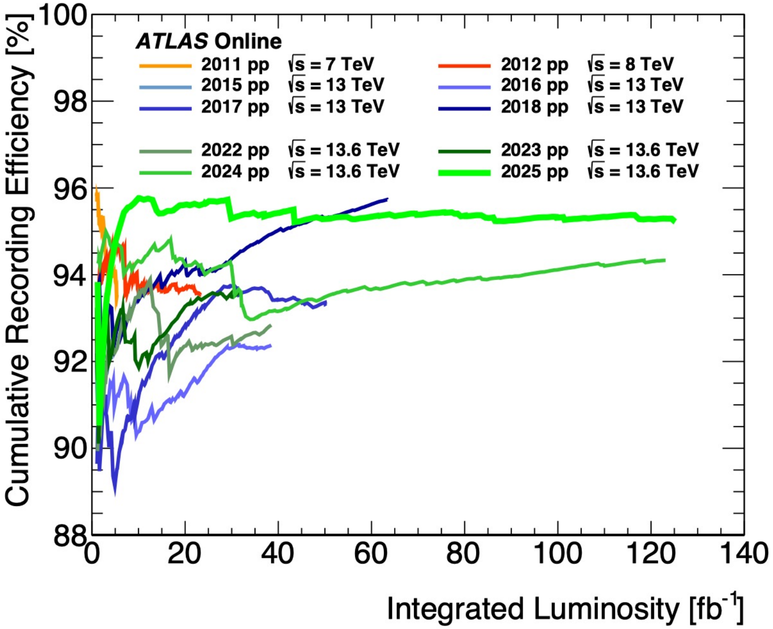


The LHC can probe the full dynamical cascade from free partons at the TeV scale to confined hadrons at MeV scale

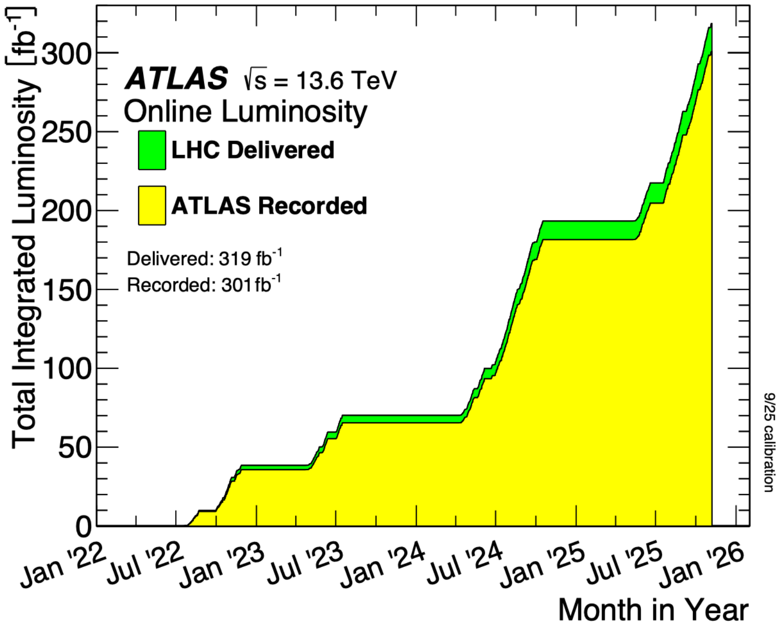
- QCD is unique among the fundamental interactions - non-Abelian gauge theory.
- The same theory is weakly coupled at short distances and strongly coupled at long distances
  - -- At high energy, asymptotic freedom
  - -- At low energy, confinement
  - -- Between these regimes, infrared singularities require parton-shower and resummation descriptions, while confinement necessities non-perturbative hadronization models.
- Heavy flavor provides another window to look into QCD

LHC Runs – in a nutshell

- Run-1 (2010-2012)
  - -- 2010-11: $\sqrt{s}$=7 TeV, $\int \mathcal{L}dt$ ~5 /fb
  - -- 2012: $\sqrt{s}$=8 TeV, $\int \mathcal{L}dt$ ~20 /fb
- Run-2 (2015-18)
  - -- $\sqrt{s}$=13 TeV, $\int \mathcal{L}dt$ ~ 140 /fb



- Run-3 (2022-)
  - -- $\sqrt{s}$=13.6 TeV, $\int \mathcal{L}dt$ ~ 300 /fb (until 2025)



This talk picks up some of highlight QCD and heavy flavor ATLAS results that benefit from these large volume of datasets

- Excellent data-taking efficiency and excellent data quality over years
- Run3 data-taking and Run2 full-data analysis are ongoing in parallel

QCD

- Jets
  -- Multi-dimensional di-jet cross section

HOT! Public since this winter (last Nov-)

NEW Public since last year

arXiv:2512.19073

(22 Dec 2025, submitted to EPJC)

Multi-dim. di-jet cross section

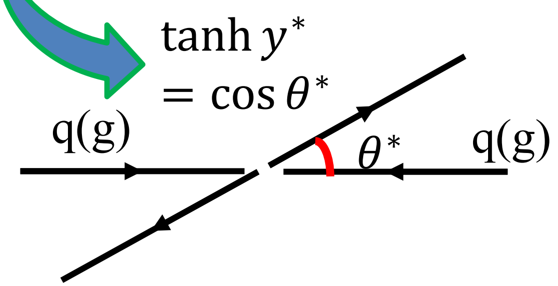
- With full Run-2 data (140 /fb), providing unprecedented statistics and substantially reduced statistical uncertainties
- Improved jet energy calibration, reducing the jet energy scale uncertainty by up to ~3 for central dijet with $m_{jj} > 1$ TeV
- Measurements are in terms of

-- $m_{jj} = \sqrt{(p_1 + p_2)^2}$

-- $y^* = \frac{1}{2}|y_1 - y_2|$

-- $y_{boost} = \frac{1}{2}|y_1 + y_2|$

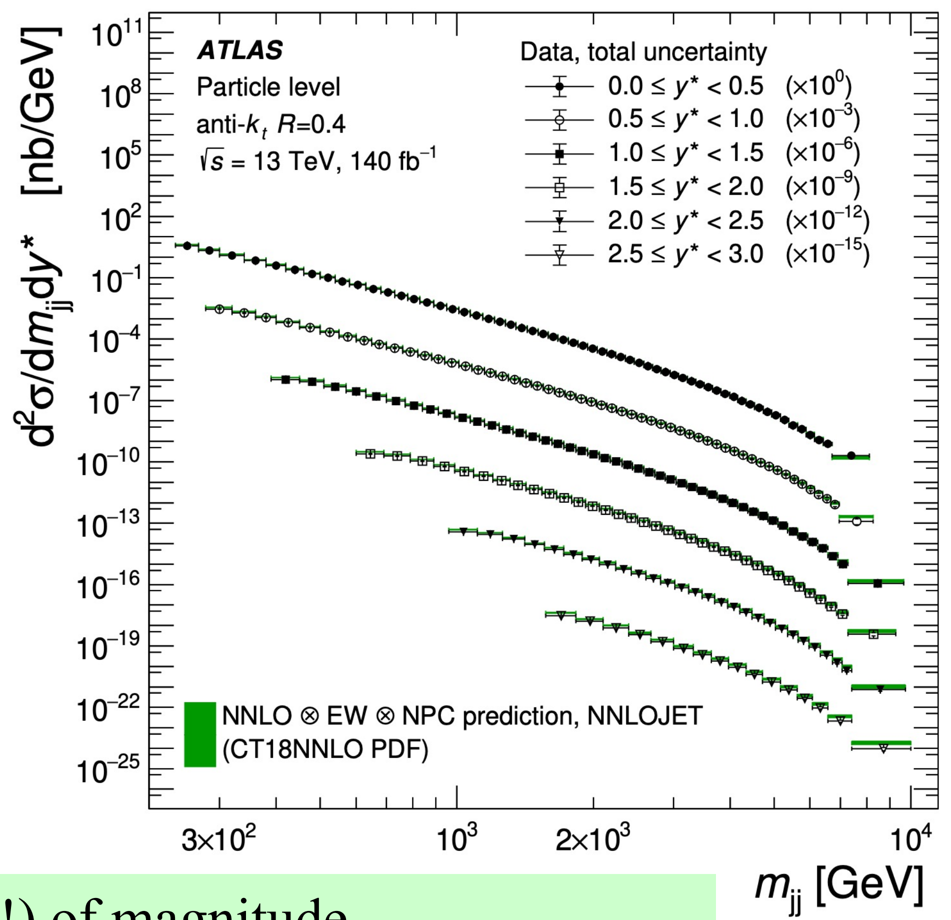
$p_{1(2)}$: jet 1(2) 4-mom.
$y_{1(2)}$: jet 1(2) rapidity



For back-to-back di-jet at Born level

$$x_{1,2} = \frac{m_{jj}}{\sqrt{s}} e^{\pm y_{boost}}$$

$$m_{jj} = 2p_T \cosh y^*$$



- Precise measurements over 20 orders (!) of magnitude
- Sensitive to PDFs and higher-order QCD effects across large phase space (these three variables provide sensitivity to x_1 and x_2)

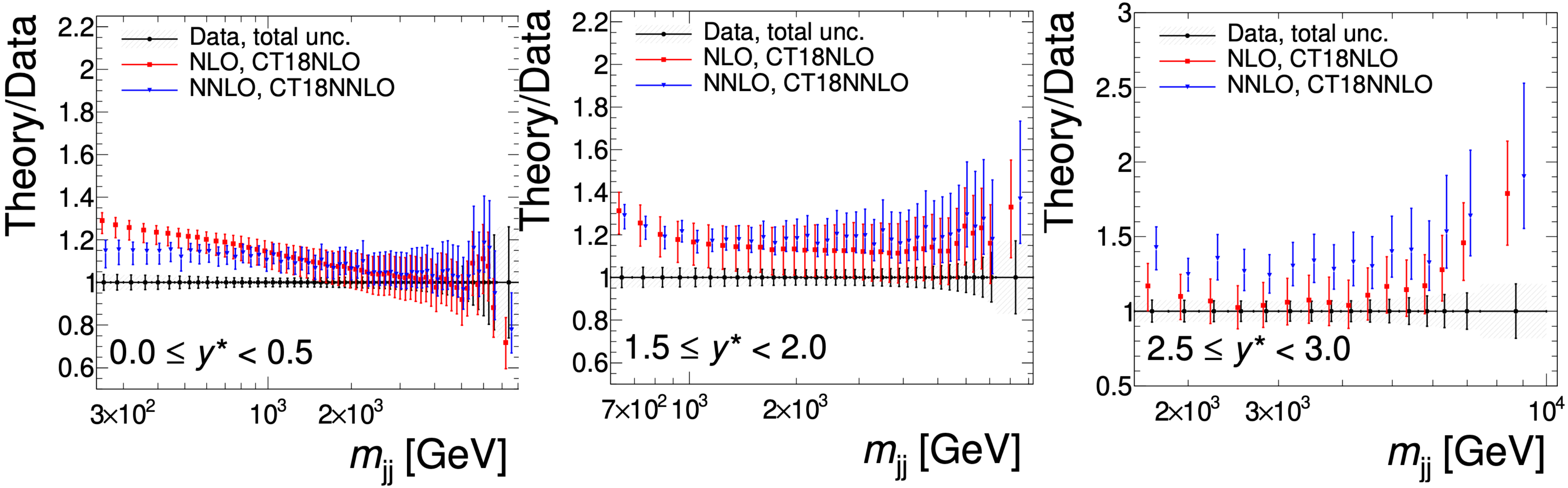
HOT!

arXiv:2512.19073

Multi-dim. di-jet cross section

(22 Dec 2025, submitted to EPJC)

- Detailed comparison to pQCD calculations (with EW corr, non-pert. corr)
  -- NLO +NLO PDF, NNLO + NNLO PDF



- Both NLO/NNLO predictions tend to lie above the data by 15-20% on average
- At low y^* ($y^* < 1.5$), the overestimation gradually decreases toward high m_{jj}. NNLO provides an improved description of shape.
- At higher y^*, both NLO/NNLO remain higher than data with a clear rise in the theory/data ratio with increasing y^*

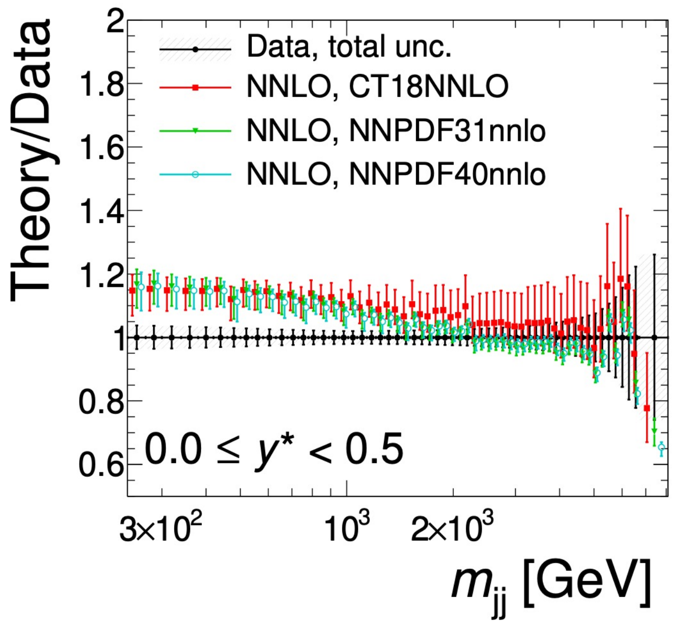
arXiv:2512.19073

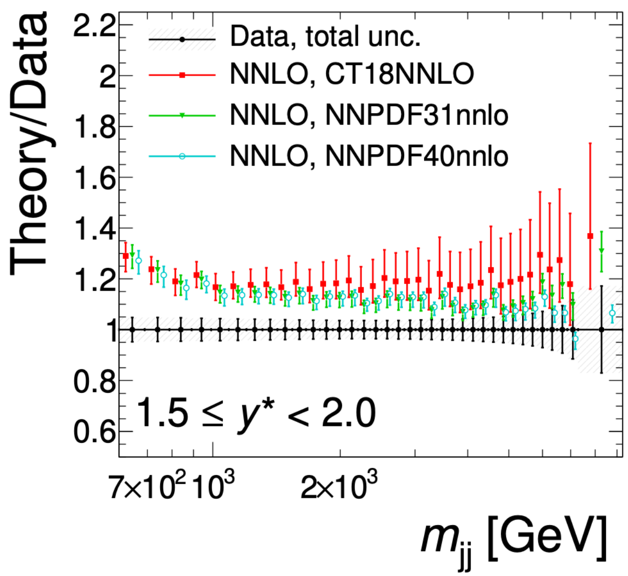
(22 Dec 2025, submitted to EPJC)

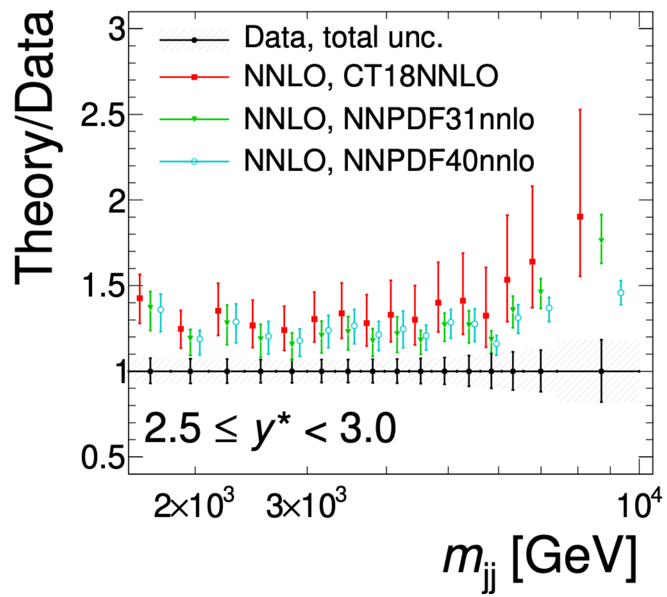
HOT!

Multi-dim. di-jet cross section

- Detailed comparison to pQCD calculations (with EW corr, non-pert. corr)
  - -- NLO +NLO PDF, NNLO + NNLO PDF
  - -- With different PDFs







- The conventional prescriptions for estimating theory uncertainties (i.e. based on scale and PDF variations) do not necessarily capture the difference
- These observations might be attributed to be the limitation of fixed-order pQCD – e.g. renormalization/factorization scales, absence of resummation effects

Heavy Flavor

- Production
  -- $D^{\pm}$ and $D_s^{\pm}$ differential cross section
- Spectroscopy
  -- J/ψ+$\psi(2S)$ resonance structures
- Rare decay
  -- $B^0_{(s)} \to \mu\mu$ future reach at HL-LHC

HOT! Public since this winter (last Nov-)

NEW Public since last year

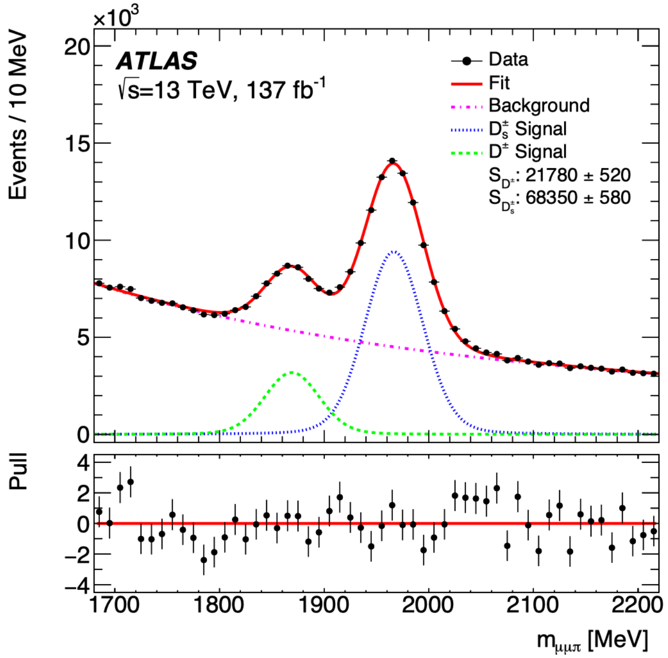
NEW

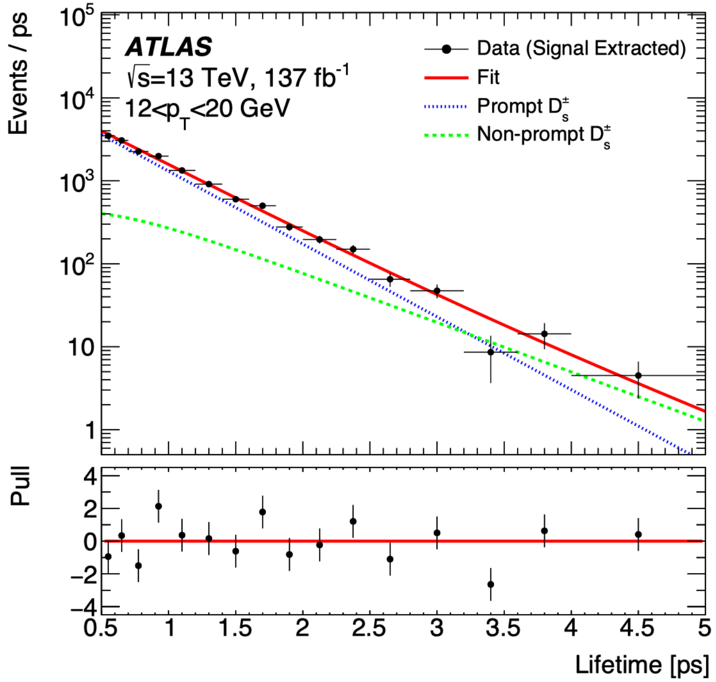
JHEP 07 (2025)

Differential $D^{\pm}$ and $D_s^{\pm}$ production cross section

- With full Run-2 data (137 /fb), benefitting large dataset and energy compared to the ATLAS past measurements based on Run1
- A crucial QCD test with heavy-quark masses introduce an additional perturbative scale close to the hard scattering processes
- Moreover, heavy quarks can be produced via promptly or non-promptly (e.g. c-quarks in decays of b-quarks) – challenges are to model non-pert. effects as hadronization, fragmentation functions

  -- For each p_T bin, the non-prompt fraction is determined with template fitting



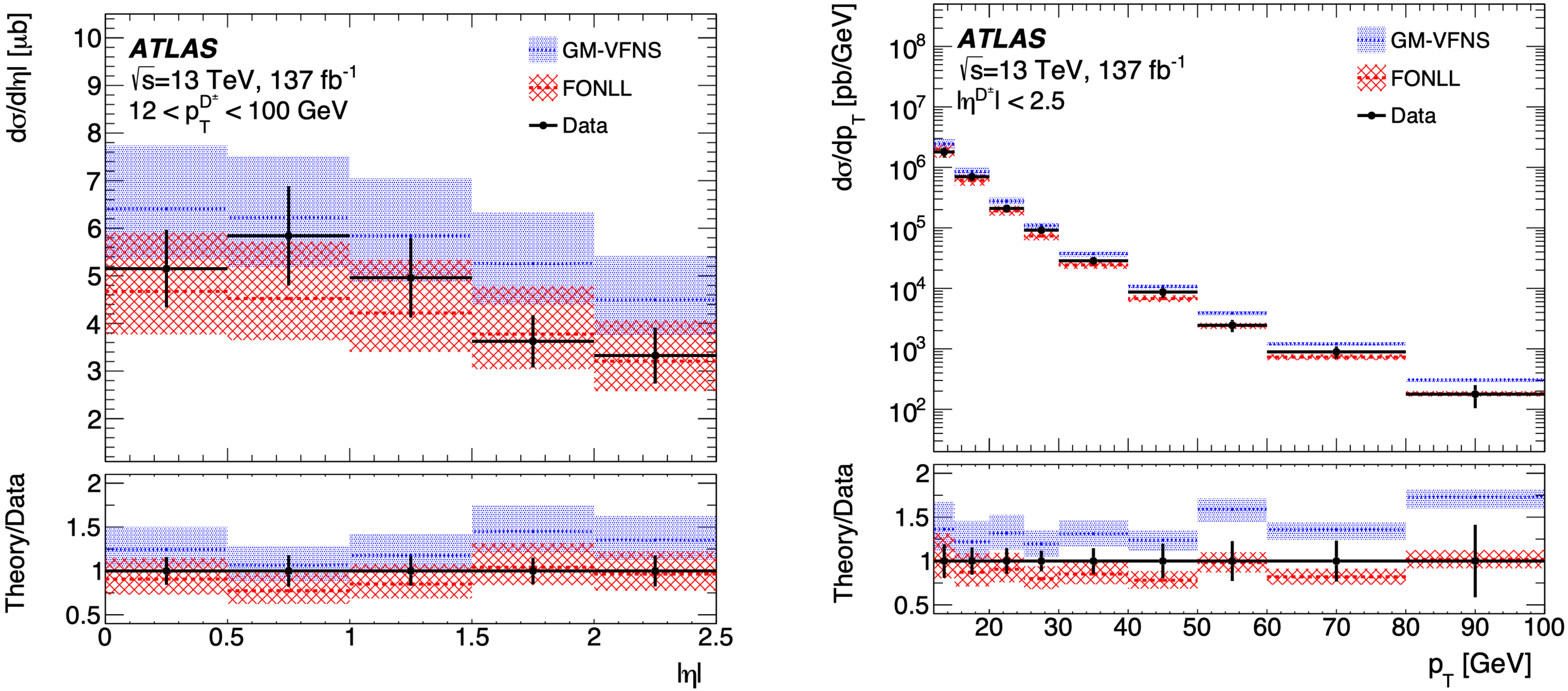


NEW

JHEP 07 (2025)

Differential $D^{\pm}$ and $D_s^{\pm}$ production cross section

- $D^{\pm}$ cross section : compared with the General-Mass Variable Flavor Number (GM-VFN) and Fixed-Order Next-to-Leading-Log (FONLL)



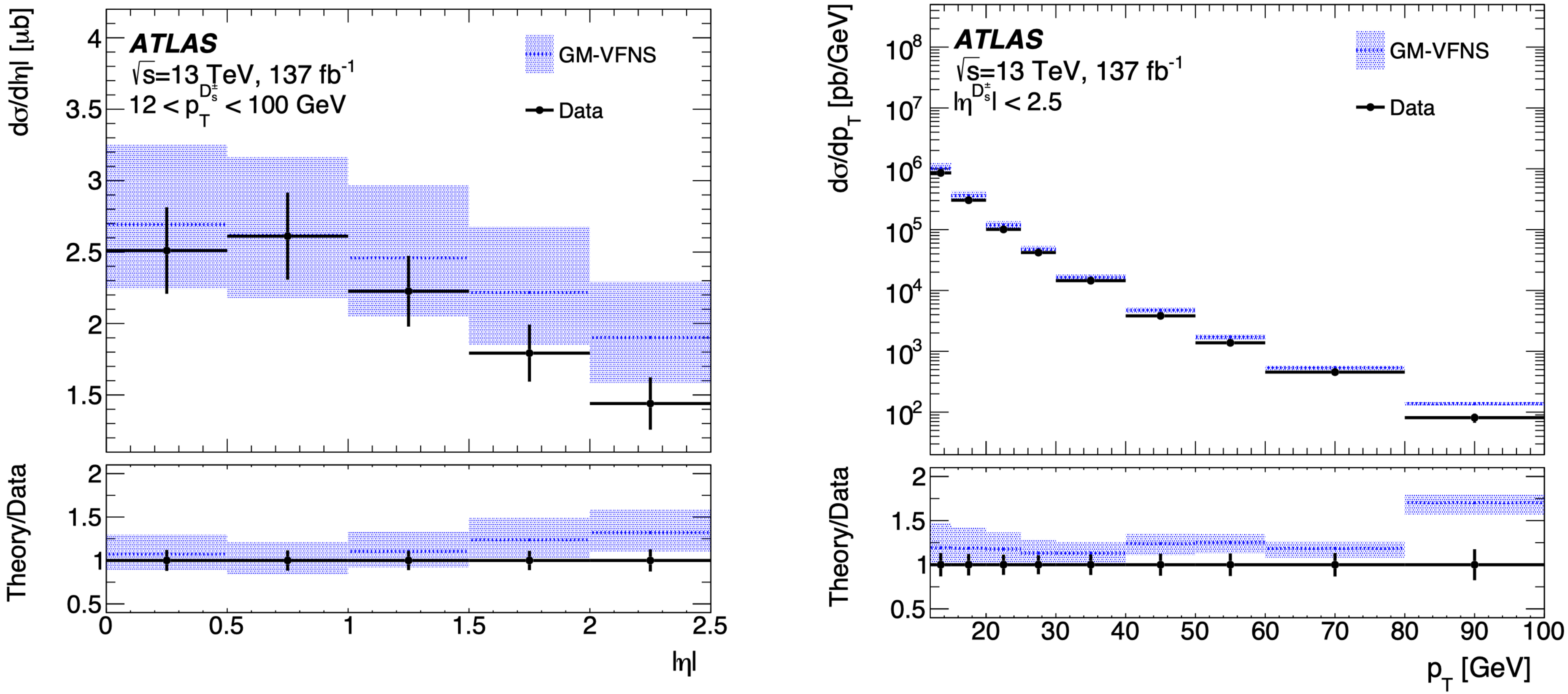
- Good agreement at low p_T for both GM-VFN and FONLL
- For higher p_T, GM-VFN is larger while FONLL is still consistent
- In $|\eta|$, good agreement is observed

JHEP 07 (2025)

NEW

Differential $D^{\pm}$ and $D_s^{\pm}$ production cross section

- $D_s^{\pm}$ cross section : compared with GM-VFN (FONLL not available)



- Similar behavior (GM-VFN is larger) is observed

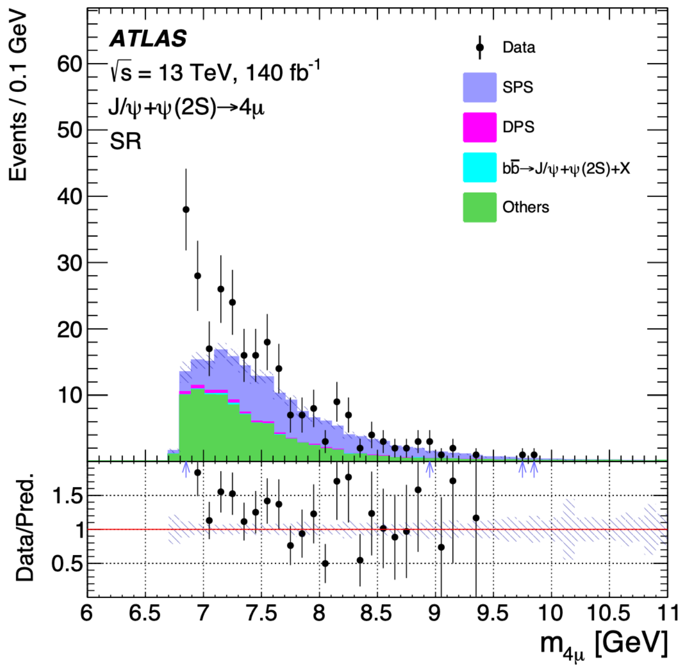
Extending heavy-flavor production into high p_T regime unique to the LHC energy frontier.

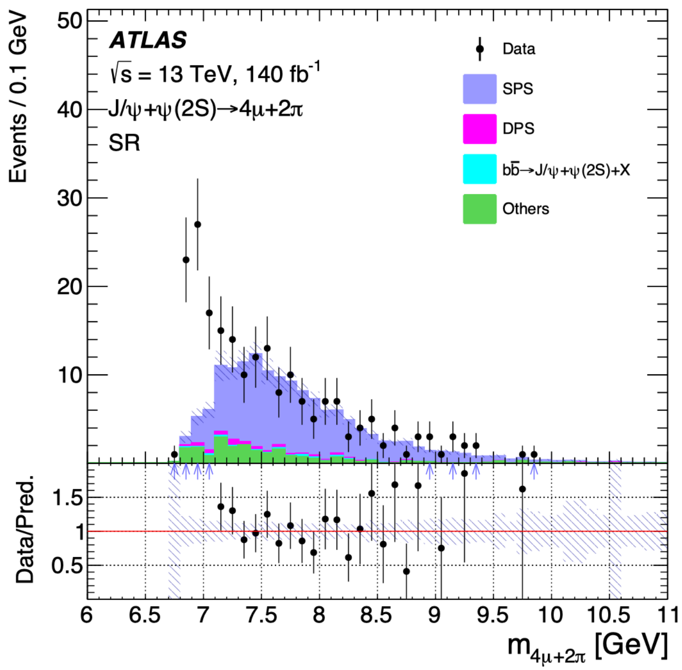
arXiv:2509.13101

NEW

Resonance in $J/\psi + \psi(2S)$ mass spectrum

- LHCb first observed a narrow resonance (X(6900)) in di-J/ψ mass spectrum, which is interpreted as all-charm tetra quark ($qq\bar{q}\bar{q}$)
  -- Studies of the tetra quark probe QCD in the non-perturbative regime
  -- ATLAS and CMS confirmed X(6900), as well as broad structure at 6.6 GeV
  -- Recently, CMS reported measurements on the three states, i.e. including a new structure at 7.1 GeV
- With full Run-2 data (140 /fb), J/ψ+$\psi(2S)$ → 4μ and $4\mu + 2\pi$ (first time in this analysis) mass spectra are examined.
  -- $4\mu + 2\pi$: large background from di-J/ψ (2π by random tracks)
  * A BDT is developed, resulting 65% of background rejection while 92% of signals are retained



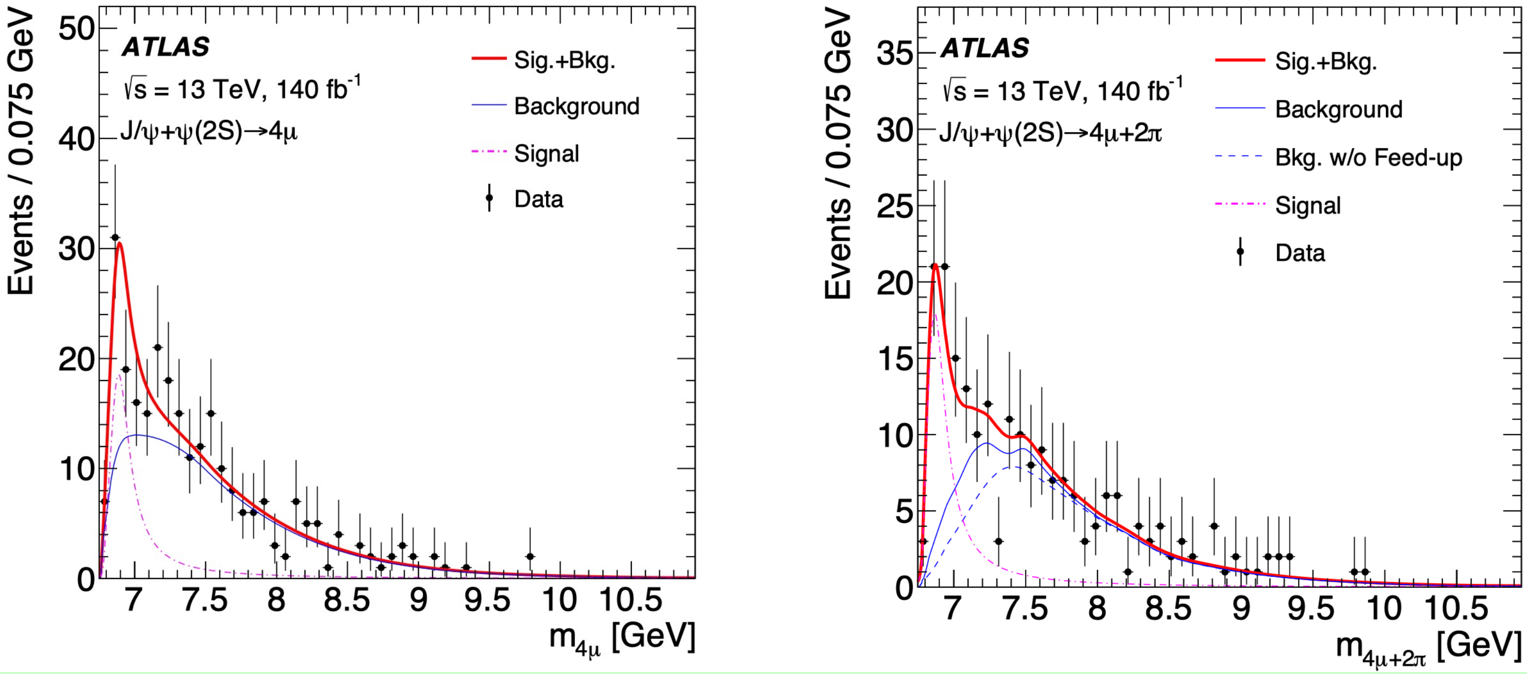


arXiv:2509.13101

NEW

Resonance in $J/\psi + \psi(2S)$ mass spectrum

- Unbinned likelihood fit to extract signal information from data in the mass spectrum
  - -- Simultaneous fit on J/ψ+$\psi(2S)$ 4μ and 4μ+2π (mass and width are shared) with a single Breit-Wigner (BW) function
  - -- In addition, another fit with a standalone X(7200) included as well

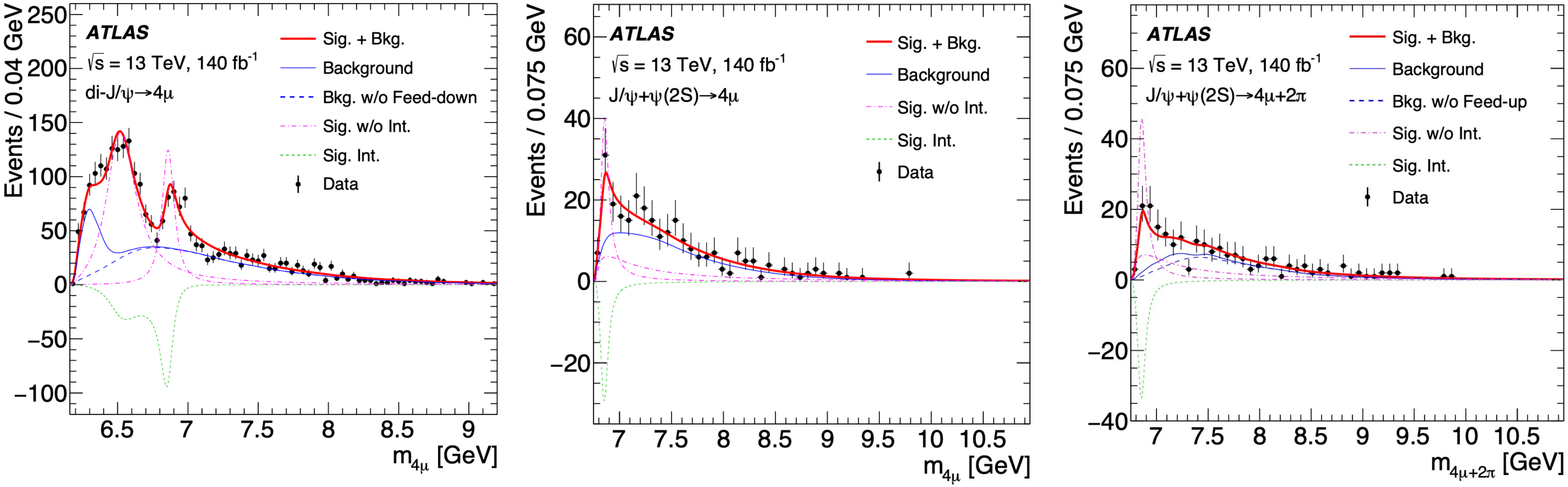


- The significance of X(6900) reaches 8.9 σ
- The ratio of X(7200)/X(6900): $r = 0.12 \pm 0.11$ - favoring a single resonance near 6.9 GeV, while resonance 7.2 GeV is not supported (95% CL upper limit is r<0.41)

NEW

Resonance in $J/\psi + \psi(2S)$ mass spectrum

- Another fit, by assuming X(6900) decays into both on di-J/ψ and J/ψ+$\psi(2S)$:
  - -- Fit both on di-J/ψ and J/ψ+$\psi(2S)$
    - * di-J/ψ is from a previous study Phys. Rev. Lett. 131 (2023) 151902
  - -- With two BW interfering each other



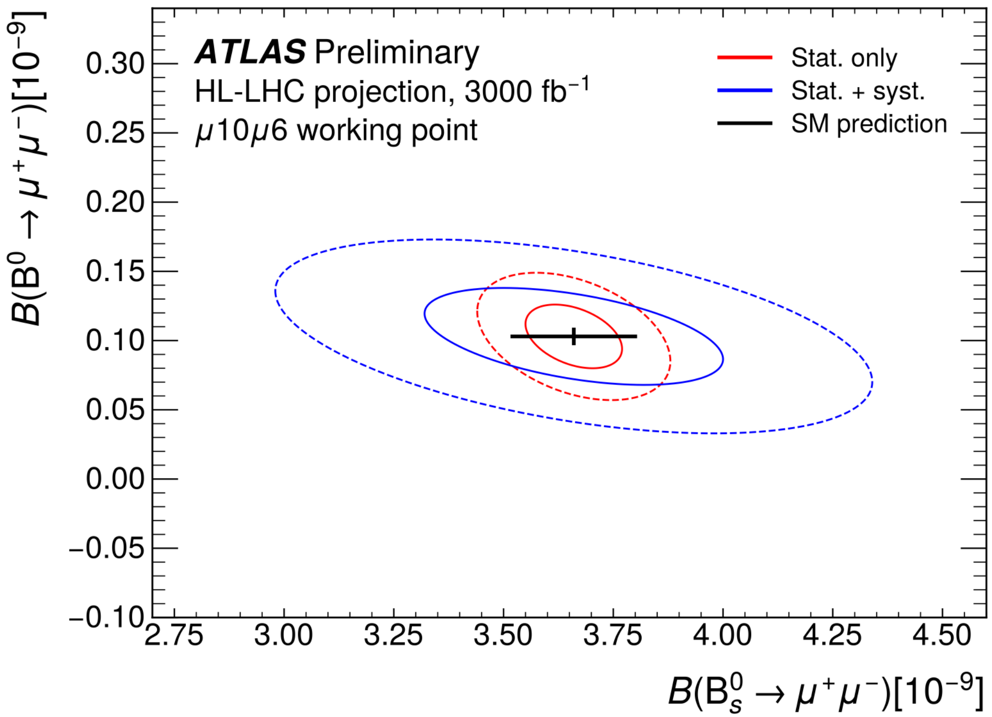
- $m = 6.860 \pm 0.023 \pm 0.010$ GeV
- $R = \frac{\Gamma_{X(6900)\to J/\psi+\psi(2S)}}{\Gamma_{X(6900)\to di-J/\psi}} = 1.08 \pm 0.20^{+0.40}_{-0.17}$

  which is opposite to a naïve expectation from the available phase space

NEW

HL-LHC projection $B^0_{(s)} \to \mu\mu$ rare decay

- The decays $B^0_{(s)} \to \mu\mu$ are heavily suppressed in the SM, as Flavour Changing Neutral Current (FCNC) – an ideal place to look for new physics effects
- An updated HL-LHC projection with 3000 /fb on both branching fraction and the lifetime



Quantity	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ $[10^{-9}]$			$\mathcal{B}(B^0 \to \mu^+\mu^-)$ $[10^{-10}]$			$\tau_{\mu\mu}$ [ps]		
SM value	3.66 ± 0.14 [1]			1.03 ± 0.05 [1]			1.624 ± 0.009 [7]		
ATLAS 2015–2016 measurements	$3.21^{+0.96+0.49}_{-0.91-0.30}$ [2]			< 4.3 at 95% CL. [2]			$0.99^{+0.42}_{-0.07} \pm 0.17$ [8]		
Projected uncertainty	Stat.	Syst.	Total	Stat.	Syst.	Total	Stat.	Syst.	Total
$\mu10\mu10$	0.17	0.36	0.40	0.36	0.32	0.48	+0.09 −0.06	0.06	+0.11 −0.08
$\mu10\mu6$	0.11	0.32	0.34	0.23	0.26	0.35	+0.06 −0.03	0.05	+0.08 −0.06
$\mu6\mu6$	0.09	0.32	0.33	0.19	0.26	0.32	+0.05 −0.03	0.05	+0.07 −0.05

Summary

- ATLAS is turning QCD and heavy flavor into precision tools :
  -- multi-dimensional jets stress-test NNLO QCD and PDFs
  -- heavy-flavour measurements span production, exotic spectroscopy, and rare-decay NP sensitivity with HL-LHC pushing key modes into the precision regime

- ATLAS uniquely connects QCD dynamics and heavy-flavor observables within a single high-energy framework.

- There are a large variety of ATLAS QCD and Heavy Flavor physics results that cannot be unfortunately introduced in this talk – please visit
  -- https://twiki.cern.ch/twiki/bin/view/AtlasProtected/AtlasPhysics