B-physics in ATLAS: production and spectroscopy

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Introduction

B-physics in ATLAS

- Possible to measure heavy flavour production at *highest possible energies*
- Much *higher HF yields* in pp environment compared to B-factories
- Possible to produce *all possible heavy states* → extended spectroscopy studies
- ATLAS and CMS, although not specially optimized for B-physics, provide *complementary kinematic region to LHCb*
  - Benefit from *higher statistics* in certain analyses

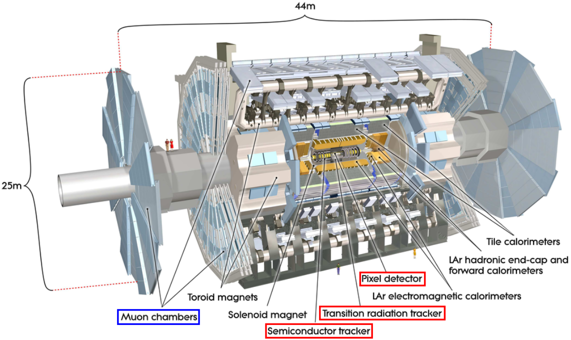
- This talk covers a selection of ATLAS results on heavy flavour production and spectroscopy of last 2–3 years
  - Heavy flavour decay results are presented in the talk by Vladimir Lyubushkin

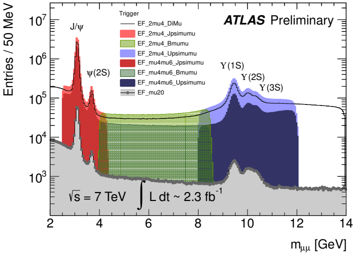
ATLAS results overview

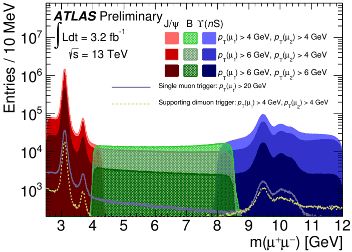
(red = in this talk)

- Search for structures in $B_s^0\pi^\pm$ mass spectrum (Run 1) – Submitted to Phys. Rev. Lett.
- Quarkonia production in $p+Pb$ and pp at 5.02 TeV – Submitted to Eur. Phys. J. C
- b hadron pair production measurement at 8 TeV – JHEP 11 (2017) 62
- Prompt di-J/ψ production at 8 TeV – Eur. Phys. J. C 77 (2017) 76
- $X(3872)$ and $\psi(2S)$ production in decays to $J/\psi\pi\pi$ in at 8 TeV – JHEP 01 (2017) 117
- Production of J/ψ and $\psi(2S)$ at 7 and 8 TeV – Eur. Phys. J. C 76 (2016) 283
- Charmed meson production at 7 TeV – Nucl. Phys. B 907 (2016) 717
- Measurement of b quark fragmentation ratio f_s/f_d in at 7 TeV – Phys. Rev. Lett. 115 (2015) 262001
- Associated production of J/ψ and Z boson at 8 TeV – Eur. Phys. J. C75 (2015) 229
- Non-prompt fraction of J/ψ production at 13 TeV – ATLAS-CONF-2015-030
- Search for hidden beauty states in $\Upsilon(1S)\pi\pi$ final state at 7 TeV – Phys. Lett. B 740 (2015) 199
- $\psi(2S)$ production in decays to $J/\psi\pi\pi$ in at 7 TeV – JHEP 09 (2014) 079
- Observation of an excited state of B_c meson (Run 1) – Phys. Rev. Lett. 113 (2014) 212004
- $\chi_{c1,2}$ production at 7 TeV – JHEP 07 (2014) 154
- Associated production of J/ψ and Z boson at 7 TeV – JHEP 04 (2014) 172
- B^+ production at 7 TeV – JHEP 10 (2013) 042
- Observation of $\chi_b(3P)$ through radiative decays – Phys. Rev. Lett. 108 (2012) 152001

ATLAS detector and trigger for B-physics







D meson production cross-section measurement

Nucl. Phys. B 907 (2016) 717 / `arXiv:1512.02913`

Motivation

- Heavy quark production measurement at LHC → test of pQCD calculations at highest possible energies
    - Charmed mesons are produced in *charm hadronization* and b *hadron decays*
- Various theoretical approaches available
    - Fixed-order + next-to-leading-logarithm (FONLL) predictions
    - General-mass variable-flavour-number-scheme (GM-VFNS) calculations
    - NLO QCD calculations matched to LL parton-shower MC
        - MC@NLO matched to HERWIG
        - POWHEG matched to HERWIG or PYTHIA

Analysis overview

- Data of 2010 at $\sqrt{s} = 7$ TeV are used
  - 1.04 nb^{-1} collected with minimum-bias triggers used for $p_{\mathrm{T}} < 20$ GeV range
  - 280 nb^{-1} with jet triggers for $20 < p_{\mathrm{T}} < 100$ GeV range
- Measurement kinematic range:
  - $3.5 < p_{\mathrm{T}}(D) < 100$ GeV
  - $|\eta(D)| < 2.1$
- D meson decays used:

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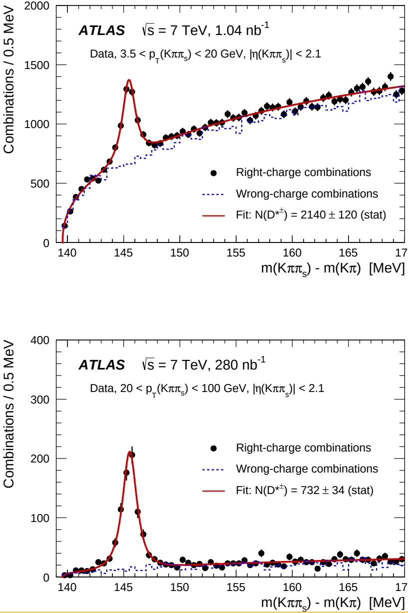

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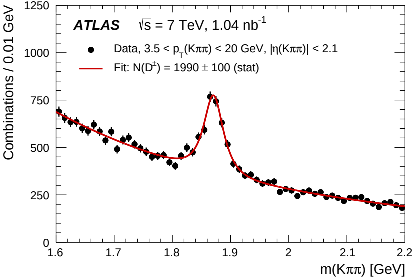

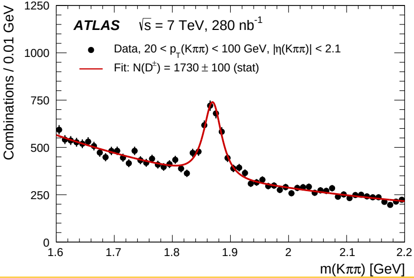

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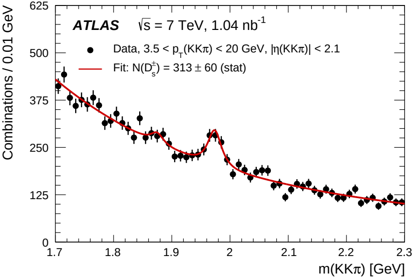
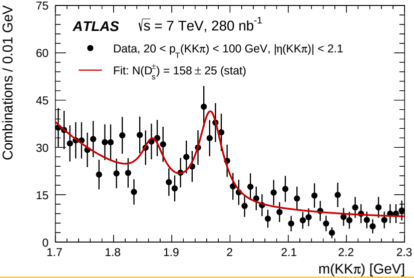
  - $D^+ \to K^-\pi^+\pi^+$
  - $D_s^+ \to \phi\pi^+ \to (K^+K^-)\pi^+$





Results: visible cross-sections

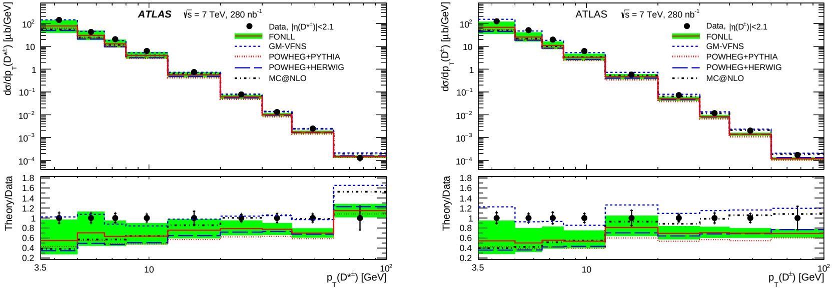
- Visible cross-sections measured:

	$\sigma^{\text{vis}}(D^{*\pm})$		$\sigma^{\text{vis}}(D^{\pm})$		$\sigma^{\text{vis}}(D_s^{*\pm})$	
Range [units]	low-p_T [μb]	high-p_T [nb]	low-p_T [μb]	high-p_T [nb]	low-p_T [μb]	high-p_T [nb]
ATLAS	331 ± 36	988 ± 100	328 ± 34	888 ± 97	160 ± 37	512 ± 104
GM-VFNS	340^{+130}_{-150}	1000^{+120}_{-150}	350^{+150}_{-160}	980^{+120}_{-150}	147^{+54}_{-66}	470^{+56}_{-69}
FONLL	202^{+125}_{-79}	753^{+123}_{-104}	174^{+105}_{-66}	617^{+103}_{-86}	-	-
POWHEG+PYTHIA	158^{+179}_{-85}	600^{+300}_{-180}	134^{+148}_{-70}	480^{+240}_{-130}	62^{+64}_{-31}	225^{+114}_{-69}
POWHEG+HERWIG	137^{+147}_{-72}	690^{+380}_{-160}	121^{+129}_{-64}	580^{+280}_{-140}	51^{+50}_{-25}	268^{+107}_{-62}
MC@NLO	157^{+125}_{-72}	980^{+460}_{-290}	140^{+112}_{-65}	810^{+390}_{-260}	58^{+42}_{-25}	345^{+175}_{-87}

- Statistical and systematics uncertainties generally of the same order
  - Tracking efficiency, luminosity and $\mathcal{B}$ are the main systematics sources

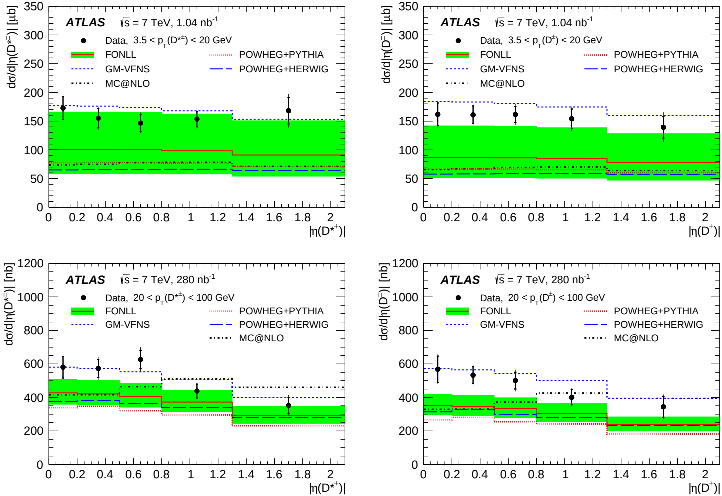
- GM-VFNS approach shows the best description of data
- FONLL and NLO+PS approaches are generally below data, but still consistent within uncertainties

Results: differential cross-sections – p_{T}



- GM-VFNS describes well both shape and normalization
- FONLL and NLO+PS are still consistent with data
- MC@NLO predicts harder p_{T} spectrum than in data

Results: differential cross-sections – η



- GM-VFNS is still the best
- MC@NLO has different η shape

Results: extrapolation

- For extrapolation to the full phase space, *FONLL* predictions are used (including subtraction of b contribution)
  - POWHEG+PYTHIA are used for extraction of fragmentation ratios
- Full $c\bar{c}$ production x-section:

$$\sigma^{\text{tot}}_{c\bar{c}} = 8.6 \pm 0.3\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.3\,(\text{lum}) \pm 0.2\,(\text{ff})^{+3.8}_{-3.4}\,(\text{extr})\,\text{mb}$$

  - Good agreement with ALICE measurement
- Charm fragmentation ratios:

$$\gamma_{s/d} = 0.26 \pm 0.05\,(\text{stat}) \pm 0.02\,(\text{syst}) \pm 0.02\,(\text{br}) \pm 0.01\,(\text{extr})\,,$$

$$P^d_{\text{v}} = 0.56 \pm 0.03\,(\text{stat}) \pm 0.01\,(\text{syst}) \pm 0.01\,(\text{br}) \pm 0.02\,(\text{extr})\,.$$

  - Good agreement with ALICE, HERA (ep) measurements and LEP averages
  - P^d_{v} is smaller than expectation from HQET (0.75), string fragmentation and thermodynamical approach (2/3)

Overall uniquely advanced measurement for LHC general-purpose detectors!

b hadron pair production measurement

JHEP 1711 (2017) 062 / `arXiv:1705.03374`

Motivation and strategy

- A number of recent measurement of b production highlighted certain disagreements between models and data
- Especially $b\bar{b}$ production at small open angles is *sensitive to the details of various calculations*, but only *loosely constrained experimentally*
- Studies of $H \to b\bar{b}$ much rely on modelling of $b\bar{b}$ production in this region

- Measure $b\bar{b}$ pair production
    - one b is identified via $H_b \to J/\psi + X$ decay
    - the other via $H_b \to \mu + X$
- Differential cross-sections are measured in
    - $\Delta\phi(J/\psi, \mu)$,
    - $p_\mathrm{T}(J/\psi, \mu)$,
    - $\Delta R(J/\psi\mu)$ overall and in bins of $p_\mathrm{T}(J/\psi, \mu) < 20\,\mathrm{GeV}$ and $p_\mathrm{T}(J/\psi, \mu) > 20\,\mathrm{GeV}$,
    - $\Delta y(J/\psi, \mu)$,
    - average rapidity of J/ψ and μ, y_boost,
    - $m(J/\psi, \mu)$
    - $p_\mathrm{T}(J/\psi, \mu)/m(J/\psi, \mu)$ and its inverse
- 11.5 fb^{-1} of $\sqrt{s} = 8\,\mathrm{TeV}$ are used

Analysis details

- Fiducial volume definition:
  - $p_{\mathrm{T}}(\mu) > 6$ GeV for all three muons
  - $|\eta(\mu)| < 2.3$ for the J/ψ muons and < 2.5 for the 3rd muon
- Signal extraction, in each bin

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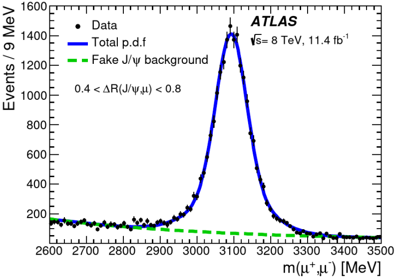

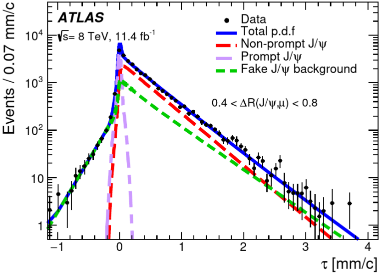

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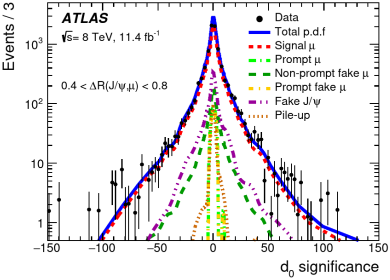
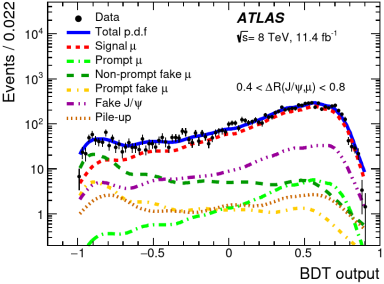
  - Yield of 3rd muon from b determined by fit to $d_0/\sigma(d_0)$ and BDT output
    - in signal-enriched region of $\tau > 0.25\,\mathrm{mm}/c$





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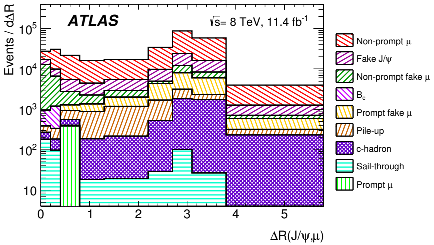
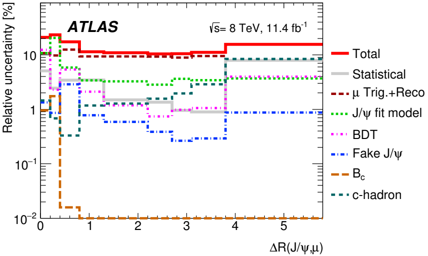
  - Subtract irreducible backgrounds
    - $B_c^+ \to J/\psi\mu^+X$, prompt charm, fake muons





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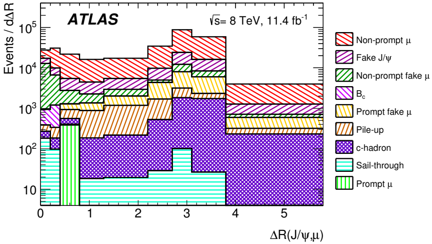
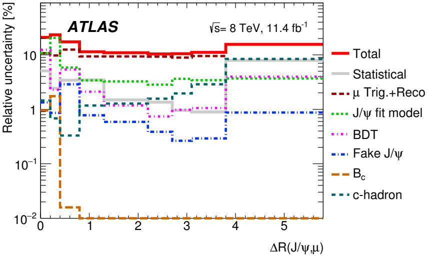
  - Subtract irreducible backgrounds
    - $B_c^+ \to J/\psi\mu^+ X$, prompt charm, fake muons
  - Extrapolate to full τ range
  - Correct for detector resolution effects



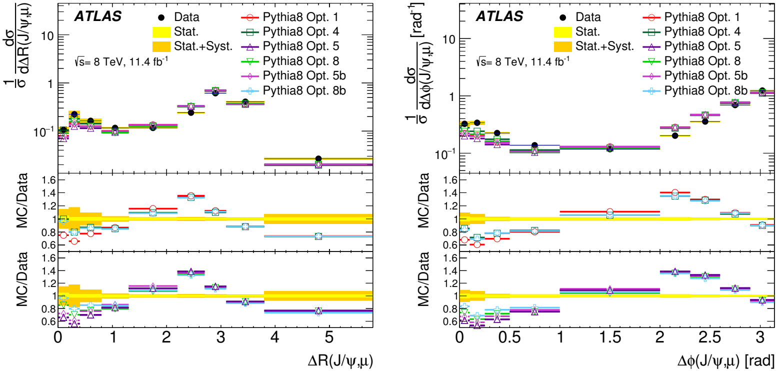


Results (1)

- Full fiducial cross-section:

$$\sigma(B(\to J/\psi[\to \mu^+\mu^-] + X)B(\to \mu + X)) = 17.7 \pm 0.1(\mathrm{stat}) \pm 2.0(\mathrm{syst})\ \mathrm{nb}.$$

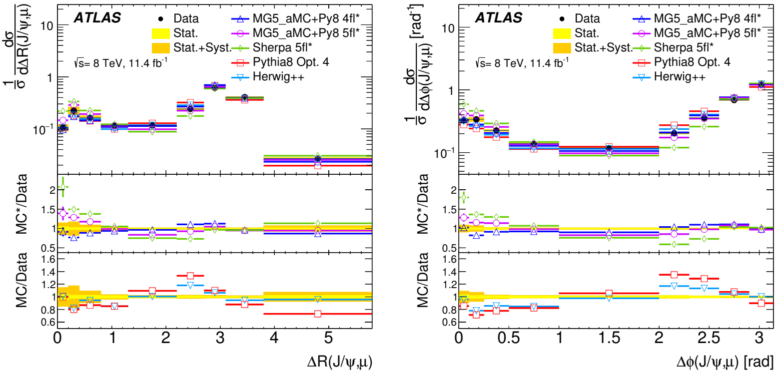
- Test various gluon splitting kernels in PYTHIA 8:



- PYTHIA generally does not describes these shapes
- p_{T}-based scale splitting kernels behave better for close-by $b\bar{b}$

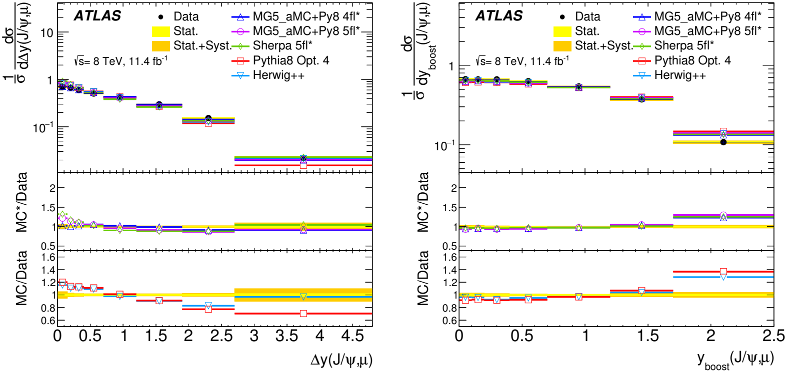
Results (2)

- Comparison with other generator predictions:
  - HERWIG++
  - MADGRAPH_AMC@NLOv2.2.2 interfaced to PYTHIA 8, 5- and 4-FNS
  - SHERPA 2.1.1 (5-FNS)
- HERWIG++ reproduces ΔR and $\Delta\phi$ best
- 4-FNS works better for ΔR and $\Delta\phi$ than 5-FNS (on either sides VS data)



Results (3)

- Comparison with other generator predictions:
  - Herwig++
  - MadGraph_aMC@NLOv2.2.2 interfaced to Pythia 8, 5- and 4-FNS
  - Sherpa 2.1.1 (5-FNS)
- MG and Sherpa has better agreemend in Δy, y_{boost}
- Overall, 4-FNS provides better description of data; Pythia and Herwig++ are comparable and further tuning may improve



Conclusion

- **Very comprehensive measurement** of differential cross-section of $b\bar{b}$ production performed
  - in 10 kinematic observables
- Particularly sensitive to close-by $b\bar{b}$ pairs down to zero open angle
- Various predictions compared to data
  - different ME, PS models, 4-/5-flavour treatment; g splitting kernels

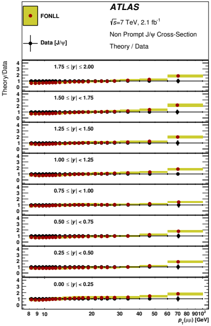
- *New test of QCD, motivate the choice of calculations used to model b hadron production and their further tuning*

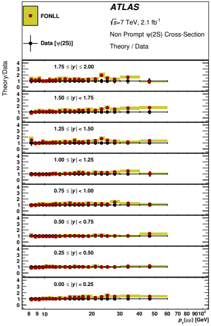
Non-prompt J/ψ production fraction measurement at $\sqrt{s} = 13\,\text{TeV}$

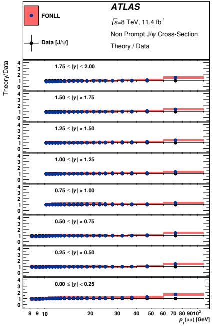
ATLAS-CONF-2015-030

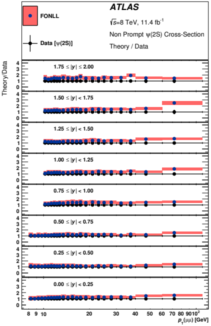
Motivation

- Heavy quarkonium producion is of interest for testing QCD calculations at the boundary of perturbative and non-perturbative regimes
  - Despite a large progress for last decades, challenges still remain in a coherent theoretical picture to explain all measurements simultaneously
- Some discrepancy earlier observed between FONLL description of non-prompt charmonia and data in ATLAS (Eur. Phys. J. C 76 (2016) 283)
- Methodically, J/ψ is a good tool for early calibration of detector









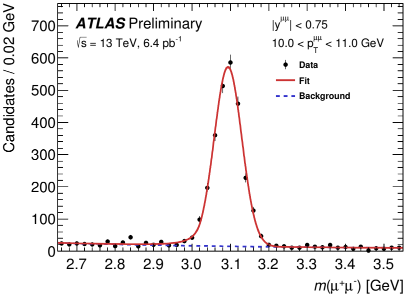
Analysis technique

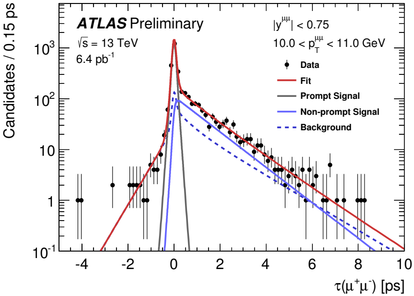
- Use 6.4 pb^{-1} of $\sqrt{s} = 13$ TeV data
- Fiducial region: $p_{\mathrm{T}}(J/\psi) > 8$ GeV, $|\eta(J/\psi)| < 2.0$
- Measure non-prompt J/ψ fraction, in bins of p_{T} and $|\eta|$ as

$$f_b^{J/\psi} \equiv \frac{pp \to b + X \to J/\psi + X'}{pp \xrightarrow{\text{Inclusive}} J/\psi + X'} = \frac{N^{\mathrm{NP}}_{J/\psi}}{N^{\mathrm{NP}}_{J/\psi} + N^{\mathrm{P}}_{J/\psi}}$$

- Simultaneous mass and pseudo-proper lifetime fit with PDF

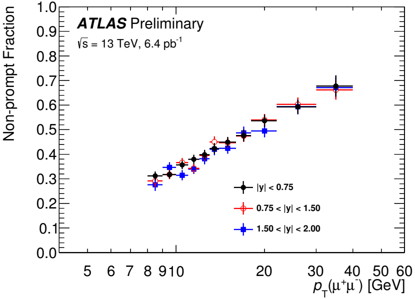
$$\mathrm{PDF}(m,\tau,\delta\tau) = \sum_{i=1}^{5} \kappa_i f_i(m) \cdot h_i(\tau) \otimes R(\tau,\delta\tau) \cdot g_i(\delta\tau)$$

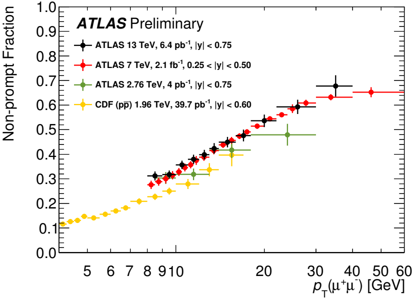




Results

- The NP fraction grows steadily from 0.25 to 0.65 between 8 and 40 GeV
- No sizeable dependence on rapidity
- Very similar shape to $\sqrt{s} = 7\,\text{TeV}$, but certain change compared to lower energies



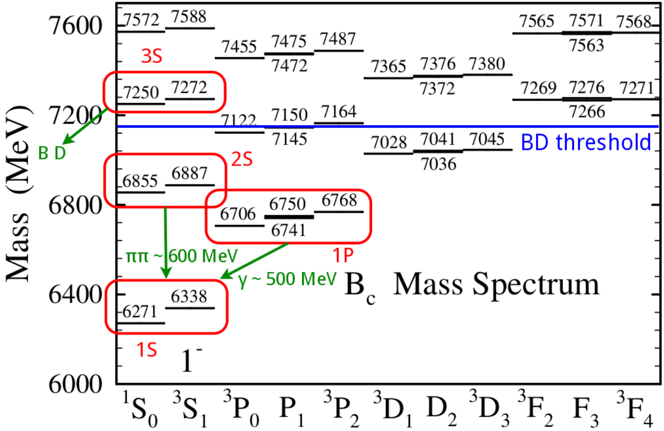


Observation of an excited state of B_c meson

Phys. Rev. Lett. 113 (2014) 212004 / `arXiv:1407.1032`

Motivation

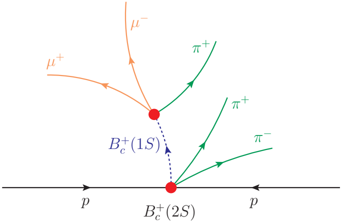
- No excited states of B_c^+ reported previously
- The spectrum and properties of B_c^+ family are predicted by non-relativistic potential models, perturbative QCD and lattice calculations
- Measurements of the ground and excited states → test of these predictions



Phys. Rev. D 70 (2004) 054017

Overview of $B_c^+(2S)$ search

- The analysis uses *7 TeV and 8 TeV pp collisions data*
  - 4.9 $\text{fb}^{-1}$and 19.2 fb^{-1}, respectively



- *J/ψ candidates* reconstructed by fitting a muon pair to a common vertex
- Combining a J/ψ candidate with another track → *$B_c^+(1S)$ candidate*
  - Di-muon mass is constrained to the J/ψ world average in 3-prong vertex fit
- *$B_c^+(2S)$ candidates* formed from $B_c^+(1S)$ and two tracks from primary vertex with $\pi^\pm$ masses assigned
  - Cascade fit with $B_c^+(1S)$ combined momentum *constrained to point to $B_c^+(2S)$ vertex*

$B_c^+(1S)$ selection and fit

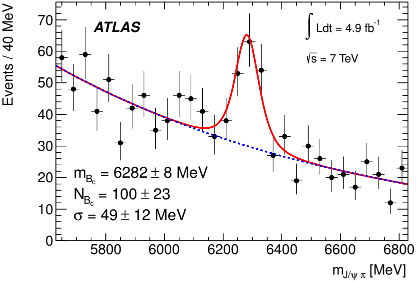
$\mathbf{B_c^+(1S)}$ selection for 2011 (2012) data

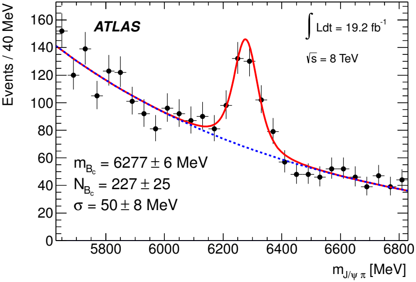
- $p_{\mathrm{T}}(\mu_1, \mu_2) > 4, 6$ GeV
- $\chi^2/\mathrm{n.d.f.}(J/\psi) < 15$
- $m(J/\psi)$ within $\pm 3\sigma$ of the nominal (σ depending on the rapidity range)

- $\chi^2/\mathrm{n.d.f.}(B_c^+) < 2.0\ (1.5)$
- $p_{\mathrm{T}}(B_c^+) > 15$ GeV (18 GeV)
- $\frac{d^0_{xy}}{\sigma(d^0_{xy})}(\pi^+) > 5\ (4.5)$

Extended unbinned fit of the mass distribution

- *Signal*: Gaussian with per-candidate errors
- *Background*: exponential





$B_c^+(2S)$ selection and fit

Selection of $\mathbf{B_c^+(2S) \to B_c^+(1S)\pi^+\pi^-}$ candidates

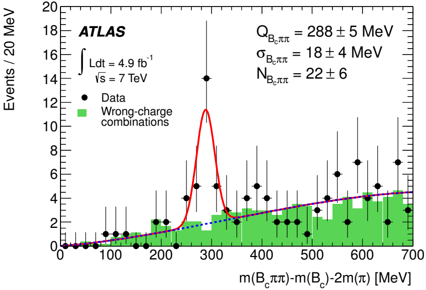
- $B_c^+(1S)$ candidates within $\pm 3\sigma$ of the fitted mass
- $p_{\mathrm{T}}(\pi^+, \pi^-) > 400$ MeV
- for several candidates in event, the one with the best cascade fit χ^2 is kept

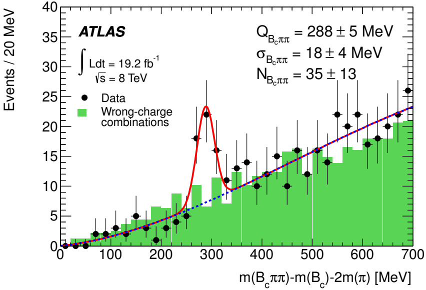
Extended unbinned fit of Q-value distribution

$$Q_{B_c^+\pi\pi} = m(B_c^+\pi^+\pi^-) - m(B_c^+) - 2m(\pi^+)$$

- *Signal*: Gaussian
- *Background*: 3rd order polynomial

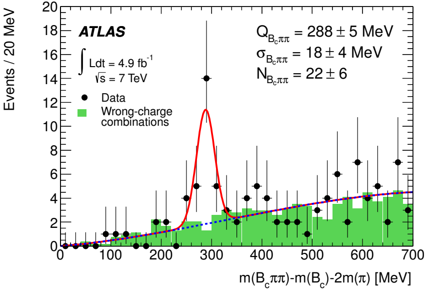
Wrong charge combination (same-sign π) used for background control

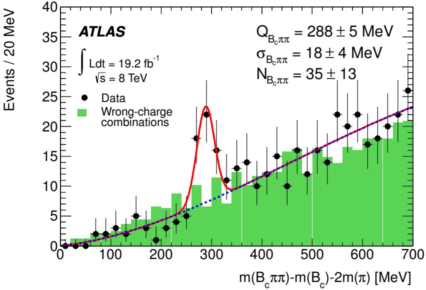




$B_c^+(2S)$ observation

- Significance of the observed signal calculated with toy studies accounting for a *"look elsewhere effect"*
  - 3.7σ in 7 TeV data
  - 4.5σ in 8 TeV data
  - Combined significance is 5.2σ
  - (local significance is 5.4σ)
- Dominant source of systematic of the Q-value is the *fitting procedure*
- A new state observed at $Q = 288.3 \pm 3.5\ (\text{stat.}) \pm 4.1\ (\text{syst.})$ MeV (error-weighted mean of 7 and 8 TeV values)
- Corresponds to a mass $6842 \pm 4\ (\text{stat.}) \pm 5\ (\text{syst.})$ MeV, that is consistent with the predicted mass of $B_c^+(2S)$





Search for hidden beauty states in $\Upsilon(1S)\pi\pi$ final state

Phys. Lett. B 740 (2015) 199 / `arXiv:1410.4409`

Motivation

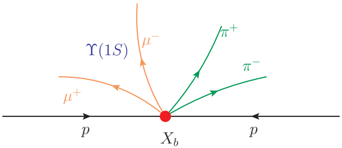
- $X(3872)$ is the best-studied new hidden-charm state, observed by many experiments (ATLAS measurement JHEP 01 (2017) 117)
- Mass, narrow width, $J^{PC} = 1^{++}$ → unlikely a conventional quarkonium
  - weakly bound $D^0 \bar{D}^{*0}$ *molecule*?
  - $[qc][\bar{q}\bar{c}]$ *tetraquark*?
- $$\frac{\sigma(pp \to X(3872))\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)}{\sigma(pp \to \psi(2S))\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi)} = (6.56 \pm 0.29 \pm 0.65)\%$$

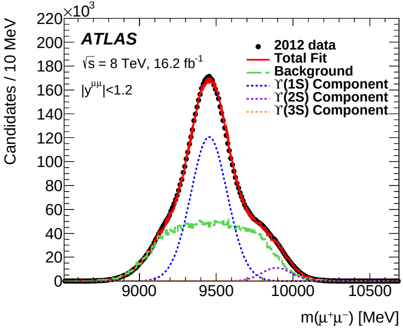
  (CMS, JHEP 04 (2013) 154, arXiv:1302.3968)
- Heavy-quark symmetry suggests a hidden-beauty partner X_b
  - Mass predictions vary (e.g. 10561 MeV for the molecular model of Swanson, Phys. Rep. 429 (2006) 243, arXiv:hep-ph/0601110)
- Decay $X_b \to \pi^+\pi^-\Upsilon(1S)$ is a straightforward way to reconstruct X_b

X_b reconstruction and selection

$\Upsilon(1S)$ reconstruction

- Use 16.2 fb^{-1} of $\sqrt{s} = 8$ TeV data (due to trigger prescales)
- $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.3$
- Dimuons in mass range ± 350 MeV around $\Upsilon(1S)$ mass





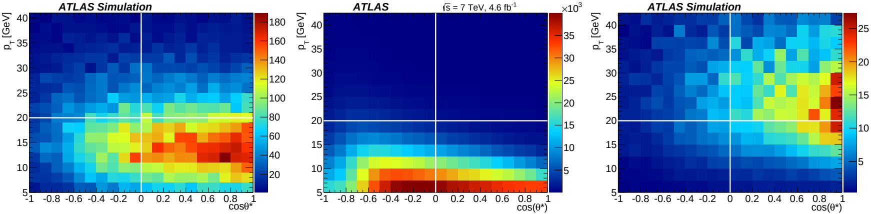
Adding two tracks

- $p_T(\pi) > 400$ MeV
- $|\eta(\mu)| < 2.5$
- Fit a 4-track vertex:
  - Dimuon mass is constrained to nominal $\Upsilon(1S)$ mass – substantially improves resolution
  - $\chi^2 < 20$
  - Candidates with mass < 11.2 GeV are retained

Analysis binning

The analysis is performed in 8 bins

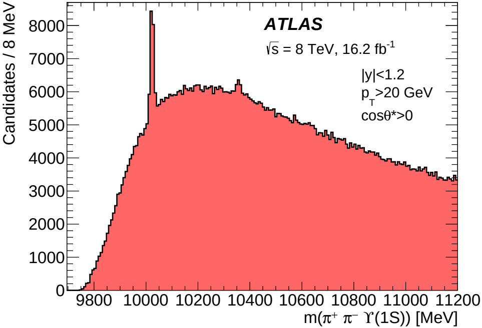
- $|y(X_b)|$: barrel ($|y| < 1.2$) and endcap ($1.2 < |y| < 2.4$) due to different mass resolution
- $(p_{\mathrm{T}}(X_b), \cos\theta^*)$: split into 4 quadrants – different S/B ratio
  - θ^* is an angle between $\pi^+\pi^-$ momentum in the parent rest frame and the parent momentum in lab frame
- Fraction of the signal in each bins are defined by *splitting functions* derived from the simulation

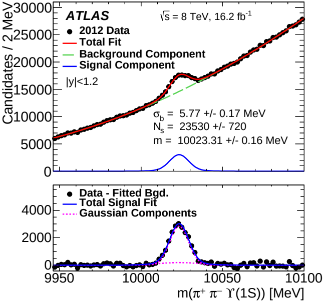


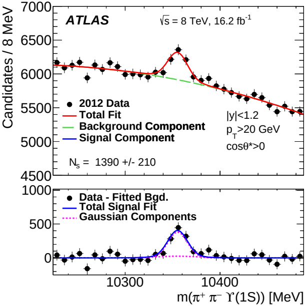
Signal Background $S/\sqrt{B}$

$\Upsilon(2S)$ and $\Upsilon(3S)$ fits

- Clear peaks of $\Upsilon(2S)$ and $\Upsilon(3S)$ are observed; no other visible signals
- $\Upsilon(2S)$: signal shape and distribution over bins found consistent with MC
- $\Upsilon(3S)$: simultaneous fit in all bins (significance $z = 8.7$, cf. 6.5 in one bin)
- Both yields agree with predictions







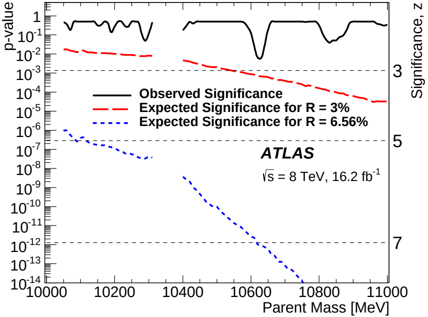
X_b local significance

Strategy:

- Test for signal presence across 10–11 GeV range every 10 MeV
- Simultaneous fit in 8 analysis bins
  - Binned ML fit
- For each mass, extract p-value and significance

Assumptions:

- Look for *narrow state*
- Resolution dependence on $|y|$, p_{T} is $\Upsilon(nS)$-like
- Phase-space shape of $m(\pi^+\pi^-)$



Mass ranges near $\Upsilon(2S)$ and $\Upsilon(3S)$ are excluded

X_b upper limits

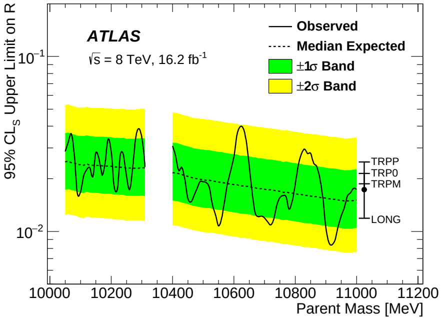
CL_s limit on $(\sigma\mathcal{B})/(\sigma\mathcal{B})_{2S}$ at 95% CL is evaluated as a function of mass

Systematic uncertainties

- Included as Gaussian-constrained nuisance parameters

Unknown X_b production polarisation

- Assumed unpolarised
- Various assumptions shift the limits
- Shifts depend depend weakly on mass
- Shown with error bars



Mass ranges near $\Upsilon(2S)$ and $\Upsilon(3S)$ are excluded

The limit is most restrictive to date for $m > 10.1$ GeV

Search for structures in $B_s^0\pi^\pm$ mass spectrum

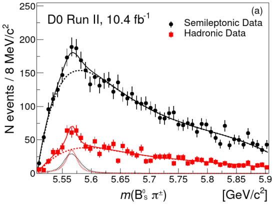
submitted to Phys. Rev. Lett. / `arXiv:1802.01840`

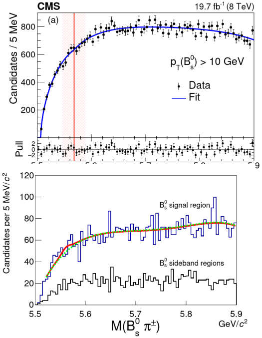
Motivation

- A narrow structure $X(5568)$ was observed in $B_s^0\pi^\pm$ system by D0
  - In $B_s^0 \to J/\psi\phi$ mode (Phys. Rev. Lett. 117 (2016) 022003) with significance 3.9–5.1σ
  - Recently also in $B_s^0 \to D_s^+\mu X$, combined 6.7σ claimed (`arXiv:1712.10176`); $\rho = (8.4 \pm 1.9 \pm 1.4)\%$ for $p_\mathrm{T}(B_s^0) > 10\,\mathrm{GeV}$
  - Would be a clear charged *tetraquark candidate*
- Non-confirmations shortly published by LHCb (Phys. Rev. Lett. 117 (2016) 152003), CMS (`arXiv:1712.06144`) and CDF (`arXiv:1712.09620`): 95% C.L. upper limits on ρ between 1.1 and 6.4%

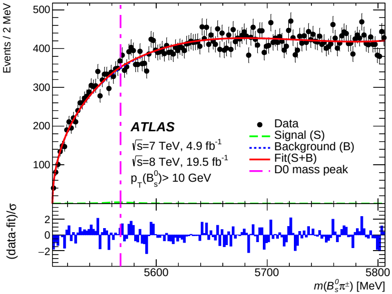
$$m = 5566.9^{+3.2}_{-3.1}(\mathrm{stat})^{+0.6}_{-1.2}(\mathrm{syst})\ \mathrm{MeV}$$

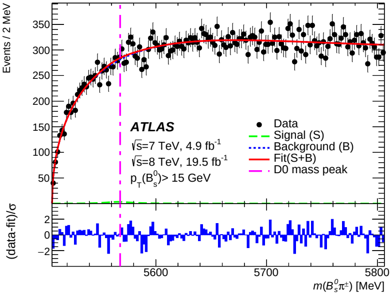
$$\Gamma = 18.6^{+7.9}_{-6.1}(\mathrm{stat})^{+3.5}_{-3.8}(\mathrm{syst})\ \mathrm{MeV}$$



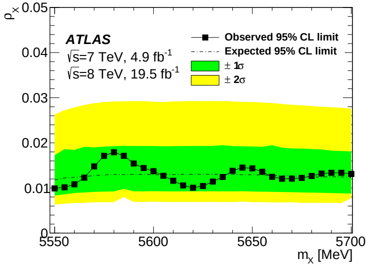


ATLAS results





- No signal found
- For the D0 kinematics and mass, $\rho < 1.5\%$ @ 95% C.L.
- For $p_{\mathrm{T}}(B_s^0) > 15$ GeV (CMS-like), $\rho < 1.6\%$ @ 95% C.L.



Summary

- Although not being a dedicated B-physics facility, ATLAS has a wide B-physics program and delivers competitive results
    - only a few highlights on production and spectroscopy were shown
    - see the other talk for the HF decay studies
- So far most of analyses use Run 1 data
    - Run 2 provides an extremely abundant and good HF data sample, despite various challenges (trigger, pile-up)
    - Main limitation is only lack of manpower

Keep tuned for further interesting results on B-physics from ATLAS!

Backup slides

Systematics in the D meson measurement

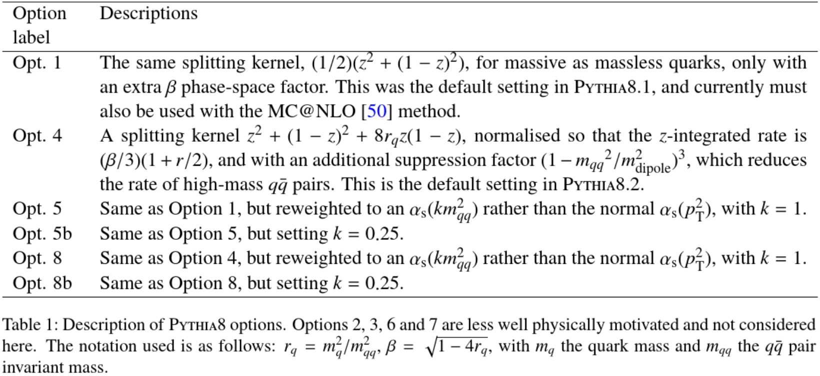
Source	$\sigma^{\text{vis}}(D^{*\pm})$		$\sigma^{\text{vis}}(D^{\pm})$		$\sigma^{\text{vis}}(D_s^{\pm})$	
	Low-p_{T}	High-p_{T}	Low-p_{T}	High-p_{T}	Low-p_{T}	High-p_{T}
Trigger (δ_1)	-	$^{+0.9}_{-1.0}\%$	-	$^{+0.9}_{-1.0}\%$	-	$^{+0.9}_{-1.0}\%$
Tracking (δ_2)	$\pm 7.8\%$	$\pm 7.4\%$	$\pm 7.7\%$	$\pm 7.4\%$	$\pm 7.6\%$	$\pm 7.4\%$
D selection (δ_3)	$^{+2.8}_{-1.6}\%$	$^{+1.7}_{-1.4}\%$	$^{+1.6}_{-1.0}\%$	$^{+0.9}_{-0.6}\%$	$^{+2.6}_{-1.6}\%$	$^{+1.1}_{-0.9}\%$
Signal fit (δ_4)	$\pm 1.3\%$	$\pm 0.9\%$	$\pm 1.3\%$	$\pm 1.5\%$	$\pm 6.4\%$	$\pm 5.3\%$
Modelling (δ_5)	$^{+1.0}_{-1.7}\%$	$^{+2.7}_{-2.3}\%$	$^{+2.3}_{-2.6}\%$	$^{+2.9}_{-2.4}\%$	$^{+1.7}_{-2.4}\%$	$^{+2.8}_{-2.4}\%$
Size of MC sample (δ_6)	$\pm 0.6\%$	$\pm 0.9\%$	$\pm 0.8\%$	$\pm 0.8\%$	$\pm 2.9\%$	$\pm 3.1\%$
Luminosity (δ_7)	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$
Branching fraction (δ_8)	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 2.1\%$	$\pm 2.1\%$	$\pm 5.9\%$	$\pm 5.9\%$

LEP average fragmentation fractions

Eur. Phys. J. C 75 (2015) 19

	LEP data
$f(c \to D^{*+})$	$0.236 \pm 0.006 \pm 0.003$
$f(c \to D^{+})$	$0.225 \pm 0.010 \pm 0.005$
$f(c \to D_s^{+})$	$0.092 \pm 0.008 \pm 0.005$
$f(b \to D^{*\pm})$	$0.221 \pm 0.009 \pm 0.003$
$f(b \to D^{\pm})$	$0.223 \pm 0.011 \pm 0.005$
$f(b \to D_s^{\pm})$	$0.138 \pm 0.009 \pm 0.006$

Gluon splitting kernels in PYTHIA



Option label	Descriptions
Opt. 1	The same splitting kernel, $(1/2)(z^2 + (1-z)^2)$, for massive as massless quarks, only with an extra β phase-space factor. This was the default setting in PYTHIA8.1, and currently must also be used with the MC@NLO [50] method.
Opt. 4	A splitting kernel $z^2 + (1-z)^2 + 8r_q z(1-z)$, normalised so that the z-integrated rate is $(\beta/3)(1 + r/2)$, and with an additional suppression factor $(1 - m_{qq}{}^2/m^2_{\mathrm{dipole}})^3$, which reduces the rate of high-mass $q\bar{q}$ pairs. This is the default setting in PYTHIA8.2.
Opt. 5	Same as Option 1, but reweighted to an $\alpha_{\mathrm{s}}(km^2_{qq})$ rather than the normal $\alpha_{\mathrm{s}}(p^2_{\mathrm{T}})$, with $k = 1$.
Opt. 5b	Same as Option 5, but setting $k = 0.25$.
Opt. 8	Same as Option 4, but reweighted to an $\alpha_{\mathrm{s}}(km^2_{qq})$ rather than the normal $\alpha_{\mathrm{s}}(p^2_{\mathrm{T}})$, with $k = 1$.
Opt. 8b	Same as Option 8, but setting $k = 0.25$.

Table 1: Description of PYTHIA8 options. Options 2, 3, 6 and 7 are less well physically motivated and not considered here. The notation used is as follows: $r_q = m_q^2/m_{qq}^2$, $\beta = \sqrt{1 - 4r_q}$, with m_q the quark mass and m_{qq} the $q\bar{q}$ pair invariant mass.

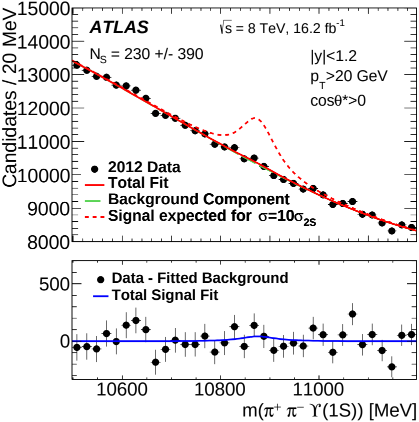
Results for $\Upsilon(1^3D_J)$, $\Upsilon(10860)$, $\Upsilon(11020)$

$\boldsymbol{\Upsilon(1^3D_J)}$ triplet

- Two extra peaks added to the fit model (masses fixed to theoretical predictions)
- Significance $z = 0.12$
- $\sigma(\Upsilon(1^3D_J))/\sigma(\Upsilon(2S)) < 0.55$ (use known $\mathcal{B}$ from BaBar)

$\boldsymbol{\Upsilon(10860)}$, $\boldsymbol{\Upsilon(11020)}$

- Broad states → different fit model
- No evidence for either state found

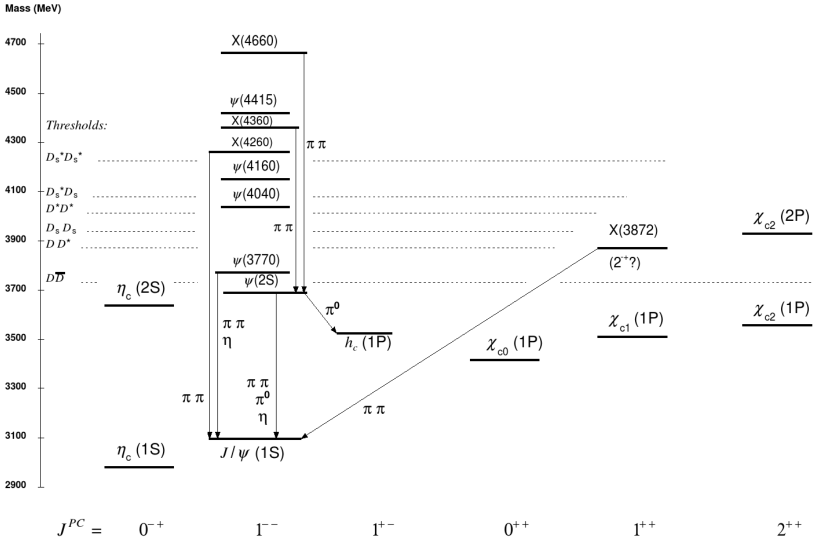


Further plans:

- The studied topology is isospin suppressed
- Searches in $\Upsilon(1S)\phi$ and $\Upsilon(1S)\omega$ can be more sensitive

Charmonium spectrum

Chin. Phys. C 40 (2016) 100001



Bottomonium spectrum

Chin. Phys. C 40 (2016) 100001