ATLAS Analysis Highlights
More data & smarter tools — highlights and plans

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Krvavec Strategic Meeting
Monday, September 28, 2026

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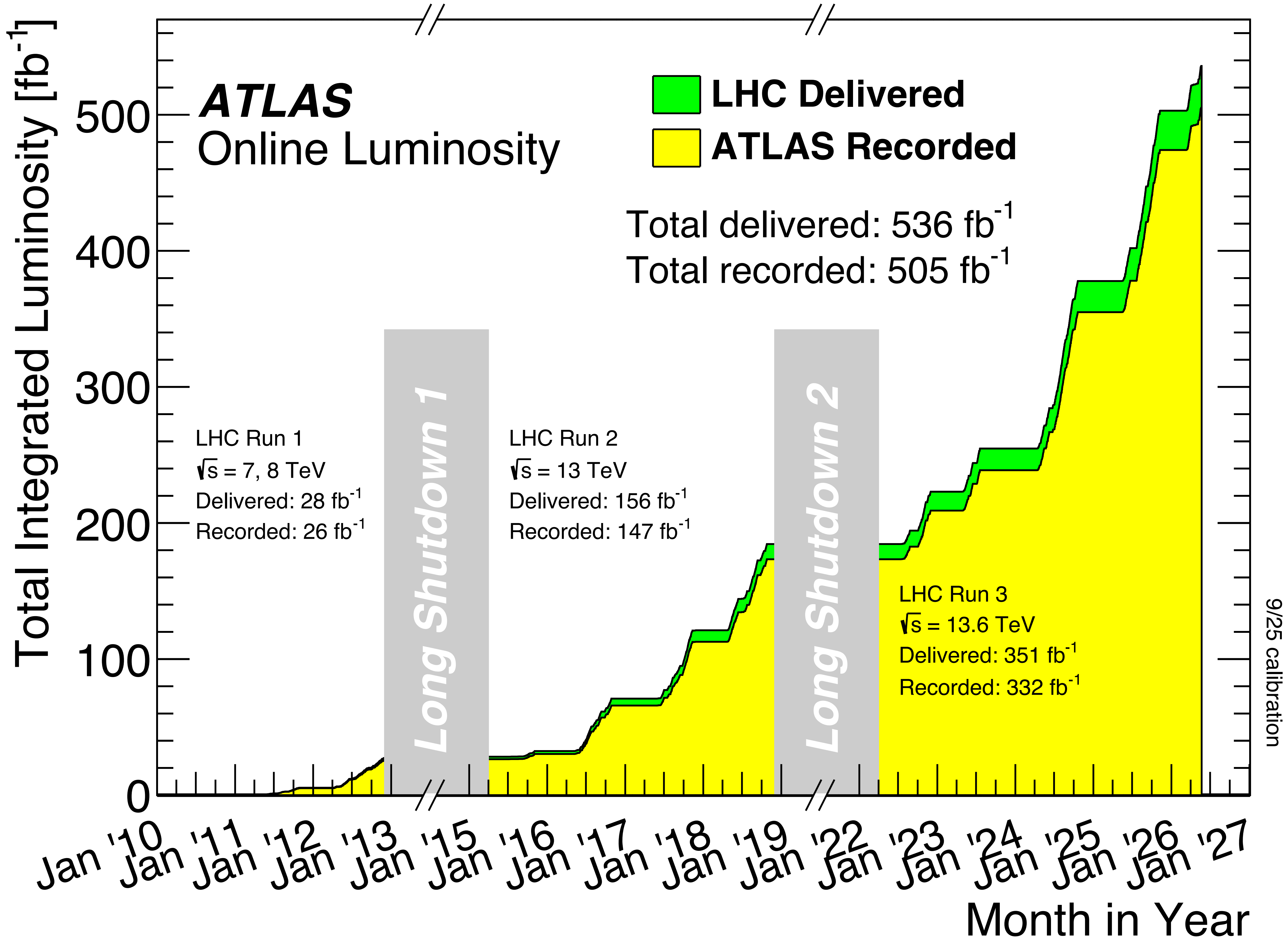
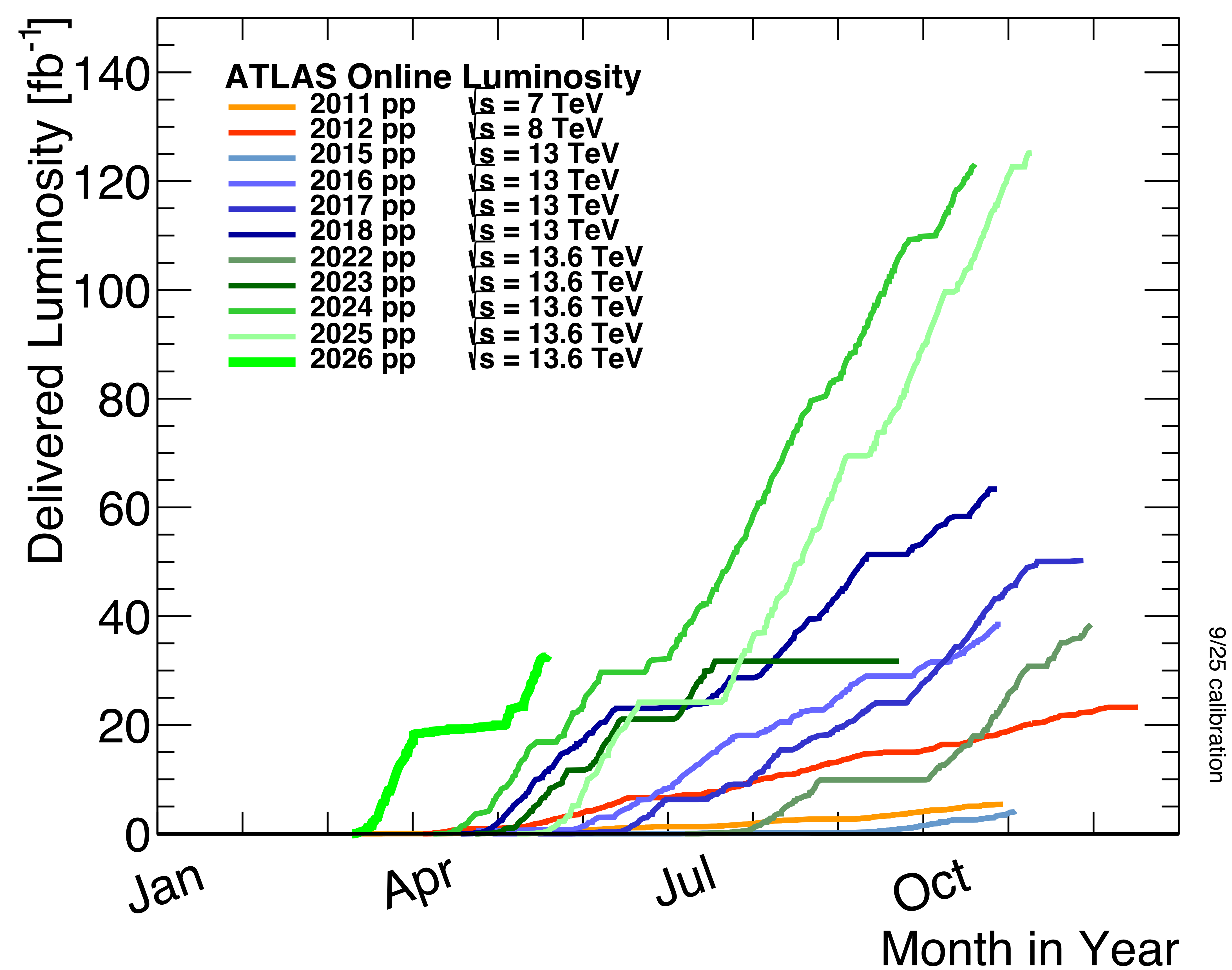
ATLAS EXPERIMENT
"YOU ARE WELCOME HERE!"

The dataset: LHC Run 2 + Run 3

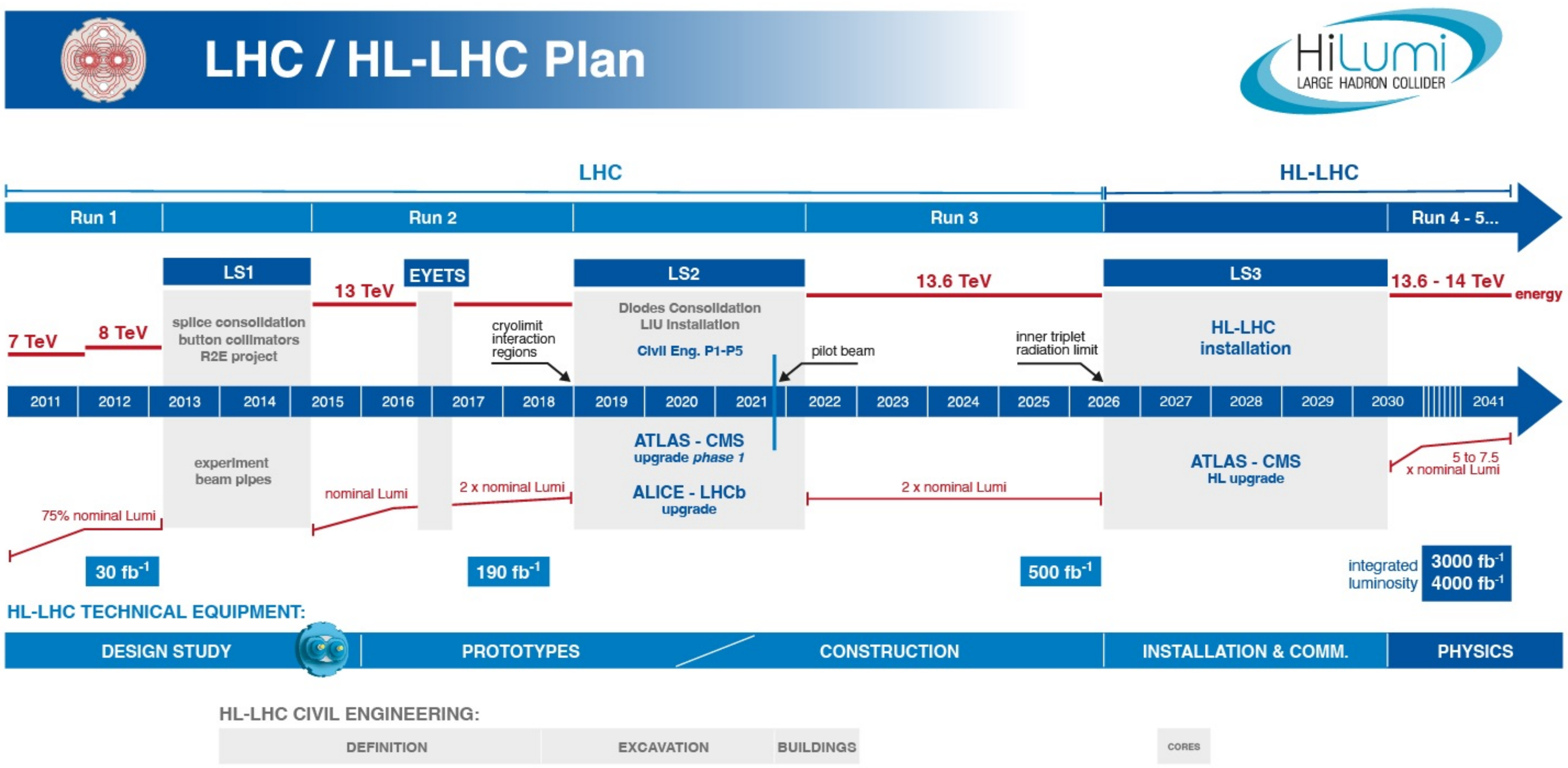
- **Run 2 (2015–2018)**, √s=13 TeV: 140 fb^{-1} good for physics
- **Run 3 (2022–2026)**, √s=13.6 TeV: 312 fb^{-1} good for physics
  - 2024 and 2025 were record years with ≈110 fb^{-1} each; Run 3 alone is 2.2× Run 2
  - Andrej Gorišek was the ATLAS Run Coordinator for those record breaking years!
- Together ≈450 fb^{-1} — produced, approximately: 26 million Higgs bosons, 400 million $t\bar{t}$ pairs, 2 billion Z→ee,μμ





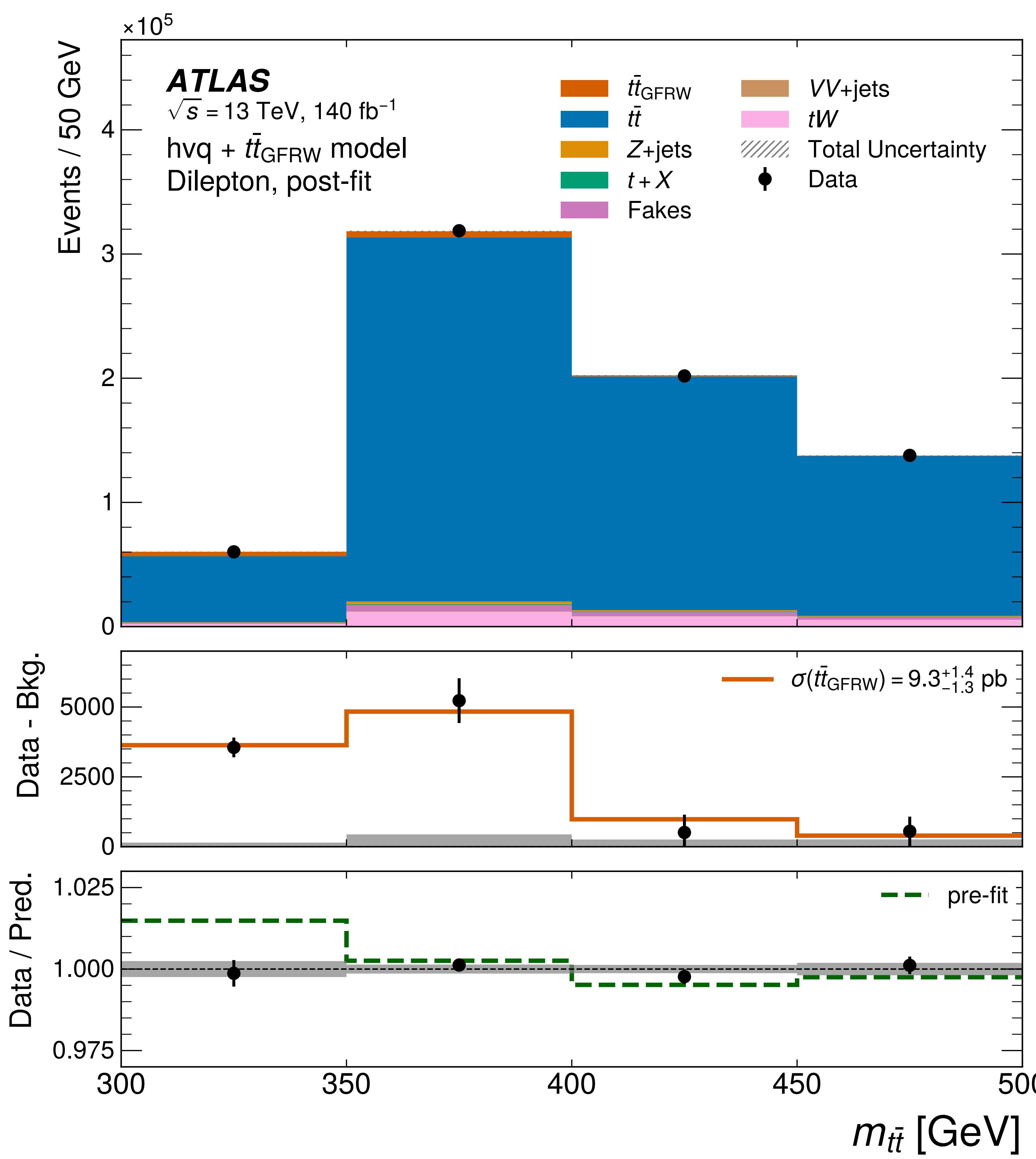
Now: Long Shutdown 3, preparing for the HL-LHC

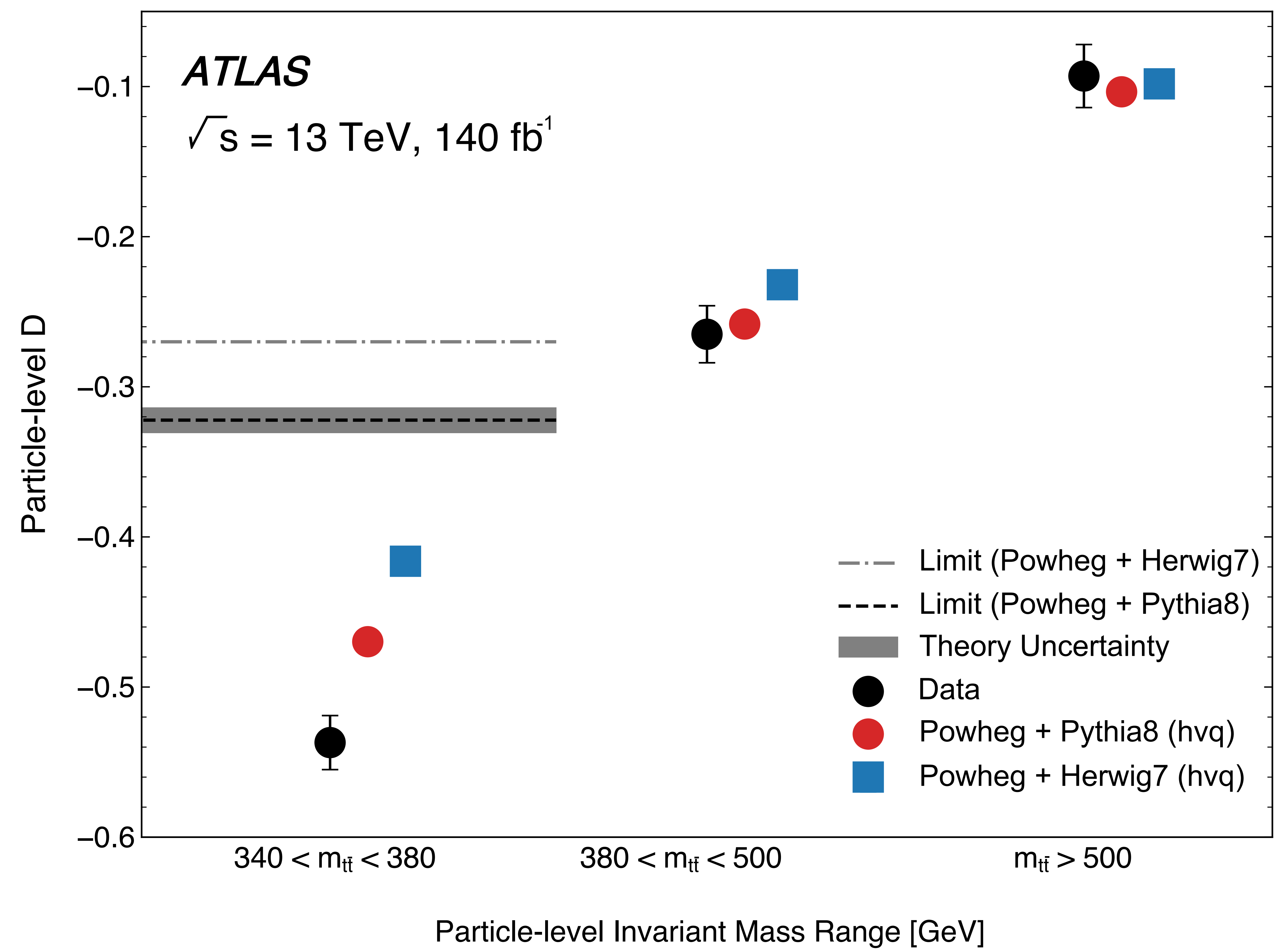
- **Run 3 proton physics ended in May 2026**, last beams on 27 June; LS3 started on 29 June 2026
- **HL-LHC from June 2030**: up to 7.5×10^{34} cm^{-2}s^{-1}, pile-up up to 200, 3000 fb^{-1} by 2041 (up to 4000)
- **ATLAS Phase-II**: all-silicon ITk (178 m² of silicon, 5 billion channels, |η|<4), HGTD timing (30–50 ps), 1 MHz trigger
  - F9 builds parts of it: HGTD, ITk strips, BCM' — see the talks on Monday evening and Wednesday
- For the next couple of years, ATLAS physics comes from the Run 2 + Run 3 data



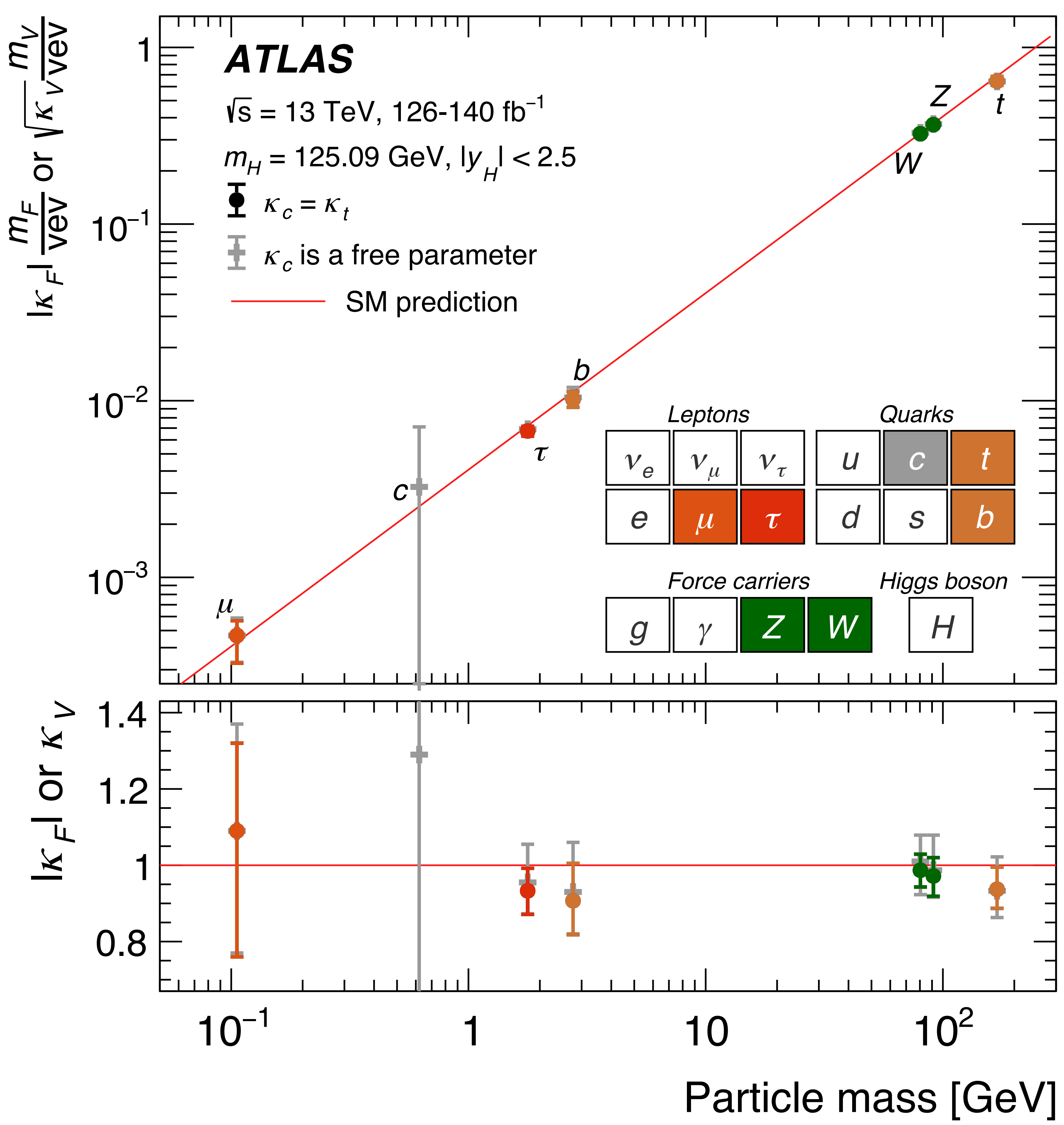
ATLAS highlights: the top quark

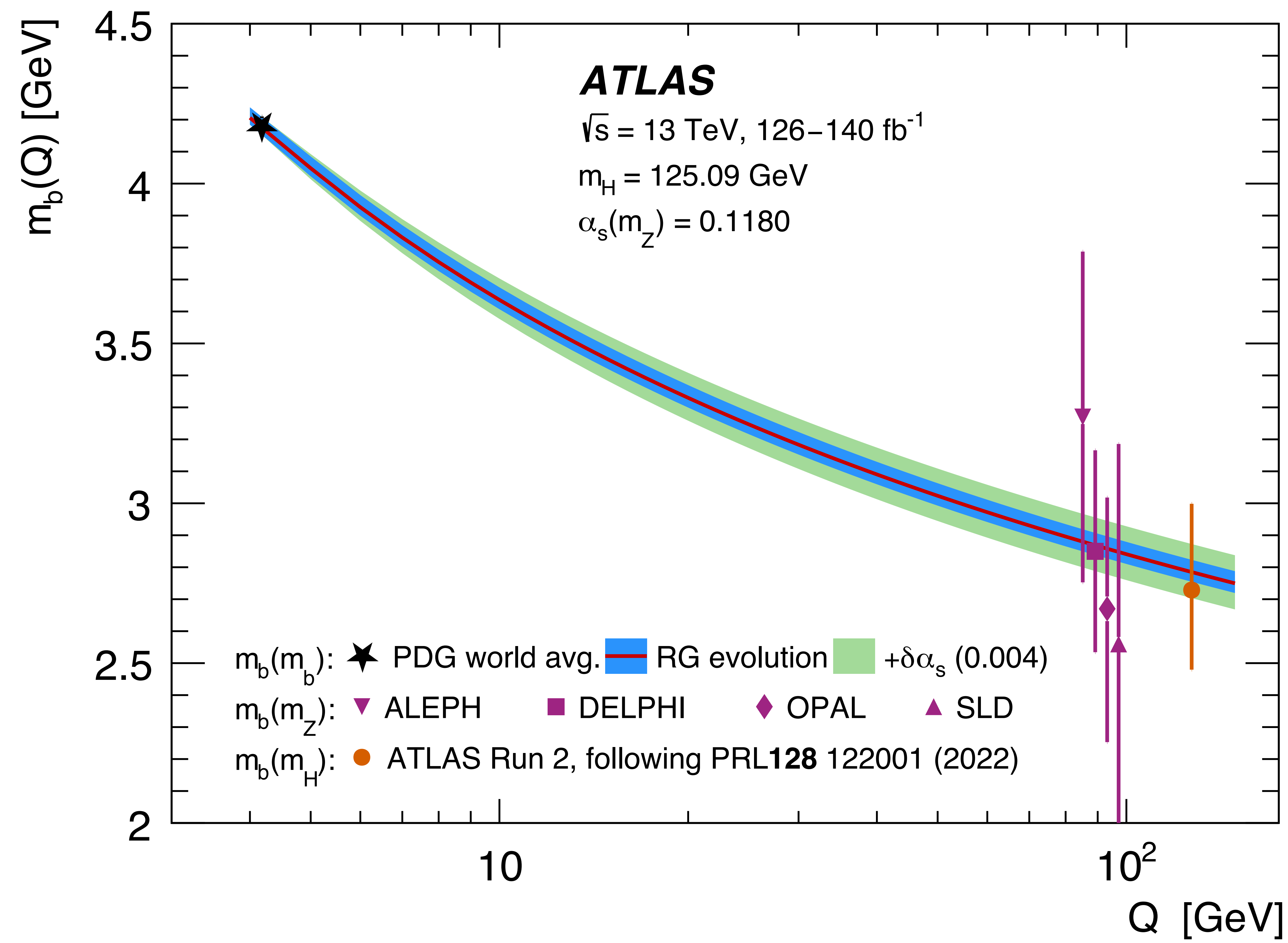
- Toponium-like state at the $t\bar{t}$ threshold: excess over perturbative QCD at >8σ [Rep. Prog. Phys. 89 (2026) 057801]
  - The top quark decays in ~5×10^{-25} s, before it can form hadrons — yet the $t\bar{t}$ pair binds near threshold
  - Confirms the 2025 CMS observation: a new QCD effect at a hadron collider
- Quantum entanglement of top quarks: D=−0.537±0.019, below the −1/3 limit at >5σ [Nature 633 (2024) 542]
  - First entanglement observed between quarks, and at the highest energies so far
  - Also: entangled Z bosons in H→ZZ*→4ℓ at 4.7σ [PRL 137 (2026) 111804]



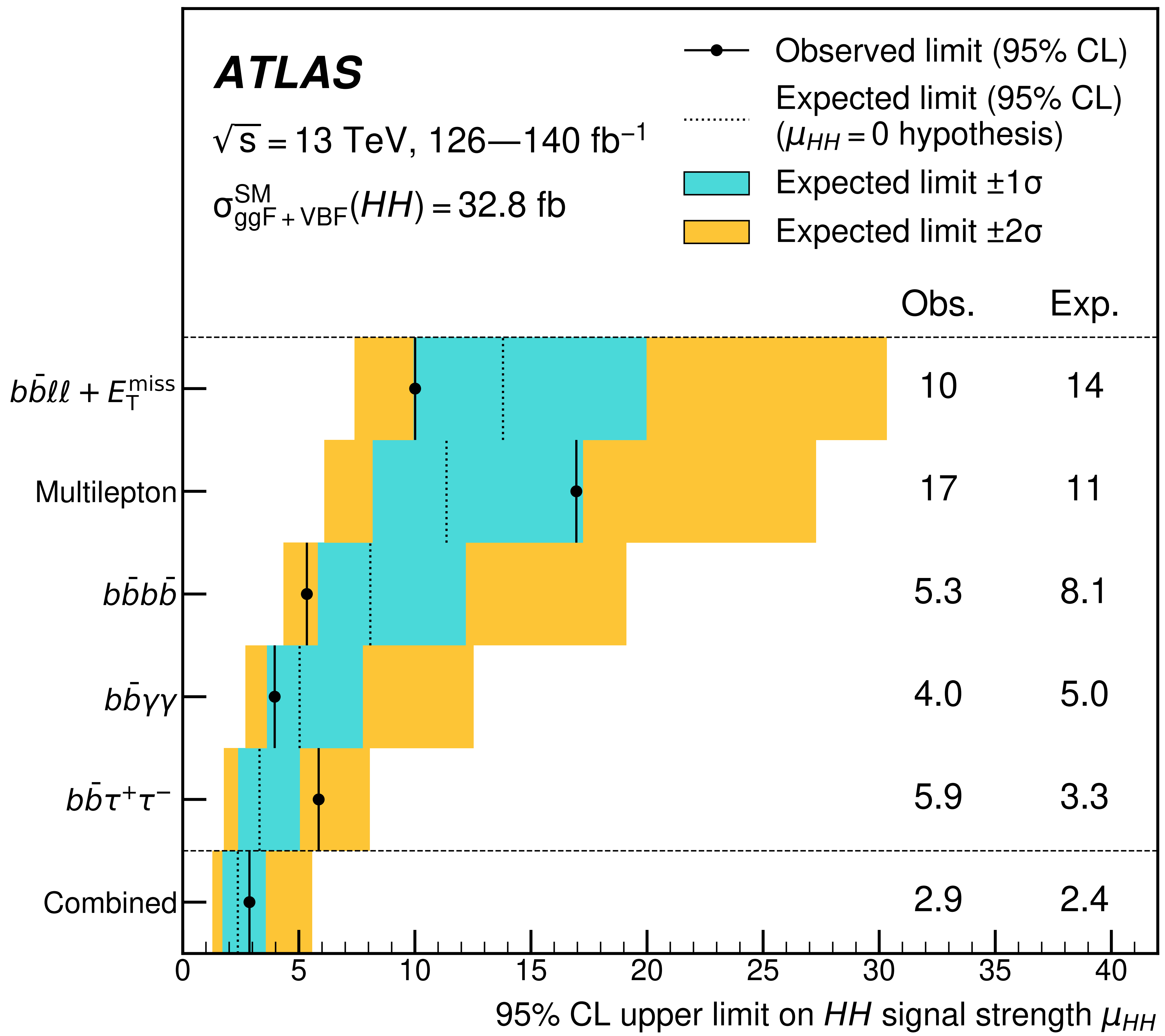


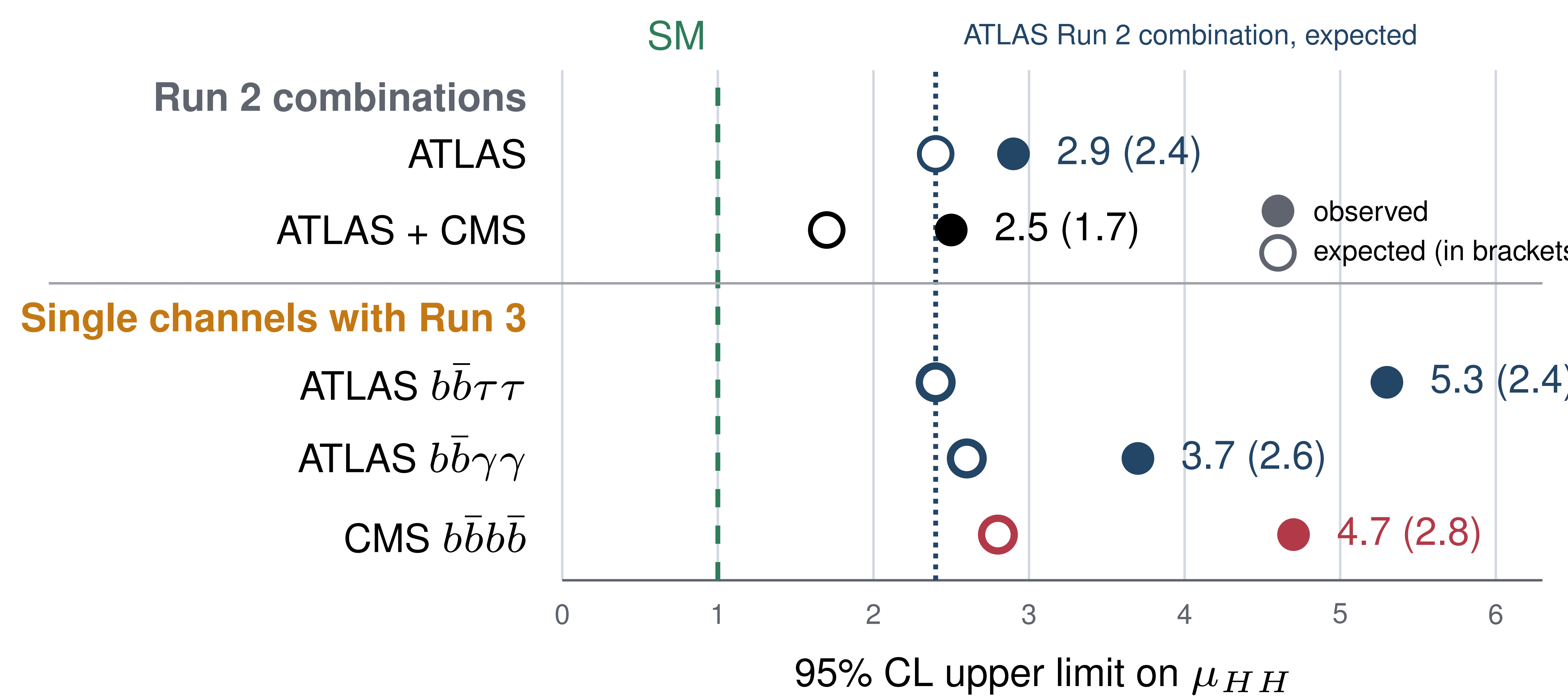
- Run 2 legacy combination: signal strength μ=0.990 +0.053/−0.051 — the SM Higgs at 5% precision [arXiv:2608.07332]
  - Couplings from muons to top quarks follow the mass pattern over three orders of magnitude
  - Width Γ_H=3.6 +2.1/−1.6 MeV; even the b-quark mass at the Higgs scale, $m_b(m_H)$=2.73 +0.27/−0.25 GeV
- Evidence for H→μμ with Run 2 + Run 3: 3.4σ (2.5σ expected), μ=1.4±0.4 [PRL 135 (2025) 231802]
  - Only ~1 in 5000 Higgs bosons decays to muons: the Higgs also talks to the second generation
  - H→Zγ with Run 2 + Run 3: 2.5σ [PLB 876 (2026) 140313]



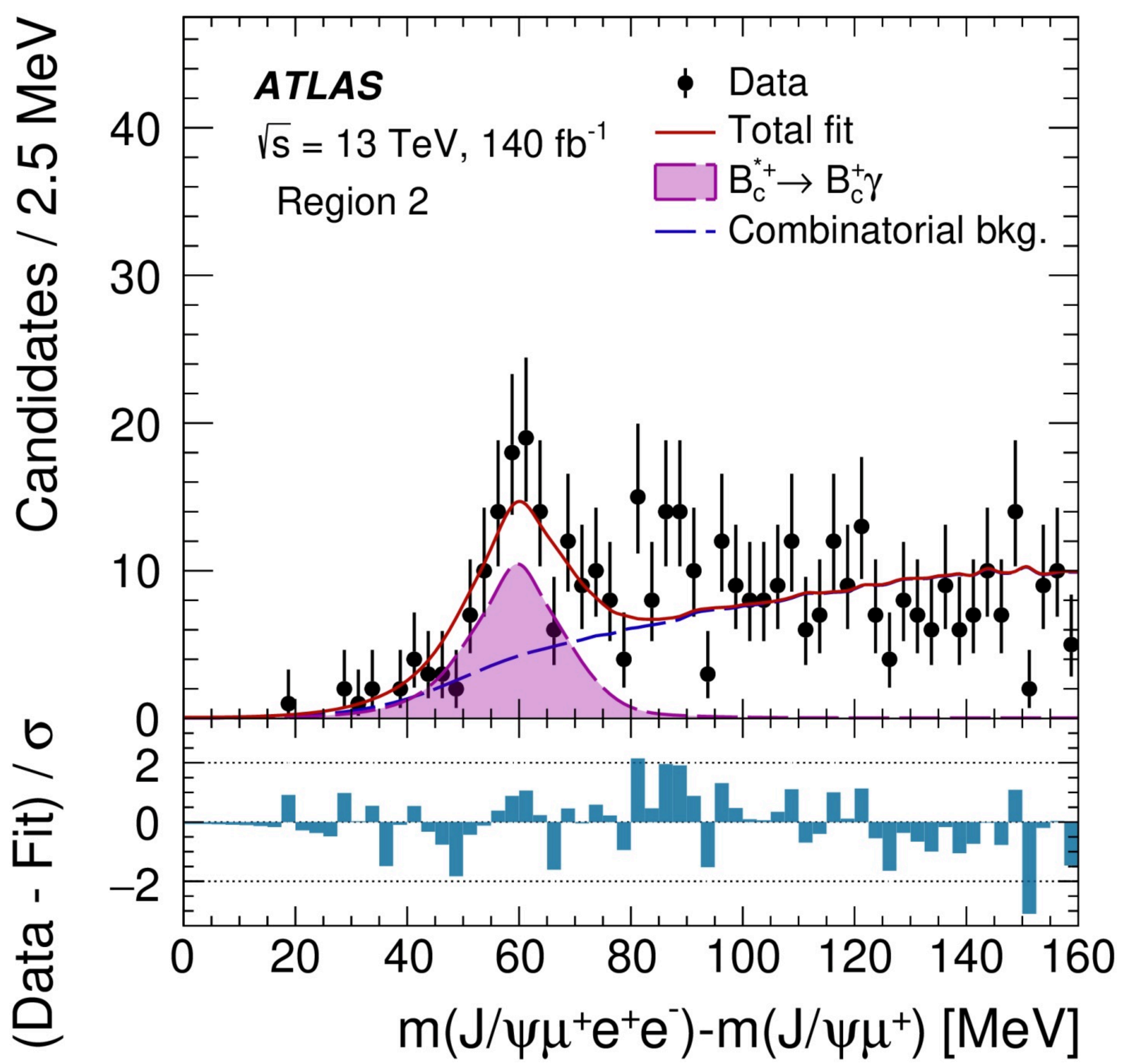


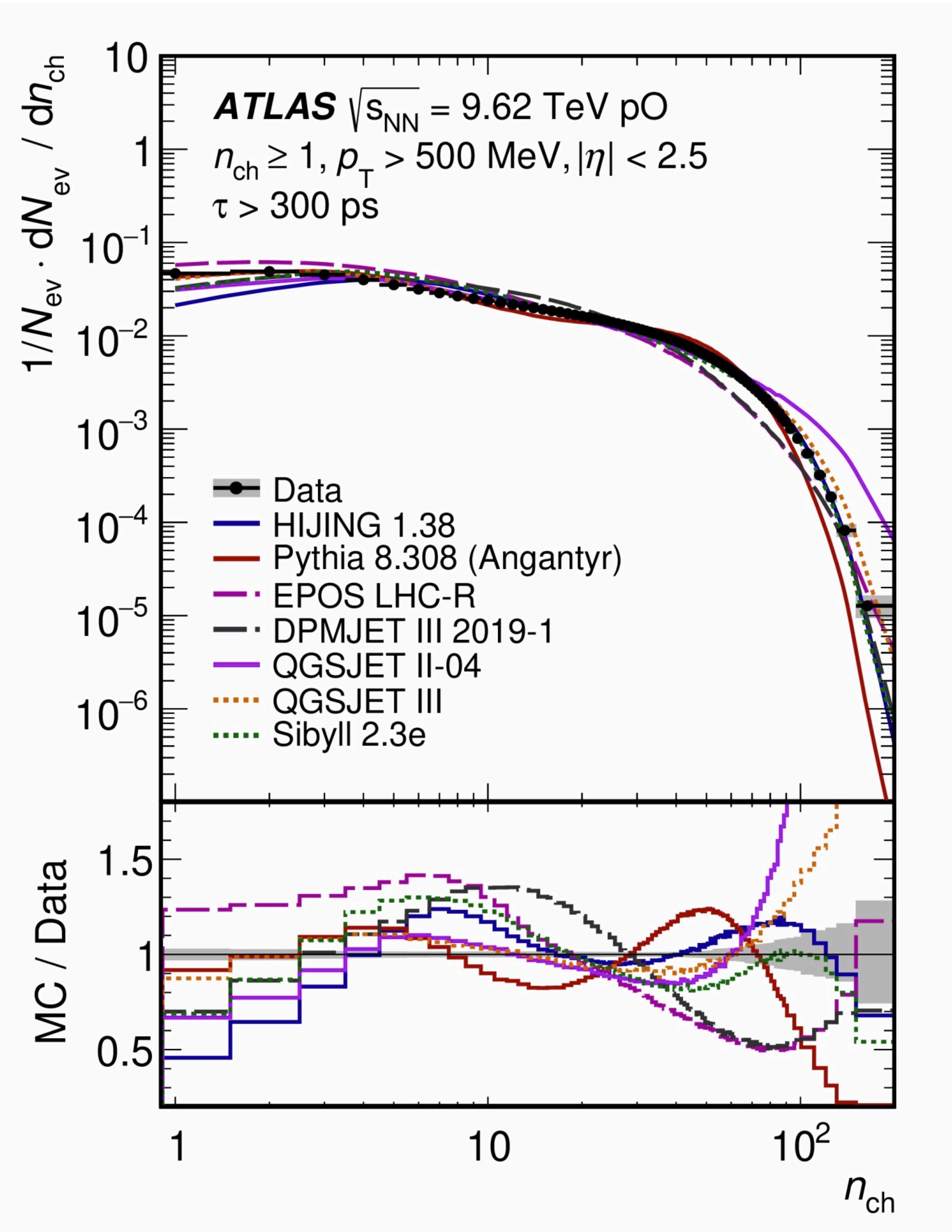
- Self-coupling = shape of the Higgs potential, from HH production; strongest channels $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$
- Strongest constraint today: ATLAS + CMS Run 2, μ_{HH}<2.5 (1.7 exp.), $-0.71<\kappa\lambda<6.1$ [arXiv:2602.23991]
- With Run 3, one channel matches the whole ATLAS Run 2 combination (expected limit 2.4)
  - $b\bar{b}\tau\tau$ (140 + 56 fb^{-1}): expected 2.4, 60% better than before; observed 5.3 = 2.6σ excess [arXiv:2607.26879]
  - $b\bar{b}\gamma\gamma$ (308 fb^{-1}): expected 2.6; $-1.6<\kappa\lambda<6.6$ [PLB 876 (2026) 140280] → Jakob, $b\bar{b}WW$, Mon 16:30

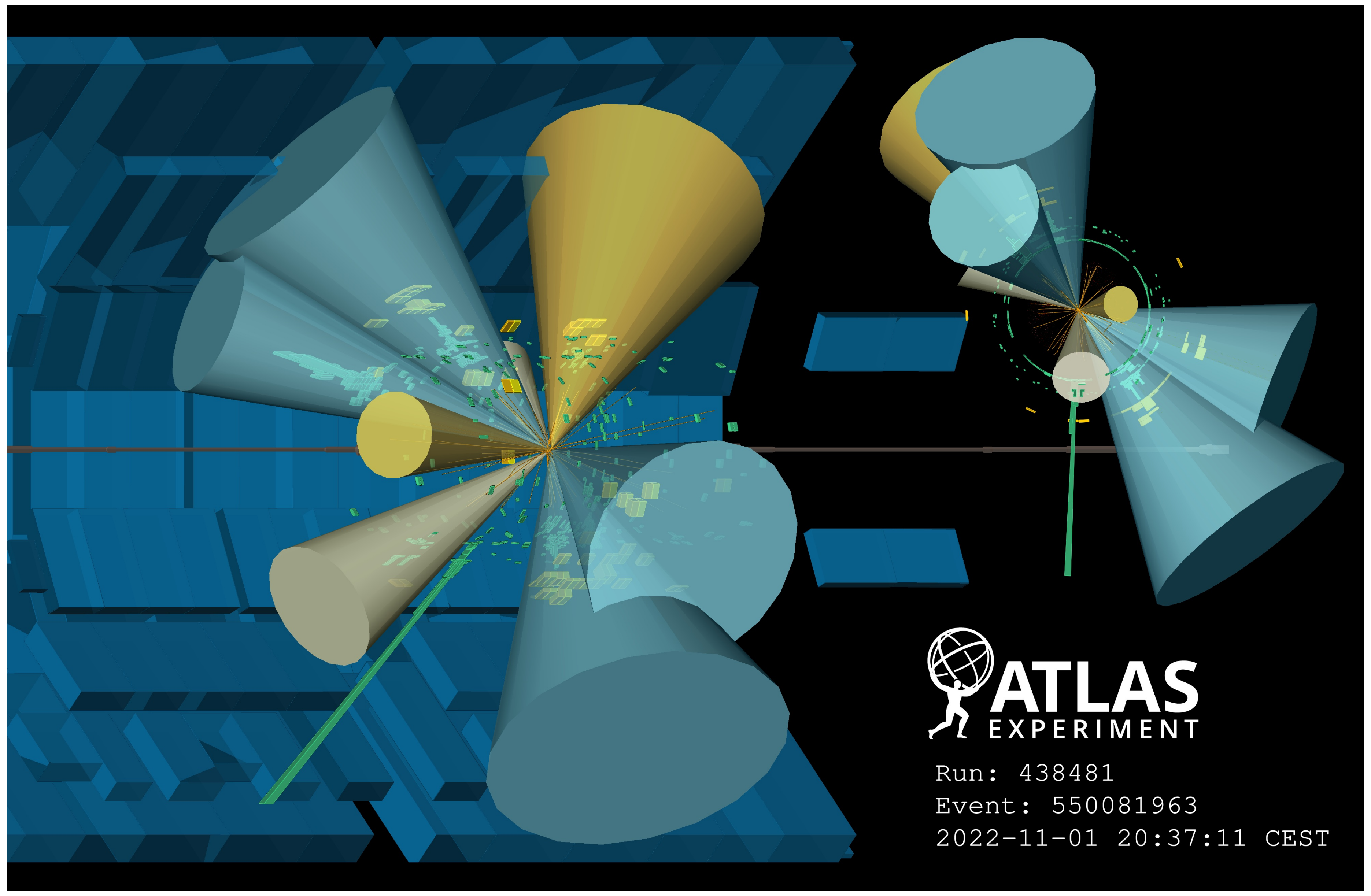




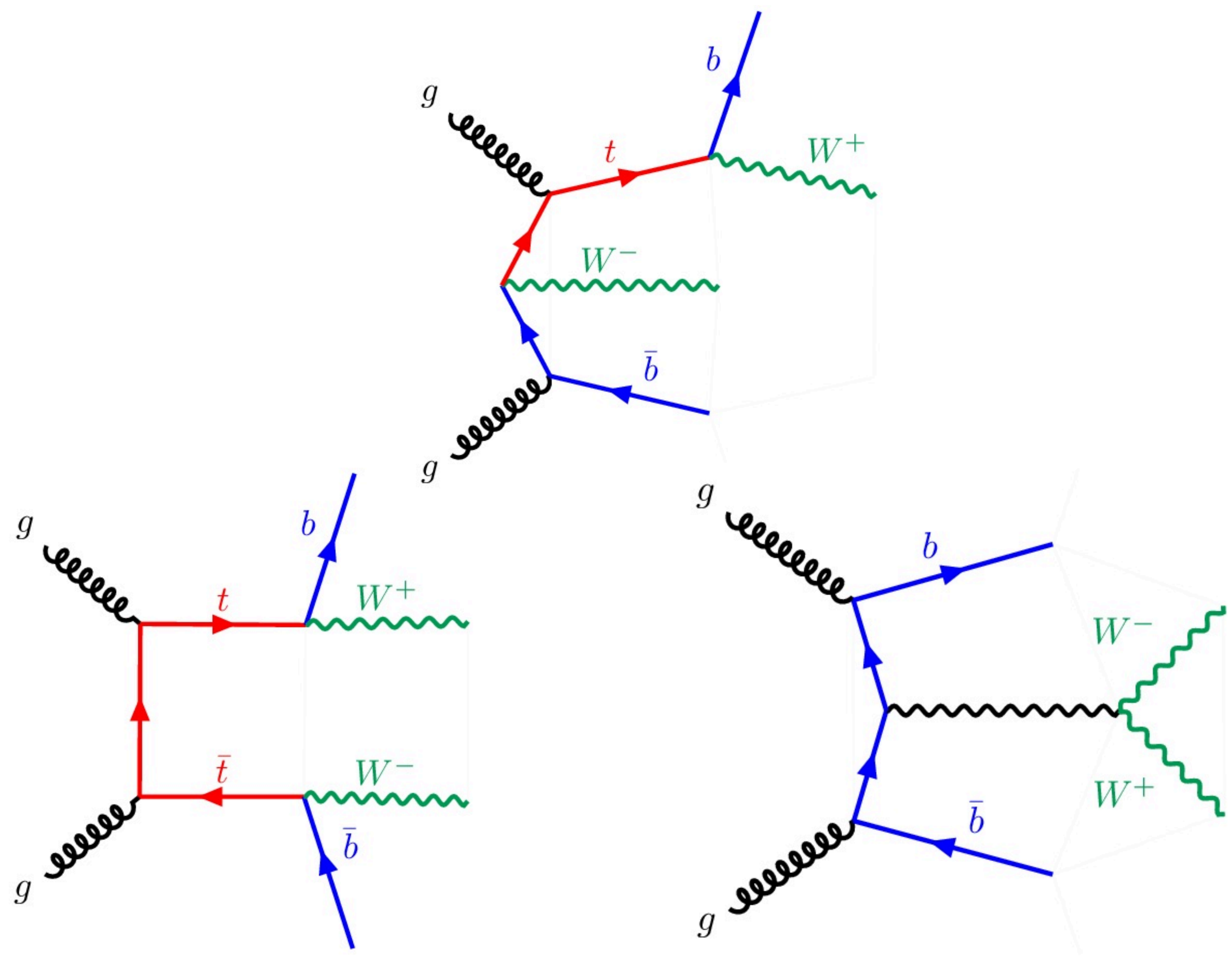
- ATLAS reports the first observation of the Bc*⁺ meson ($\bar{b}c$), the lowest excited state of the Bc⁺, at >8σ [arXiv:2605.16228]
  - Bc*⁺→Bc⁺γ with a converted soft photon: Δm=64.5±1.4 (stat) +1.0/−1.4 (syst) MeV
  - Like electrons in an atom, quarks inside hadrons have energy levels — heavy-quark spectroscopy at the LHC
- Proton–oxygen at √sNN=9.62 TeV (July 2025): charged particles measured at the few-percent level [arXiv:2604.05512]
  - Recreates cosmic rays hitting air nuclei — air-shower models used by cosmic-ray exp. disagree with each other
  - "The LHC as a cosmic-ray laboratory": direct input for the Auger and CTAO colleagues

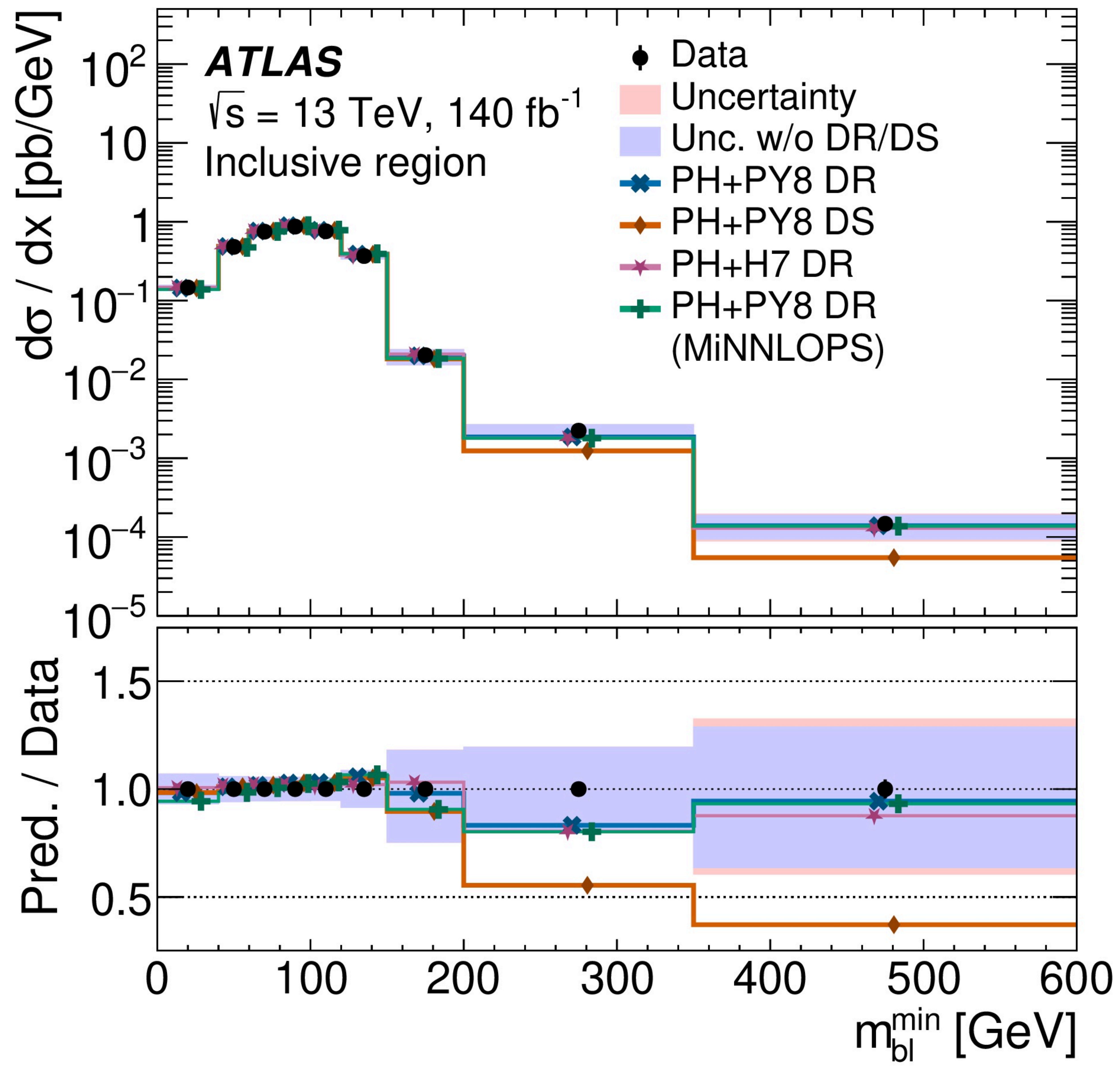






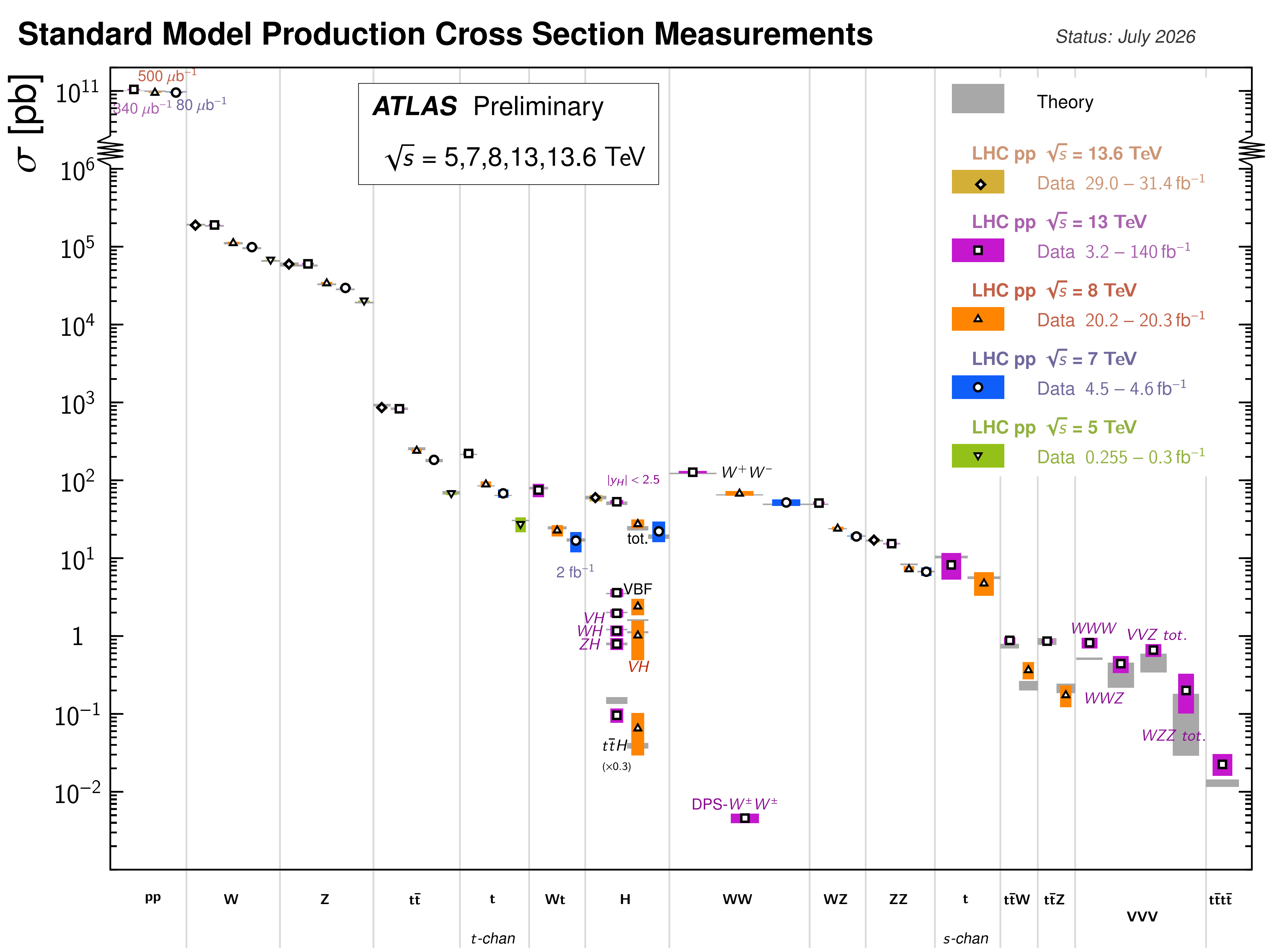
- The $WWb\bar{b}$ final state comes from $t\bar{t}$ (doubly resonant), tW (singly resonant) and non-resonant diagrams
  - Generators treat the interference only approximately (diagram removal vs subtraction, DR/DS)
- ATLAS measured WbWb differential cross sections in regions optimised for the interference
  - Dilepton [JHEP 02 (2026) 153] and lepton + jets [JHEP 07 (2026) 028]; Tadej Novak analysis contact of both
- Significant discrepancies with predictions where the interference matters ⇒ new input for top-quark Monte Carlo and the top-mass programme

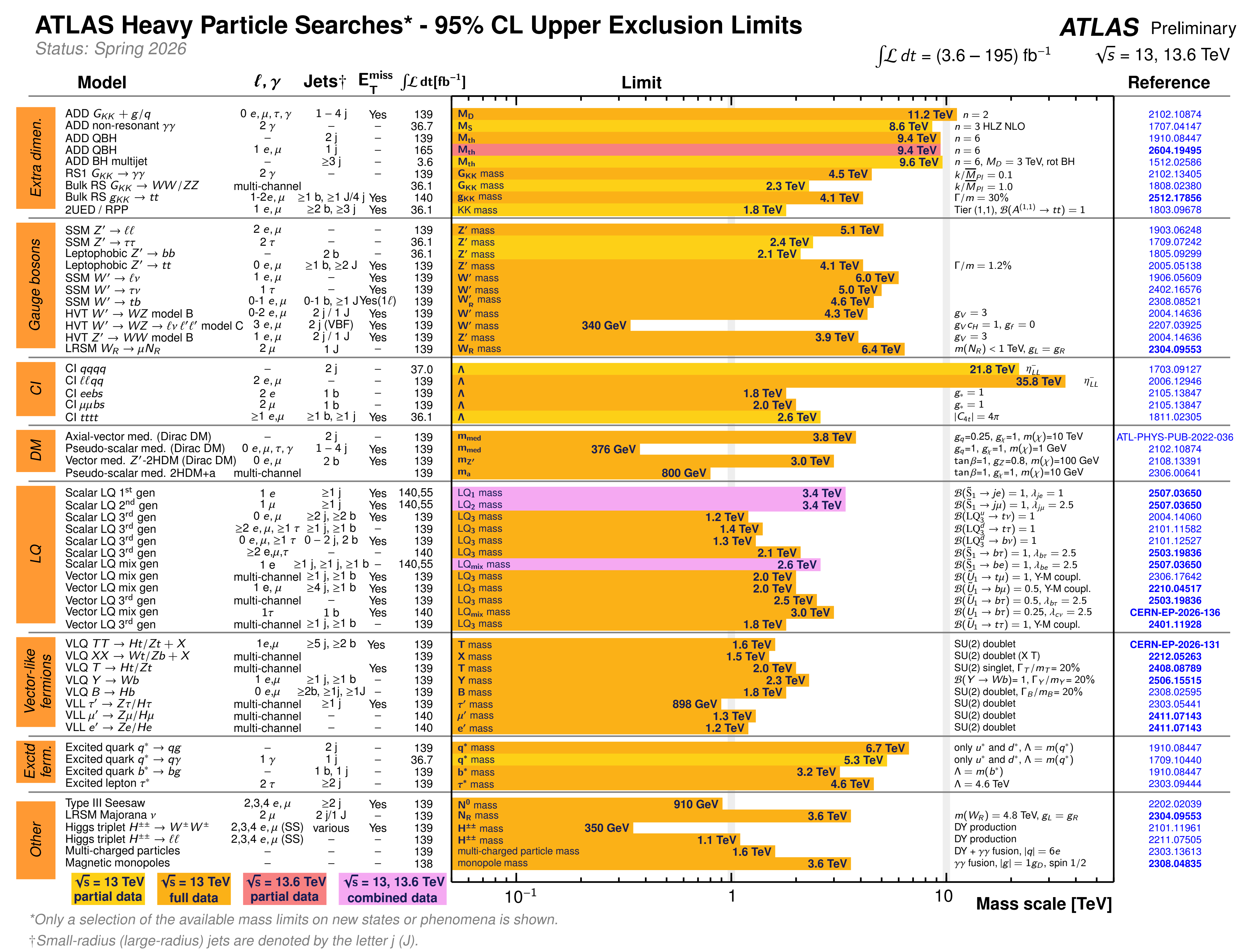




Run 2: the Standard Model everywhere

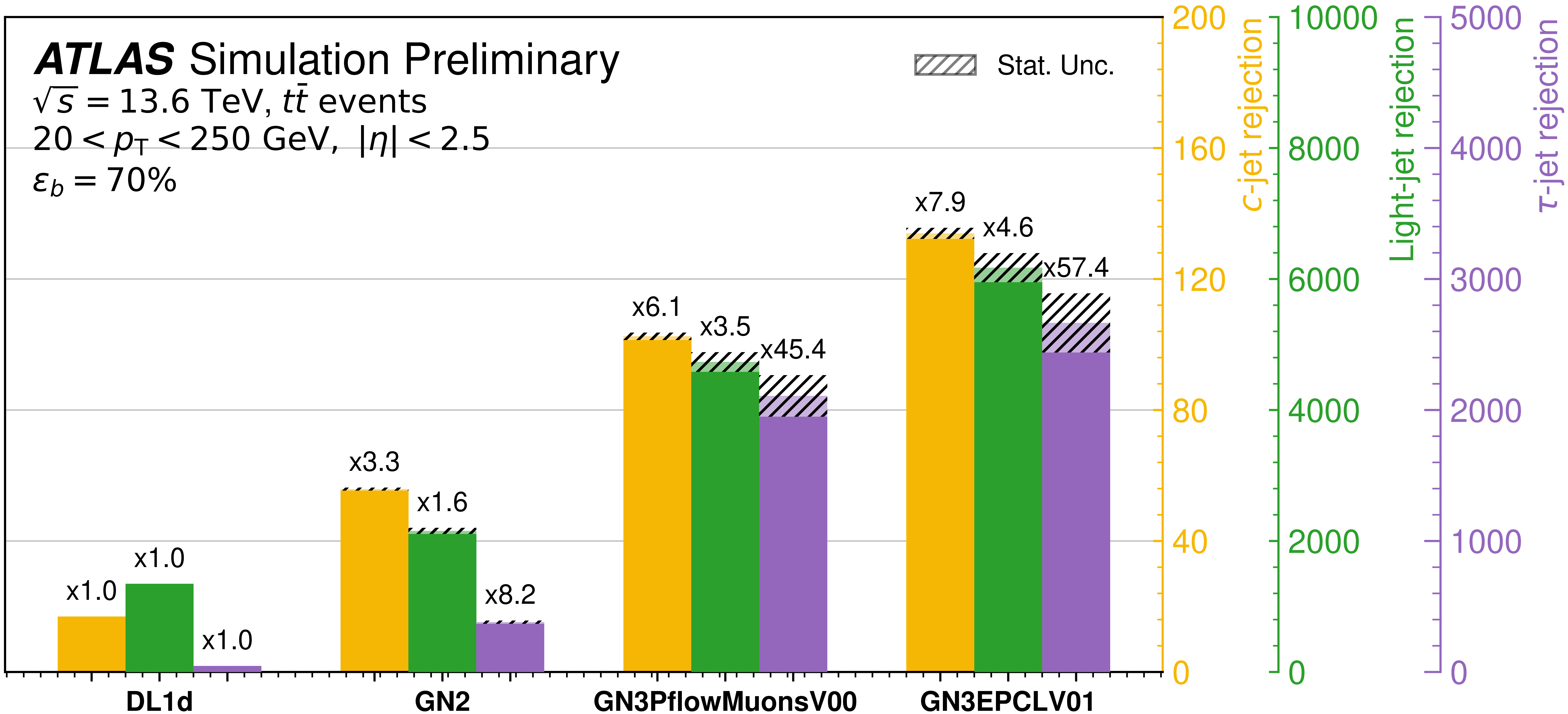
- Cross sections over 13 orders of magnitude agree with the SM; searches exclude new particles up to several TeV
- Run 3 gives 2.2× the Run 2 data, but statistics-limited sensitivity grows only as $\sqrt{(450/140)} \approx 1.8$
  - A real 2σ hint in Run 2 would become ≈3.6σ with Run 2 + Run 3 — not a discovery
  - Mass reach grows even more slowly (steeply falling parton luminosities)
- **We need to get creative**: better objects (ML tagging), new final states (hadronic τ), new observables (jet charge, fragmentation, asymmetries)





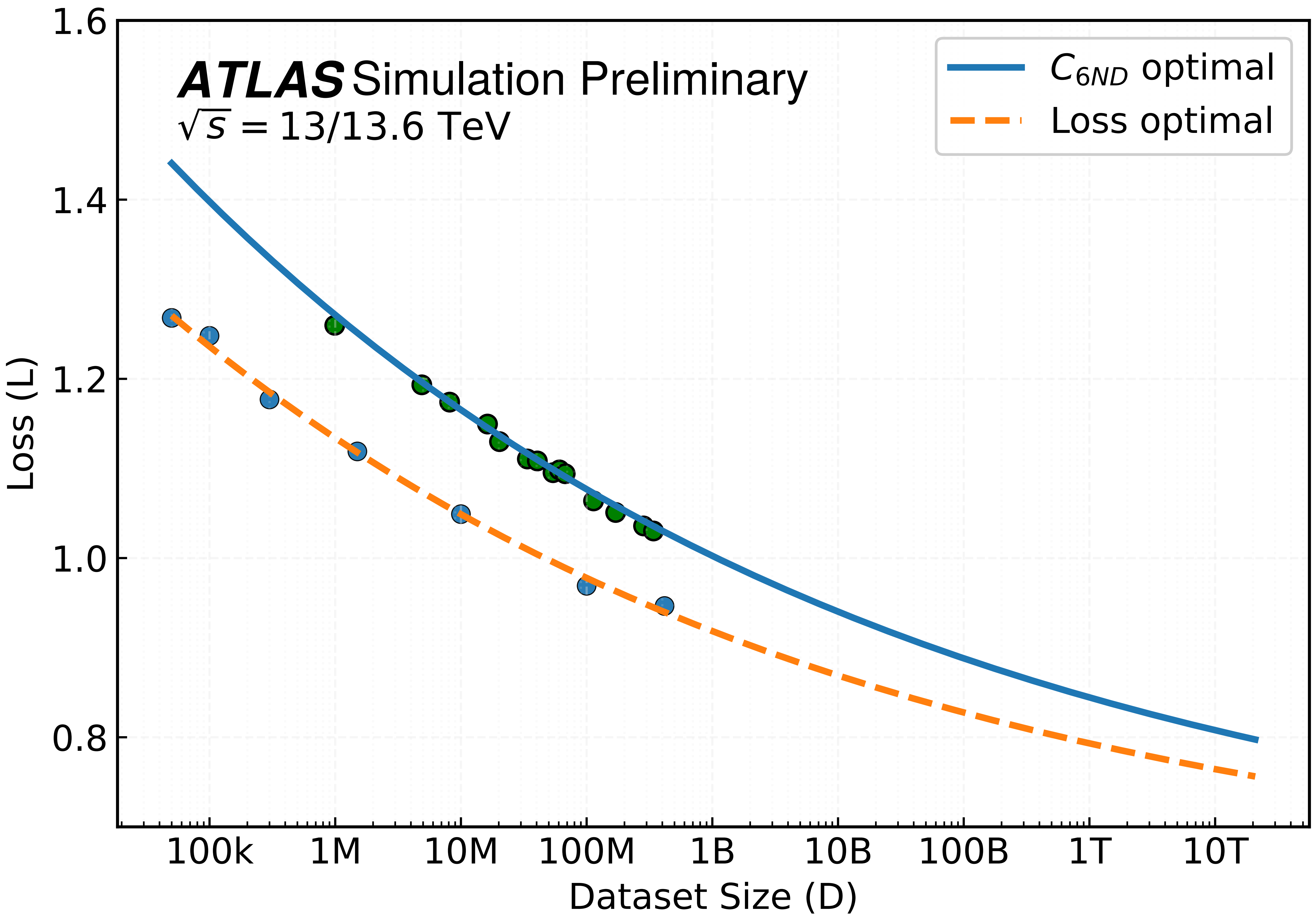
Machine learning is transforming flavour tagging

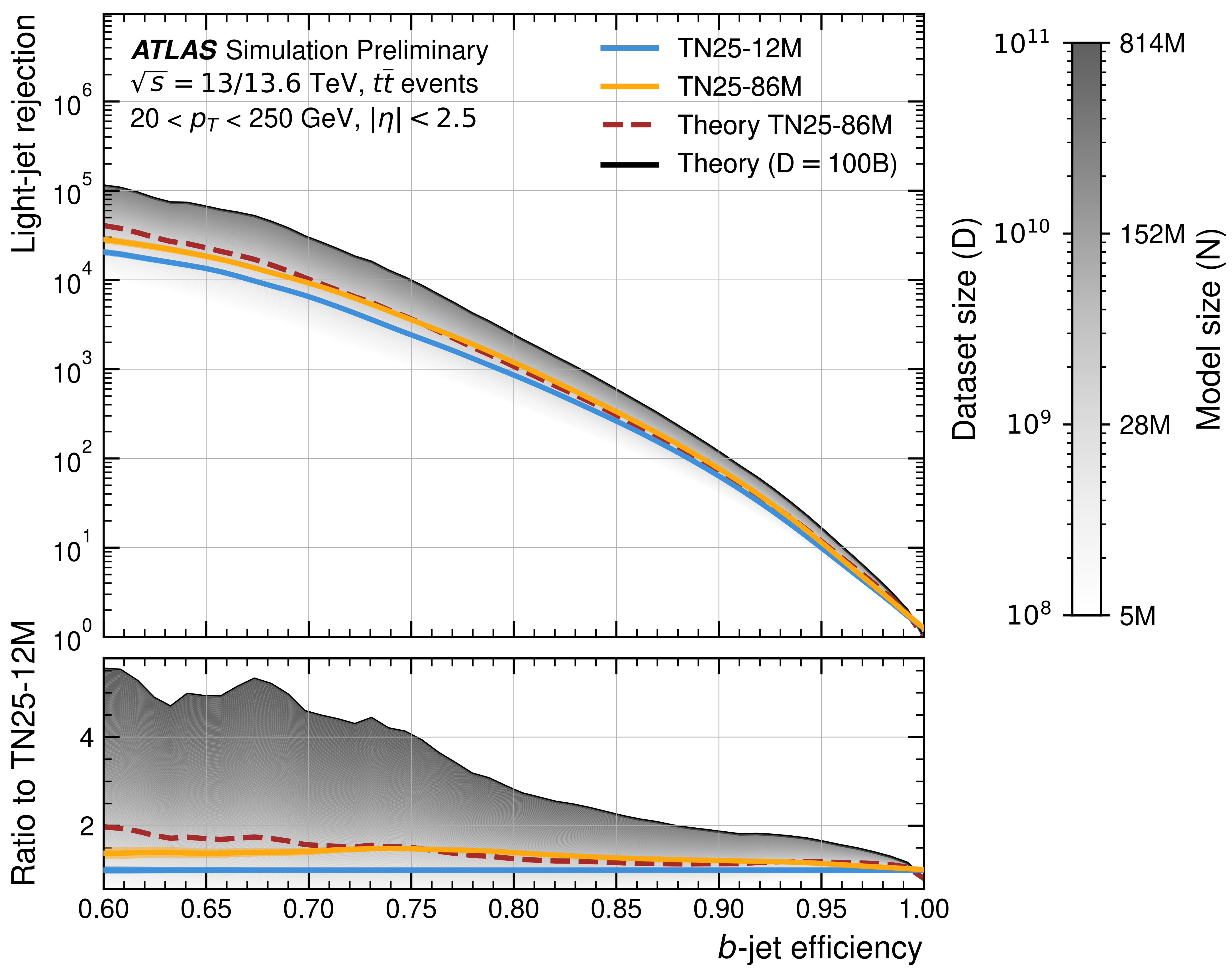
- From DL1 (high-level inputs) to transformers on all tracks: GN2 [Nature Commun. 17 (2026) 541] and GN3 [ATL-PHYS-PUB-2026-001]
  - **At the same 70% b-efficiency**: ×7.9 c-jet and ×4.6 light-jet rejection (GN3 vs DL1d, simulation)
  - **Confirmed in data**: GN2 vs DL1d after calibration gives ×3.5 c-jet and ×1.8 light-jet rejection
- **In our analyses**: DL1 for Run 2 → GN2 for Run 2 + partial Run 3 (incl. $t\bar{t}H(c\bar{c})$) → GN3 for full Run 3
- **F9 contribution**: c-jet calibration in the GN2 paper (Zoja Rokavec)



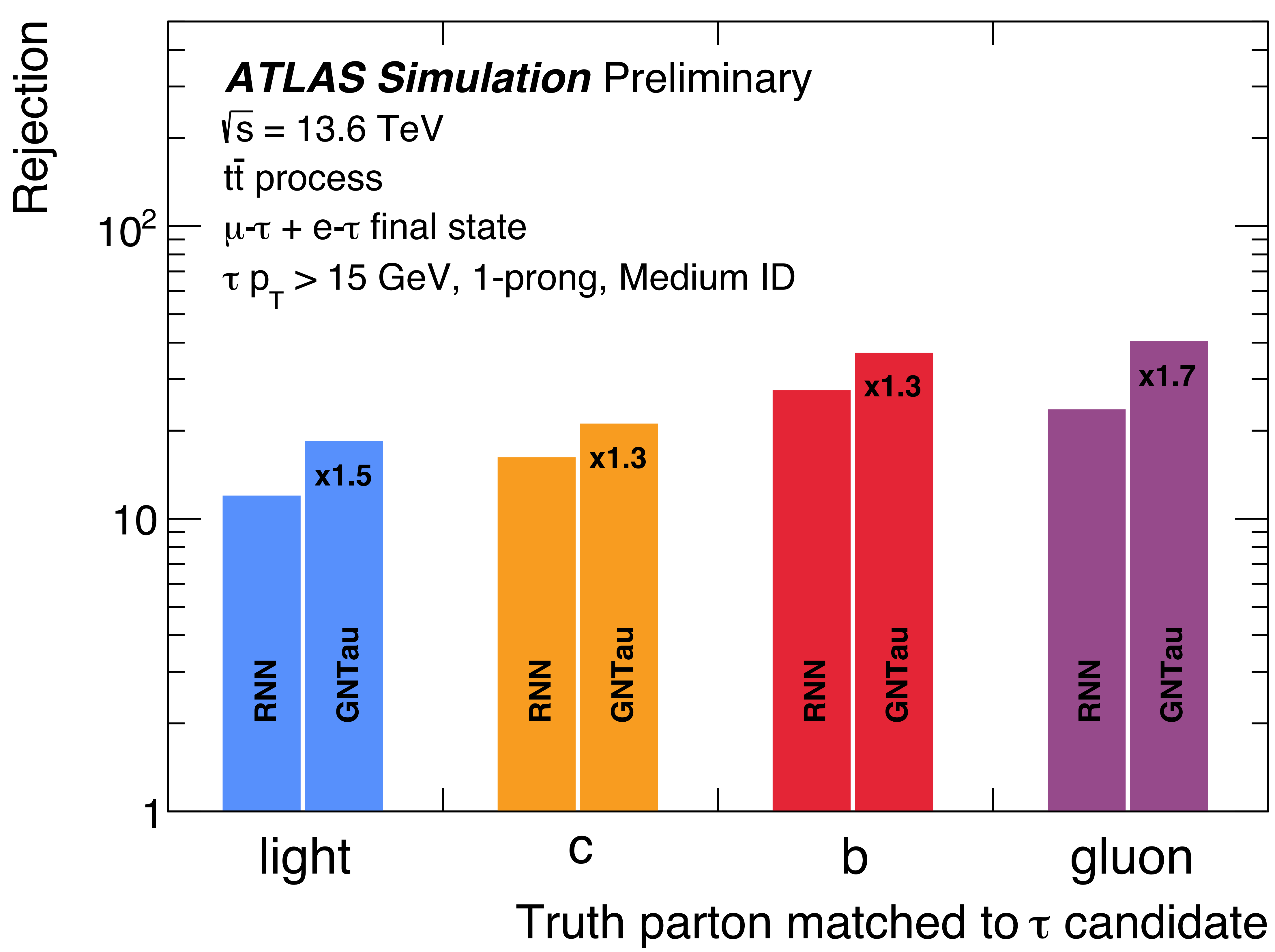
Flavour tagging follows scaling laws — like large language models

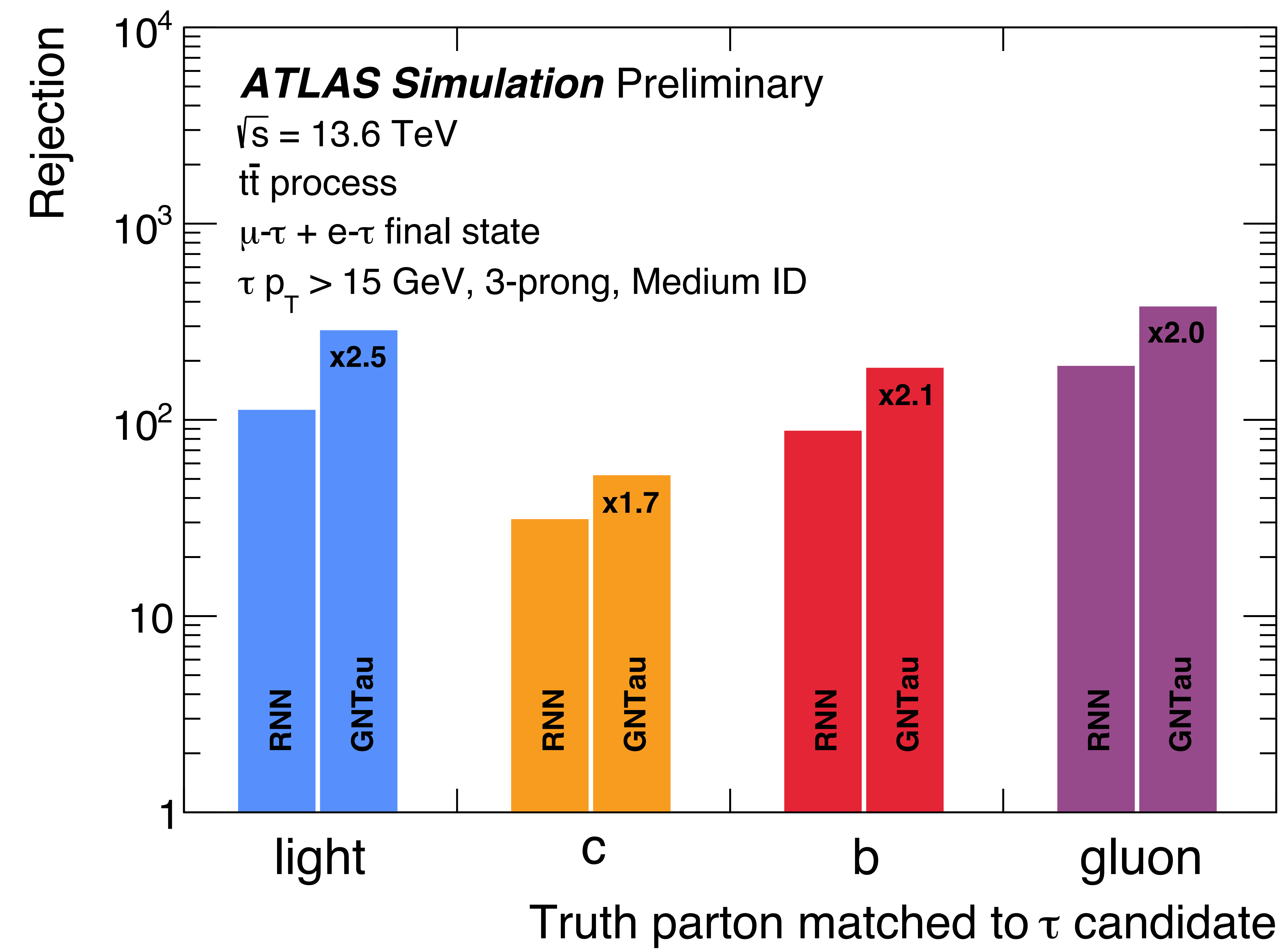
- ATLAS studied how transformer taggers scale with model size, training data and compute [ATL-SOFT-PUB-2026-002 "Carpe Datum"]
- The test loss falls as a power law in the number of training jets
- 86M-parameter model trained on 7.7B jets vs the 12M / 417M baseline: ×1.4–1.5 more rejection
- **Not saturated**: billion-parameter models on trillions of jets are expected to give order-of-magnitude gains
  - The bottleneck is simulated training data and compute





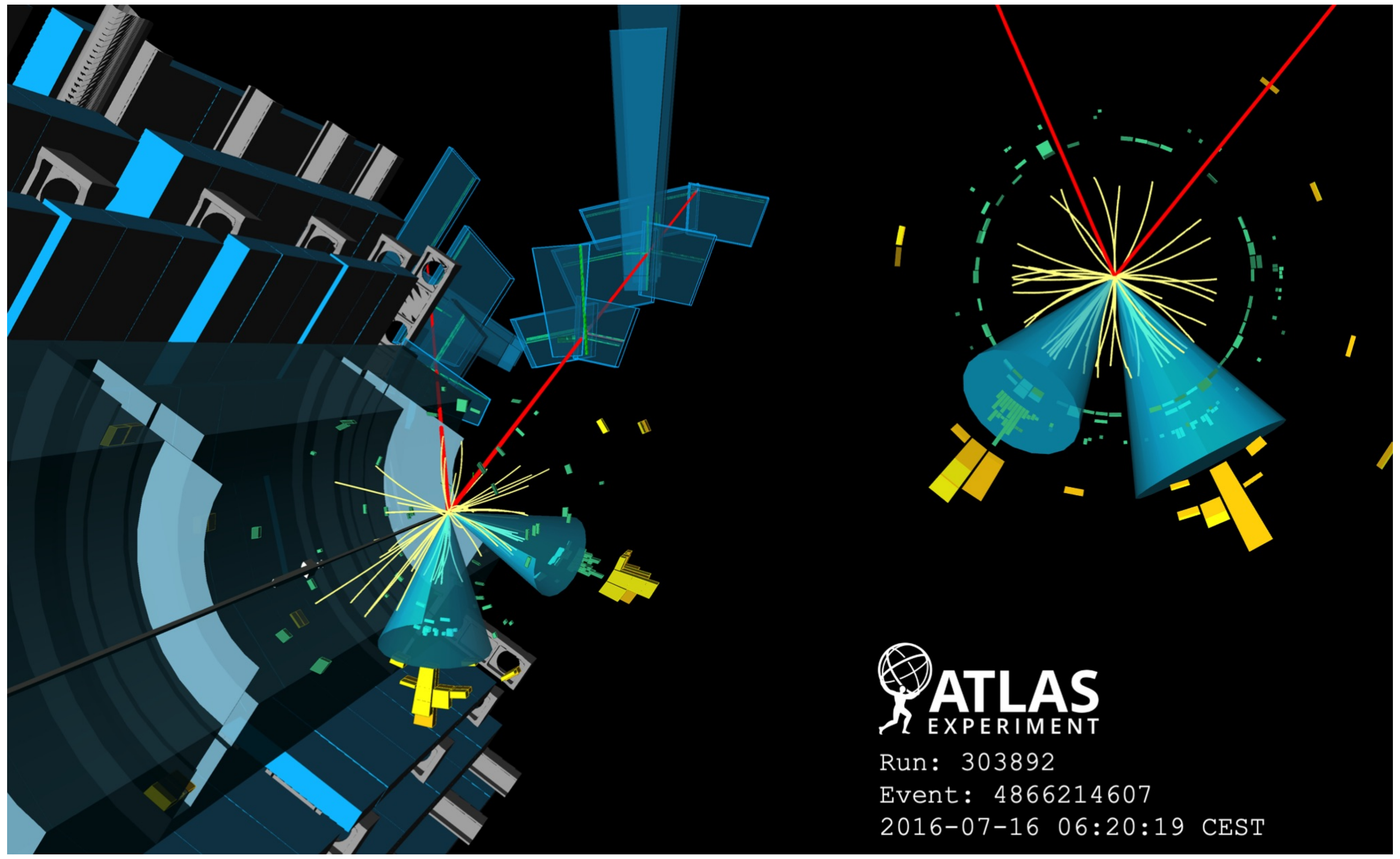
- Hadronic τ decays (65%) give narrow jets with 1 or 3 tracks — easily faked by quark and gluon jets
- **GNTau**: hybrid graph transformer inspired by GN2, replaces the RNN-based tau ID [TAUP-2026-01]
  - Same τ efficiency: ×1.4–1.8 (1-prong) and ×2.0–3.5 (3-prong) more light-jet rejection
  - More robust against pile-up; first physics use in $t\bar{t}H/tH(\tau\tau)$ [arXiv:2607.27276]
- Better b, c and τ tagging from the same data ⇒ this is where our group focuses
- **Possible next development**: one tagger for b, c and hadronic τ jets — flavour and τ tagging are the same problem

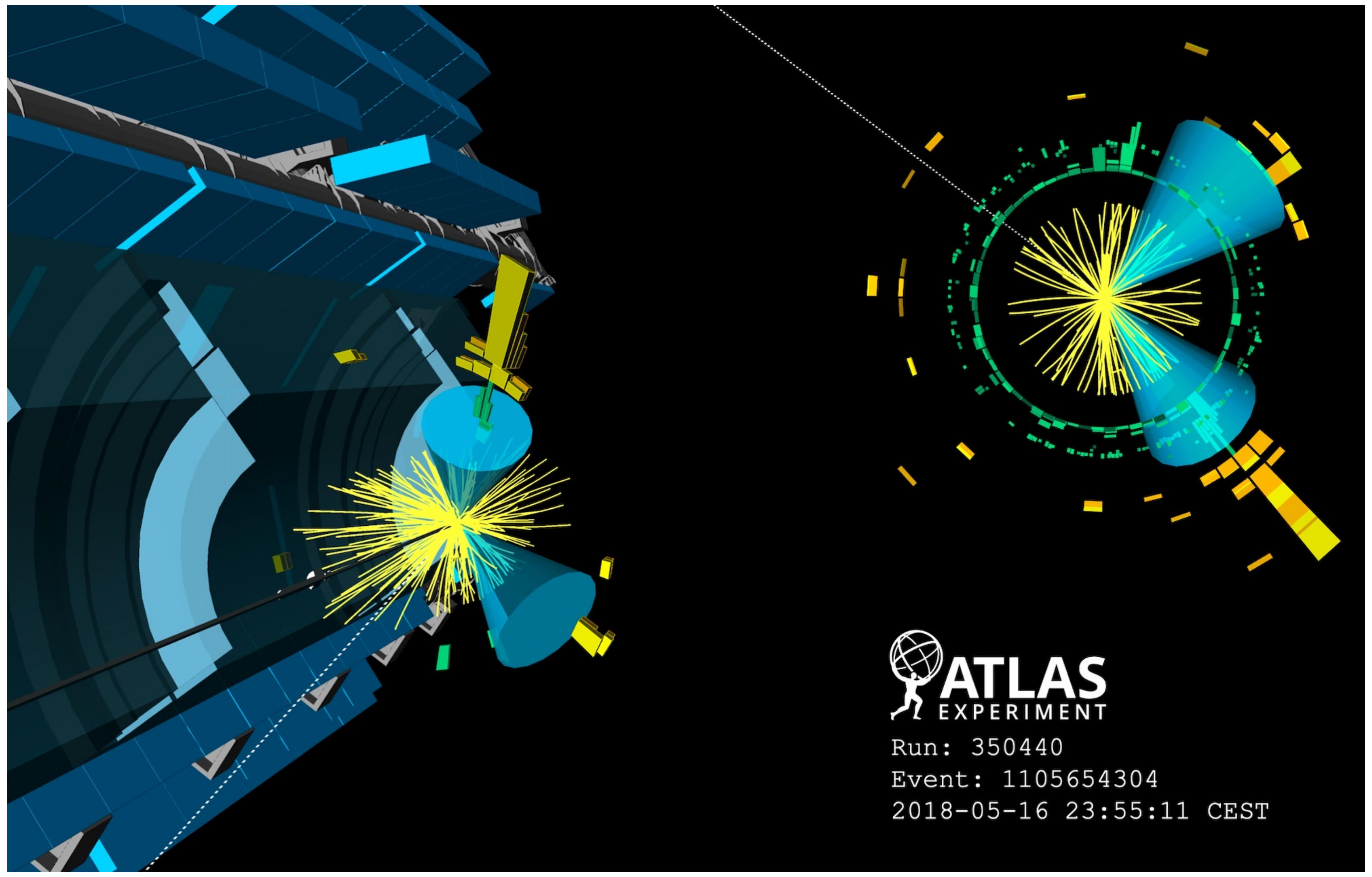




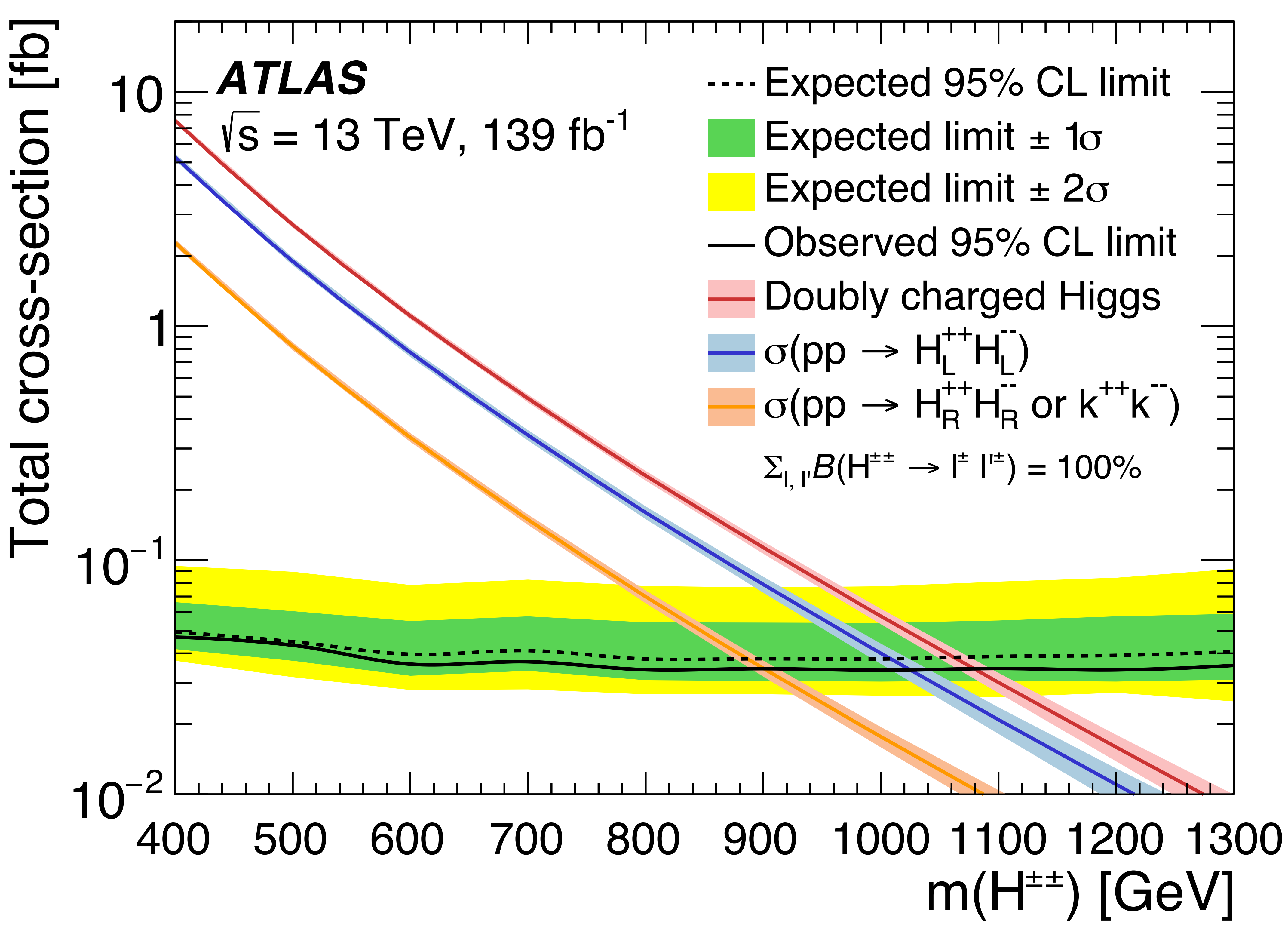
The F9 ATLAS programme: four big questions

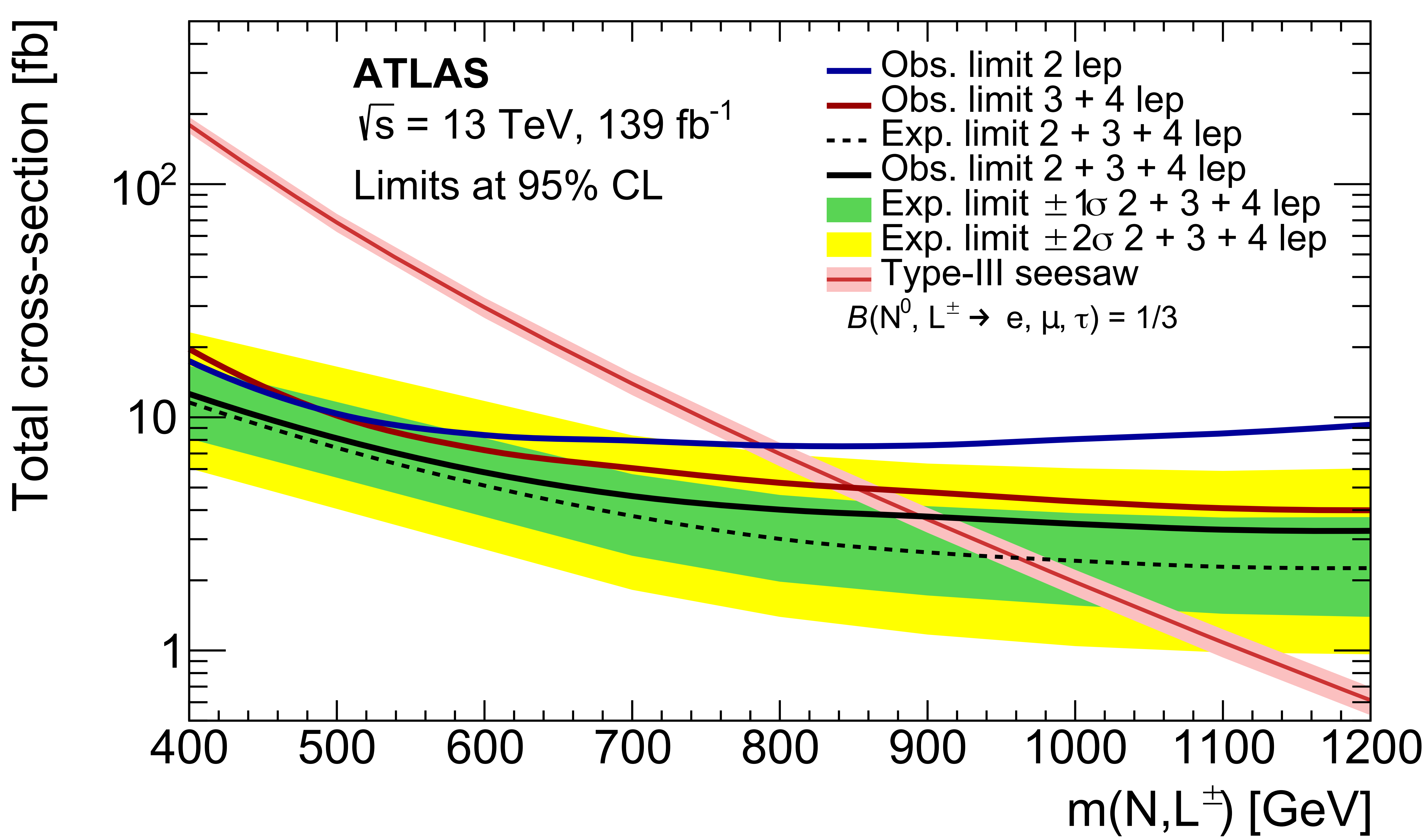
- **Where do neutrino masses come from?**
  - Seesaw searches — now with hadronic τ
- **Does the Higgs give mass to second-generation quarks?**
  - $t\bar{t}H(c\bar{c})$: closing in on the charm Yukawa
- **How do quarks turn into hadrons?**
  - W+D, charm fragmentation, the new ATLAS Pythia tune
- **Is the 20-year-old LEP b-quark anomaly real?**
  - Z+c and Z+b asymmetries with charge tagging
- **Common enablers**: ML tagging, event classification and our own software



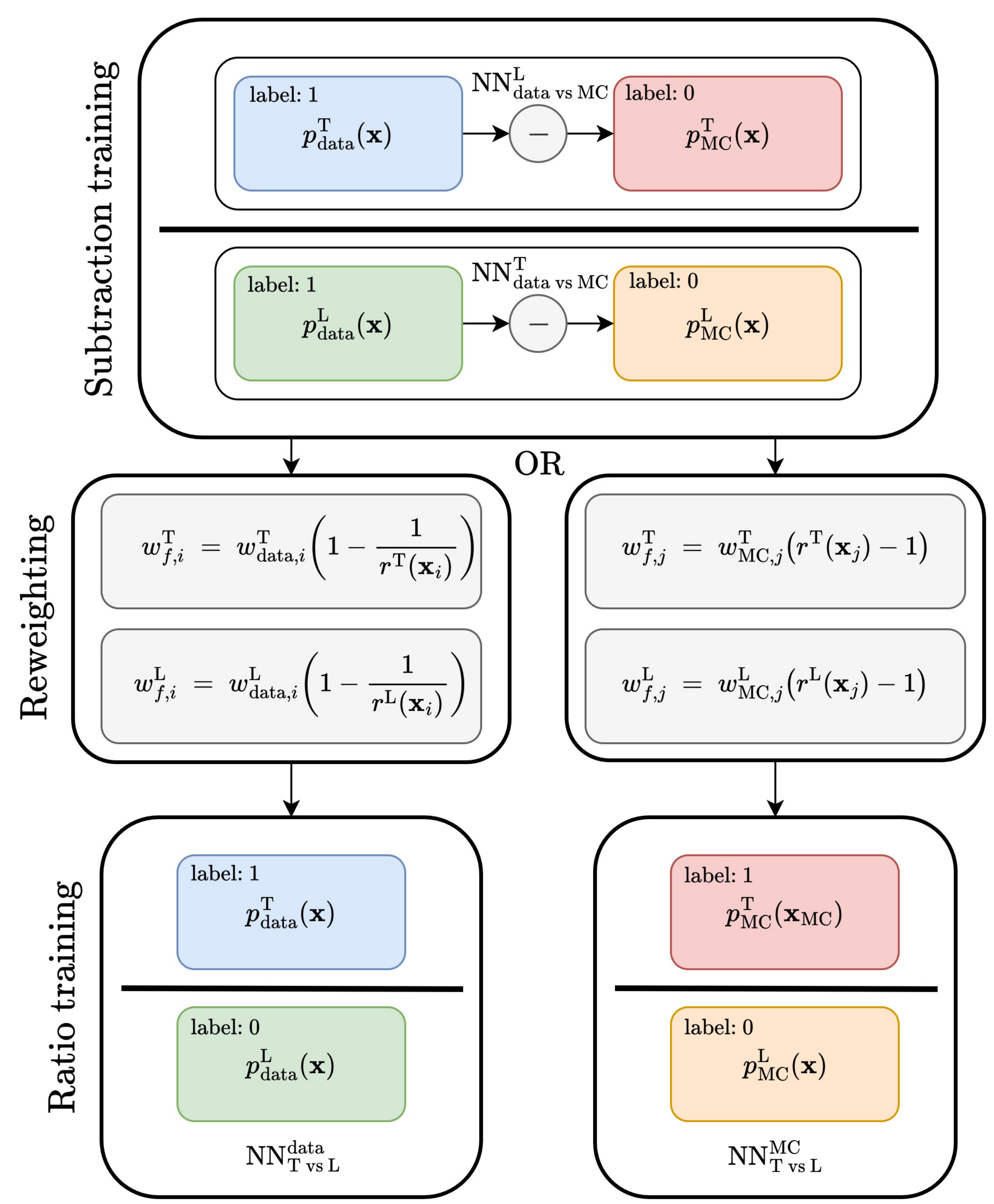


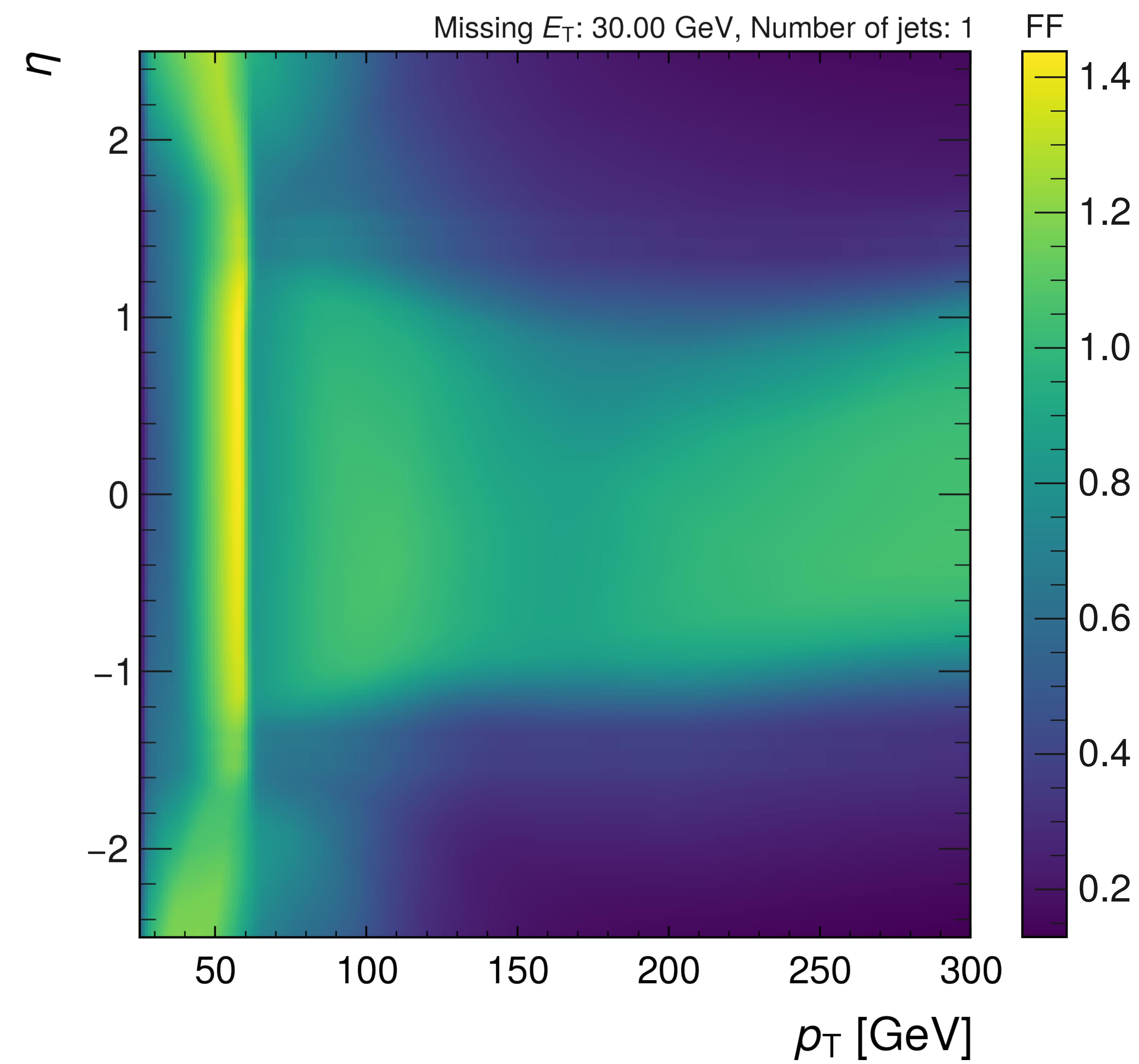
- Seesaw mechanisms explain tiny neutrino masses with new heavy states
  - **Type-II**: a scalar triplet with a doubly charged Higgs, H±±→ℓ±ℓ'±; type-III: heavy leptons N^0, L±
- A long-standing F9 speciality, most searches led from Ljubljana (analysis contacts and editors)
  - H±±: 36 fb^{-1} [EPJC 78 (2018) 199] and full Run 2, m(H±±)>1080 GeV [EPJC 83 (2023) 605]
  - Type-III: 2ℓ [EPJC 81 (2021) 218] and 3/4ℓ combination, m(N^0,L±)>910 GeV [EPJC 82 (2022) 988]
  - Heavy Majorana/Dirac neutrinos and W_R, 36 fb^{-1}: m(WR) up to 4.7 TeV excluded [JHEP 01 (2019) 016]





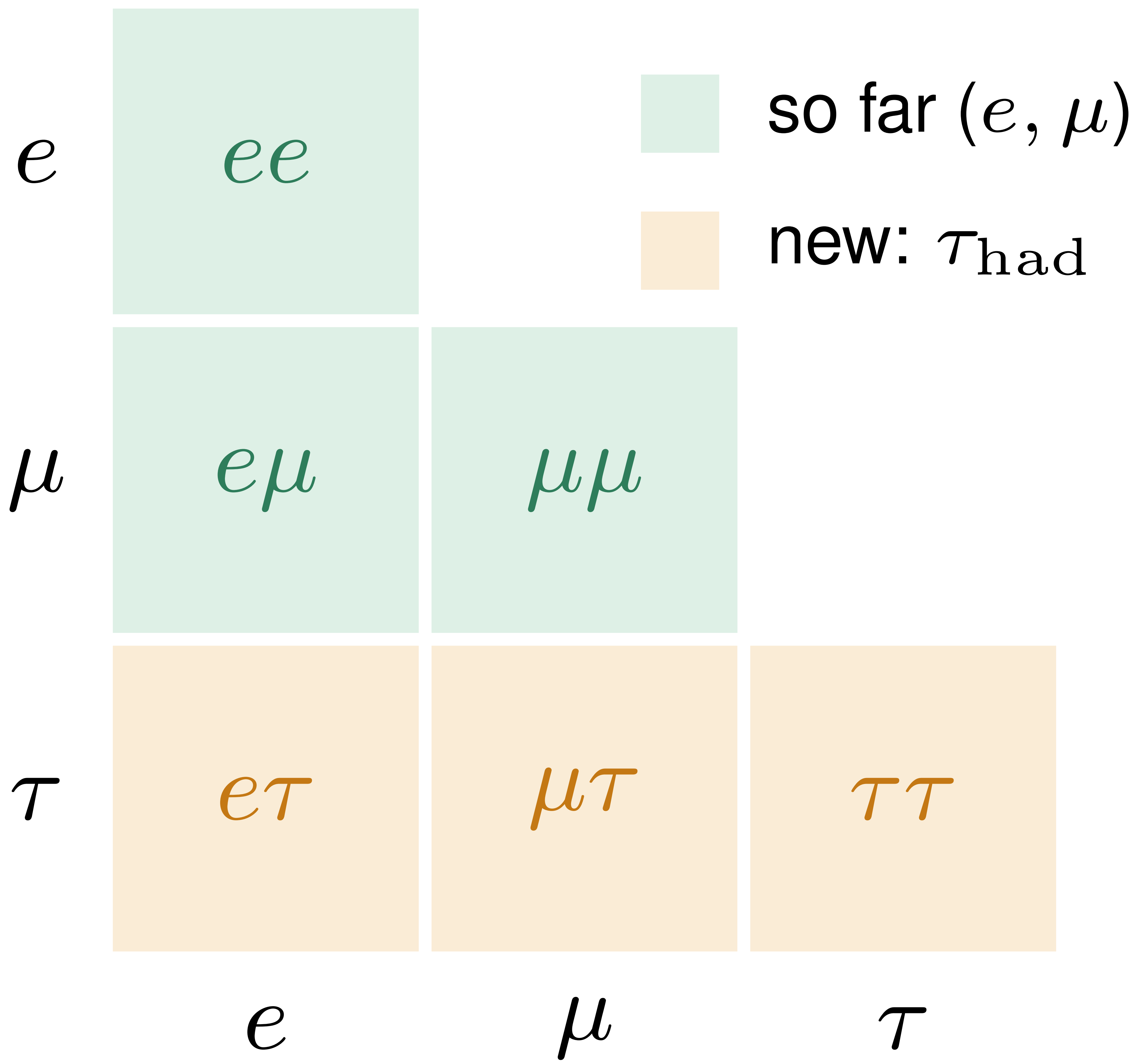
- Fake and non-prompt leptons are the key background in same-sign and multilepton searches
- Classic fake-factor method: ratio of tight to loose leptons in data, in a few bins of p_T and η
- **Neural fake factors**: density-ratio estimation with neural networks trained directly on data
  - Unbinned, per event, in many dimensions; smoother and more stable extrapolation to signal regions
  - J. Gavranovič, L. Čalić, J. Debevc, E. Lytken, B. P. Kerševan [JHEP 04 (2026) 188]
- → Jan Gavranovič, Mon 15:30

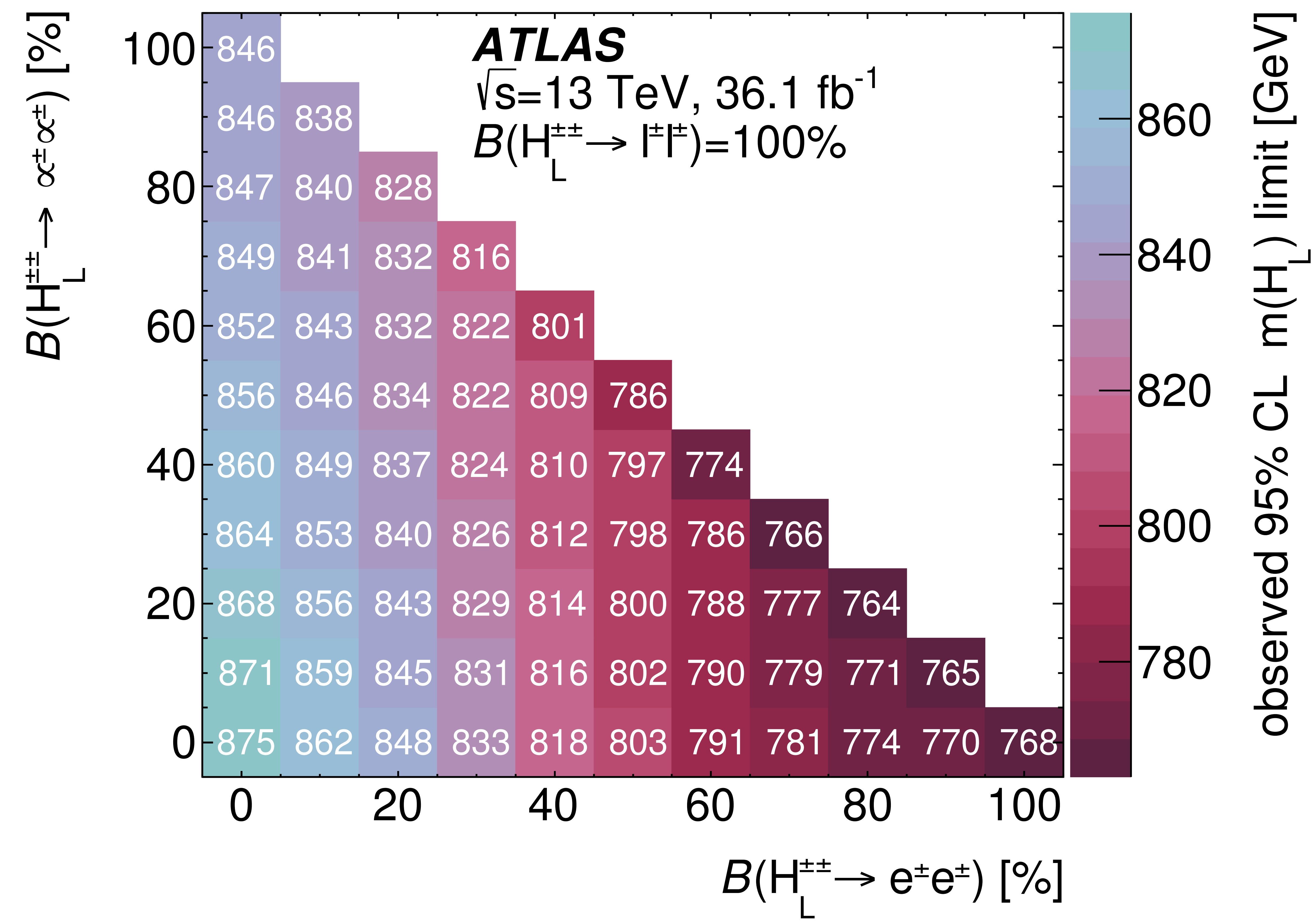




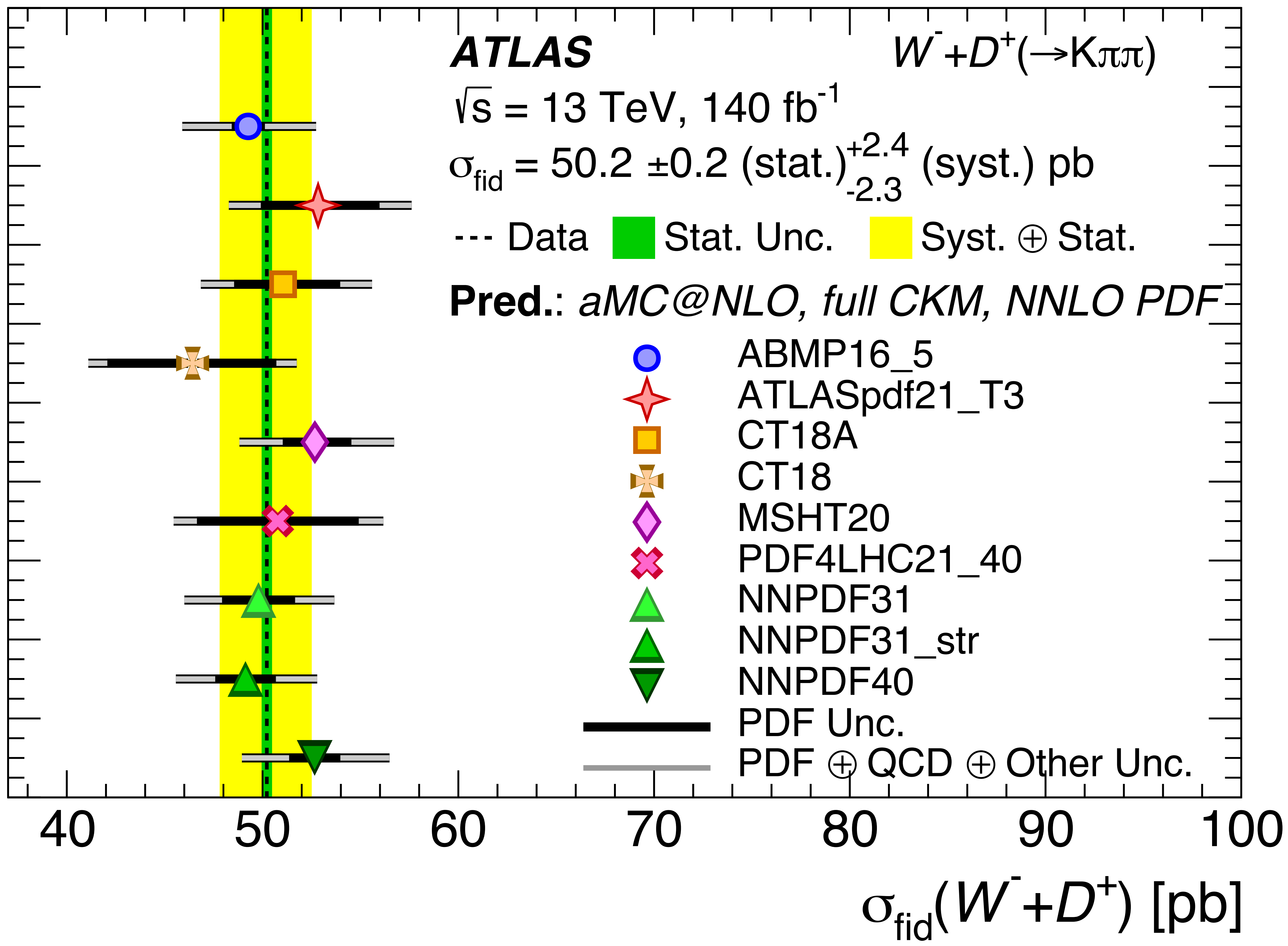
Next: Run 2 + Run 3, now with hadronic τ

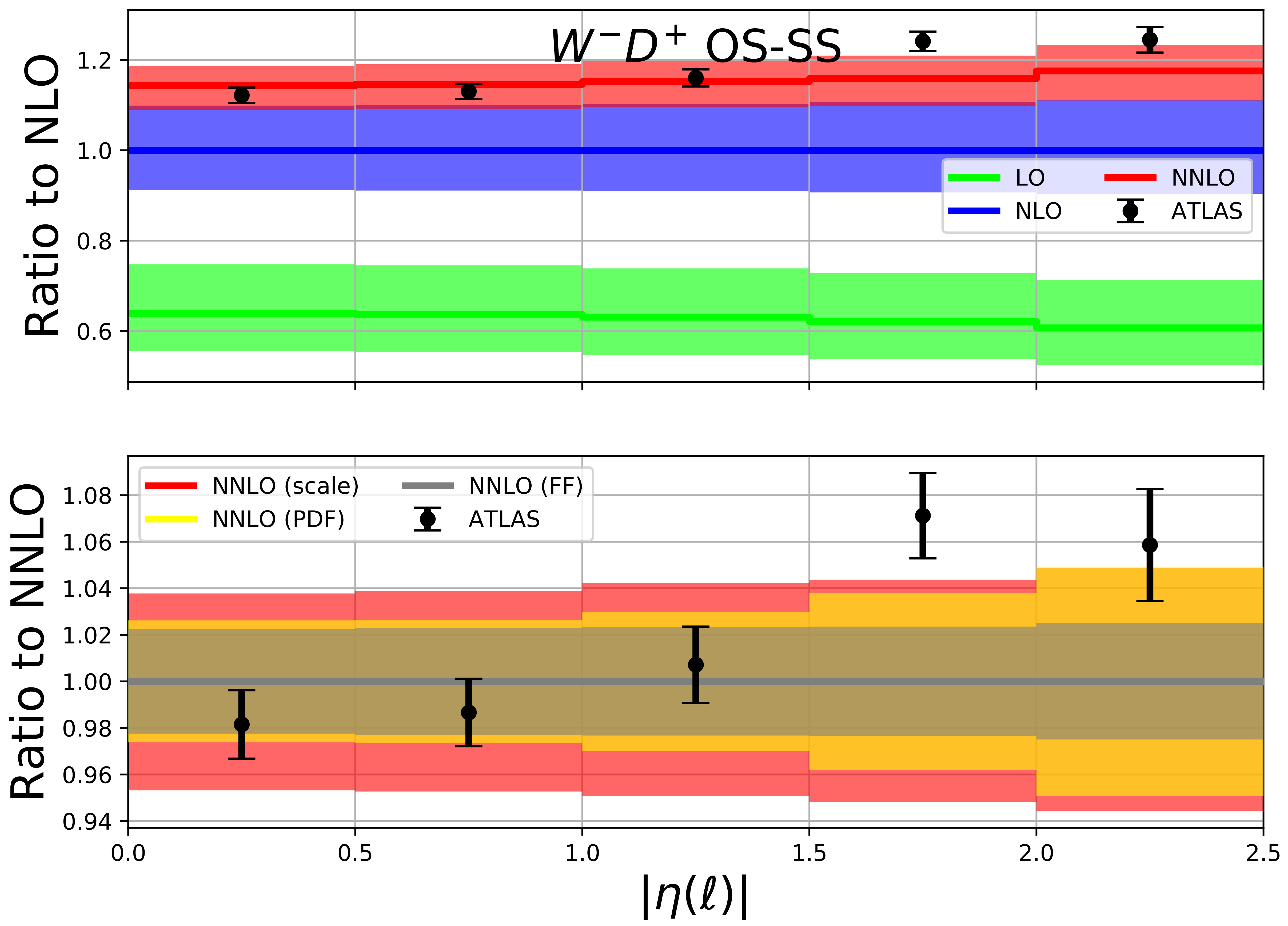
- **Type-II seesaw**: the H±± branching fractions follow the neutrino mass matrix ⇒ sizeable τ channels are possible
- ATLAS seesaw searches so far used only e and μ (τ only via τ→ℓνν): H±± decays to hadronic τ never tested by ATLAS
- **Now**: type-II, type-III and LRSM with Run 2 + Run 3, adding hadronic τ → Jernej Debevc, Mon 15:45
- **Complementary to Belle II**: rare τ→ℓℓℓ probe the EFT, ATLAS the UV-complete theory (the H±± itself)



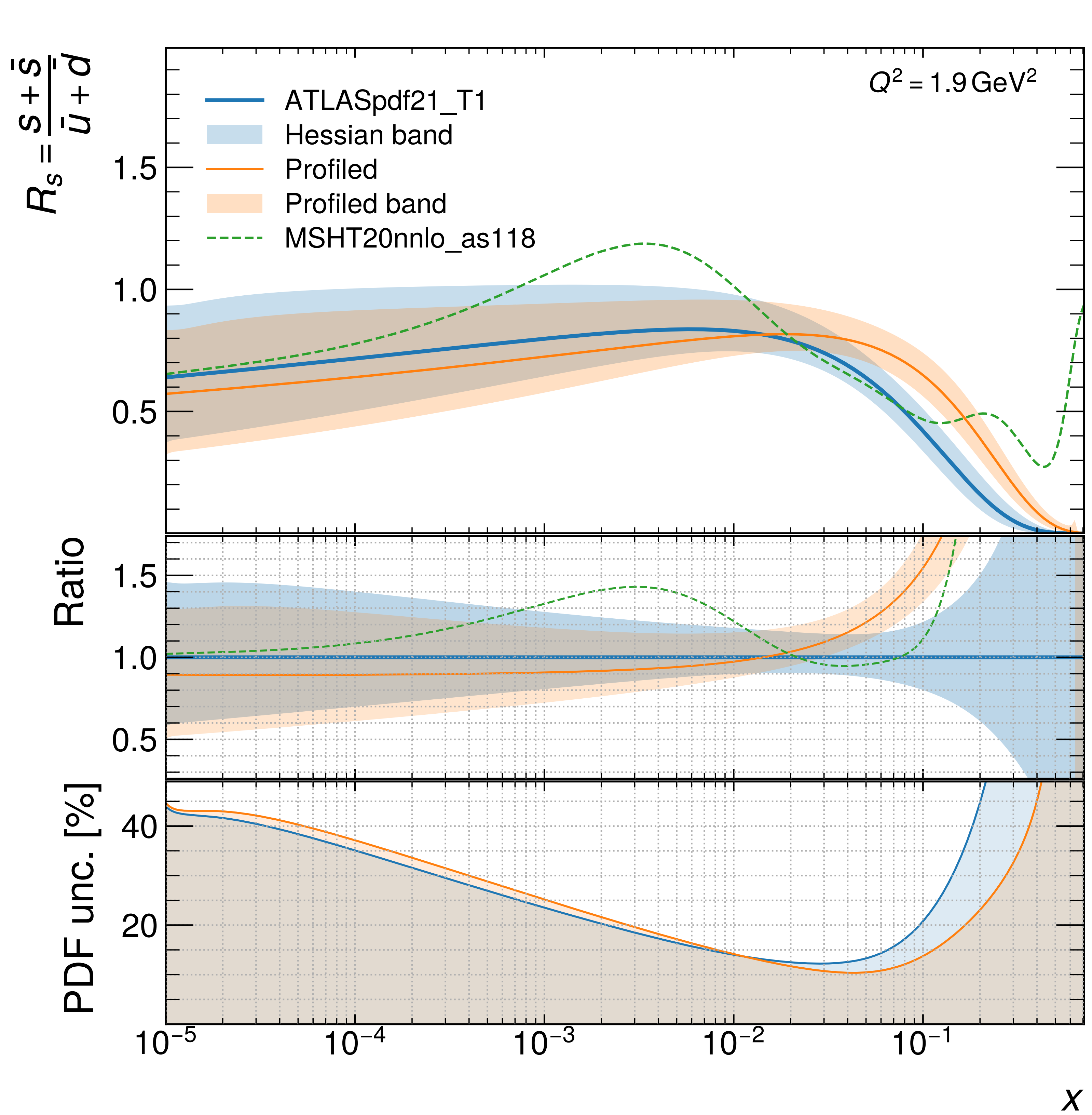


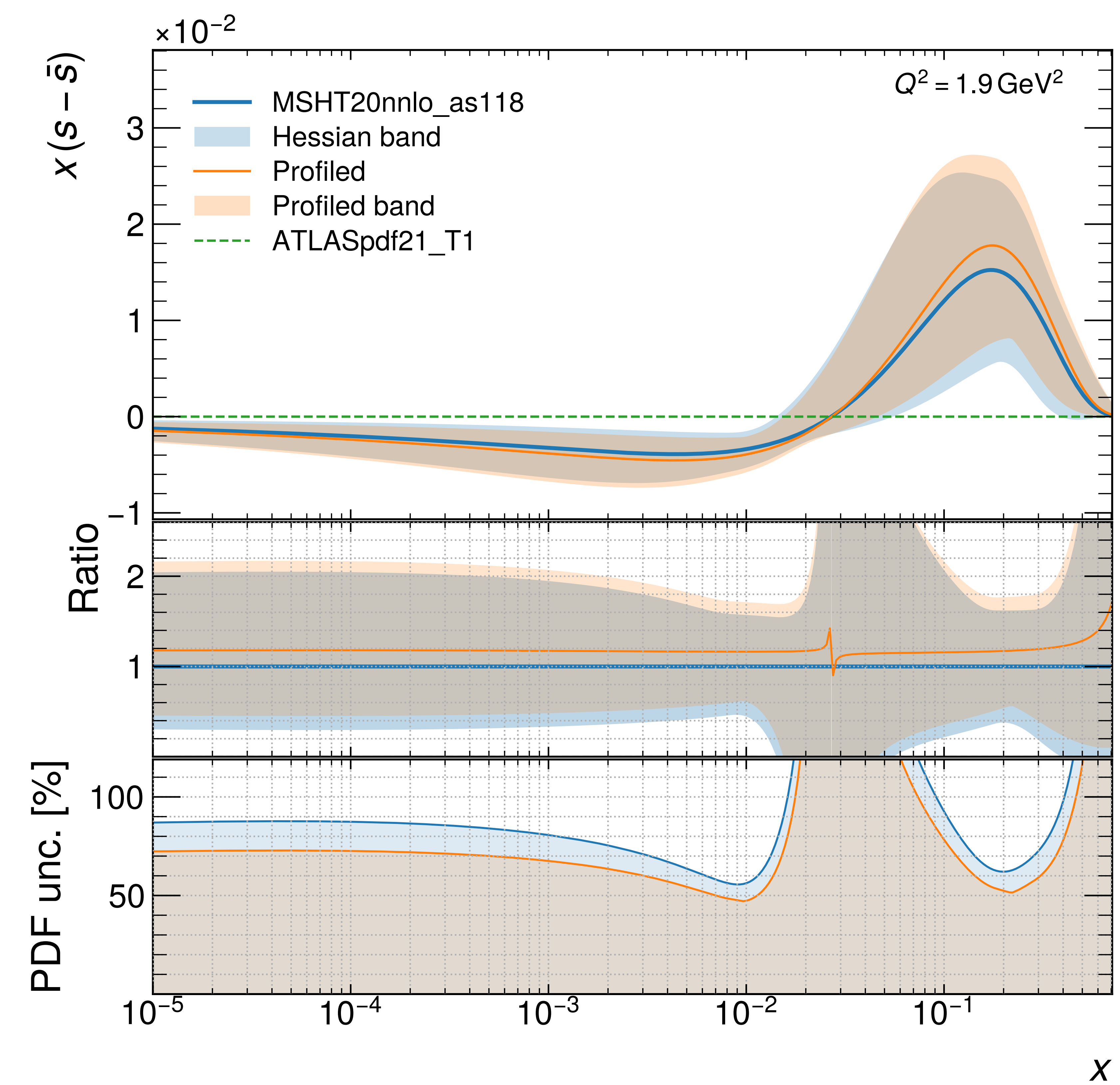
- **W + charm is produced mostly from sg→Wc**: a direct handle on the strange-quark content of the proton
- **ATLAS W+D(*) (analysis led by M.M.)**: charm tagged by fully reconstructing D mesons [PRD 108 (2023) 032012]
  - Opposite-minus-same-sign charge (OS−SS) removes gluon splitting and other charge-symmetric backgrounds
  - $R_c^{\pm}=\sigma(W^+D^-)/\sigma(W^-D^+)=0.971\pm0.013$ probes the s–s̄ asymmetry
- Precise enough to discriminate between PDF sets — but needs NNLO theory



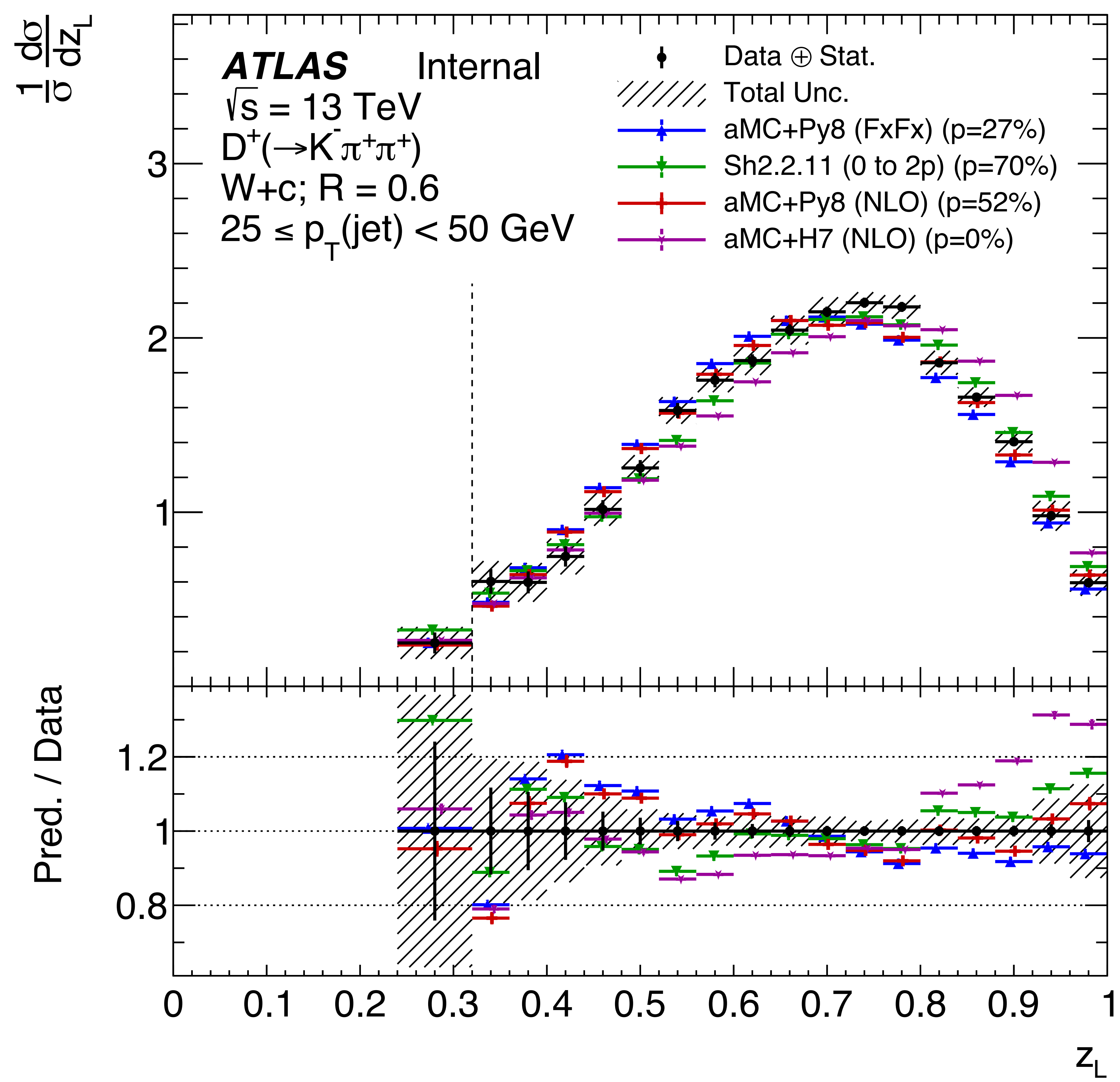


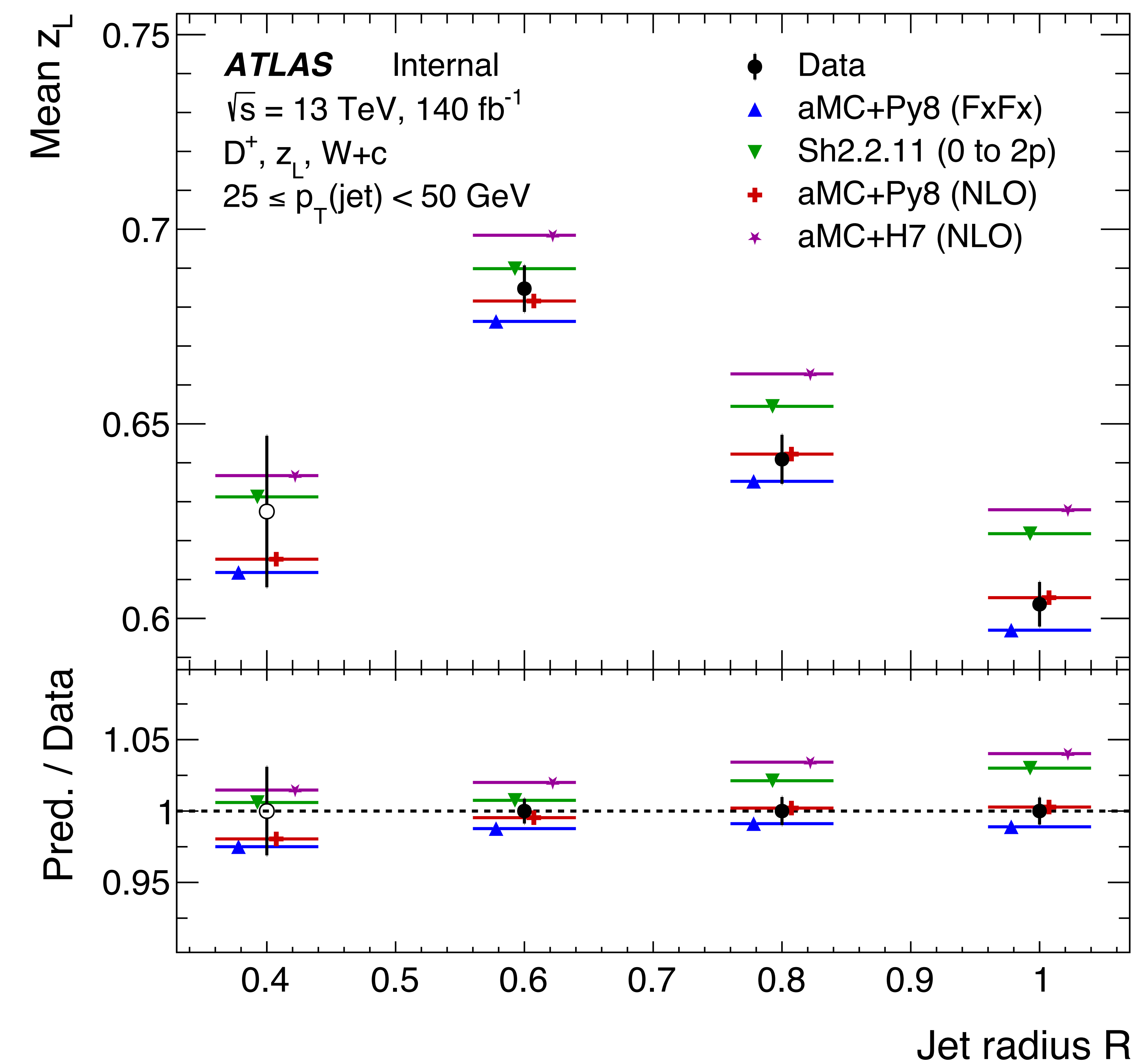
- **First differential NNLO QCD predictions for W± D(*)∓** — T. Generet, R. Poncelet, M.M. [JHEP 02 (2026) 023]
  - Scale uncertainty from ±10% (NLO) to ±5%; better description of the ATLAS data
- PDF profiling with the ATLAS W+D data
  - ATLASpdf21: χ^2 from 40.4 to 21.2 for 18 d.o.f. (p from 0.2% to 27%); strangeness pulled towards MSHT20
  - MSHT20: strange PDFs shifted by up to 20% at x≈0.3–0.4, uncertainties reduced by up to 10%
  - Charge-separated W^+D^- / W^-D^+: sensitive to the strangeness asymmetry $s-\bar{s}$
- First PDF profiling with W+D — promising for global PDF fits





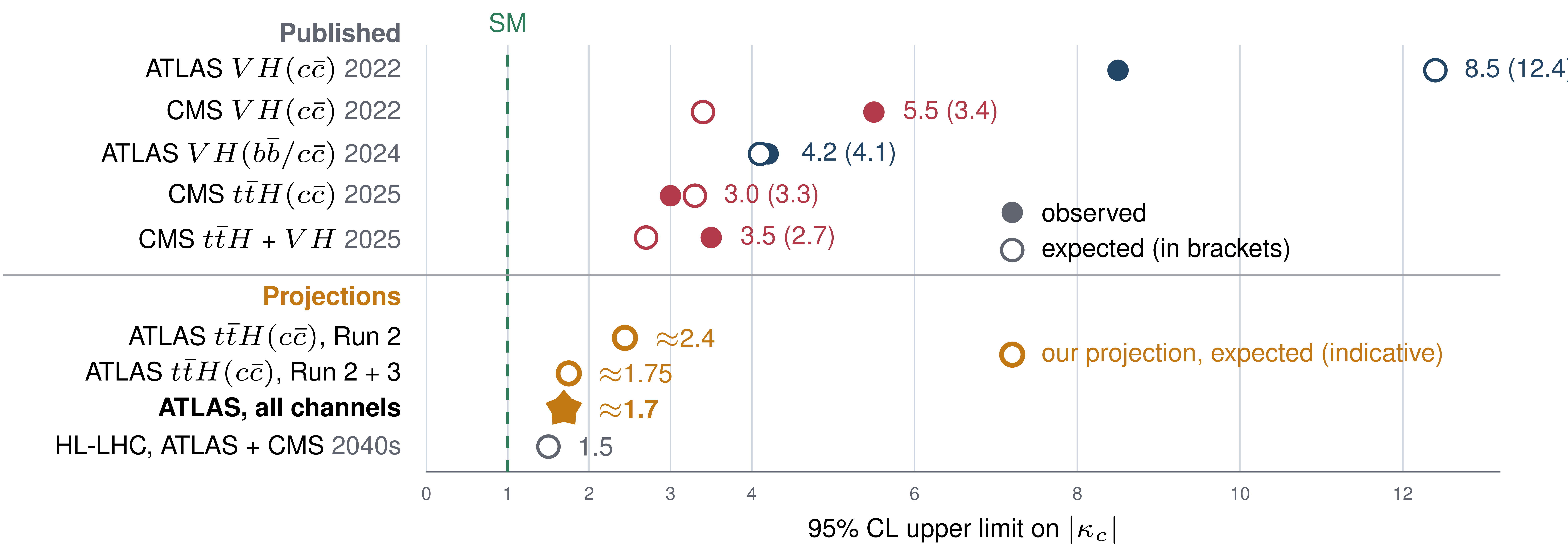
- **Charm fragmentation function**: how much of the charm quark's momentum ends up in the D meson?
  - Observables: zL, zT, pT(rel) of the D meson in jets with R=0.4–1.0, unfolded to particle level
  - OS−SS removes gluon splitting and b jets ⇒ charm from the hard scatter
- **First high-statistics LHC measurement**; complements e^+e^- at the Y(4S) (CLEO, Belle) and the Z pole (LEP)
- **Herwig 7 shower strongly disfavoured**; Pythia 8 prefers its default Bowler–Lund charm parameter
- Key input to the new ATLAS Pythia 8 tune (A26), together with CLEO and ALEPH





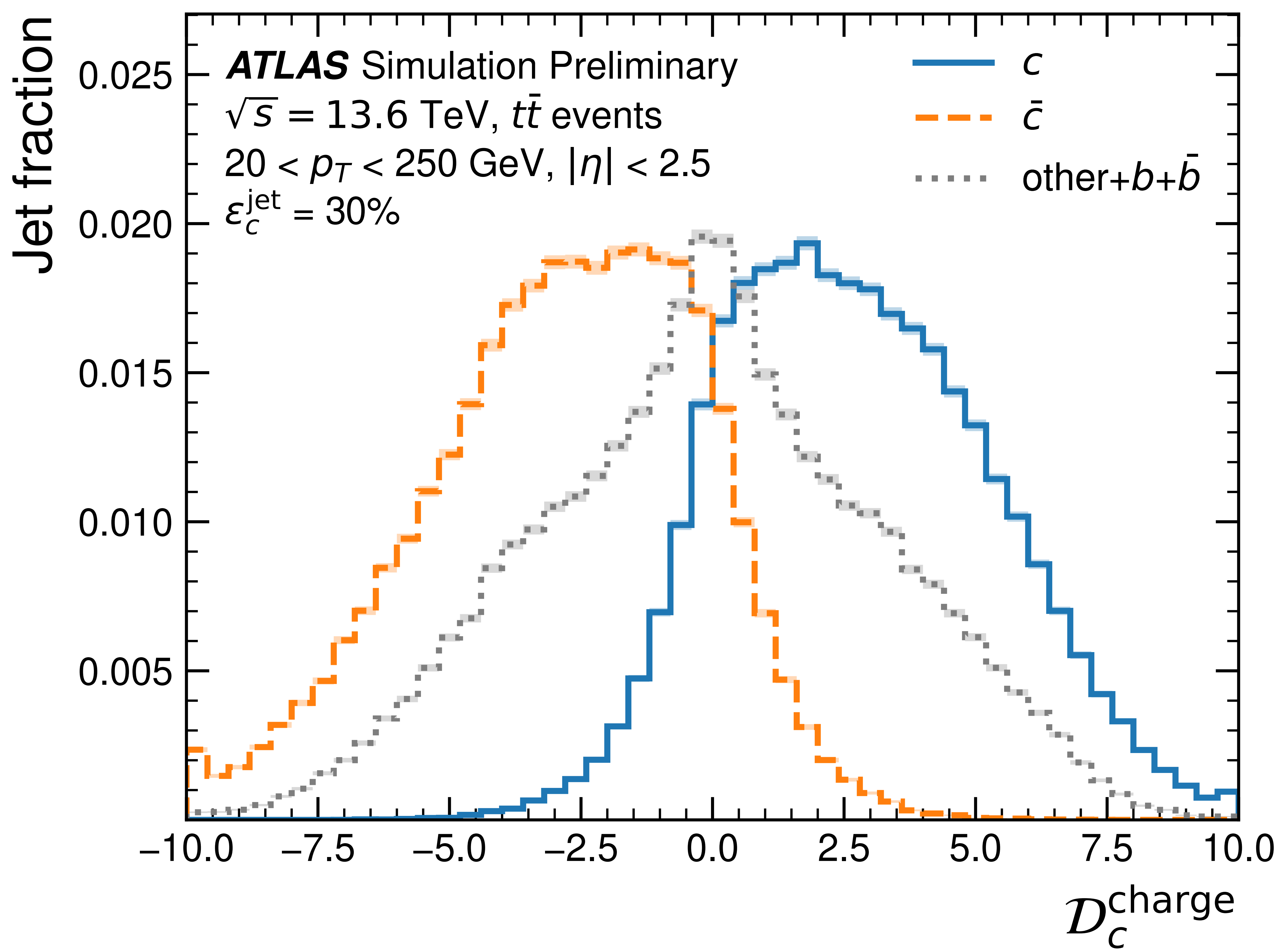
$t\bar{t}H(c\bar{c})$: closing in on the charm Yukawa

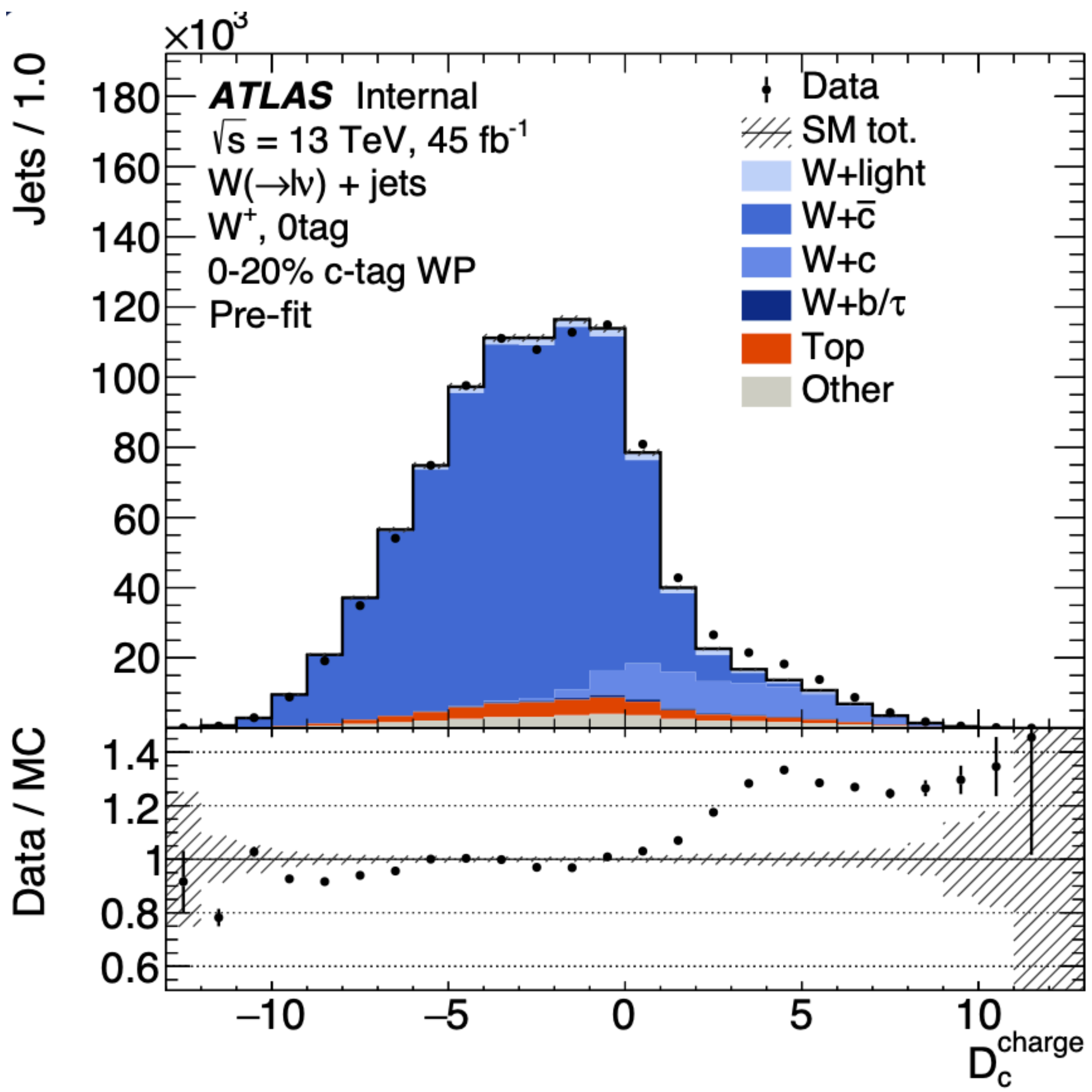
- κ_c: the only second-generation quark Yukawa within LHC reach; since 2018 $VH(c\bar{c})$ was the main channel
  - Now CMS $t\bar{t}H(c\bar{c})$ is the most powerful single channel
- **ATLAS $t\bar{t}H(c\bar{c})$, led from Ljubljana**: transformer event classification on GN2 c-tagging, 0/1/2 leptons
  - **Run 2 alone**: ~40% better than CMS $t\bar{t}H(c\bar{c})$ — then add Run 3 → Zoja, Andraž, Mon 15:00
- All ATLAS channels before the HL-LHC: $|\kappa_c|\approx1.7$ expected — close to the full HL-LHC projection (1.5)



Next frontier: telling c from c̄, jet by jet

- New ATLAS transformer tagger identifies the charge of heavy-flavour jets: c vs c̄, b vs b̄ [ATL-PHYS-PUB-2026-005]
  - GN3 with electron inputs and the jet charge as an extra training target
- At 30% c-tag efficiency, keeping half of the c jets lets through only ≈1% of c̄ jets
- Charm works best: b-hadron decays through charm dilute the b charge
- CMS has a similar tagger [CMS-DP-2025-071]: a new tool for Higgs physics, searches and precision EWK measurements

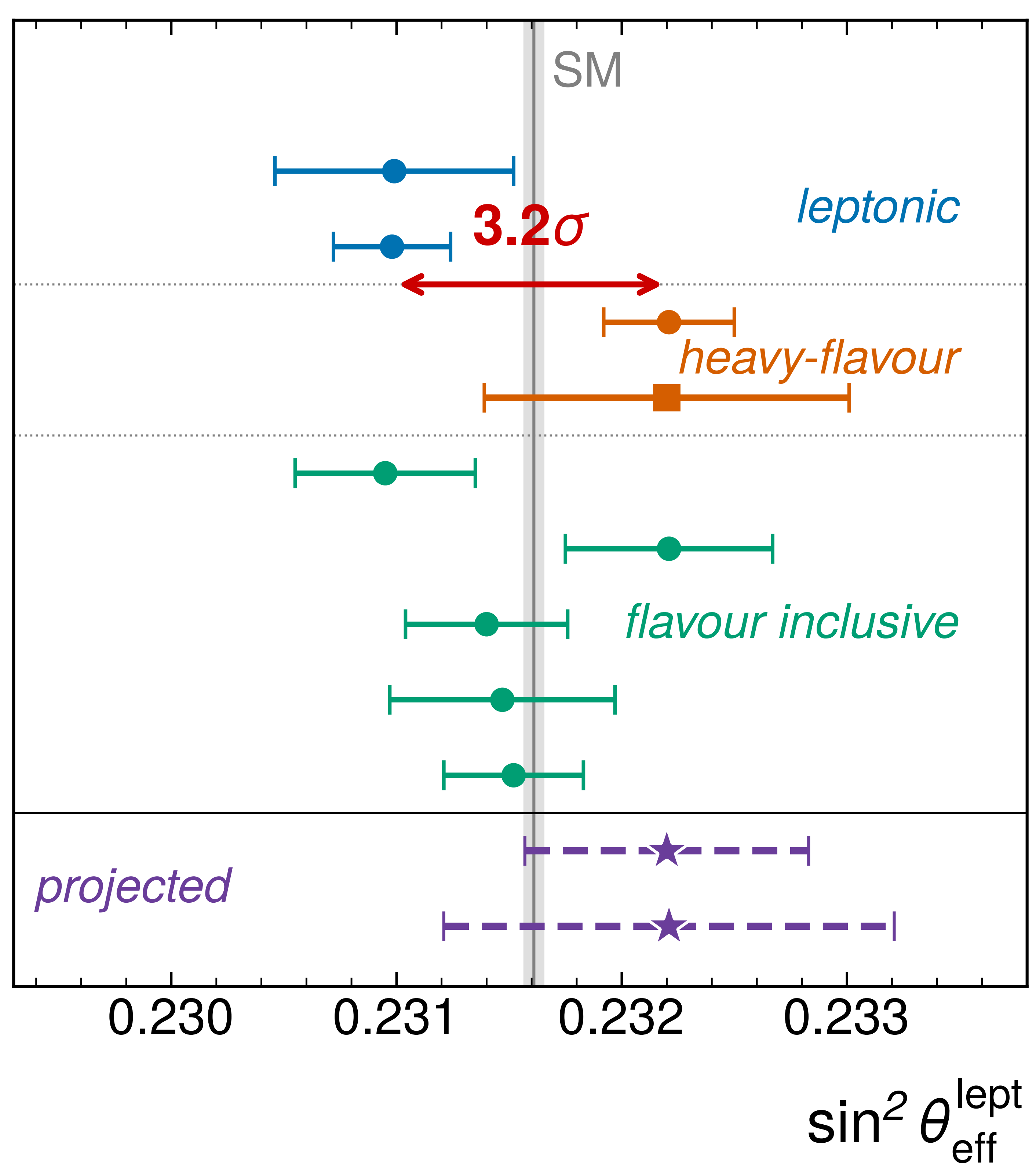


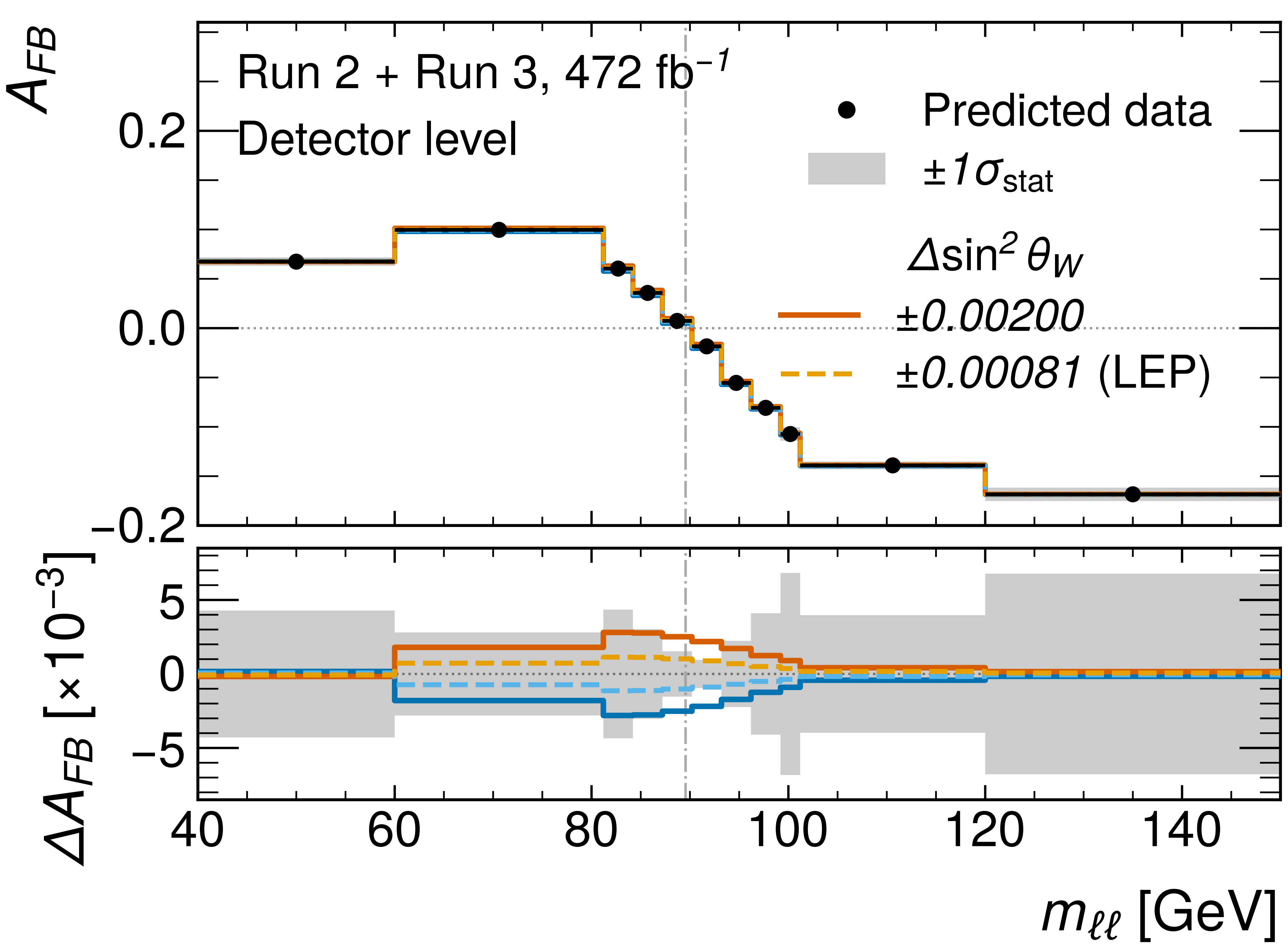


AFBStar: a flavour-resolved forward–backward asymmetry at the LHC

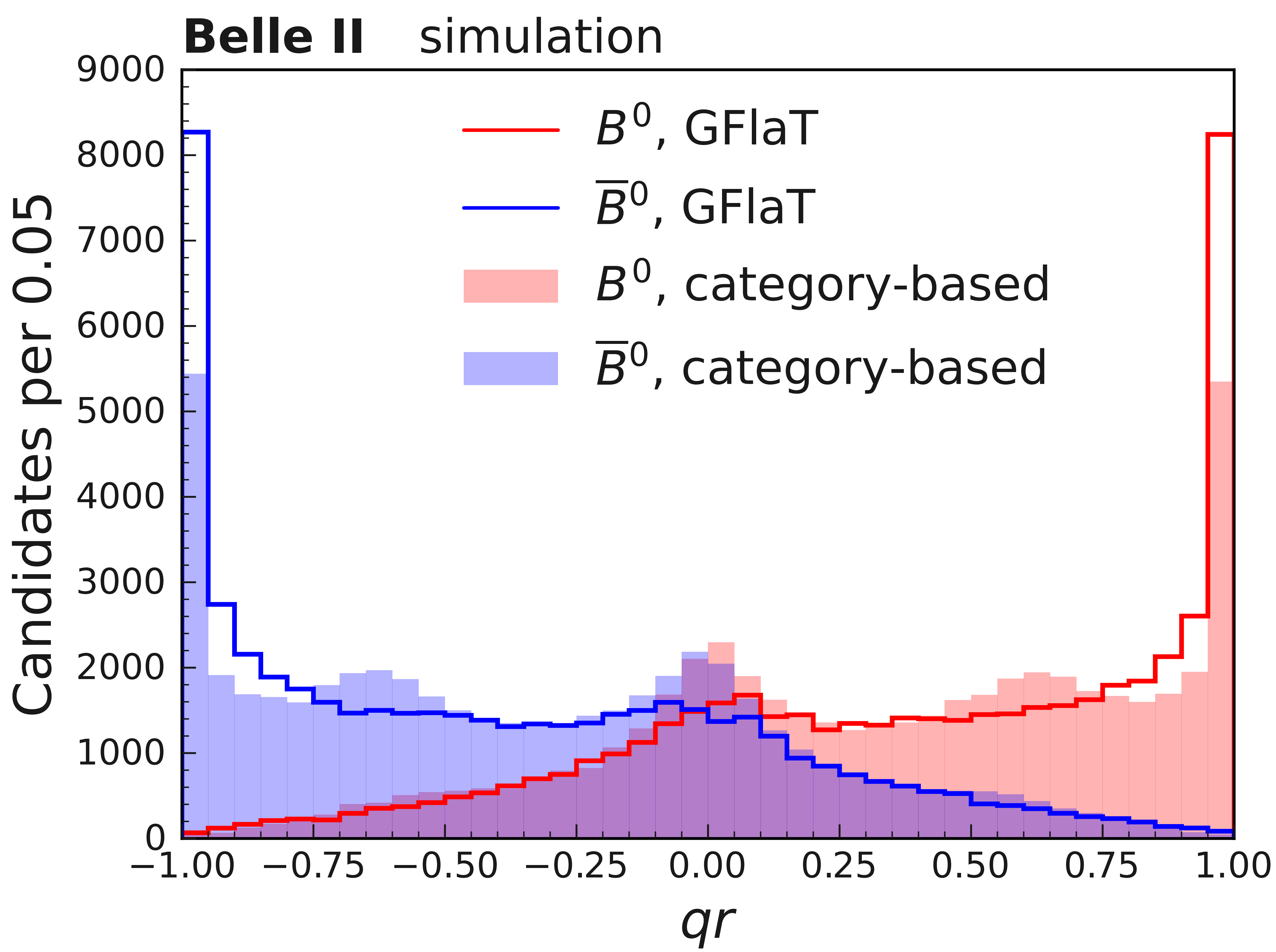
- LEP/SLD: the b-quark forward–backward asymmetry and the leptonic measurements of $\sin^2\theta_{eff}$ differ by 3.2σ
  - Unresolved for 20 years; the charm asymmetry is 3× less precise and was never remeasured
- **New idea**: Z(→ℓℓ)+c-jet, angle between ℓ^- and the jet signed by the jet charge
  - First flavour-resolved AFB measurement at a hadron collider
- **MC projection (full Run 2 + 3, stat. only)**: $\sigma(\sin^2\theta_{eff}) \approx 0.00063$ for charm, below the LEP charm uncertainty (0.00081)
- ERC Starting Grant proposal "AFBStar" (being submitted): Z+c, then Z+b

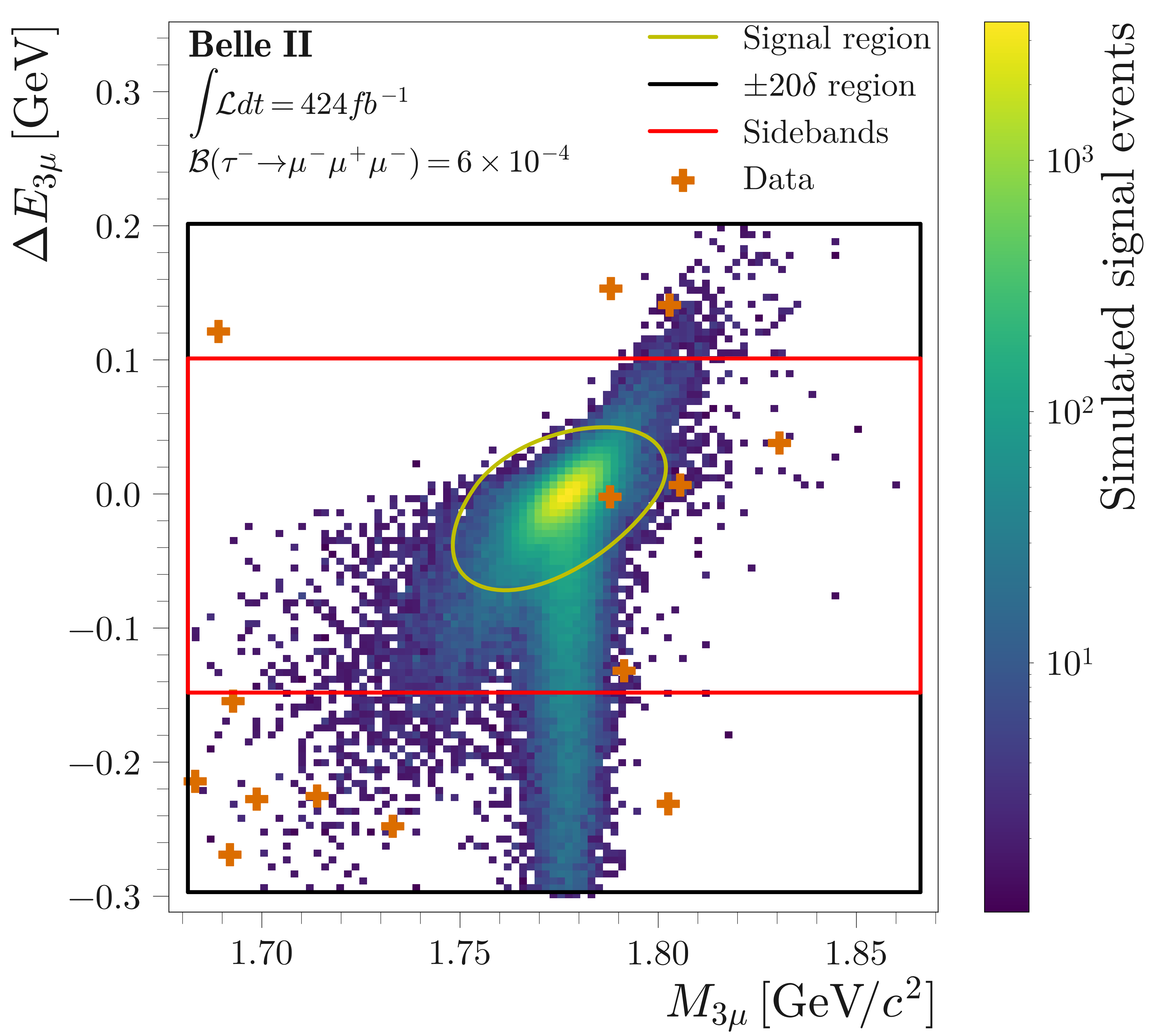
Determination	$\sin^2\theta_{eff}^{lept}$
$A_{FB}^{0,\ell}$ (LEP)	*0.23099 ± 0.00053*
A_ℓ (SLD)	*0.23098 ± 0.00026*
$A_{FB}^{0,b}$ (LEP+SLD)	*0.23221 ± 0.00029*
$A_{FB}^{0,c}$ (LEP+SLD)	*0.23220 ± 0.00081*
D0 ($p\bar{p}$)	*0.23095 ± 0.00040*
CDF ($p\bar{p}$)	*0.23221 ± 0.00046*
ATLAS (pp)	*0.23140 ± 0.00036*
LHCb (pp)	*0.23147 ± 0.00050*
CMS (pp)	*0.23152 ± 0.00031*
AFBStar charm	*± 0.00063*
AFBStar bottom	*± 0.00100*



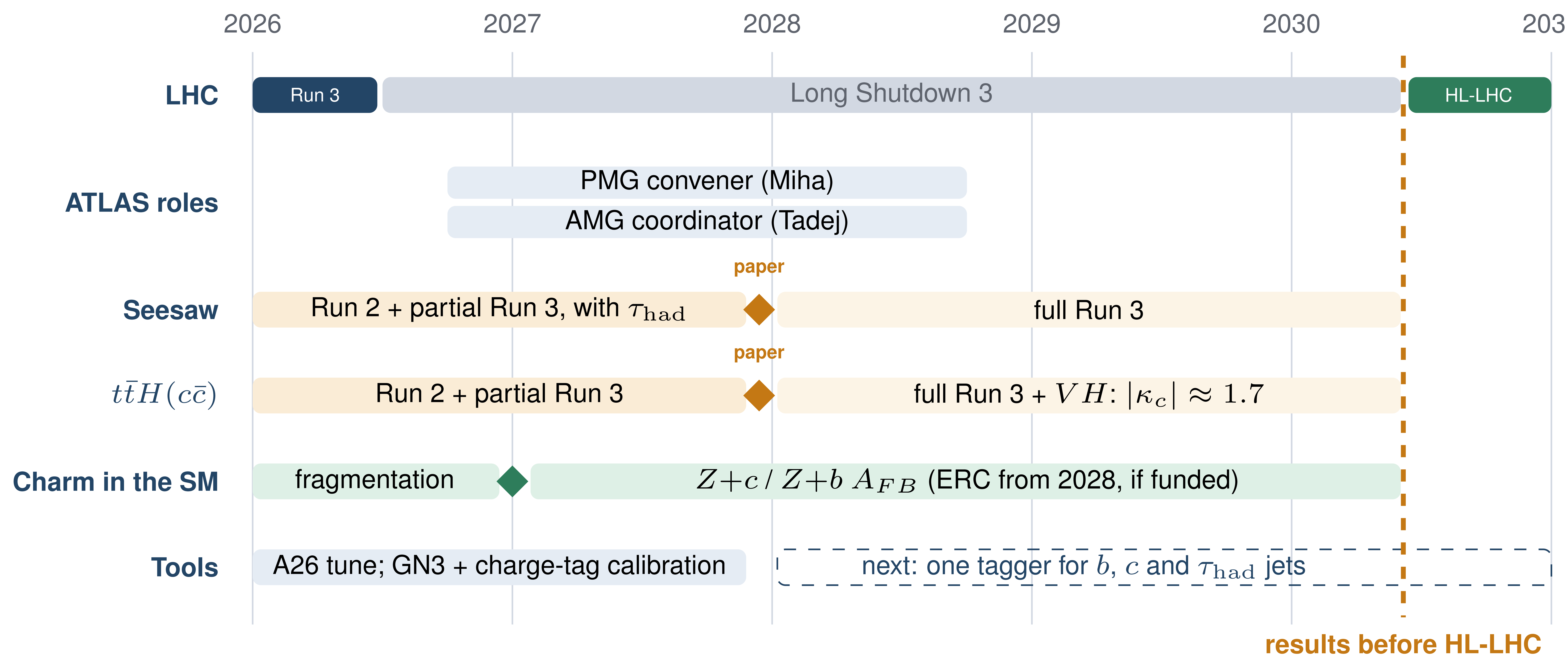


- **Graph networks on all charged particles** — Belle II's GFlaT separates B^0 from $\bar{B}^0$ (18% better effective tagging efficiency) [PRD 110 (2024) 012001]; ATLAS separates c from c̄ jets
- **Charm fragmentation: is it universal?** W+D at the LHC vs $e^+e^- \to c\bar{c}$ at the Υ(4S)
- **Rare τ decays meet the UV completion**: Belle II $\tau \to \ell\ell\ell$ constrains four-lepton EFT operators; in type-II seesaw they come from H±± exchange— ATLAS searches for the H±± itself, now with τ channels
  - Belle II: $B(\tau \to 3\mu) < 1.9 \times 10^{-8}$ [arXiv:2405.07386]
- **Possibility for collaborations?** Shared ML methods, software and computing at F9, joint seminars, …





- **Run 2 + Run 3 data taking done**, four years before the start of the HL-LHC — new reach comes from better tools
- **In 2027**: seesaw (with hadronic τ) and tt̄H(cc̄) papers with partial Run 3
- **Before the HL-LHC**: full Run 3 SeeSaw and tt̄H(cc̄) analysis, first flavour-resolved AFB with Z+c and Z+b, …



End