CP violation and related measurements with baryons at LHCb

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on behalf of the LHCb collaboration

Friday 8th June 2018

LHCP 2018, Bologna, Italy

Heavy baryons

- The LHC offers a unique opportunity to study heavy flavour baryons
  - Large production cross-sections for a suite of states
- The LHCb experiment is particularly well-suited to studying them
  - Large production fraction in high-rapidity acceptance $2 < y < 5$
  - High-precision tracking down to low momenta
  - Excellent particle identification
- Have established a broad experimental programme
  - Discovery: new ground states and excited states
  - Characterisation: Masses, widths, lifetimes of known states
  - Asymmetries: CP violation, P- and T-odd

Topics

- CP violation in Λ_b^0 and $\Xi_b^0 \to ph^-h^+h^-$ decays
- CP violation in $\Lambda_b^0 \to pK^-$ and $p\pi^-$ decays
- Baryon number violation in Ξ_b^0 oscillations
- CP violation in $\Lambda_c^+ \to p\pi^-\pi^+$ and pK^-K^+ decays

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Further interesting charm baryon results

- Properties of the Ξ_{cc}^{++}
- Ω_c^0 lifetime
- Search for $\Lambda_c^+ \to p\mu^-\mu^+$

See Marianna's talk, up next!

CP violation in Λ_b^0 and $\Xi_b^0 \to ph^-h^+h^-$ decays

- LHCb found $3.3\,\sigma$ evidence for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays last year[1]
  - Also searched in $\Lambda_b^0 \to p\pi^-K^+K^-$
- Now perform similar measurements with other $X_b^0 \to ph^-h^+h^-$ decays
  - $\Lambda_b^0 \to pK^-\pi^+\pi^-$ and $pK^-K^+K^-$
  - $\Xi_b^0 \to pK^-K^+\pi^-$
- Measure integrated asymmetries and in phase space bins using triple products

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$$a_P^{\widehat{T}\text{-odd}} = \frac{1}{2}(A_{\widehat{T}} + \overline{A}_{\widehat{T}}), \qquad a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}(A_{\widehat{T}} - \overline{A}_{\widehat{T}})$$

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Method

- Reconstruct and select $X_b^0 \to pK^-h^+h^-$ with $3.0\,\text{fb}^{-1}$ of data
- Study efficiencies with $\Lambda_b^0 \to \Lambda_c^+\pi^+$, $\Lambda_c^+ \to pK^-\pi^+$ decays
- Split samples by proton charge and $C_{\widehat{T}}/\overline{C}_{\widehat{T}}$ sign

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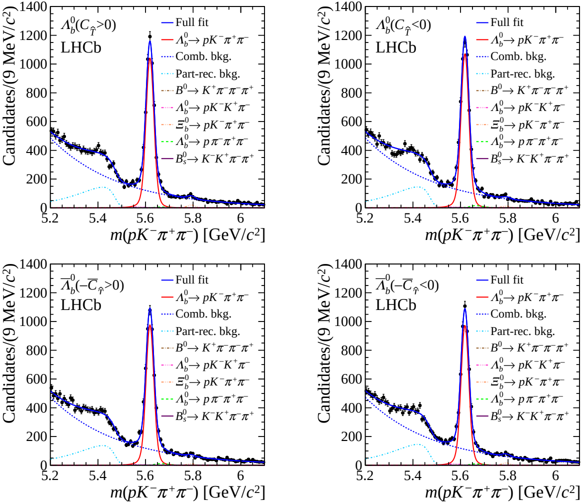

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arXiv:1805.03941

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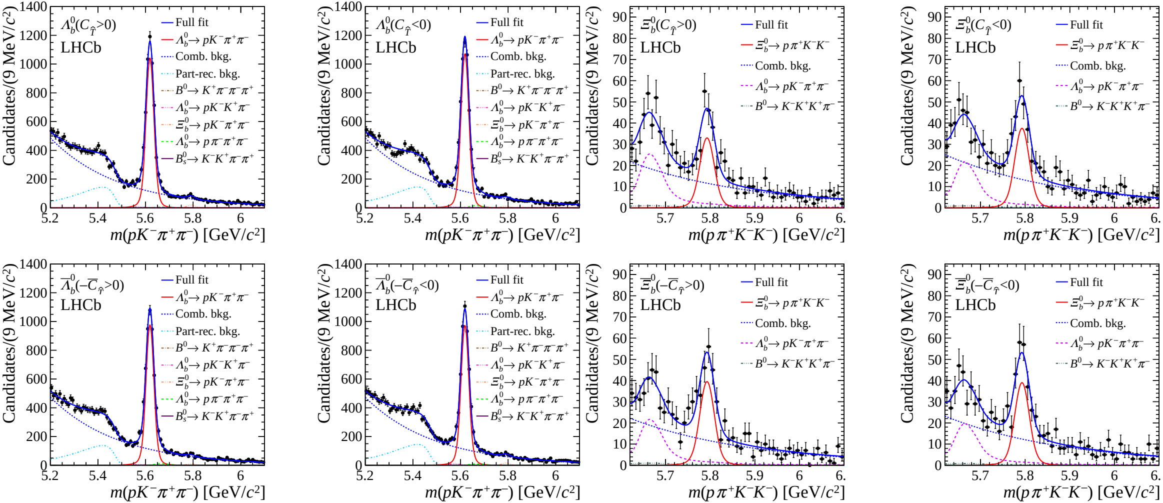

Results

- Measure integrated asymmetries for all modes

	$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to pK^-K^+K^-$	$\Xi_b^0 \to pK^-K^-\pi^+$
$a_P^{\widehat{T}\text{-odd}}$ (%)	$-0.60 \pm 0.84 \pm 0.31$	$-1.56 \pm 1.51 \pm 0.32$	$-3.04 \pm 5.19 \pm 0.36$
$a_{CP}^{\widehat{T}\text{-odd}}$ (%)	$-0.81 \pm 0.84 \pm 0.31$	$1.12 \pm 1.51 \pm 0.32$	$-3.58 \pm 5.19 \pm 0.36$

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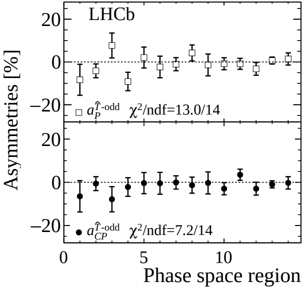
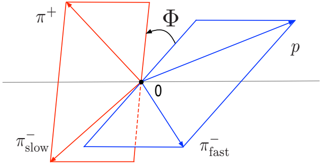
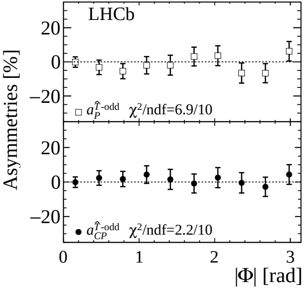
- Also measure asymmetries in phase space bins for Λ_b^0 samples
  - $\Lambda_b^0 \to pK^-\pi^+\pi^-$ (left), $\Lambda_b^0 \to pK^-K^+K^-$ (right)







CP violation in $\Lambda_b^0 \to pK^-$ and $p\pi^-$ decays

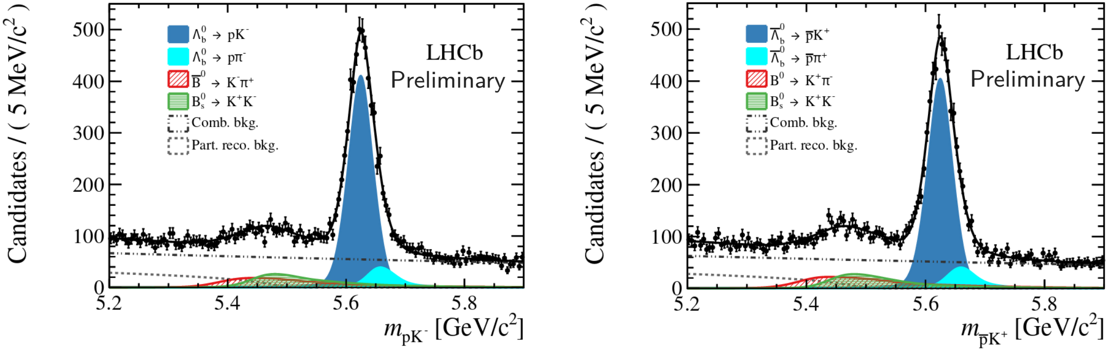
- Two-body charmless Λ_b^0 decays predicted to exhibit CPV at $\sim 6\,\%$ to $\sim 30\,\%$ level

$$A_{CP}(\Lambda_b^0 \to ph) = \frac{\Gamma(\Lambda_b^0 \to ph^-) - \Gamma(\overline{\Lambda}_b^0 \to \overline{p}h^+)}{\Gamma(\Lambda_b^0 \to ph^-) + \Gamma(\overline{\Lambda}_b^0 \to \overline{p}h^+)}$$

- Most recent measurements are from CDF, consistent with zero, $\sim 7\,\%$ precision
- Challenging due to contributions from production and detection asymmetries
- Can control production asymmetry in the difference
  - May be particularly sensitive if U-spin transformation flips CP sign

$$\Delta A_{CP}(\Lambda_b^0 \to ph) = A_{CP}(\Lambda_b^0 \to p\pi) - A_{CP}(\Lambda_b^0 \to pK)$$

- Reconstruct $\Lambda_b^0 \to h^+h^-$ vertex highly displaced from the PV with large p_T
- Form orthogonal sub-samples for all PID hypothesis $(h \in p, \pi, K)$
- All eight spectra fitted simultaneously to determine mis-ID contributions to signal samples



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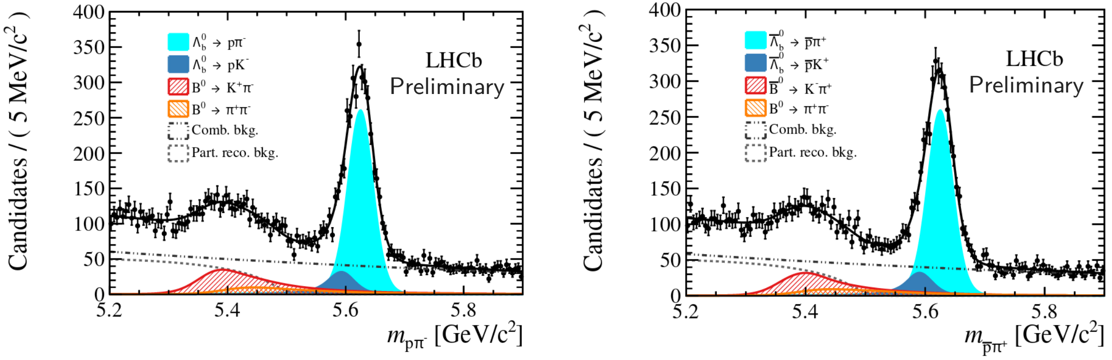

Results

- Combine proton-charge-dependent yields to measure individual asymmetries

$$A_{CP}(\Lambda_b^0 \to pK^-) = (-1.9 \pm 1.3\,(\text{stat.}) \pm 1.7\,(\text{syst.}))\,\%,$$
$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7\,(\text{stat.}) \pm 1.8\,(\text{syst.}))\,\%$$

- Dominant systematic uncertainty from knowledge of Λ_b^0 production asymmetry
- Measure difference, remaining contributions from pion and kaon detection asymmetries

$$\Delta A_{CP} = A_{CP}(\Lambda_b^0 \to pK^-) - A_{CP}(\Lambda_b^0 \to p\pi^-)$$
$$= (1.5 \pm 2.1\,(\text{stat.}) \pm 1.1\,(\text{syst.}))\,\%$$

- Improvement in precision close to a factor of 4

Baryon number violation in Ξ_b^0 oscillations

Phys. Rev. Lett. **119**, 181807 (2017)

- Baryon number violation is one of the Sakharov conditions
- Six-fermion operators allowed in some leptoquark and R-parity violating models
  - NP models strongly constrained by proton decay measurements
  - Such operators strongly suppressed in proton decay, however, requiring two FCNCs
- Experimental signatures require presence of all three fermion generations
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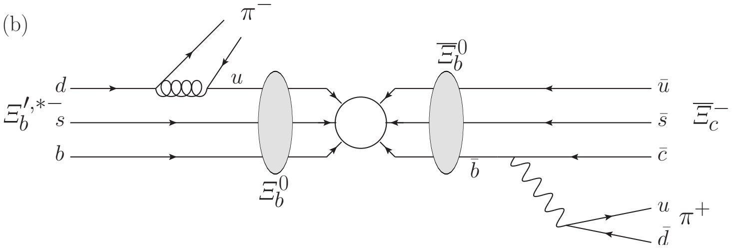
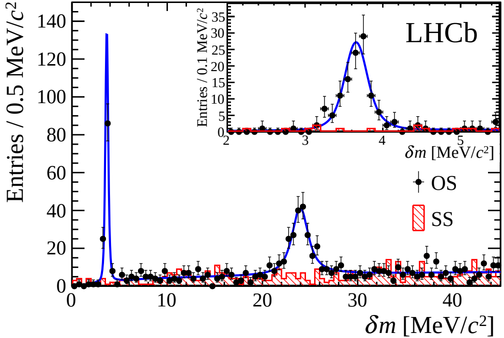
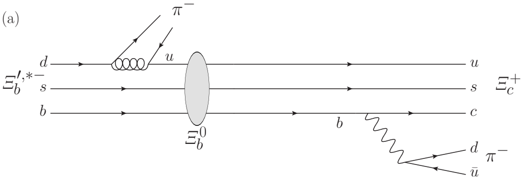


- LHCb discovered the $\Xi_b'^-$ and Ξ_b^{*-} in 2014[2]
- Can use the $\Xi_b^{\prime,*-} \to \Xi_b^0\pi^-$ chain to tag the Ξ_b^0 flavour at production
- Define opposite sign ($p + \pi^-$) and same sign ($\overline{p} + \pi^-$) samples





[2]Phys. Rev. Lett. **114** (2015) 062004

Method and results

- Measure OS yields in bins of Ξ_b^0 decay time
- Constrain SS models
    - Signal model mean and width from integrated OS fit
    - Background distribution from sidebands outside $\Xi_b^{\prime -}$ and Ξ_b^{*-} signal regions
- Expected SS yields then completely determined by mixing freqency ω
- Form a likelihood $L(\omega)$ and find best fit value in data $L(\hat{\omega})$, compare with $L(0)$

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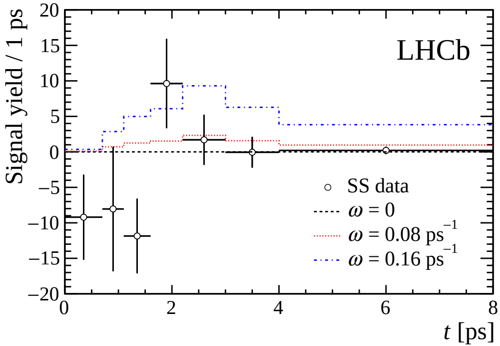

- Find $\hat{\omega} = 0$
- Use pseudo-experiments to set limit

$$\omega < 0.08\,\text{ps}^{-1} \text{ @ } 95\,\%\text{ CL}$$

- Search for direct CPV in $\Lambda_c^+ \to f$ decays, $A_{CP}(pK^-K^+)$ and $A_{CP}(p\pi^-\pi^+)$

$$\begin{aligned}\Delta A_{CP} &= A_{\mathrm{Raw}}(pK^-K^+) - A_{\mathrm{Raw}}(p\pi^-\pi^+) \\ &\approx A_{CP}(pK^-K^+) - A_{CP}(p\pi^-\pi^+)\end{aligned}$$

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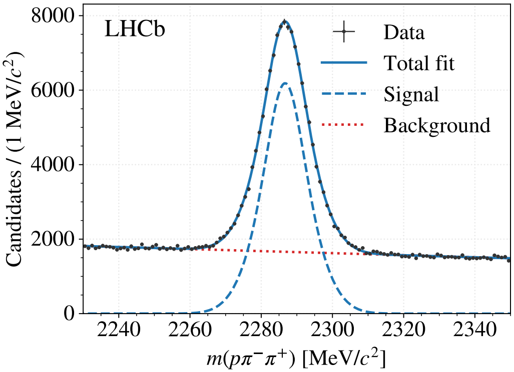
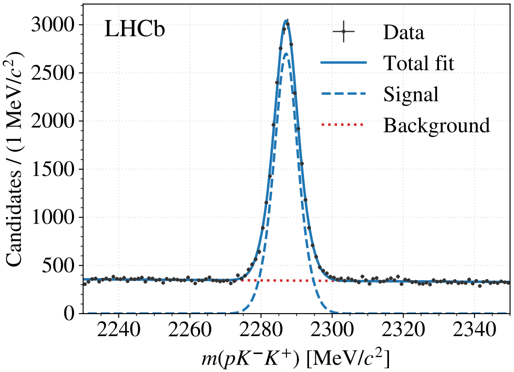
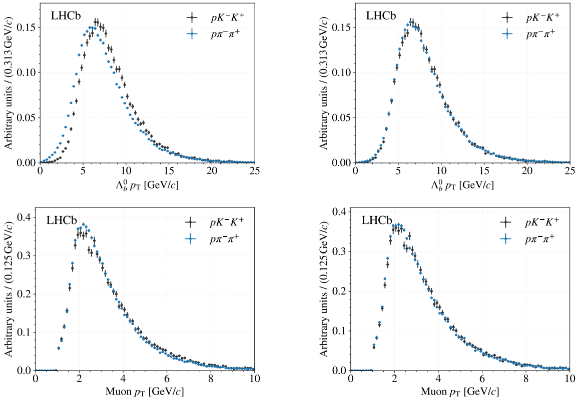




Kinematic equalisation

- Hadron and muon detection asymmetries, and Λ_b^0 production asymmetry, mimic CPV
- Estimates available from data and MC, but generally with large uncertainties
- Weight $p\pi^-\pi^+$ kinematics to match pK^-K^+ to ensure cancellation in ΔA_{CP}
  - Show before (left) and after (right) weighting



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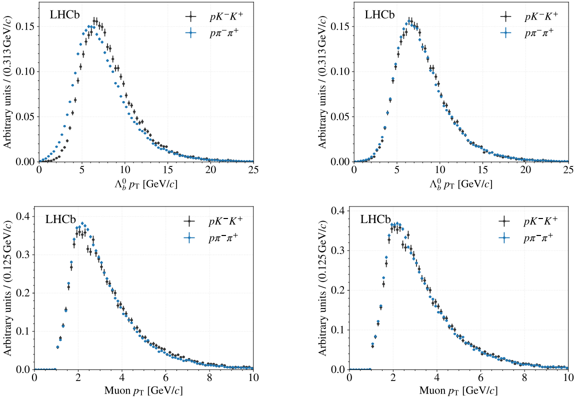
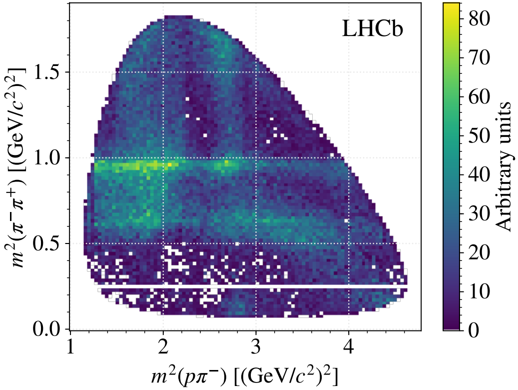
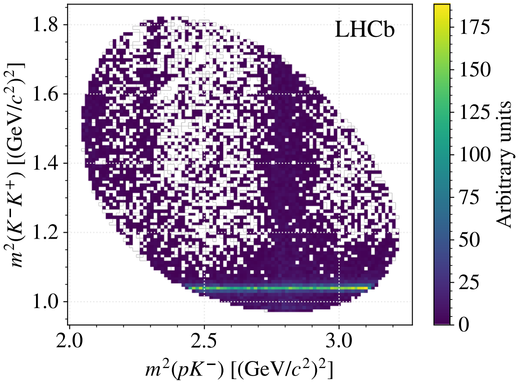


- The $p\pi^-\pi^+$ asymmetry is alternated by this procedure

$$\Delta A_{CP}^{\text{wgt}} \approx A_{CP}(pK^-K^+) - A_{CP}^{\text{wgt}}(p\pi^-\pi^+)$$

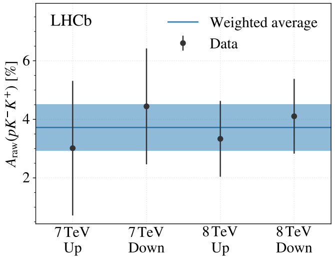
- Efficiencies varies across the complex 5D $\Lambda_c^+ \to p h^+ h^-$ phase space
- CPV can also vary across this, so must correct for experimental effects

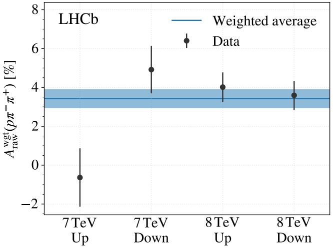


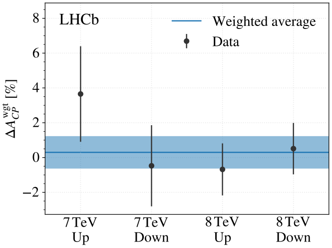


JHEP **03** (2018) 182

- Measure asymmetries separately for each data-taking condition







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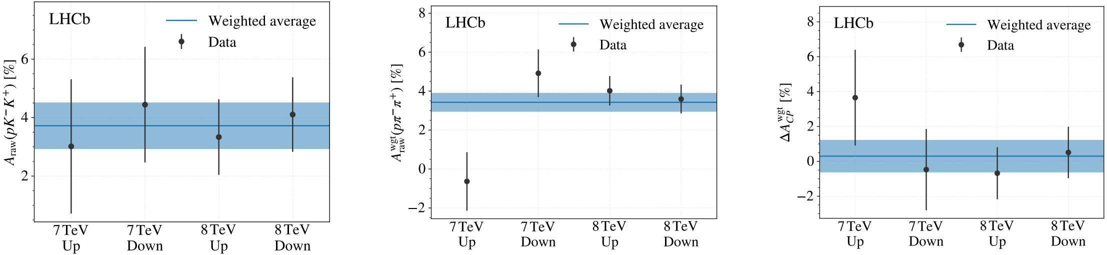

- Averages across all conditions

$$A_{\mathrm{Raw}}(pK^-K^+) = (3.72 \pm 0.78\,(\mathrm{stat.}))\,\%$$
$$A^{\mathrm{wgt}}_{\mathrm{Raw}}(p\pi^-\pi^+) = (3.42 \pm 0.47\,(\mathrm{stat.}))\,\%$$
$$\Delta A^{\mathrm{wgt}}_{CP} = (0.30 \pm 0.91\,(\mathrm{stat.}) \pm 0.61\,(\mathrm{syst.}))\,\%$$

Summary

- Baryons provide a rich laboratory within which to study QCD and *CP* violation
- LHCb has collected the world's largest samples of charm and beauty baryons
  - Have not discussed recent discoveries of ground states, Ξ_{cc}^{++}, and excited states, Ω_c^*
- Exploiting data to produce range of new and interesting results
- Plenty more to come with Run 2 data

Back up