Baryonic *B* decays at LHCb

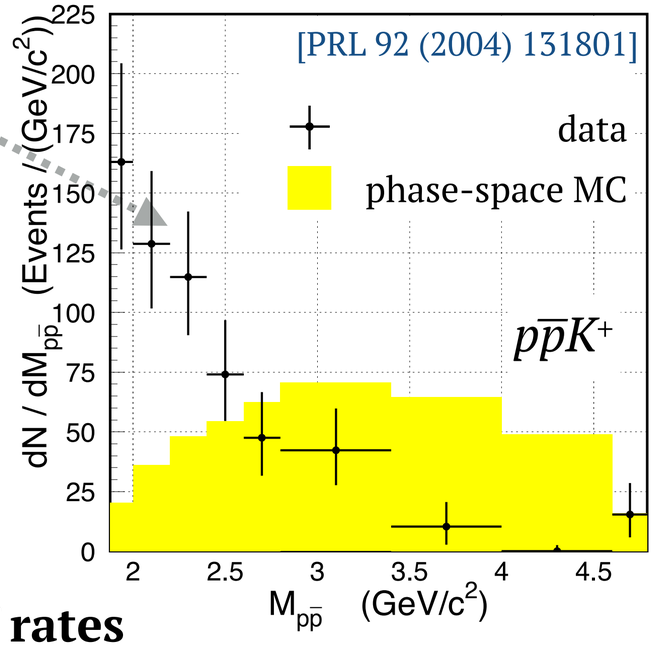
EPS-HEP 2023 — Hamburg — 21-25 August

Simon Akar
on behalf of the LHCb Collaboration

Physics landscape

Motivations

- **Dynamics of *B*-meson baryonic decays are not well understood**
  - **ARGUS first observed charmless baryonic *B* decays in $p\bar{p}\pi^+(\pi^+)$** [PLB 209 (1988) 119]
  - **Belle observed threshold enhancement effect at $m(p\bar{p}) = m(p) + m(\bar{p})$** in three-body $p\bar{p}K^+$ final state [PRL 88 (2002) 181803] latter confirmed in other $p\bar{p}h$ final states [PRL 92 (2004) 131801]
  - **Recent work describe the baryon-antibaryon enhancements via:** Gluonic and fragmentation mechanisms [PRD 68 (2003) 014004] Pole models [J. Phys. G 34 (2007) 283] Intermediate X(1835) baryonium bound state [PLB 567 (2003) 273]



- **Purely-baryonic *B* decays**
  - **QCD sum rules and perturbative QCD models used to predict low $B^0_{(s)} \to p\bar{p}$ rates**
  - **No predictions for 4-body purely baryonic $B^0_{(s)} \to p\bar{p}p\bar{p}$ decays**

New measurements of purely-baryonic *B* decays would provide new insight in the understanding of the non-trivial processes involved

Search for the rare baryonic decay $B_s^0 \to p\bar{p}$

Full Run2 data (6 fb^{-1})

PRD 108 (2023) 1, 012007

Motivations

[PRD 108 (2023) 1, 012007]

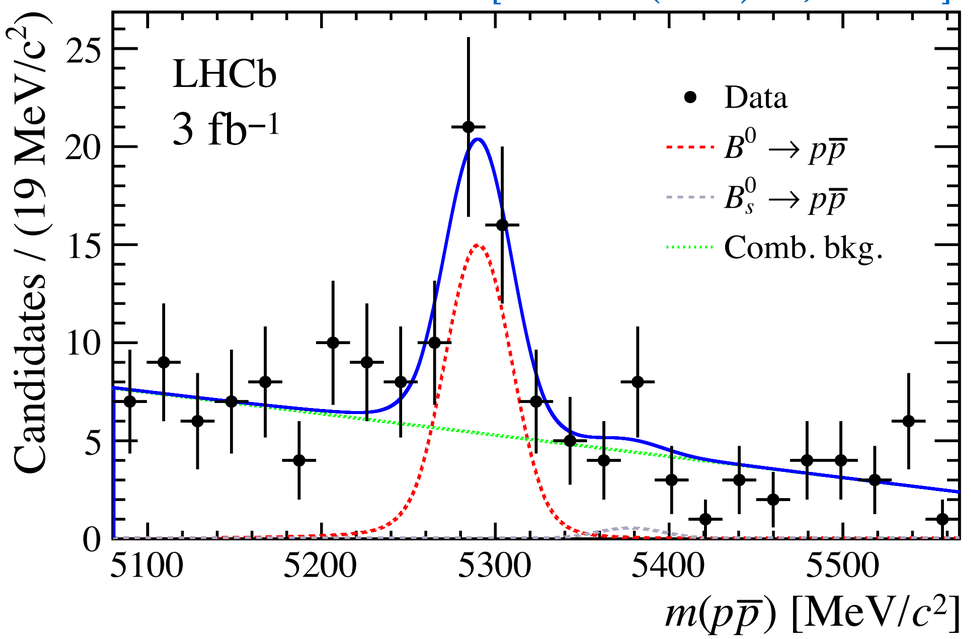
- **Two-body baryonic decays suppressed with respect to multibody decays**
- **LHCb observation of $B^0 \to p\bar{p}$ using Run1 data (3 fb^{-1}):**

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$$

$$\mathcal{B}(B^0_s \to p\bar{p}) < 1.5 \times 10^{-8}$$

  - Some predictions expect $B^0_s \to p\bar{p}$ to be further suppressed (no penguin-level gluon-exchange and annihilation contributions)
    [PRD 89, 056003 (2014), PRD 95, 096004 (2017)]
  - Other predictions expect $B^0_s \to p\bar{p}$ rates similar to that of $B^0 \to p\bar{p}$
    [JHEP2004, 035 (2020)]

[PRL 119 (2017) 23, 232001]



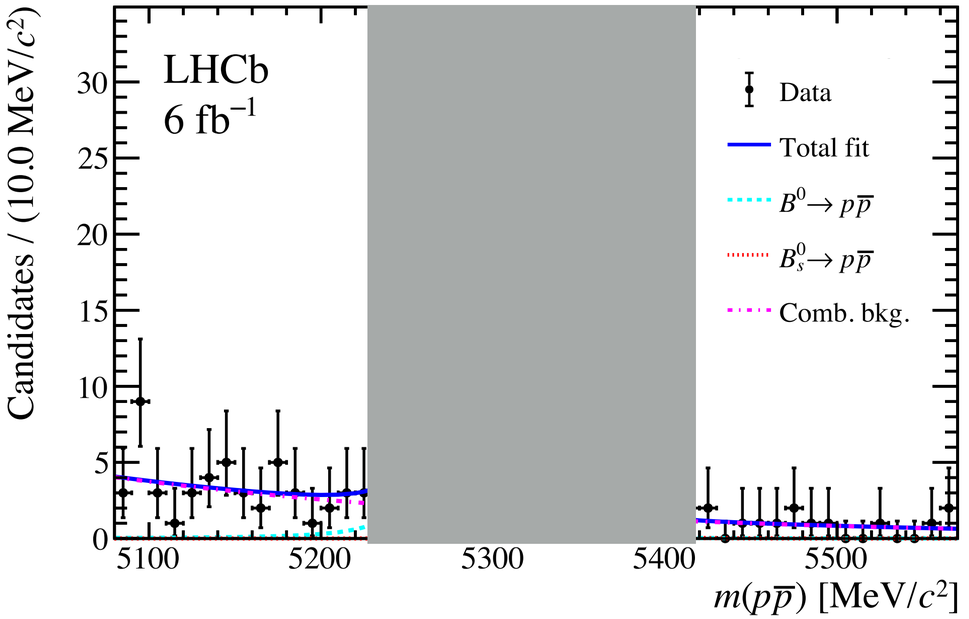
- **Using full Run2 (6 fb^{-1}) data ➙ updated search for $B^0_s \to p\bar{p}$ decays**

Analysis overview

[PRD 108 (2023) 1, 012007]

- **Similar strategy as analysis on Run1 data**
  - Using full 6 fb^{-1} of Run2 data
  - Blind analysis: $m(p\bar{p}) \notin [5230, 5417]$ MeV/c^2
  - $B^0 \to K^+\pi^-$ as normalisation channel
  - Sig. and norm. yields from individual fits
  - Updated selection optimized for $B^0_s \to p\bar{p}$ search

- **Selection in a nutshell**
  - Initial selection step (mostly) based on topological variables to reduce combinatorial background
  - Intermediate selection based on PID variables to reduce candidates with mis-ID daughters
  - Final selection using BDT (TMVA) to further reduce backgrounds while keeping high signal efficiency



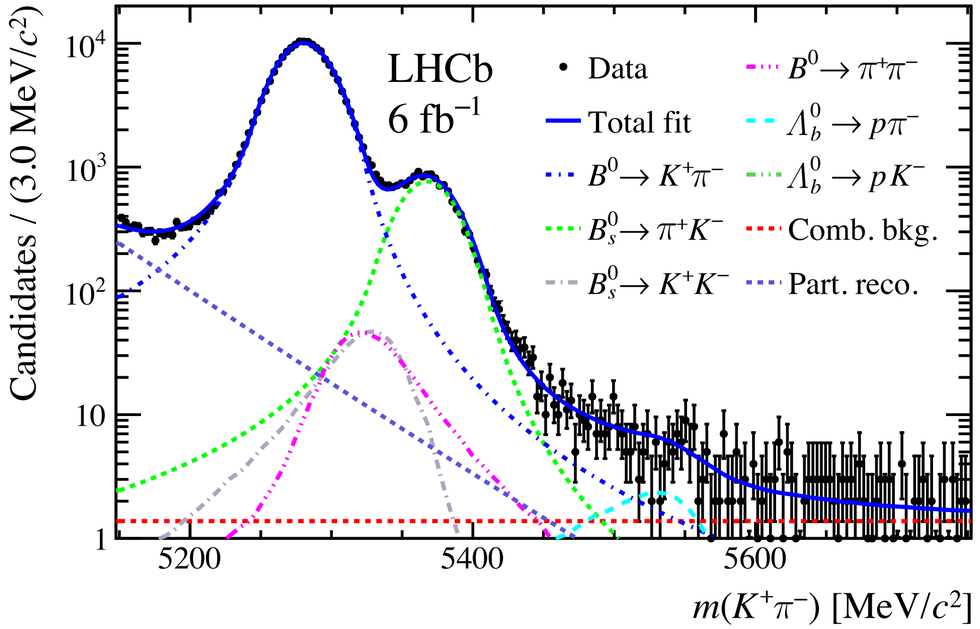
Normalisation channel

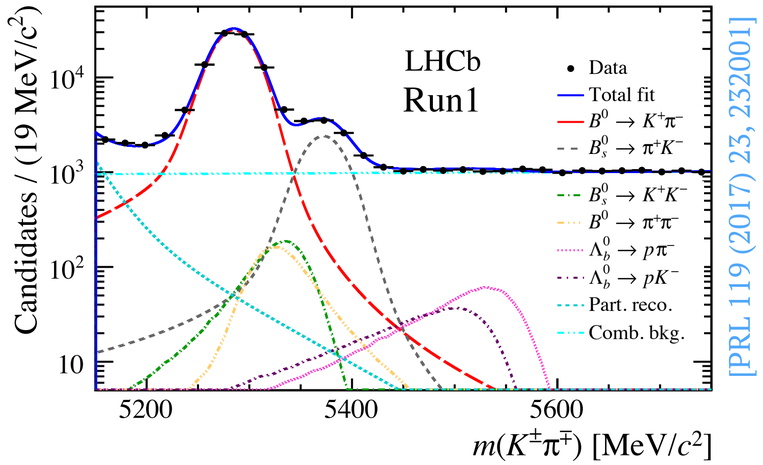
[PRD 108 (2023) 1, 012007]

- **Fit to $m(K^+\pi^-)$**
  - Several contributions included
    - $B^0 \to K^+\pi^-$; $B_s^0 \to \pi^+K^-$; $B_s^0 \to K^+K^-$
    - mis-ID bkg.
    - partially reco bkg.
    - comb bkg.

- **Signal yield result**
  - N($B^0 \to K^+\pi^-$) = 179890 ± 350 (Run2)

Improved S/B with respect to Run1 analysis with
N($B^0 \to K^+\pi^-$) = 88961 ± 341





[PRL 119 (2017) 23, 232001]

Results

[PRD 108 (2023) 1, 012007]

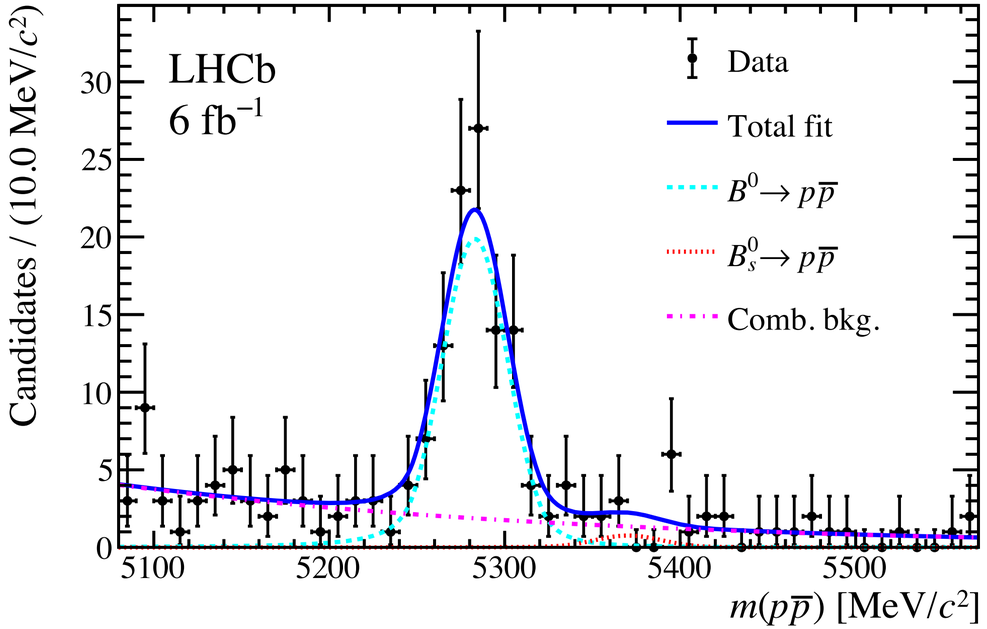
- **Fit to $m(p\bar{p})$: signal yields**
  - $N(B^0 \to p\bar{p}) = 98 \pm 11$
  - $N(B_s^0 \to p\bar{p}) = 4 \pm 5$

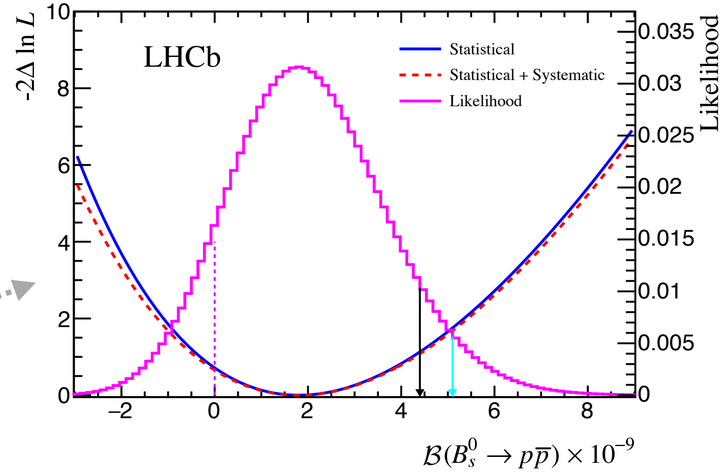
- **Branching fraction measurements**
  - $B^0 \to p\bar{p}$ Run2 alone:

    $\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.15 \pm 0.05 \pm 0.04) \times 10^{-8}$
  - **$B^0 \to p\bar{p}$ combination with Run1:**

    $\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.13 \pm 0.05 \pm 0.03) \times 10^{-8}$
  - **Improved UL on $B_s^0 \to p\bar{p}$ by factor 3**

    $\mathcal{B}(B_s^0 \to p\bar{p}) < 4.4\ (5.1) \times 10^{-9}$ at 90% (95%) CL





Search for the rare baryonic decays $B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$

Full Run1 & Run2 data (9 fb^{-1})

Accepted by PRL

LHCb-PAPER-2022-032
arXiv:2211.08847

Motivations

- **Main goal: first observation of a purely baryonic 4-body decay**

$$\mathcal{B}(B^0 \to p\bar{p}p\bar{p}) < 2.0 \times 10^{-7} \text{ at } 90\% \text{ confidence level.}$$ [BaBar, PRD 98 (2018) 7, 071102]

- **Very rare decay** with **clean expected experimental signature**
  ↳ accessible if $\mathcal{B}$~[10^{-8}, 10^{-7}]

- $B_s^0 \to p\bar{p}p\bar{p}$ expected to be **further suppressed** with respect to B^0
  ↳ hadronisation fraction f_s/f_d ~ 25%, and $|V_{us}/V_{ud}|^2$ ~ 5%

- An observation would constitute a first step toward an amplitude analysis to study the baryon-antibaryon subsystem and threshold effects with LHCb Upgrade

Analysis strategy

- The $p\bar{p}p\bar{p}$ **data samples are blinded** in the signal region: $[5240, 5407]$ MeV/c^2
  - **Tighter selection** applied for B^0_s search & branching fraction determination due to the lower expected yield wrt B^0 (tight PID for B^0 & very tight PID for B^0_s)
  - Charmonium contribution to $p\bar{p}p\bar{p}$ spectrum expected to be small to negligible
    ↳ perform inclusive measurement and qualitative statement after $c\bar{c}$ vetoes

  - **Signal significances** measured from fits to $m(p\bar{p}p\bar{p})$ alone
  - **Branching fractions** measured from simultaneous fits to sig. and norm. channels
    ↳ $B^0 \to J/\psi(p\bar{p})K^{*0}(K\pi)$ and $B^0_s \to J/\psi(p\bar{p})\phi(KK)$:

$$\mathcal{B}(B^0 \to p\bar{p}p\bar{p}) = \mathcal{B}_{\text{vis}}(B^0 \to J/\psi\, K^{*0}) \times \frac{N(B^0 \to p\bar{p}p\bar{p})}{N(B^0 \to J/\psi\, K^{*0})} \times \frac{\epsilon(B^0 \to J/\psi\, K^{*0})}{\epsilon(B^0 \to p\bar{p}p\bar{p})}$$

similarly for B^0_s with $J/\psi\phi$

Taken from PDG

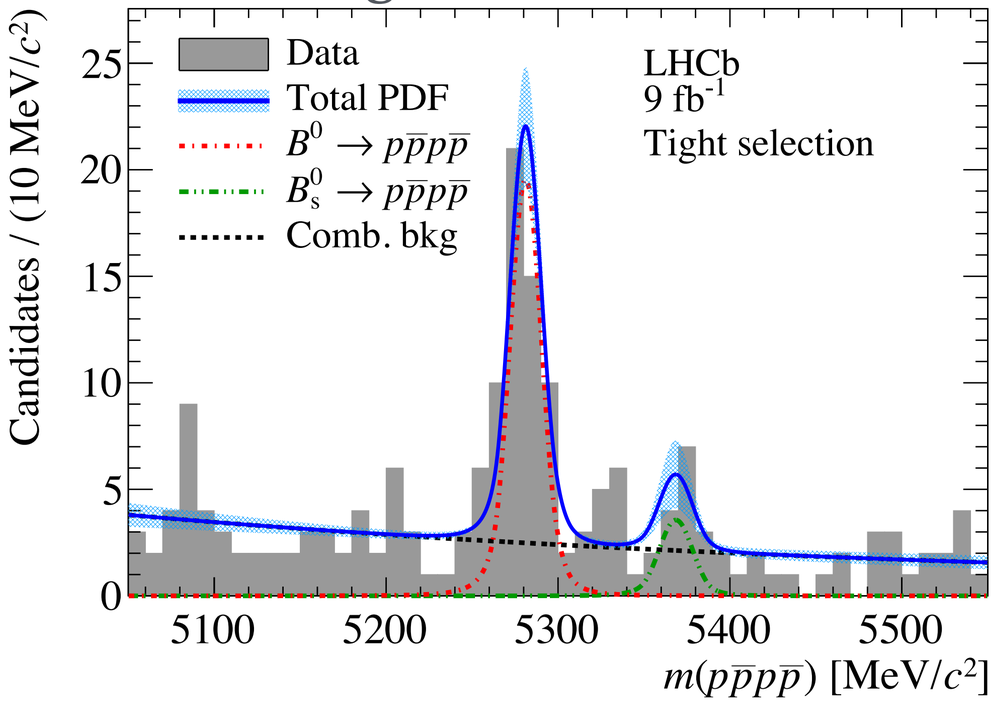
UML fit to data

From simulation corrected with norm. channels

Measurement of signal significances

- **Fit to $m(p\bar{p}p\bar{p})$:**

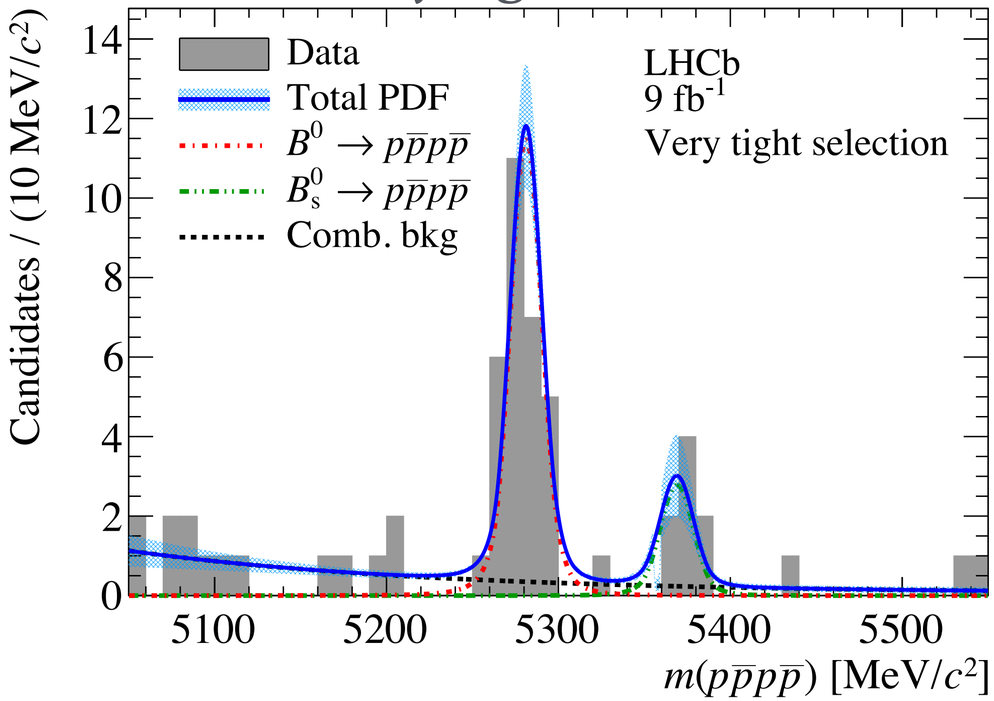
Tight selection



$N(B^0 \to p\bar{p}p\bar{p}) = 48 \pm 8$

Significance: > 9σ

Very tight selection



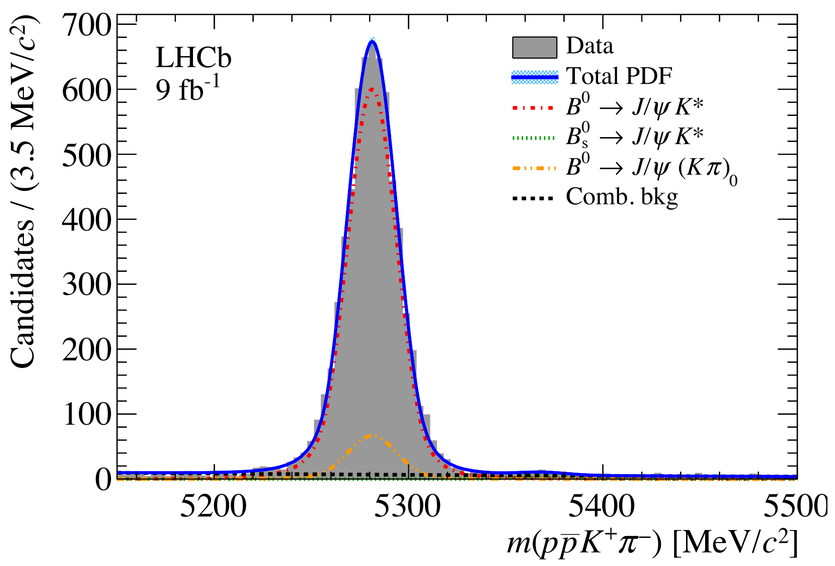
$N(B_s^0 \to p\bar{p}p\bar{p}) = 7.1 \pm 2.9$

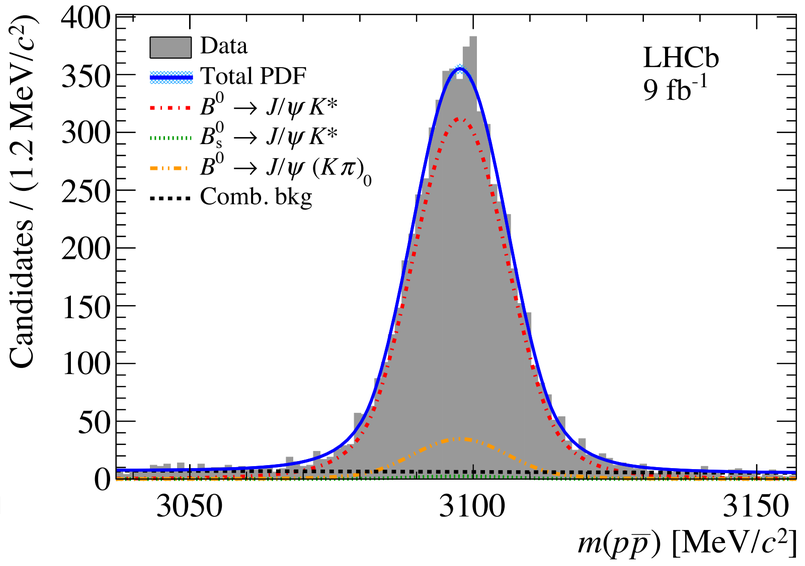
Significance: 4σ

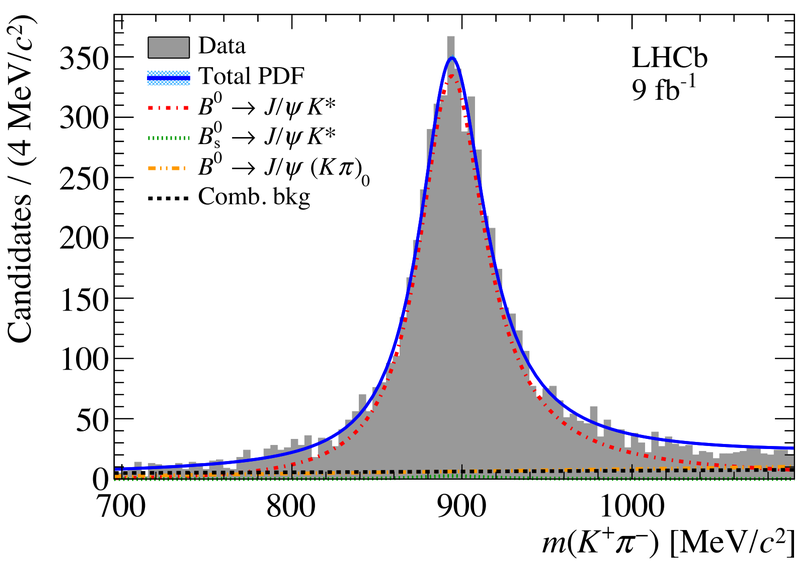
Including stat. and syst. uncertainties

Branching fractions: normalisation channels

- **Simultaneous fit to $m(p\bar{p}p\bar{p})$, $m(p\bar{p}K\pi)$ and $m(p\bar{p}KK)$**
  - Normalisation modes described by 3D fit model
    ↳ allow accounting for $(K\pi)$ S-wave component in $p\bar{p}K\pi$ data







Similar plots from fit to $p\bar{p}KK$ data in back-up

Branching fractions: results

- **Inclusive branching fractions**

$$\mathcal{B}(B^0 \to p\bar{p}p\bar{p}) = (2.2 \pm 0.4 \pm 0.1 \pm 0.1) \times 10^{-8}$$ Tight selection

$$\mathcal{B}(B_s^0 \to p\bar{p}p\bar{p}) = (2.3 \pm 1.0 \pm 0.2 \pm 0.1) \times 10^{-8}$$ Very tight selection

First measurement of $\mathcal{B}(B^0 \to p\bar{p}p\bar{p})$
Unexpectedly large $\mathcal{B}(B_s^0 \to p\bar{p}p\bar{p})$

- Branching fractions with $c\bar{c}$ veto
  - $m(p\bar{p}) < 2.85$ GeV for all 4 possible $p\bar{p}$ pairs

$$\mathcal{B}(B^0 \to p\bar{p}p\bar{p}) = (1.6 \pm 0.4) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to p\bar{p}p\bar{p}) = (2.2 \pm 1.2) \times 10^{-8}$$

stat uncertainties only

Data is consistent with decays proceeding primarily through charmless transitions

Summary & outlook

- **Summary:**
  - **Searched for $B^0_s \to p\bar{p}$ decays**
    ↳ improved UL by factor 3 $\quad \mathcal{B}(B^0_s \to p\bar{p}) < 4.4\ (5.1) \times 10^{-9}$ at 90% (95%) CL
    ↳ improved $\mathcal{B}(B^0 \to p\bar{p})$ $\quad \mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.13 \pm 0.05 \pm 0.03) \times 10^{-8}$
  - **Searched for $B^0 \to p\bar{p}p\bar{p}$ & $B^0_s \to p\bar{p}p\bar{p}$ decays**
    ↳ clear B^0 signal observed (9σ) with unexpectedly large B^0_s signal (4σ):

$$\mathcal{B}(B^0 \to p\bar{p}p\bar{p}) = (2.2 \pm 0.4 \pm 0.1 \pm 0.1) \times 10^{-8}$$
$$\mathcal{B}(B^0_s \to p\bar{p}p\bar{p}) = (2.3 \pm 1.0 \pm 0.2 \pm 0.1) \times 10^{-8}$$

- **Outlook:**
  - Very promising prospects regarding study of purely baryonic decays with LHCb Upgrade (removal of hardware trigger)
  - Enable improving understanding of the non-trivial processes involved in the decays of B mesons to charmless hadronic multi-body final states

Additional material

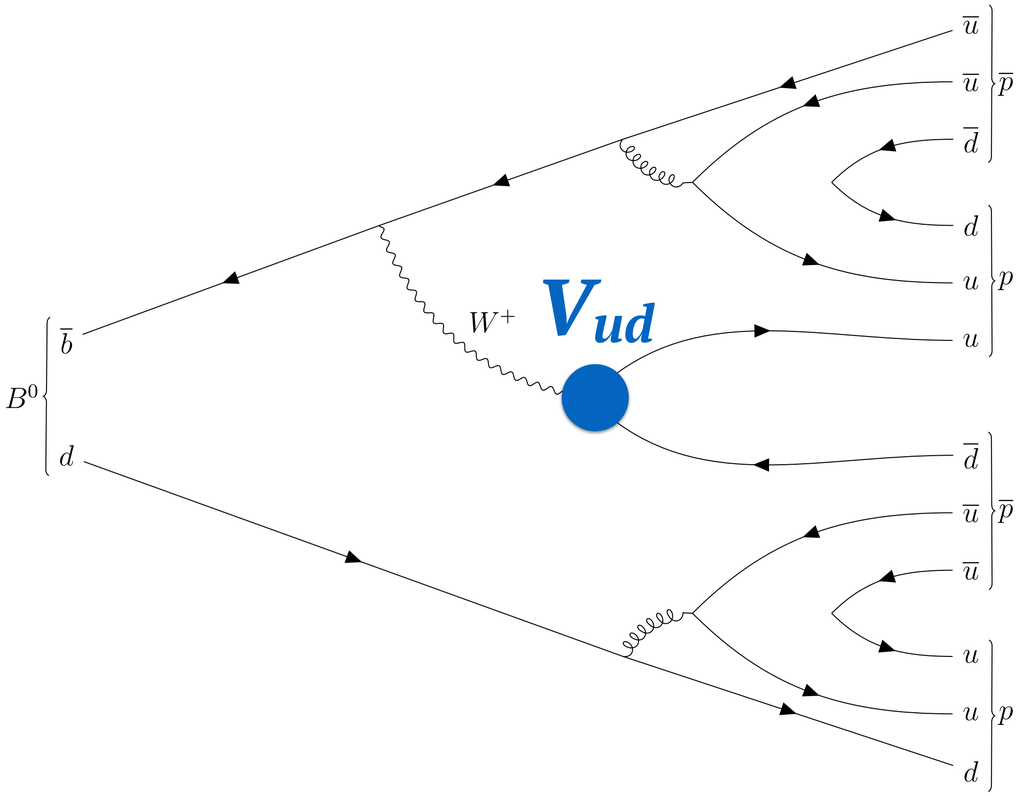
$B_s^0 \to p\bar{p}$: Systematics

Source of systematic uncertainties	$B^0 \to p\bar{p}$	$B_s^0 \to p\bar{p}$
f_s/f_d	-	3.1
L0 trigger efficiency	1.0	1.0
Selection efficiency relative to $B^0 \to K^+\pi^-$	2.0	2.0
Tracking efficiency	1.9	1.9
PID efficiency	2.4	2.4
Fit model	1.0	22.0
Total	3.9	22.5

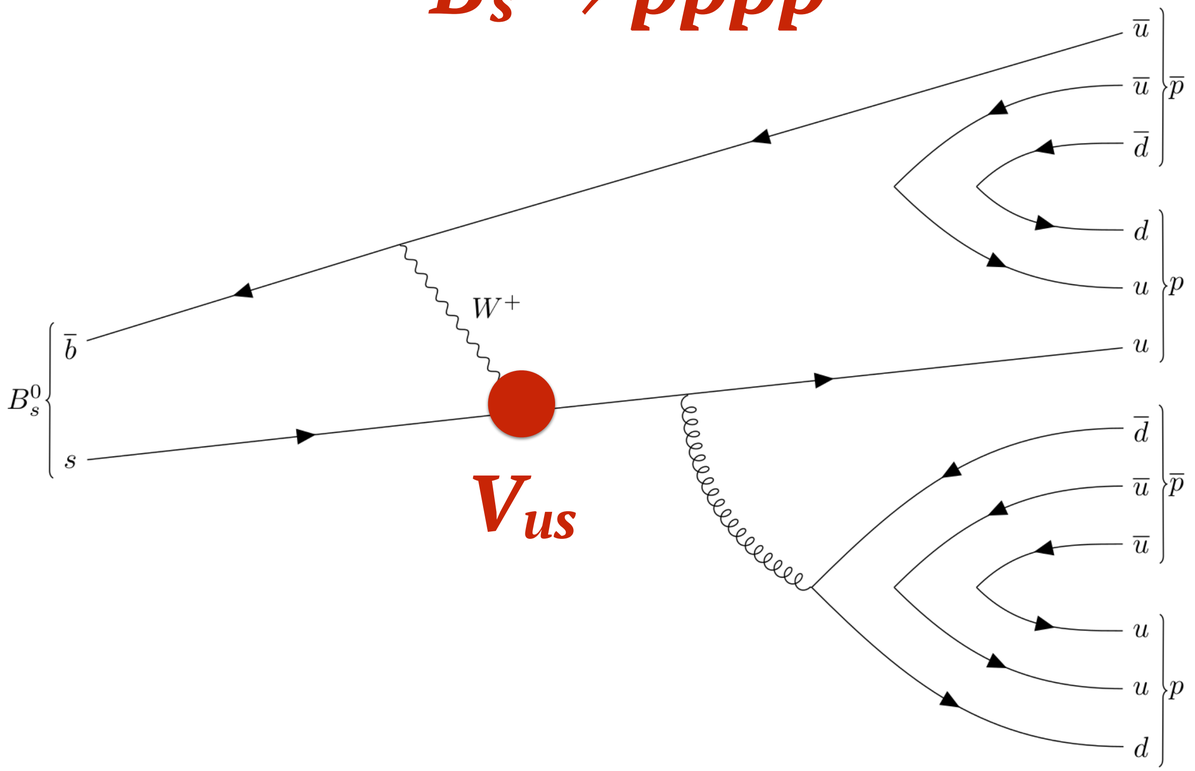
Uncertainties in %

$B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$: Feynman diagrams

$B^0 \to p\bar{p}p\bar{p}$



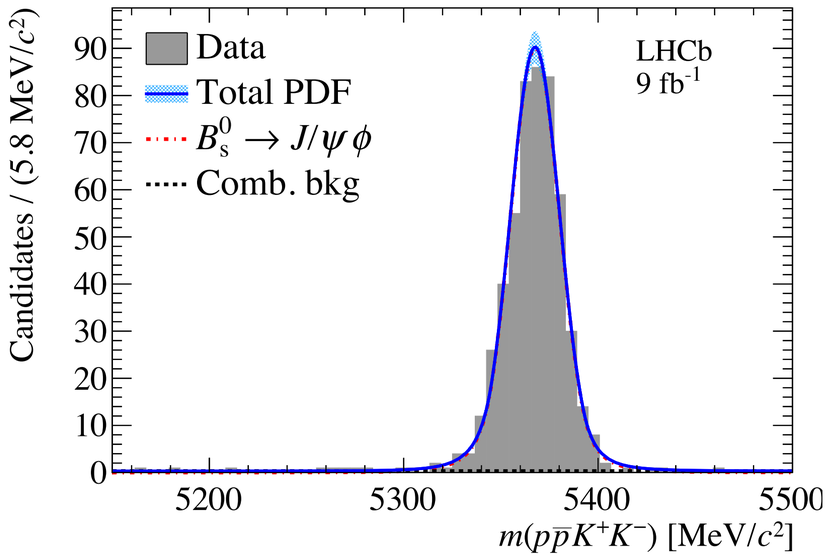
$B_s^0 \to p\bar{p}p\bar{p}$

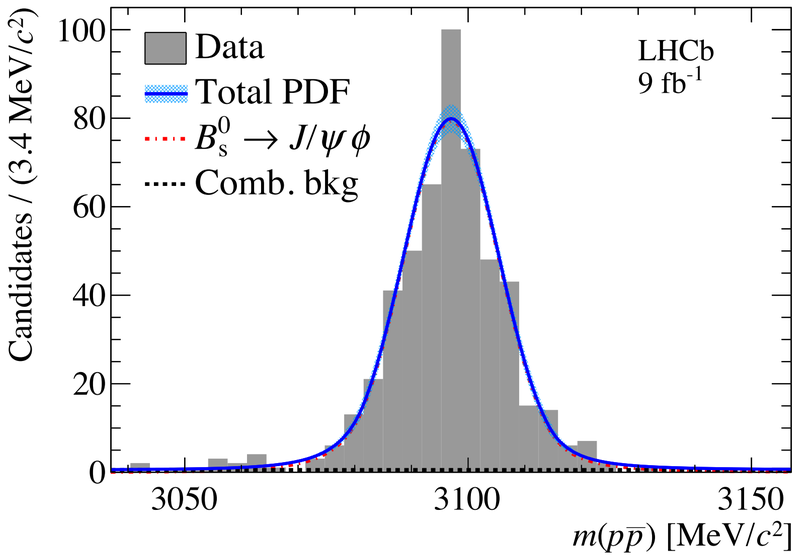


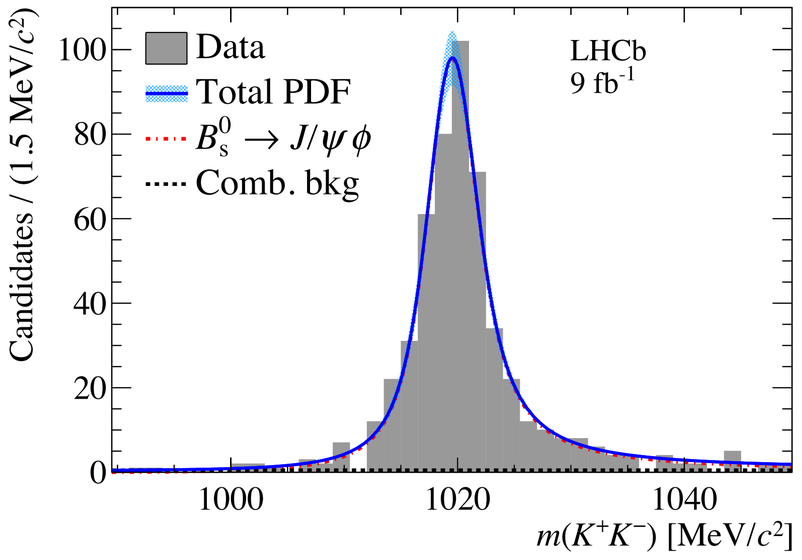
- $B_s^0 \to p\bar{p}p\bar{p}$ expected to be **suppressed** with respect to B^0
  ↳ hadronisation fraction f_s/f_d ~ 25%, and $|V_{us}/V_{ud}|^2$ ~ **5%**

$B^0 \to p\bar{p}p\bar{p}$ and $B^0_s \to p\bar{p}p\bar{p}$: Fit to $p\bar{p}KK$ data

- **Simultaneous fit to $m(p\bar{p}p\bar{p})$, $m(p\bar{p}K\pi)$ and $m(p\bar{p}KK)$**
  - Projections from 3D fit to $p\bar{p}KK$ data







$B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$: Systematics

Nominal $\mathcal{B}(B^0_{(s)} \to p\bar{p}p\bar{p}) \times 10^{-8}$	$B^0 \to p\bar{p}p\bar{p}$ 2.21 ± 0.37	$B_s^0 \to p\bar{p}p\bar{p}$ 2.30 ± 0.96
Systematic source		
Efficiencies (MC stat)	0.02	0.03
Efficiencies (weights)	0.06	0.09
PID	0.03	0.03
Tracking	0.02	0.02
Fixed PDF parameters	0.02	0.02
Signal model	0.00	0.04
Background model	0.03	0.17
Quadratic sum	0.08	0.20
Normalisation $\mathcal{B}$	0.09	0.13

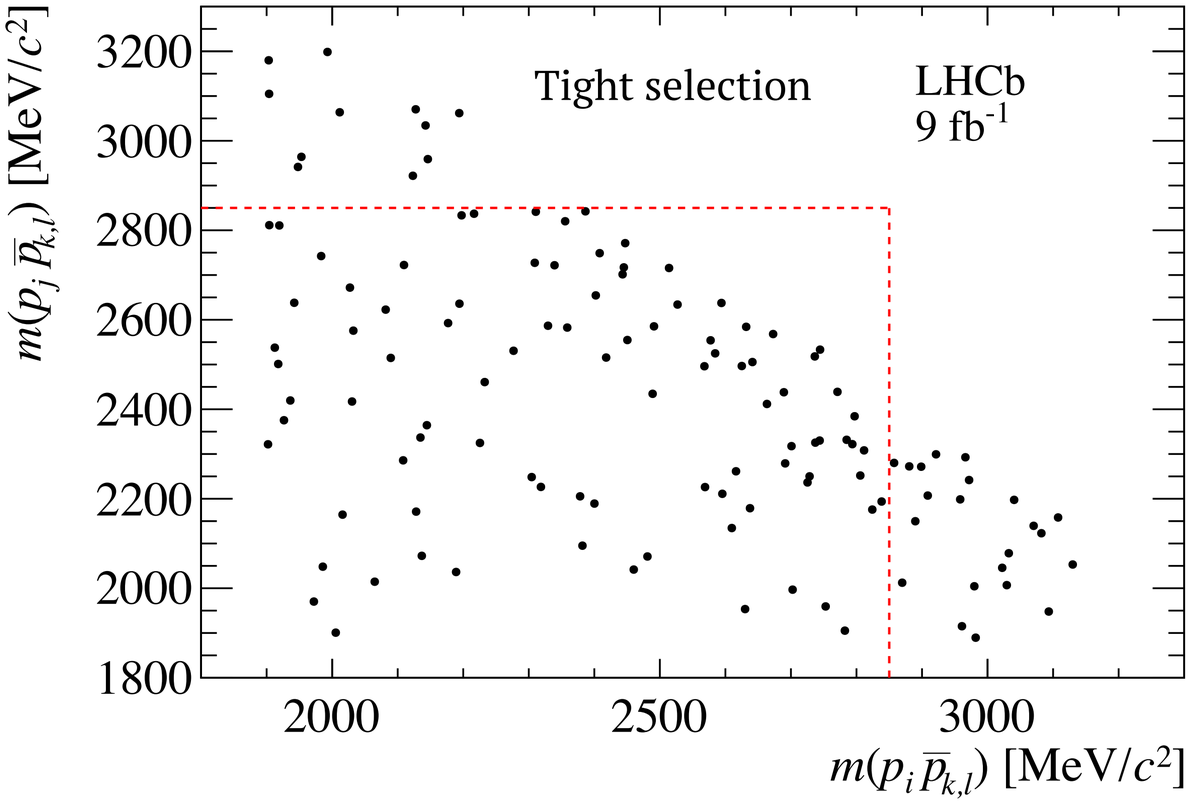
Uncertainties in absolute values

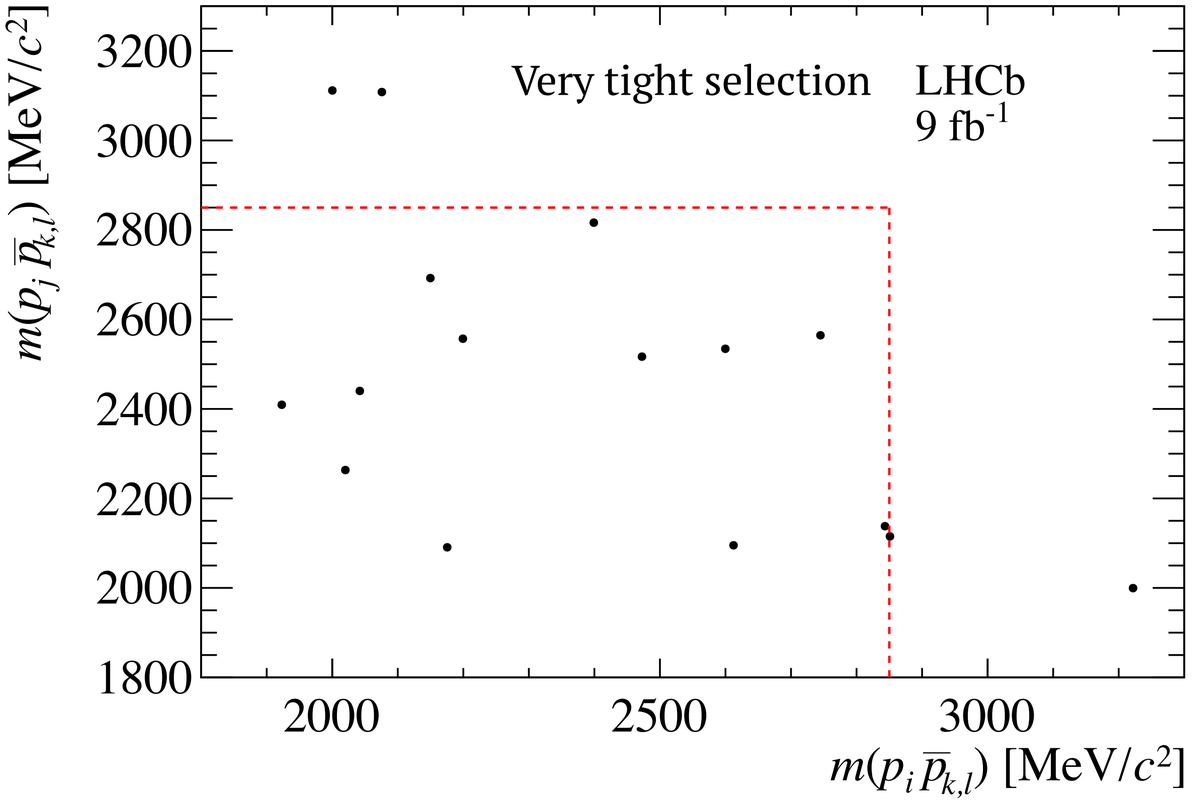
$B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$: $m(p\bar{p})$

$c\bar{c}$ veto:

$m(p\bar{p}) < 2.85$ GeV for all 4 possible $p\bar{p}$ pairs

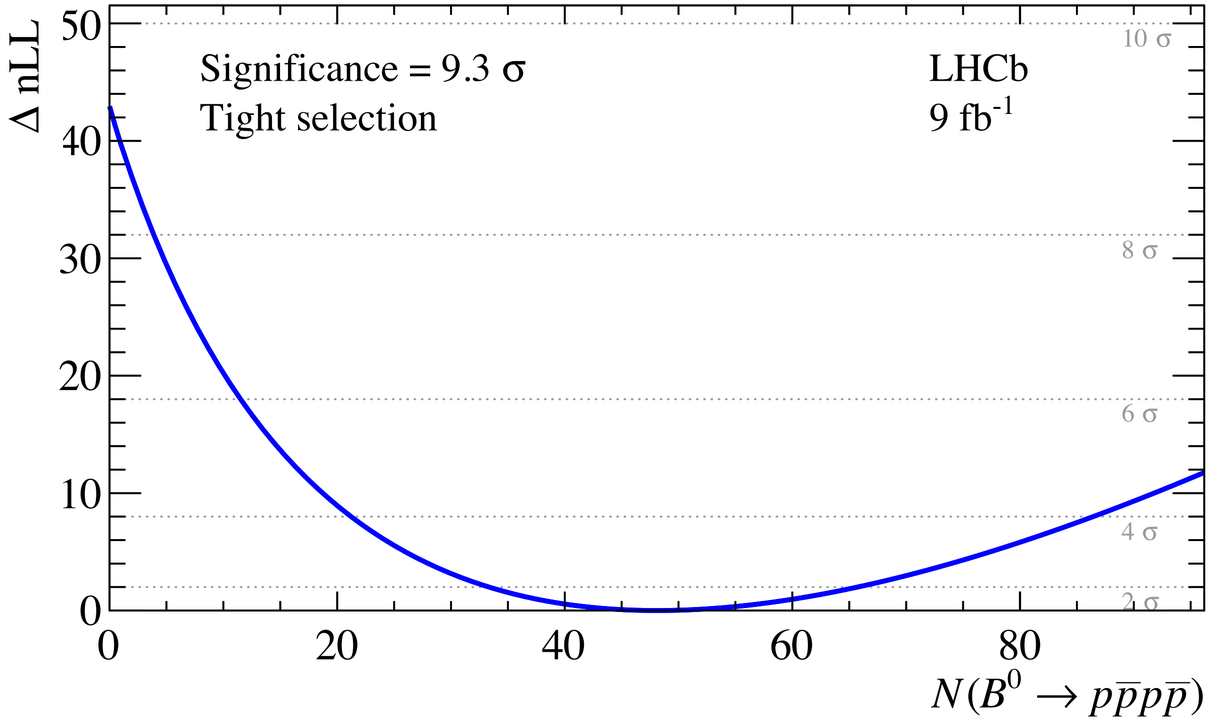
(two entries per candidate)





$B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$: Significances

$B^0 \to p\bar{p}p\bar{p}$



$B_s^0 \to p\bar{p}p\bar{p}$