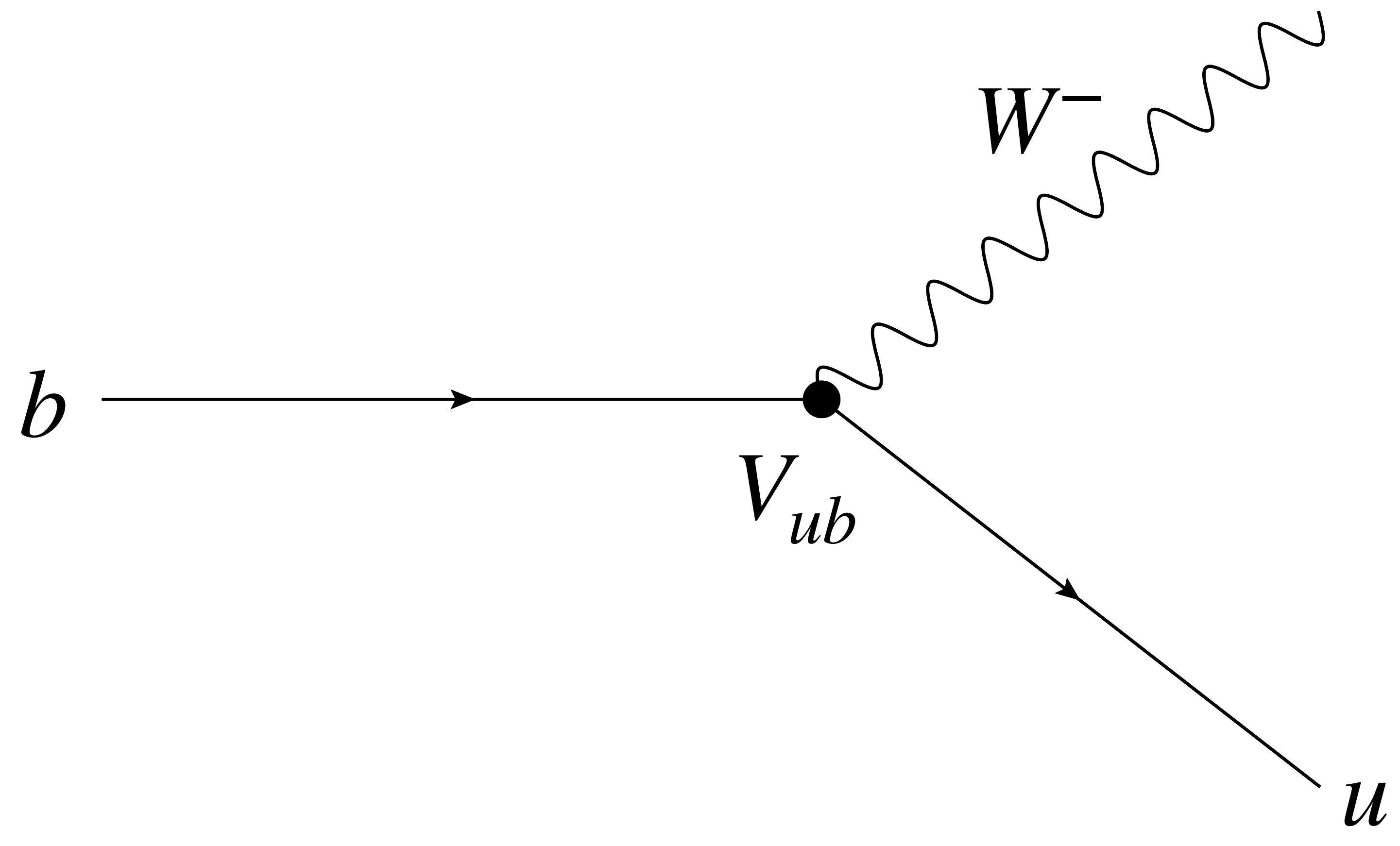
# Measurement of the $V_{ub}$ element of the CKM matrix

## Run 2 Exclusive Analysis of the $B_s^0 \to K^-\mu^+\nu_\mu$ Decay at LHCb

GDR Intensity Frontier Annual Workshop
08/11/2024

Alois Caillet (LPNHE)

# $V_{ub}$ element of the CKM matrix



Plays a role in the **amplitude** of charged **weak interaction transitions** involving the $u$ and $b$ quarks.

**Feynman Rule** for the charged weak interaction at the $b \to u$ vertex:

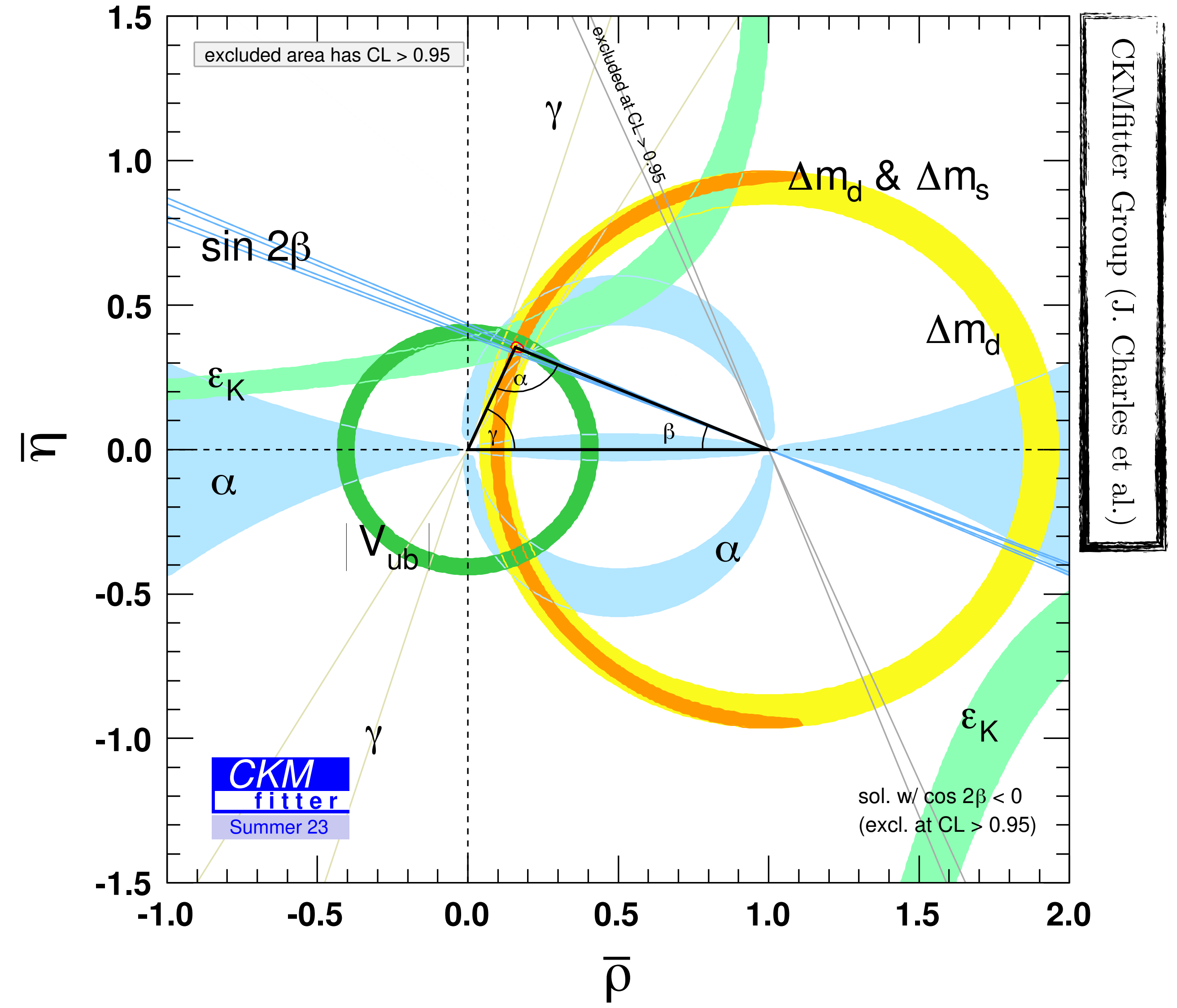
$$\longrightarrow \quad \frac{-ig_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)\boxed{V_{ub}}$$

Abundance of b quark produced at LHC ⇒ LHCb good experiment to explore these transition

# Motivation

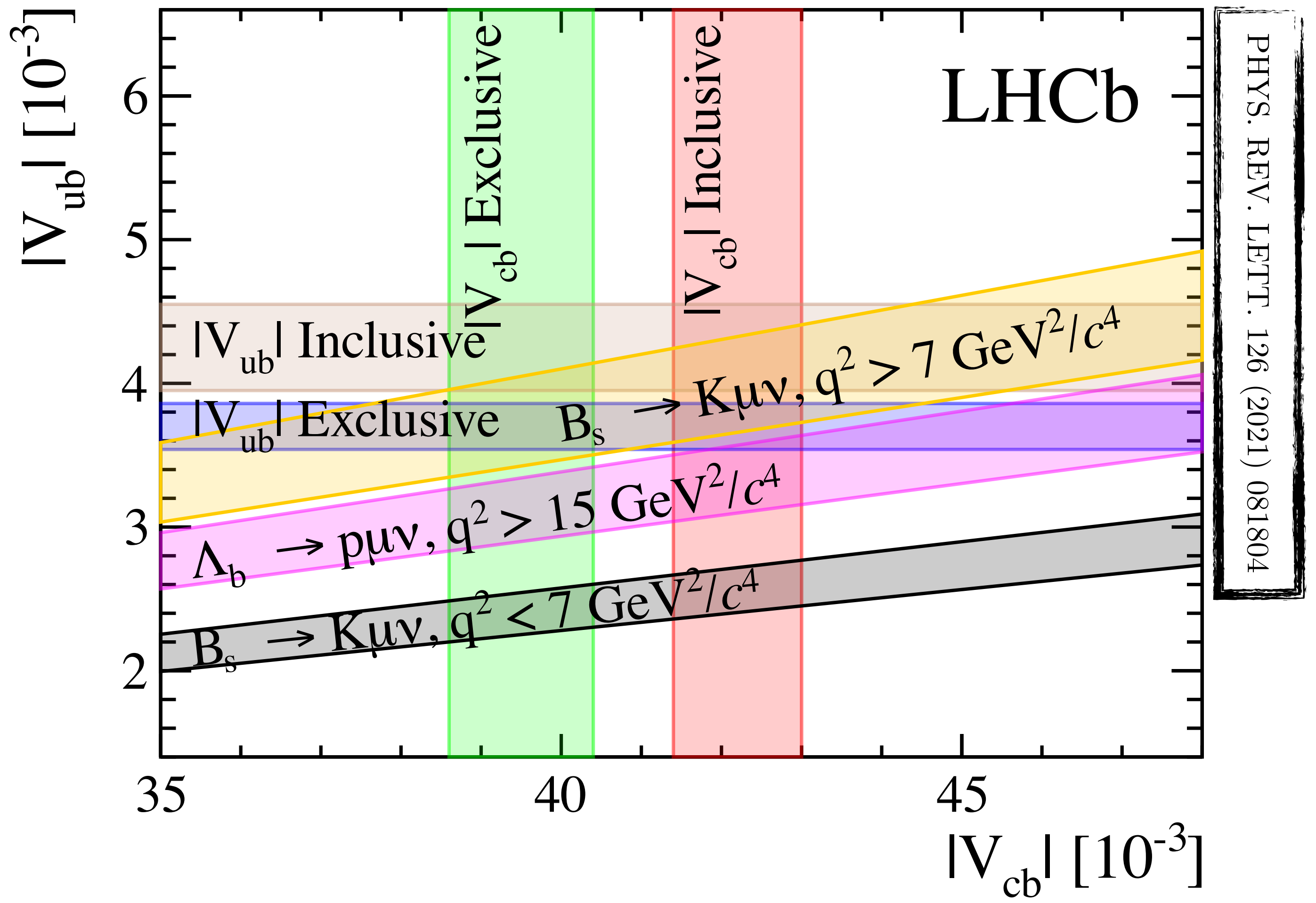
✦ **This measurement can allow :**

- ➡ Constraining the **Unitarity Triangle** of the CKM matrix
- ➡ Improving **precision** on the **least well known** CKM element
- ➡ Probing **New Physics**
- ➡ Helping to resolve **tension** between **exclusive** and **inclusive** measurement



CKMfitter Group (J. Charles et al.)

$$|V_{CKM}| = \begin{bmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & \boxed{0.00369 \pm 0.00011} \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{bmatrix}$$



PHYS. REV. LETT. 126 (2021) 081804

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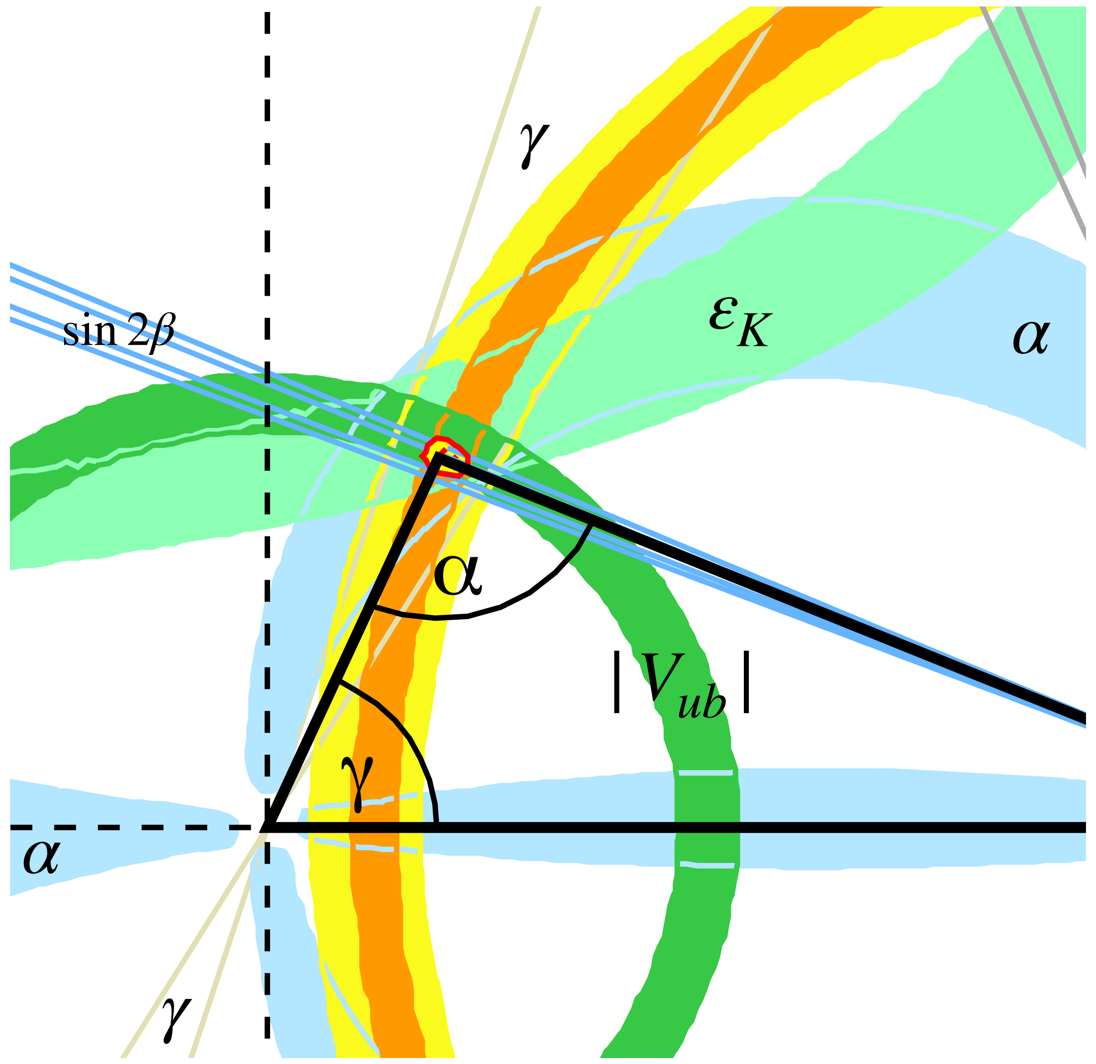

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➡ Improving **precision** on the **least well known** CKM element

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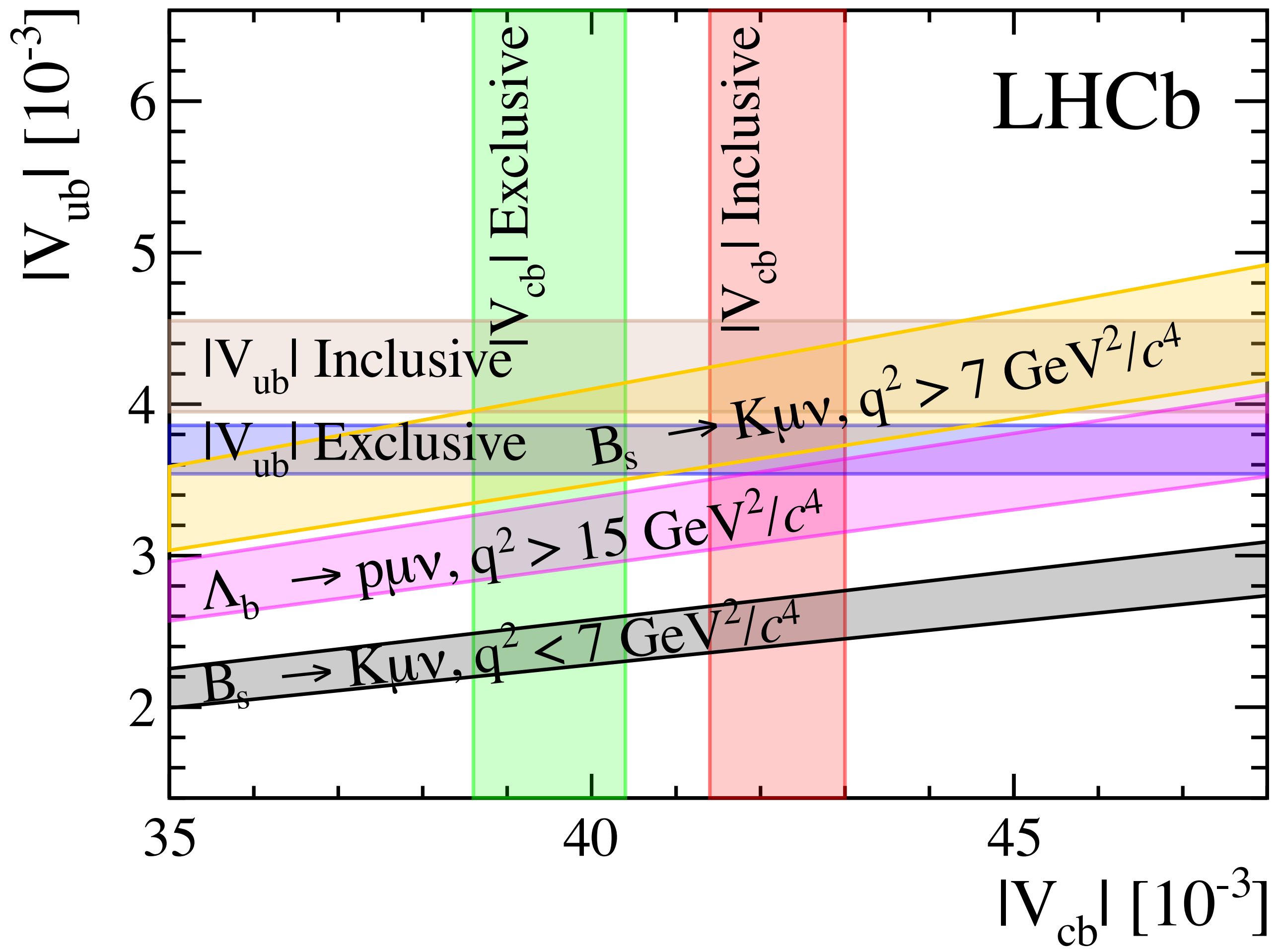

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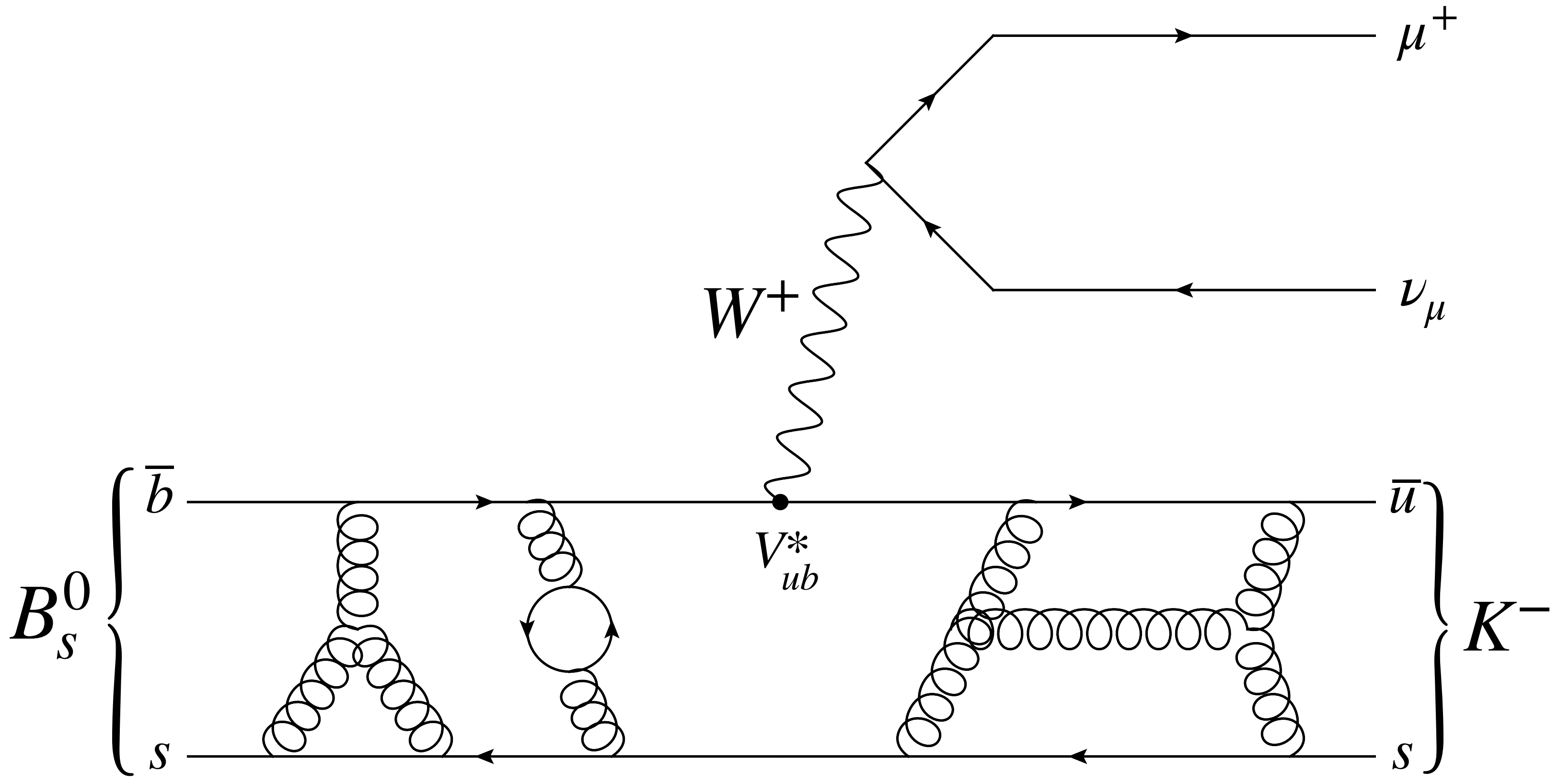
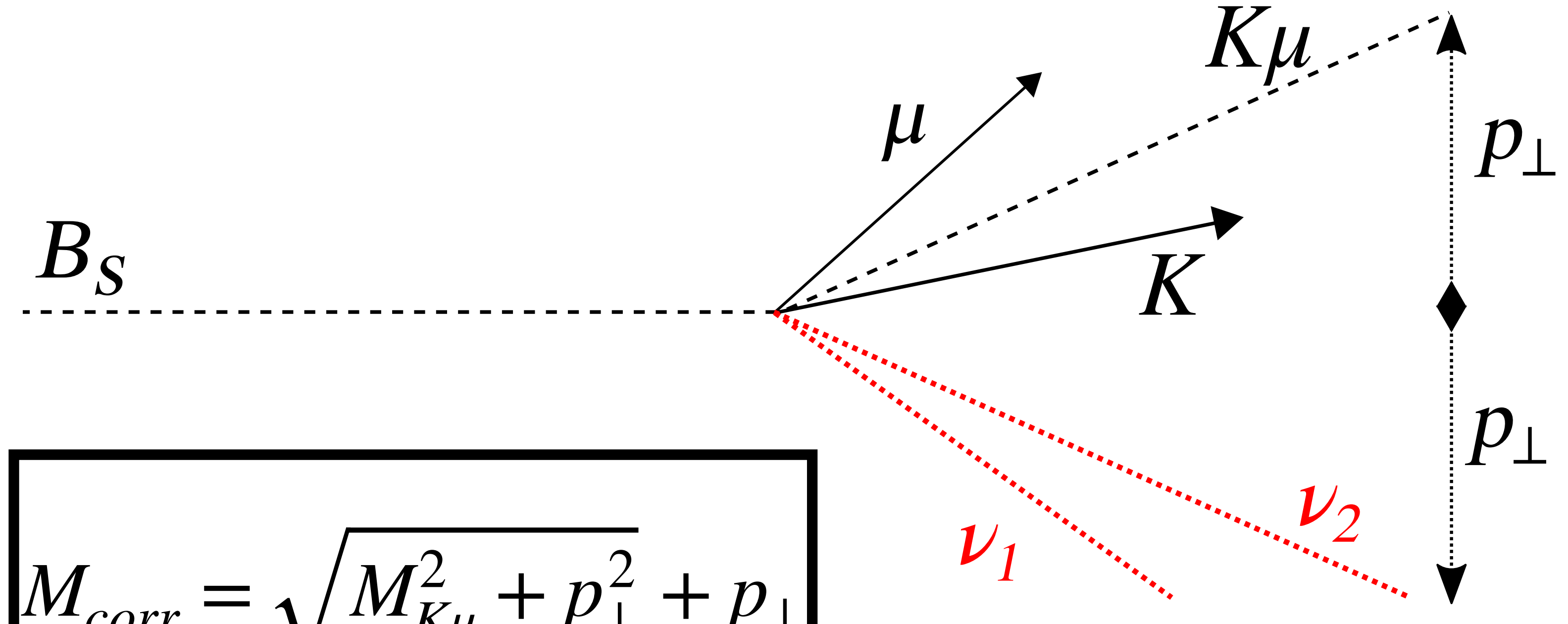
# Analysis strategy for the $B_s^0 \to K^-\mu^+\nu_\mu$ decay



Described by **form factors (FFs)** as function of $q^2 = (p_\mu + p_\nu)^2$ calculated with **LCSR** (small $q^2$) or **LQCD** (high $q^2$)

No $\nu$ reconstruction at LHC ⇒ $B_s^0$ **mass** obtained with a reconstruction technique using the **visible** decay products $K\mu$ and kinematic constraints



$$M_{corr} = \sqrt{M_{K\mu}^2 + p_\perp^2} + p_\perp$$

$$\left|V_{ub}\right|^2 \propto \frac{Br(B_s^0 \to K^-\mu^+\nu_\mu)}{\int |FF| \, \mathrm{d}q^2} \times \frac{1}{\tau_{B_s}}$$

**Fit** on the $B_s^0$ **mass** to access to $Br(B_s^0 \to K^-\mu^+\nu_\mu)$ and then $V_{ub}$

# Last LHCb $V_{ub}$ measurement

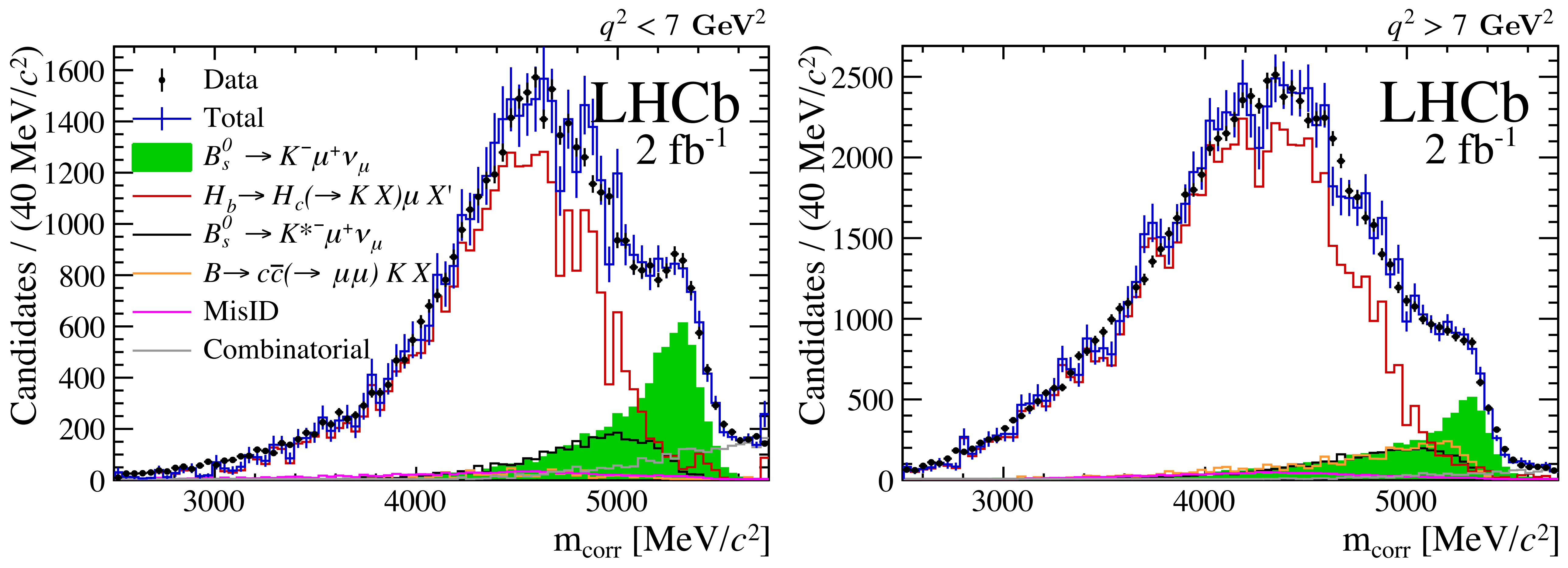
## Run 1

2012 / $pp$ collisions : 2fb$^{-1}$ @ 7 TeV

**Normalization** decay : $B_s^0 \longrightarrow D_s^- \, \mu^+ \, \nu_\mu$

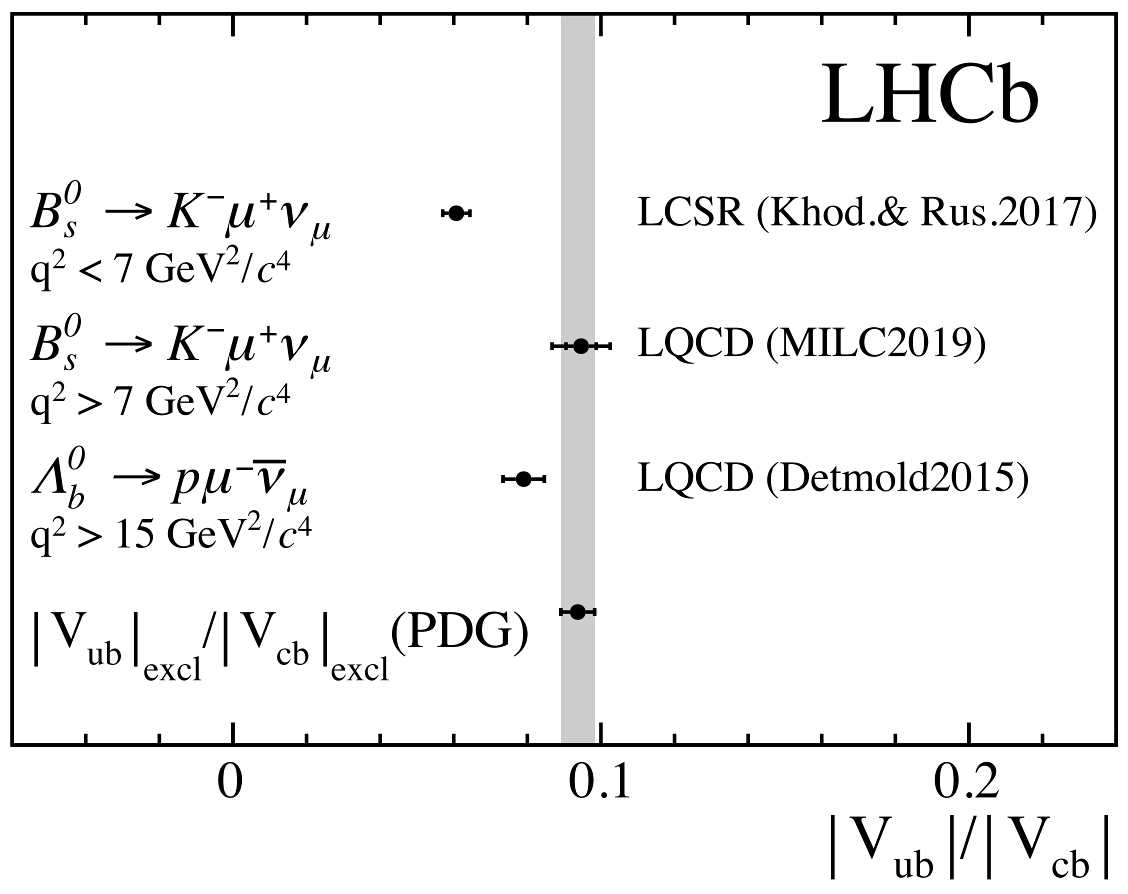
Analysis in **two bins** $q^2 \lessgtr 7 \text{ GeV}^2/c^4$

$|V_{ub}|/|V_{cb}|$ extract



$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015\,(\text{stat}) \pm 0.0013\,(\text{syst}) \pm 0.0008\ (D_s) \pm 0.0030\ (\text{FF})$$

$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030\,(\text{stat})^{+\ 0.0024}_{-\ 0.0025}\,(\text{syst}) \pm 0.0013\ (D_s) \pm 0.0068\ (\text{FF}),$$



Phys. Rev. Lett. 126, 081804

# Changes from last LHCb $V_{ub}$ measurement

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$|V_{ub}|/|V_{cb}|$ extract

## Run 2

2016-2017-2018 / $pp$ collisions : $\sim 5.67$fb$^{-1}$ @ 13 TeV

**Normalization** decay : $B^+ \longrightarrow J/\psi(\rightarrow \mu\mu)\, K^+$

**Increase** $q^2$ bin number to **8 – 10** bins

$|V_{ub}|$ extract

### Team

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[3]University of Syracuse
[4]Laboratoire de physique nucléaire et de hautes énergies

# Challenges for the analysis

- **Theoretical** and **experimental** contributions are nearly **equal** in the **precision** of the measurement

## Run 1

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\begin{aligned}
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$$

Experimental

Theoretical

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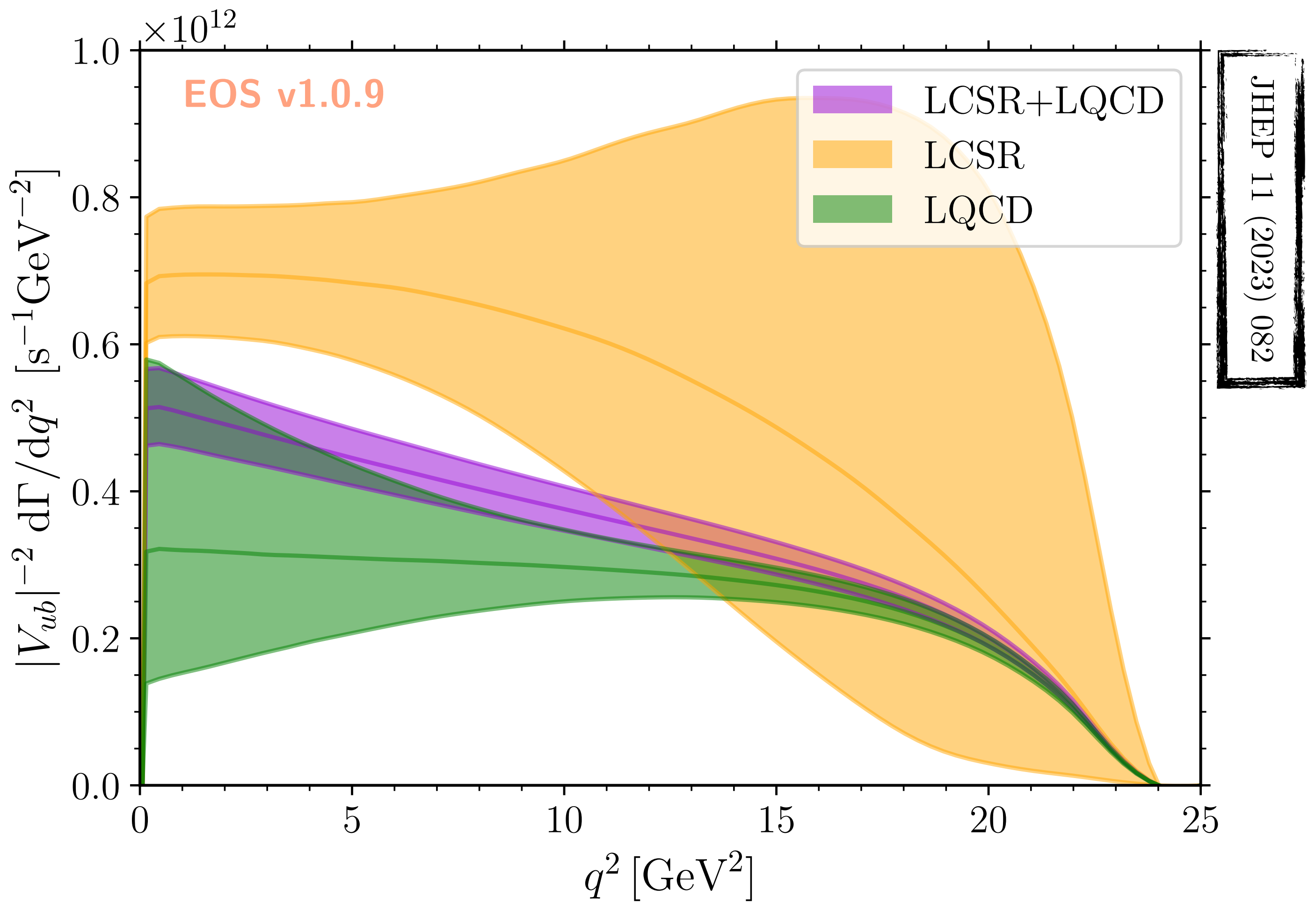
- **Different QCD** models at **low and high** $q^2$ for FFs ⇒ Discrepancy between the 2 regions



JHEP 11 (2023) 082

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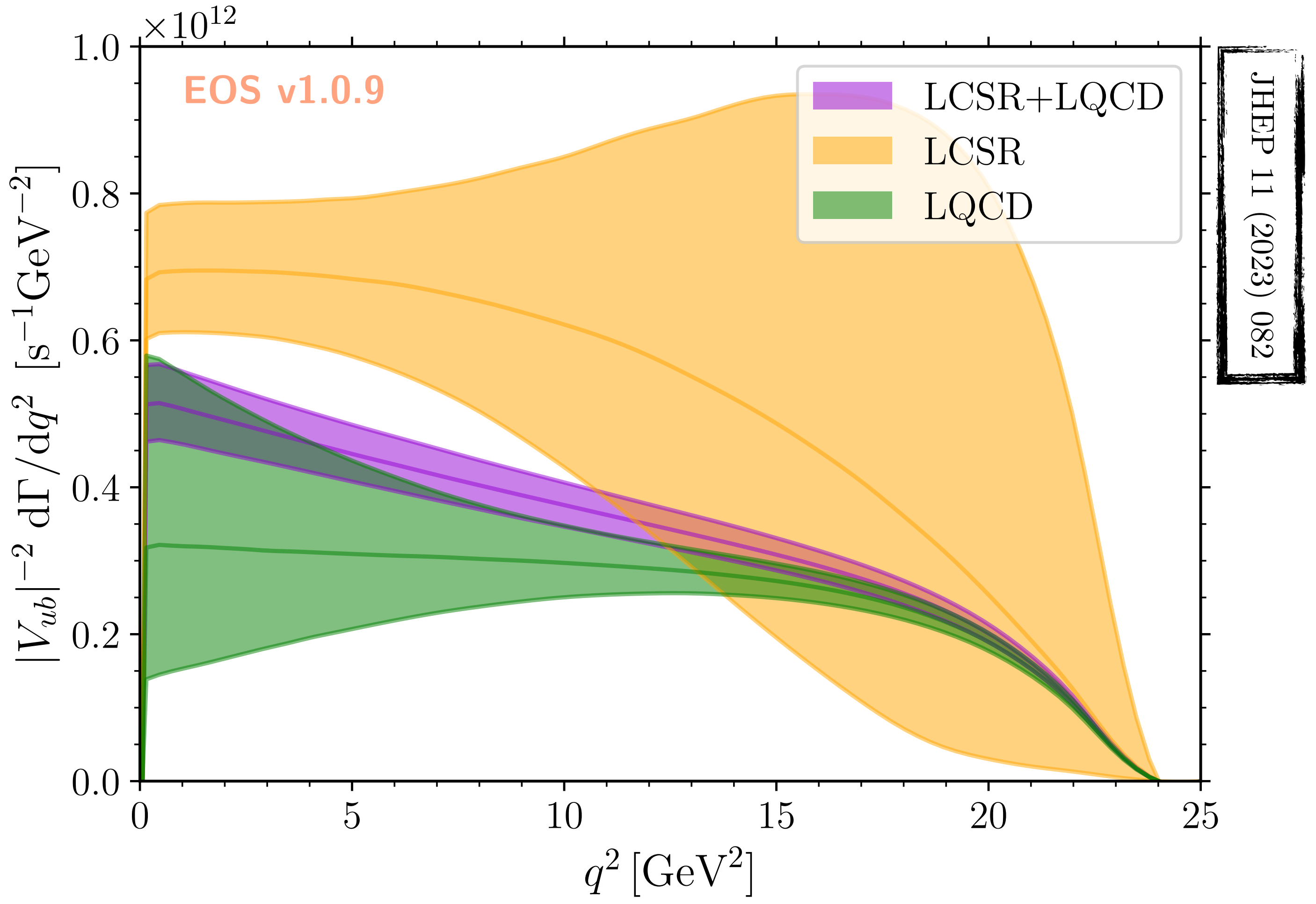
- Big amount of **physical background** with $K\mu$ in the decay product ⇒ Delicate **bkg discrimination**



JHEP 11 (2023) 082

$H_b \to H_c(\to K^{\pm}X)\mu^{\mp}X'$ / $B^{\pm} \to c\bar{c}(\to \mu^{+}\mu^{-})K^{\pm}X$

$B_s^0 \to K^{*\pm}\,\mu^{\mp}\,\nu_\mu$ / $B_s^0 \to K_0^{*\pm}(1430)\,\mu^{\mp}\,\nu_\mu$ / $B_s^0 \to K_2^{*\pm}\,\mu^{\mp}\,\nu_\mu$

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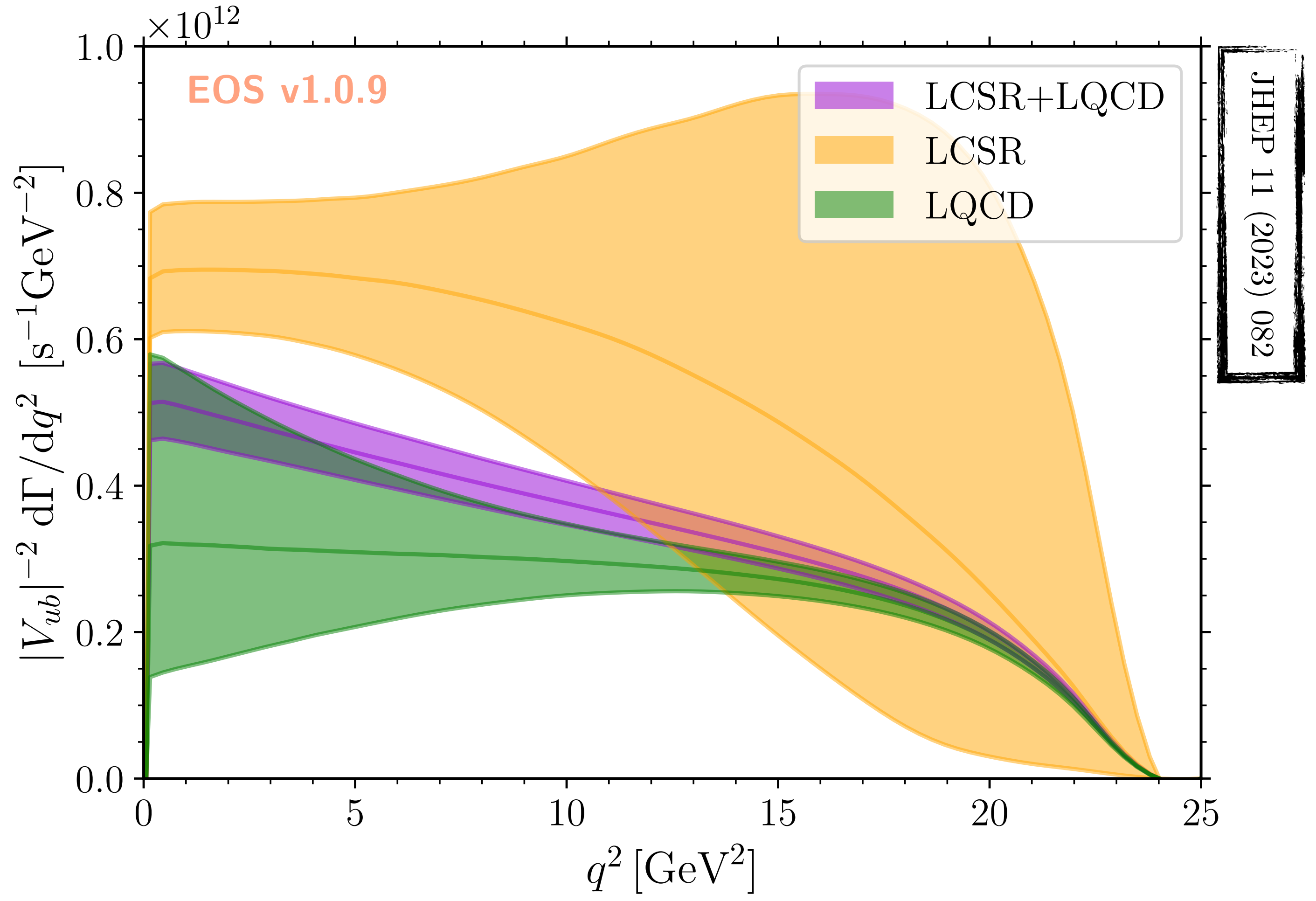

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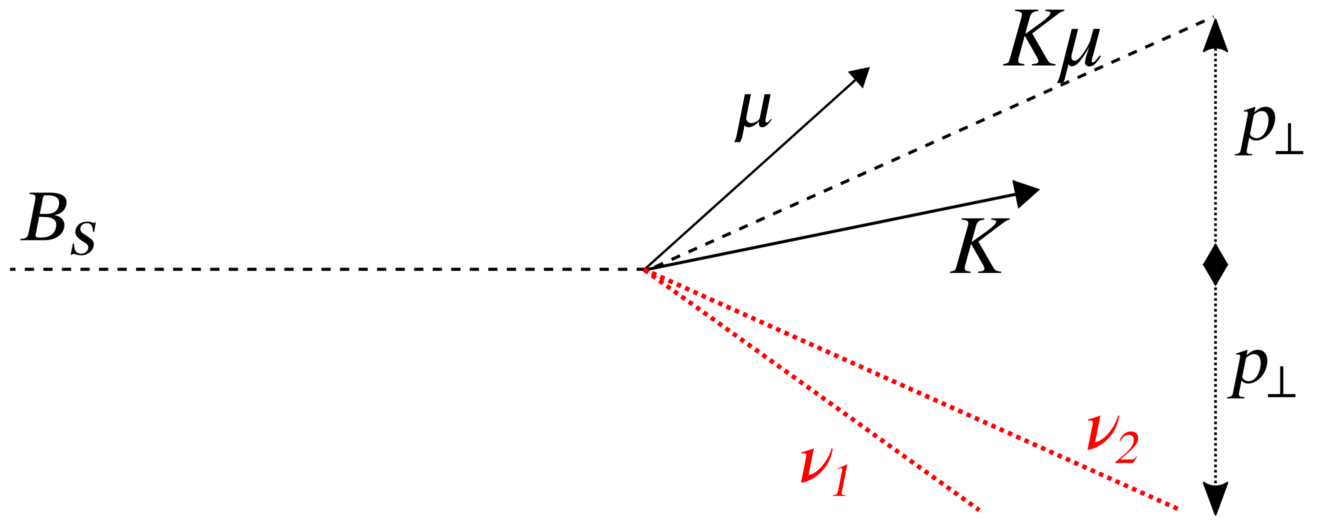
- Two $\nu$ **solutions** are compatible with the **reconstruction technique**



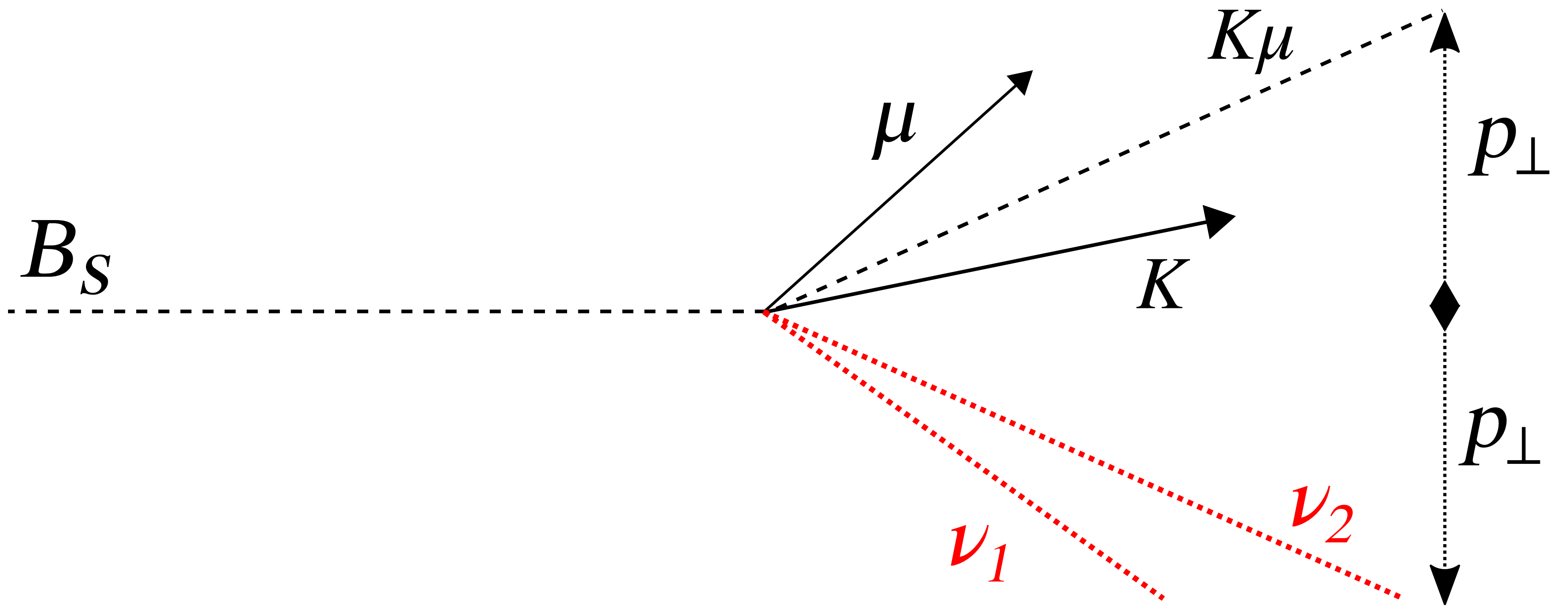
# $B_s^0 \to K^-\mu^+\nu_\mu$ decay reconstruction at LHCb

- Taking **PV to SV** direction as $B_s^0$ **flight direction** $\Rightarrow p_\perp(\nu_\mu) = -p_\perp(K\mu)$

- 4-momentum conservation equations lead to a **2-fold ambiguity** for the $\nu_\mu$ kinematic

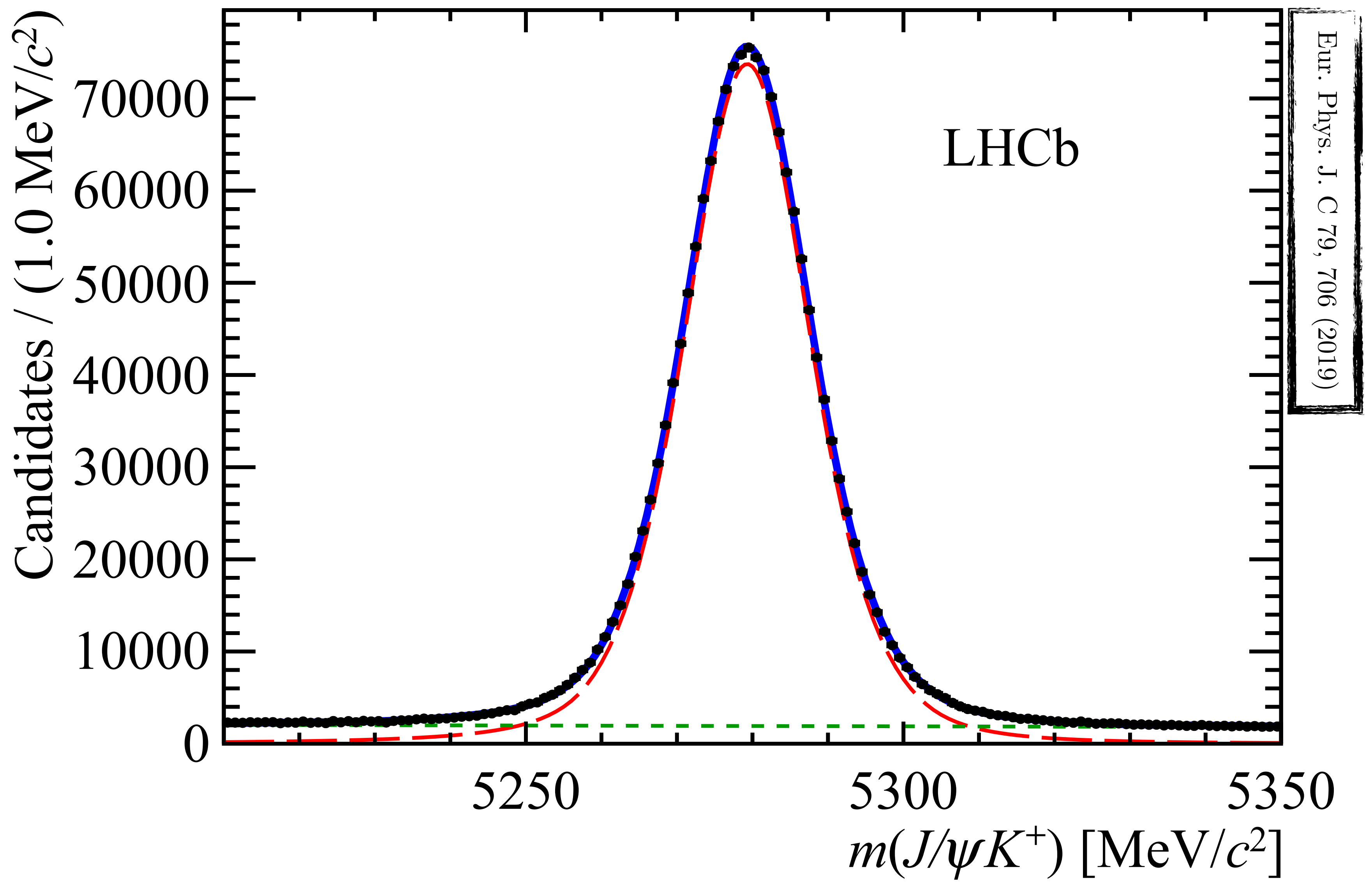
  ➡ Use a **regression algorithm** to pick-up the **best solution** and evaluate $q^2$ JHEP02(2017)021

- Use **corrected mass** as **discriminating** variable : $M_{corr} = \sqrt{M_{K\mu}^2 + p_\perp^2} + p_\perp$



# $B_s^0 \to K^-\mu^+\nu_\mu$ Normalization

- **Normalisation** mode $\Rightarrow B^{\pm} \longrightarrow J/\psi(\mu\mu)K^{\pm}$



Eur. Phys. J. C 79, 706 (2019)

- **Clean** and **large** sample :
  - ➡ **Small** additional **statistical** uncertainty

- Same **number of tracks** and similar **topology** to signal when one $\mu$ is neglected
  - ➡ **Reduced systematic** uncertainty on efficiencies ratio

- **Ratio** of $B_s^0$ to $B^{\pm}$ production fractions **precisely measured** by LHCb Phys.Rev.D104,032005
  - ➡ $f_s/f_d(13 \text{ TeV}) = 0.2539 \pm 0.0079$

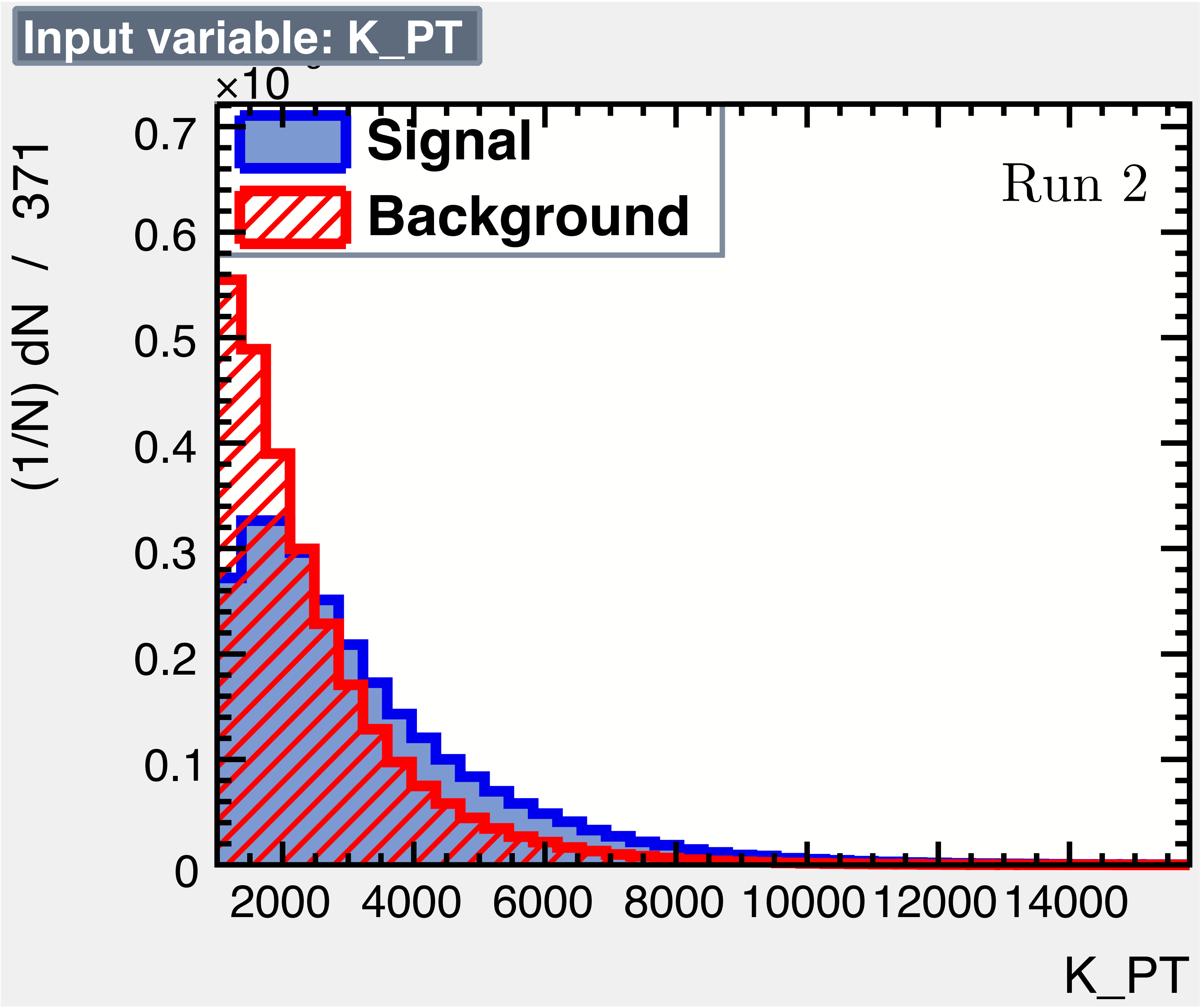
- External **systematic** uncertainty from **normalization** will be slightly **smaller** than in Run 1 measurement
  - ➡ 1.9 % from $\mathscr{B}(B^{\pm} \longrightarrow J/\psi(\mu\mu)K^{\pm})$ and 3.1 % from $f_s/f_d \implies$ 5 % which is four less than Run 1

# Physical background discrimination

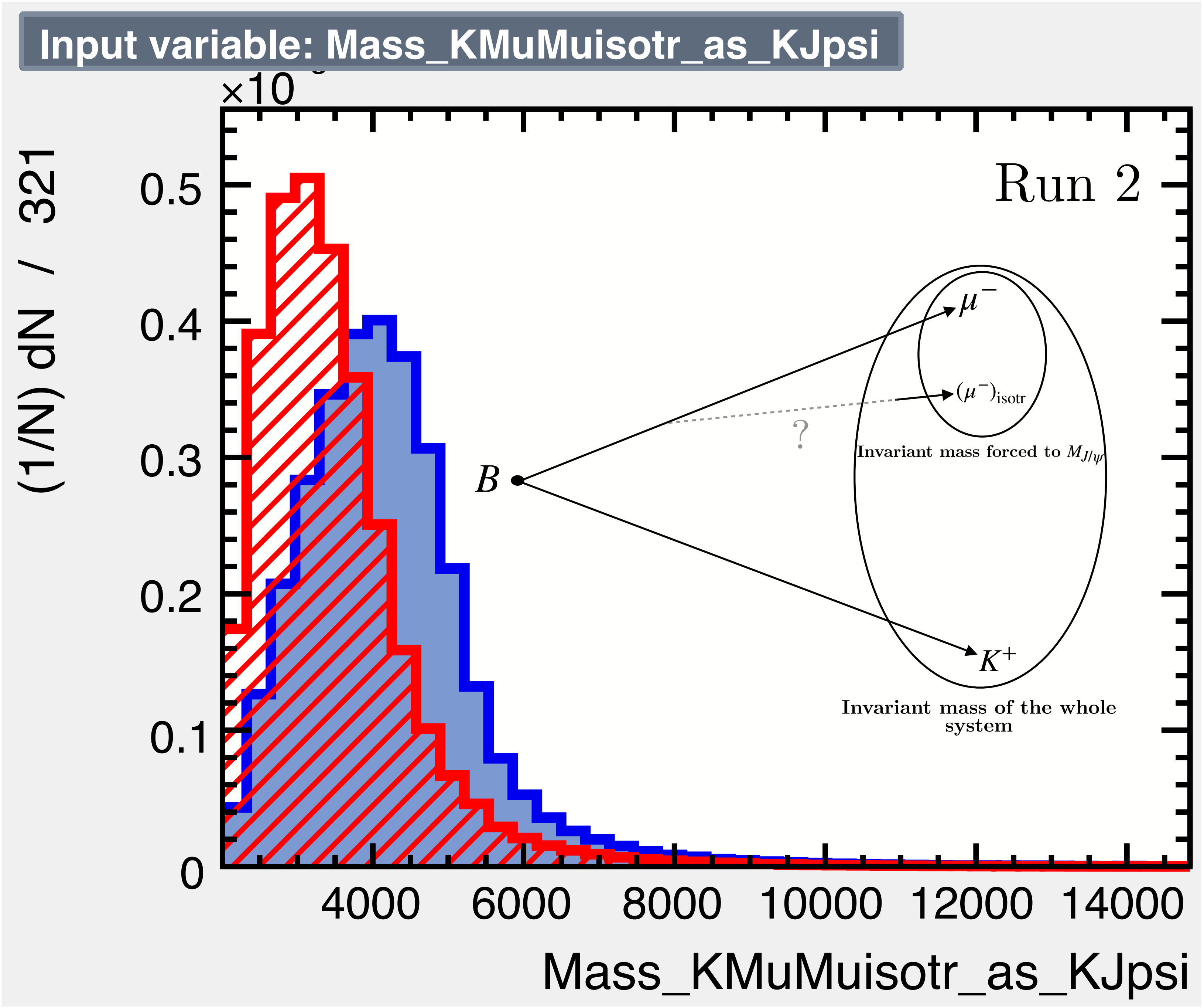
- ❖ Main **physical background** sources : $H_b \longrightarrow H_c(\to K^- X)\,\mu^+ X'$ & $B^+ \longrightarrow c\bar{c}(\to \mu\mu)\,K^+ X$
- ❖ Contributions from : $B_s^0 \to K^{*-}(K^-\pi^0)\mu^+\nu_\mu$ with $K^* = K^*(892)$ , $K_0^*(1430)$ or $K_2^*(1430)$ with unreconstructed $\pi^0$

➡ Creation of a **multivariate classifier** based on **neural network** with **kinematical** and **topological** variables, trained on **simulation**

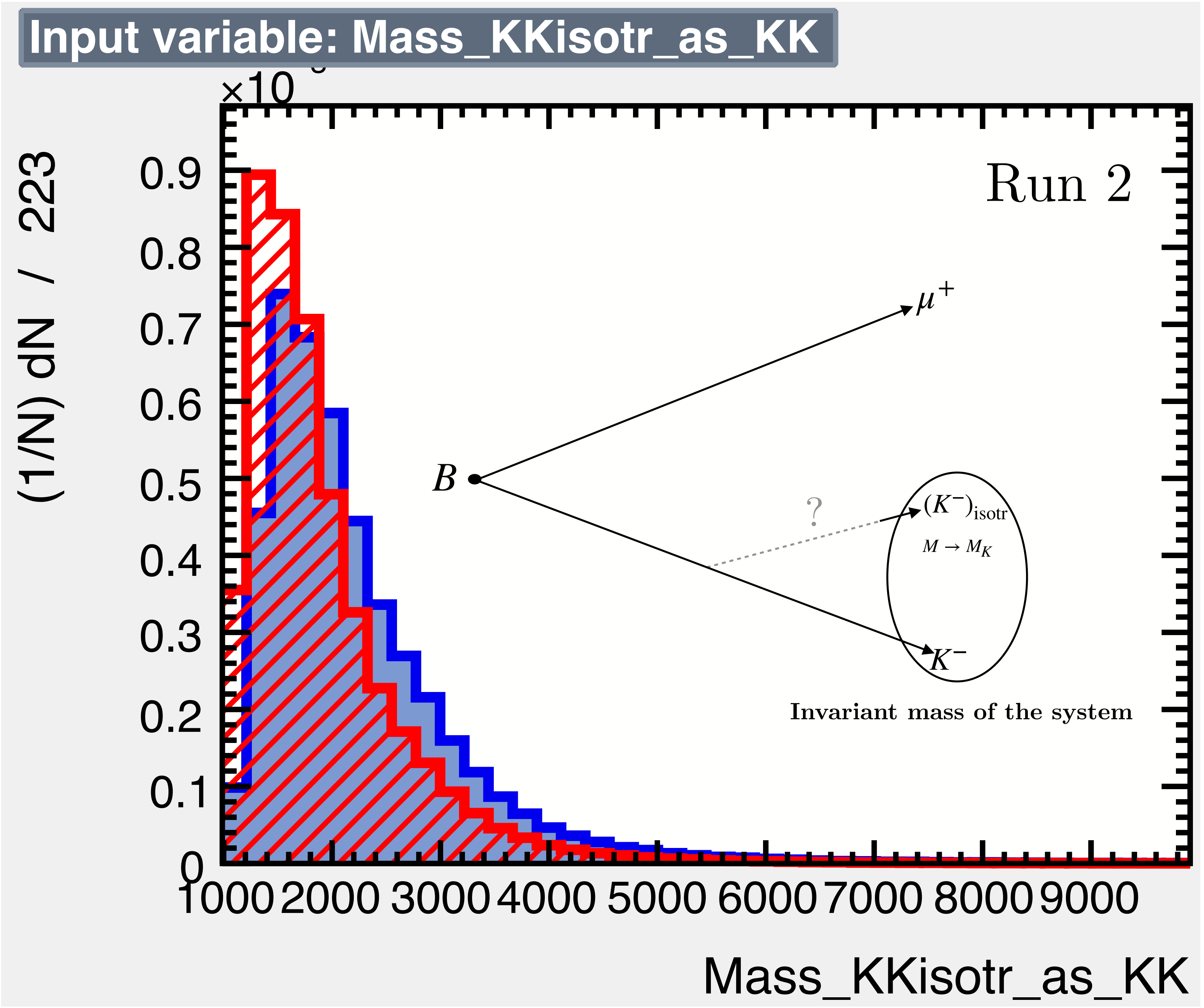
Good against $H_b \longrightarrow H_c(\to K^- X)\,\mu^+ X'$



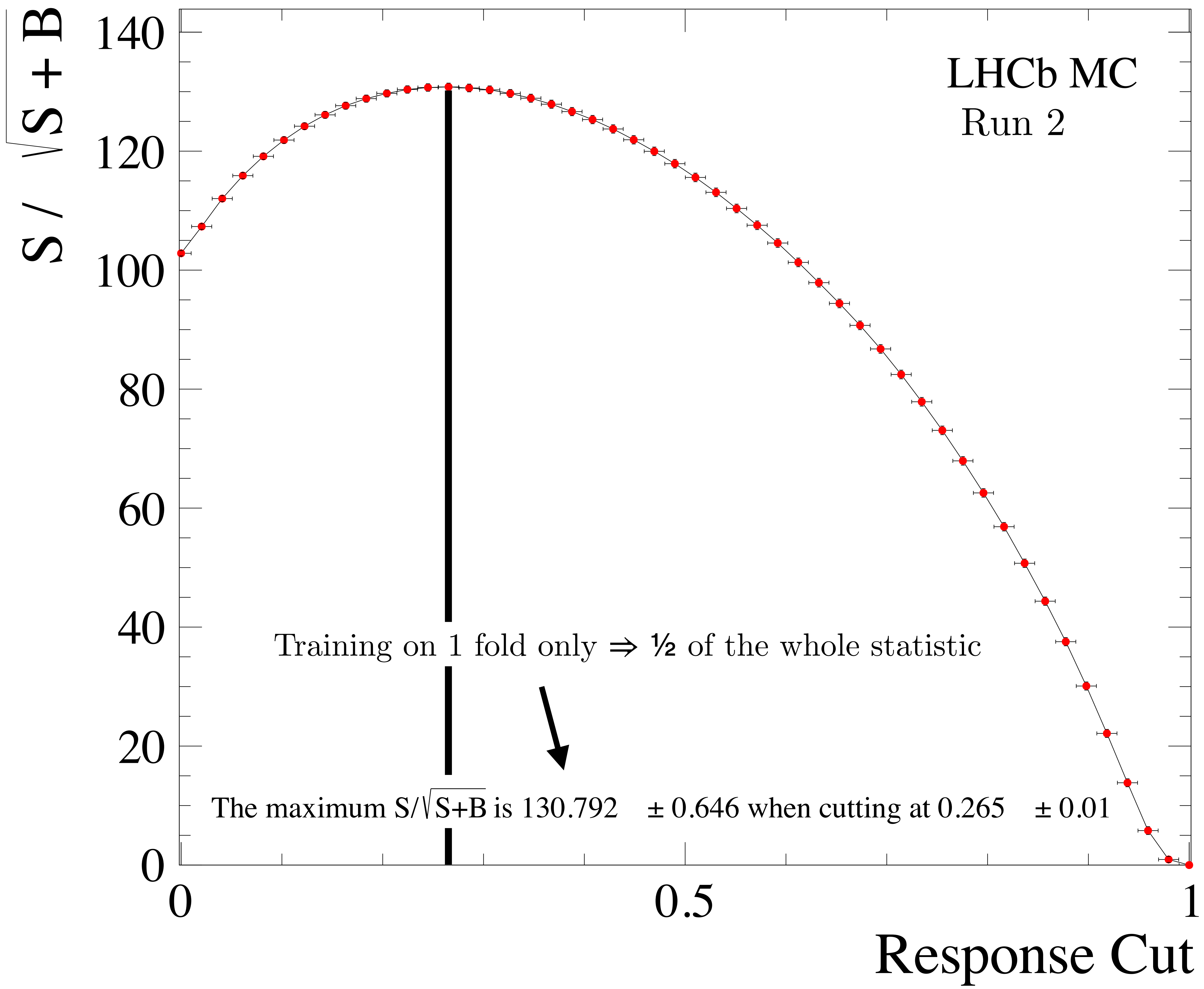
Good against $B^+ \longrightarrow c\bar{c}(\to \mu\mu)\,K^+ X$

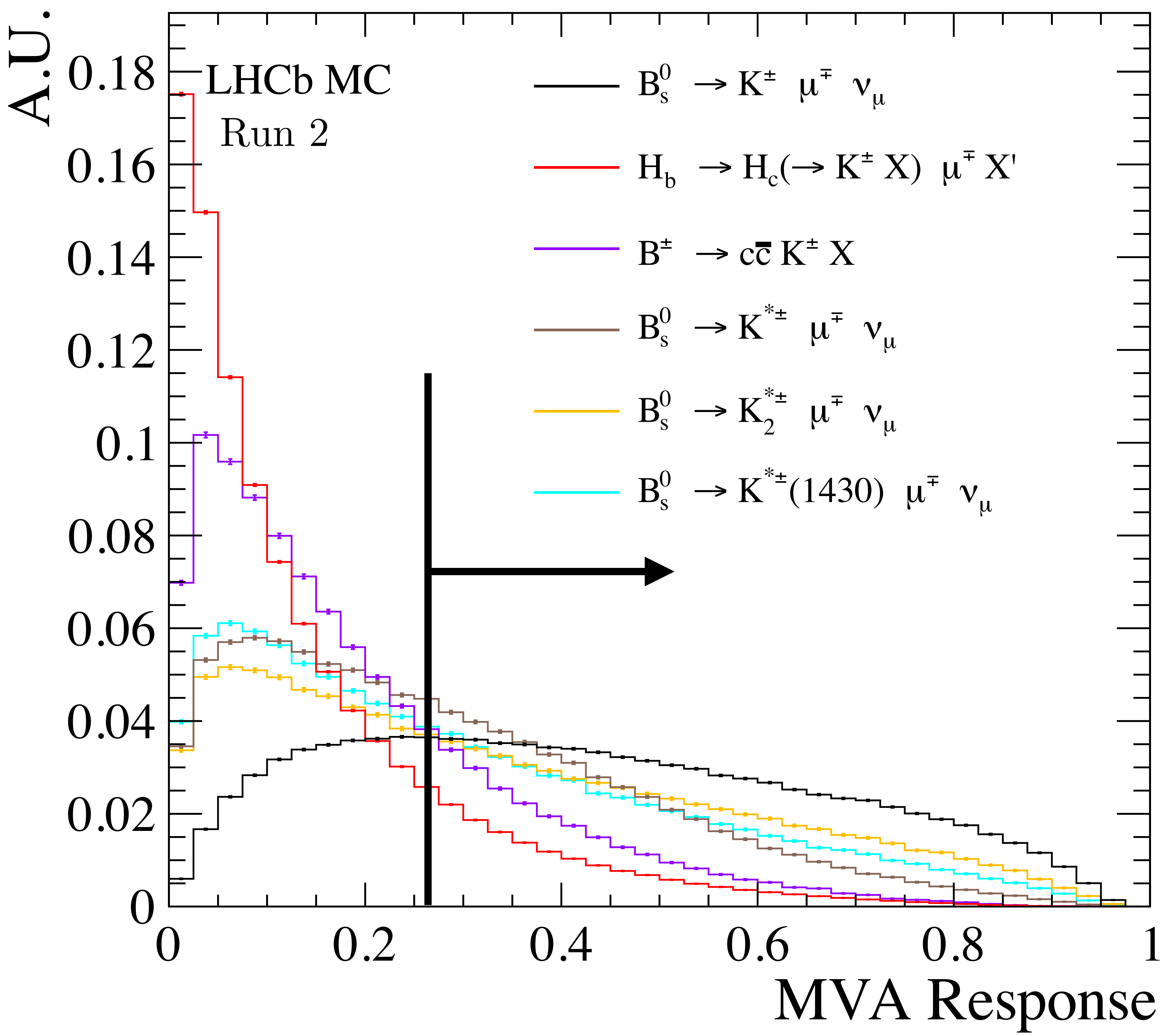


Good against $B_s^0 \to K^{*-}(K^-\pi^0)\mu^+\nu_\mu$



# Physical background discrimination





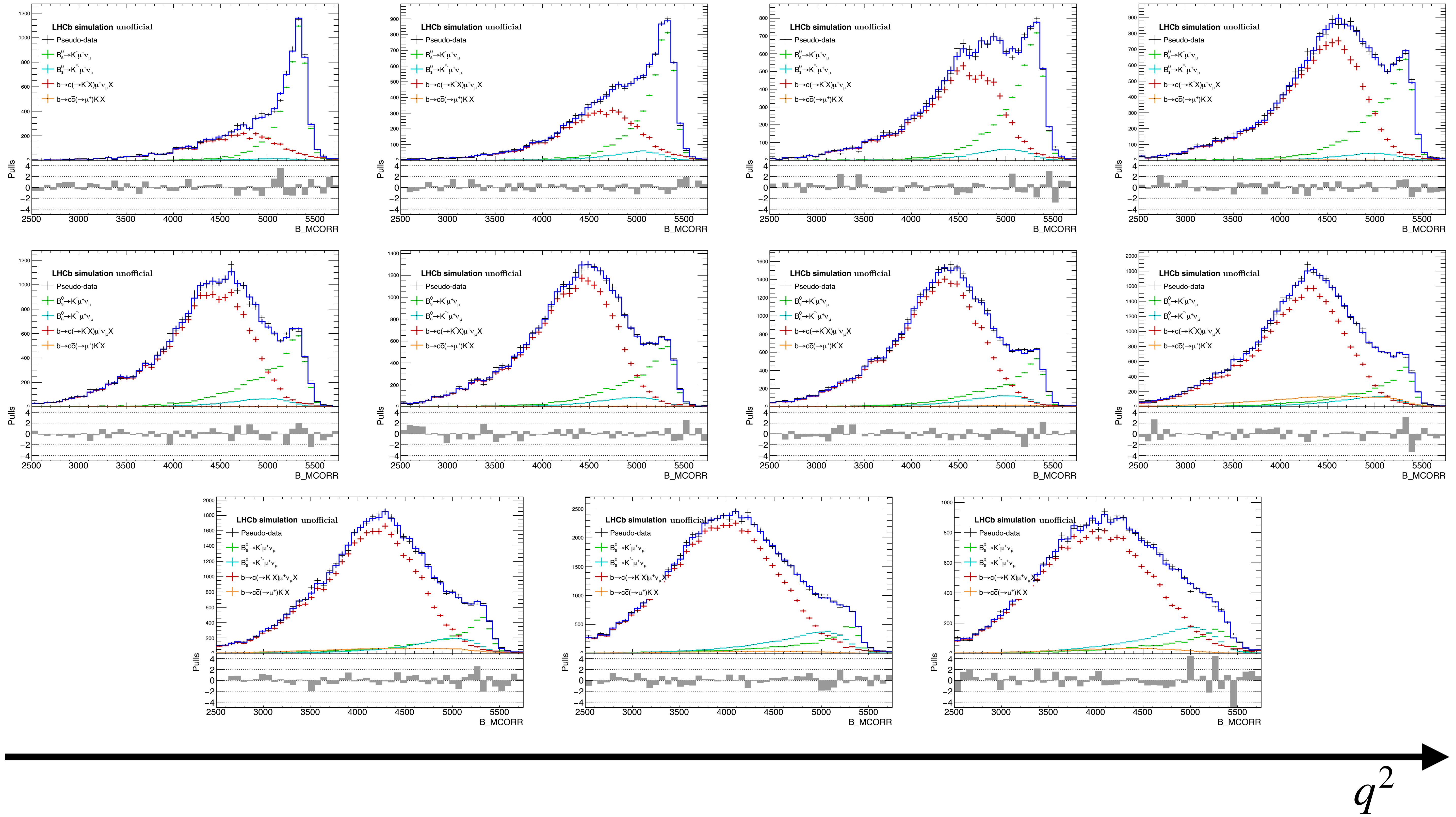
⇒ Significance increased by ∼ 27 % wrt Run1 MVA selection

# $B_s^0 \to K^-\mu^+\nu_\mu$ signal fit

- Maximum-likelihood fit in HistFactory framework
- Simultaneous in $q^2$ bins and three data-taking years. Bins optimization not final.

Toy MonteCarlo with signal and background contributions (Last bin splitted in two sub-bins with equal statistics)

Davide Fazzini



# Conclusion & Outlook

- ❖ $V_{ub}$ measurement in $B_s^0 \to K^-\mu^+\nu_\mu$ decays is being updated using **Run 2** data

  ⇒ Expected **improvements** from **higher data sample** and enhanced analysis

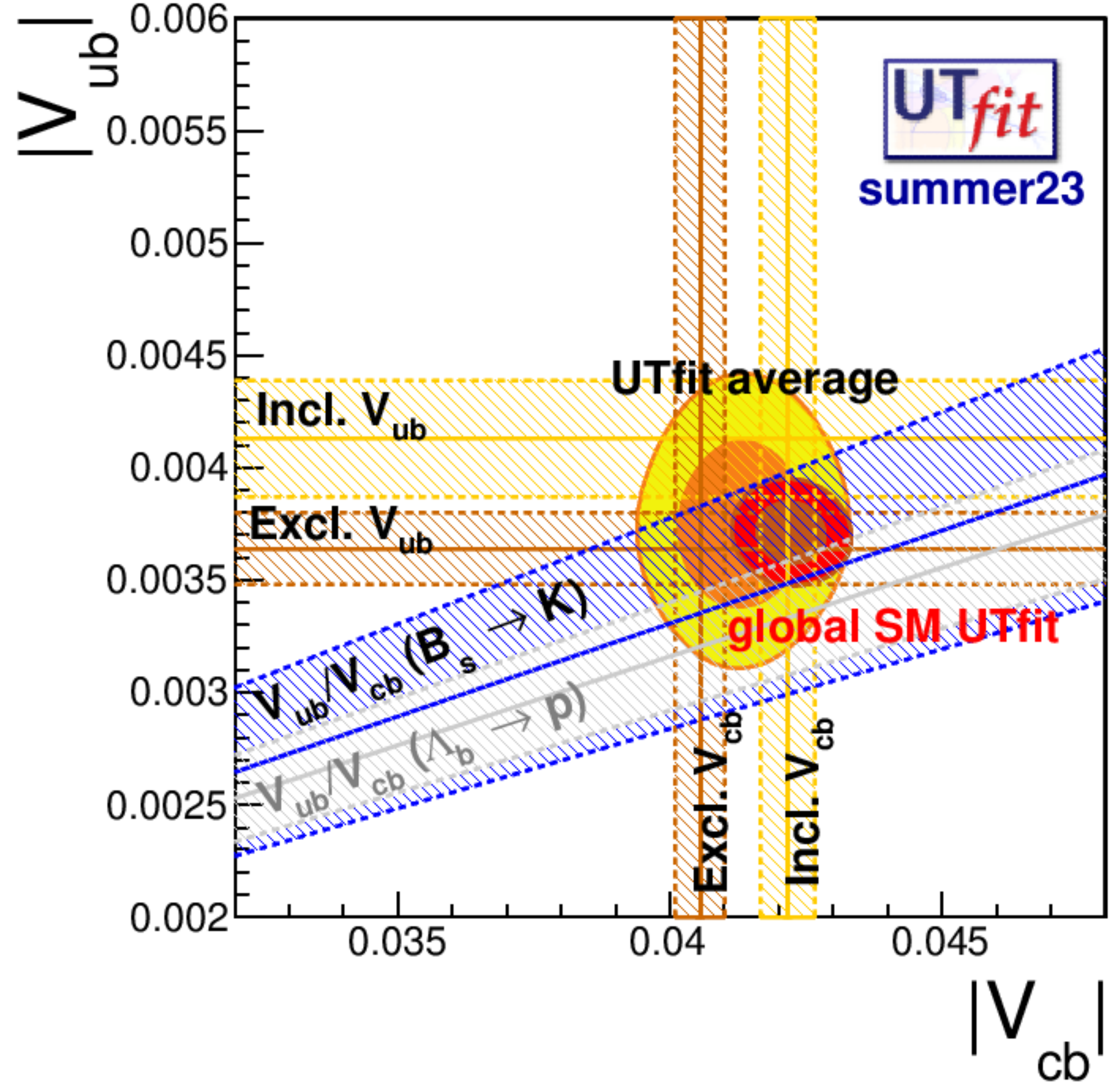
- ❖ Taking into account **other contributions** (Mis-ID, Combinatronic, ...)

- ❖ Baseline **Form Factor scheme** to be determined (FLAG24 average?)

- ❖ $V_{ub}$ measurement in $B^+ \to \rho^0(\pi^+\pi^-)\mu^+\nu_\mu$ also expected with Run 2 data

# Back-Up

# More recent state on $V_{(u/c)b}$



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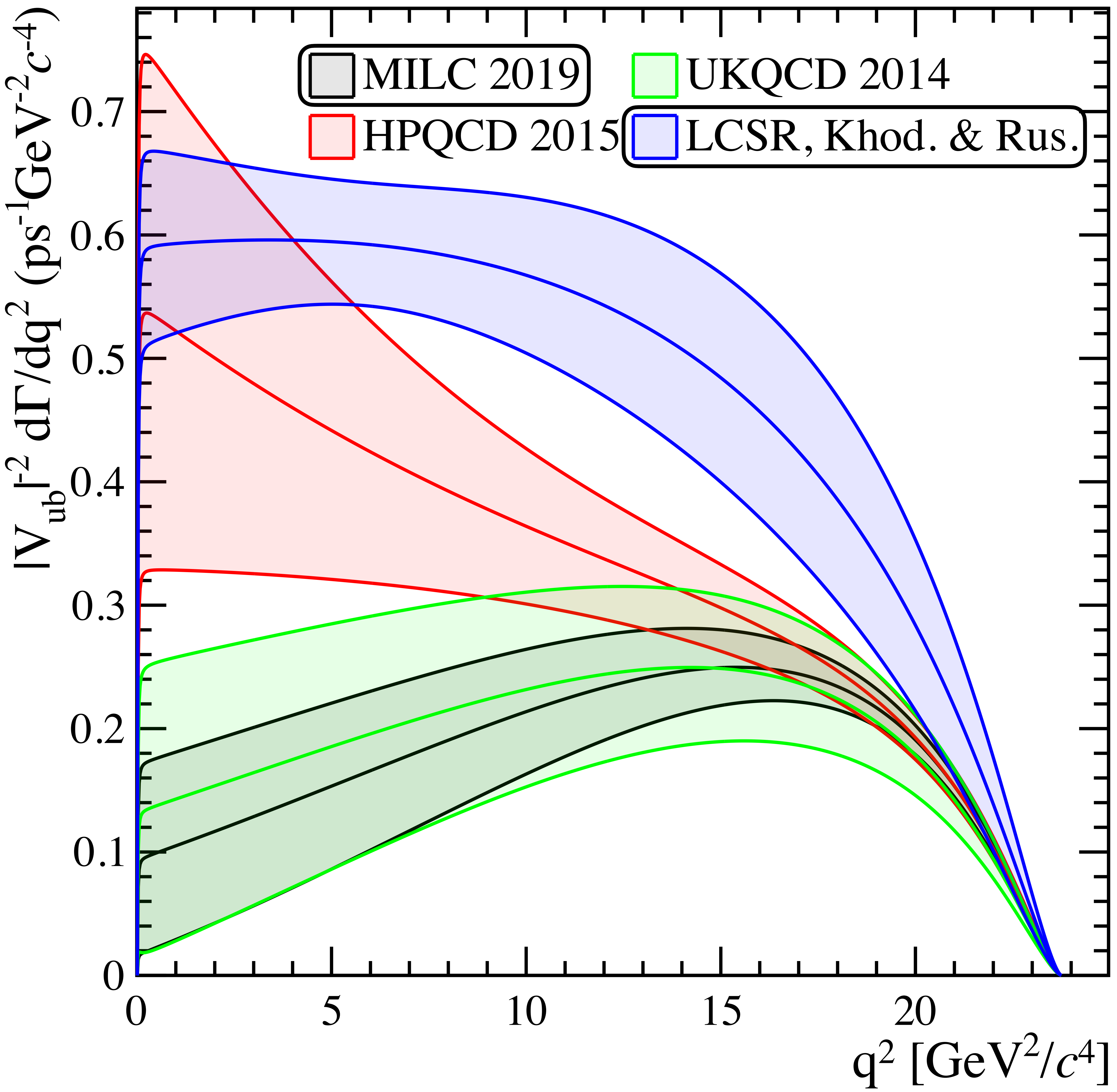
# Form Factors used for the Run 1 analysis



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# Relative systematic uncertainties on $\mathscr{B}(B_s^0 \to K^-\mu^+\nu_\mu) \big/ \mathscr{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)$

| Uncertainty | All $q^2$ | low $q^2$ | high $q^2$ |
|---|---|---|---|
| Tracking | 2.0 | 2.0 | 2.0 |
| Trigger | 1.4 | 1.2 | 1.6 |
| Particle identification | 1.0 | 1.0 | 1.0 |
| $\sigma(m_{\text{corr}})$ | 0.5 | 0.5 | 0.5 |
| Isolation | 0.2 | 0.2 | 0.2 |
| Charged BDT | 0.6 | 0.6 | 0.6 |
| Neutral BDT | 1.1 | 1.1 | 1.1 |
| $q^2$ migration | – | 2.0 | 2.0 |
| Efficiency | 1.2 | 1.6 | 1.6 |
| Fit template | $^{+2.3}_{-2.9}$ | $^{+1.8}_{-2.4}$ | $^{+3.0}_{-3.4}$ |
| Total | $^{+4.0}_{-4.3}$ | $^{+4.3}_{-4.5}$ | $^{+5.0}_{-5.3}$ |

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