Detecting new hadrons
Excited QCD 2010

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on behalf of ATLAS

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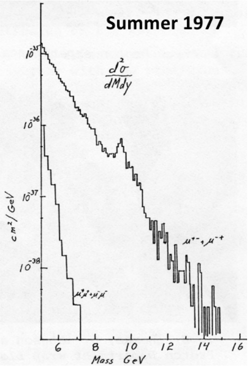
A bit of history

- 1974 Richter & Ting discovered J/ψ, the first hadron containing c-quark. At present day PDG table lists 22 charmed mesons, 16 charmed baryons, and 11 charmonia.
- 1977 Lederman discovered Υ, opening discovery window for b-hadrons
- At present day, PDG lists 7 b-mesons but only one b-baryon Λ_b^0

$p + (\text{Cu}, \text{Pt}) \rightarrow \mu^+\mu^- + X$



$M(\mu\mu)$

- Parameters of b-mesons were well measured at B-factories (CLEO, BaBar, Belle, ...) but b-baryons are out of their reach. We need hadron colliders: Tevatron, LHC

Tevatron

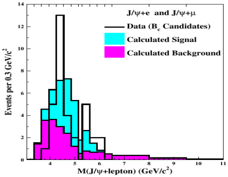
- $p\bar{p}$ collider with c.m. energy 1.96 TeV
- Located in Fermi National Accelerator Laboratory near Chicago, Illinois, USA
- Tevatron Run II since March 2001 delivered integrated luminosity of about 5 fb^{-1}
- Two detectors CDF and D0 at collision points

Tevatron

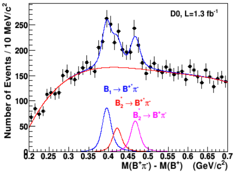
- Tevatron Run II contributed significantly to the search for new hadrons

New Mesons at Tevatron

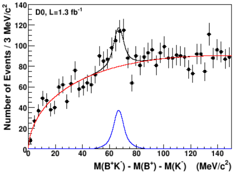
- **Before Tevatron**: B^+, B^0, B_s^0, B^*, D-mesons
- **Tevatron**:
  - B_c^+ last unobserved B meson in ground state [1]
  - Excited states B^{**} [2] (B_2^* seen already by LEP [3])
  - Excited states B_s^{**} and D_s^{**} [4]



B_c



B_1^0, B_2^{*0}



B_{s2}^*

[1] Phys.Rev.D58, 112004 (1998); Phys.Rev.Lett.97, 012002 (2006); Phys.Rev.Lett.96, 082002 (2006)

[2] D0: Phys. Rev. Lett. 99, 172001 (2007); CDF Public Note 8945 (2007)

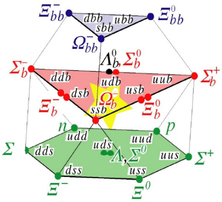
[3] Phys.Lett.B, Volume 425, Issues 1-2, Pages 215-226 (1998)

[4] D0: arXiv:0711.0319[hep-ex] (2007); CDF: arXiv:0710.4199[hep-ex] (2007); D0 5034-CONF(2006).

- **Before Tevatron**: only Λ_b was observed
- **Tevatron**:
  - $\Sigma_b^{\pm}$, Σ_b^{*} bottom strange-less baryon [5]
  - Ξ_b^{-} bottom strange baryon [6]
  - Ω_b^{0} bottom double-strange baryon [7]

D0 search for Ξ_b^- and Ω_b^0 lead by Eduard De La Cruz Burelo and Jianming Qian from the University of Michigan

$J = 1/2$



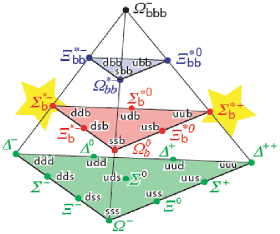
3b

2b (unobserved)

1b (incomplete)

0b (established)

$J = 3/2$



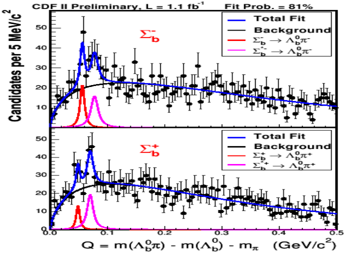
[5] CDF Phys. Rev. Lett. 99, 202001 (2007); arXiv:0706.3868v2

[6] D0: Phys. Rev. Lett. 99, 052001 (2007) and CDF: Phys. Rev. Lett. 99, 052002 (2007)

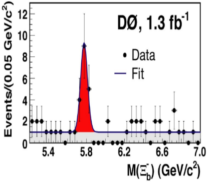
[7] D0: Phys.Rev.Lett. 101, 232002 (2008); CDF: Phys.Rev D 80, 72003 (2009)

- $\Sigma_b^{\pm}$ $(buu,\ bdd)$ observed by CDF in decay channel $\Sigma_b^{\pm} \rightarrow \Lambda_b^0 \pi^{\pm}$
- Excited state $\Sigma_b^{*\pm}$ was observed in the same decay mode
- Ξ_b^- (dsb) observed in decay $\Xi_b^+ \rightarrow J/\psi \Xi^-$ (CDF, D0) and $\Xi_b^+ \rightarrow \Xi_c^0 \pi^-$ (CDF)
- Ω_b^- (bss) observed by D0 and CDF in decay channel $\Omega_b^- \rightarrow J/\psi \Omega^-$
- Σ_b^0 and Ξ_b^0 weren't observed

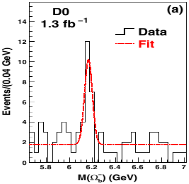
$\Sigma_b^{\pm}$, $\Sigma_b^{*\pm}$



Ξ_b^-



Ω_b^-

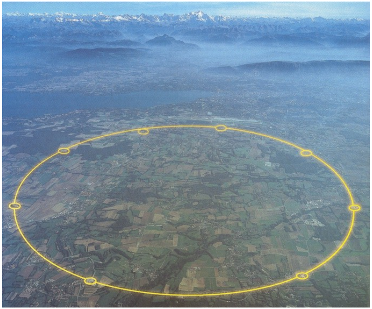


B-baryon summary table

Notation	Quark content	J^P	(I, I_3)	S		Mass (MeV)
Λ_b^0	b[ud]	$1/2^+$	(0,0)	0		5620.2 ± 1.6
Ξ_b^-	b[sd]	$1/2^+$	(1/2,-1/2)	-1		5792.4 ± 3.0
Σ_b^+	buu	$1/2^+$	(1,1)	0		5807.8 ± 2.7
Σ_b^-	bdd	$1/2^+$	(1,-1)	0		5815.2 ± 2.0
Ω_b^-	bss	$1/2^+$	(0,0)	-2	D0	$6165 \pm 10(\text{stat}) \pm 13(\text{syst})$
					CDF	$6054.4 \pm 6.8(\text{stat}) \pm 0.9(\text{syst})$
Σ_b^{*+}	buu	$3/2^+$	(1,1)	0		5829.0 ± 3.4
Σ_b^{*-}	bdd	$3/2^+$	(1,-1)	0		5836.4 ± 2.8

Large Hadron Collider

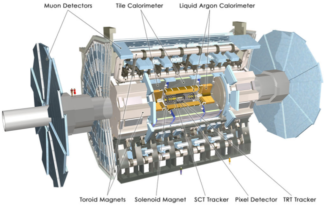
- *pp* collider with design c.m. energy 14 TeV
- Located in CERN at Swiss-Franco border near Geneva
- LHC started its operation in November 2009
- In November and December 2009 LHC experiments were collecting collision events at 900 GeV and 2.38 TeV



LHC

- Four experiments occupy four interaction points along the ring
- Experiment LHCb is designed to study b-hadrons. In addition, two general purpose experiments ATLAS and CMS can be used to search for new hadrons

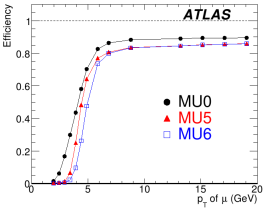
- For new searches for Heavy Flavour Hadrons the most important subsystems are **Inner Detector** (for full decay reconstruction) and **Muon Spectrometer** (for muon identification and trigger)
- Inner Detector consists of 3 pixel layers in barrel and 10 end-cap wheels, 4 silicon strip layers in barrel and 18 end-cap wheels, and Transition Radiation Tracker
- Trigger system has 3 levels, first one is hardware based
  - Low p_T muon trigger for $J/\psi(\mu^+\mu^-)$ final state
  - Level-1 low p_T jet with level-2 b-tagging for fully hadronic final states. It requires presence of tracks with large impact parameter in the jet.

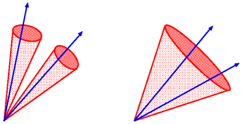


ATLAS $J/\psi(\mu^+\mu^-)$ trigger

- Level-1 muon trigger: $|\eta| < 2.4$, full ϕ coverage
- ATLAS level-2 trigger is RoI based. Due to timing constraints only regions of the detector around level-1 objects are reconstructed at level-2
- Two $J/\psi \rightarrow \mu^+\mu^-$ trigger strategies are available: [8]
  - Level-1 di-muon trigger, where each level-1 muon is confirmed at level-2 (topological trigger)
  - Only one level-1 muon is required. At level-2 both muons are found inside RoI around this level-1 muon (level-2 di-muon trigger)

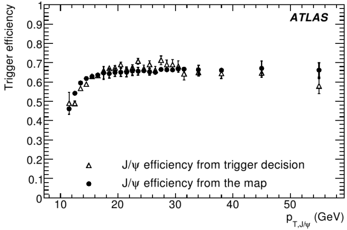
Level-1 muon trigger efficiency (MC study)



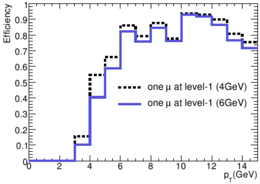


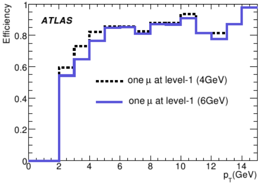
[8] arXiv:0901.0512 ; CERN-OPEN-2008-020

- Efficiency of topological trigger (MC study)



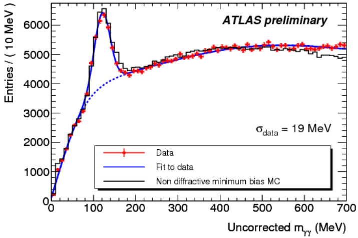
- Efficiency of level-2 di-muon trigger (MC study)



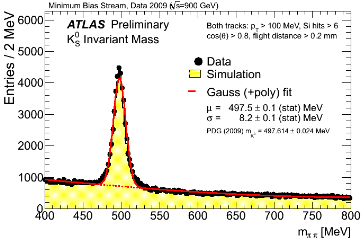


- **First step**: before we start to search for new particles we have to re-discover the known ones
- So far ATLAS has collected about 538,000 collision candidates at 900 GeV

Particles reconstructed in early data

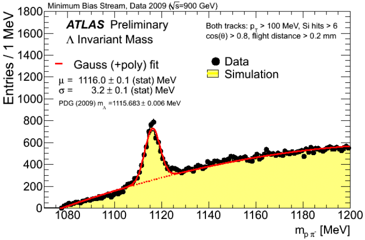


$\pi^0(\gamma\gamma)$

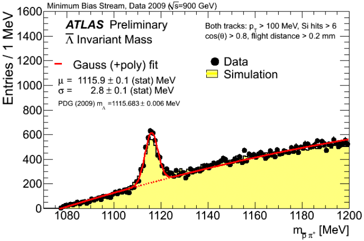


$K^0_s(\pi^+\pi^-)$

Particles reconstructed in early data



$\Lambda^0(p\pi^-)$



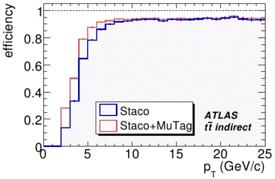
$\bar{\Lambda}^0(\bar{p}\pi^+)$

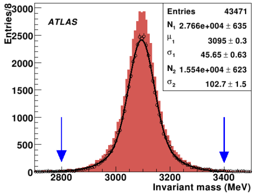
- These particles are final states of many heavy baryons decays
- It is important to be able to reconstruct them with good efficiency and resolution

- Decays with $J/\psi \to \mu^+\mu^-$ in the final state are favored because they can be used for triggering
- Several muon reconstruction algorithm are used to reconstruct low and high p_T muons
- Opposite charged muon pairs are combined in a vertex fit to reconstruct J/ψ
- Plot shows reconstructed mass peak of J/ψ in MC data of Λ_b^0 decay

Monte Carlo study

low p_T muon reconstruction efficiency



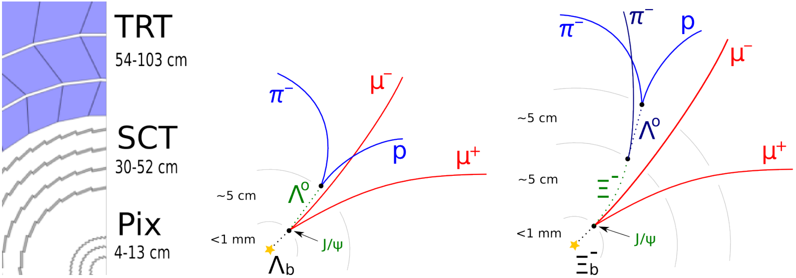


$J/\psi(\mu^+\mu^-)$

- ATLAS Beauty physics program's aim is to measure properties of b-mesons and baryons
- Part of the goal is to search for new hadrons and repeat the measurements done by Tevatron

Decay			Trigger
B_c	$\rightarrow$	$J/\psi(\mu^+\mu^-)\pi^+$	di-muon J/ψ trigger
Λ_b	$\rightarrow$	$\Lambda^0(p\pi^-)J/\psi(\mu^+\mu^-)$	di-muon J/ψ trigger
Ξ_b^-	$\rightarrow$	$\Xi^-(\Lambda^0\pi^-)J/\psi(\mu^+\mu^-)$	di-muon J/ψ trigger
	$\rightarrow$	$\Xi_c^0\pi^-$	
	$\rightarrow$	$D^-\Lambda^0$	b-jet
	$\rightarrow$	$\Lambda_c^+K^-\pi^-$	
$\Sigma_b^\pm$	$\rightarrow$	$\Lambda_b^0(\Lambda^0 J/\psi)\pi^\pm$	di-muon J/ψ trigger
	$\rightarrow$	$\Lambda_b^0(\Lambda_c^+\pi^-)\pi^\pm$	b-jet
Ω_b^-	$\rightarrow$	$J/\psi(\mu^+\mu^-)\Omega^-(\Lambda^0K^-)$	di-muon J/ψ trigger

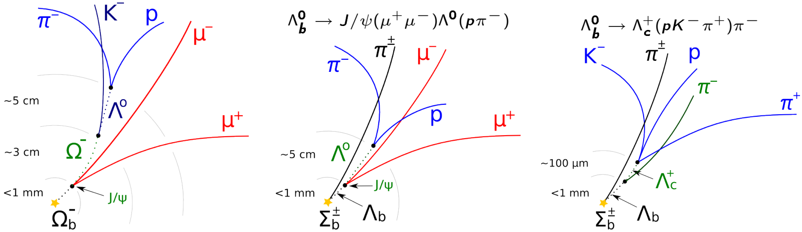
Decay topologies $\Lambda_b^0 \to J/\psi\Lambda^0$ $\Xi_b^- \to J/\psi\Xi^-$



- Λ^0, Ξ^-, Ω^- are long living particles, therefore the decays will have cascade topology
- V^0's must decay inside SCT to reconstruct secondary vertex

New Heavy Flavour Hadrons at ATLAS

$\Omega_b^- \to J/\psi\Omega^-$ $\qquad$ $\Sigma_b^\pm \to \Lambda_b^0\pi^\pm$



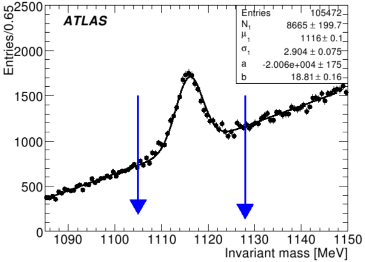
Signal reconstruction:

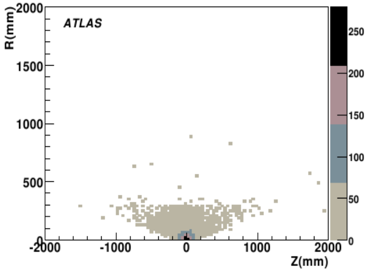
1. Reconstruction of last generation decays (J/ψ, Λ^0, Λ_c^+, Λ_b^0, ...) using Kalman vertex fitter
2. Reconstructed candidates are combined to global cascade fit
3. Cuts on invariant mass, decay lengths, collimation, etc. reduce combinatorial background

Background estimation: wrong sign combinations, MC simulation

Λ_b^0 example (MC study)

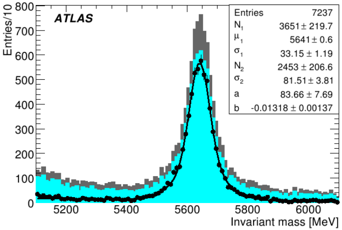
- J/ψ reconstruction: muon pair coming from a single vertex, cut on vertex quality and invariant mass is applied
- Λ^0 reconstruction: opposite charge track pair coming from a single vertex. Cut on invariant mass $M(p\pi^-)$ and vertex quality is applied. Λ^0 must decay inside SCT to be reconstructed (only about 60%)





Λ_b^0 example (MC study)

- J/ψ and Λ^0 candidates are combined in a cascade fit to reconstruct Λ_b^0
- Cut on fit χ^2, invariant mass and Λ_b^0 decay length is applied to reduce background



$\Lambda_b \rightarrow J/\psi\Lambda^0$

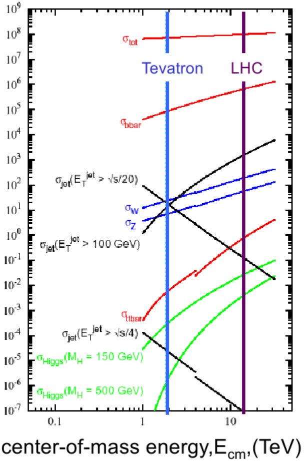
- ATLAS should collect about 13k Λ_b^0 events with 30 fb^{-1} of data [9]

[9] arXiv:0901.0512 ; CERN-OPEN-2008-020

Search for new heavy baryons at ATLAS

- Apart from confirmation of Tevatron results ATLAS will also look for new particles: *cb*-baryons, *bb*-baryons, etc.
- Decay modes with large enough B.R. must be used to collect sufficient number of events:
  - Tevatron CDF collected ca. 20 events of $B_c \to J/\psi(\mu^+\mu^-)l\nu$ with 0.11 fb^{-1}. B.R. of this decay is $\approx 0.3\%$
  - We assume the production cross section of double heavy quark baryons is about two times smaller
  - **Therefore** we are interested in processes with
    B.R. $\gtrsim 6 \times 10^{-4}$ for 1 fb^{-1} of data,
    B.R. $\gtrsim 6 \times 10^{-5}$ for 10 fb^{-1},
    B.R. $\gtrsim 2 \times 10^{-5}$ for 30 fb^{-1}

- **Of course** improvements in coverage, experimental techniques, and larger production cross section at LHC may allow us to access smaller B.R.



Promising decays with J/ψ in the final state

- Easy to trigger but low B.R. of $b \to s\ J/\psi \approx 10^{-3}$

Decay			B.R. estimate
Bottom charmed baryons			
$\Xi^0_{cb}(dcb)$	$\to$	$\Xi^0_c(\Lambda^0 \bar{K}^0)J/\psi$	$< 2 \times 10^{-7}$
$\Omega^0_{cb}(scb)$	$\to$	$\Omega^0_c(\Omega^-\pi^+)J/\psi$	$< 1.5 \times 10^{-6}$
	$\to$	$\Omega^0_c(\Omega^-\mu^+\nu)J/\psi$	$\sim$
	$\to$	$\Omega^0_c(\Xi^- K^-\pi^+\pi^+)J/\psi$	$\sim$
	$\to$	$\Omega^0_c(\Omega^-\pi^+\pi^+\pi^-)J/\psi$	$\sim$
$\Xi^+_{cb}(ucb)$	$\to$	$\Lambda^+_c(pK^-\pi^+)J/\psi$	Cabbibo suppressed
	$\to$	$\Xi^+_c(\Xi^-\pi^+\pi^+)J/\psi$	$< 2 \times 10^{-7}$
Double bottom baryons			
$\Xi^0_{bb}(ubb)$	$\to$	$\Xi^+_{cb}\pi^-$	
	$\to$	$\Lambda^0_b(\Lambda^+_c\pi^-)J/\psi$	Cabbibo suppressed
$\Omega^0_{bb}(dbb)$	$\to$	$\Xi^-_b\ J/\psi$	Cabbibo suppressed

Promising fully hadronic decays (b-Jet trigger)

Decay			B.R. estimate
Bottom charmed baryons			
$\Xi^0_{cb}(dcb)$	$\rightarrow$	$D^{*+}(K^-\pi^+\pi^+)p\pi^-K^-$	$\approx 4\times10^{-5}$
	$\rightarrow$	$D^0(K^-\pi^+)pK^-$	
$\Xi^+_{cb}(ucb)$	$\rightarrow$	$D^{*+}(K^-\pi^+\pi^+)pK^-$	$\approx 4\times10^{-5}$
	$\rightarrow$	$D^0(K^-\pi^+)p\bar{K}^0$	
Double bottom baryons			
$\Xi^0_{bb}(ubb)$	$\rightarrow$	$\Xi^+_{cb}\pi^-$	
$\Xi^-_{bb}(ubb)$	$\rightarrow$	$\Xi^0_{cb}\pi^-$	

- Larger B.R. but no muons to trigger on at level-1
- Low p_T b-jet trigger will have to be used (prescaled)
- Double heavy quark baryons will produce number of tracks with large impact parameter that can be used as level-2 trigger

Summary and conclusion

- Tevatron experiments contributed significantly to the discovery of new hadrons
- New ground state meson B_c and excited states B^{**}, B_s^{**}, D_s^{**} were discovered at Tevatron
- In heavy baryon search Tevatron contributed with discoveries of b-baryons $\Sigma_b^{\pm}$, $\Sigma_b^{*\pm}$, Ξ_b^-, and Ω_b^-
- LHC started its operation in November 2009 and early data from ATLAS shows its capability to reconstruct long living particles like Λ^0 and K^0
- Once larger statistics is collected ATLAS will search for hadrons discovered at Tevatron
- Some promising decays of double heavy quark baryons were listed. They may be used to search for new hadrons at ATLAS