New results on heavy flavour production at LHCb

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On behalf of the LHCb collaboration

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CERN LHC seminar

Outline

- Introduction

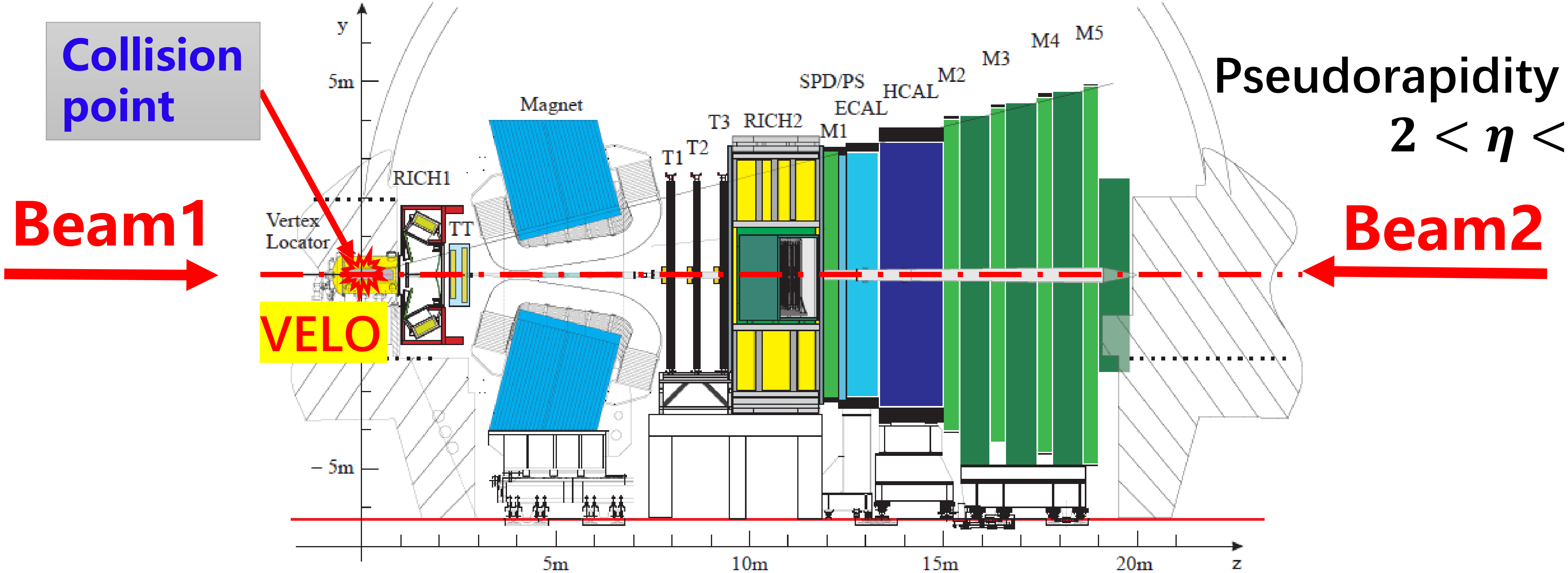
- New results on heavy flavour production
  - b-hadron production fractions at 13 TeV — LHCb-PAPER-2018-050, in preparation
  - The mass and production rate of Ξ_b^- baryons — LHCb-PAPER-2018-047, arXiv:1901.07075 submitted to Phys.Rev.D
  - $\psi(2S)$ production at 13 TeV and 7 TeV — LHCb-PAPER-2018-049, in preparation

- Prospects and summary

The LHCb experiment

The LHCb detector

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022



Collision point

Beam1

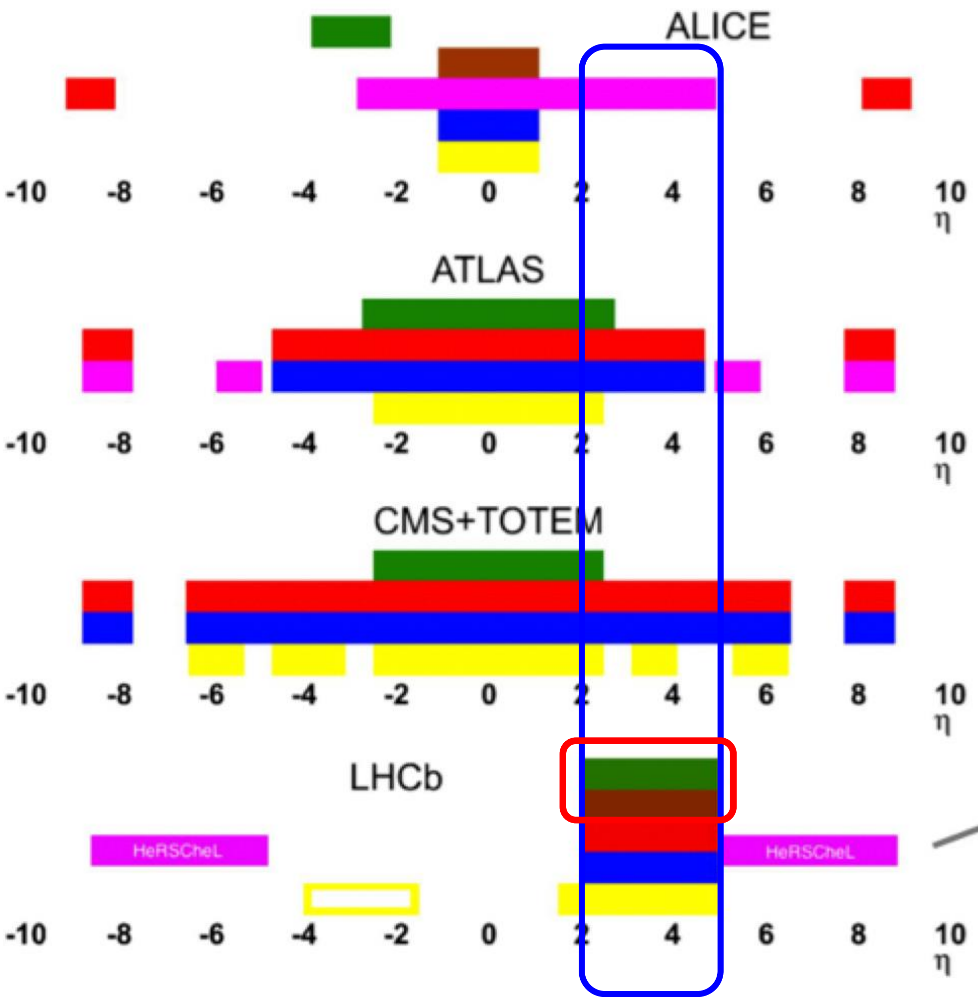
Beam2

VELO

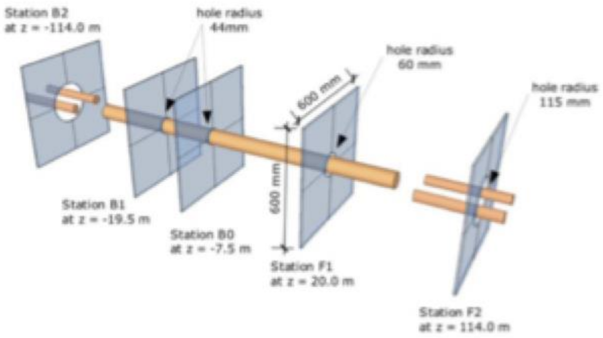
Pseudorapidity coverage
$2 < \eta < 5$

Vertex:	$\sigma_{IP} = 20\ \mu m$	
Time:	$\sigma_\tau = 45$ fs	for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ \mathrm{GeV}/c)$	
Mass :	$\sigma_m = 8\ \mathrm{MeV}/c^2$	for $B \to J/\psi X$ (constraint $m_{J/\psi}$)
Hadron ID:	$\varepsilon(K \to K) \sim 95\%$	mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID:	$\varepsilon(\mu \to \mu) \sim 97\%$	mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1\% \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$	

Fully instrumented at forward coverage



🟫 hadron PID
🟩 muon system
🟪 lumi counters
🟥 HCAL
🟦 ECAL
🟨 tracking



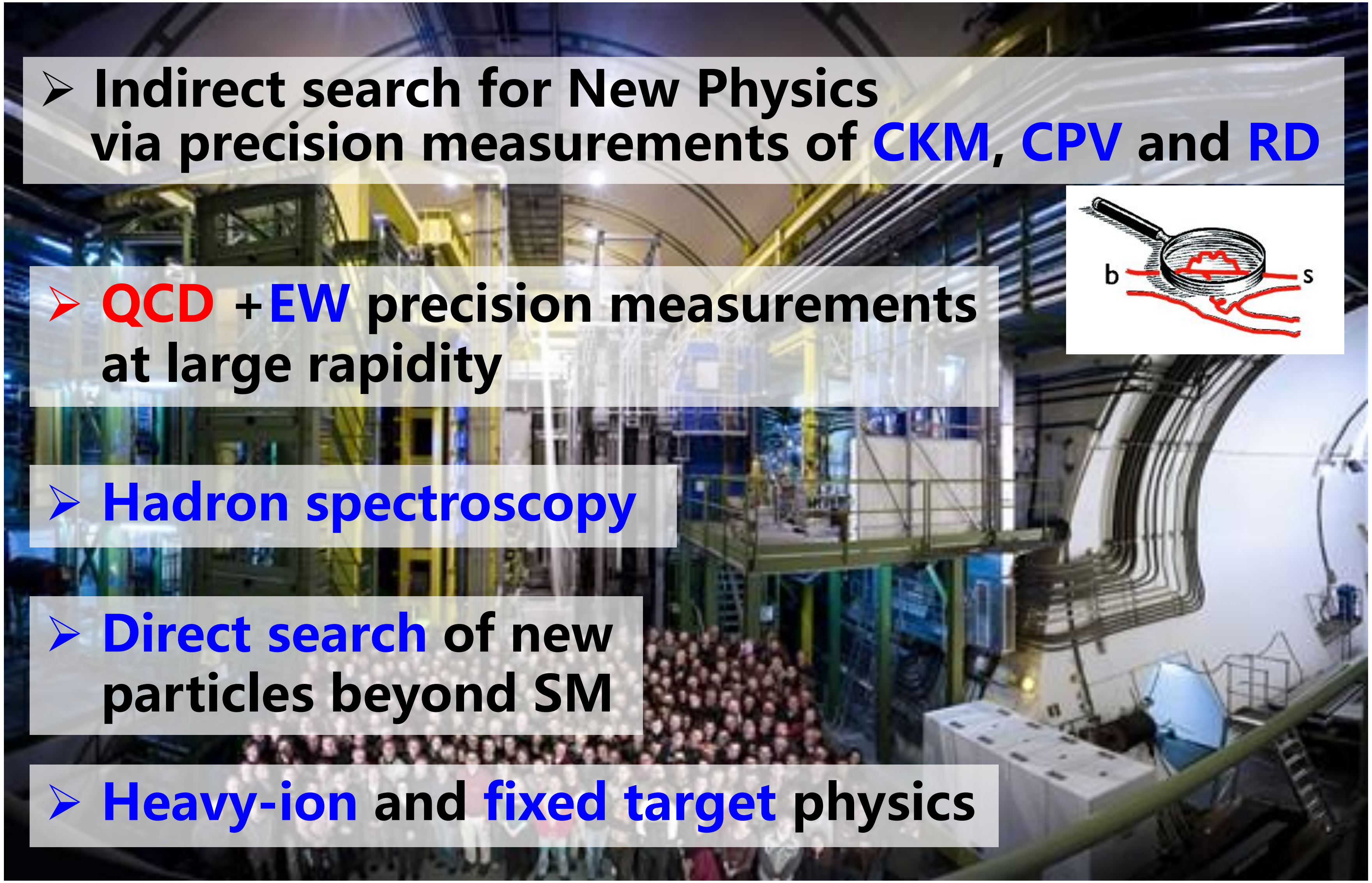
🟪 HeRSCHeL

$-7.5<\eta<-3.5$

$5.0<\eta<8.0$

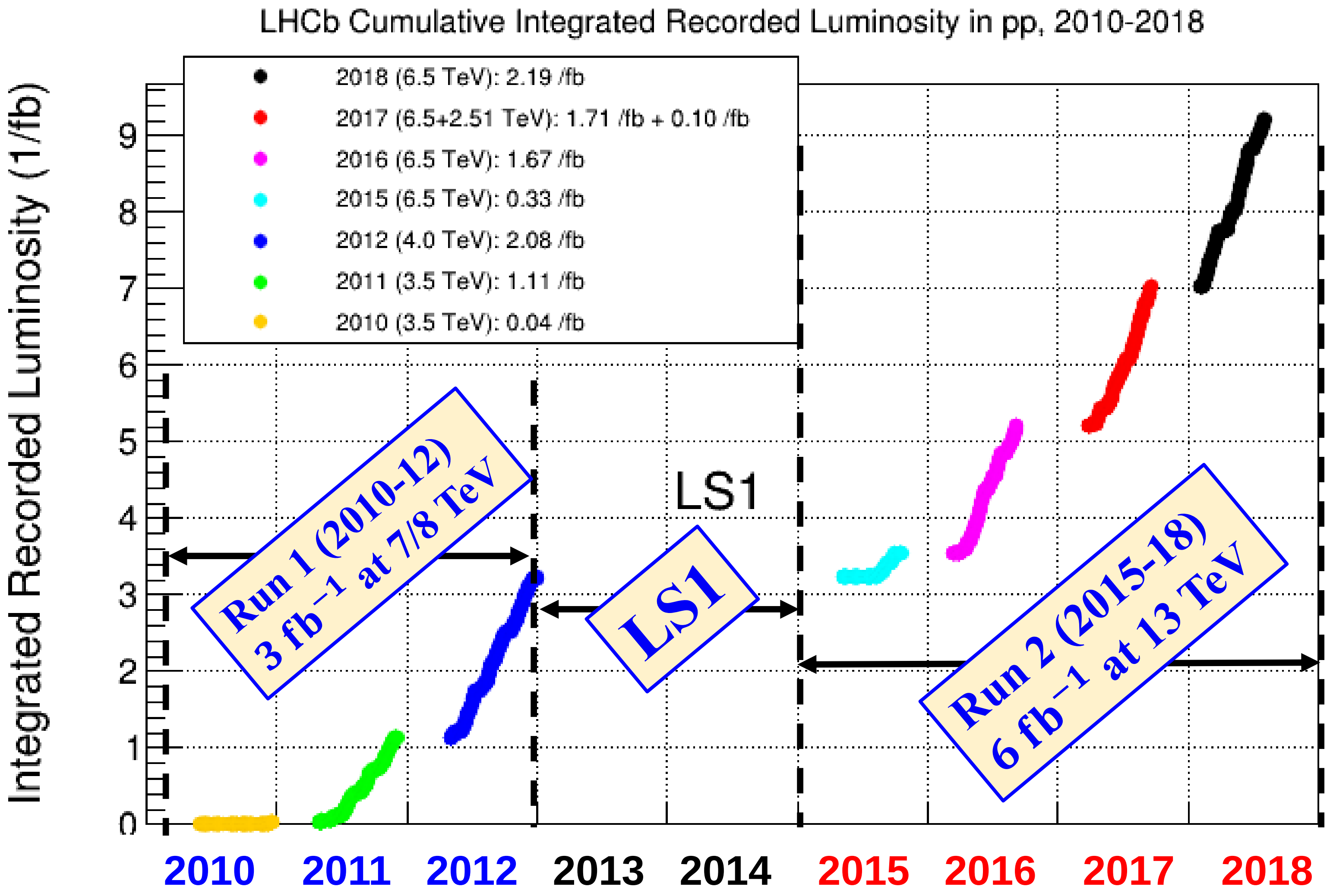
- HeRSCHeL offers extended coverage and physics reach

The Physics of LHCb



- **Indirect search for New Physics via precision measurements of CKM, CPV and RD**
- **QCD + EW precision measurements at large rapidity**
- **Hadron spectroscopy**
- **Direct search of new particles beyond SM**
- **Heavy-ion and fixed target physics**

Data taking (run1+run2)

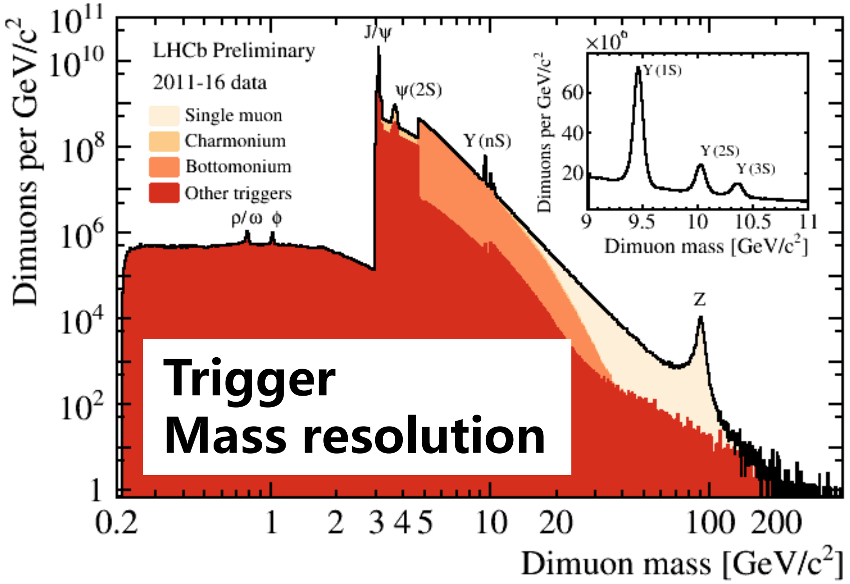


Great thanks to the LHC!

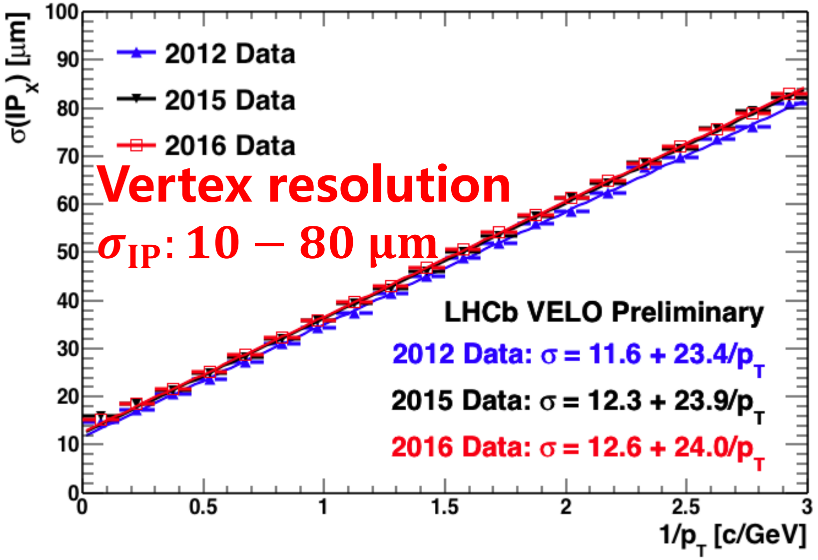
- ➢ A huge amount of $b\bar{b}$ and $c\bar{c}$ have been produced
  - $\sim 10^{12}\ b\bar{b}$
  - $\sim 10^{13}\ c\bar{c}$
- ➢ Many impressive results have been achieved

More than 9 $\mathbf{fb^{-1}}$ accumulated in Run1+Run2

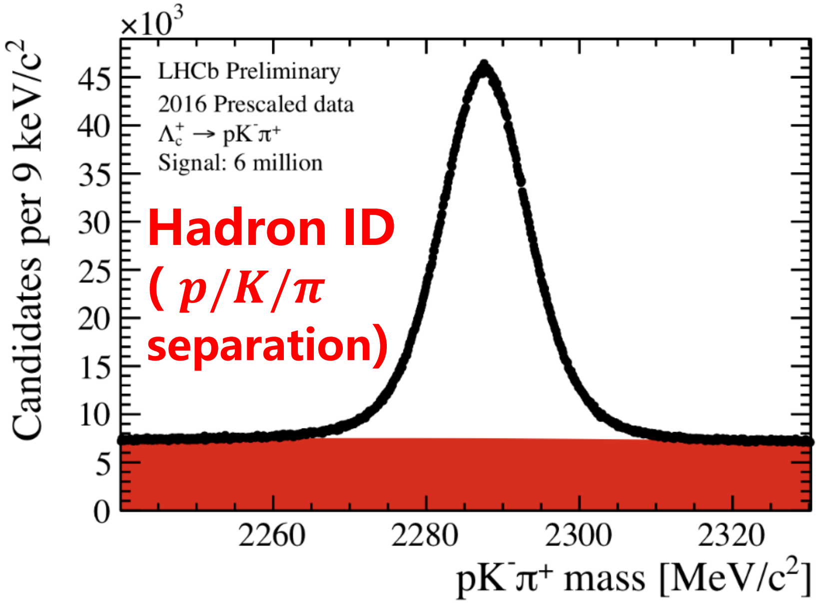
Pros of heavy flavour measurement at LHCb



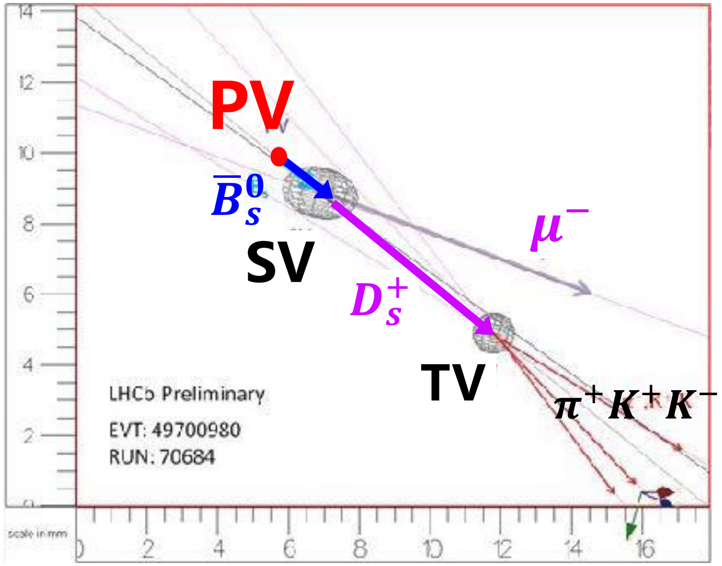
Trigger
Mass resolution



Vertex resolution
σ_{IP}: 10 − 80 μm



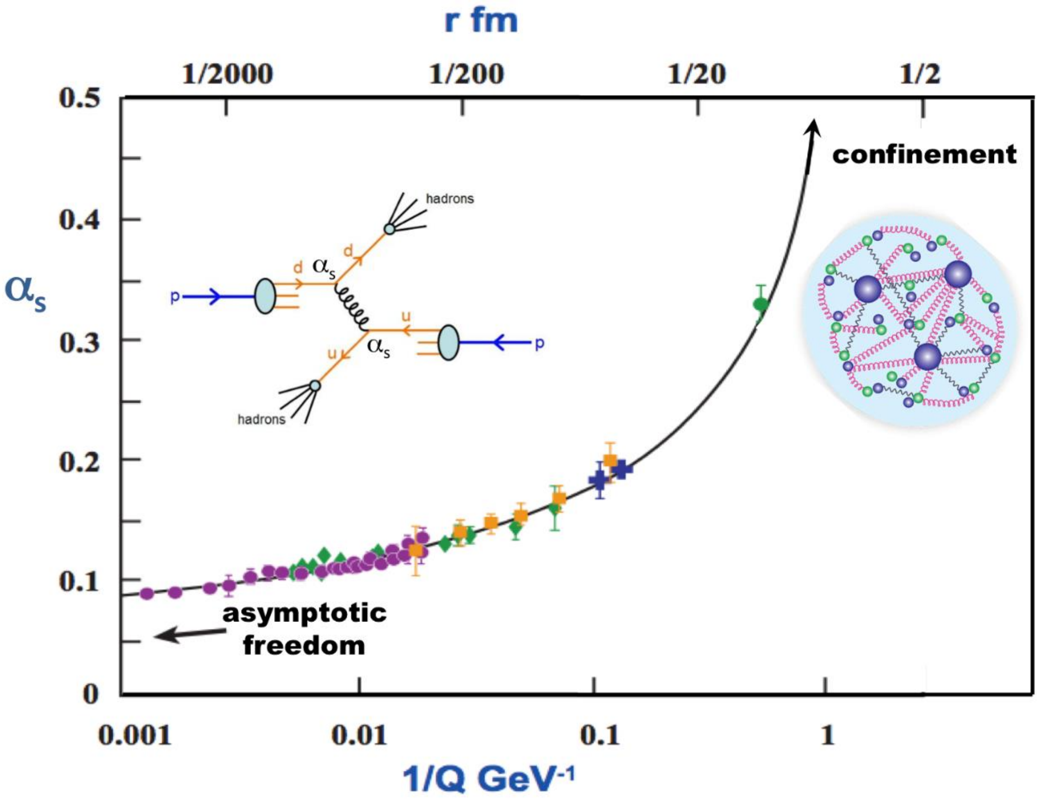
Hadron ID
($p/K/\pi$ separation)



- Large production cross-section
- Efficient trigger
- Vertex locator with high precision
- High precision tracking system
- Powerful hadron identification
- Efficient muon system

Physics motivation

- **The theory of strong interactions, quantum chromodynamics (QCD), is the least understood part of the Standard Model**
  - Well tested in the perturbative region
  - Nonperturbative behaviours remain mysterious
- **Measurements of heavy flavour production and other properties can provide essential information to deeply understand QCD**
  - Understanding of QCD is also important to improve sensitivity of New Physics searches



[S. Olsen et al, Rev. Mod. Phys. 90 (2018) 015003]

b-hadron fractions in pp collisions at 13 TeV: $f_s/(f_u + f_d)$ and $f_{\Lambda_b^0}/(f_u + f_d)$

New

LHCb-PAPER-2018-050
in preparation

b-hadron fragmentation fractions

- Knowledge of b-hadron fragmentation fractions is essential in many aspects
  - To allow for relating the $b\bar{b}$ production cross-section from pQCD to the observed b hadrons
  - To convert the observed $\bar{B}_s^0$ or Λ_b^0 production ratios at the LHC into absolute branching fractions
    - For example, Measurement of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
  - To characterise the signal (background) composition in inclusive (exclusive) b-hadron analyses
- These fractions must be determined experimentally
  - They cannot be reliably predicted because they are dominated by long-distance strong interactions

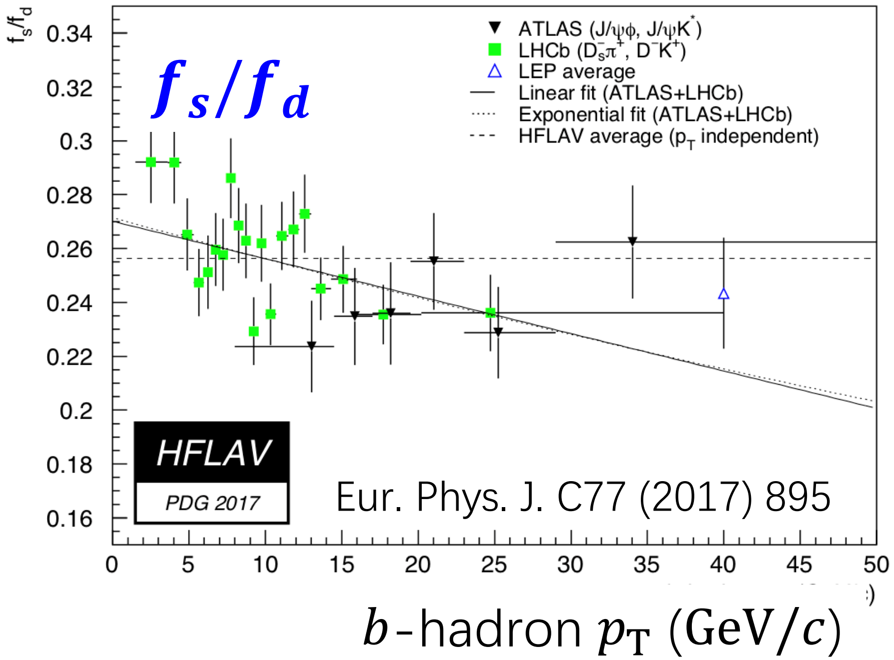
Previous measurements

Phys. Rev. D 85 (2012) 032008
JHEP 04 (2013) 001
JHEP 08 (2014) 143

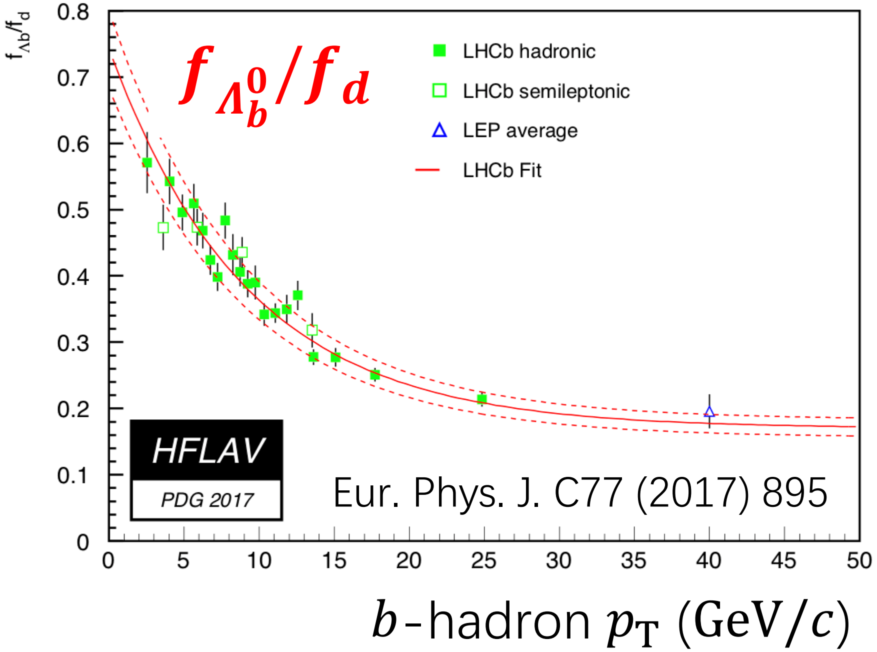
- LHCb measured kinematic dependences of f_s/f_d and $f_{\Lambda_b^0}/f_d$ at 7 TeV using both semileptonic and hadronic decays

- The dependence of f_s/f_d on the b-hadron p_T is not conclusive

- $f_{\Lambda_b^0}/f_d$ is observed to be strongly dependent on the b-hadron p_T



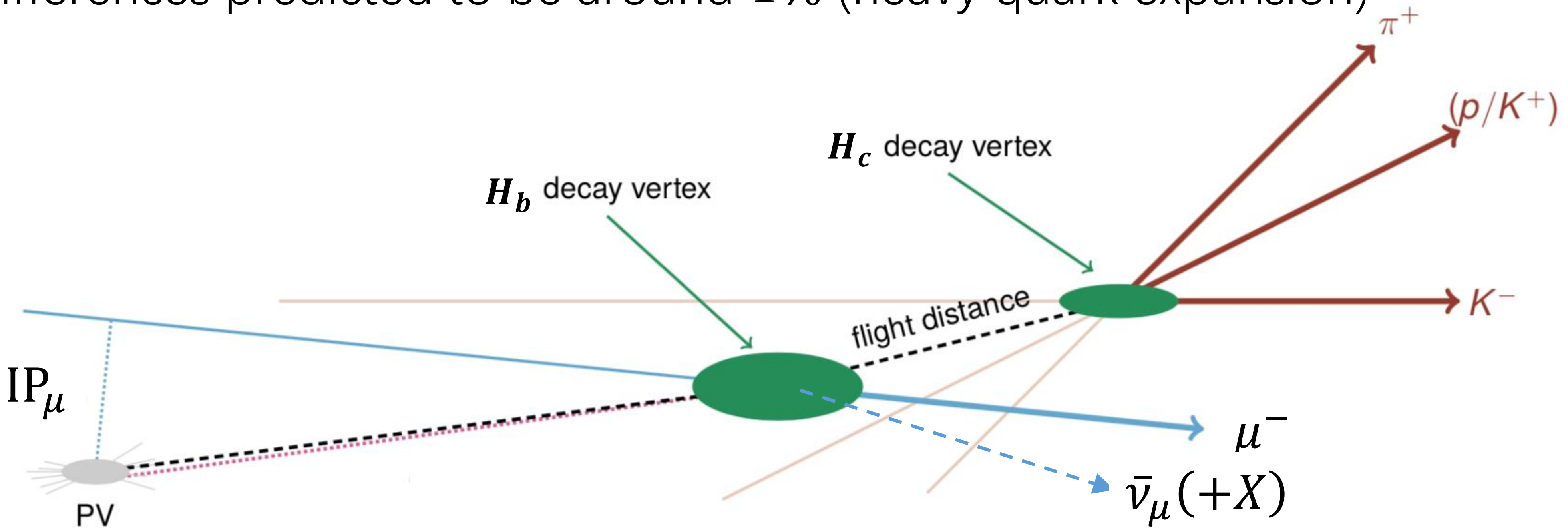
Eur. Phys. J. C77 (2017) 895



Eur. Phys. J. C77 (2017) 895

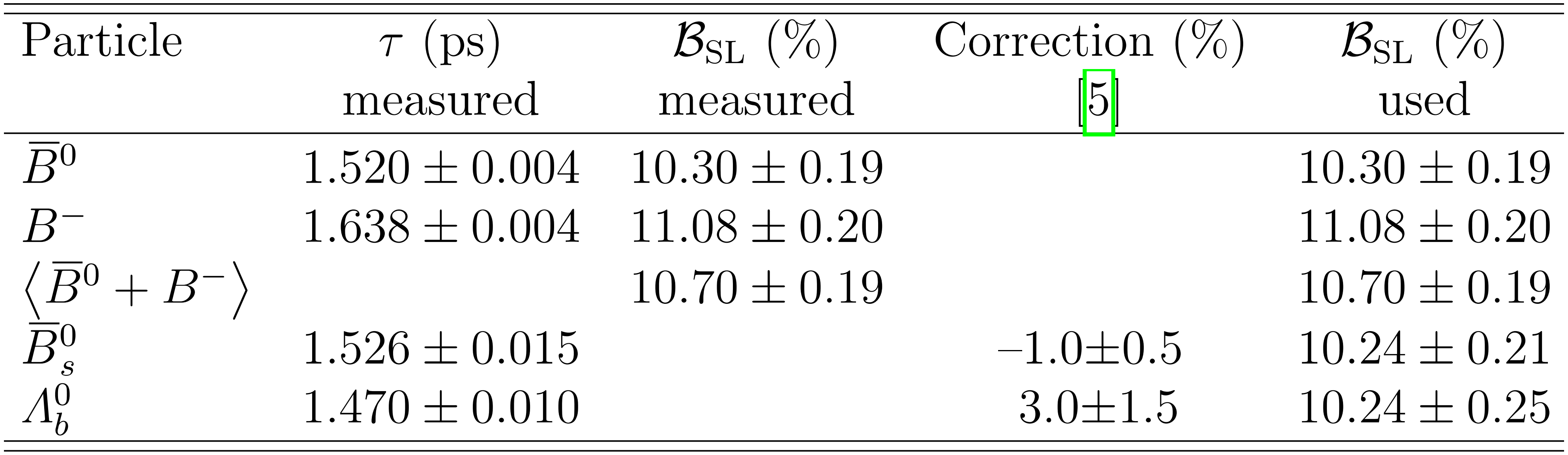
Analysis strategy at 13 TeV

- Data sample: $1.67\ \mathrm{fb}^{-1}$ collected in 2016
- Inclusive semileptonic decays $H_b \to H_c \mu^- \bar{\nu}_\mu X$
- Theoretical basis: Semileptonic widths for all b-hadrons are almost equal ($\Gamma_{SL}(H_b) = \Gamma_{SL}$) [I. Bigi et al, JHEP 09 (2011) 012]
  - Differences predicted to be around 1% (heavy quark expansion)



Analysis strategy (cont.)

- Semileptonic branching fractions $\mathcal{B}_{\text{SL}}$ for $\bar{B}_s^0$ and Λ_b^0 calculated with well measured lifetimes and $\mathcal{B}_{\text{SL}}$ for $\bar{B}^0$ and B^-
  - $\mathcal{B}_{\text{SL}}(H_b) = \Gamma_{\text{SL}}/\Gamma(H_b) = \Gamma_{\text{SL}} \cdot \tau_{H_b}$
- With known $\mathcal{B}_{\text{SL}}(H_b)$, only the ratios of yields need to be measured



Particle	τ (ps) measured	$\mathcal{B}_{\text{SL}}$ (%) measured	Correction (%) [5]	$\mathcal{B}_{\text{SL}}$ (%) used
$\overline{B}^0$	1.520 ± 0.004	10.30 ± 0.19		10.30 ± 0.19
B^-	1.638 ± 0.004	11.08 ± 0.20		11.08 ± 0.20
$\left\langle \overline{B}^0 + B^- \right\rangle$		10.70 ± 0.19		10.70 ± 0.19
$\overline{B}_s^0$	1.526 ± 0.015		-1.0 ± 0.5	10.24 ± 0.21
Λ_b^0	1.470 ± 0.010		3.0 ± 1.5	10.24 ± 0.25

Ref. [5]: I. Bigi et al, JHEP 09 (2011) 012

Formula of the fragmentation ratio: $f_{s(\Lambda_b^0)}/(f_u+f_d)$

$$\frac{N^{\rm obs}_{\rm SL}(\bar{B}^0_s)}{N^{\rm obs}_{\rm SL}(B)} = \frac{\sigma_{b\bar{b}}\,\boldsymbol{f_s}}{\sigma_{b\bar{b}}(\boldsymbol{f_u}+\boldsymbol{f_d})}\,\frac{\boldsymbol{\mathcal{B}_{\rm SL}(\bar{B}^0_s)}}{\boldsymbol{\mathcal{B}_{\rm SL}(B)}}\,\frac{\varepsilon(\bar{B}^0_s)}{\varepsilon(B)}$$

$$= \frac{\boldsymbol{f_s}}{\boldsymbol{f_u}+\boldsymbol{f_d}}\,\frac{\boldsymbol{\Gamma_{\rm SL}(\bar{B}^0_s)\tau_{\bar{B}^0_s}}}{\boldsymbol{\Gamma_{\rm SL}(B)(\tau_{B^-}+\tau_{\bar{B}^0})/2}}\,\frac{\varepsilon(\bar{B}^0_s)}{\varepsilon(B)}$$

Similar for $\boldsymbol{\Lambda_b^0}$

Consider the corrections and use $\mathcal{B}_{\rm SL}(H_b) = \Gamma_{\rm SL}\cdot\tau_{H_b}$

$$\boxed{\frac{\boldsymbol{f_s}}{\boldsymbol{f_u}+\boldsymbol{f_d}}} = \underset{\text{Measurable}}{\boxed{\frac{N^{\rm corr}_{\rm SL}(\bar{B}^0_s)}{N^{\rm corr}_{\rm SL}(B)}}}\;\underbrace{\boxed{\frac{\boldsymbol{2\tau_{\bar{B}^0_s}}}{\boldsymbol{\tau_{B^-}+\tau_{\bar{B}^0}}}}\;\boxed{(\boldsymbol{1-\xi_s})}}_{\text{Known}} + \underset{\text{Measurable}}{\boxed{\textbf{corr. term}}}$$

Formula of the fragmentation ratio: $f_{s(\Lambda_b^0)}/(f_u+f_d)$

$$\boxed{\frac{f_s}{f_u+f_d}} = \boxed{\frac{n_{\rm corr}(\bar{B}_s^0\to D_s\mu)}{n_{\rm corr}(B\to D^0\mu)+n_{\rm corr}(B\to D^+\mu)}}\,\frac{\tau_{B^-}+\tau_{\bar{B}^0}}{2\tau_{\bar{B}_s^0}}\boxed{(1-\xi_s)}\;\boxed{-\frac{\mathcal{B}(B\to D_sK\mu)}{\langle\mathcal{B}_{SL}\rangle}\,\frac{\epsilon(\bar{B}\to D_s^+)}{\epsilon(\bar{B}_s^0\to D_s^+)}},$$

SU(3) breaking correction
$\xi_s = (-1\pm0.5)\%$

Corrected yields
of $\bar{B}_s^0$, $\bar{B}^0$, B^-

Subtraction of $\bar{B}^0(B^-)\to$ $D_s^+K\mu^-\bar{\nu}_\mu X$ contributions in $\bar{B}_s^0$ signals

$$\boxed{\frac{f_{\Lambda_b^0}}{f_u+f_d}} = \boxed{\frac{n_{\rm corr}(\Lambda_b^0\to H_c\mu^-)}{n_{\rm corr}(B\to D^0\mu^-)+n_{\rm corr}(B\to D^+\mu^-)}}\,\frac{\tau_{B^-}+\tau_{\bar{B}^0}}{2\tau_{\Lambda_b^0}}\boxed{(1-\xi_{\Lambda_b^0})}$$

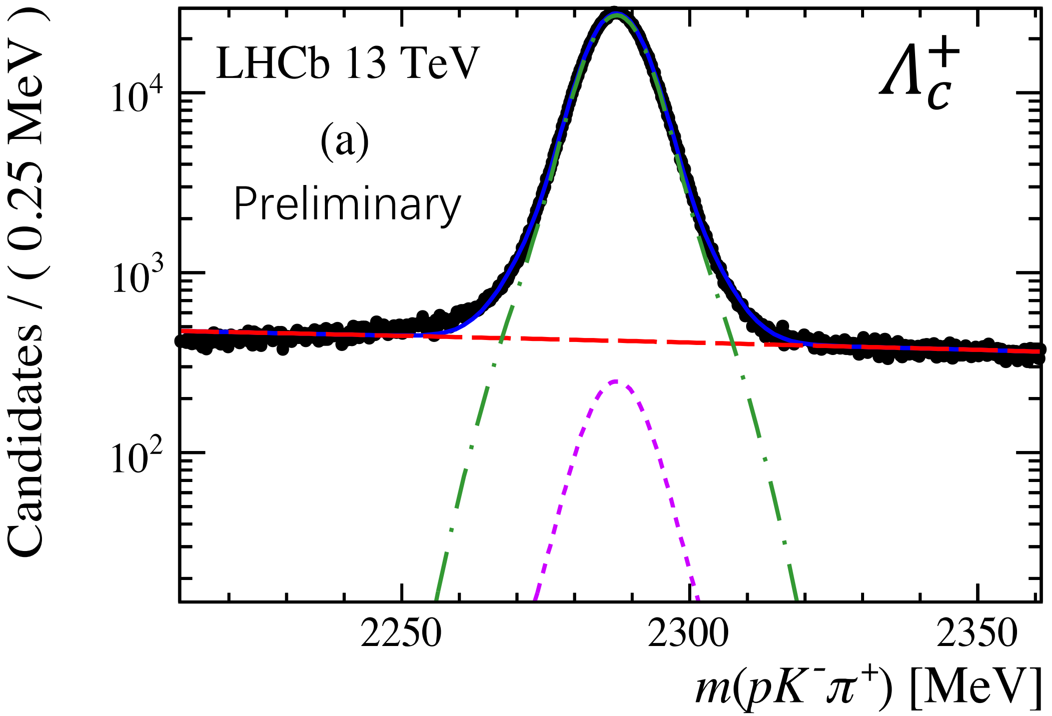
Corrected yields
of Λ_b^0, $\bar{B}^0$, B^-

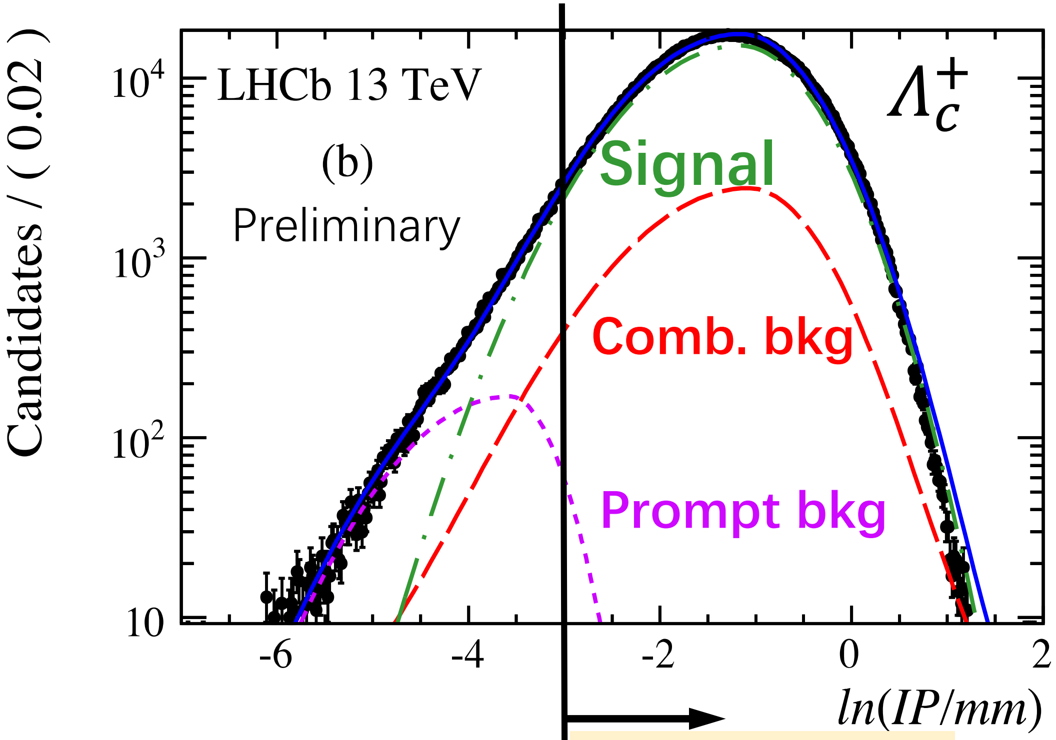
Chromomagnetic correction
$\xi_{\Lambda_b^0} = (3\pm1.5)\%$

Removal of prompt charmed hadrons

LHCb-PAPER-2018-050
in preparation

- Greatly suppressed by lifetime related requirements
  - χ^2 of charmed hadron flight distance and χ^2_{IP} of final tracks (μ, p, K, π)
- Remaining prompt H_c removed by requiring $\ln\left(\text{IP}_{H_c}/\text{mm}\right) > -3$
  - Prompt component reduced to below 0.1%, while signal loss is around 3%





$\text{IP}_{\Lambda_c^+} > e^{-3}$ mm

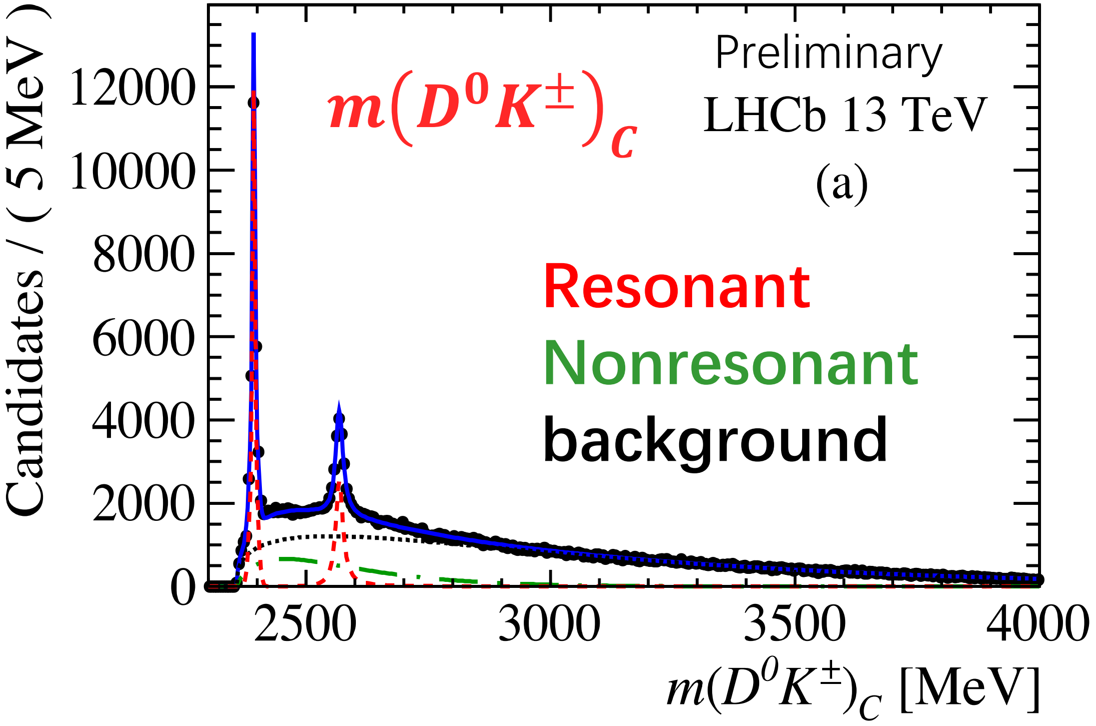
Nonresonant contribution: $\bar{B}_s^0 \to DK\mu^-\bar{\nu}_\mu X$

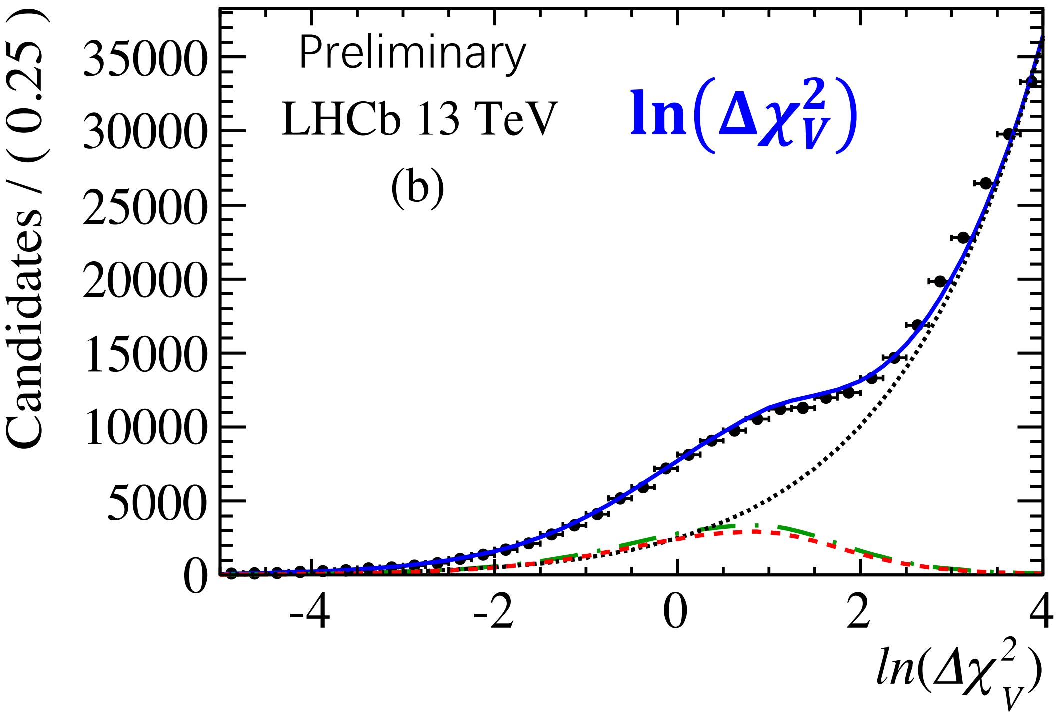
LHCb-PAPER-2018-050
in preparation

- Signals for $\bar{B}_s^0$ and background for $\bar{B}^0(B^-)$
- Extracted by 2D fits: $m(D^0K^\pm)_C$ v.s. $\ln(\Delta\chi_V^2)$

$\boldsymbol{m(D^0K^\pm) - m(D^0) + m(D^0)_{\mathrm{PDG}}}$

logarithm of the vertex χ^2 difference between $D\mu K$ and $D\mu$





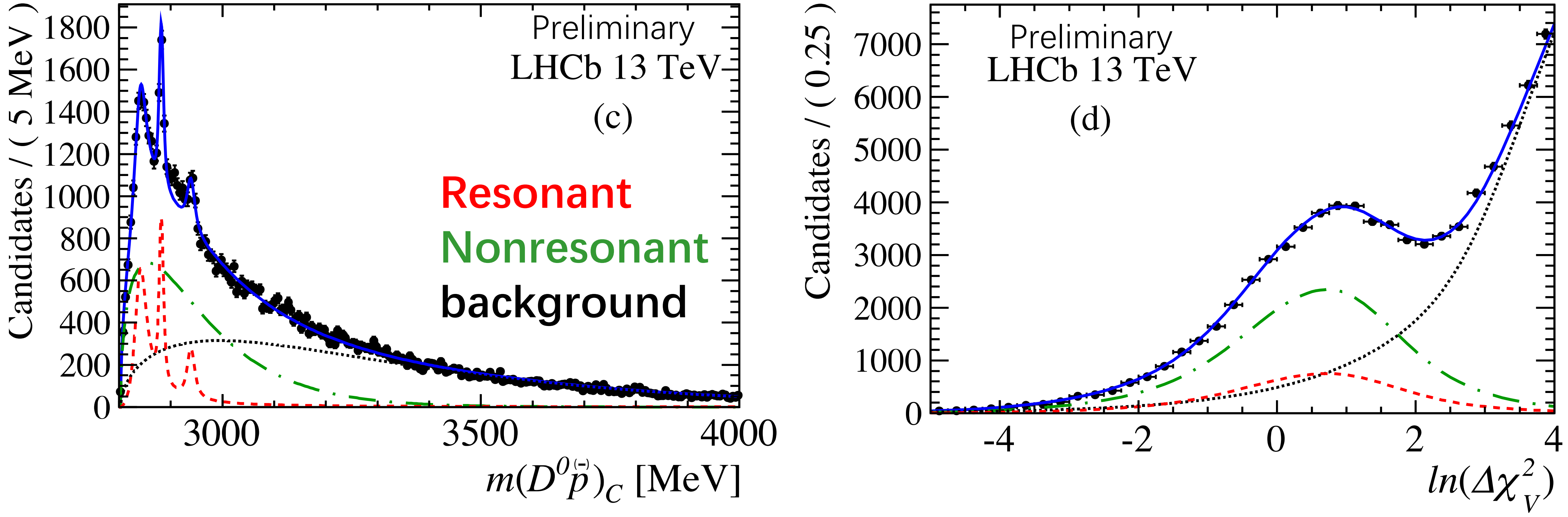
Nonresonant contribution: $\Lambda_b^0 \to D^0 p \mu^- \bar{\nu}_\mu X$

LHCb-PAPER-2018-050
in preparation

- Signals for Λ_b^0 and background for $\bar{B}^0 (B^-)$
- Extracted by 2D fits: $m(D^0 p)_C$ v.s. $\ln(\Delta\chi^2_V)$

$\boldsymbol{m(D^0 p) - m(D^0) + m(D^0)_{\mathrm{PDG}}}$

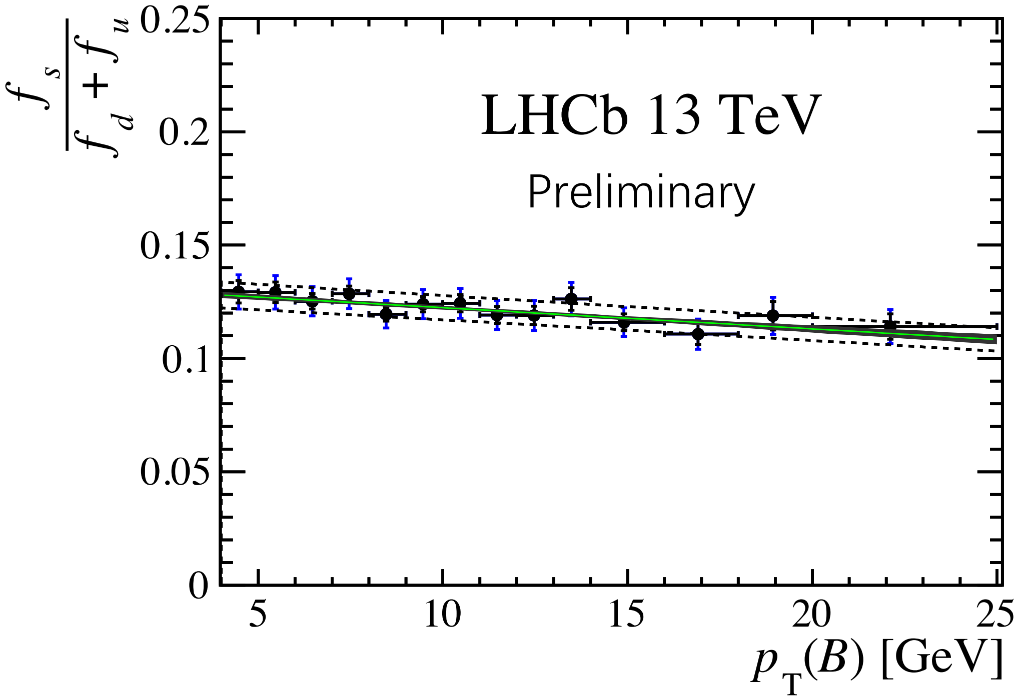
logarithm of the vertex χ^2 difference between $\boldsymbol{D\mu p}$ and $\boldsymbol{D\mu}$

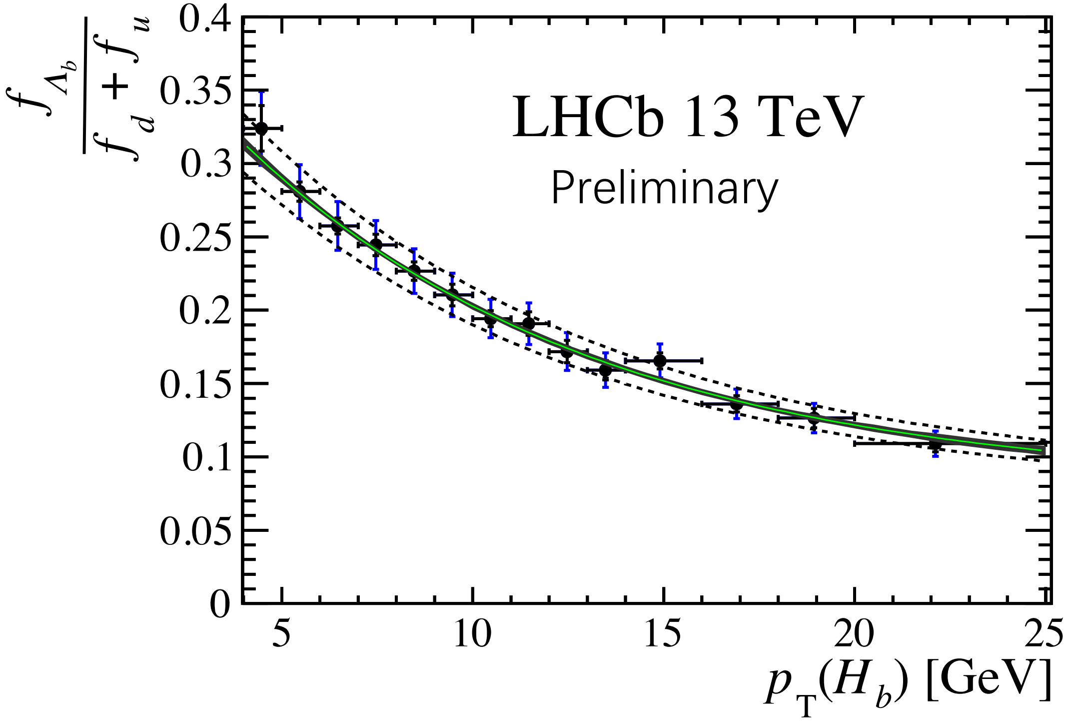


p_{T} dependence

LHCb-PAPER-2018-050
in preparation

- $p_{\mathrm{T}}(H_b) = k\, p_{\mathrm{T}}(H_c\mu)$: correction factor $k = \langle p_{\mathrm{T}}^{\mathrm{rec}} \rangle / p_{\mathrm{T}}^{\mathrm{true}}$ from simulation

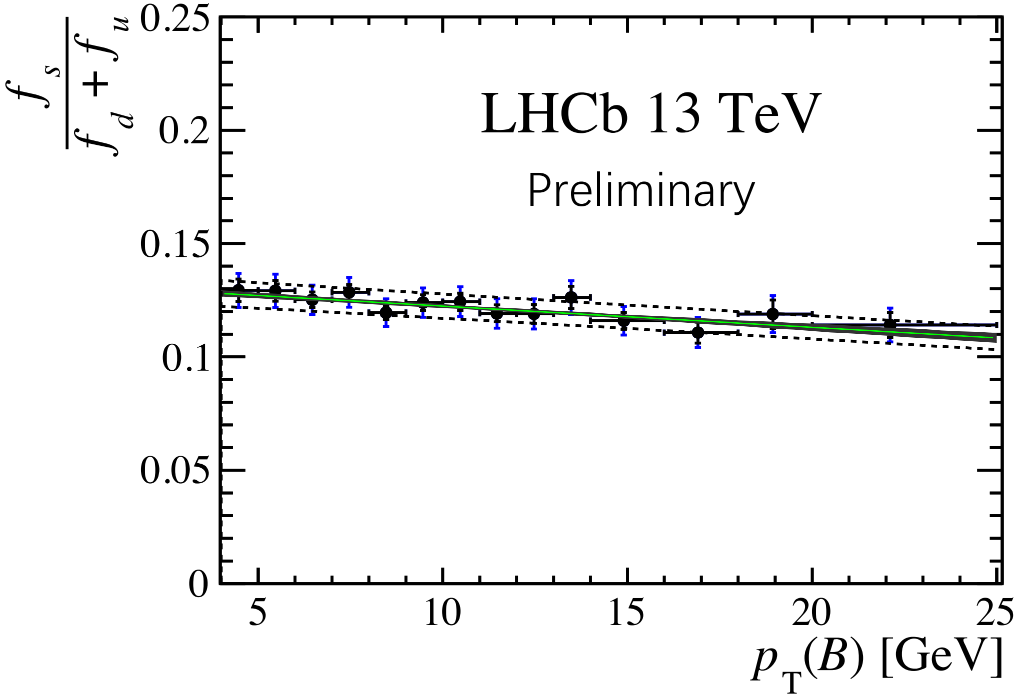


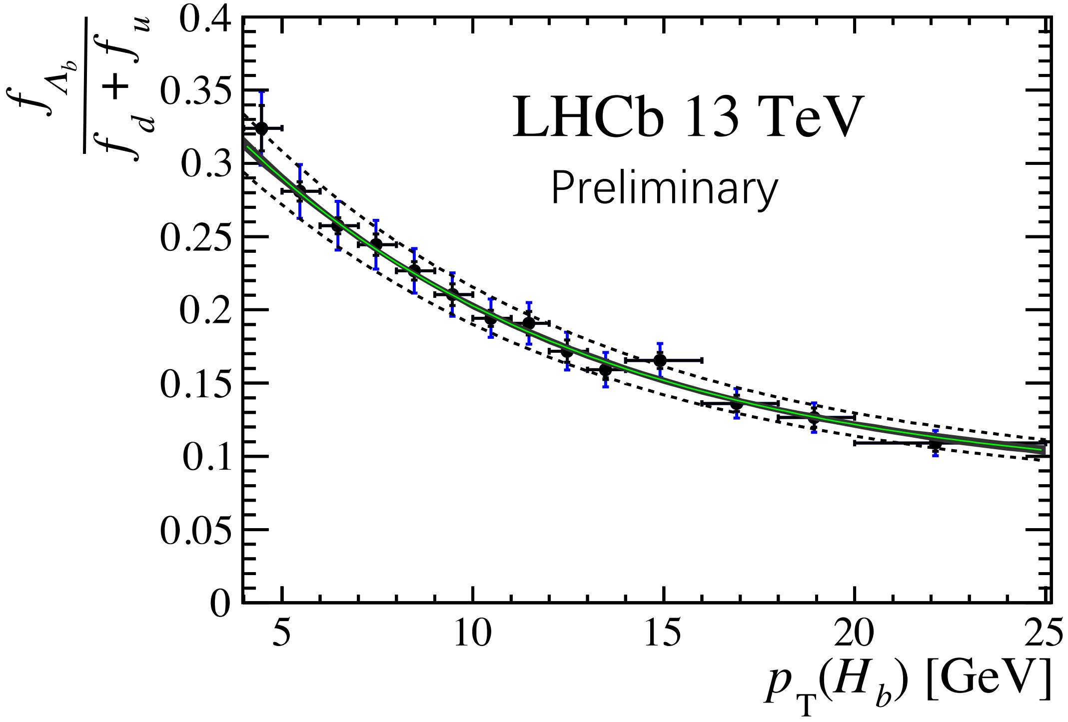


- **$f_s/(f_u+f_d)$ slightly depends on $p_{\mathrm{T}}(B)$**
- **$f_{\Lambda_b^0}/(f_u+f_d)$ strongly depends on $p_{\mathrm{T}}(\Lambda_b)$**

p_T dependence

LHCb-PAPER-2018-050
in preparation





- $\frac{f_s}{f_u+f_d}(p_{\mathrm{T}}) = A[(0.119 \pm 0.001) + (-0.91 \pm 0.25) \cdot 10^{-3}(p_T - \langle p_{\mathrm{T}} \rangle)/\mathrm{GeV}]$ **Linear**
- $\frac{f_{\Lambda_b^0}}{f_u+f_d}(p_{\mathrm{T}}) = A\left[(7.93 \pm 1.41) \cdot 10^{-2} + e^{(-1.022 \pm 0.047)+(-0.107 \pm 0.002)p_{\mathrm{T}}/\mathrm{GeV}}\right]$ **Exponential**

η dependence

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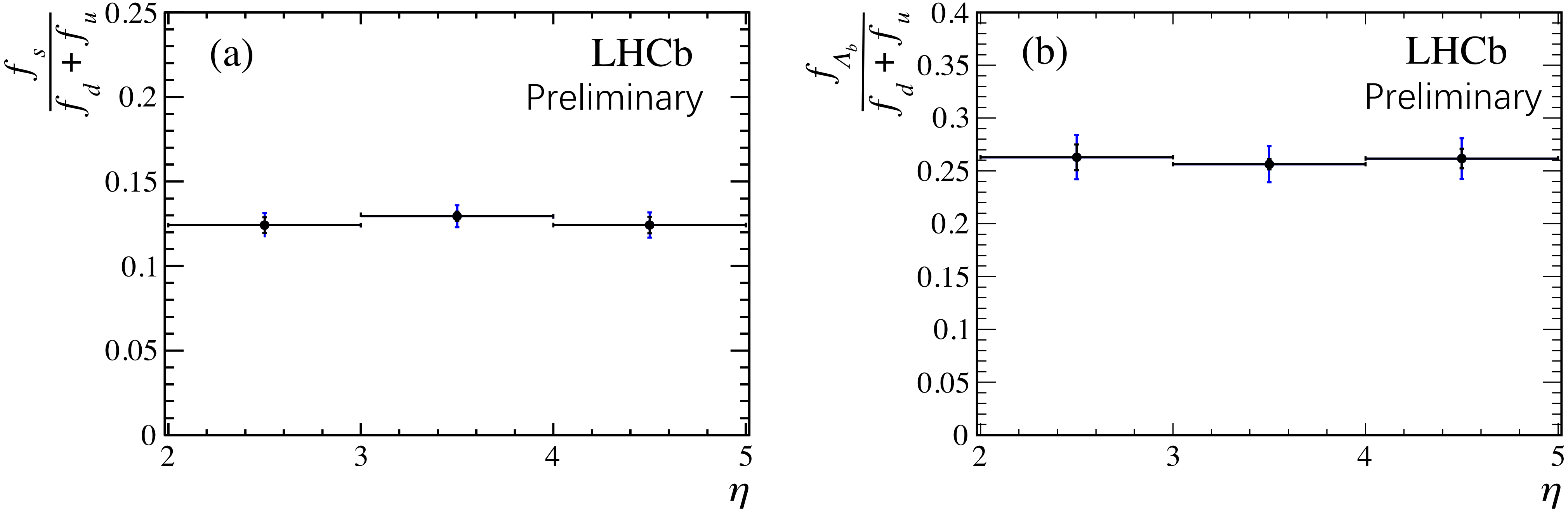

- **No η dependence of the ratios is visible**

Average fragmentation fractions

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in preparation

Preliminary results

$$\frac{f_s}{f_u + f_d} = 0.122 \pm 0.006$$

$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = 0.259 \pm 0.018$$

- **Statistical and systematic uncertainties combined**
- **Systematic uncertainty dominates**

Kinematic region:

$$4 < p_T(H_b) < 25 \text{ GeV}/c$$
$$2 < \eta < 5$$

LHCb 7 TeV result:

$$\frac{f_s}{f_u + f_d} = 0.128 \pm 0.010$$

[LHCb, JHEP 04 (2013) 001]

Ξ_b^- production ratio

New

LHCb-PAPER-2018-047
arXiv:1901.07075, submitted to PRD

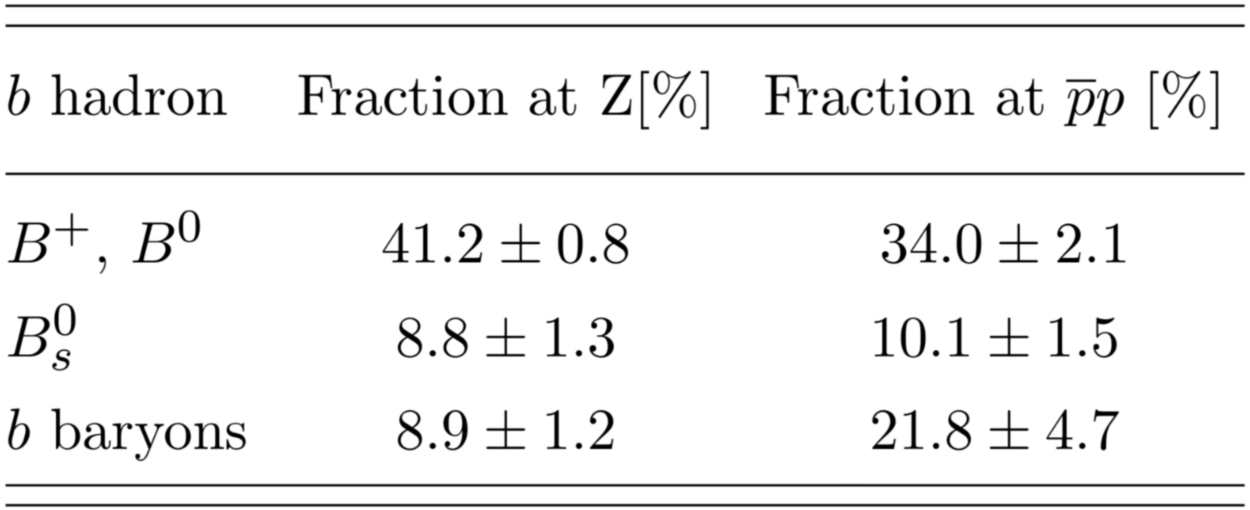
Introduction

- The b-hadron fragmentation fractions (f_u, f_d, f_s and f_{baryon}) are available at the Z resonance and at $p\bar{p}$ collisions
- Complete measurements of b-hadron production fractions at the LHC do not exist yet
- To achieve this, measurements of other b baryons are needed

$$f_u + f_d + f_s + f_{\text{baryon}} = 1$$

$$\begin{aligned} f_{\text{baryon}} &= f_{\Lambda_b^0} + f_{\Xi_b^0} + f_{\Xi_b^-} + f_{\Omega_b^-} \\ &= f_{\Lambda_b^0}\left(1 + 2\boxed{\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}} + \boxed{\frac{f_{\Omega_b^-}}{f_{\Lambda_b^0}}}\right) \end{aligned}$$

PDG 2018



b hadron	Fraction at Z[%]	Fraction at $\bar{p}p$ [%]
B^+, B^0	41.2 ± 0.8	34.0 ± 2.1
B_s^0	8.8 ± 1.3	10.1 ± 1.5
b baryons	8.9 ± 1.2	21.8 ± 4.7

Measurement of $f_{\Xi_b^{0(-)}}/f_{\Lambda_b^0}$

- The best way is to measure $f_{\Xi_b^{0(-)}}/f_d$ using $\Xi_b^{0(-)} \to \Xi_c^{+(0)}\mu^-\bar{\nu}_\mu X$ decays
  - Limited knowledge of absolute BRs of Ξ_c^0 decays [Belle, arXiv:1811.09738]
  - No absolute BRs of Ξ_c^+ decays available
    - Precision measurements should be feasible at Belle II
- Alternative way is to measure $f_{\Xi_b^-}/f_{\Lambda_b^0}$ using the SU(3) related decays $\Lambda_b^0 \to J/\psi\Lambda$ and $\Xi_b^- \to J/\psi\Xi^-$
  - SU(3) symmetry ➔ the partial width ratio: $\frac{\Gamma(\Xi_b^- \to J/\psi\Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi\Lambda)} = \frac{3}{2}$ [M. Savage et al, NPB326 (1989) 15] [M. Voloshin, arXiv:1510.05568] [Y. Hsiao et al, PLB751(2015) 127]
    - Uncertainty around 30%

$$R \equiv \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}\frac{\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}\boxed{\frac{\Gamma(\Xi_b^- \to J/\psi\,\Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi\,\Lambda)}\frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}}} = \boxed{\frac{N(\Xi_b^- \to J/\psi\,\Xi^-)}{N(\Lambda_b^0 \to J/\psi\,\Lambda)}\frac{\epsilon_{\Lambda_b^0}}{\epsilon_{\Xi_b^-}}}$$

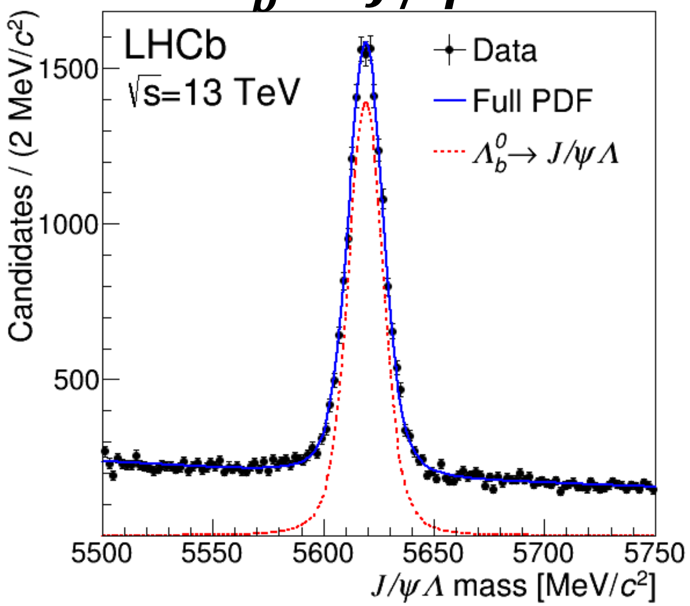
Known (theo. + exp.) **Measurable**

Data sample and mass fits

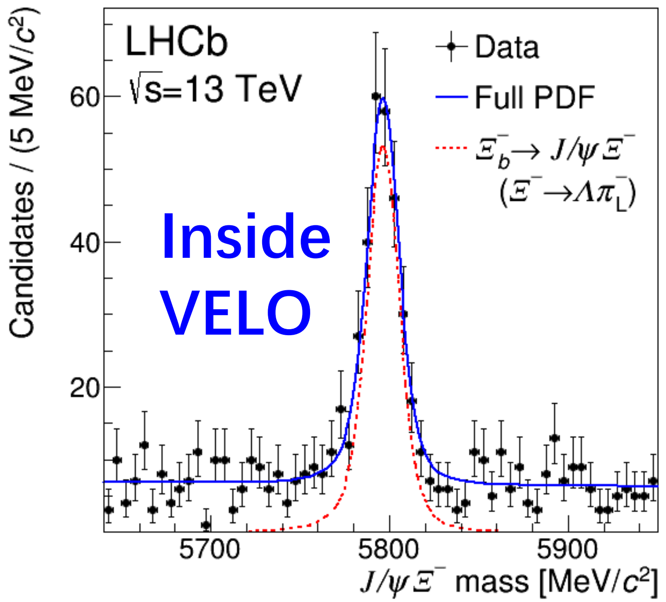
LHCb-PAPER-2018-047
arXiv:1901.07075

- Use Run1 (7&8 TeV) and 2016 (13 TeV) data
- $\Xi^- \to \Lambda\pi^-$ decays either inside VELO or outside VELO
- Signal: sum of two Crystal-Ball functions
  Background: exponential

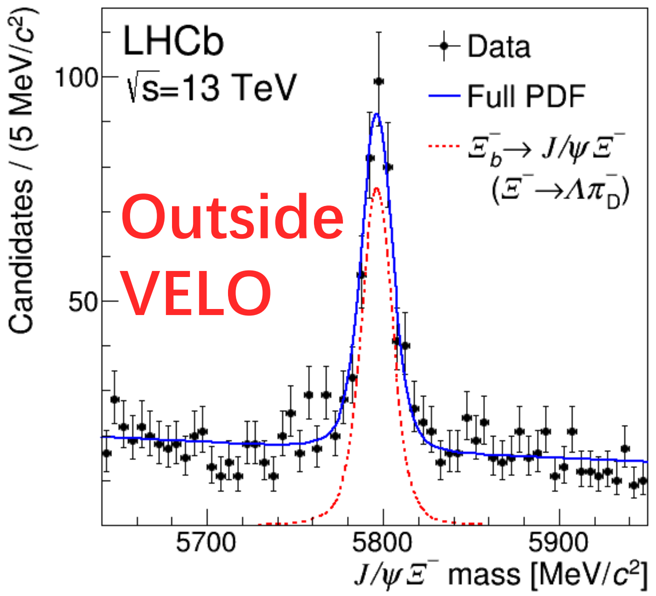
$\Lambda_b^0 \to J/\psi\Lambda$



$\Xi_b^- \to J/\psi\Xi^-(\to \Lambda\pi_L^-)$



$\Xi_b^- \to J/\psi\Xi^-(\to \Lambda\pi_D^-)$



Results: Ξ_b^- mass

LHCb-PAPER-2018-047
arXiv:1901.07075

- **Simultaneous fit** to mass distributions of six subsamples:
  - $\Lambda_b^0 \to J/\psi\Lambda$: Run1 (7&8 TeV) and 2016 (13 TeV)
  - $\Xi_b^- \to J/\psi\Xi^-(\to \Lambda\pi_L^-)$: Run1 (7&8 TeV) and 2016 (13 TeV)
  - $\Xi_b^- \to J/\psi\Xi^-(\to \Lambda\pi_D^-)$: Run1 (7&8 TeV) and 2016 (13 TeV)
- Mass difference $\delta m \equiv m(\Xi_b^-) - m(\Lambda_b^0)$ and Ξ_b^- mass with systematic uncertainties taken into account

$$\delta m = 177.30 \pm 0.39 \pm 0.15\,\mathrm{MeV}/c^2,$$
$$m(\Xi_b^-) = 5796.70 \pm 0.39 \pm 0.15 \pm 0.17\,\mathrm{MeV}/c^2$$

The most precise determination of Ξ_b^- mass

Consistent with previous most precision result:

$$\boldsymbol{\delta m = 178.36 \pm 0.46 \pm 0.16\,\mathrm{MeV}/c^2}$$ [LHCb, PRL113 (2014) 242002]

Results: Ξ_b^- production asymmetry

LHCb-PAPER-2018-047
arXiv:1901.07075

- Repeat the fit by splitting into baryon (Ξ_b^-) and antibaryon ($\bar{\Xi}_b^+$)

$$A_{\rm prod}(\Xi_b^-) - \boxed{A_{\rm prod}(\Lambda_b^0)} = \boxed{\alpha(\Xi_b^-) - \alpha(\Lambda_b^0)} - \boxed{A_{\rm det}(\pi^-)}$$

Previous measurements
$A_{\rm prod}(\Lambda_b^0) = (2.4 \pm 1.4 \pm 0.9)\%$

LHCb, Phys.Lett. B774 (2017) 139
LHCb, Phys.ReV. D91 (2015) 054022
LHCb, Chin.Phys.C40 (2016) 011001

Raw yield asymmetry from fits

Previous measurements consistent with zero

LHCb, Phys.Rev.Lett. 117 (2016) 061803
LHCb, JHEP 08 (2018) 008

$$\boxed{\begin{aligned} A_{\rm prod}(\Xi_b^-) &= (1.1 \pm 5.6 \pm 1.9)\% \quad [\sqrt{s} = 7, 8\,\mathrm{TeV}], \\ A_{\rm prod}(\Xi_b^-) &= (-3.9 \pm 4.9 \pm 2.5)\% \quad [\sqrt{s} = 13\,\mathrm{TeV}]. \end{aligned}}$$

Ξ_b^- production asymmetry consistent with zero

Results: Production ratio $f_{\Xi_b^-}/f_{\Lambda_b^0}$

LHCb-PAPER-2018-047
arXiv:1901.07075

$$R \equiv \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \boxed{\frac{\Gamma(\Xi_b^- \to J/\psi\,\Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi\,\Lambda)} \frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}}} = \boxed{\frac{N(\Xi_b^- \to J/\psi\,\Xi^-)}{N(\Lambda_b^0 \to J/\psi\,\Lambda)} \frac{\epsilon_{\Lambda_b^0}}{\epsilon_{\Xi_b^-}}}$$

Known

Measurable

- Signal yields + efficiencies + systematic uncertainties

$$\boxed{\begin{aligned} R &= (10.8 \pm 0.9 \pm 0.8) \times 10^{-2} \quad [\sqrt{s} = 7, 8\,\mathrm{TeV}],\\ R &= (13.1 \pm 1.1 \pm 1.0) \times 10^{-2} \quad [\sqrt{s} = 13\,\mathrm{TeV}],\end{aligned}}$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5 \pm 0.5 \pm 2.0) \times 10^{-2} \quad [\sqrt{s} = 7, 8\,\mathrm{TeV}],$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.4) \times 10^{-2} \quad [\sqrt{s} = 13\,\mathrm{TeV}].$$

(stat.) (syst.) (SU(3) breaking)

Theoretical predictions using estimated $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$ and experimental inputs:

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (5.4 \pm 2.0) \times 10^{-2}$$

[H.-Y. Jiang et al, EPJC78 (2018) 224]

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.5 \pm 2.0) \times 10^{-2}$$

[D. Wang, arXiv:1901.01776]

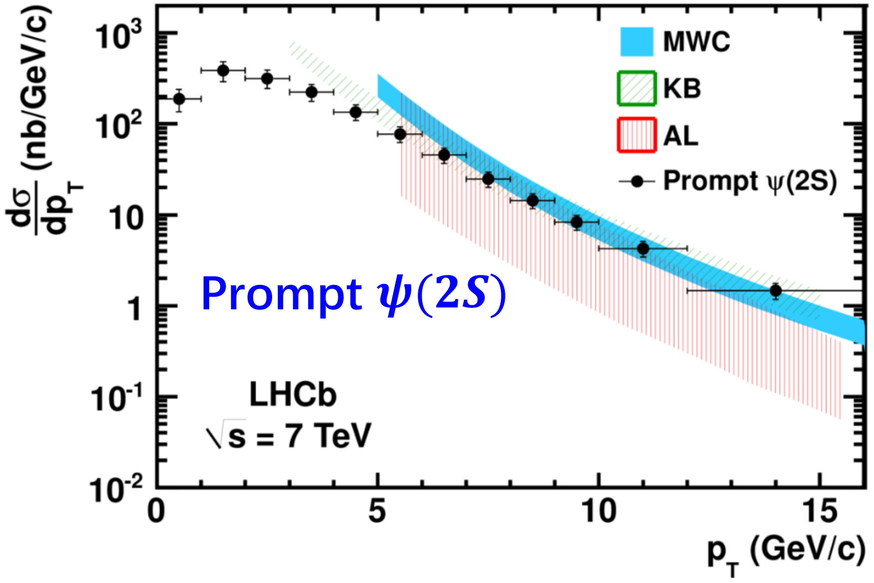
$\psi(2S)$ production cross-sections at 7 and 13 TeV

LHCb-PAPER-2018-049
in preparation

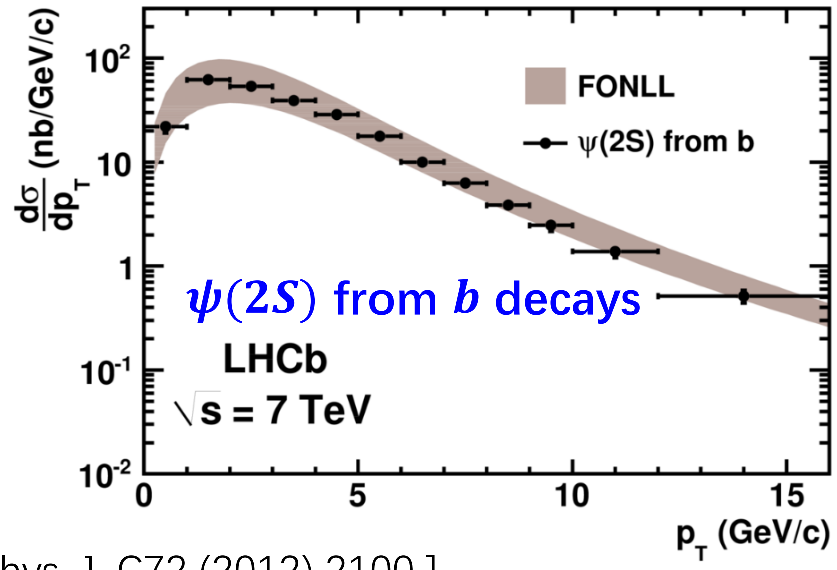
New

Introduction

- Study of heavy quarkonium production at hadron colliders provides important test to QCD models
  - Many models (NRQCD, CSM, COM, k_{T} factorization, FONLL, et al) available
  - Many measurements of heavy quarkonia performed at Tevatron and the LHC
- Previous $\psi(2S)$ measurement in pp collisions at 7 TeV



Prompt $\psi(2S)$

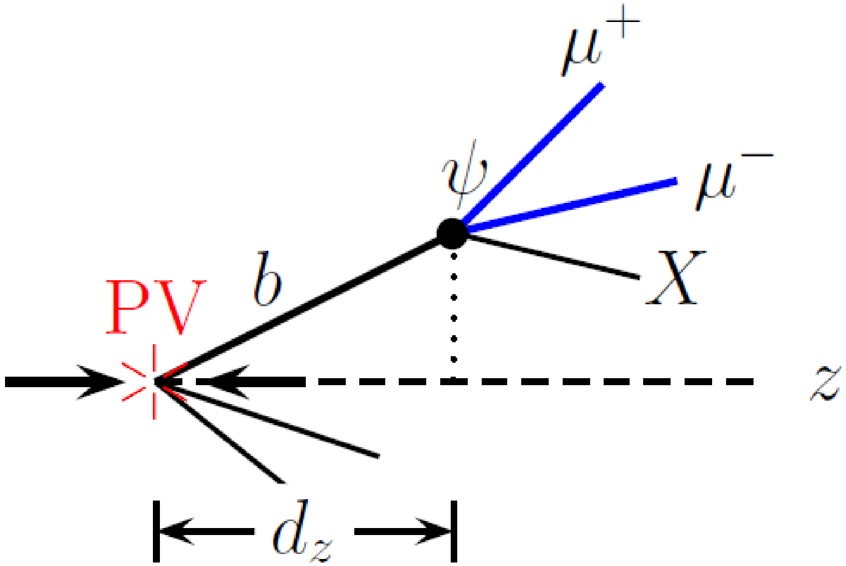


$\psi(2S)$ from b decays

[LHCb, Eur. Phys. J. C72 (2012) 2100]

Separation of prompt and non-prompt $\psi(2S)$

- A fraction of $\psi(2S)$ comes from b-hadron decays
  - Prompt : direct (**negligible feed-down contribution for $\boldsymbol{\psi(2S)}$**)
  - Non-prompt: from b-hadron decays (i.e. $\psi(2S)$ from b)
- Prompt and non-prompt separated by **pseudo decay time** in longitudinal or transverse direction



$\equiv z_{\psi(2S)} - z_{\rm PV}$

$$\boxed{t_z = \frac{\left(z_{\psi(2S)} - z_{\rm PV}\right) \times M_{\psi(2S)}}{p_z}}$$

Data sample and cross-section determination

- ➢ $275\ \mathrm{pb}^{-1}$ at 13 TeV (2015) and $614\ \mathrm{pb}^{-1}$ at 7 TeV (2011)
  - Previous measurement at 7 TeV: $36\ \mathrm{pb}^{-1}$ (2010)
- ➢ $\psi(2S) \rightarrow \mu^+\mu^-$ used owing to high efficiencies
- ➢ Cross-section determined in each (p_T, y) bin

Signal yields from fits

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_\mathrm{T}} = \frac{\boxed{N(p_\mathrm{T}, y)}}{\boxed{\varepsilon_\mathrm{tot}(p_\mathrm{T}, y)} \times \boxed{\mathcal{L}_\mathrm{int}} \times \boxed{\mathcal{B}} \times \boxed{\Delta y \times \Delta p_\mathrm{T}}}$$

Efficiencies from simulation calibrated with data

Integrated luminosity

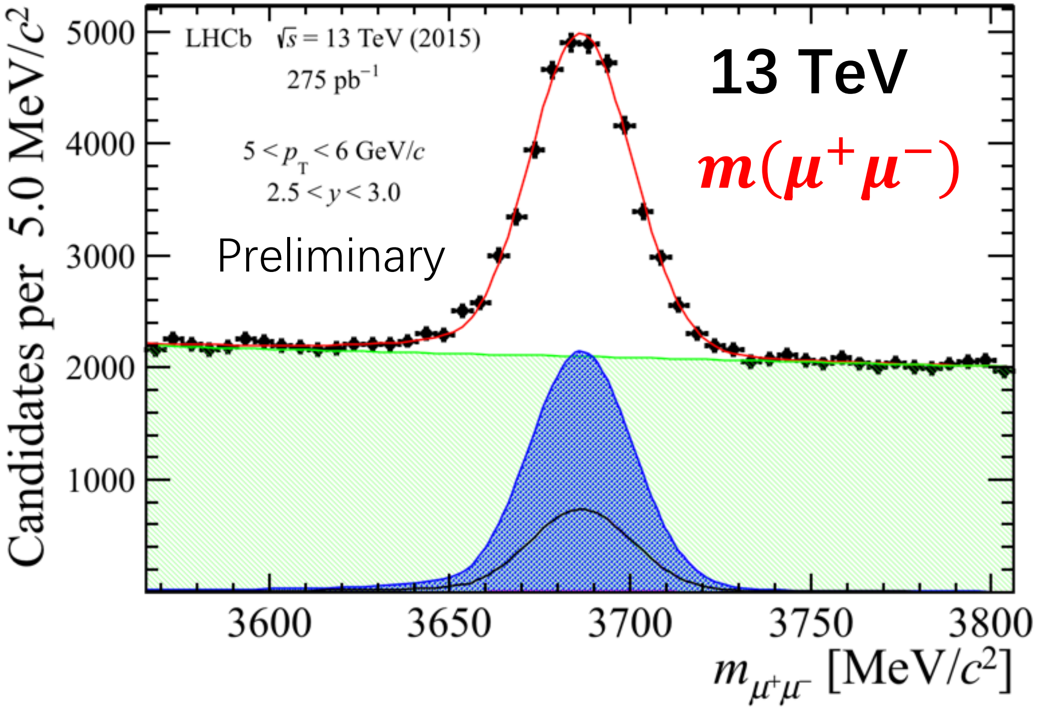
$\mathcal{B}(\boldsymbol{\psi(2S) \rightarrow \mu^+\mu^-})$

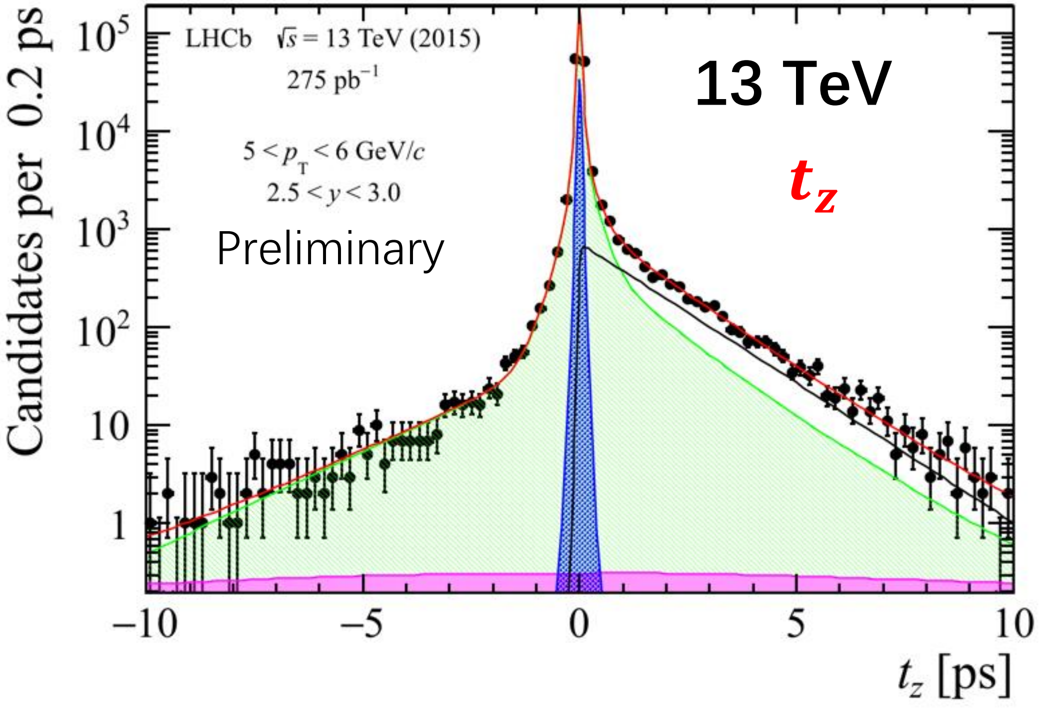
Bin width

Signal yields

LHCb-PAPER-2018-049
in preparation

- 2D fits to the $m(\mu^+\mu^-)$ and t_z distributions in each (p_T, y) bin
  - ➔ $\boldsymbol{N_p(p_\mathrm{T}, y)}$: **Signal yields of prompt** $\boldsymbol{\psi(2S)}$
    $\boldsymbol{N_b(p_\mathrm{T}, y)}$: **Signal yields of** $\boldsymbol{\psi(2S)}$ **from** $\boldsymbol{b}$





Results: Integrated cross-sections

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in preparation

Preliminary:

$$\sigma(\text{prompt } \psi(2S),\ 13\,\text{TeV}) = 1.430 \pm 0.005\,(\text{stat}) \pm 0.099\,(\text{syst})\,\upmu\text{b},$$
$$\sigma(\psi(2S)\text{-from-}b,\ 13\,\text{TeV}) = 0.426 \pm 0.002\,(\text{stat}) \pm 0.030\,(\text{syst})\,\upmu\text{b}.$$

Kinematic region:
$2 < p_{\mathrm{T}} < 20\ \mathrm{GeV}/c$ and $2.0 < y < 4.5$

$$\sigma(\text{prompt } \psi(2S),\ 7\,\text{TeV}) = 0.471 \pm 0.001\,(\text{stat}) \pm 0.025\,(\text{syst})\,\upmu\text{b},$$
$$\sigma(\psi(2S)\text{-from-}b,\ 7\,\text{TeV}) = 0.126 \pm 0.001\,(\text{stat}) \pm 0.008\,(\text{syst})\,\upmu\text{b}.$$

Kinematic region:
$3.5 < p_{\mathrm{T}} < 14\ \mathrm{GeV}/c$ and $2.0 < y < 4.5$

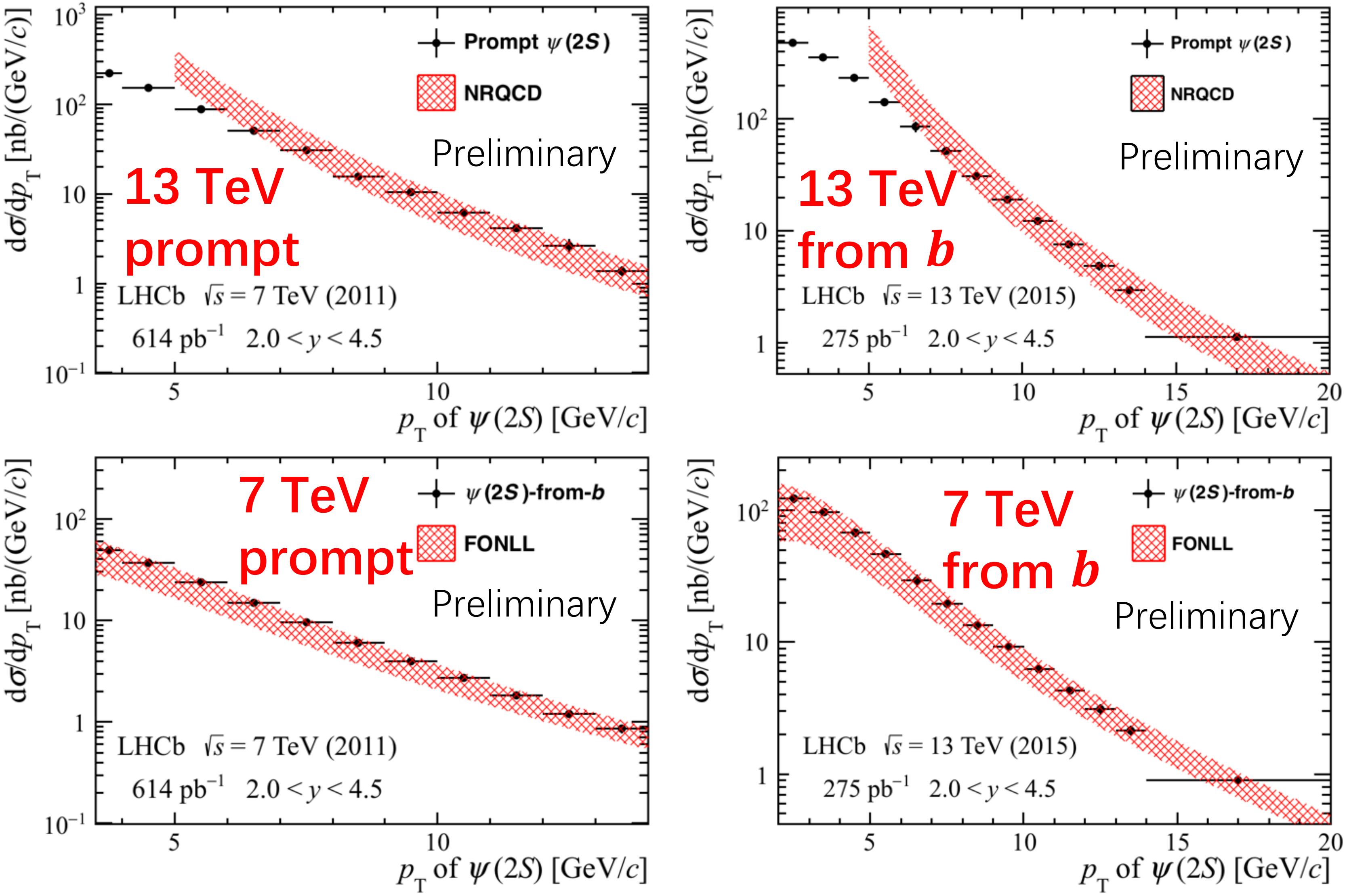
(due to tighter trigger selection)

Results: cross-section v.s. p_{T}

LHCb-PAPER-2018-049
in preparation

- Prompt results compared with NRQCD
- Non-prompt results compared with FONLL
- Good agreement for high p_{T}

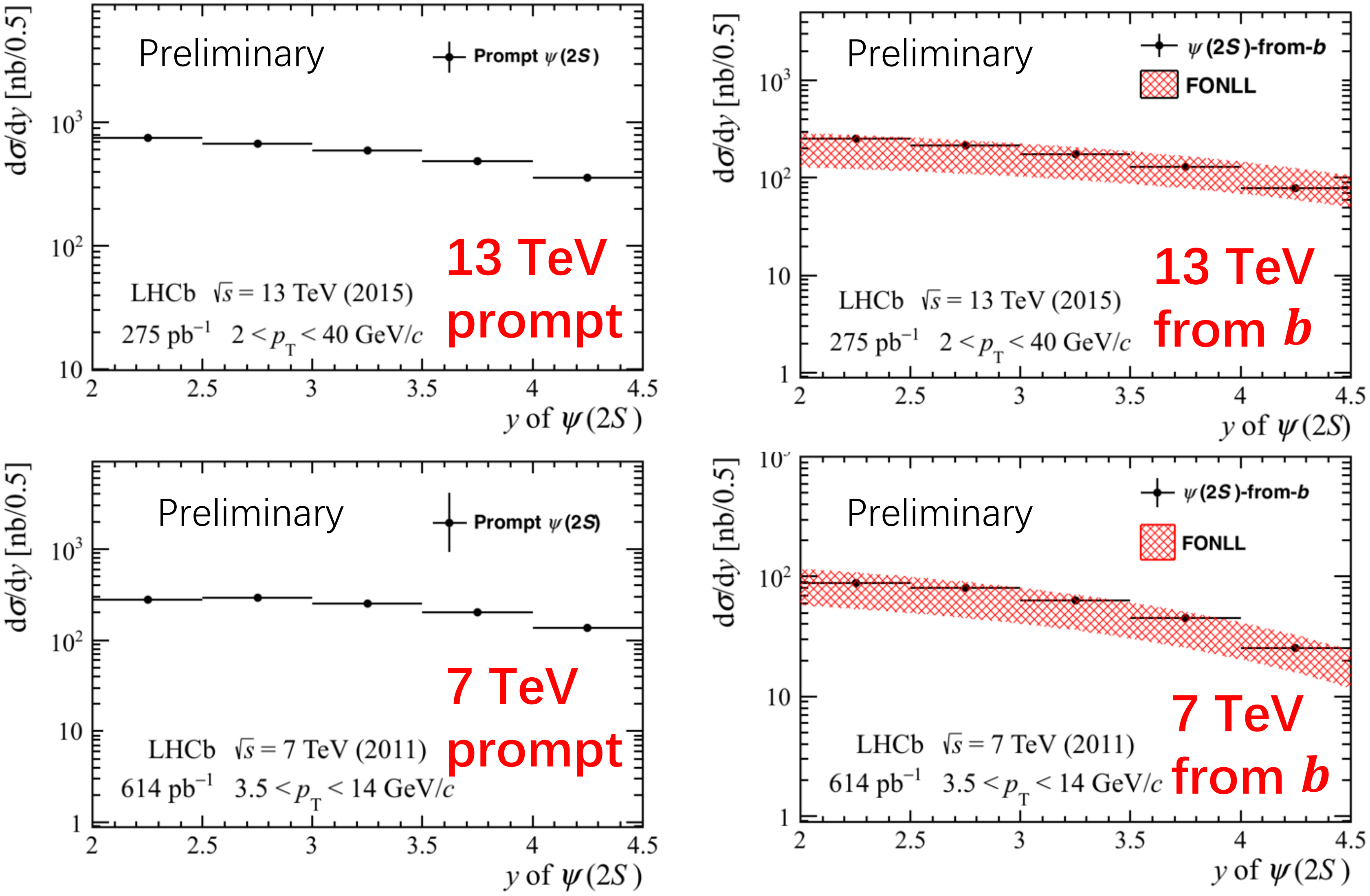
NRQCD:
[H.-S. Shao et al, JHEP 05 (2015) 103]
FONLL:
[M. Cacciari et al, JHEP 05 (1998) 007]
[M. Cacciari et al, JHEP 10 (2012) 137]
[M. Cacciari et al, EPJC75 (2015) 610]



Results: cross-section v.s. y

LHCb-PAPER-2018-049
in preparation

- Non-prompt results compared with FONLL
- Good agreement



FONLL:
[M. Cacciari et al, JHEP 05 (1998) 007]
[M. Cacciari et al, JHEP 10 (2012) 137]
[M. Cacciari et al, EPJC75 (2015) 610]

Results: 13 TeV and 7 TeV comparison

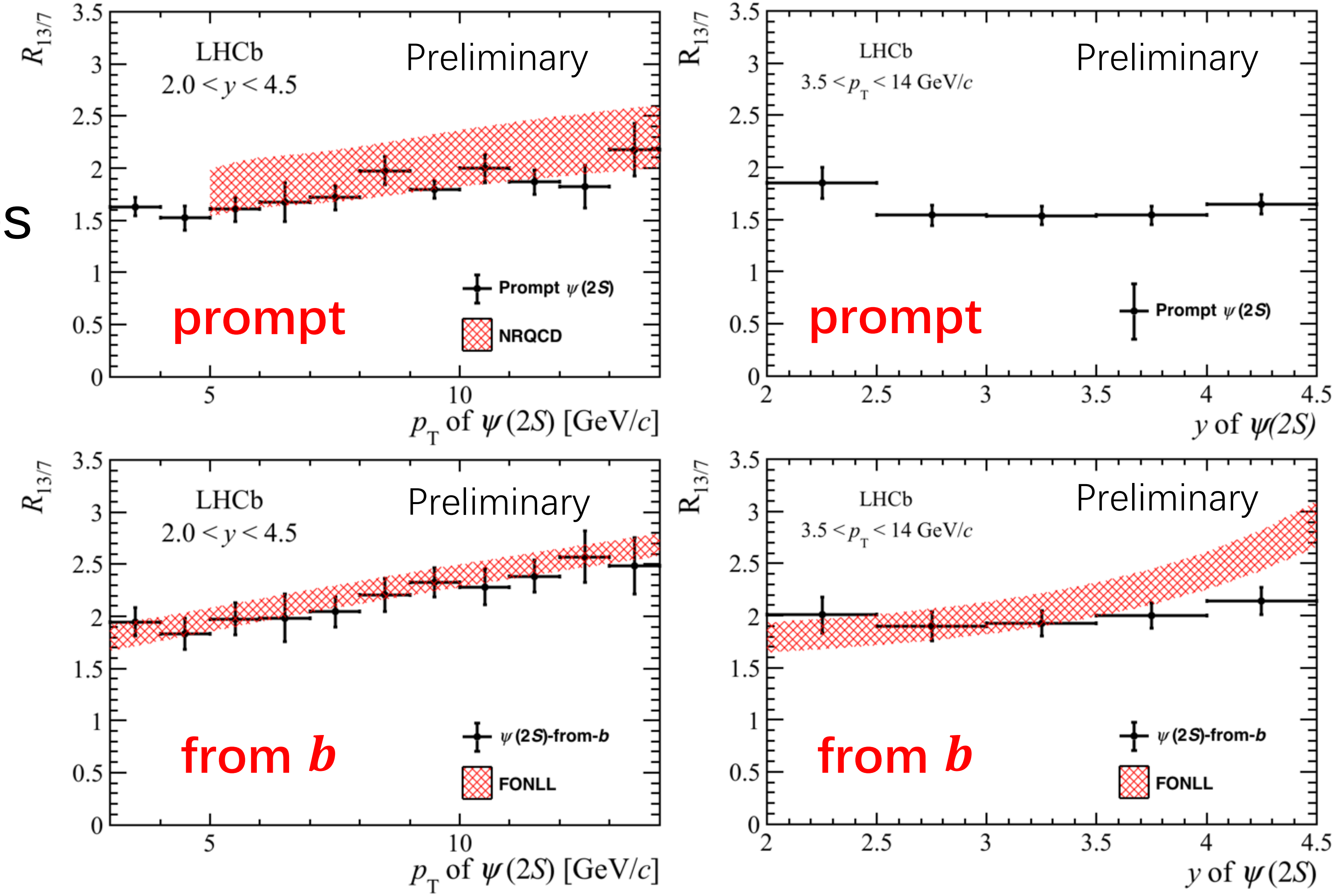
LHCb-PAPER-2018-049
in preparation

- ➢ Most uncertainties cancel out in the ratios

$$R_{13/7} = \frac{\sigma(13\ \mathrm{TeV})}{\sigma(7\ \mathrm{TeV})}$$

  - More precise test of theories

- ➢ Good agreement

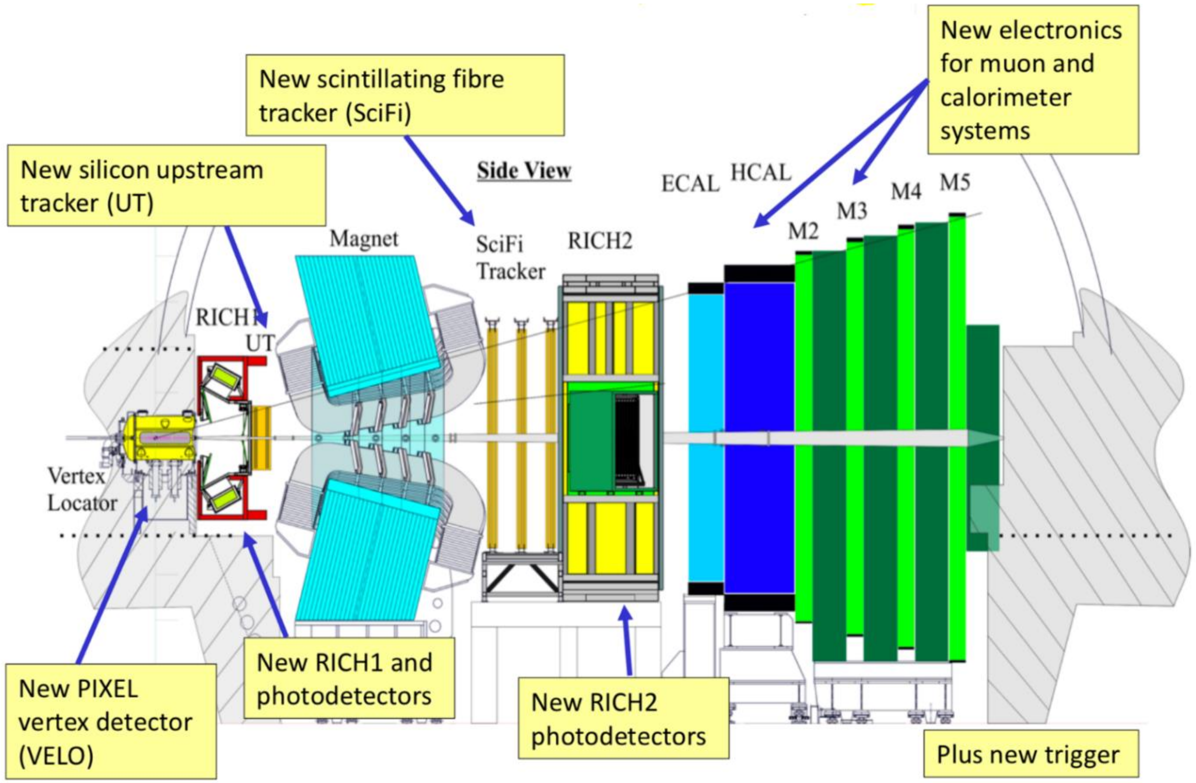


NRQCD:
[H.-S. Shao et al, JHEP 05 (2015) 103]
FONLL:
[M. Cacciari et al, JHEP 05 (1998) 007]
[M. Cacciari et al, JHEP 10 (2012) 137]
[M. Cacciari et al, EPJC75 (2015) 610]

Prospects

LHCb Upgrade (2019-2020)

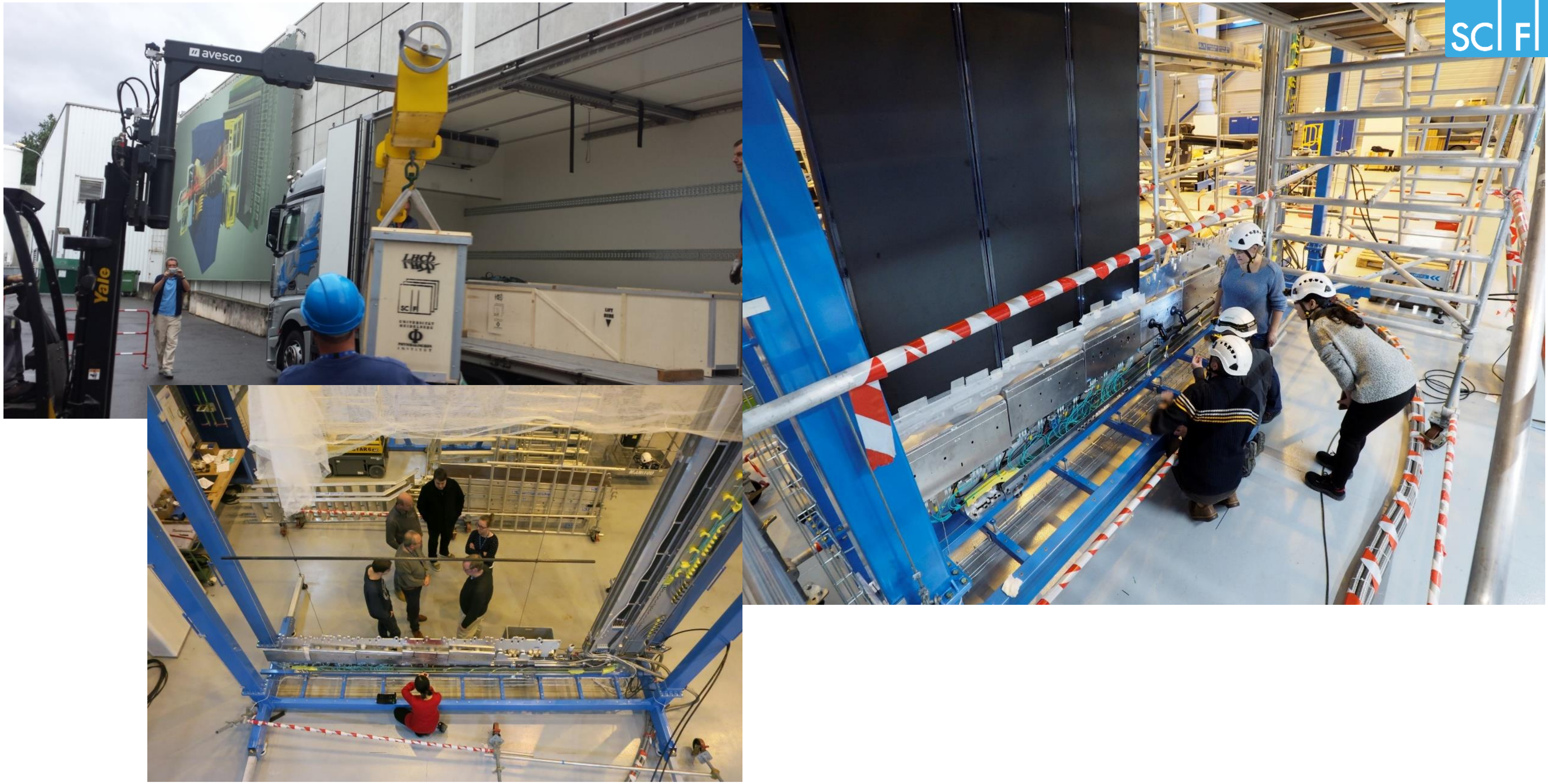
[LHCB-TDR-017]



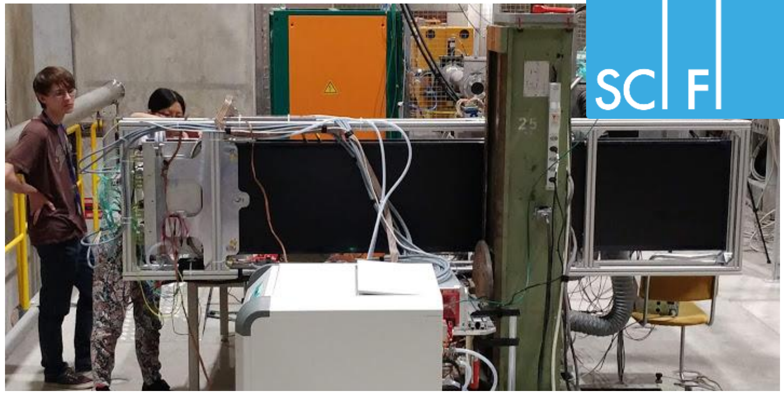
CERN-LHCC-2012-007

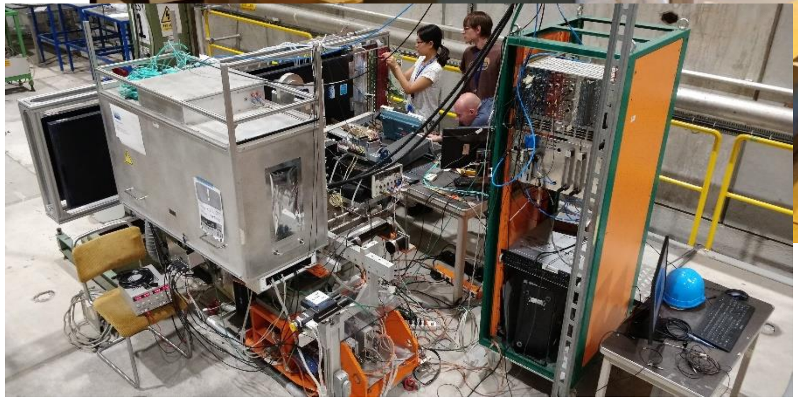
- **Increase luminosity to $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$**
  - 5 times larger than current maximum instantaneous luminosity
- **All sub-detectors read out at 40 MHz for a full software trigger**
  - Record with 10 GB/s
- **All subdetector apart from muon and calorimeter systems will be fully replaced**

Scintillating Fibre (SciFi) tracker installation



Scintillating Fibre (SciFi) tracker installation





Expected measurements

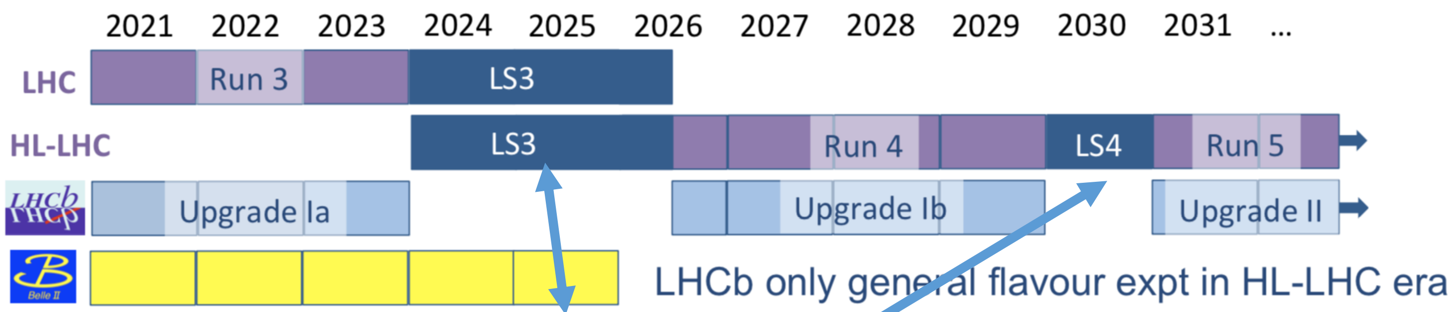
- A much larger sample of b- and c-hadrons would be collected after LS2 with the Upgrade
- More precision measurements for SM tests and NP searches with heavy flavour, CKM, CPV, RD, spectroscopy, et al
- More heavy flavour production measurements could be performed or improved, e.g.,
  - Measurement of $f_{\Omega_b^-}/f_{\Lambda_b^0}$
  - Double heavy flavour production
    - $\Upsilon(nS)+\Upsilon(nS)$

$$f_u + f_d + f_s + f_{\text{baryon}} = 1$$

$$\begin{aligned} f_{\text{baryon}} &= f_{\Lambda_b^0} + f_{\Xi_b^0} + f_{\Xi_b^-} + f_{\Omega_b^-} \\ &= f_{\Lambda_b^0}\left(1 + 2\boxed{\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}} + \boxed{\frac{f_{\Omega_b^-}}{f_{\Lambda_b^0}}}\right) \end{aligned}$$

LHCb Upgrade 2

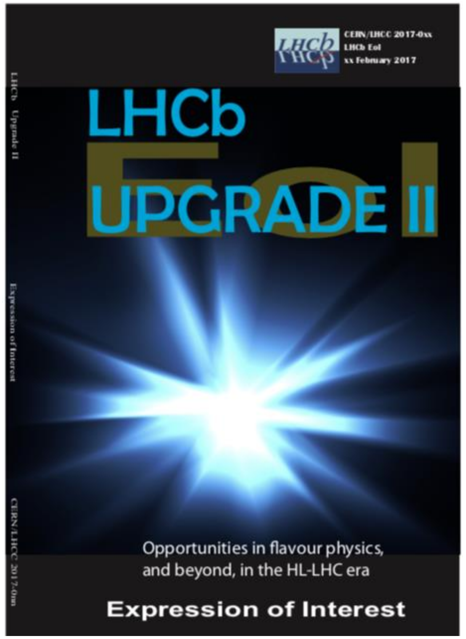
- Upgrade 2 proposed to take full profit of HL-LHC
  - $\mathcal{L} = 1 - 2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, 10 times larger than Upgrade 1
  - Aiming at $300\ \mathrm{fb}^{-1}$ after Run5



LHCb only general flavour expt in HL-LHC era

- **Consolidate in LS3**
- **Major upgrade in LS4**

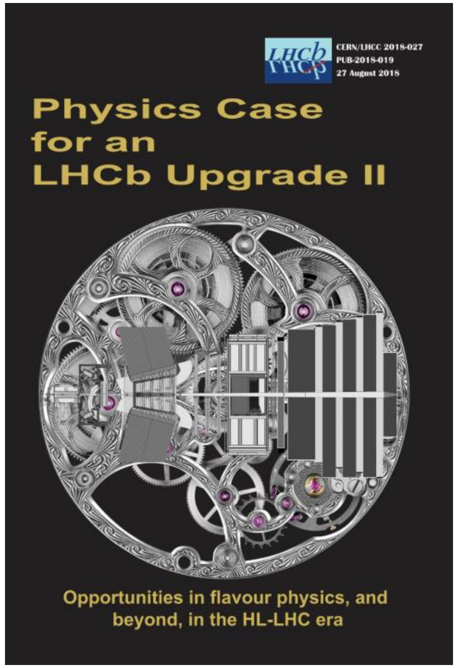
- **EOI submitted in 2017 (CERN-LHCC-2017-003)**
- **Physics document submitted in 2018 (arXiv:1808.08865)**


CERN/LHCC 2017-0xx
LHCb EoI
xx February 2017

LHCb
UPGRADE II

Opportunities in flavour physics,
and beyond, in the HL-LHC era

Expression of Interest


CERN/LHCC 2018-027
PUB-2018-019
27 August 2018

Physics Case
for an
LHCb Upgrade II

Opportunities in flavour physics, and
beyond, in the HL-LHC era

Summary

- LHCb has emphatically demonstrated its ability to perform important and unique measurements in various aspects
- New results of heavy flavour production are shown
  - b-hadron production fractions at 13 TeV
  - The mass and production rate of Ξ_b^- baryons
  - $\psi(2S)$ production at 13 TeV and 7 TeV
- LHCb Upgrade I detector will be installed during LS2
  - Full software trigger at event rate ~30 MHz
  - Real time event reconstruction
  - Expect $23\ \mathrm{fb}^{-1}$ by 2025 and $50\ \mathrm{fb}^{-1}$ by 2029
- LHCb Upgrade II aiming at $300\ \mathrm{fb}^{-1}$ with fully new detector to deepen our understanding of heavy flavour physics

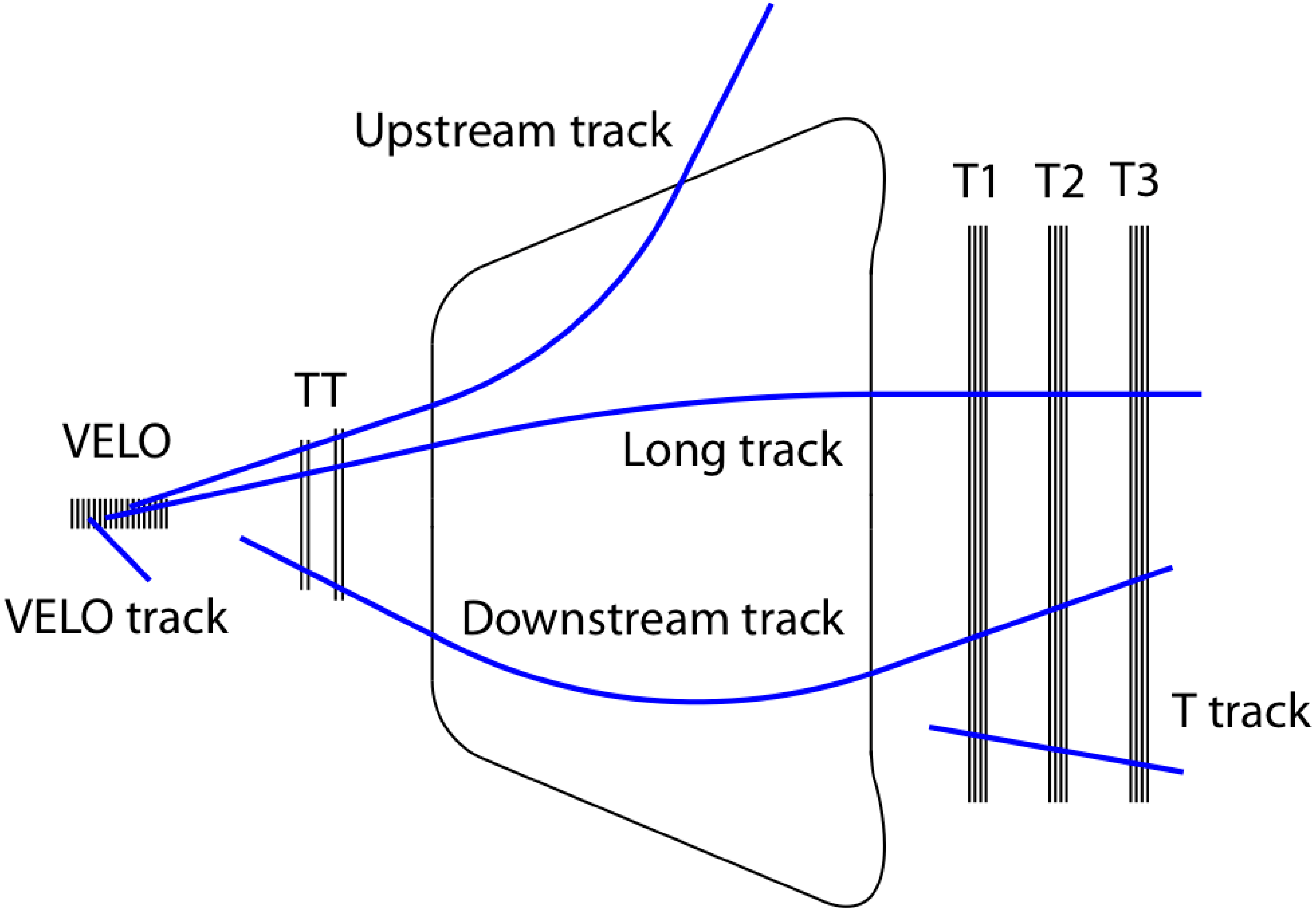
逝者如斯夫

不舍昼夜

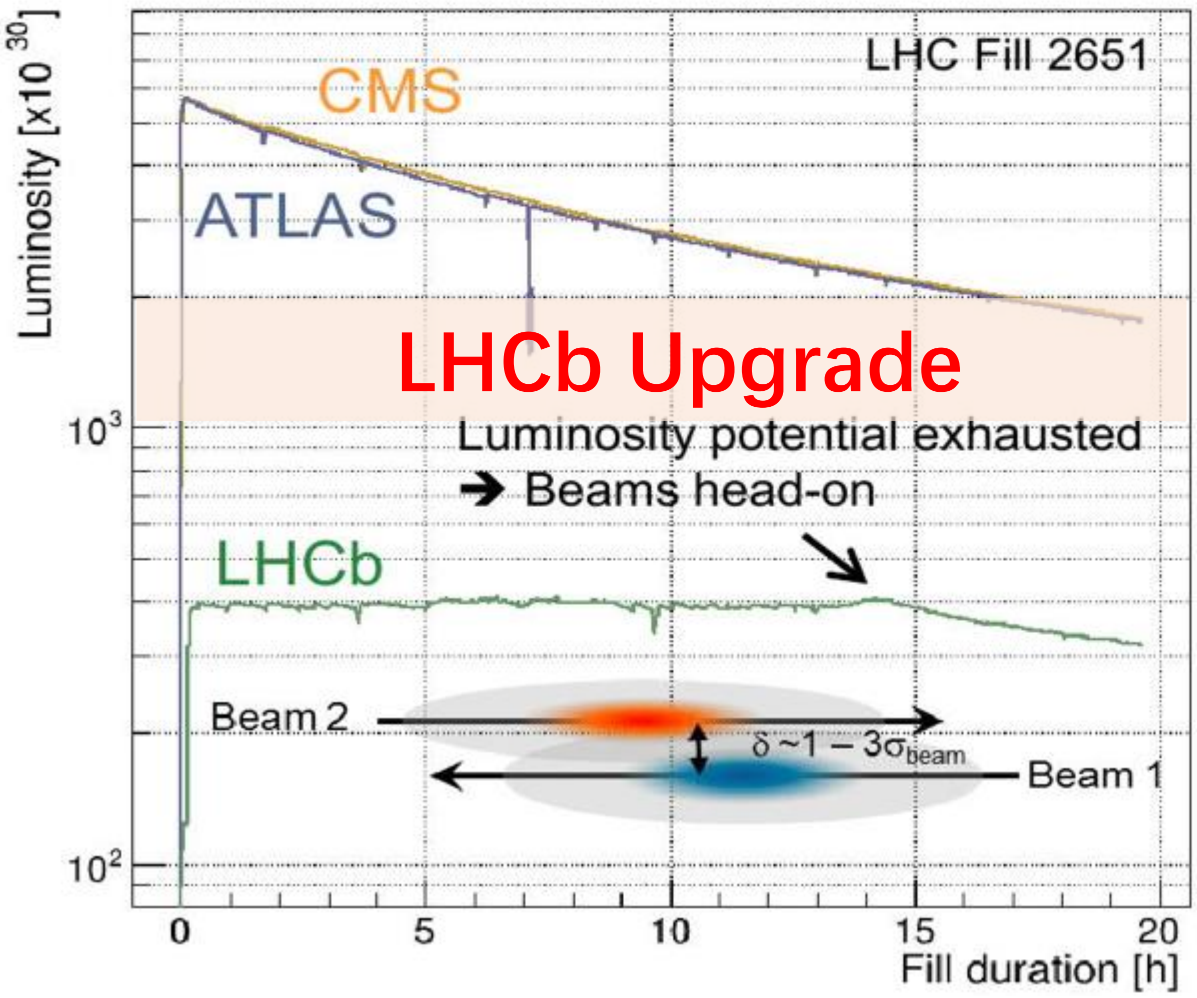
【论语】

Backup slides

Track types for the LHCb Run I and II



How to increase the LHCb statistics significantly?



➢ LHCb up to LS2 (2018)

- Running at levelled luminosity of $\sim \mathbf{4 \times 10^{32}\ cm^{-2}s^{-1}}$, pile-up~1
- First level hardware trigger running at event rate ~1 MHz
- Record ~12 kHz (0.6 GB/s)

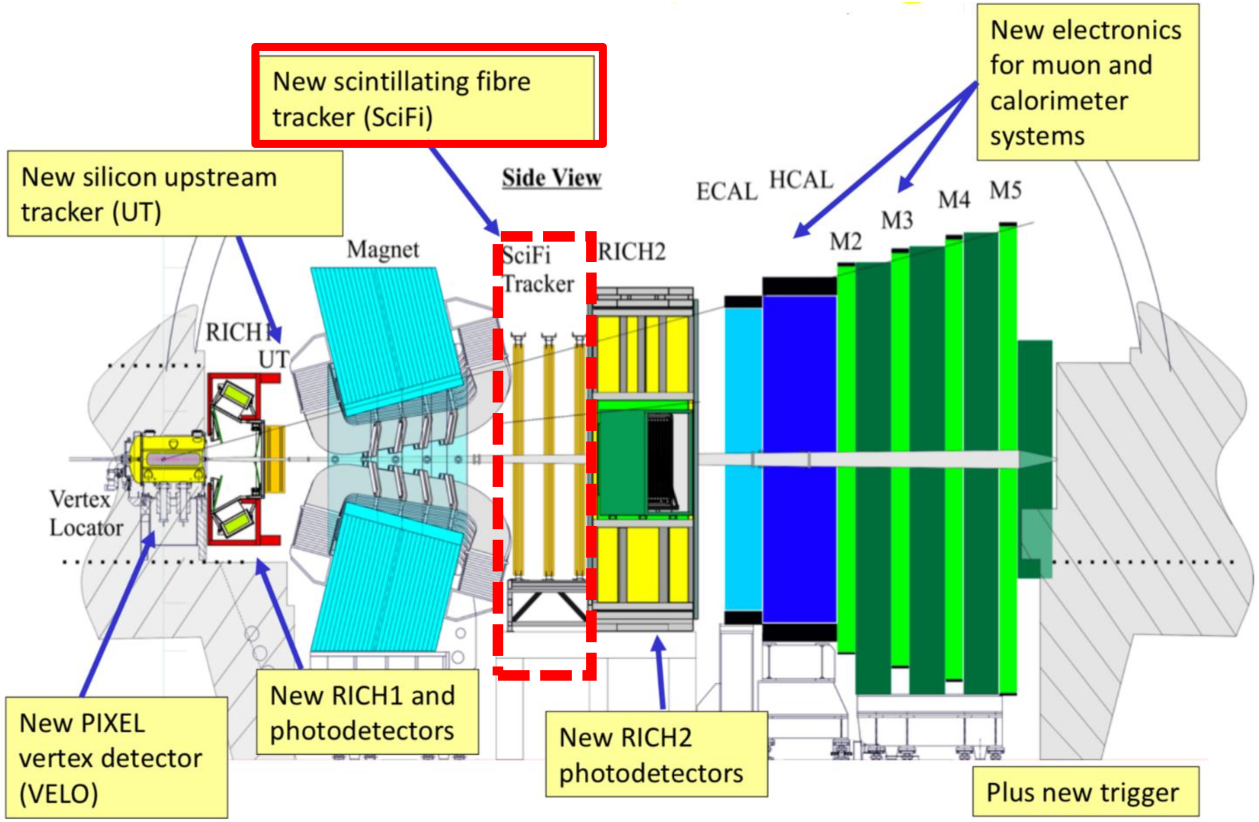
➢ LHCb Upgrade I (2021-)

- Increase luminosity to a levelled $\mathbf{2 \times 10^{33}\ cm^{-2}s^{-1}}$, pile-up~5
- Run fully flexible and efficient software trigger up to 40 MHz
- Record with 10 GB/s

The most severe bottlenecks:
- Hardware trigger limited to ~ 1 MHz
- Tracking reconstruction

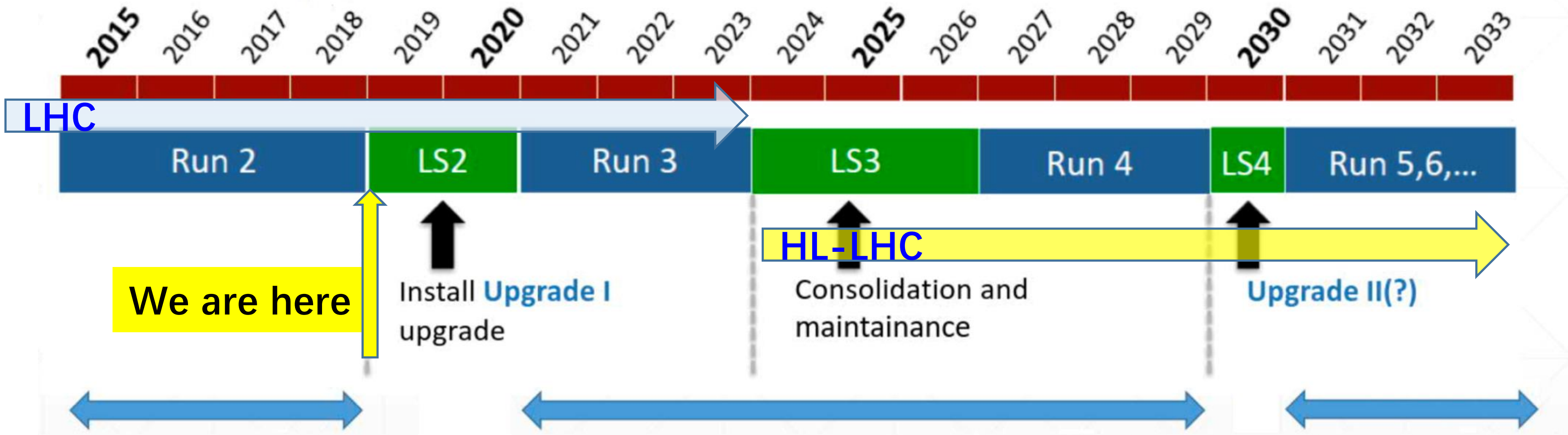
The LHCb Upgrade I detector

- A complete new detector
  - All sub-detectors read out at 40 MHz for a fully software trigger



- **Tracking system**
  - VELO: Silicon strip → $55 \times 55\ \mu\mathrm{m}^2$ PIXEL
  - TT→ UT: Silicon strip → Silicon microstrip
  - T1-T3→SciFi: Straw + silicon microstrip → Scintillating Fibre Tracker
- PID system
  - RICH: HPD → MaPMT improved optics + mechanics
  - ECAL/HCAL: remains the same ECAL inner modules replaced in LS3
  - Muon: increased granularity

Plan of the LHC(b) upgrade



$\mathcal{L}^{\max} = 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
1.1 visible interactions per bunch crossing

$\rightarrow 5\mathcal{L}^{\max}$

$\mathcal{L}^{\max} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
5.5 visible interactions per bunch crossing

$\rightarrow 50\mathcal{L}^{\max}$

$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
55 visible interactions per bunch crossing

LHCb up to 2018→ $9\ \mathrm{fb}^{-1}$

✓ Demonstrated feasibility of high precision flavour physics at hadron colliders

➢ Find/rule out large sources of NP at the TeV scale

LHCb Upgrade I → $\geq 50\ \mathrm{fb}^{-1}$

✓ Increase trigger efficiency

➢ Aim at experimental sensitivities comparable to theoretical uncertainties

LHCb Upgrade II → $\geq 300\ \mathrm{fb}^{-1}$

✓ Take full profit of HL-LHC

➢ Physics document has been submitted to LHCC arXiv:1808.08865

Corrected yields of $B \to D\mu^-$

$$n_{\text{corr}}(B \to D^0\mu^-) \;=\; \frac{1}{\mathcal{B}(D^0 \to K^-\pi^+)\epsilon(B \to D^0)} \times \left[n(D^0\mu^-) - n(D^0K^+\mu^-)\frac{\epsilon(\overline{B}{}^0_s \to D^0)}{\epsilon(\overline{B}{}^0_s \to D^0K^+)} - n(D^0p\mu^-)\frac{\epsilon(\mathit{\Lambda}_b^0 \to D^0)}{\epsilon(\mathit{\Lambda}_b^0 \to D^0p)}\right]$$

$$n_{\text{corr}}(B \to D^+\mu^-) \;=\; \frac{1}{\epsilon(B \to D^+)}\left[\frac{n(D^+\mu^-)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} - \frac{n(D^0K^+\mu^-)}{\mathcal{B}(D^0 \to K^-\pi^+)}\frac{\epsilon(\overline{B}{}^0_s \to D^+)}{\epsilon(\overline{B}{}^0_s \to D^0K^+)} - \frac{n(D^0p\mu^-)}{\mathcal{B}(D^0 \to K^-\pi^+)}\frac{\epsilon(\mathit{\Lambda}_b^0 \to D^+)}{\epsilon(\mathit{\Lambda}_b^0 \to D^0p)}\right].$$

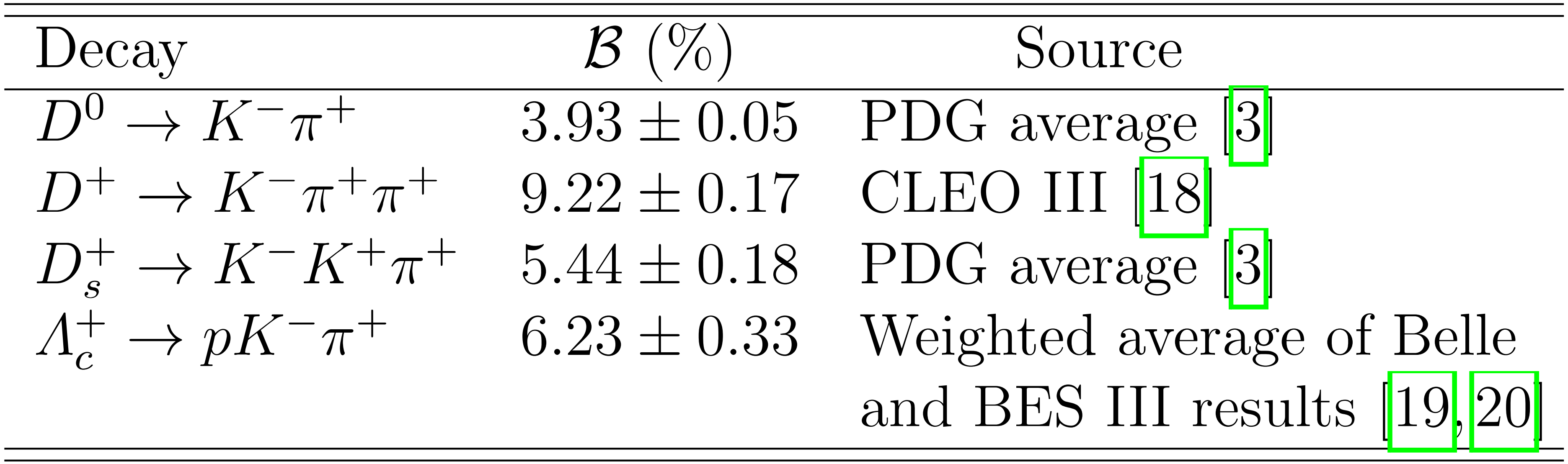
Corrected yields of $\bar{B}_s^0 \to D\mu^-(K^+)$ and $\Lambda_b^0 \to D\mu^-$

$$n_{\rm corr}(\overline{B}{}^0_s \to D_s^+\mu^-) = \frac{n(D_s^+\mu^-)}{\mathcal{B}(D_s^+ \to KK\pi)\epsilon(\overline{B}{}^0_s \to D_s^+\mu^-)} - N(\overline{B}{}^0 + B^-)\mathcal{B}(B \to D_s^+K)\frac{\epsilon(\overline{B} \to D_s^+K\mu^-)}{\epsilon(\overline{B}{}^0_s \to D_s^+\mu^-)}$$

$$n_{\rm corr}(\overline{B}{}^0_s \to D^0K^+\mu^-) = 2\frac{n(D^0K\mu^-)}{\mathcal{B}(D^0 \to K\pi)\epsilon(\overline{B}{}^0_s \to D^0K\mu^-)}$$

$$n_{\rm corr}(\Lambda_b^0 \to D\mu^-) = \frac{n(\Lambda_c^+\mu^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)\epsilon(\Lambda_b^0 \to \Lambda_c^+)} + 2\frac{n(D^0p\mu^-)}{\mathcal{B}(D^0 \to K^-\pi^+)\epsilon(\Lambda_b^0 \to D^0p)}$$

BRs of charmed hadron decays

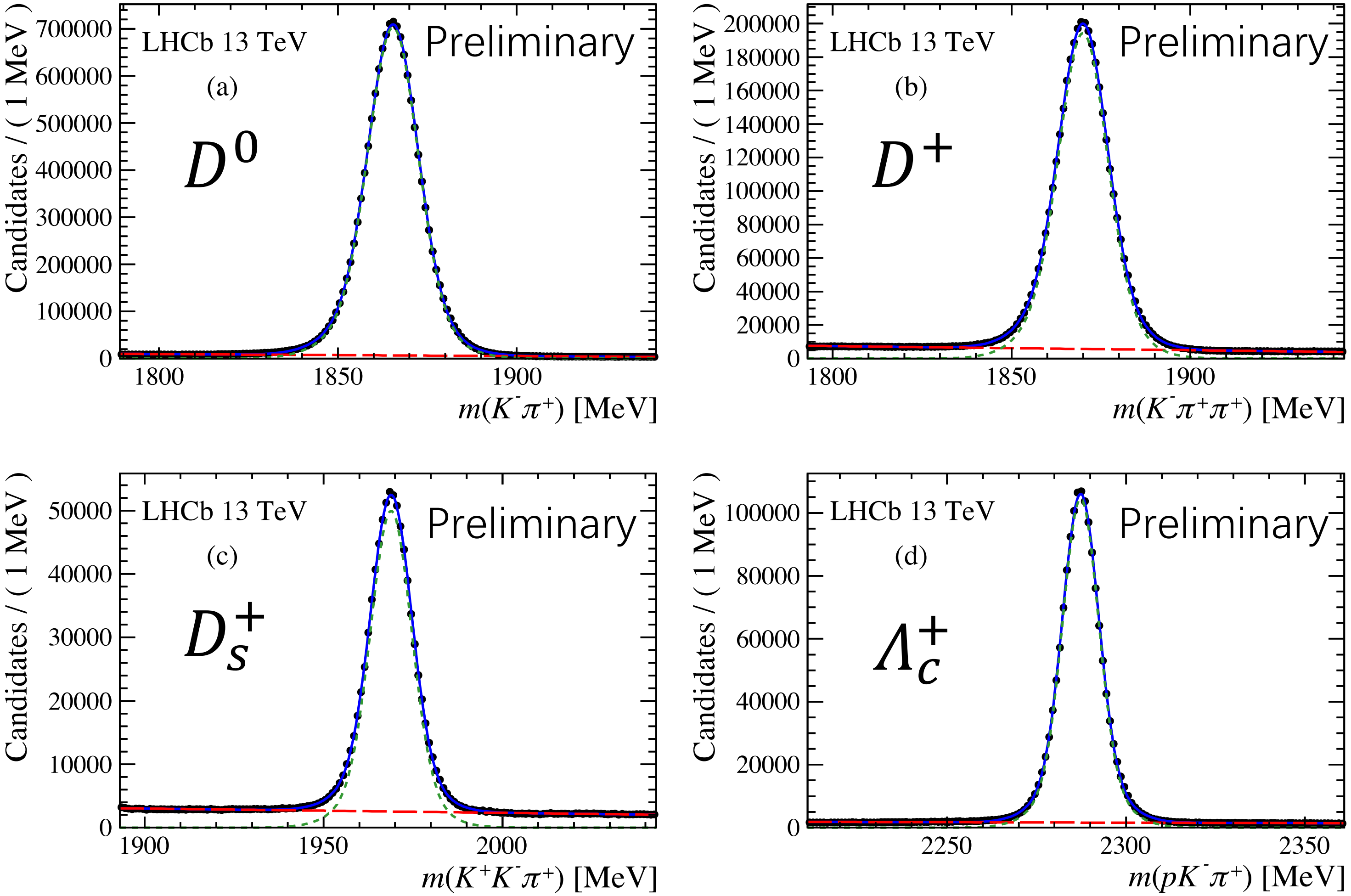


Decay	$\mathcal{B}$ (%)	Source
$D^0 \to K^-\pi^+$	3.93 ± 0.05	PDG average [3]
$D^+ \to K^-\pi^+\pi^+$	9.22 ± 0.17	CLEO III [18]
$D_s^+ \to K^-K^+\pi^+$	5.44 ± 0.18	PDG average [3]
$\Lambda_c^+ \to pK^-\pi^+$	6.23 ± 0.33	Weighted average of Belle and BES III results [19, 20]

Signal yields of charmed hadrons H_c

LHCb-PAPER-2018-050
in preparation

- Signal: two Gaussians
- Background: linear
- Signal yields
  $N\left(D^0\mu^-\bar{\nu}_\mu X\right) = 13.8\text{M}$
  $N\left(D^+\mu^-\bar{\nu}_\mu X\right) = 4.28\text{M}$
  $N\left(D_s^+\mu^-\bar{\nu}_\mu X\right) = 0.85\text{M}$
  $N\left(\Lambda_c^+\mu^-\bar{\nu}_\mu X\right) = 1.75\text{M}$
- Yields obtained in bins of (p_T, η)



Cross-feed background with misidentified particles evaluated in (p_T, η) bins

A systematic check: f_+/f_0

LHCb-PAPER-2018-050
in preparation

- Measure the ratio of $D^0\mu^-\bar{\nu}_\mu X$ to $D^+\mu^-\bar{\nu}_\mu X$: f_+/f_0
- Theoretical prediction

$$f_+/f_0 = 0.387 \pm 0.012 \pm 0.026$$

[M. Rudolph, Int.J.Mod.Phys. A33 (2018) 1850176]

- Measured result: Preliminary

$$f_+/f_0 = 0.359 \pm 0.006 \pm 0.009$$

No dependence of p_{T} and η is observed
Consistent with theoretical prediction

Systematic of b-hadron production fraction

LHCb-PAPER-2018-050
in preparation

Preliminary

Source	Value (%)		
	$f_s/(f_u+f_d)$	$f_{\Lambda_b^0}/(f_u+f_d)$	f_+/f_0
Simulation	1.7	2.4	–
Backgrounds	0.9	0.3	–
Cross-feeds	1.2	0.4	0.2
$\mathcal{B}(D^0 \to K^-\pi^+)$	1.0	1.0	1.3
$\mathcal{B}(D^+ \to K^+\pi^-\pi^-)$	0.6	0.6	1.8
$\mathcal{B}(D_s^+ \to K^+K^-\pi^+)$	3.3	–	–
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	–	5.3	–
Measured lifetime ratio	1.2	0.7	–
Γ_{sl} correction	0.5	1.5	–
Total	4.3	6.1	2.2

Systematic of Ξ_b^- production ratio

LHCb-PAPER-2018-047
arXiv:1901.07075

Source	Value (%)
Λ_b^0, Ξ_b^- polarization	3.0
Signal and background shape	2.0
Ξ_b^- production spectra	3.0
π^- tracking efficiency	4.5
Ξ^- mass resolution & non-resonant $\Lambda\pi^-$	3.0
Ξ^- selections	1.4
Ξ_b^- lifetime	0.5
Simulated sample sizes	2.0
Total	7.6