CZ+SK 2023 HEP workshop
28th - 29th June 2023

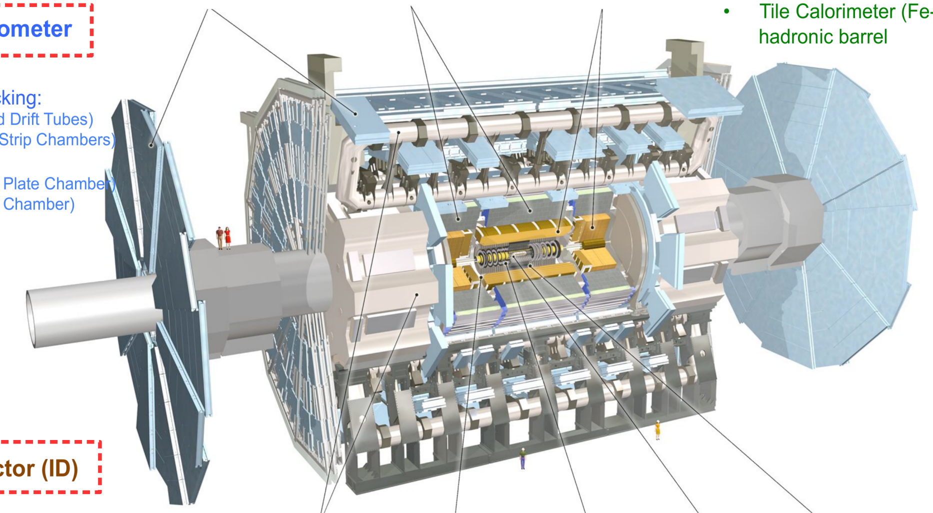
B-Physics Measurements at ATLAS

Pavel Řezníček
(Charles University)

B-Physics & ATLAS

- ATLAS is a general purpose detector, but performance good also for B-physics
  - B-mass resolution ~10x MeV, B-proper decay time resolution ~100 fs
- 40 MHz pp-bunch collisions with ~30 pp interactions producing ~10^6x $b\bar{b}$ / second
  - A B-factory, but with access to B_s, B_c, Λ_b, and other b-hadrons
- To utilize the high x-section, must collect low-p_T data
  - B-p_T ~20 MeV in analyses, low w.r.t. other ATLAS physics

- Program limited by the ability to find the B-decays in data:
  - At trigger => **mostly muonic final states**
  - In reconstructed events => **mostly decays fully reconstructable by ATLAS tracking system**

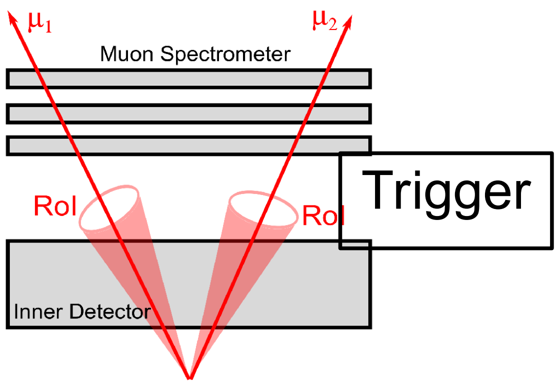


B-Physics Program

Focusing on New Physics searches in promising channels, QCD measurements, new hadron states

- **Rare Decays**
  - Search for New Physics in leptonic and semileptonic decays as $B_s \rightarrow \mu\mu$, $B \rightarrow K^*\mu\mu$, or LFV decays or LFU tests
- **Precision measurements**
  - Search for deviation from SM predictions in B-decays with (relatively) high BR
- **Spectroscopy**
  - Search for new decays, new excited states, penta/tetra-quarks
  - Properties of doubly-heavy decays as B_c
- **Heavy flavour production**
  - Production x-sections of quarkonia, b/c-hadrons
  - Associated quarkonia production

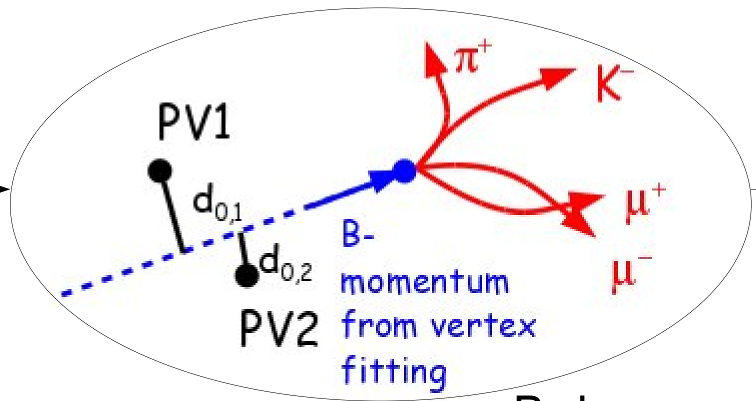
B-Physics Analysis Chain



- Cannot store all B-events, fast pre-selection based on simple signatures of the studied decay channel
- Typical analysis chain ($B^0 \to J/\psi(\mu^+\mu^-)\ K^{*0}(K\pi)$ case):

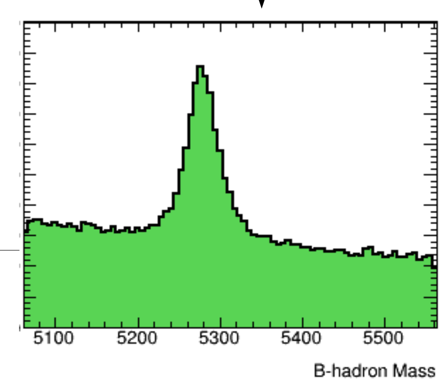
Reconstructed tracks, muons, jets etc. provided by ATLAS reconstruction

vertexing



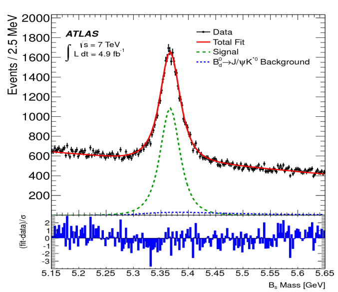
Selection (cuts, MVA, BDT) to achieve optimal S/B ratio

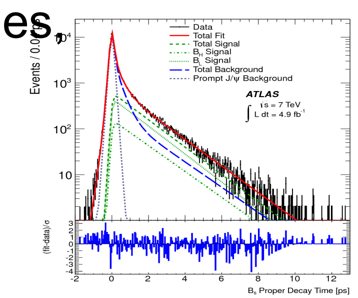
B-decay candidates



Detector efficiency and acceptance corrections (MC and/or Data based)

Statistical analysis (max. likelihood fits etc.)

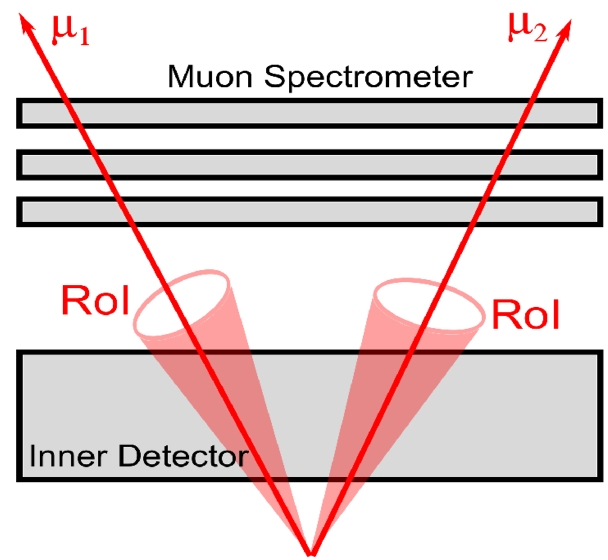


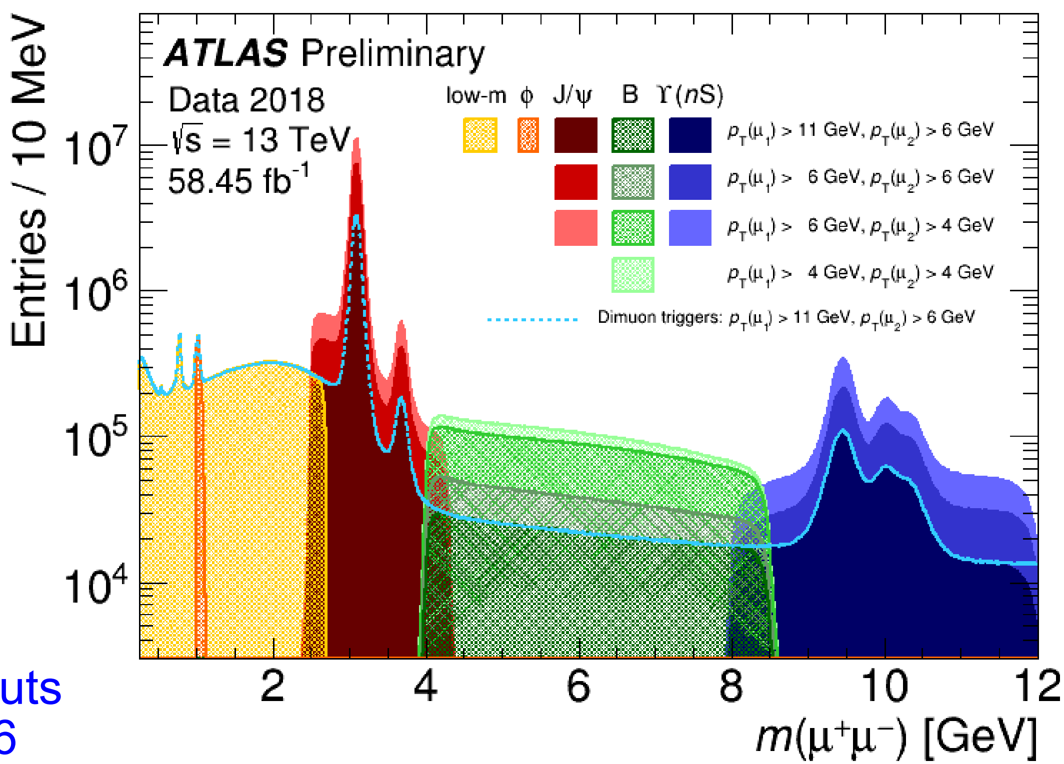


Results, limits, systematic uncertainties, ...

B-Physics Trigger

- 20/40 MHz collision rate → < 2 kHz recording
- B-physics concentrates on low-p_T di-muon signatures:
  - Quarkonia: $J/\psi \to \mu\mu$, $\Upsilon \to \mu\mu$, etc.
  - Exclusive $B \to J/\psi(\mu\mu)X$ decays
  - Rare and semi-rare $B \to \mu\mu(X)$ decays
- Trigger on low-p_T (4,6 GeV) di-muon
  - 2 muons at L1 (HW-based)
  - Confirmed at HLT
  - Tracks vertex fit and mass cuts at HLT
- 8 TeV data:
  - Low-p_T maintained introducing barrel triggers (central part of the detector with better resolution)
- 13 TeV data:
  - Low-p_T maintained using barrel triggers, introduce coarse topological cuts (HW, opening angle, inv. mass) in 2016



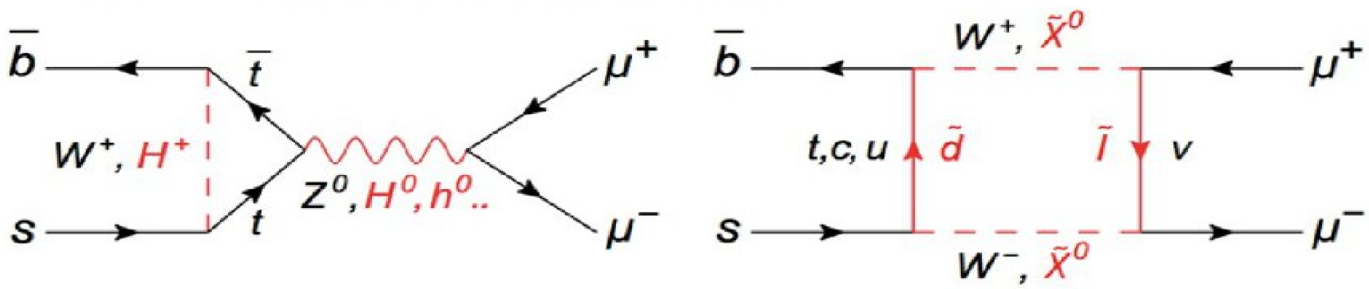


Rare Decays

- Search for New Physics

New Physics Searches in Rare Decays

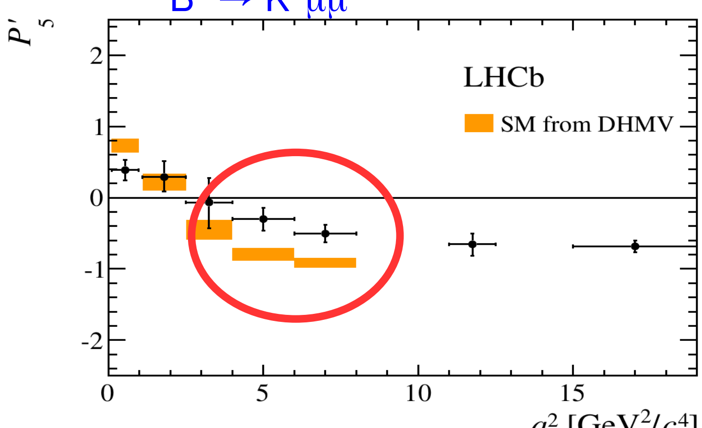
- Search for NP indirectly, through its contributions in decays of known particles



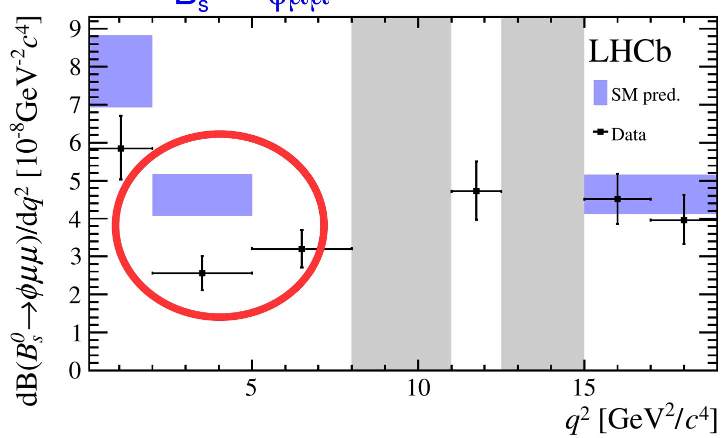
$B_s \rightarrow \mu\mu$

- Can change known decays branching ratio or differential decay cross-section
- FCNC especially sensitive: Proceed via loops, no tree diagrams; presence of small CKM elements ($|V_{ts}| \sim 0.04$, $|V_{td}| \sim 0.01$); GIM suppression in loops with charm or down-type quarks: $(m_s^2 – m_d^2) / M_W^2$; Helicity suppression in radiative or leptonic decays: helicity flip $\sim m_{b,s} / M_W$
  - While New Physics can include tree diagrams, no GIM/heliciy supression
- Observed (flavor) anomalies in $b \rightarrow sll$ transitions

Angular analysis of $B^0 \rightarrow K^*\mu\mu$

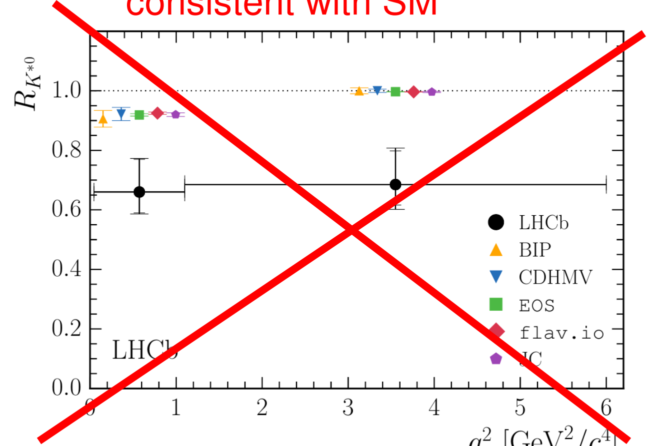


Differential decay rate $B_s \rightarrow \phi\mu\mu$



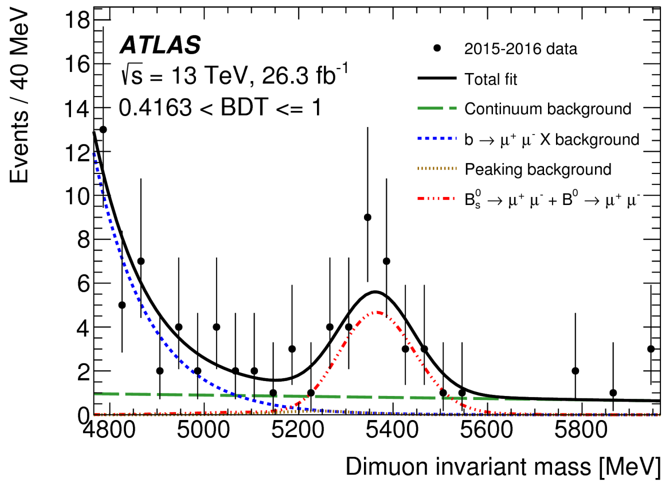
Relative production of $B^0 \rightarrow K^*\mu\mu$ / $B^0 \rightarrow K^*ee$

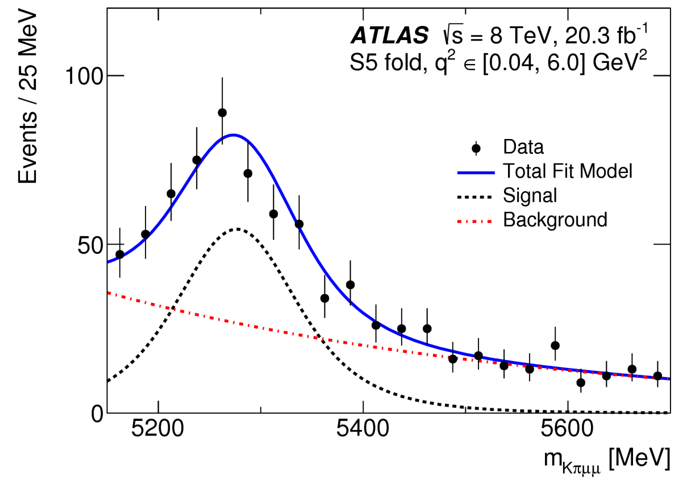
But very recent measurement consistent with SM

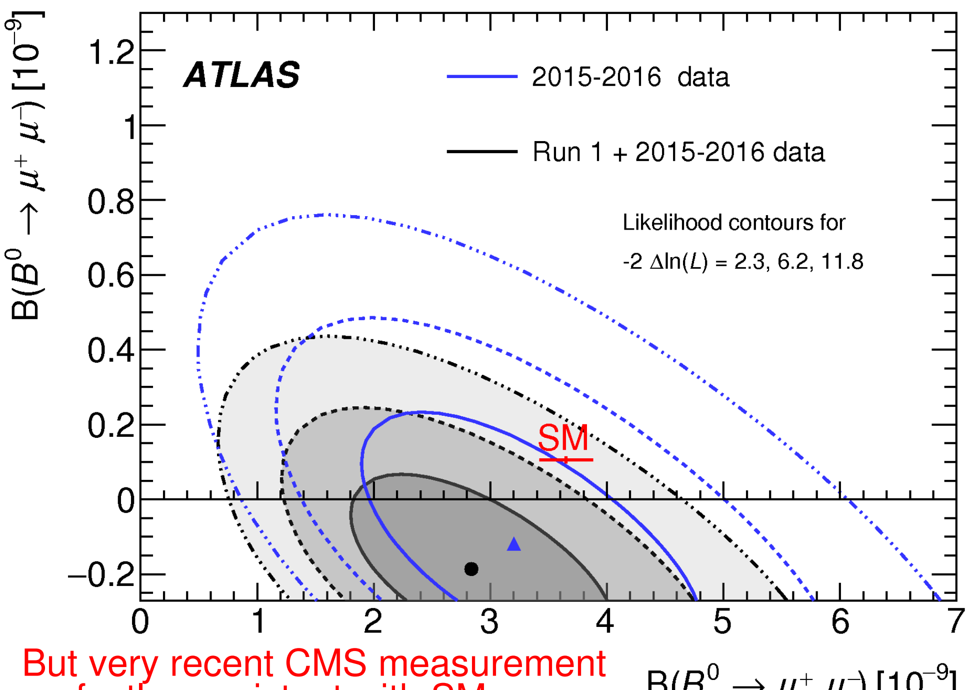


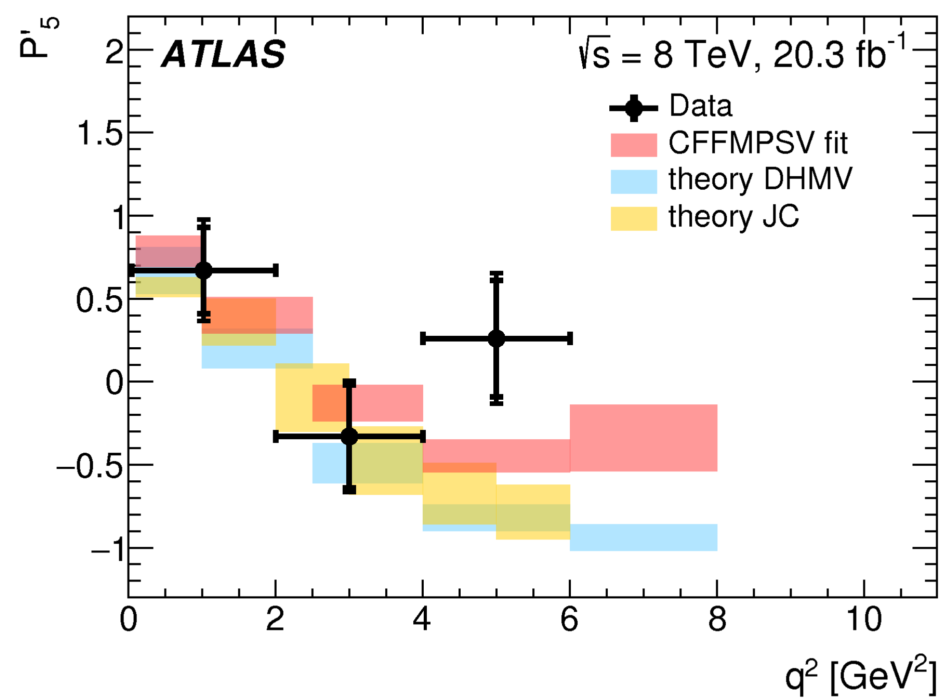
Rare B-decays at ATLAS

- Measurement of BR of $B_{(s)} \rightarrow \mu\mu$ and angular analysis of $B \rightarrow K^*\mu\mu$









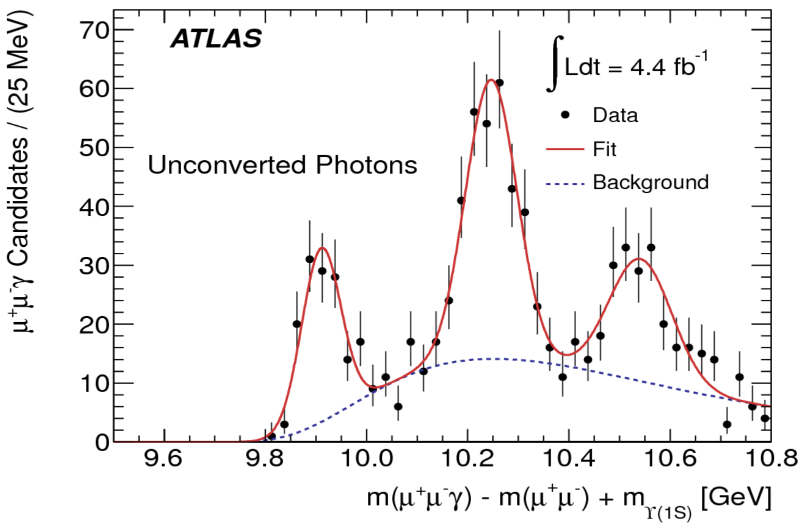
But very recent CMS measurement perfectly consistent with SM

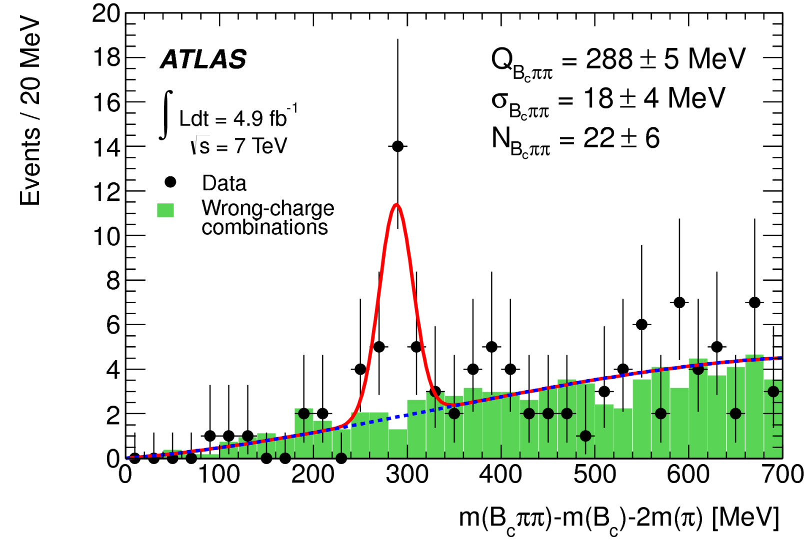
Spectroscopy

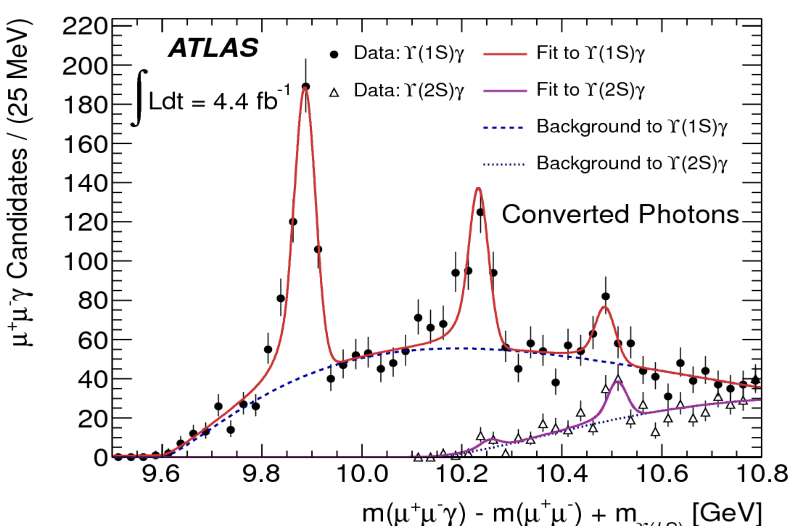
- Search for new (excited) states and decay modes
- Test QCD predictions for the production & spectrum of these states

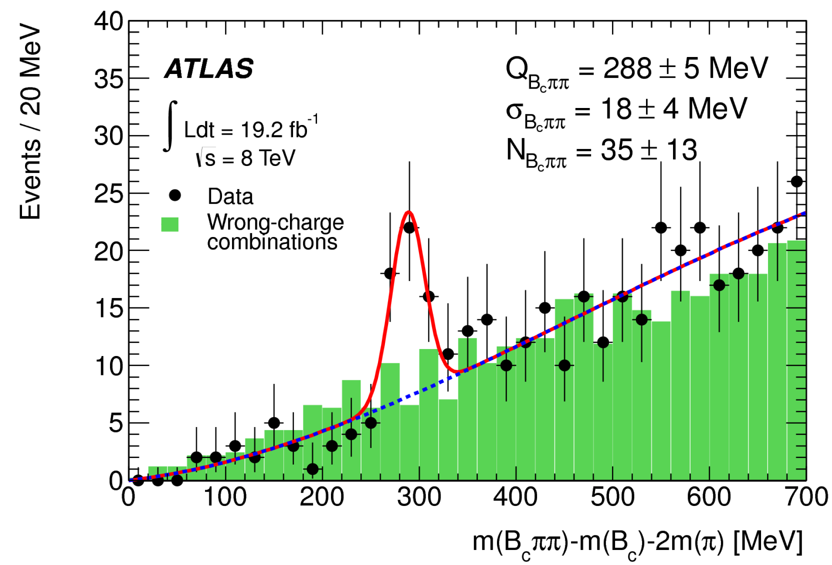
Excited States

- First new particle observed at ATLAS: $\chi_b(3P)$ in B-physics group
- First observation of excited $B_c(2S)$ state decaying to B_c and two pions
  (but also studies of ground state B_c production x-section and decays)

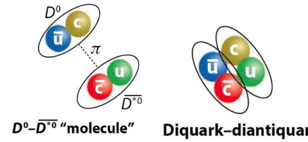




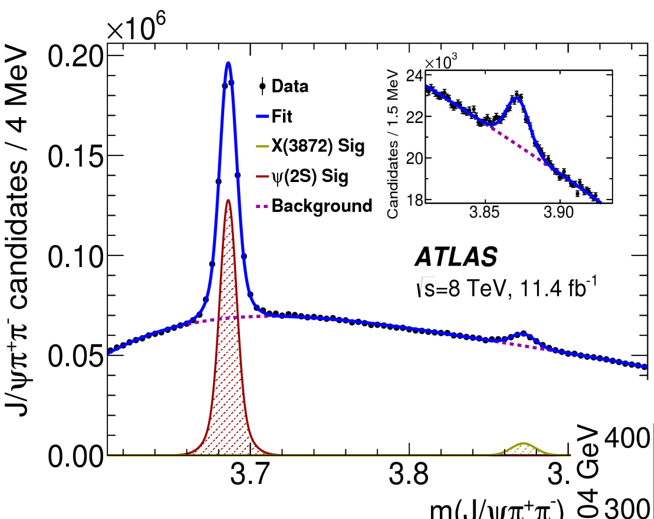


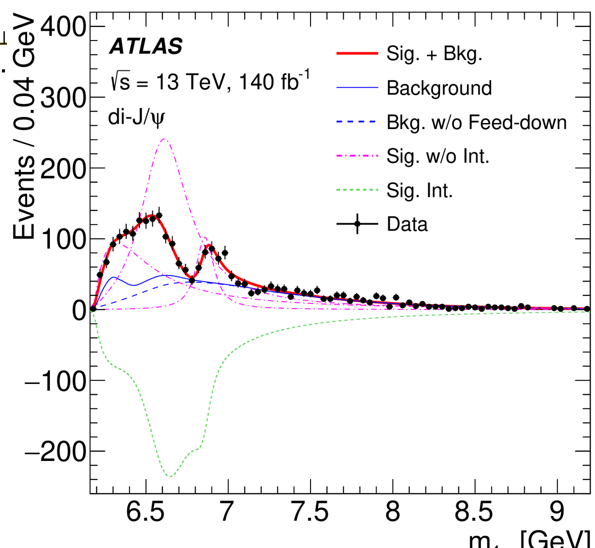


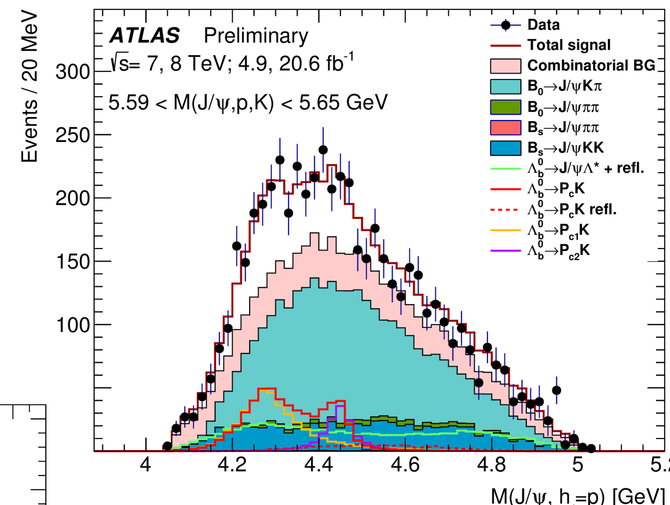
Penta / Tetra-Quarks

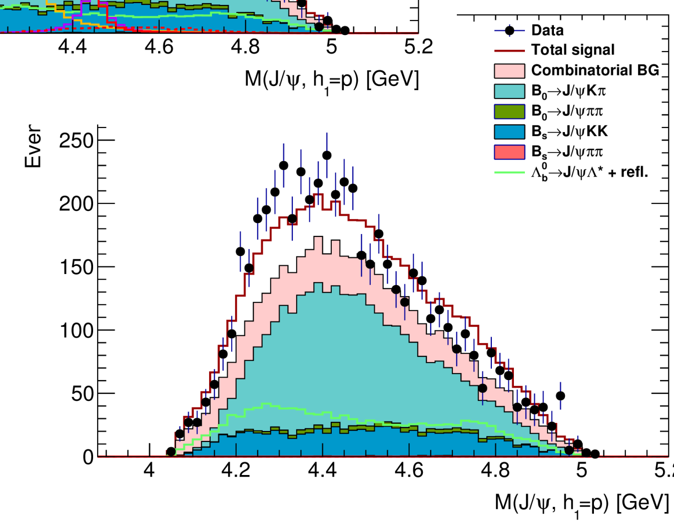


- Almost 30k of X(3872) → J/ψππ allow thorough studies (production x-section, ππ mass spectra), search for equivalent X_b → Upsilon+ππ (not found)
- 4-muon resonances $T_{cc\bar{c}\bar{c}}$ → J/ψJ/ψ observed (supports LHCb observation)
- Pentaquark search in Λ_b → J/ψpK (supports LHCb observation), Searches for X(5586) → $B_s\pi$ seen by D0 (not confirmed),







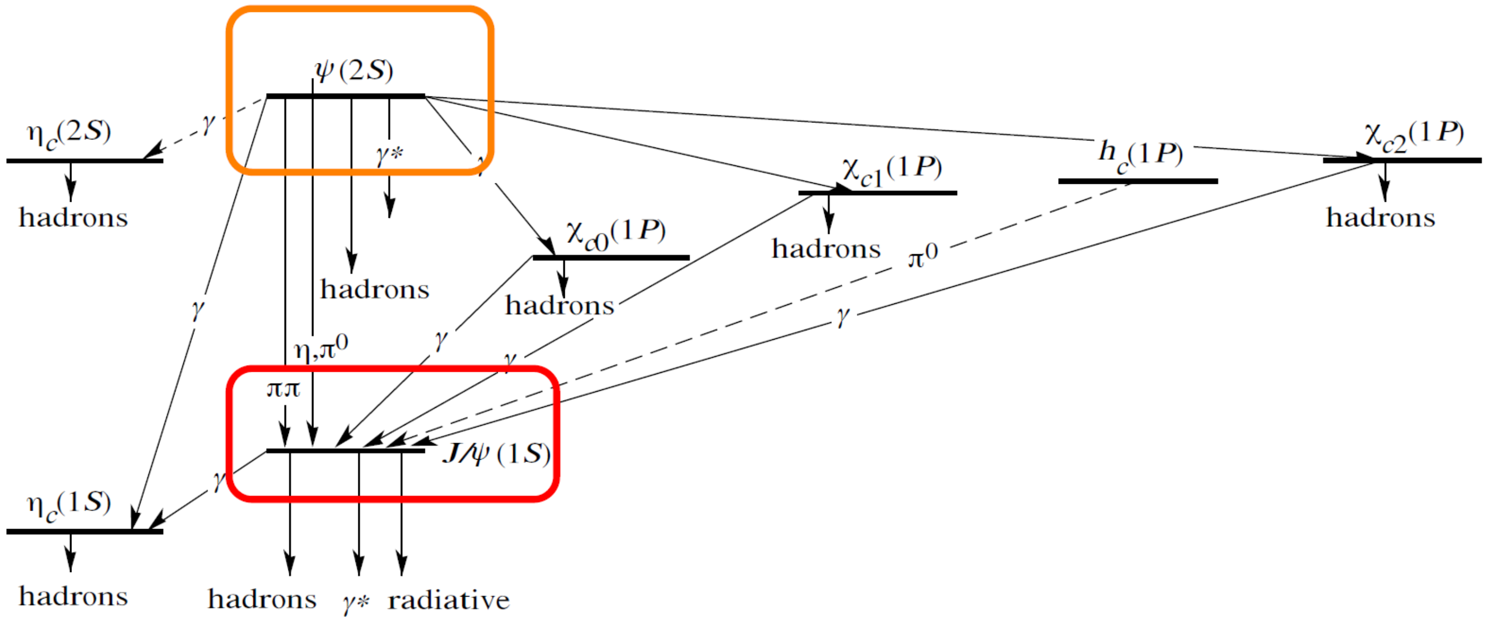


Heavy Flavour Production

- QCD calculation under test…
- Measurements serve as input to MC generators as HF is important background in many other ATLAS analyses

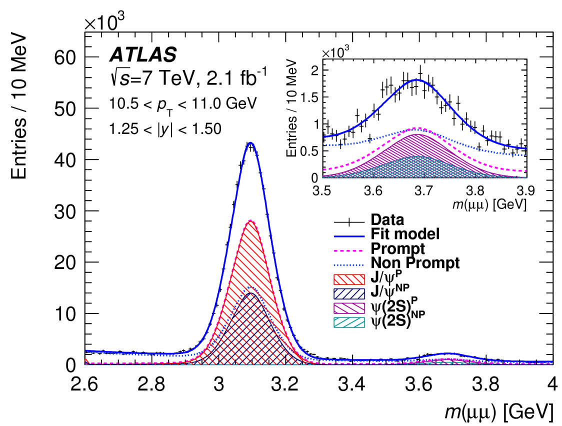
J/ψ and ψ(2S) Production

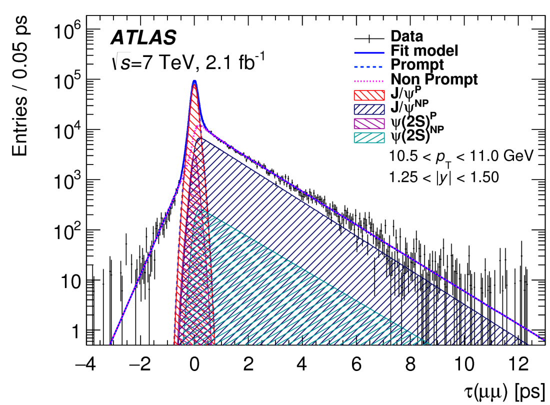
- Huge stat. at LHC



- Two distinct charmonium production mechanisms at LHC:
  - **Prompt:** produced directly in the pp or through feed-down decays of heavier states — NRQCD
  - **Non-prompt:** produced in decays of b-hadrons => displaced vertex — FONLL
- Around 35% of prompt J/ψ come from feed-down, ψ(2S) are almost all produced direct

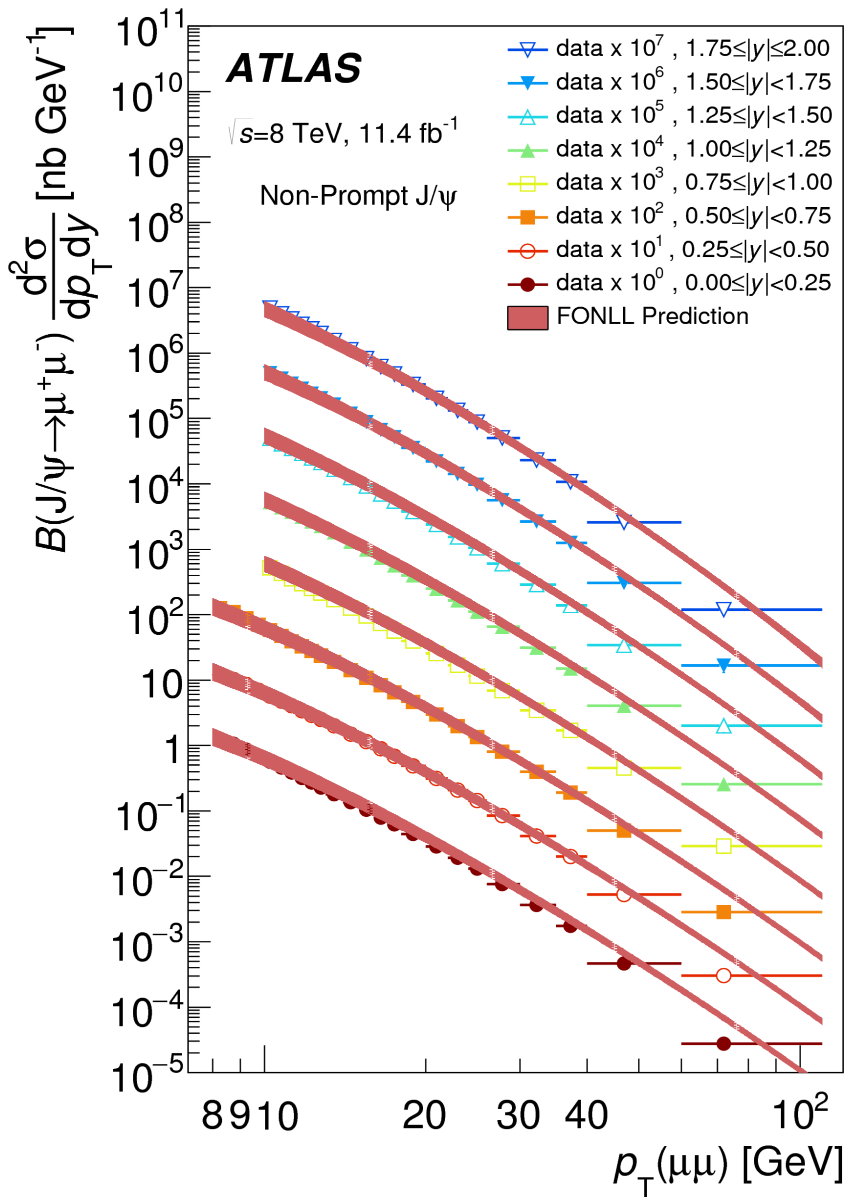
- Use mass-lifetime fits to distinguish signal/background prompt/non-prompt

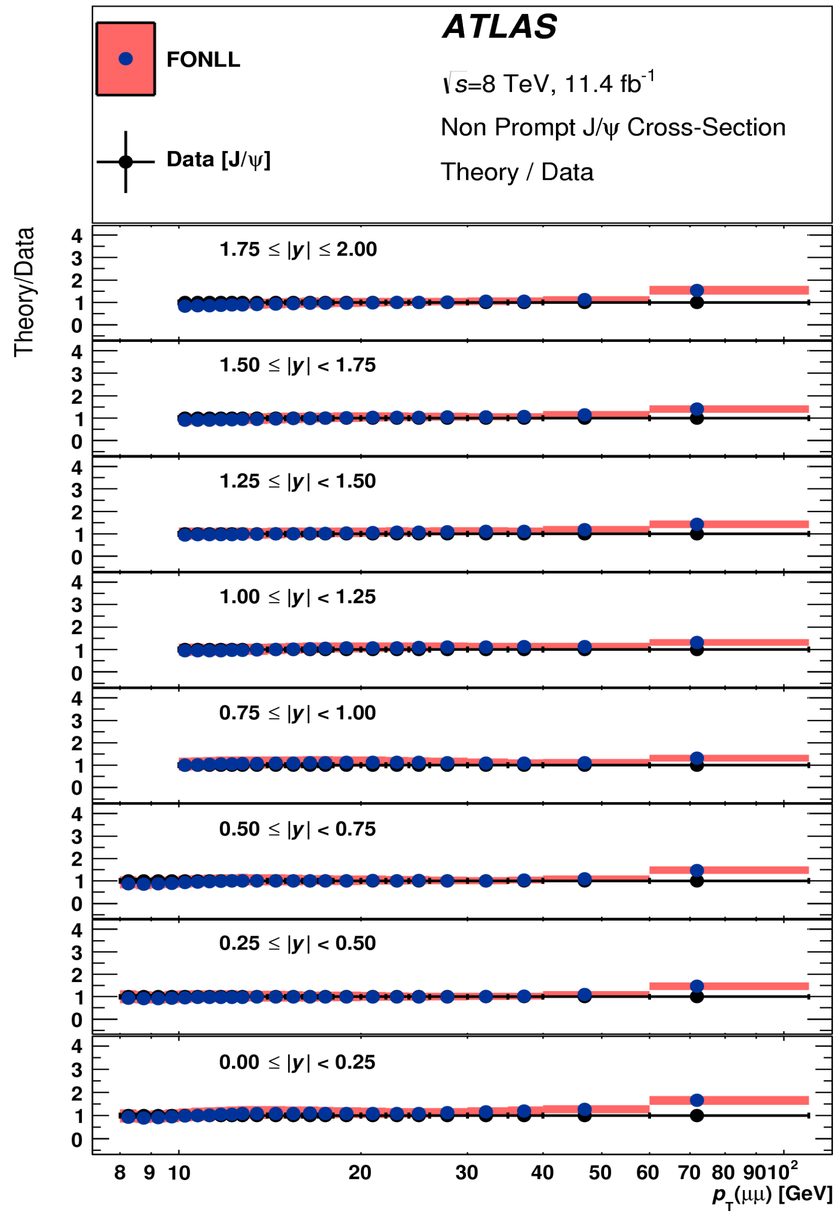




J/ψ and ψ(2S) Production

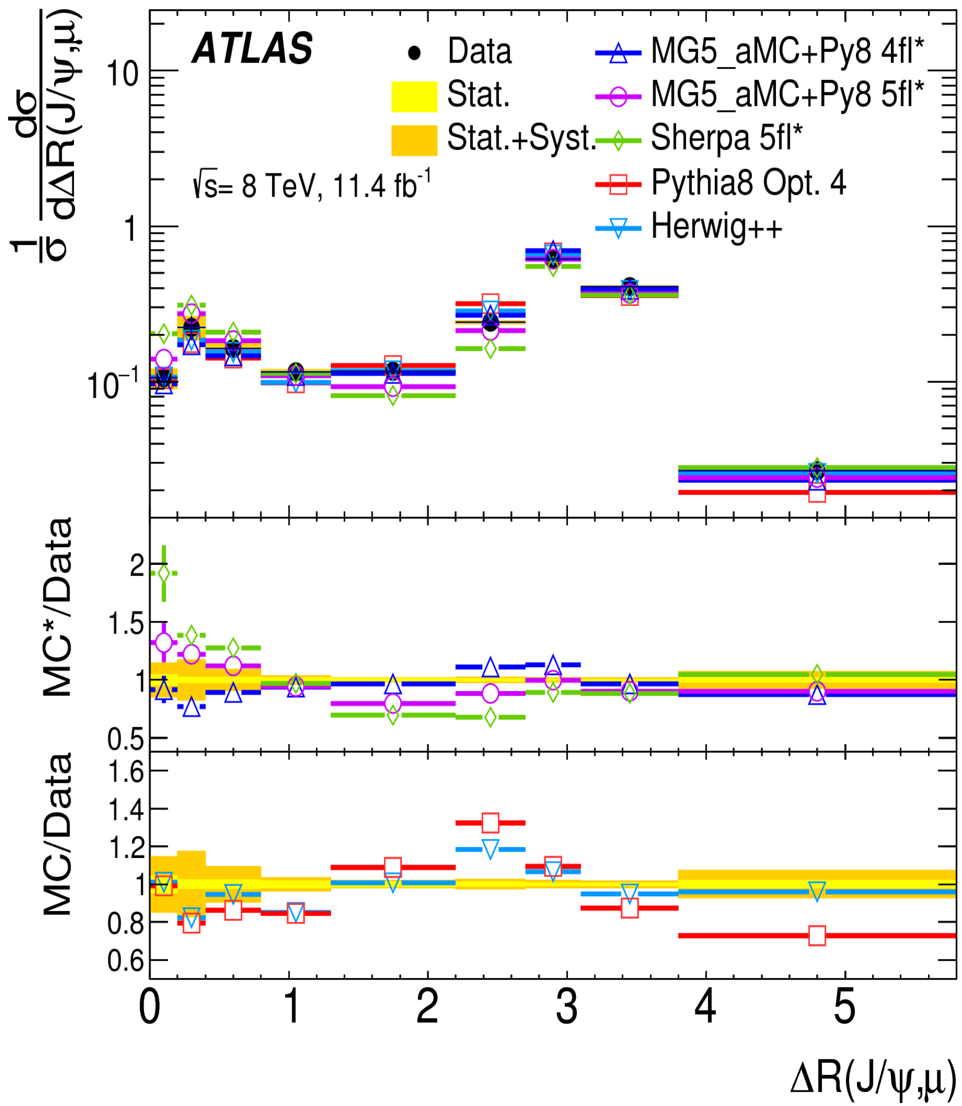
- Measure differential x-section (p_T, pseudorapidity) and fraction of prompt quarkonia

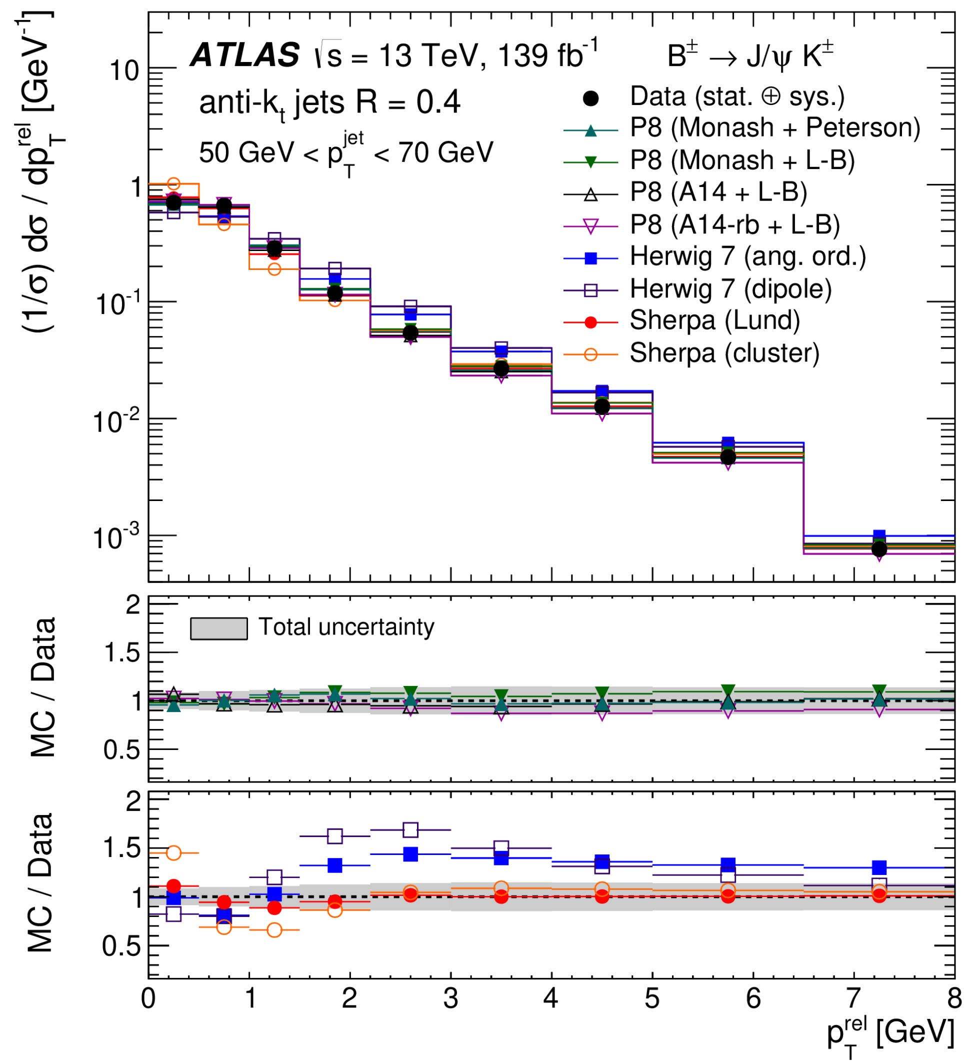




Production of b/c-hadrons

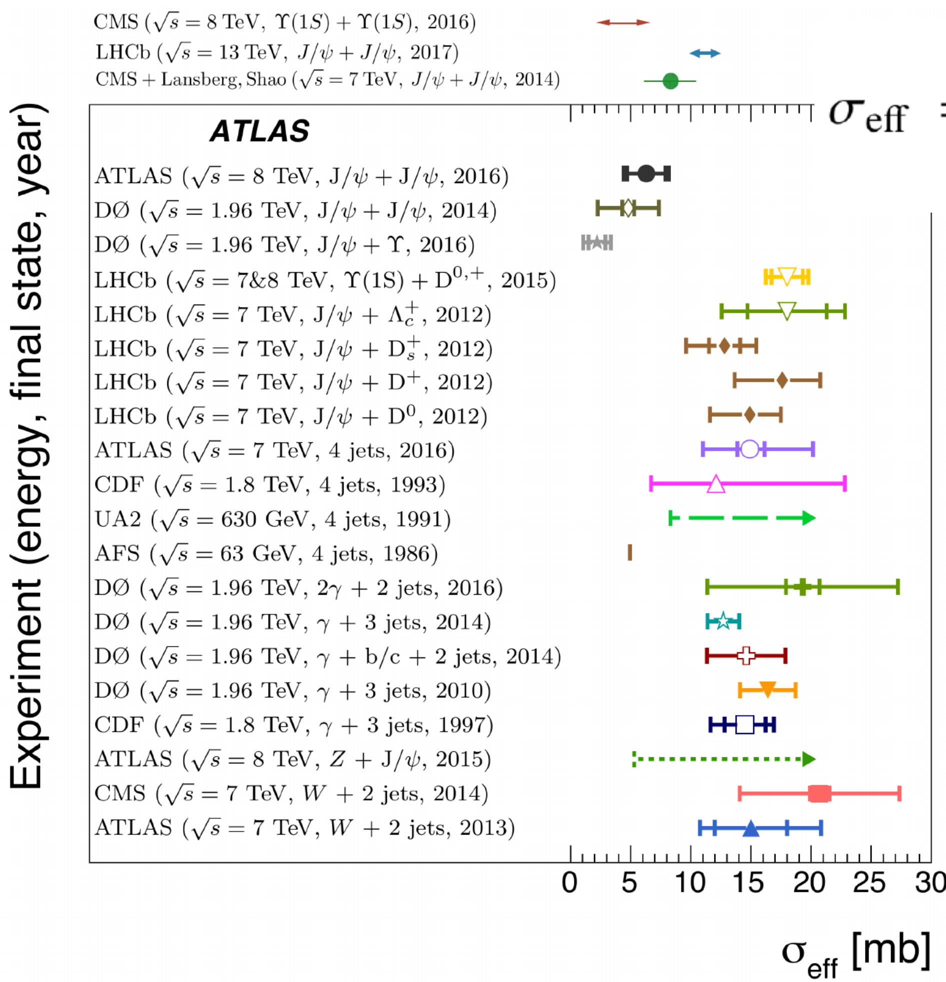
- Production x-section of b → D*μ, $B^+ \to J/\psi K^+$, b-quark fragmentation f_s/f_d
- Production of b-hadron pairs, Production of b-hadrons within jets



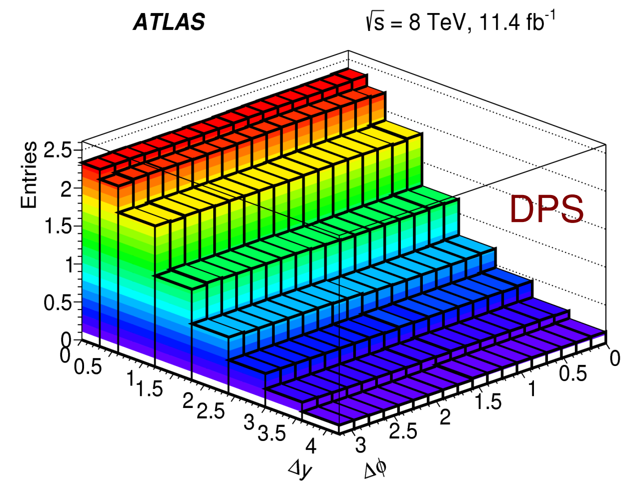


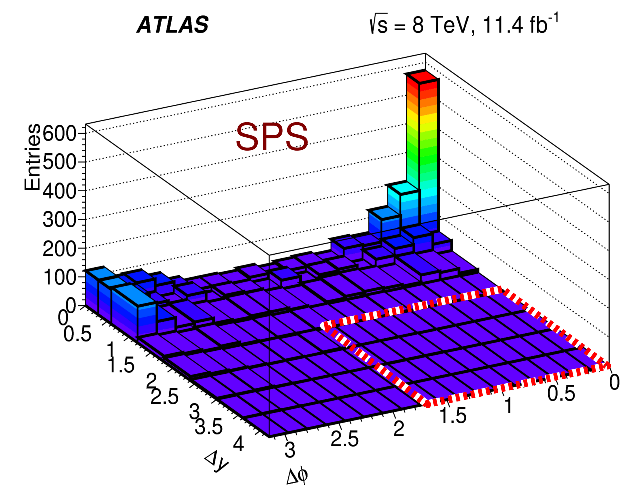
Associated J/ψ Production (+ J/ψ / W / Z)

- Test predictions of QCD (single parton scattering)
- Study J/ψ production models
- Measure double-parton scattering (background for NP searches)
  - DPS has more uniform shape in opening angle between the objects, while direct associated productions peaks at same or opposite direction (large/small Δφ)



$$\sigma_{\mathrm{eff}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{J/\psi,J/\psi}_{\mathrm{DPS}}}$$



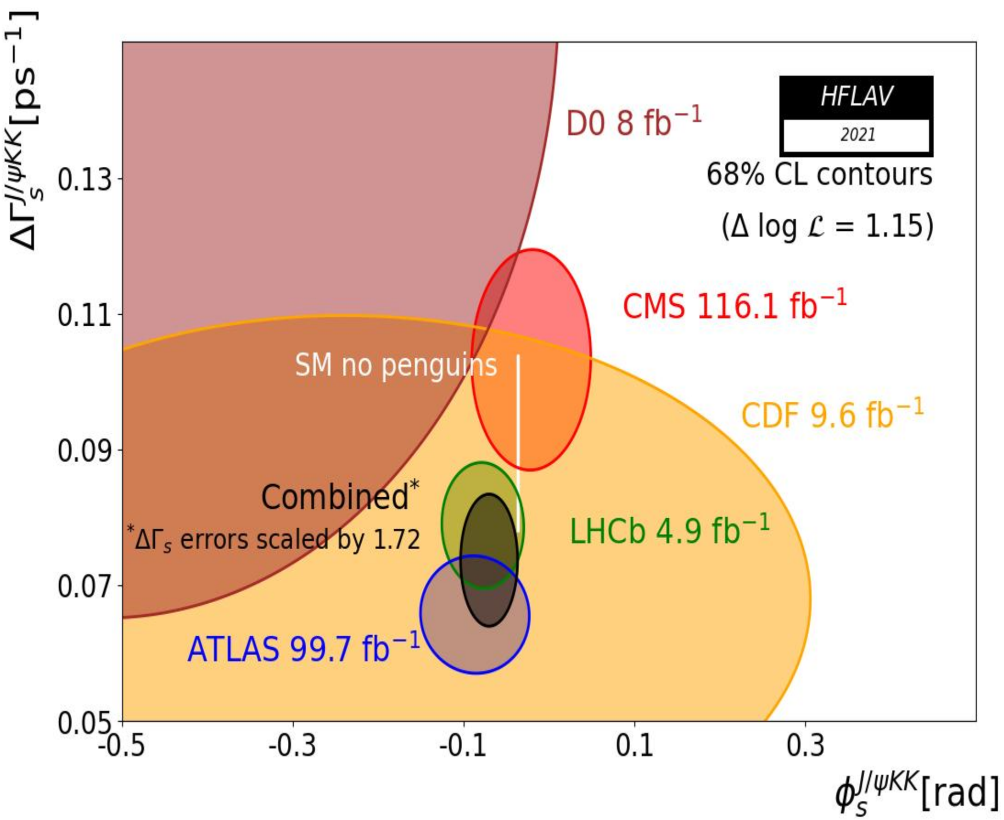


Precision Measurements

- Test SM predictions at high stat.
- CPV, oscillations, Λ_b polarization, ...

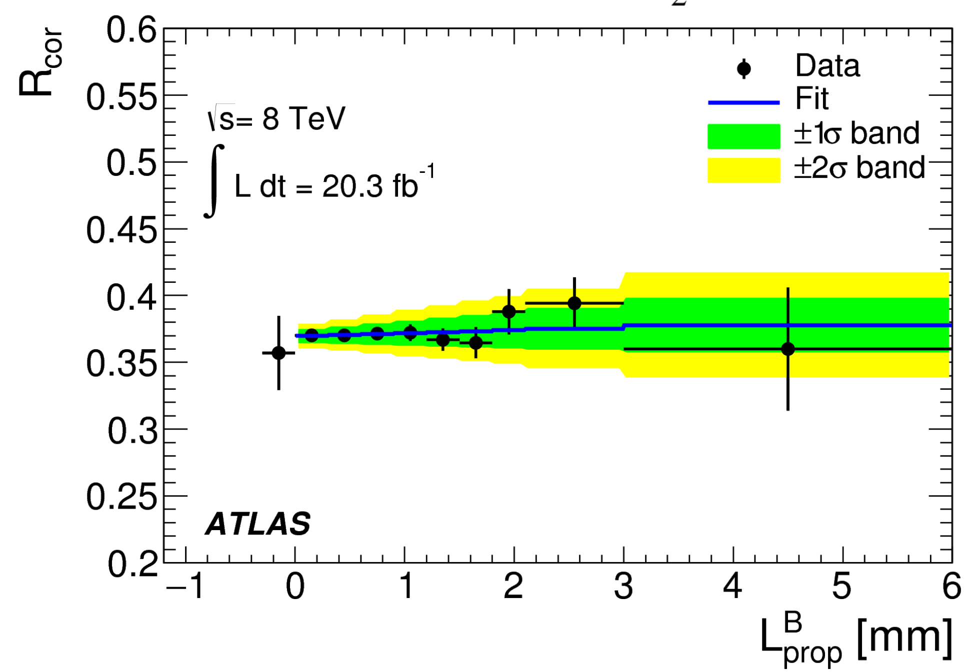
B-Meson Mixing

- CPV in $B_s \to J/\psi\varphi$ decay searching for New Physics in CPV phase φ_s
  (CPV due to interference of mixing and direct decay)
  - Almost 500k of signal decays
- $\Delta\Gamma_d/\Gamma_d$ measurement using ratio of B decays to CP eigen-state $J/\psi K_s$ and to flavor specific $J/\psi K^*$
  - 150k / 700k candidates, best single precision measurement of $\Delta\Gamma_d/\Gamma_d$ at that time



$$\Gamma[t, J/\psi K_S] \propto e^{-\Gamma_d t}\left[\cosh\frac{\Delta\Gamma_d t}{2} + \cos(2\beta)\sinh\frac{\Delta\Gamma_d t}{2} - A_P \sin(2\beta)\sin(\Delta m_d t)\right]$$

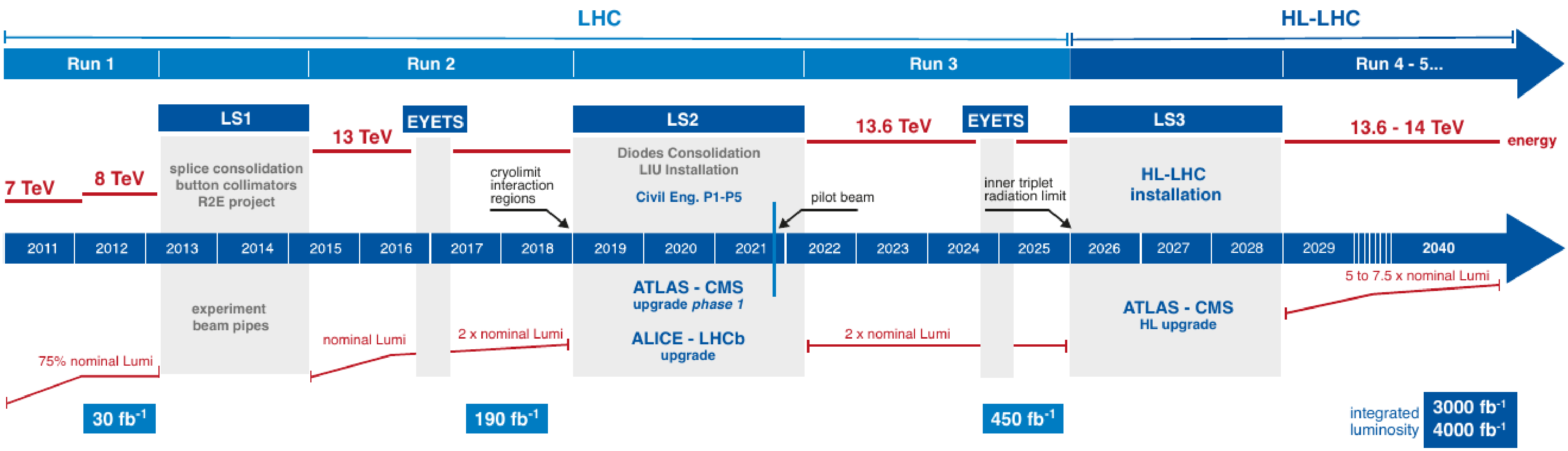
$$\Gamma[t, J/\psi K^{*0}] \propto e^{-\Gamma_d t}\cosh\frac{\Delta\Gamma_d t}{2}$$



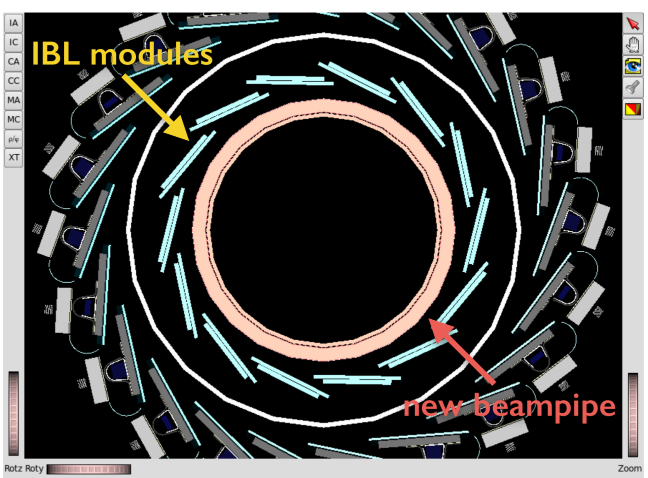
Summary

- Anomalies in flavour physics an exciting indication of possible New Physics
  - But still at statistics boundaries, some anomalies recently “disappeared”: $B_{(s)} \rightarrow \mu\mu$, R(K*)
- Experimental reach in B-decays exciting
  - Very rare decays becoming observable
  - Enough statistics for angular analyses of rare decays
  - Experimental errors getting closer to theory uncertainties
  - Huge statistics in non-rare decays
  - **Complicated analysis chains, with enough signal => useful for students training**
- But...
  - In New Physics and exotic structures searches the ATLAS precision in B-analysis is usually not the best among other (not-only) LHC experiments, providing comparable precision at best, less precise cross-checks only in the other cases

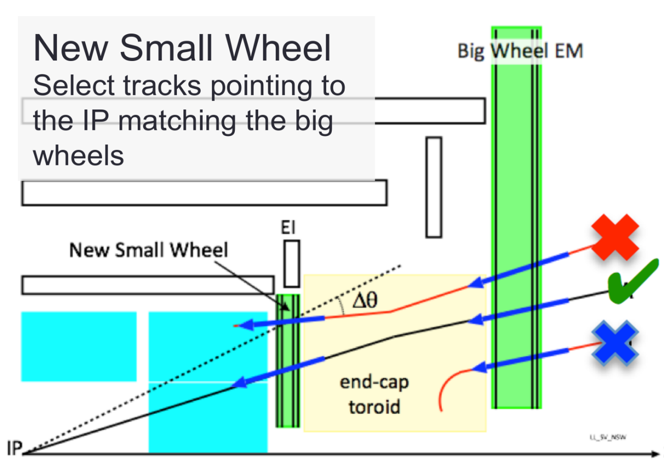
B-Physics @ ATLAS Upgrade



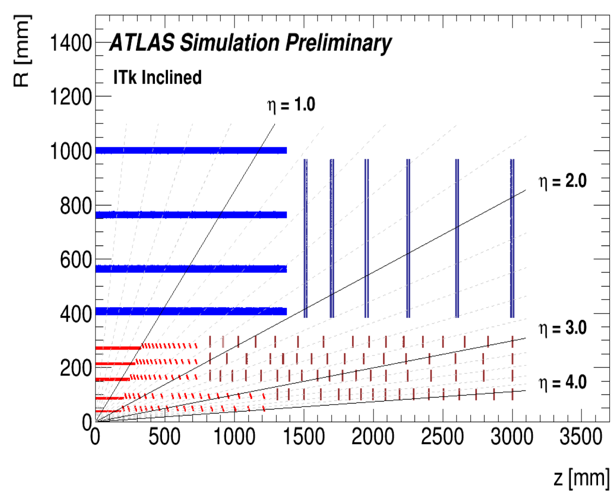
- New pixel layer (IBL, 32-38 mm) + small radius Be beam pipe
- Topological L1 trigger



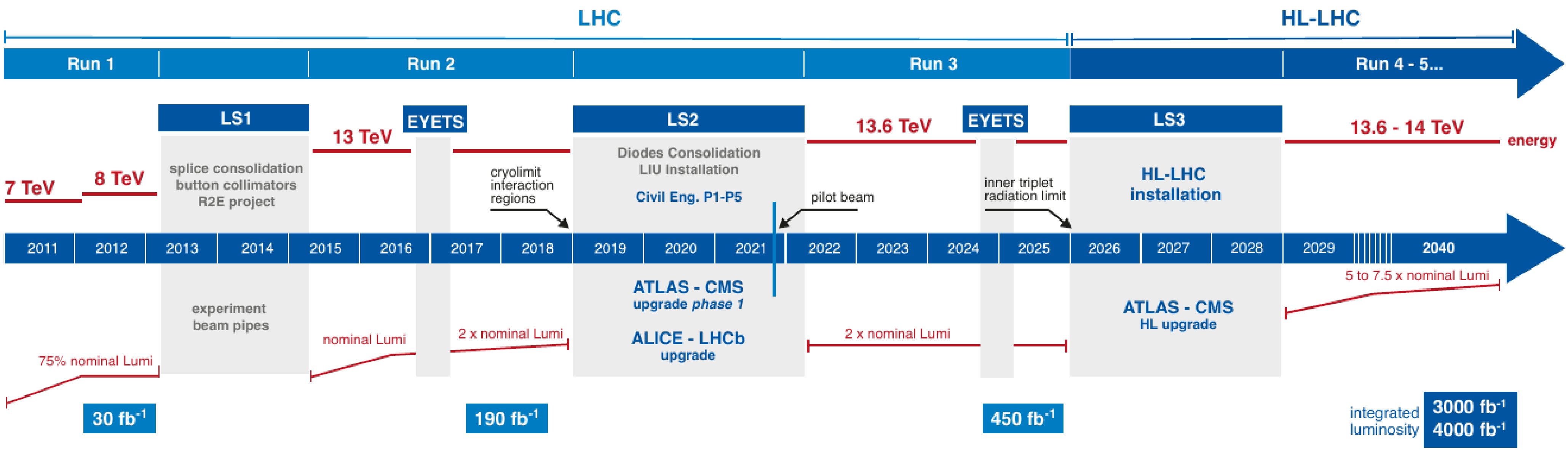
- New small muon wheel
- ~~Fast tracking trigger (FTK) at LVL 1.5~~

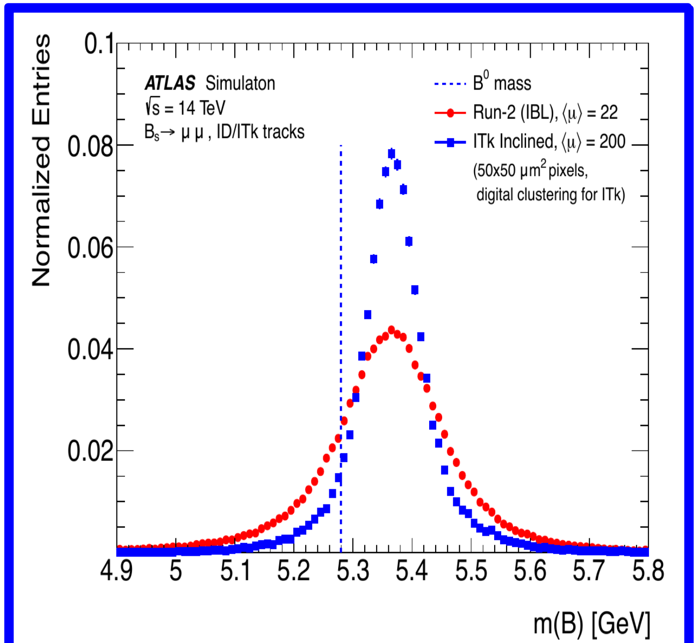


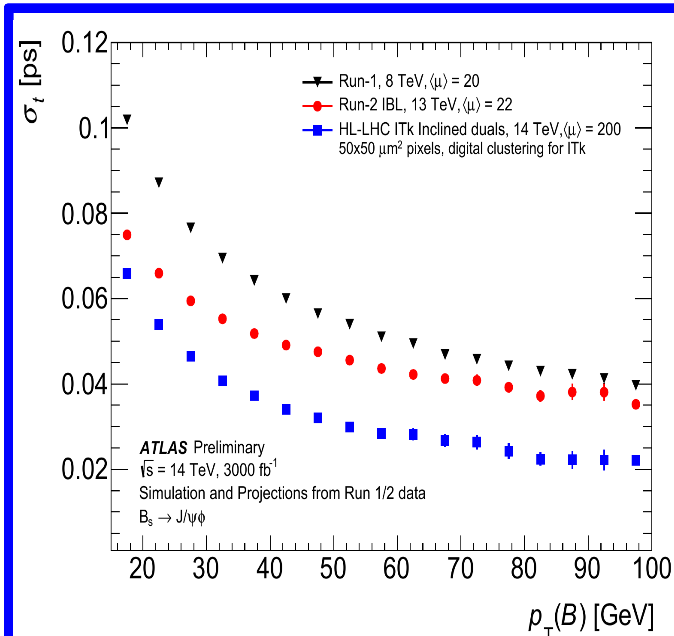
- Completely new Si based tracker (ITK)



B-Physics @ ATLAS Upgrade







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