BEAUTY 2018
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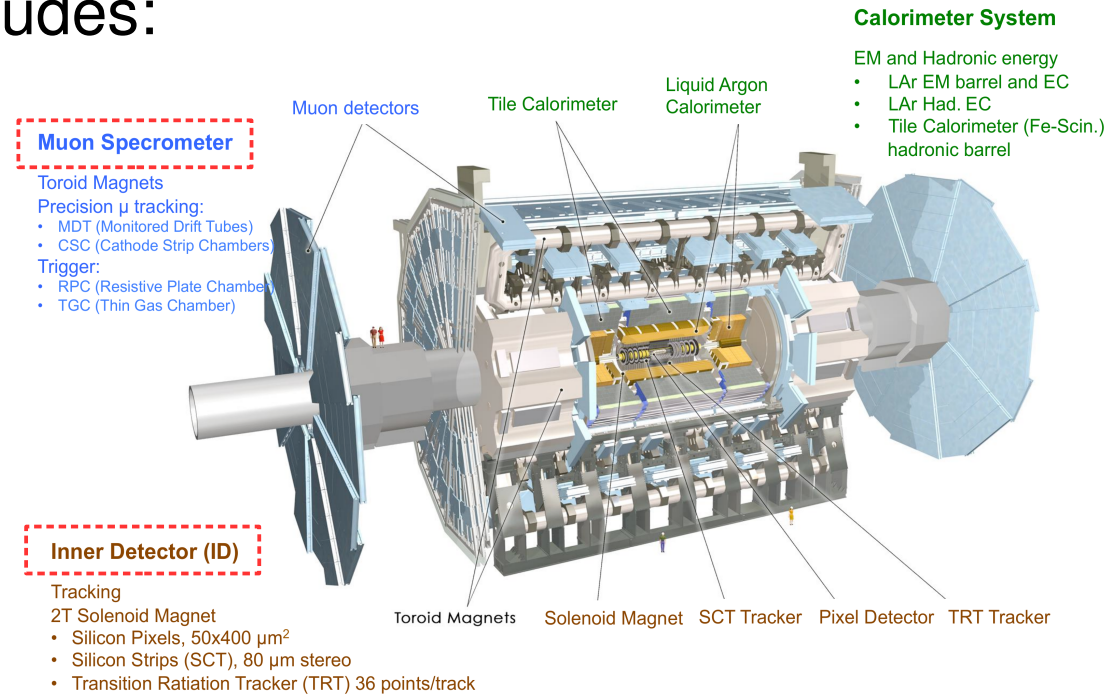
6th - 11th May 2018, La Biodola, Isola d'Elba

# Recent ATLAS Results in Charmonium Production

Pavel Řezníček
(Charles University, Prague)
on behalf of the ATLAS collaboration

# ATLAS B-Physics Programme

- ATLAS B-physics program includes:
  - **Precision measurements:**
    rare decays
    b-hadron decay properties,
    CPV
  - **Heavy flavour production:**
    b-hadrons,
    (associated) quarkonia production
  - **Spectroscopy:**
    new states and decay modes
  - Mostly in fully reconstructable exclusive decays
    with single/di-/multi-muon final states, which allows to trigger low-$p_T$ objects

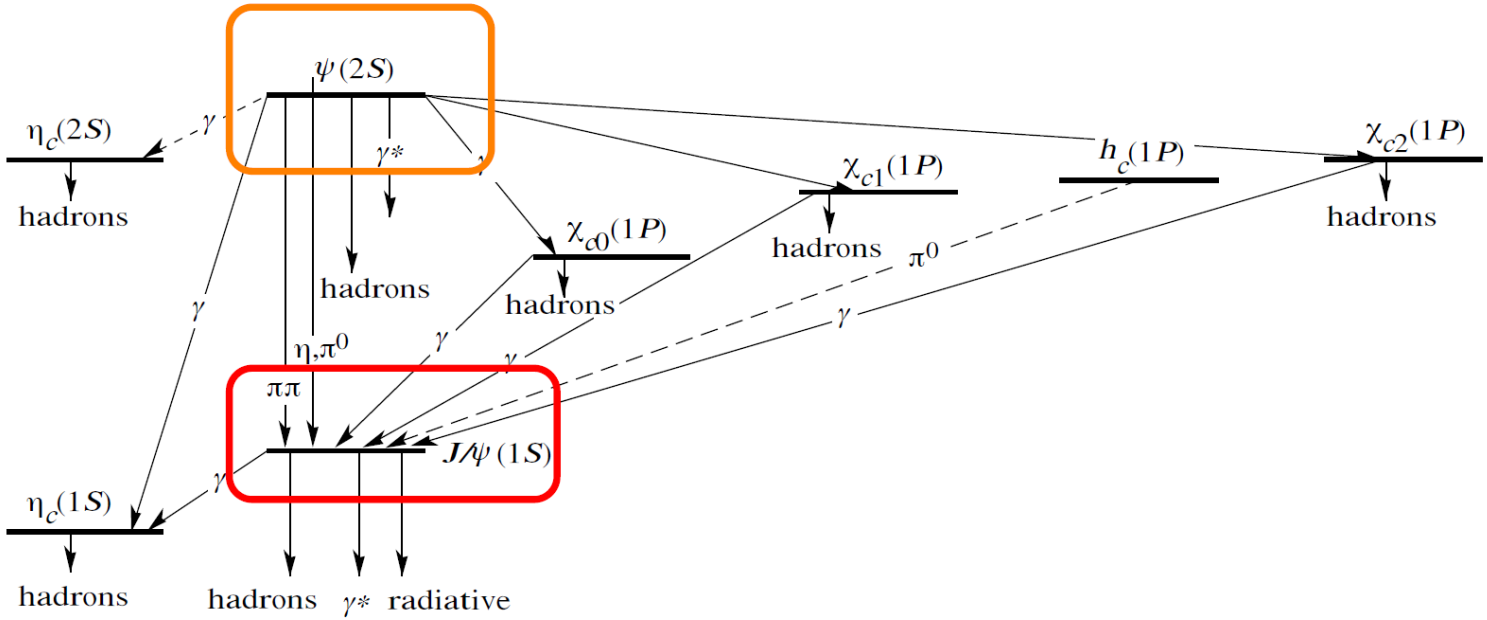



- **Outline of the talk (charmonium production):**
  - Production of J/ψ and ψ(2S) in 7 & 8 TeV pp collisions — EPJC 76(5) (2016) 283
  - Quarkonium production in 5.02 TeV pp & pPb collisions — EPJC 78 (2018) 171

# J/ψ and ψ(2S) Production at 7&8 TeV

EPJC 76(5) (2016) 283

- Quarkonia production at LHC offers unique windows on understanding strong interactions



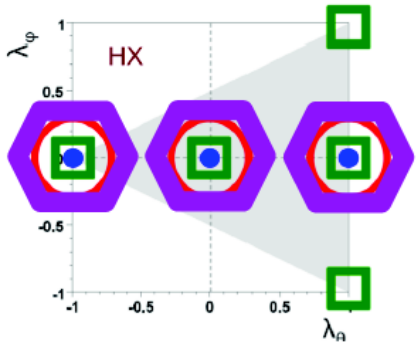

- Two distinct charmonium production mechanisms at LHC:
  - **Prompt:** produced directly in the pp interaction or through feed-down decays of heavier states
    - Theory: Non-relativistic QCD (arXiv:1009.3655), **NRQCD**
      pQCD $c\bar{c}$ production, soft evolution into quarkonium (data derived)
  - **Non-prompt:** produced in decays of b-hadrons, can be separated experimentally due to the "long" b-hadron lifetime
    - Theory: Fixed Order Next-to-Leading Logarithm (arXiv:1205.6344), **FONLL**
      perturbative $b\bar{b}$ production, data driven fragmentation and b-hadron decay model
- Around 35% of prompt J/ψ come from feed-down, prompt ψ(2S) almost all produced directly

# Measurement Method

EPJC 76(5) (2016) 283

- Data (2.1 fb$^{-1}$ @ 7 TeV and 11.4 fb$^{-1}$ @ 8 TeV) collected using di-muon triggers
- Basic di-muon selection ($p_T(\mu_{1,2}) > 4$ GeV, $|\eta(\mu_{1,2})| < 2.3$), di-muon tracks vertex fit
- Weights to correct for trigger efficiency, muon indentification and reconstruction and geometrical acceptance
  - probe various spin-alignment scenarios (not yet measured at ATLAS)

$$\frac{d^2N}{d\cos\theta^\star d\phi^\star} \propto 1 + \lambda_\theta \cos^2\theta^\star + \lambda_\phi \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta\phi} \sin 2\theta^\star \cos\phi^\star$$

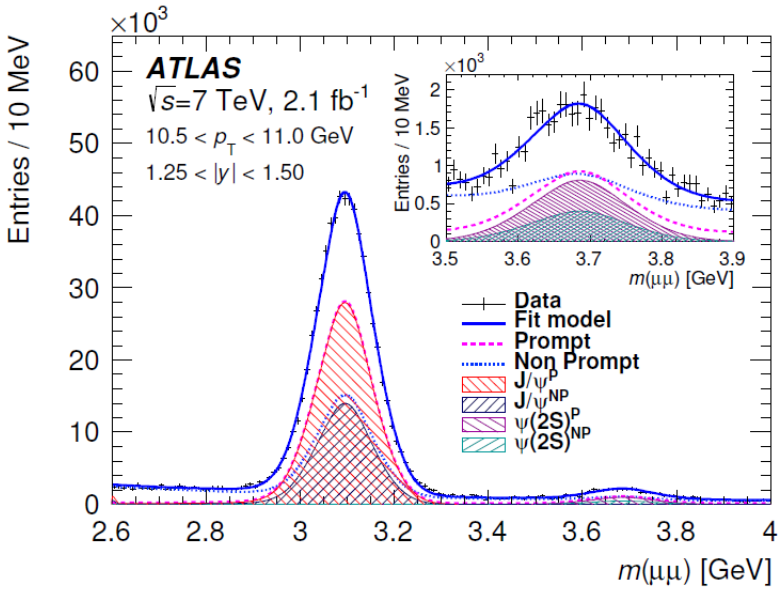


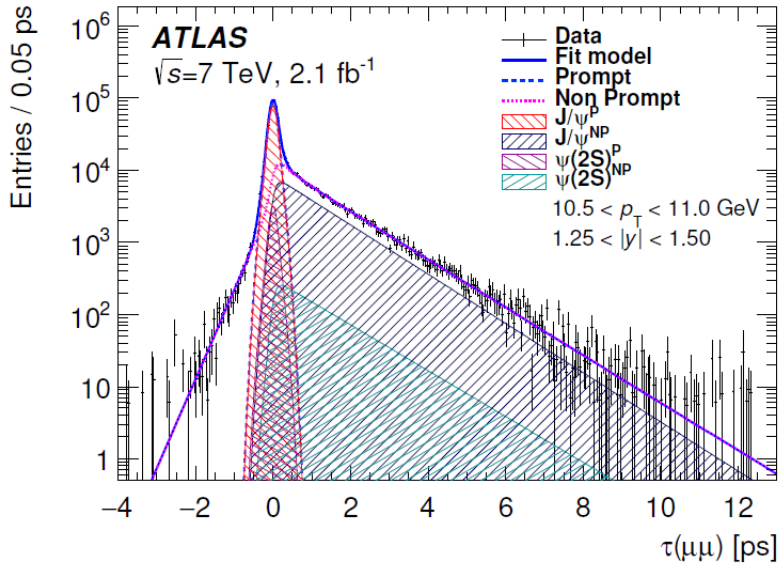

- Corrected prompt and non-prompt J/ψ and ψ(2S) yields determined from an unbinned fit to the 2D di-muon mass and pseudo-propertime distribution
  - in 22 $p_T$ x 8 rapidity bins

$$\tau = \frac{L_{xy}\, m(J/\psi)}{c\, p_T(J/\psi)}$$

xy displacement of candidate from PV; Invariant mass of candidate; $p_T$ of candidate

ATLAS CMS LHCb ALICE



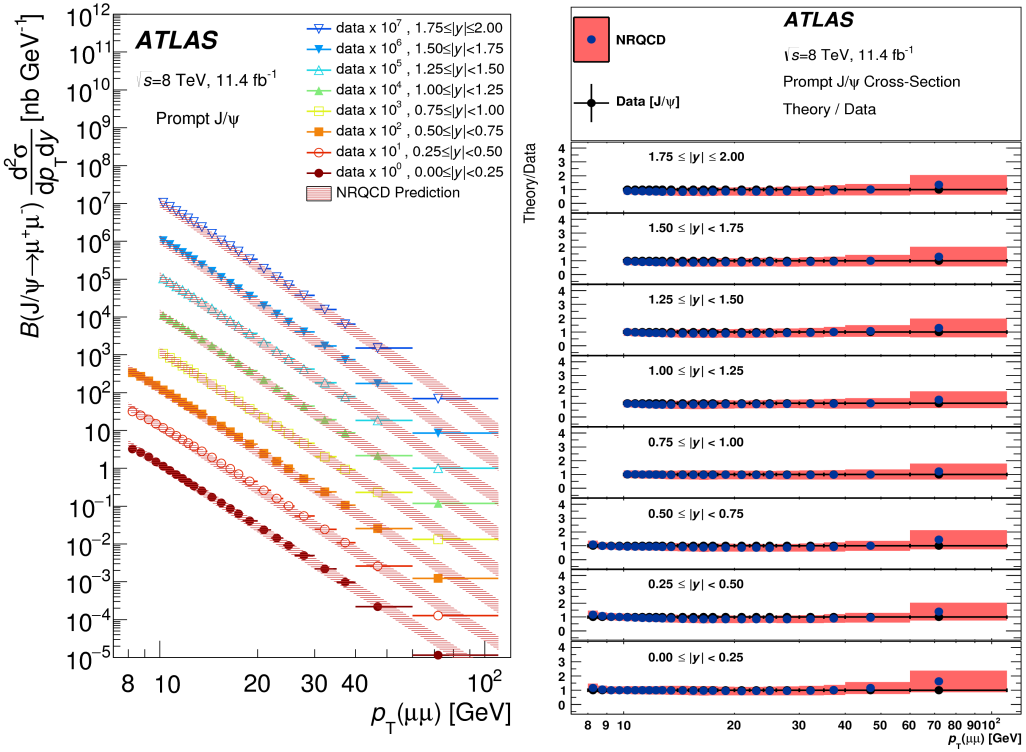



# J/ψ and ψ(2S) Prod. at 7&8 TeV: Results

EPJC 76(5) (2016) 283

- Prompt J/ψ compared to NRQCD – good agreement across range of $p_T$, no y-dependence
- Prompt ψ(2S) (no significant feed-down) compared to NRQCD – mostly well describing data, some deterioration at high-$p_T$
- Non-prompt compared to FONLL – predicts slightly harder $p_T$ spectra
- Ratio of prompt ψ(2S) / J/ψ flat across the whole $p_T$ range
- Prompt J/ψ fraction dominates at low-$p_T$, but non-prompt exceeds prompt at around 20 GeV

**Prompt J/ψ**



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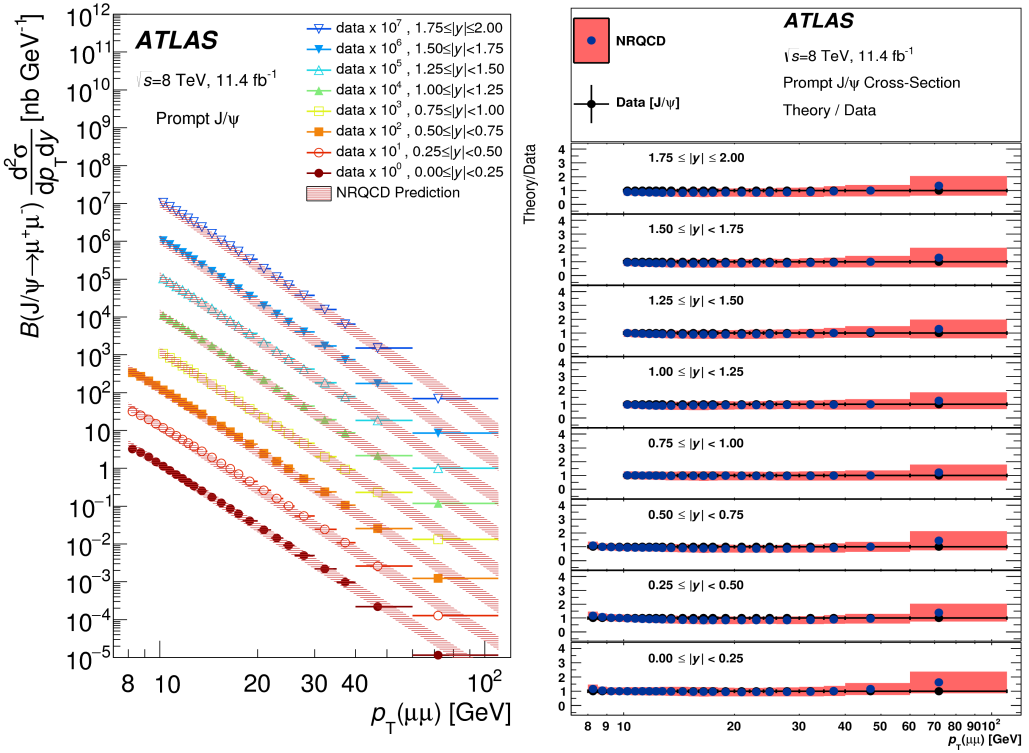
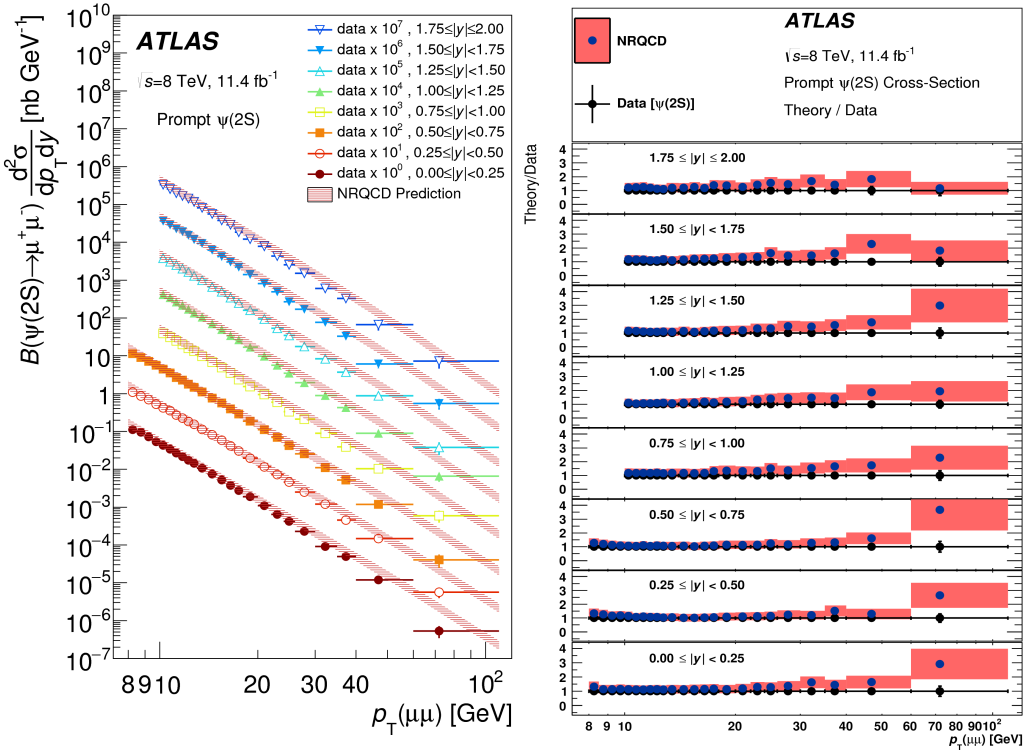



## Prompt ψ(2S)



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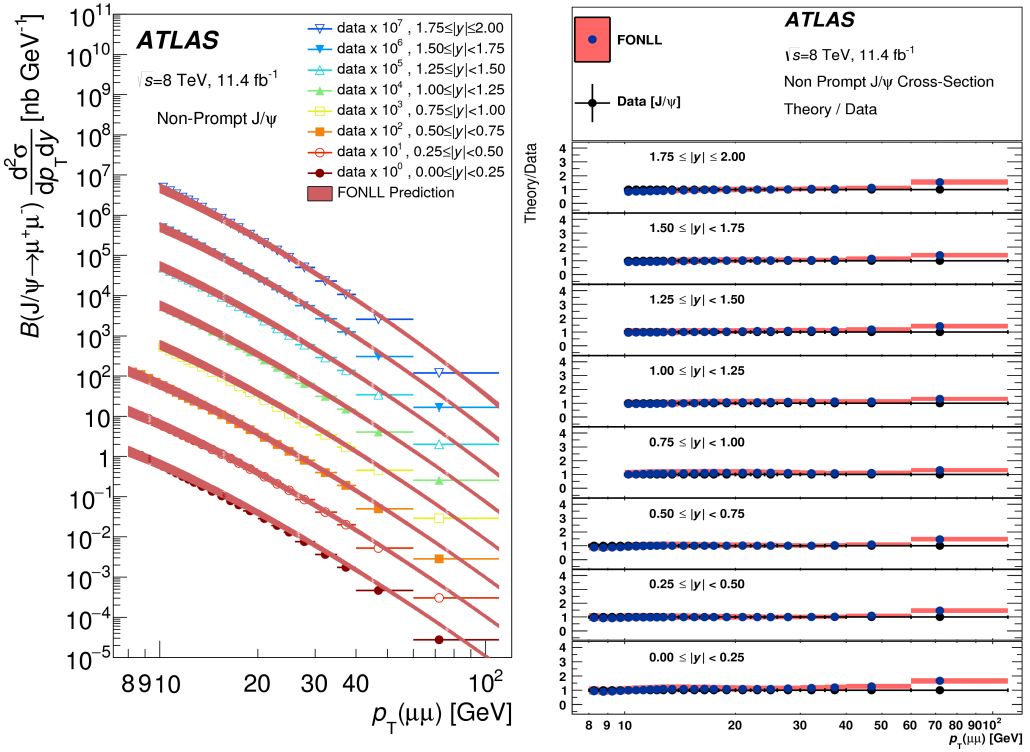
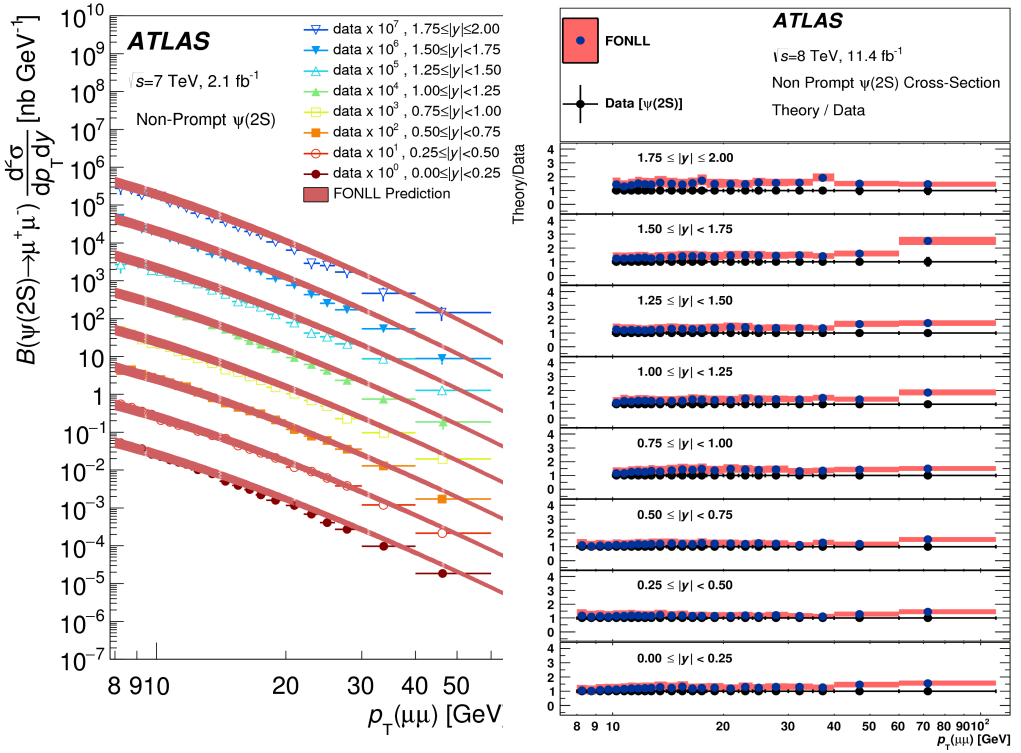
## Non-Prompt J/ψ




## Non-Prompt ψ(2S)



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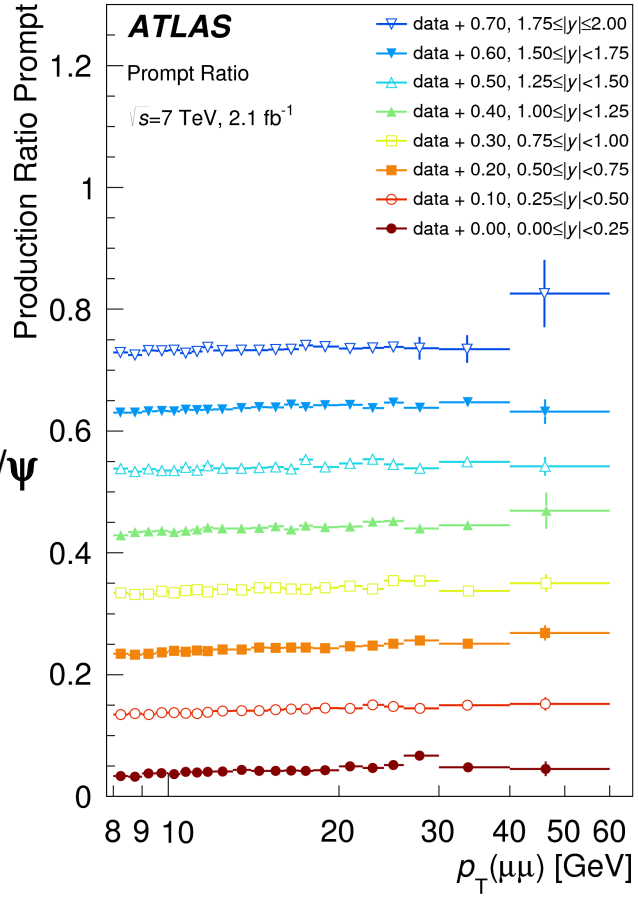
**Prompt ratio of ψ(2S) to J/ψ**



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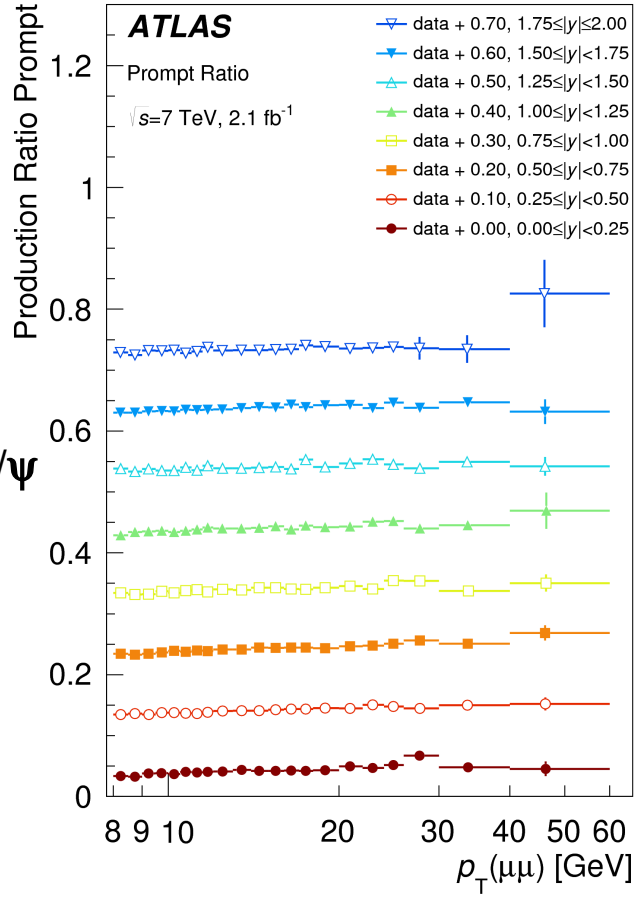
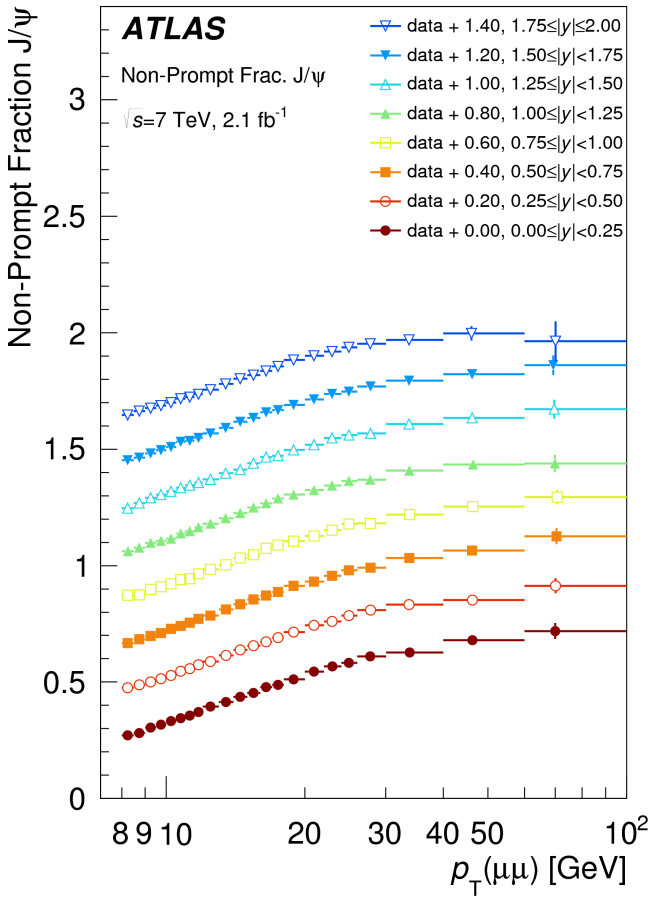


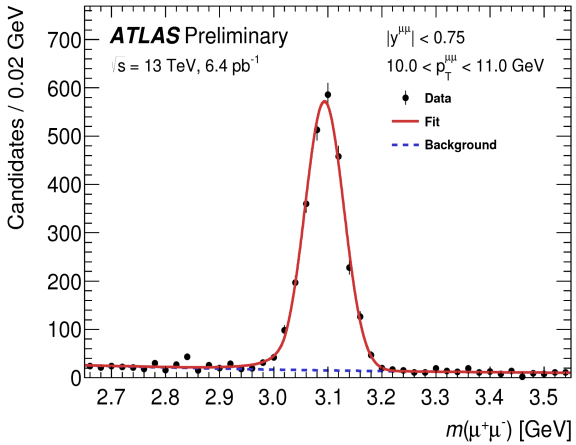



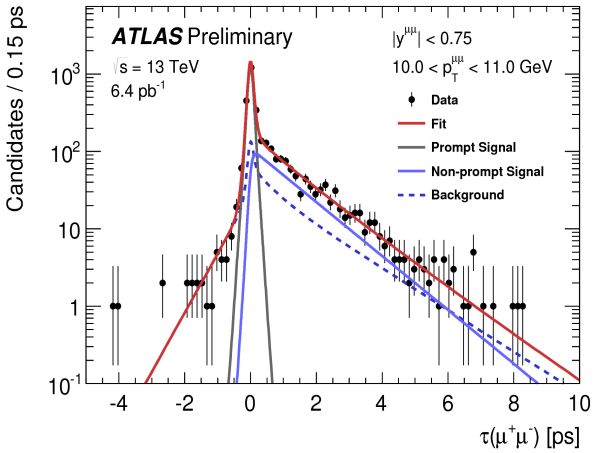

**Prompt J/ψ fraction**

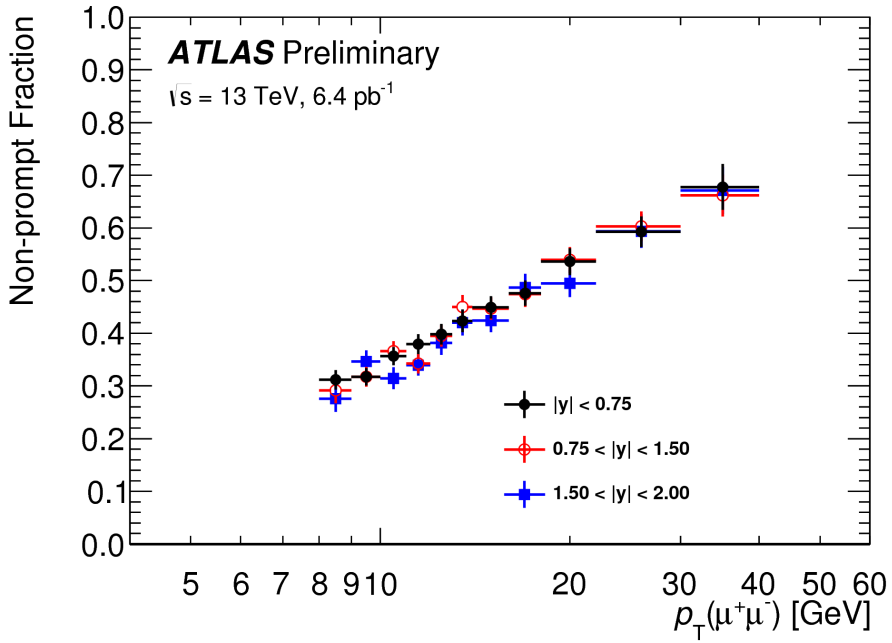
# Fraction of Non-Prompt J/ψ at 13 TeV

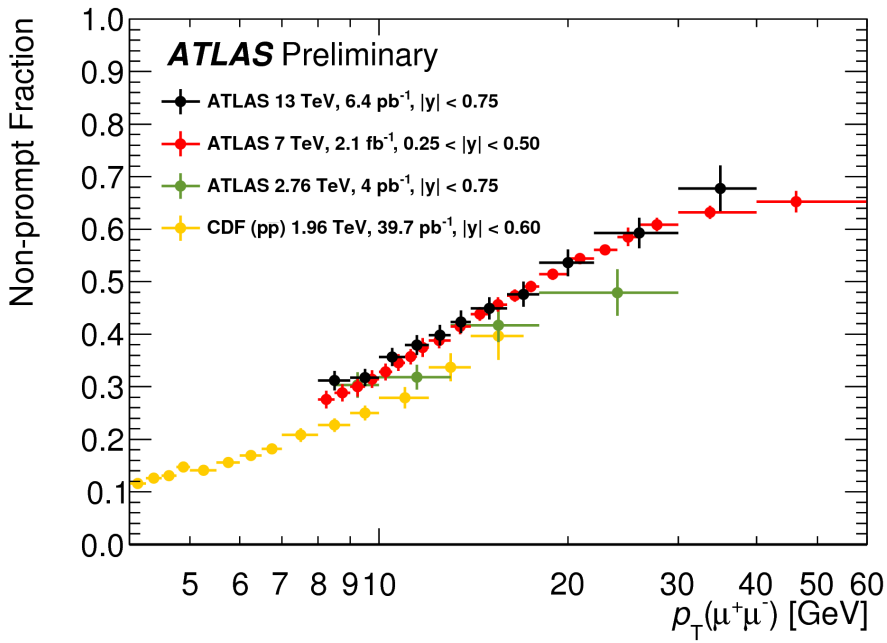


- Early data sample 6.4 pb$^{-1}$ collected with di-muon triggers
- Yields extracted from an un-weighted and unbinned fit to 2D di-muon mass and proper decay time
- Efficiencies and acceptance cancels to a good approximation in the non-prompt fraction




- Interesting trends in dependence on √s, though little change between 7 and 13 TeV

# J/ψ, ψ(2S) and ϒ(ns) Production in p+p, p+Pb collisions at 5.02 TeV

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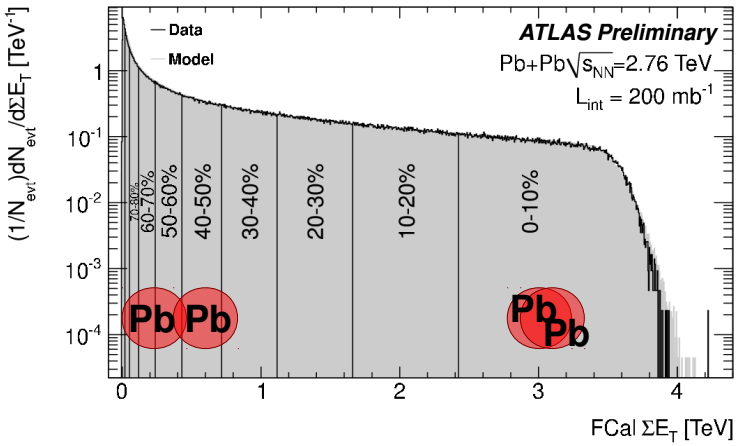
# Quarkonium Production in A/p+A Collisions

- Probe deconfined quark-gluon plasma in A+A collisions
  - Suppression (=melting) could provide info about temperature and deg. of deconfinement
  - Enhancement could also appear; at low-$p_T$ => new quarkonium formation mechanism (recombination of $c\bar{c}$ from the medium)
  - Non-prompt allows studying b-quark propagation through the medium
    - Possibly different mechanism (collisions, radiation) from $c\bar{c}$ suppression (color screening)
- Collisions of p+A to disentangle cold nuclear matter effects (CNM)
- Suppression of charmonium production relative to pp collisions
  - J/ψ suppressions in p+Pb seen at low $p_T$ and high y (LHCb, ALICE), but not at ATLAS/CMS
- Suppression of relative production of the (1S) and (nS) charmonium states in p+A (and A+A) vs. the pp coll.
  - ψ(2S) / J/ψ suppression at PHENIX, ALICE
    ϒ(nS) / ϒ(1S) suppression at CMS
  - Detector effects cancel, easy experiments comparison
  - Only final-state CNM effects (initial-states effects cancel)
  - Centrality dependence

$$R_{p\mathrm{Pb}} = \frac{1}{208}\frac{\sigma^{O(nS)}_{p+\mathrm{Pb}}}{\sigma^{O(nS)}_{pp}} \qquad \rho^{O(nS)/O(1S)}_{p\mathrm{Pb}} = \frac{R_{p\mathrm{Pb}}(O(nS))}{R_{p\mathrm{Pb}}(O(1S))}$$

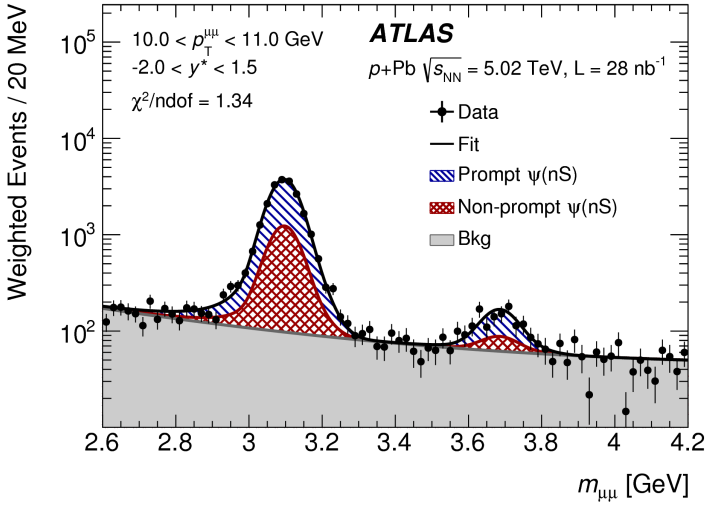
Centrality characterized by $E_T$ in forward calorimeter (FCAL) In the Pb-going side

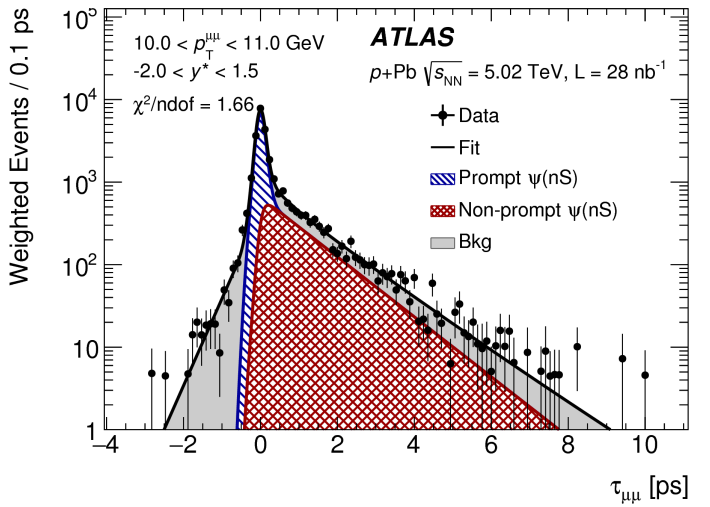


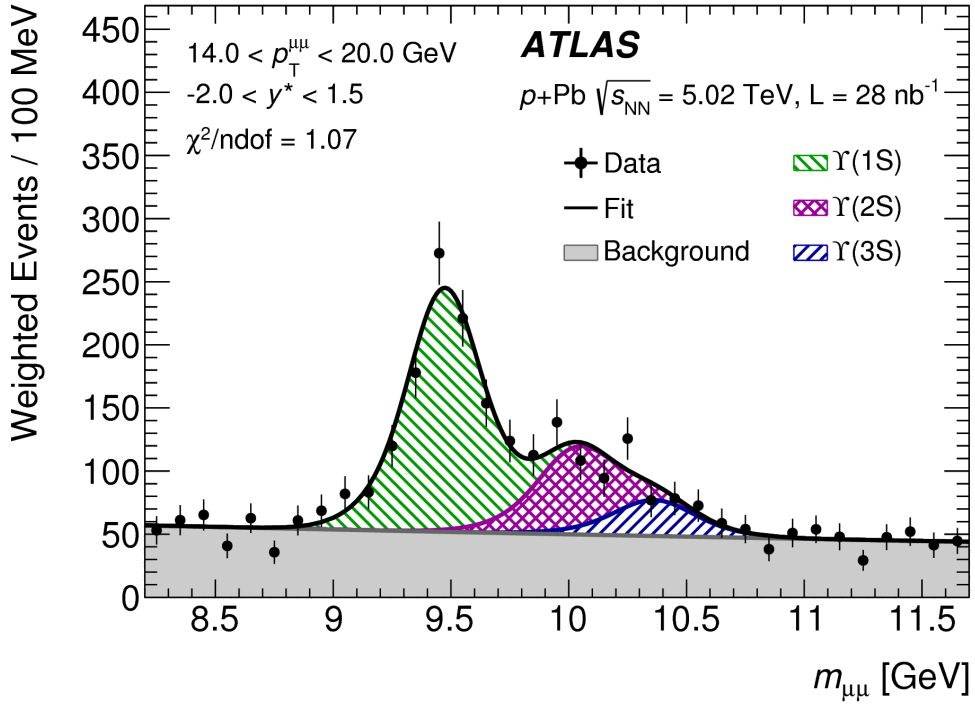
# Measurement Method



- Data (25 $pb^{-1}$ pp, 28 $nb^{-1}$ pPb @ 5.02 TeV) collected using di-muon triggers
- Basic di-muon selection: $p_T(\mu_{1,2}) > 2$ GeV (pPb) or 4 GeV (pp)
- Assuming unpolarized quarkonia
- Candidate extraction method using mass pseudo-lifetime fits; for $\Upsilon$(nS) mass fit only



# Quarkonium Production in p+Pb: Results

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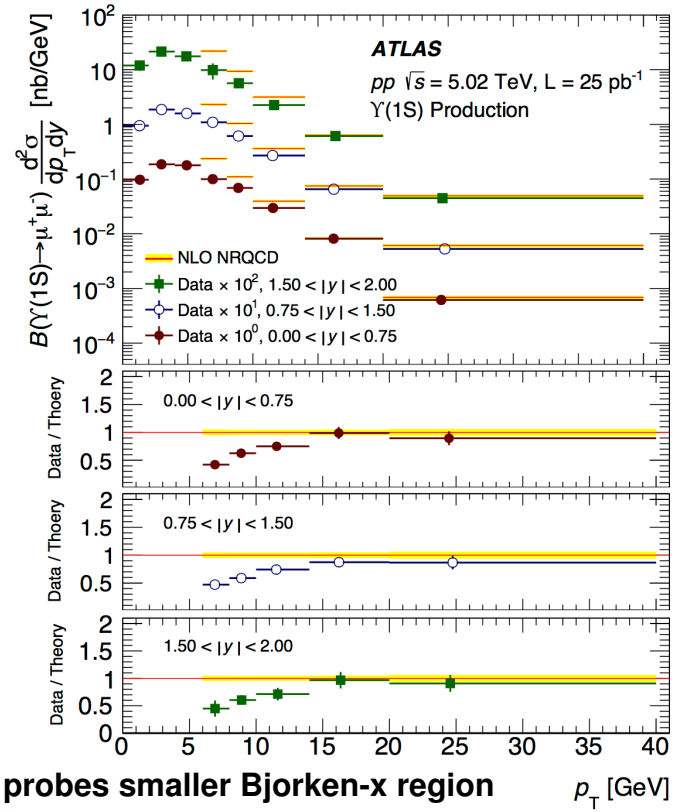
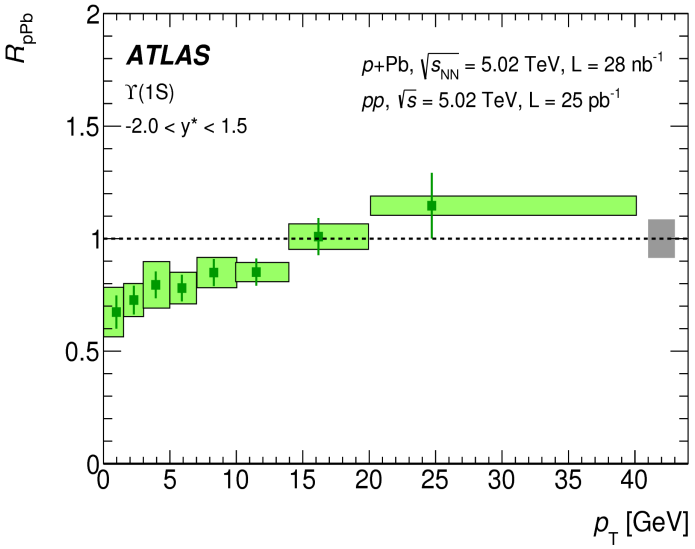
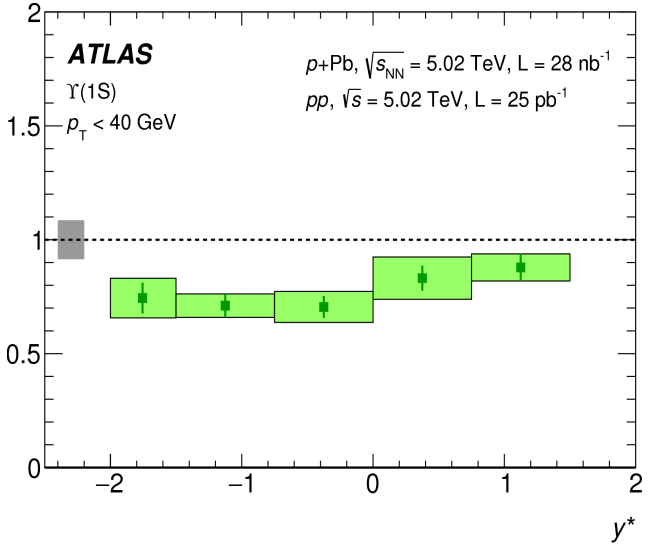
- Prompt charmonium production in $p_T$ 8-40 GeV x-section compatible with NRQCD, bottomonium only at $p_T$ > 15 GeV
- Non-prompt charmonium consistent with FONLL calculations
- R-factors of prompt and non-prompt J/ψ consistent with unity (no $p_T$ and y* dependence)
  - Weak modification of J/ψ production due to CNM effects
- R-factors of ϒ(1S) below 1 at $p_T$ < 15 GeV, compatible with 1 above; no y* dependence
  - Nuclear parton distribution functions modified relative to of nucleon (nPDF shadowing)




**probes smaller Bjorken-x region**



# Quarkonium Production in p+Pb: Results

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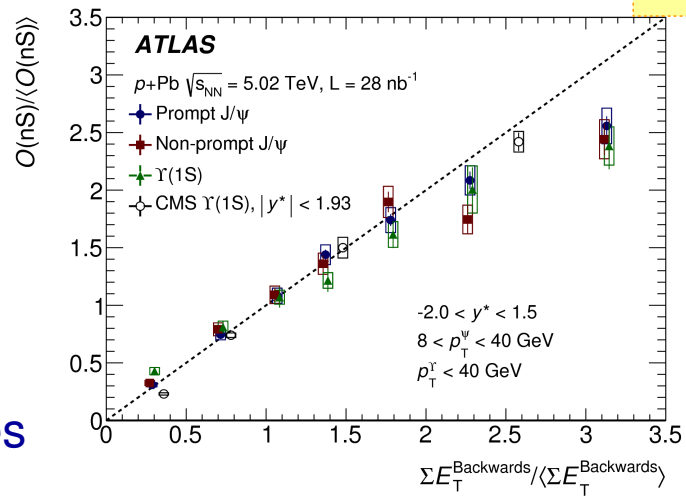
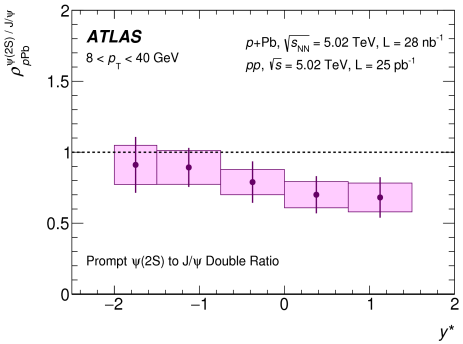
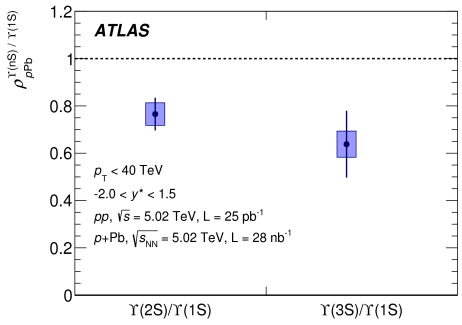
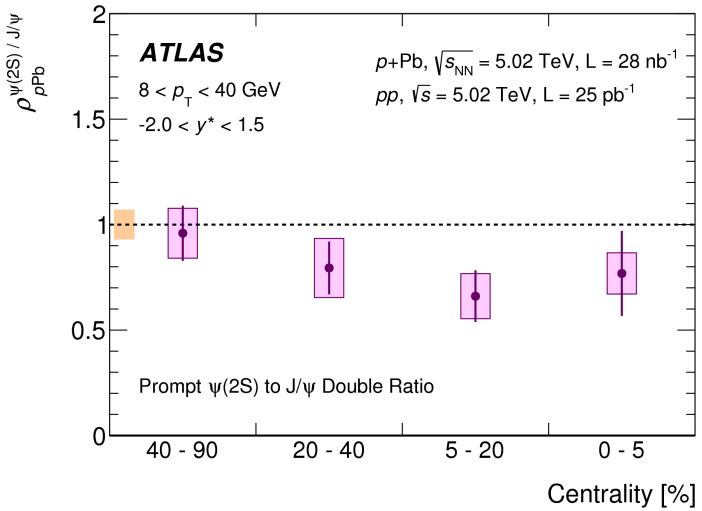
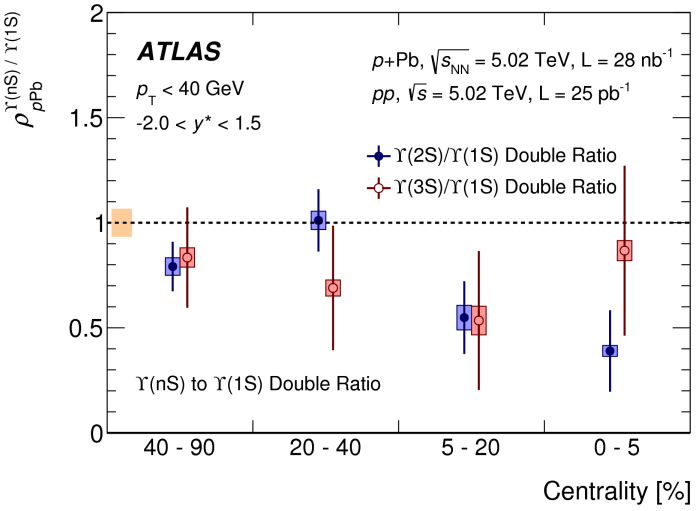
- Production of ratios of prompt and non-prompt J/ψ to Z constant vs. centrality
- Linear correlation trend in self-normalized yields of ground states vs. self-normalized event activity (2σ at deviation at the highest event activity)
  - Self-normalized event activity not robust enough scale param. ?
- Double ratios in p+Pb:
  - Charmonium suppression increases with rapidity (1σ),
  - ϒ suppression by 2σ in $p_T$ < 40 and -2 < y* < 1.5
  - Both more suppressed with more central collisions (1σ)
- Stronger CNM effect in excited quarkonium w.r.t. ground states
  ground states follow Z-boson behavior



# Summary

- Presented latest ATLAS results on charmonimum production
  - Production of J/ψ and ψ(2S) in 7 & 8 TeV p+p collisions
  - Production of J/ψ, ψ(2S) and ϒ(nS) in 5.02 TeV p+p and p+Pb collisions

- ATLAS shall continue its B-physics program in the Run 2,3 and the HL-LHC era, continue focusing on precision measurements, rare decays and heavy flavour production and spectroscopy
  - Detector upgrades (namely in **tracking** and **muon system**) and new **trigger strategies** and tools will help to cope with the high-luminosity environment
  - **See talk of Wolfgang Walkowiak on Friday 11:30**

# Backup

# B-Physics at the ATLAS Experiment

- Triggering $|\eta| < 2.4$
- Precision Tracking $|\eta| < 2.7$

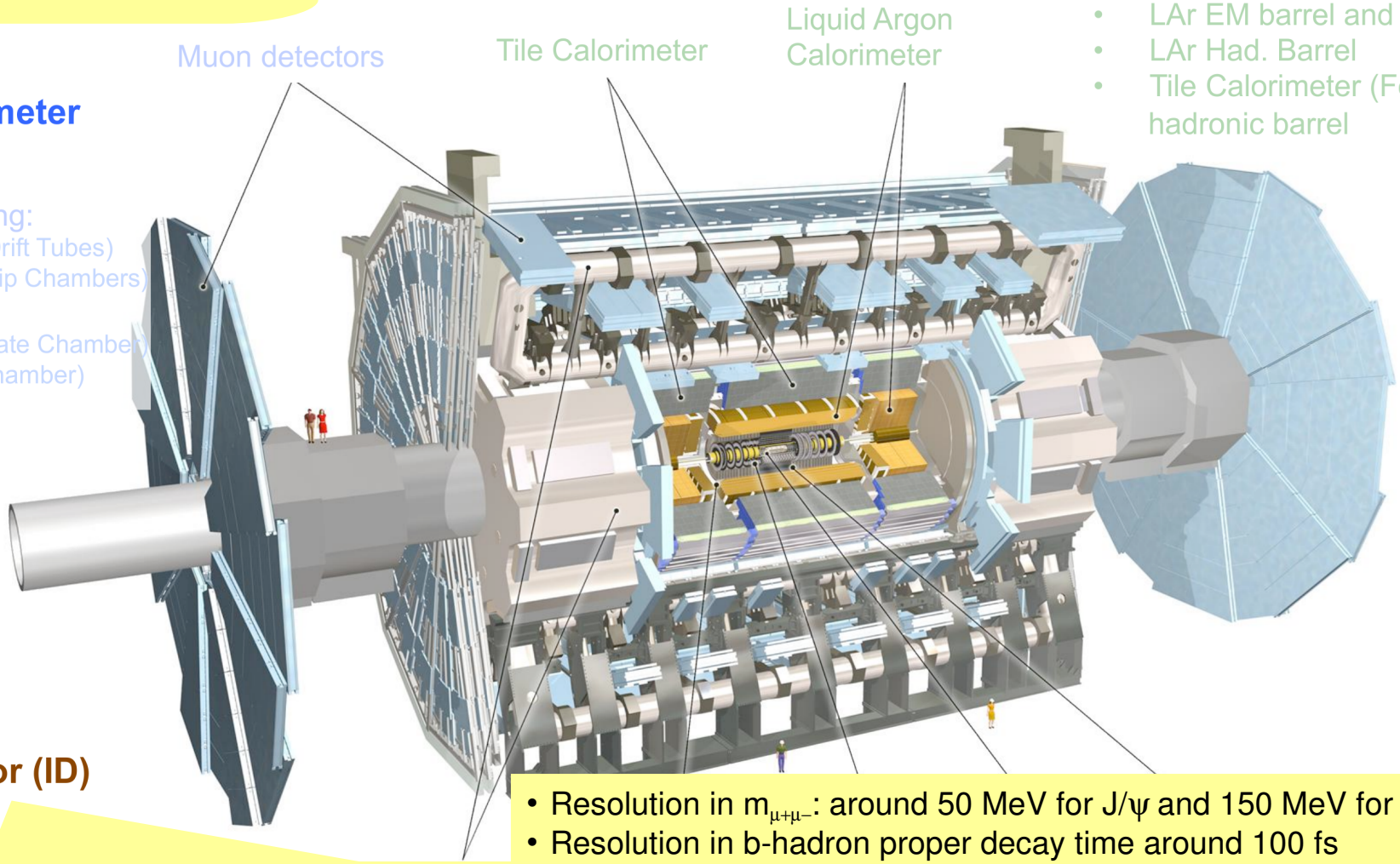
**Muon Specrometer**

Toroid Magnets
Precision μ tracking:
- MDT (Monitored Drift Tubes)
- CSC (Cathode Strip Chambers)

Trigger:
- RPC (Resistive Plate Chamber)
- TGC (Thin Gas Chamber)

**Calorimeter System**

EM and Hadronic energy
- LAr EM barrel and EC
- LAr Had. Barrel
- Tile Calorimeter (Fe-Scin.) hadronic barrel



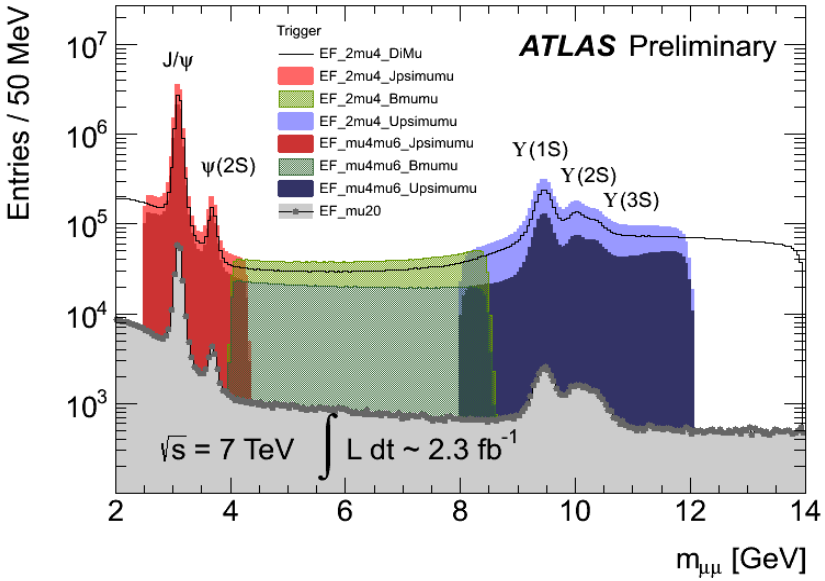

**Inner Detector (ID)**

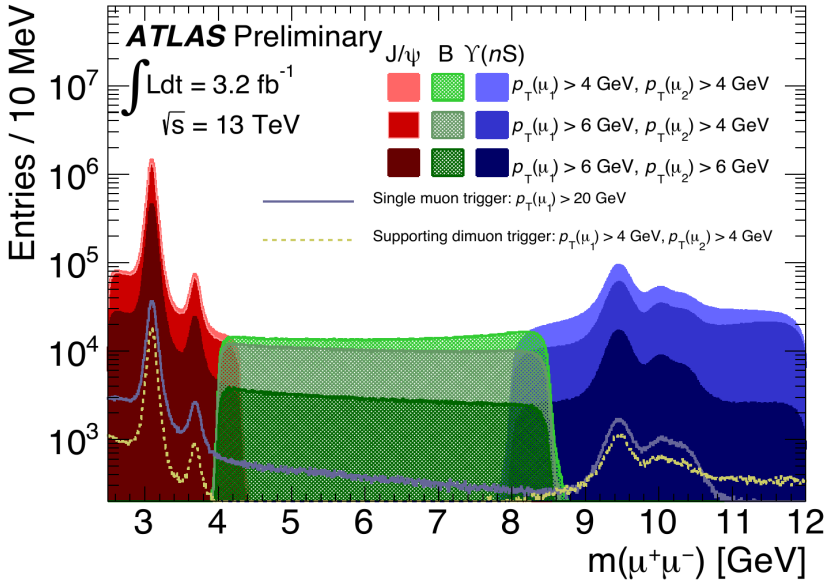
- Resolution in $m_{\mu+\mu-}$: around 50 MeV for J/ψ and 150 MeV for ϒ(nS)
- Resolution in b-hadron proper decay time around 100 fs (no IBL, ~30% improvement expected)

- $p_T > 0.4$ GeV, $|\eta| < 2.5$
- New for Run2: Insertable B-Layer (IBL): an additional inner-most pixel layer (r = 33mm) => ~30% more precise secondary vertex reconstruction

# B-Physics Trigger

- **Datasets (pp):** 7 TeV data, 5.08 $fb^{-1}$ 50ns, 3.7x$10^{33}$ $cm^{-2}s^{-1}$ | 8 TeV, 21.3 $fb^{-1}$ 50ns, 7.7x$10^{33}$ $cm^{-2}s^{-1}$ | 13 TeV, 3.9+35.6 $fb^{-1}$ 50/25ns, 13.8x$10^{33}$ $cm^{-2}s^{-1}$
- 20/40 MHz collision rate → ~400 Hz recording
- B-physics concentrates on low-$p_T$ di-muon signatures:
  - Quarkonia: J/ψ → μμ, ϒ → μμ, etc.
  - Exclusive B → J/ψ(μμ)X decays
  - Rare and semi-rare B → μμ(X) decays
- Trigger on low-$p_T$ (4,6 GeV) di-muon
  - 2 muons at L1 (HW-based)
  - Confirmed at HLT
  - Track vertex fit and mass cuts at HLT
- 8 TeV data: low-$p_T$ maintained introducing barrel triggers
- 13 TeV data: low-$p_T$ maintained using barrel triggers, introduce coarse topological cuts (HW, opening angle, inv. mass) in 2016



# Measurements in p+p, p+Pb and Pb+Pb

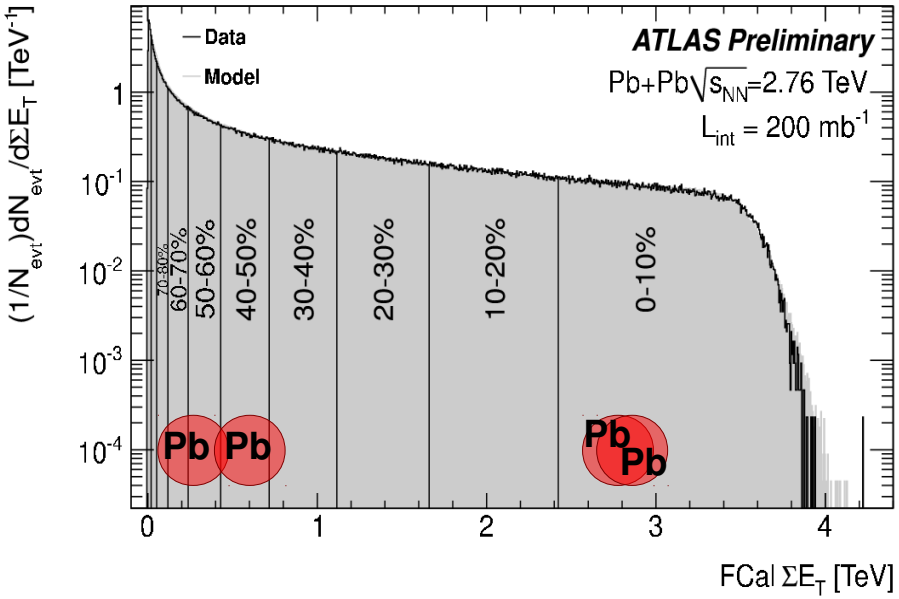
- Measured Quantities
  - Cross-sections
  - Charmonium suppression: nuclear modification factor R
  - Higher states suppression: double-ratios
  - Prompt / non-prompt charmonium
  - $p_T$ , rapidity and centrality dependences

$$R_{p\mathrm{Pb}} = \frac{1}{208}\frac{\sigma^{O(nS)}_{p+\mathrm{Pb}}}{\sigma^{O(nS)}_{pp}}$$

$$\rho^{O(nS)/O(1S)}_{p\mathrm{Pb}} = \frac{R_{p\mathrm{Pb}}(O(nS))}{R_{p\mathrm{Pb}}(O(1S))} = \frac{\sigma^{O(nS)}_{p+\mathrm{Pb}}}{\sigma^{O(1S)}_{p+\mathrm{Pb}}} \Big/ \frac{\sigma^{O(nS)}_{pp}}{\sigma^{O(1S)}_{pp}}$$

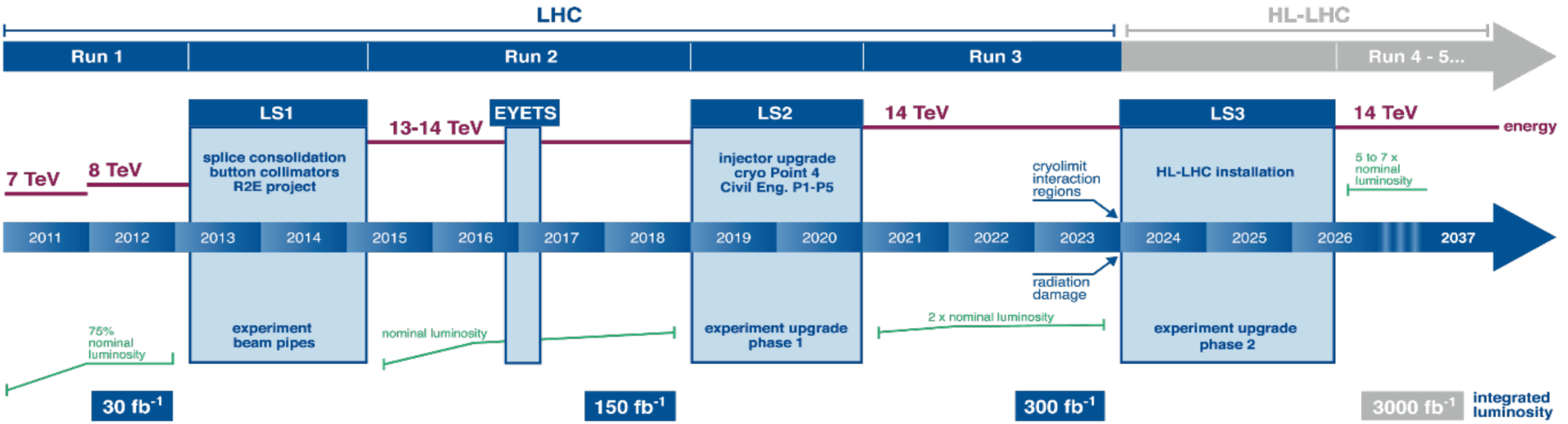
- Rapidity y* and centrality definition
  - In p+Pb collisions, the CMS y* rapidity has shift of 0.465 w.r.t. rapidity y in lab-frame
  - After 60% of data recorded, p and Pb beams were reversed

Centrality characterized by $E_T$ in forward calorimeter (FCAL)

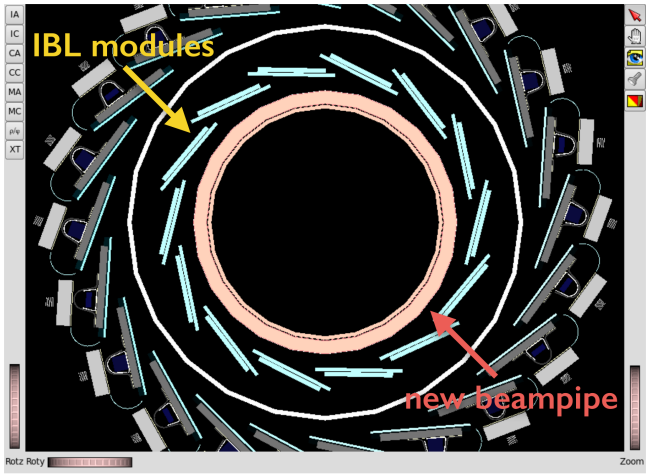


# Measurements in Run-2 and Beyond

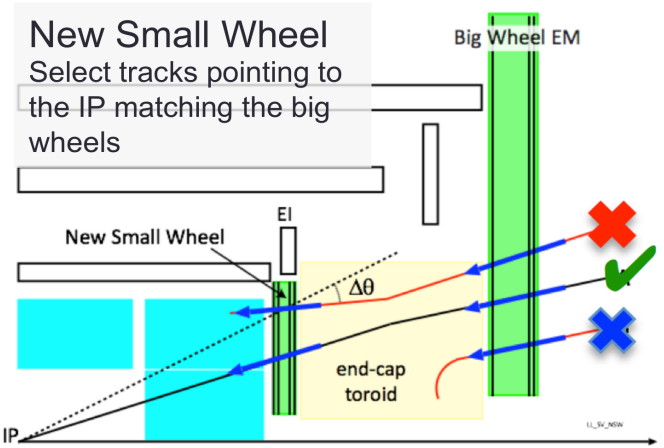
## LHC / HL-LHC Plan




- 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; available in Run-2




- Completely new Si based tracker (ITK)