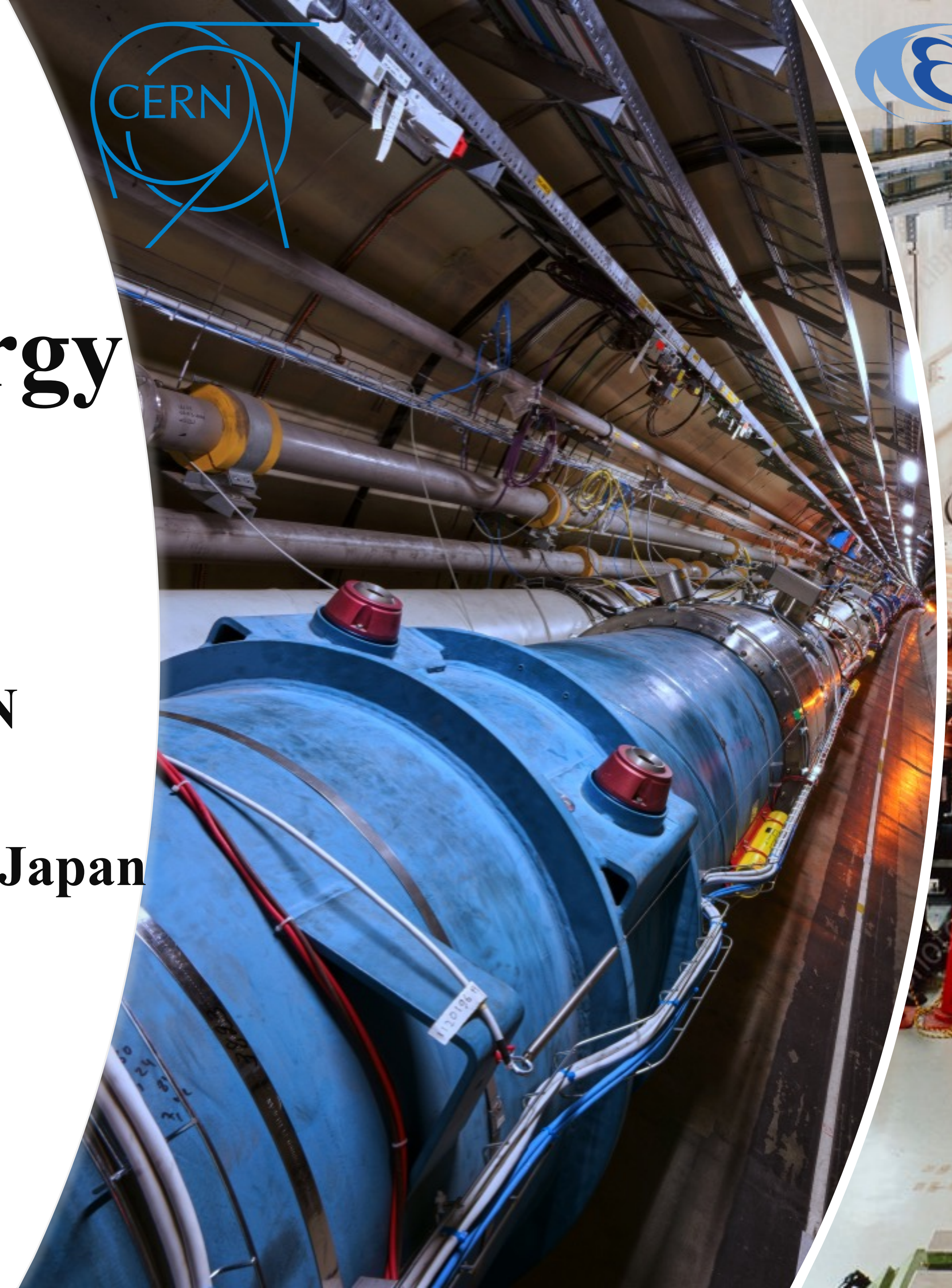
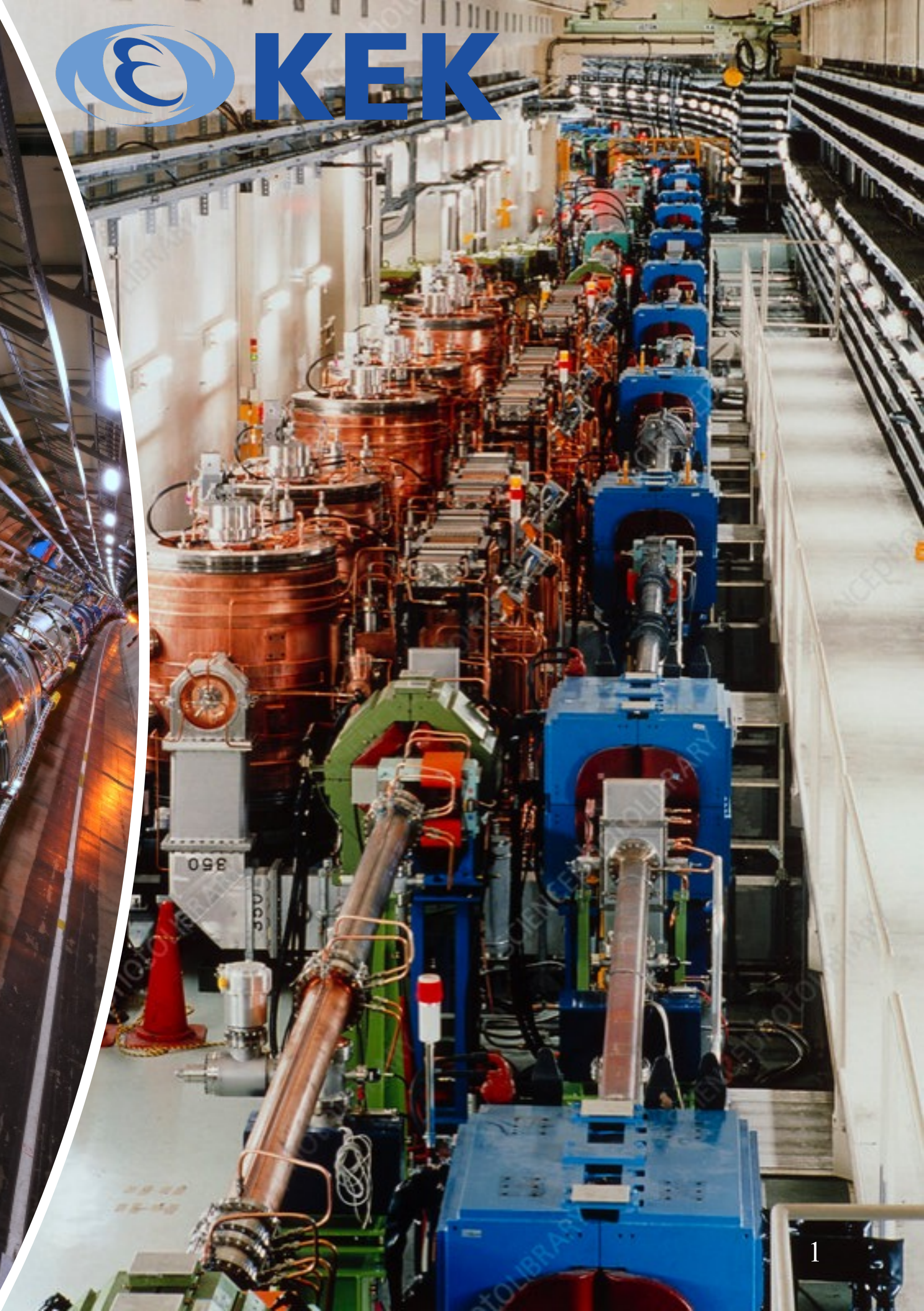
Missing energy B decays @ LHCb

Abhijit Mathad, CERN
On behalf of LHCb

Belle II Physics Week, Japan



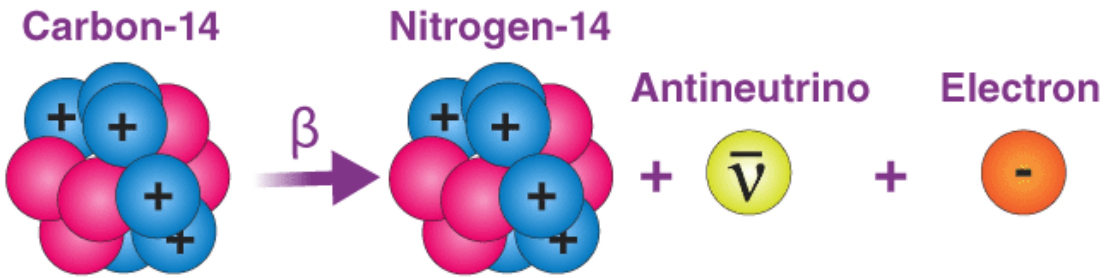


Talk content

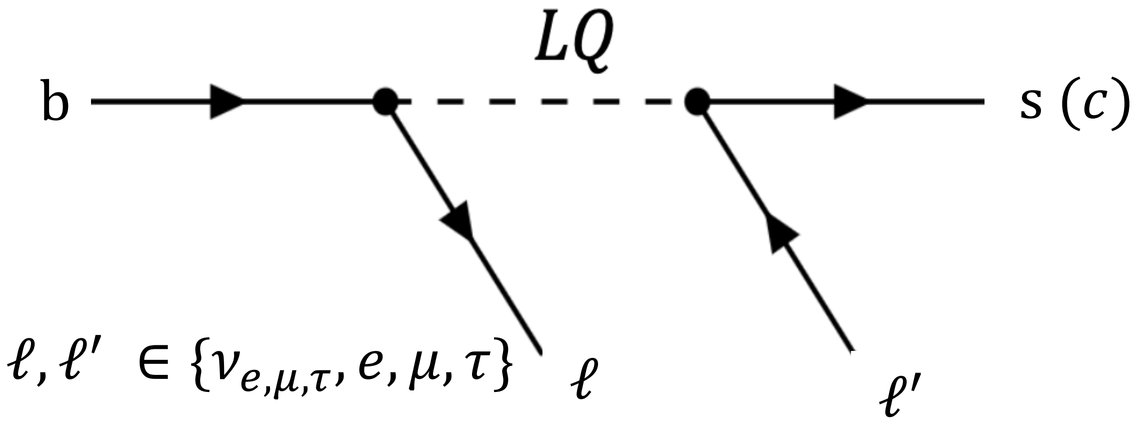
- Common techniques in missing energy decays.
- Analyses this year (newest to oldest):
  - (Rare) Searches for $B^0 \to h^+h^-\tau^+\tau^-$.
  - (Very rare) LFV search: $B^0 \to K^{*0}\tau^\pm e^\mp$.
  - (Abundant) Evidence of $B^- \to D^{**0}\tau^-\bar{\nu}$.
- Conclusions

Missing energy decays have evolved

First missing-energy β decays: **neutrino discovery, parity violation, weak theory**, and still a BSM probe (e.g. KATRIN).



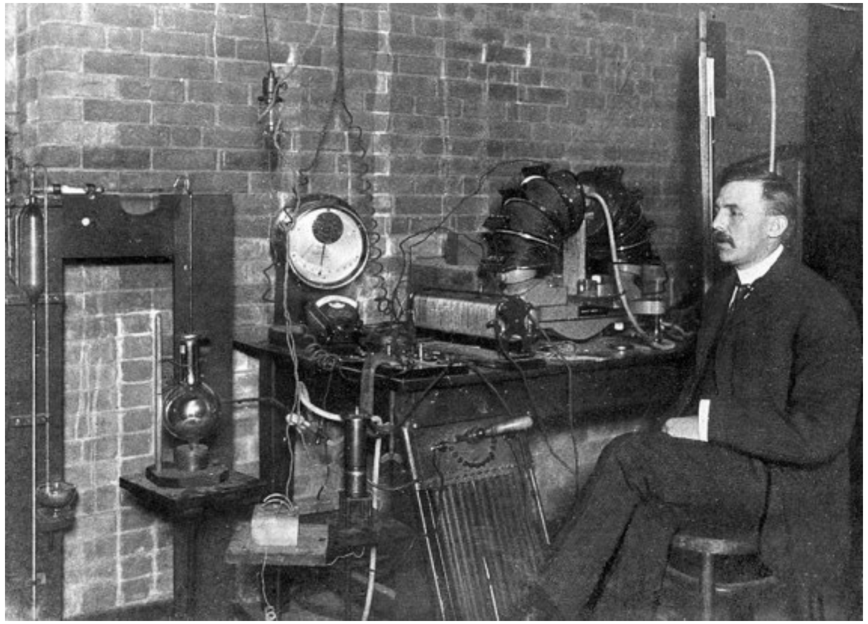
Can **heavy flavour missing energy** decays reveal new physics?



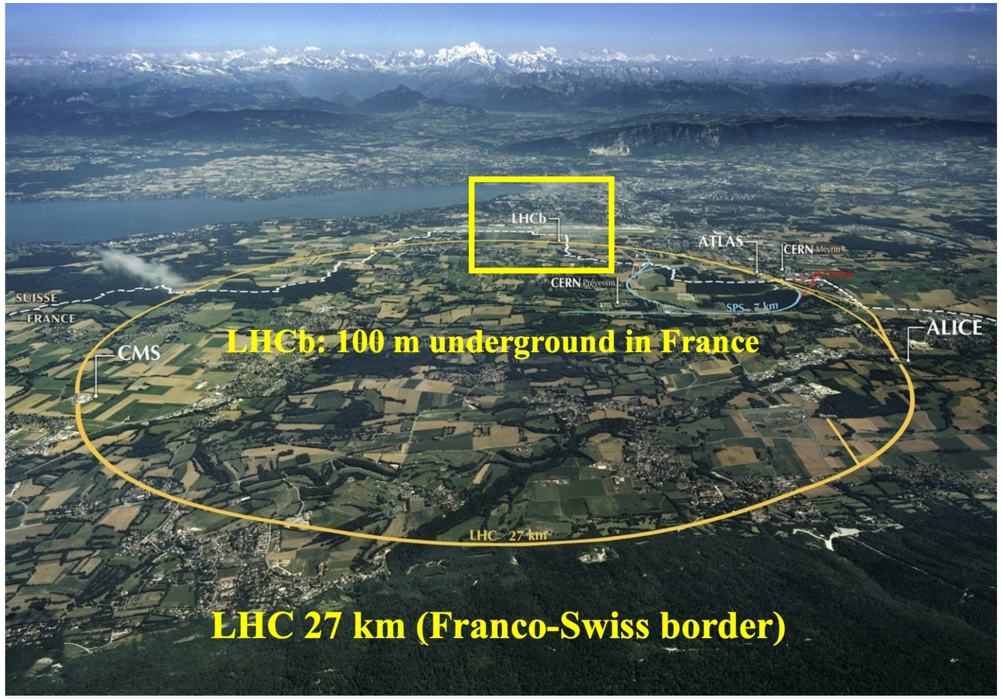
Current tensions: $R(D^{(*)})$ **3.8σ**, $\mathrm{BF}(B^+ \to K^+ \nu\bar{\nu})$ **2.7σ**, $\mathrm{BF}(K^+ \to \pi^+ \nu\bar{\nu})$ **1.7σ**!

Missing energy experiments have evolved

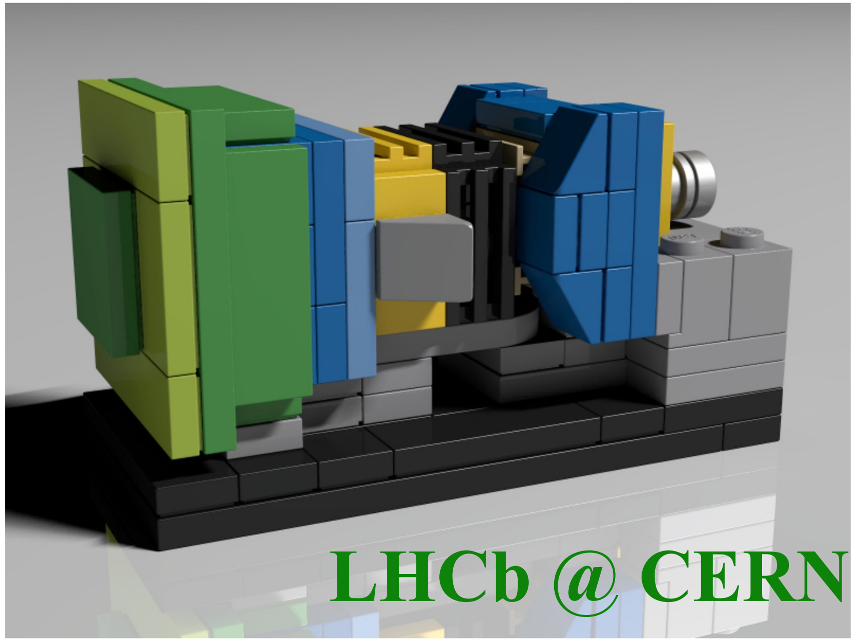
First missing energy, β decay, experiments (1890s)



Facilities hosting heavy flavour experiments (Now)



Up to 2,808 proton bunches per beam collide every 25 ns at four interaction points at $\sqrt{s} = 13.6$ TeV.

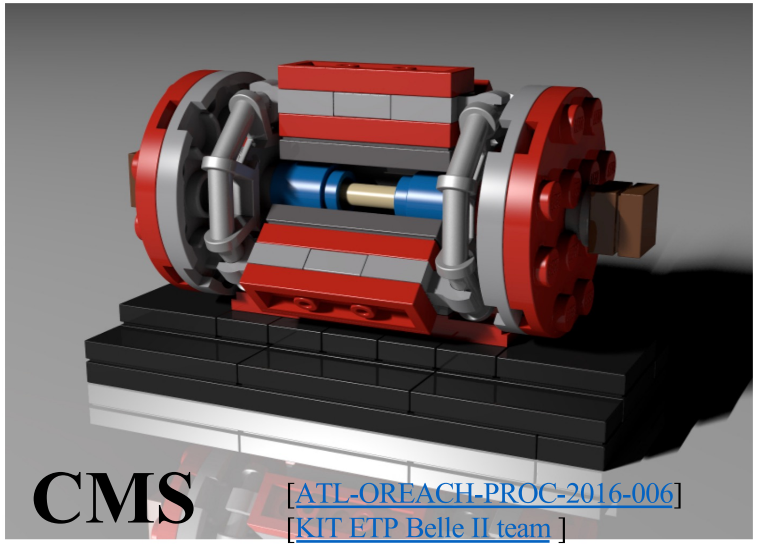


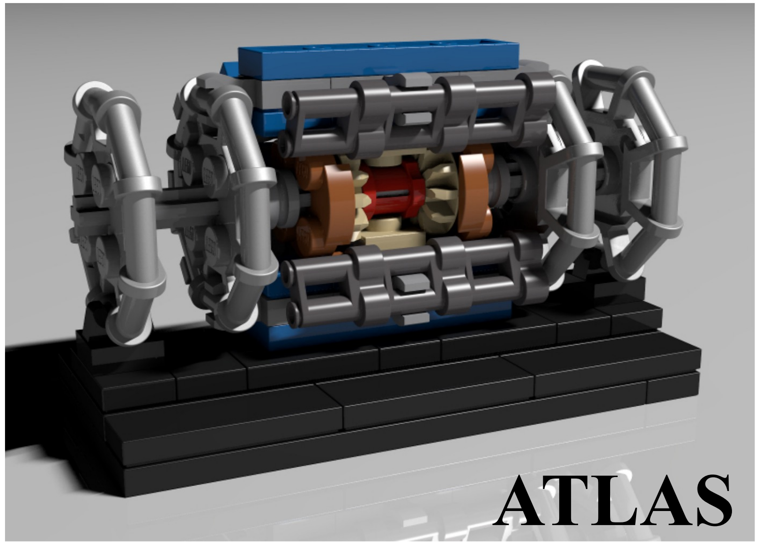
One such collision point is LHCb.

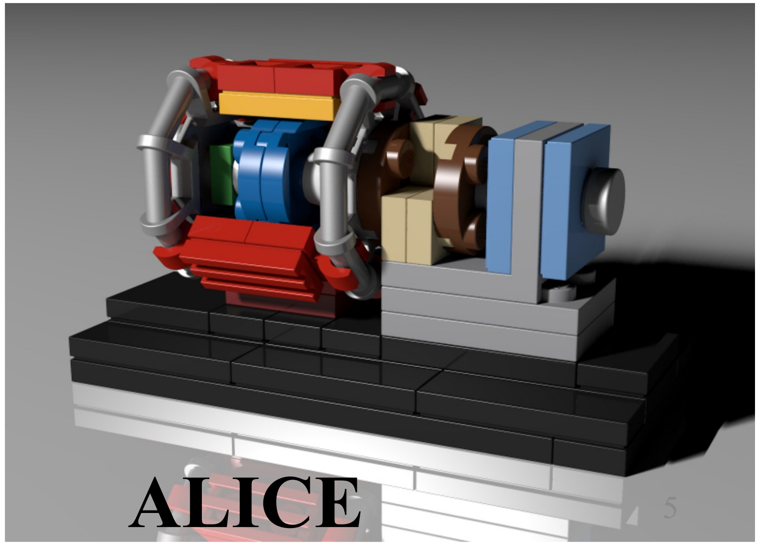
- Since its 1998 proposal, LHCb has become a **general-purpose forward detector**.
- Has rich missing-energy B decay programme from abundant to rare decays.

High-pT signatures, but **also do missing-energy B decays (e.g. $R(J/\psi)$ @ CMS)**

Heavy ion physics



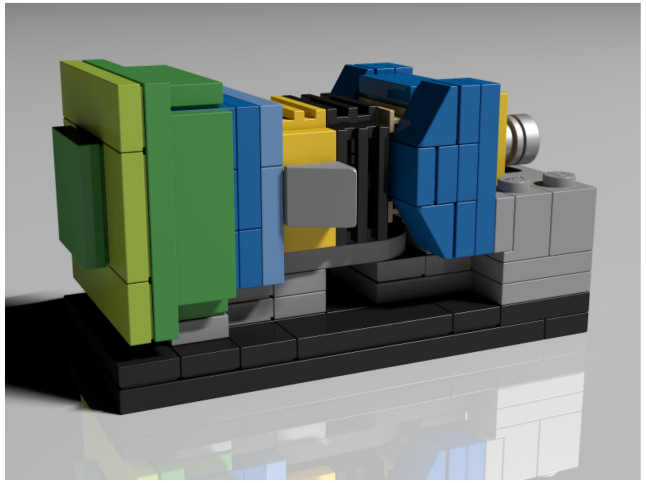




[ATL-OREACH-PROC-2016-006]
[KIT ETP Belle II team]

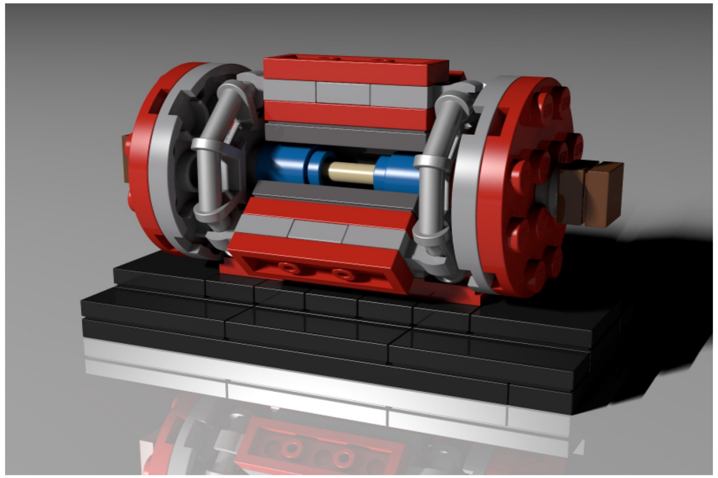
Best experiment for missing-energy B decays?

LHCb @ CERN



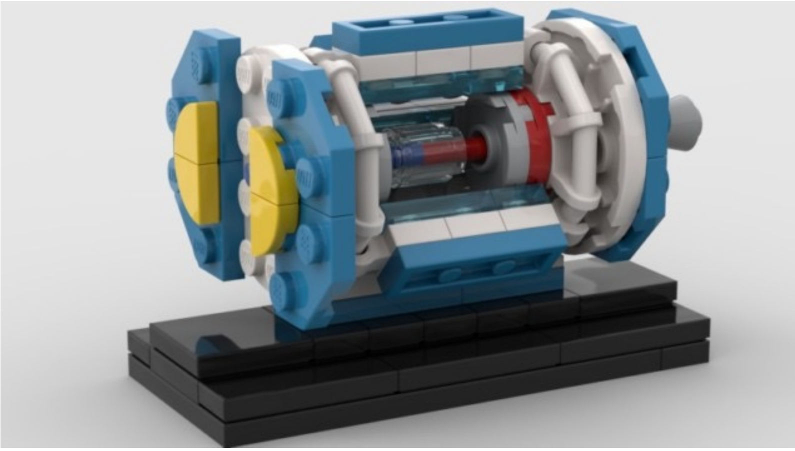
Vs

ATLAS/CMS @ CERN



Vs

Belle II @ KEK

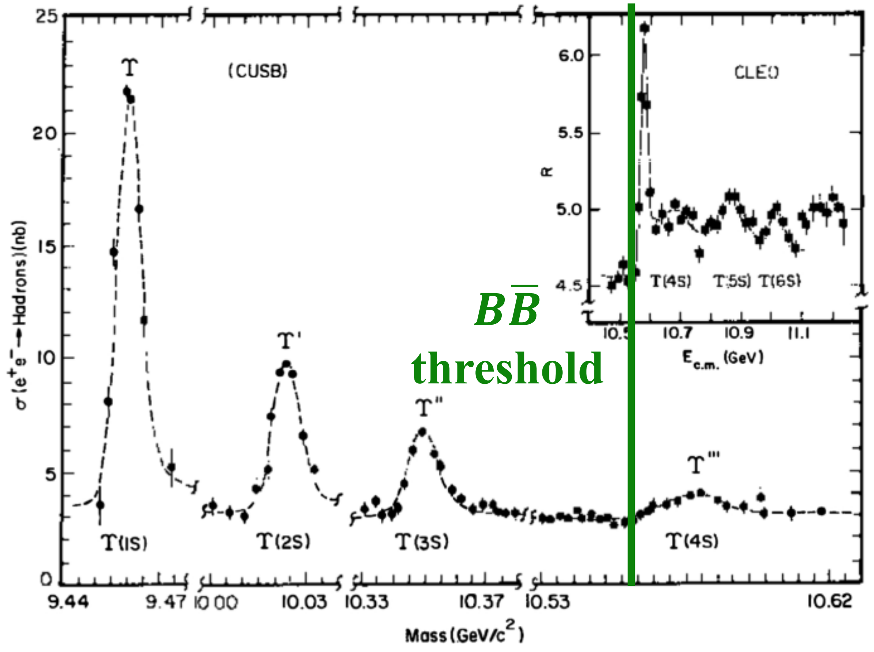


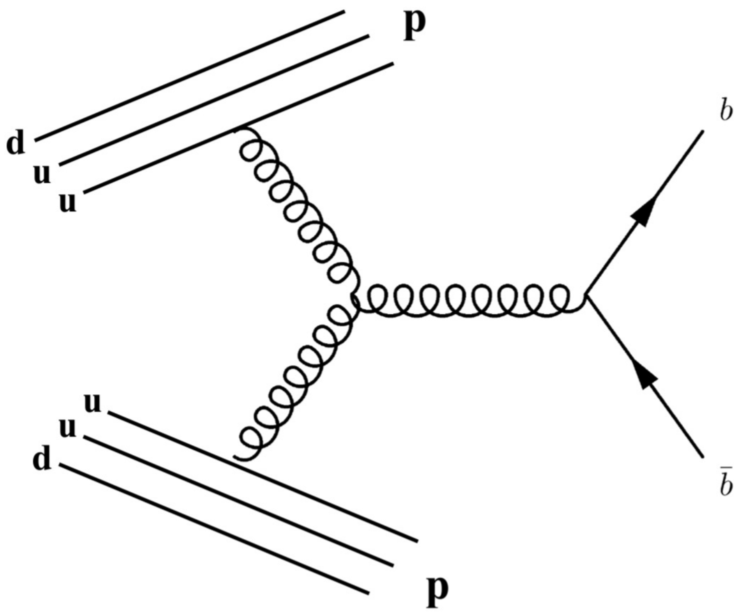
Who wins, you decide!

Ideal place is Belle II conditions

At Belle-II, $B\bar{B}$ produced via $e^+e^- \to \Upsilon(4S)$ ($\sqrt{s} = 10.58$ GeV)

At LHC, **95% of $b\bar{b}$ via gluon fusion** (pp collison @ $\sqrt{s} = 13.6$ TeV)

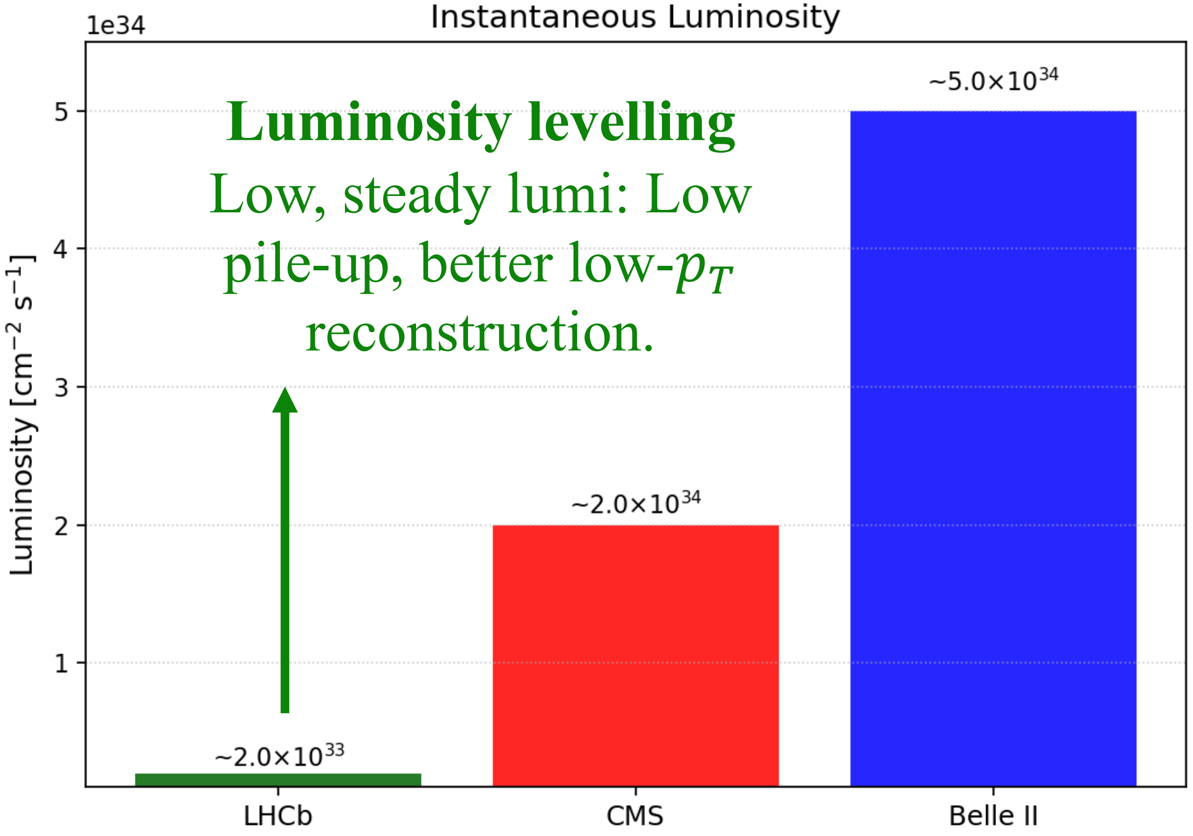


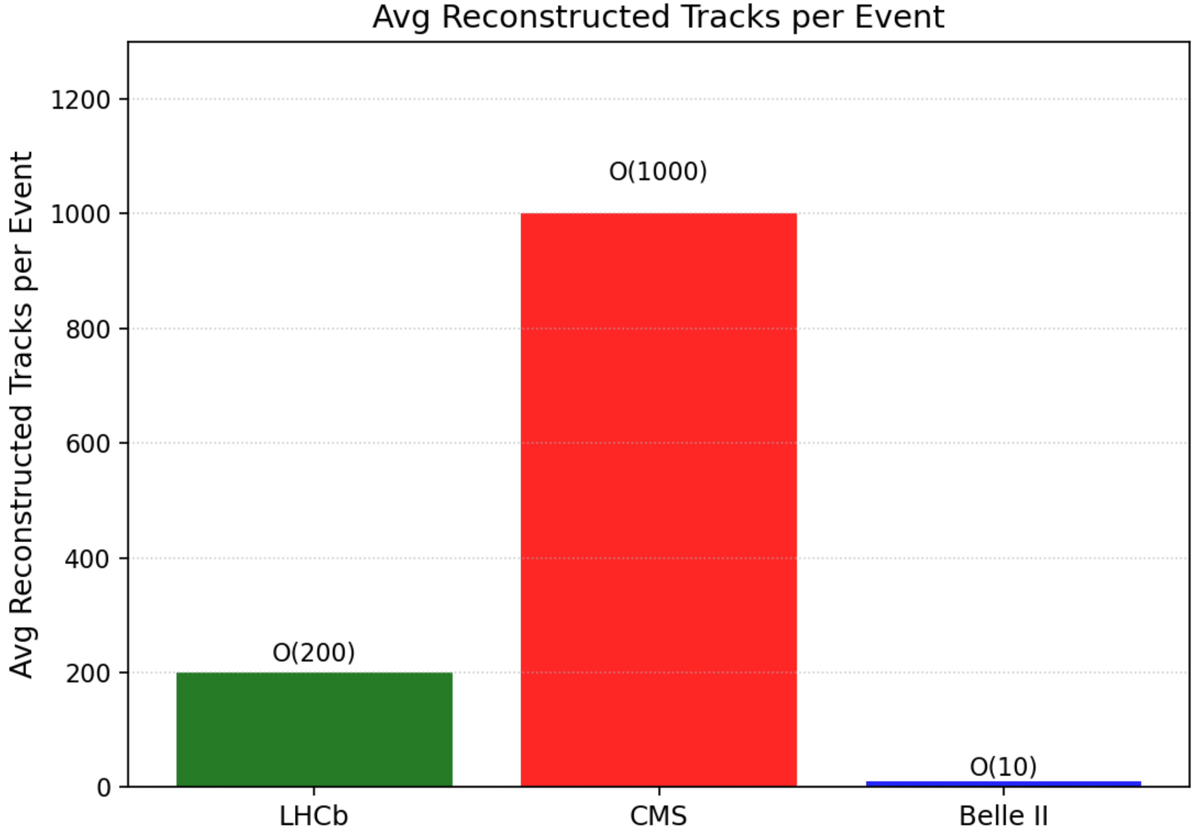


Fixed CoM energy!

How much proton momentum carried by gluon?

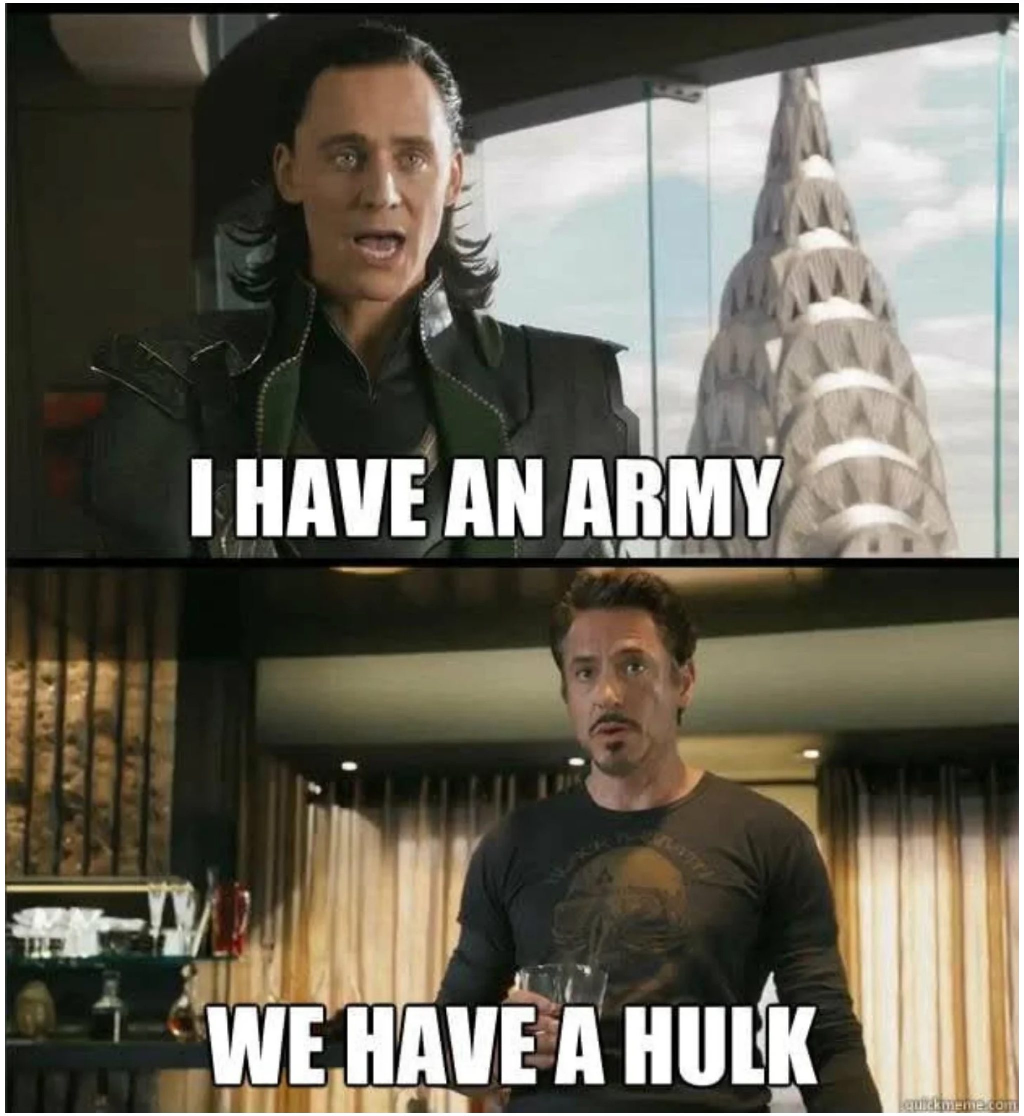
Ideal place is Belle II conditions

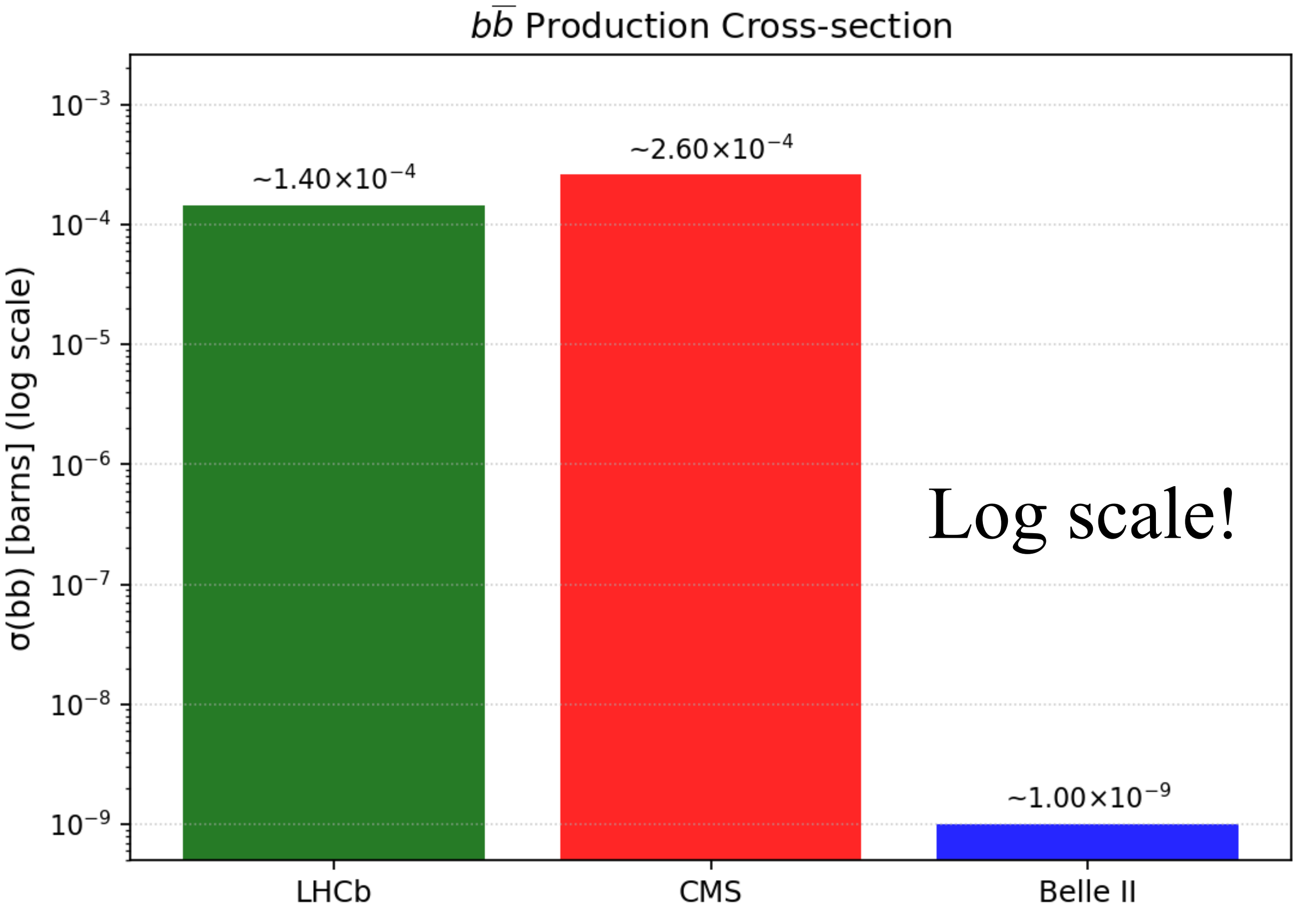




Belle II achieves large peak luminosities (**25× LHCb**), with clean reconstructed event (**factor 20 lower tracks per event than LHCb**).

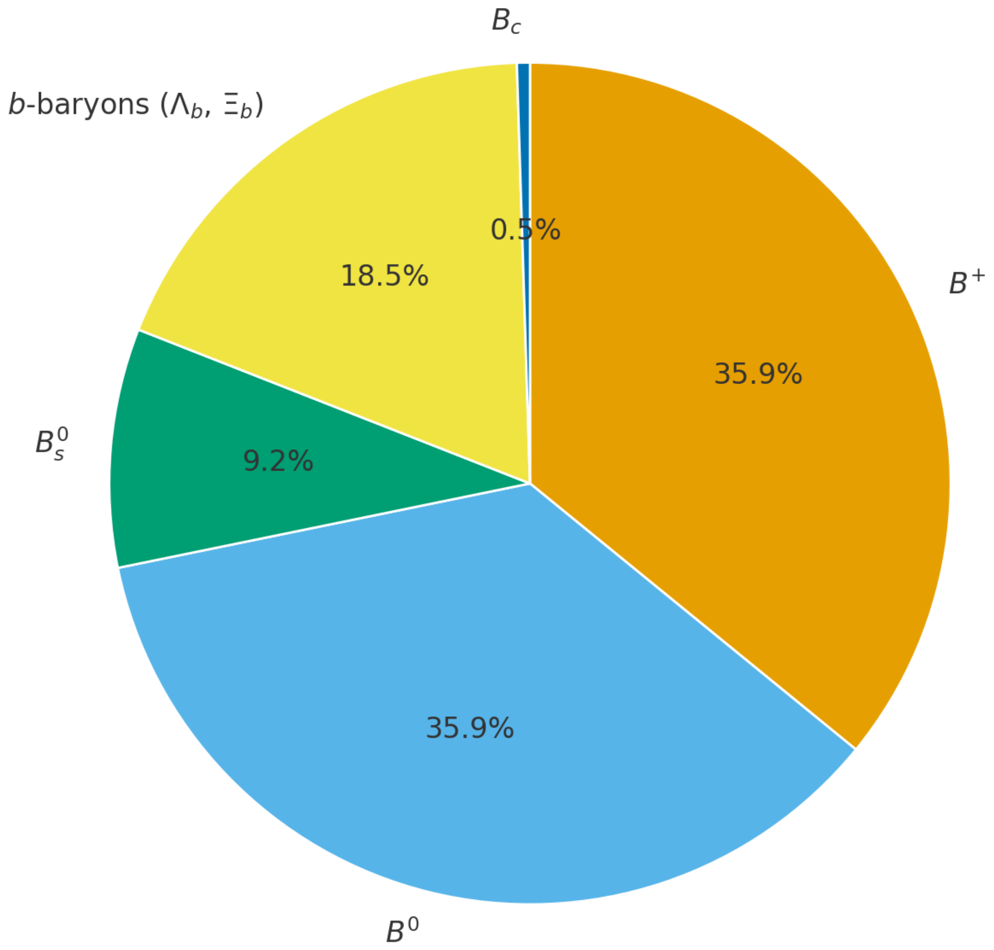
But…





$b\bar{b}$ production 5 orders of magnitude higher at LHC!

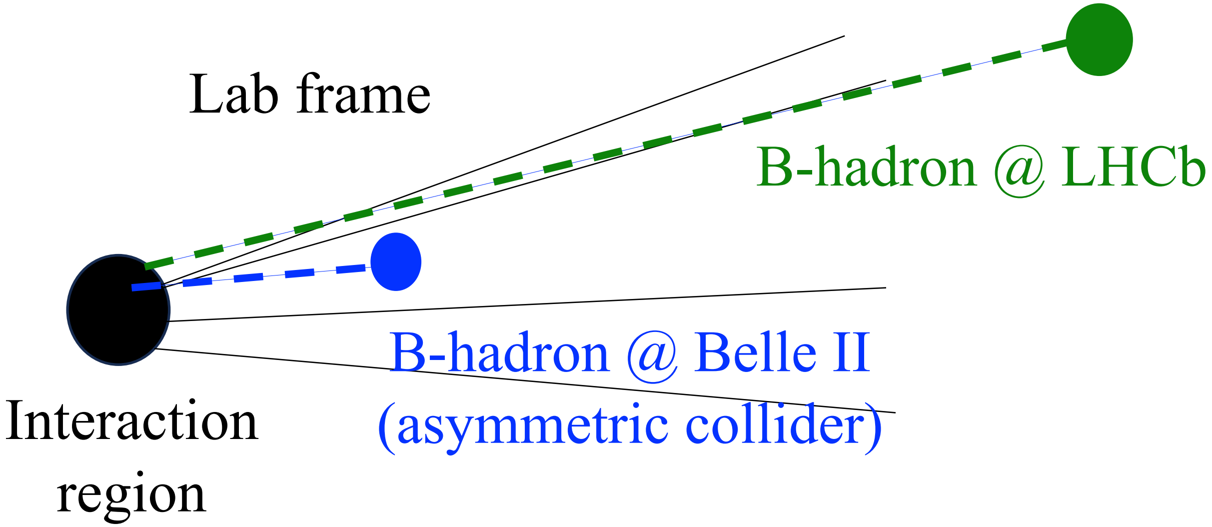
LHC produces different species of b-hadron



At Belle-II its $B^{\pm}$ or $\mathrm{B}^0/\bar{B}^0$.

Large boost and excellent vertexing/tracking

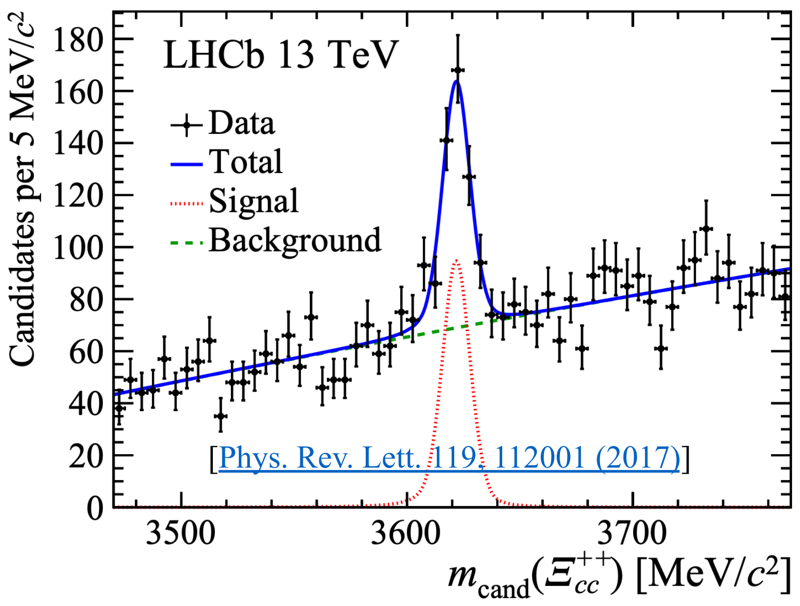
Large boosts @ LHC



Flight distance @ LHCb ~ 1 cm

Flight distance @ Belle II ~ 130 μm

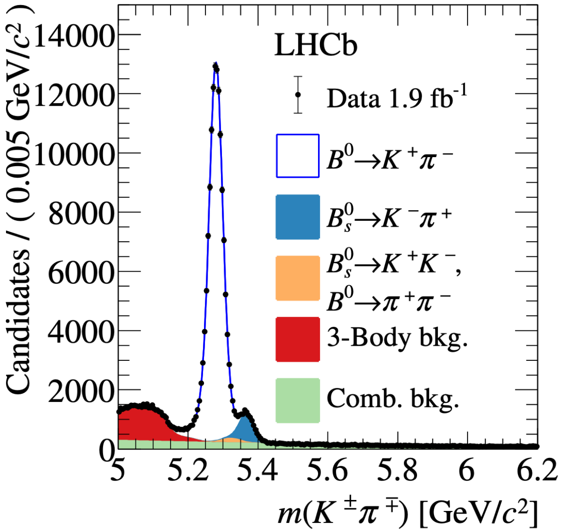
Power of vertexing and tracking



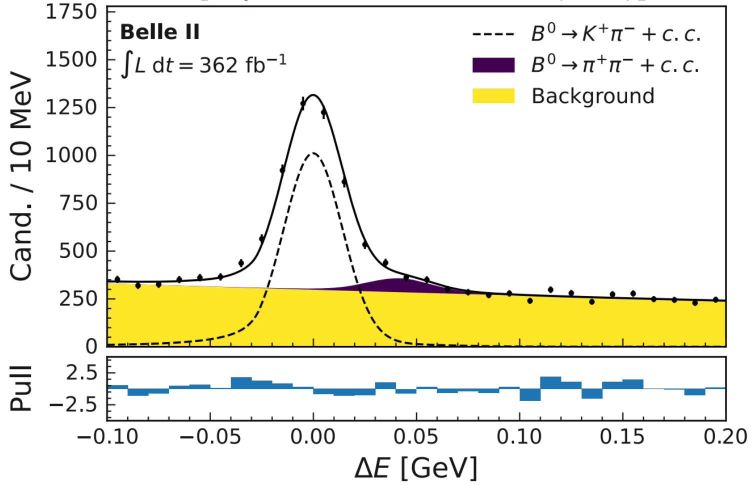
Allows to reconstruct particles (Ξ_c^{++}) with **lifetimes 6 × lower than B** ($\tau_B \sim 1.5\ ps$)!

Implications of large boosts + precise vertexing/tracking

[JHEP 03 (2021) 075]

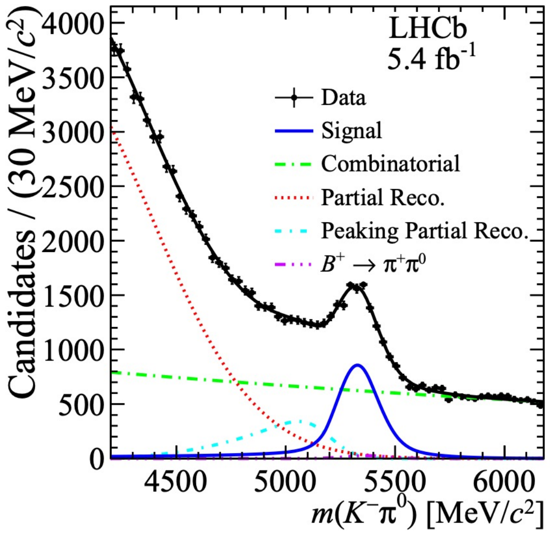


[Phys. Rev. D 109, 012001 (2024)]

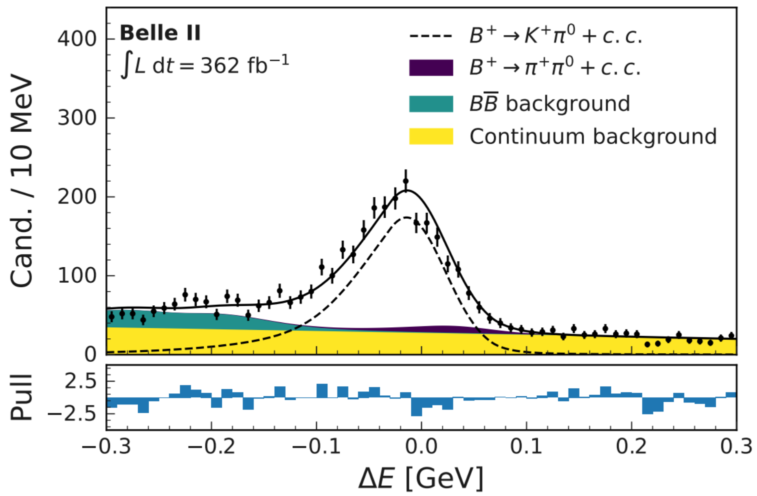


Excellent S/B for **fully reconstructed** decays.

[Phys. Rev. Lett. 126, 091802 (2021)]



[Phys. Rev. D 109, 012001 (2024)]

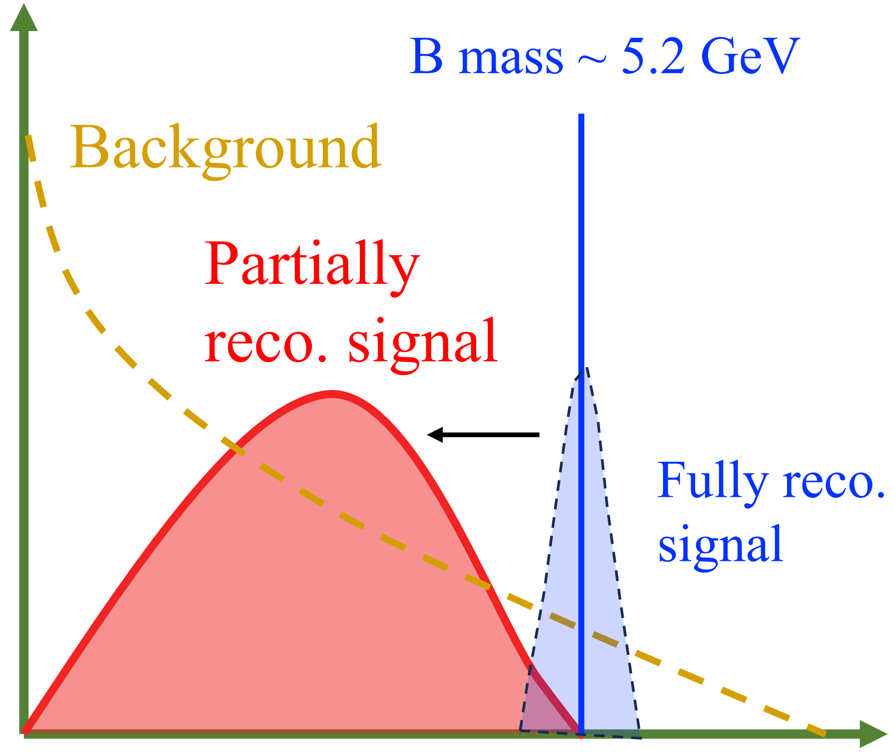


Still gives a good S/B for cases **without explicit B decay vertex**.

S/B much worse for missing energy decays

Missing particle: S/B very low.

How do we recover that lost energy?

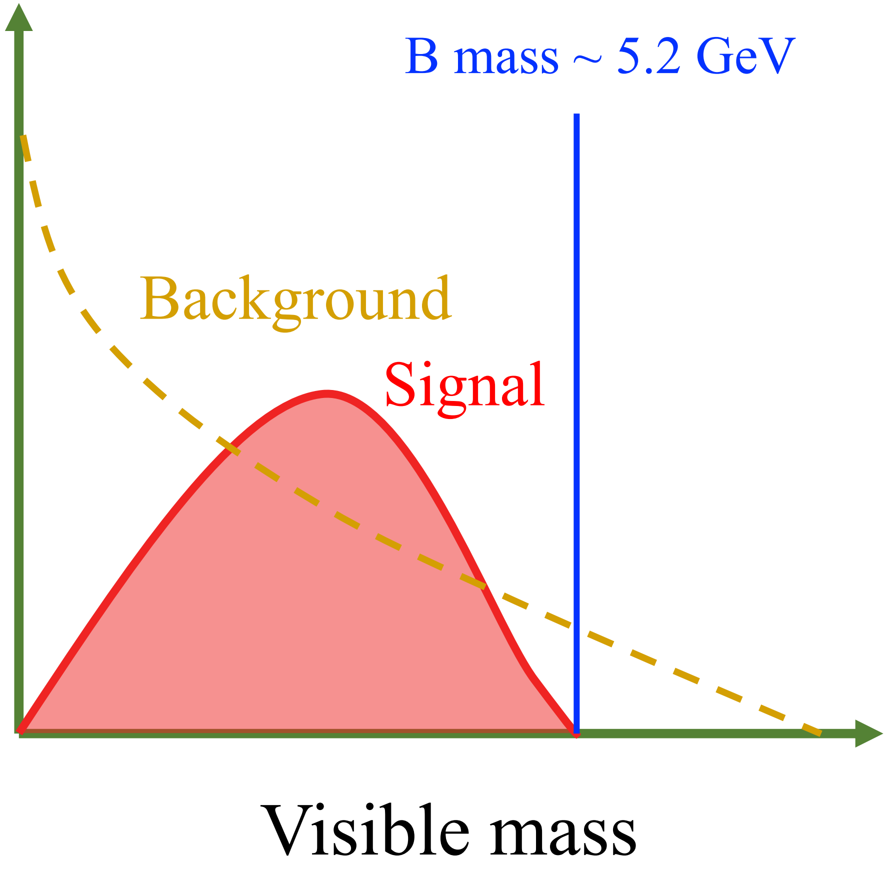


Visible mass

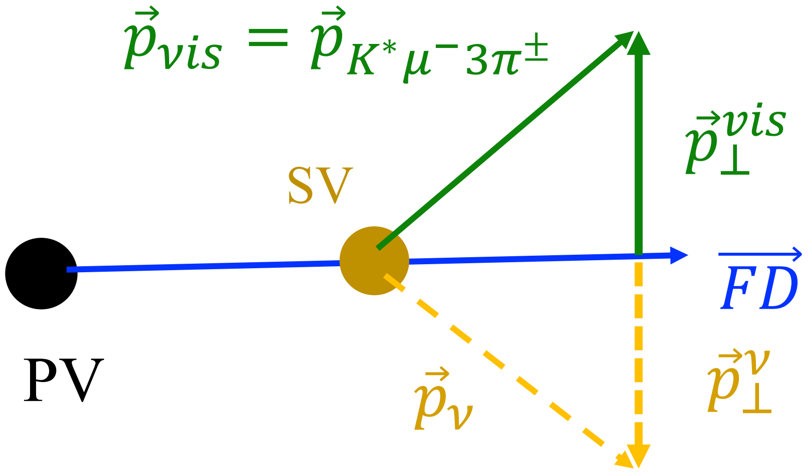
Technique 1: How do we recover a better S/B?

Missing particle: Peaks below B mass

How do we recover that low energy?



Define corrected mass

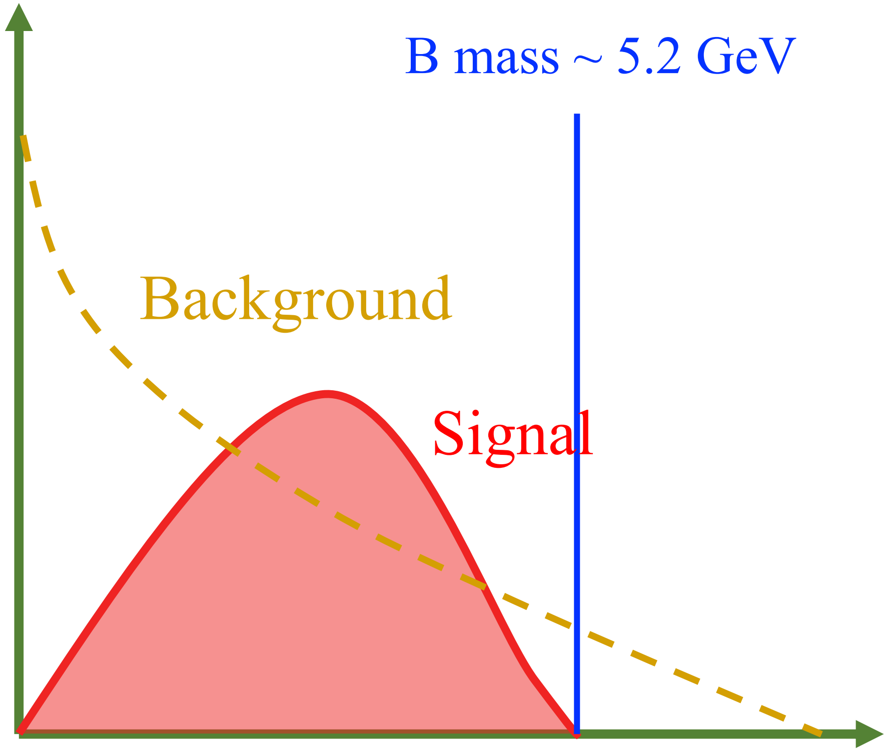


$\vec{\boldsymbol{p}}_\perp^{\boldsymbol{vis}} = -\vec{\boldsymbol{p}}_\perp^{\boldsymbol{\nu}}$ **Assume** $\left|\boldsymbol{p}_\parallel^{\boldsymbol{\nu}}\right| = \mathbf{0}$

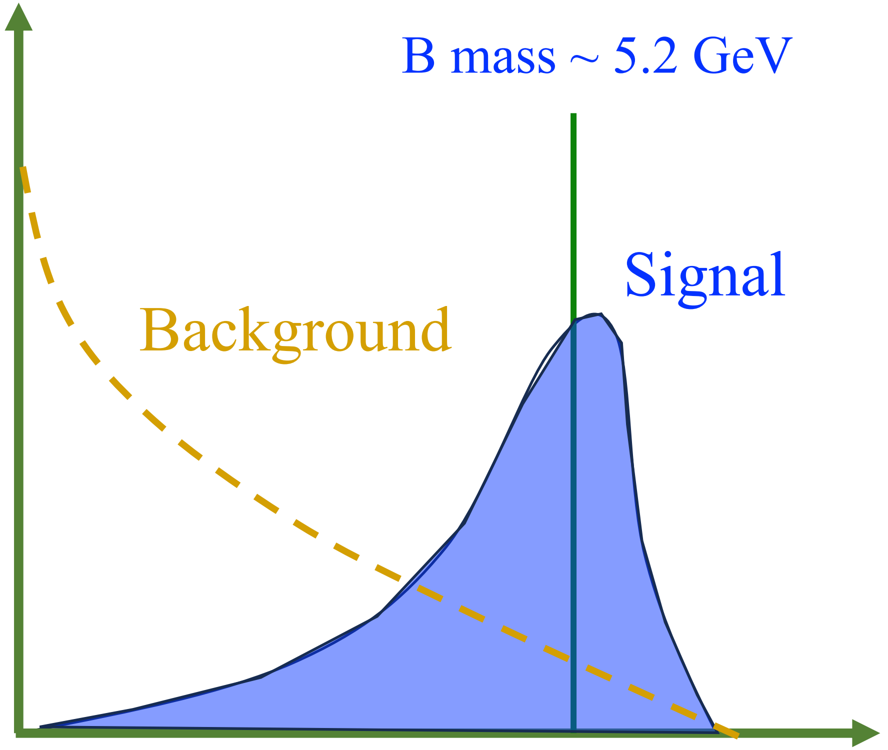
$$m_{corr} = \sqrt{M_{vis}^2 + \left|p_\perp^{vis}\right|^2} + \left|p_\perp^{vis}\right|$$

How do we recover a better S/B?

Missing particle: Peaks below B mass
How do we recover that low energy?



Corrected mass provides a much better S/B!
(used in LFV $B^0 \to K^{*0}\tau^+\mu^-$)

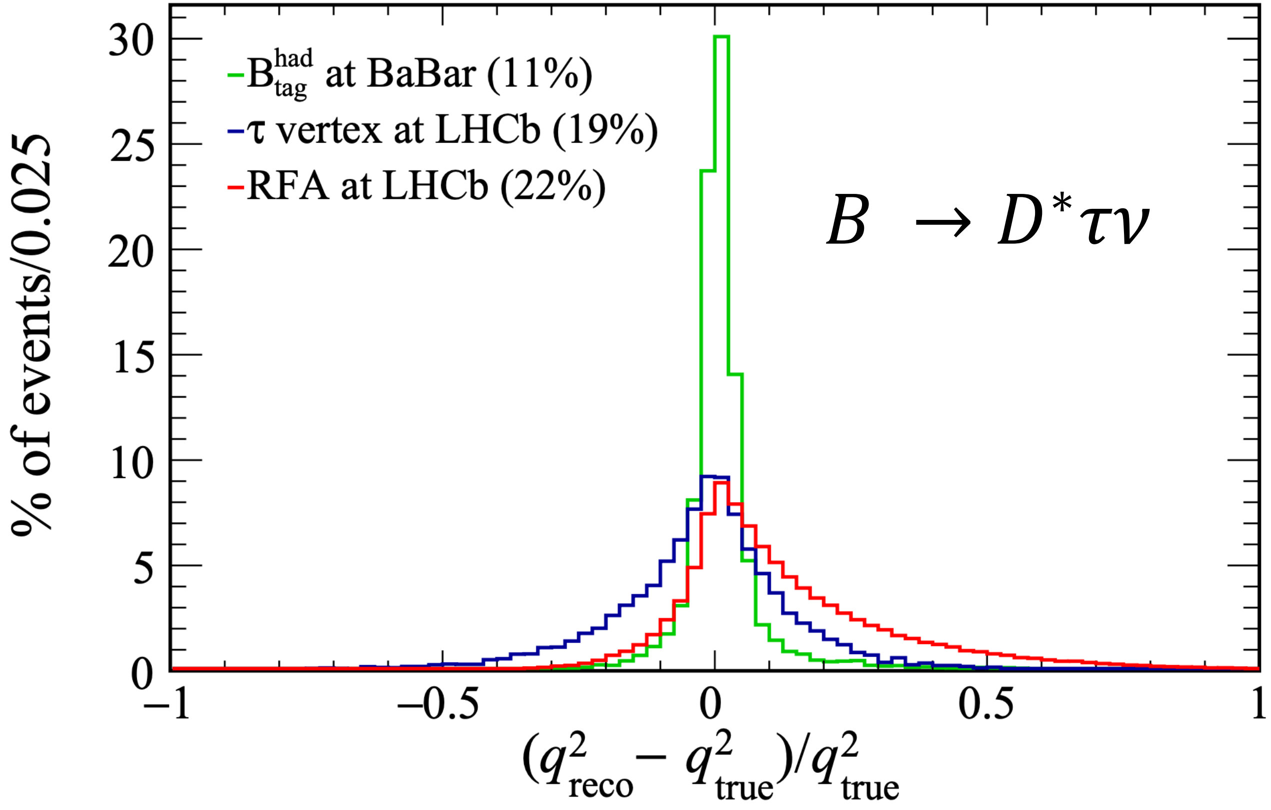


Technique 2: Kinematic reconstruction

Reconstructing B momentum, q^2, and angles depend on **decay-specific kinematic and geometric constraints**.

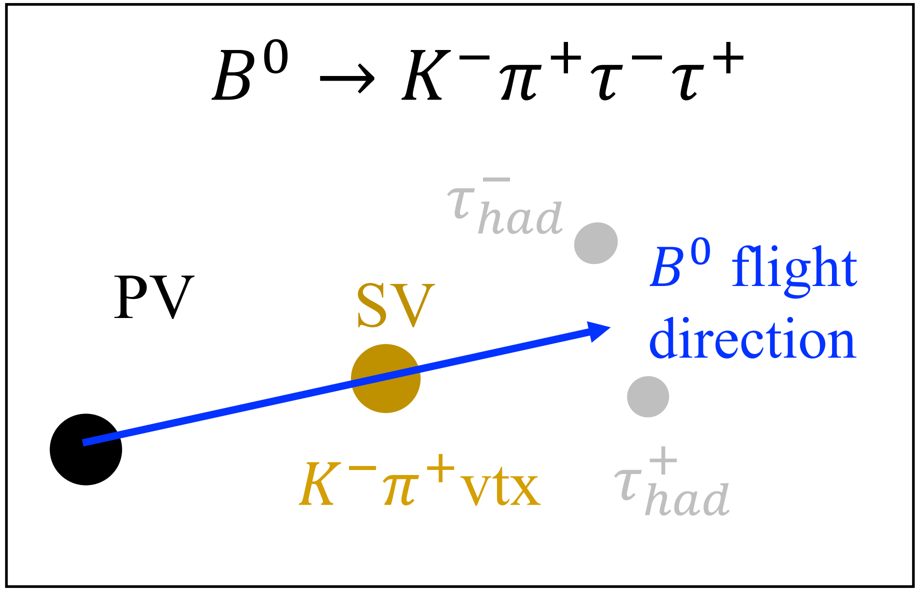
Different reconstruction methods lead to varying resolution. **Why?**

[Rev. Mod. Phys. 94 (2022) 1, 015003]



Kinematic reconstruction: Hadronic tau

Reconstructing B momentum, q^2, and angles depend on **decay-specific kinematic and geometric constraints**.



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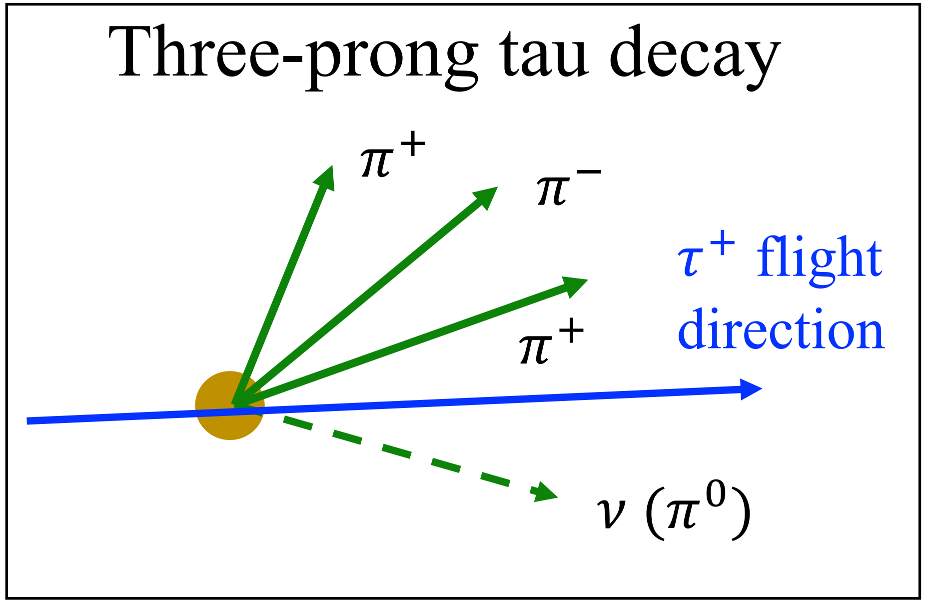


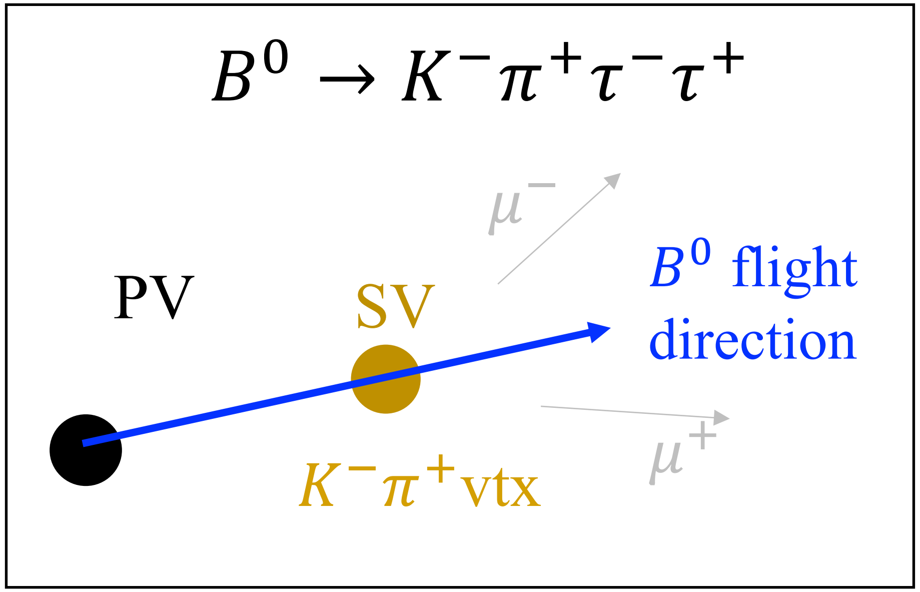
[Thesis of Alessandro Mordá]

Combining τ and B flight vertex info → **Analystic B mom. → 2-fold ambiguity!**

But low statistics (low BF of τ & low eff.)

Kinematic reconstruction: Muonic tau

Reconstructing B momentum, q^2, and angles depend on **decay-specific kinematic and geometric constraints**.



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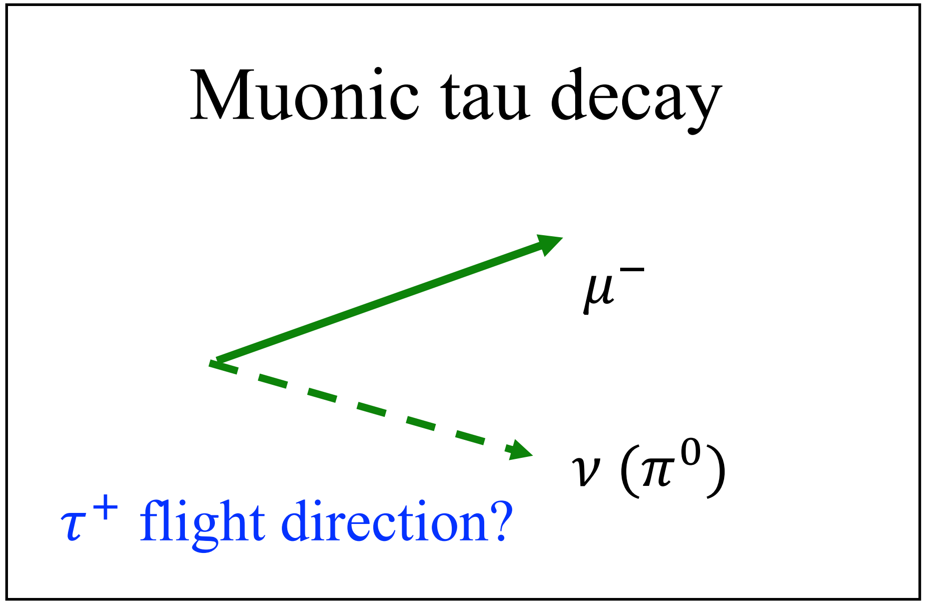


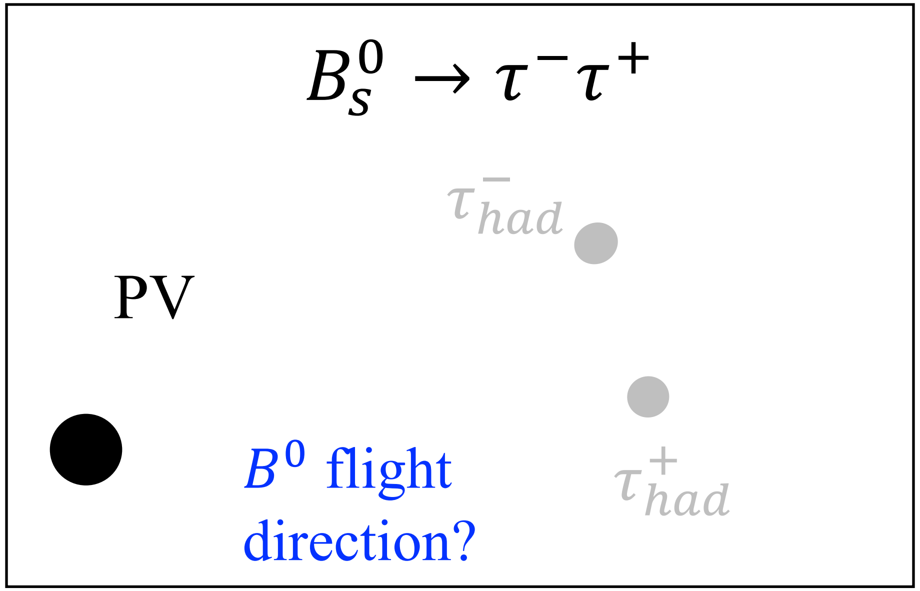
[RFA in $R(D^*)$ analysis].

Large statistics (high BF of τ & high eff.).

But no τ flight info (**rest frame approx**. $p_B^{\parallel} \propto p_{vis}^{\parallel}$), **worsens resolution.**

Situation not simple for kinematic reconstruction

Reconstructing B momentum, q^2, and angles depend on **decay-specific kinematic and geometric constraints**.



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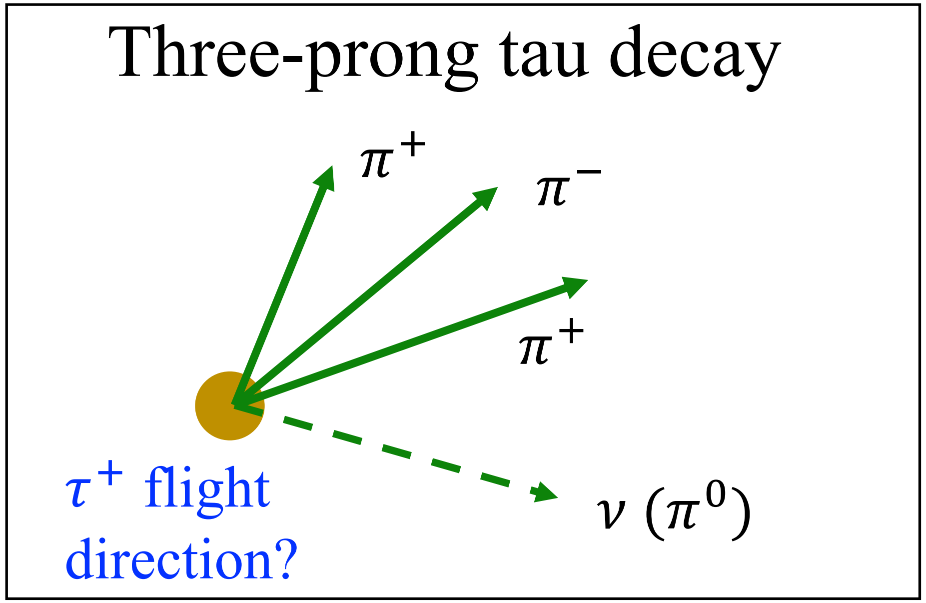
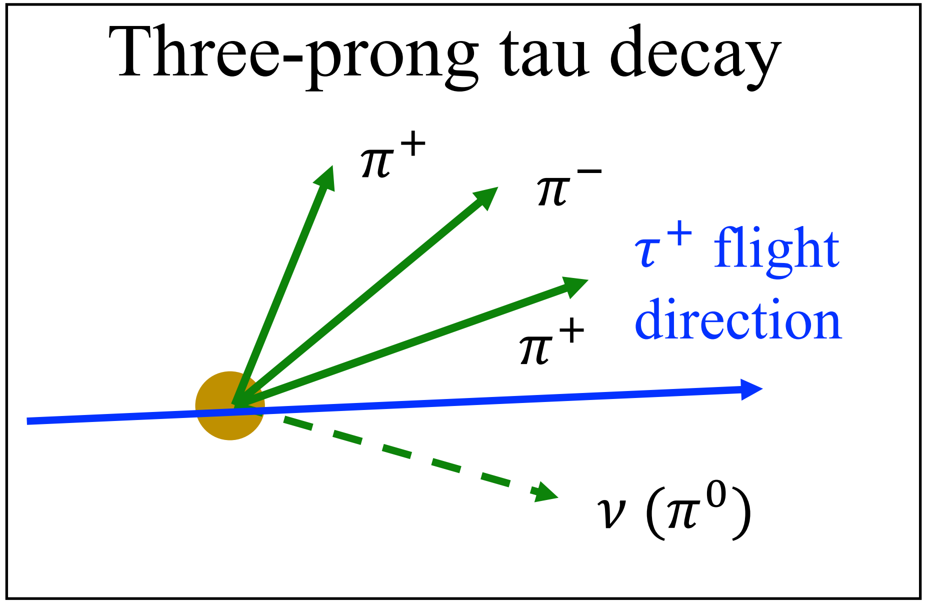


[Thesis of Alessandro Mordá]

No B flight info, but mass constraints → **Analystic B mom. → 2-fold ambiguity!**

Another advantage of hadronic τ

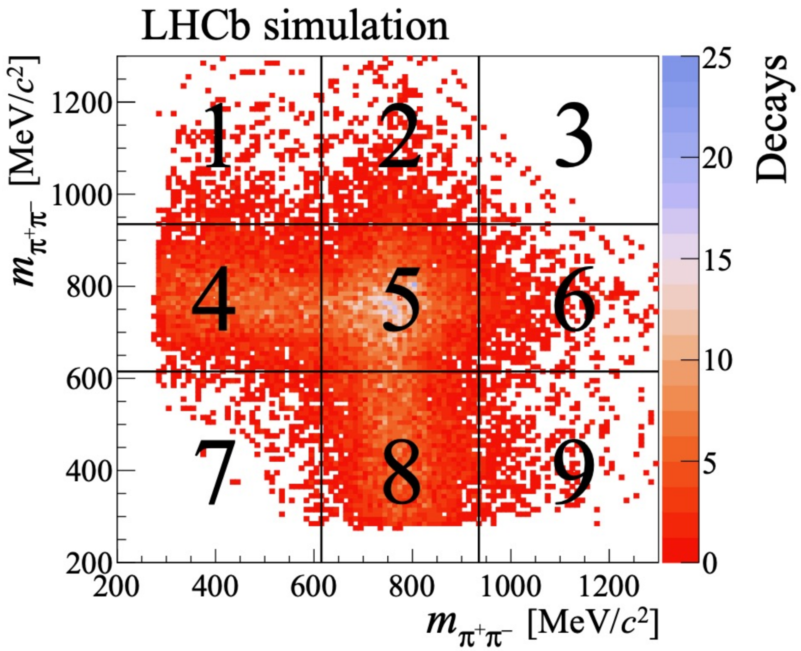
[Phys. Rev. Lett. 118, 251802 (2017)]



Proceeds mainly via

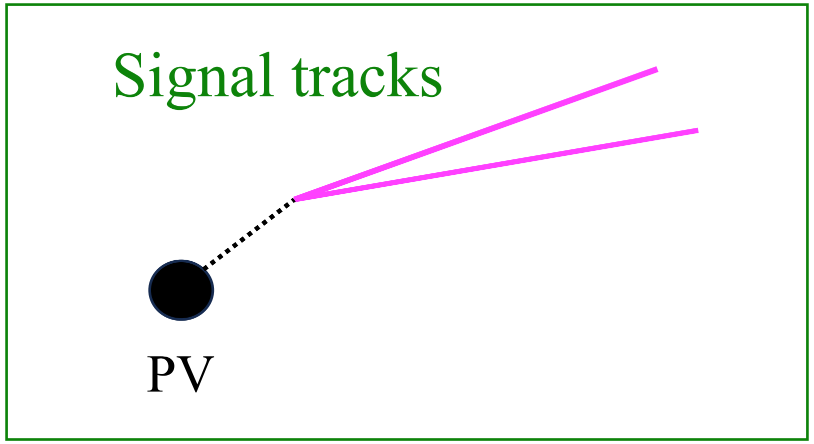
$$\tau^\pm \to a_1^\pm \bar{\nu}_\tau \to \rho^0 \pi^\pm \bar{\nu}_\tau \to \pi^+\pi^-\pi^\pm \bar{\nu}_\tau.$$

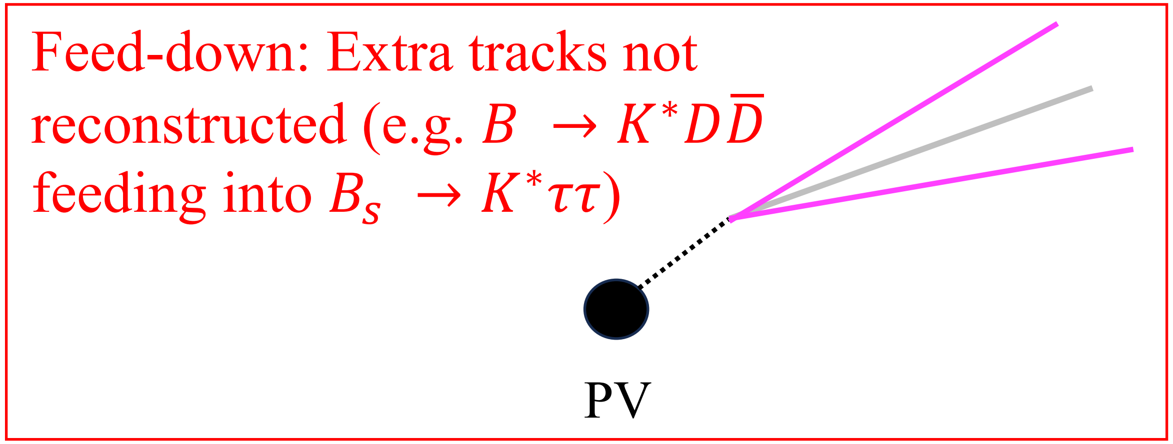
Exploited in **search for $B^0_{(s)} \to \tau^+\tau^-$**: Dalitz plane used control bkg e.g. $B^0 \to D^- D_s^+$

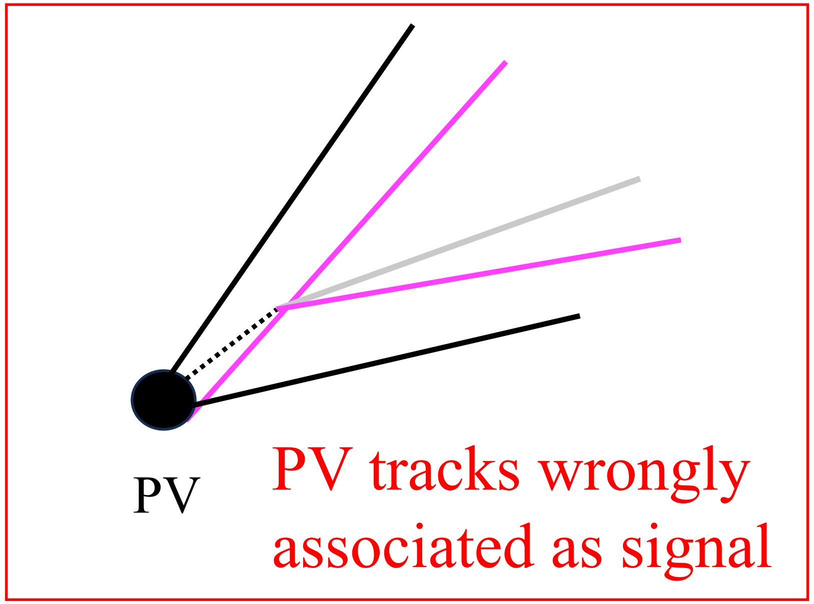


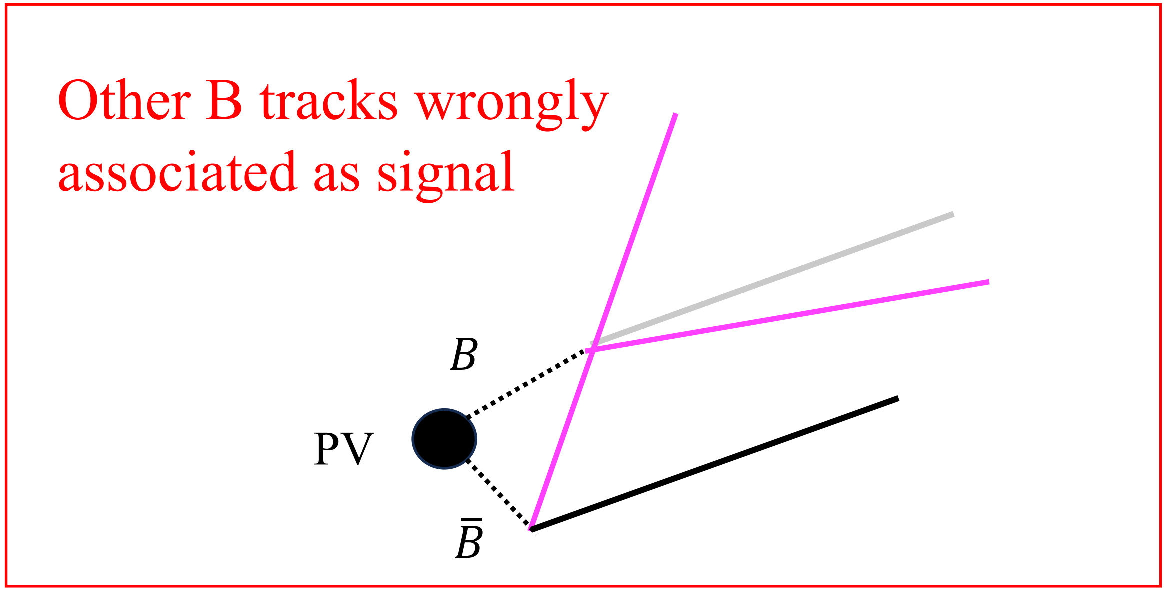
Region 5 is signal-dominated; others regions define background or optimize selection.

Technique 3: Charged and neutral isolation





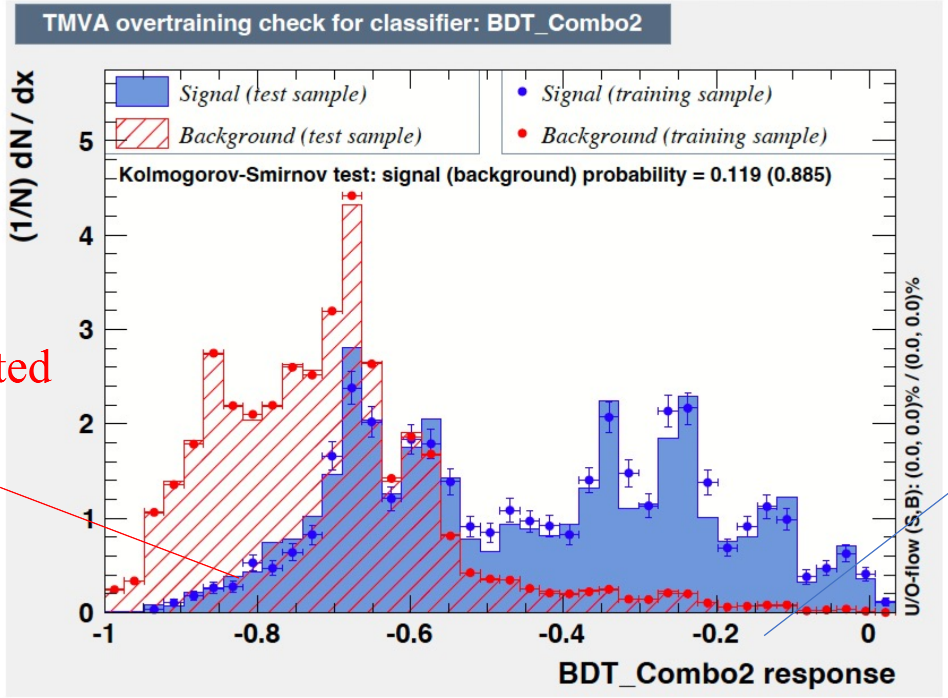




Charged and neutral isolation

Charge isolation techniques
(e.g. $B \rightarrow D^{+}\tau\nu$)

Non-isolated tracks

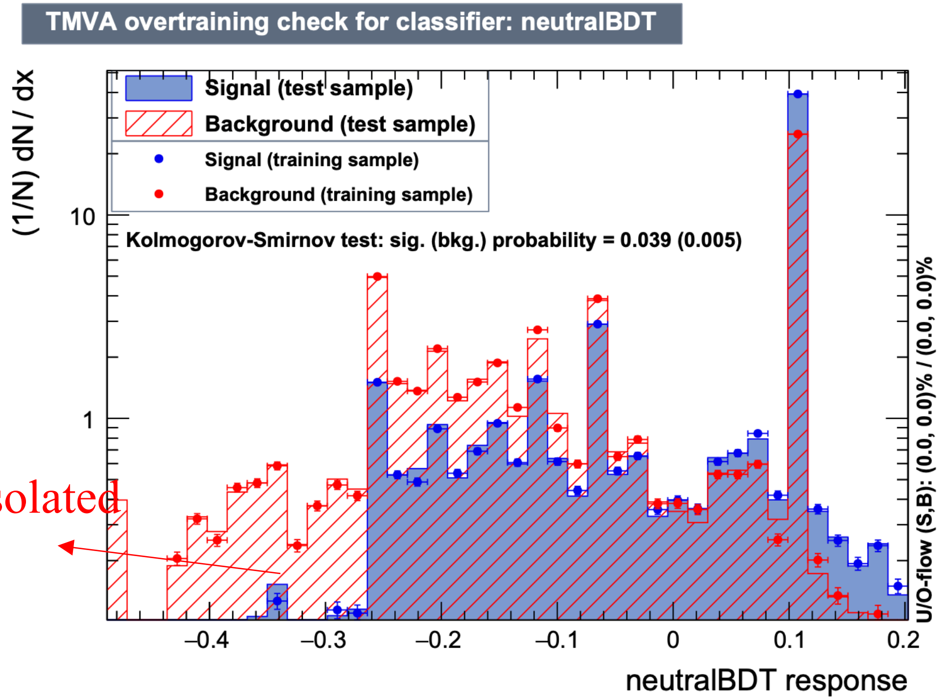


Isolated tracks

(d) IsoBDT_Combo2

Neutral isolation techniques
(e.g. $B \rightarrow D^{+}\tau\nu$ analysis)

Candidates isolated from π^{0}/γ

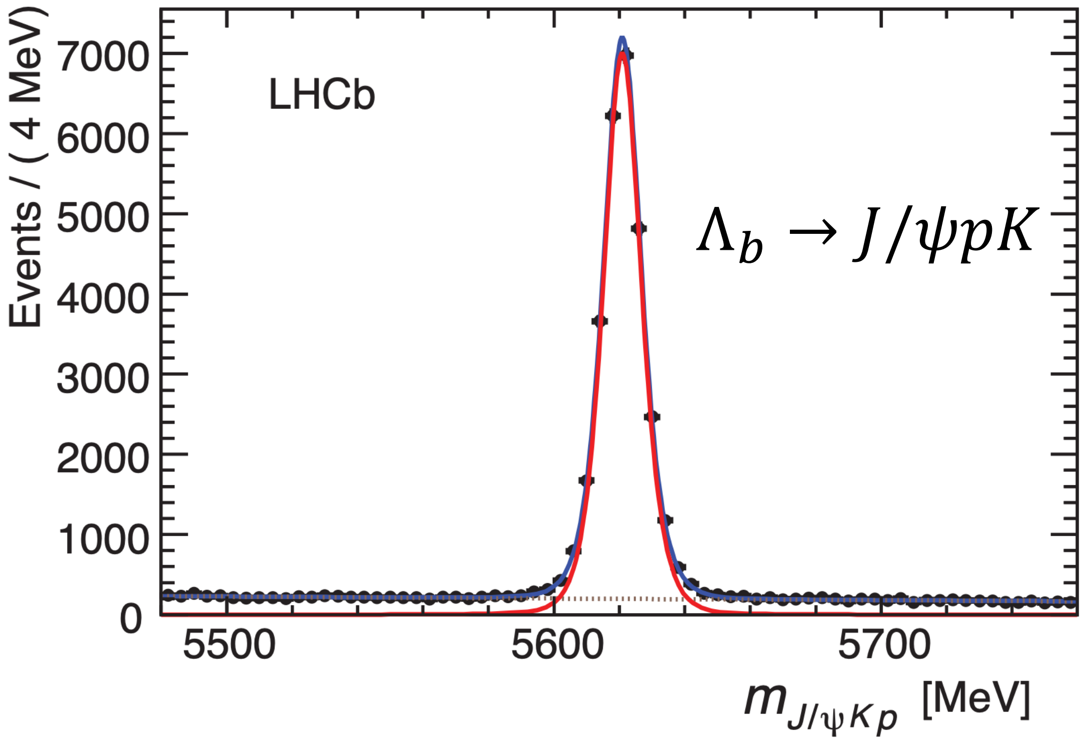


Reversing the cuts help define background enriched control regions!

MisID: Importance of PID at LHCb

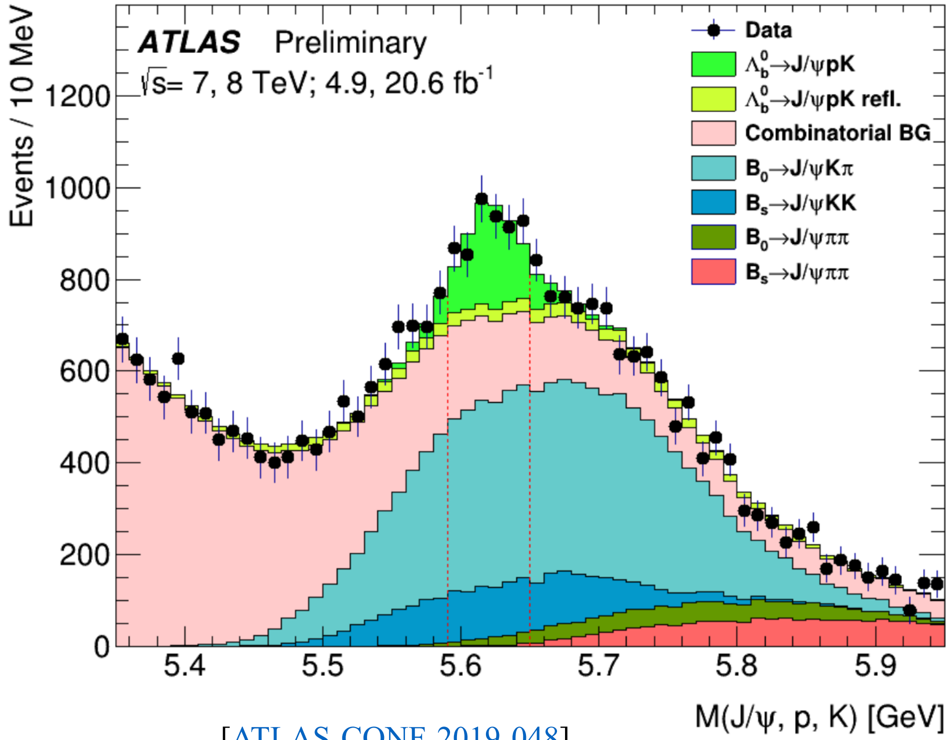
For more see Tim G's talk

LHCb pentaquark analysis



[Phys. Rev. Lett. 115, 072001 (2015)]

ATLAS pentaquark analysis



[ATLAS-CONF-2019-048]

MisID in missing energy decays

Large number of channels can be misidentified as signal.

Signal: $B^0 \to K^-\pi^+\tau^+(\to \mu^+ X)\tau^-(\to \mu^- X)$

$K \to \pi$: $X_b \to K^-K^+\mu^+\mu^- X$

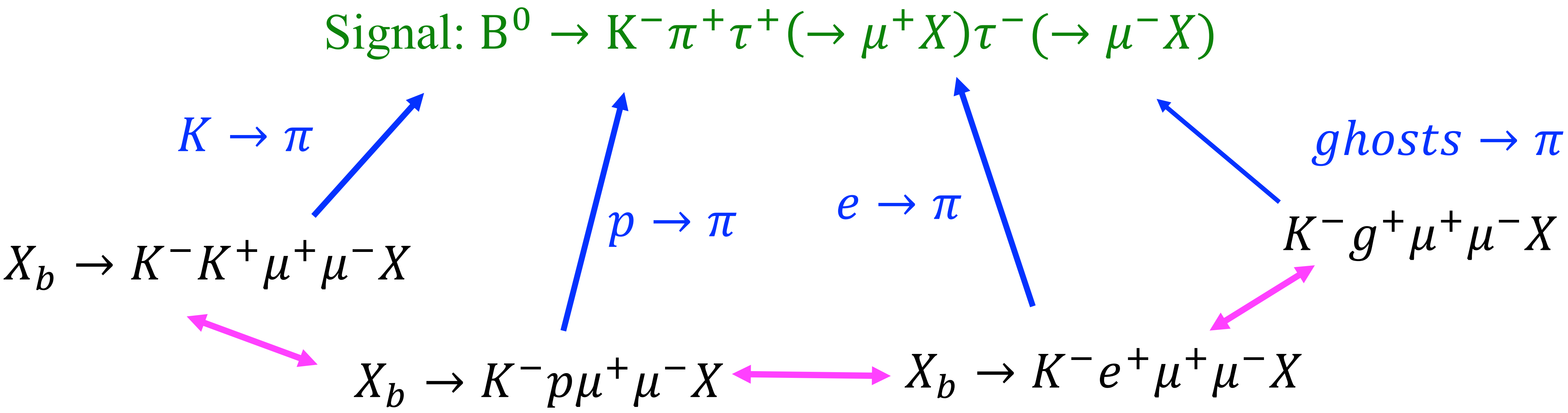
$p \to \pi$: $X_b \to K^- p \mu^+\mu^- X$

$e \to \pi$: $X_b \to K^- e^+\mu^+\mu^- X$

$ghosts \to \pi$: $K^- g^+\mu^+\mu^- X$

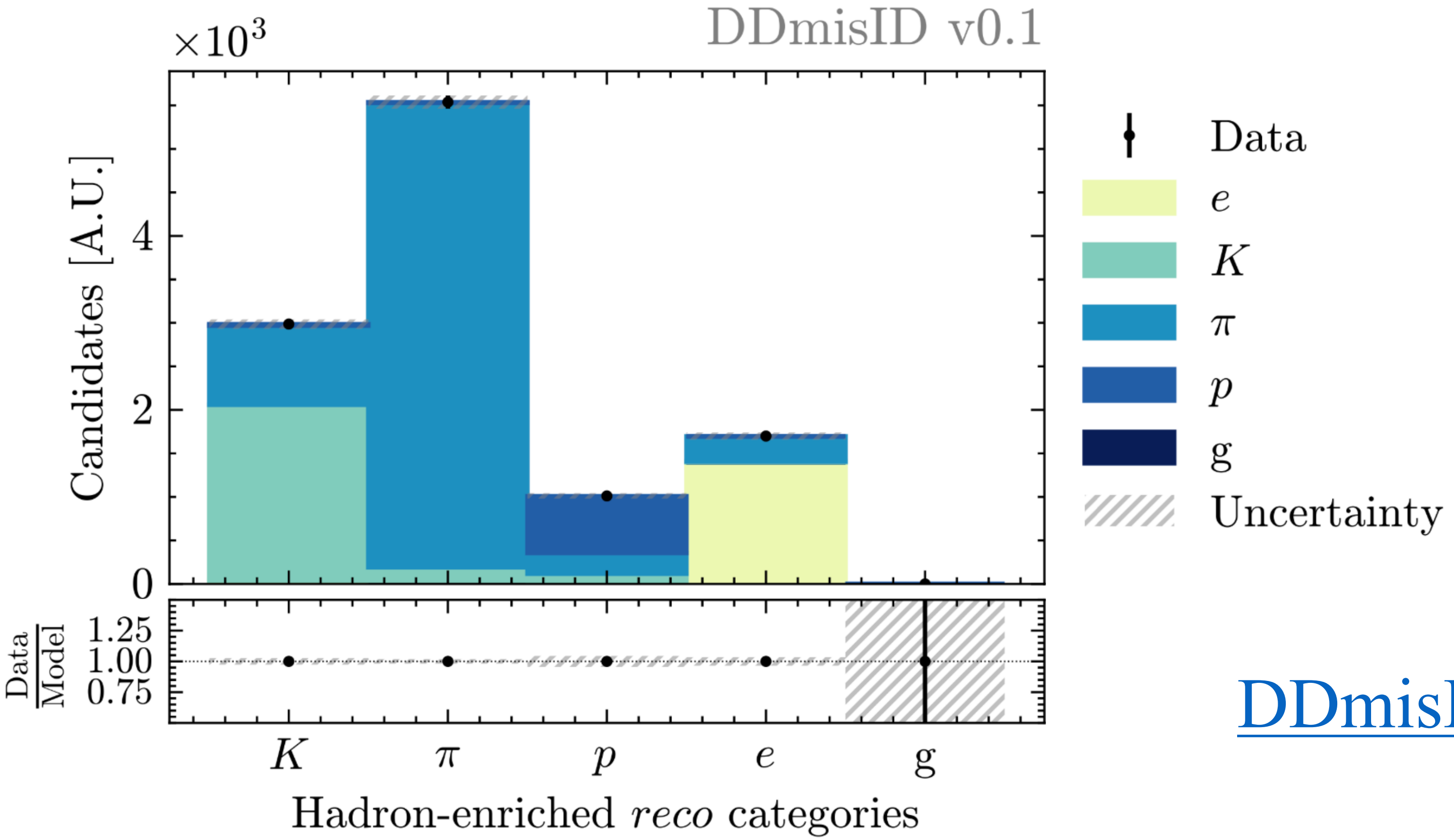
MisID in missing energy decays

Large number of channels can be misidentified as signal.
There could be cross-contamination between them.



MisID in missing energy decays

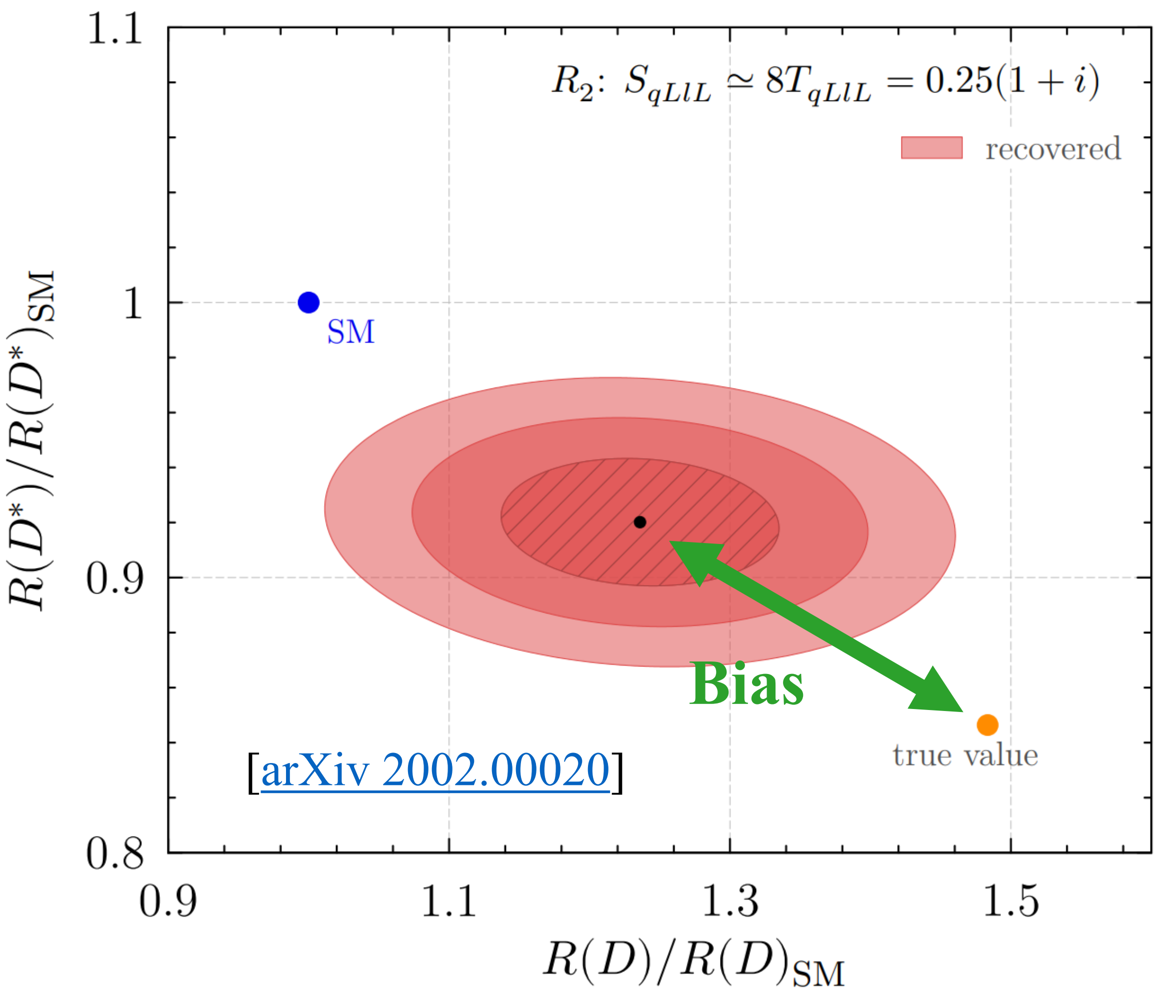
Define mis-ID enriched control regions and obtaining yield and shape from data.
Sophisticated folding/unfolding techniques (e.g. $B^0 \to D^+ \tau \nu$ analysis)



DDmisID package

Missing Energy: Model dependence

No variable that is fully independent of the signal model.

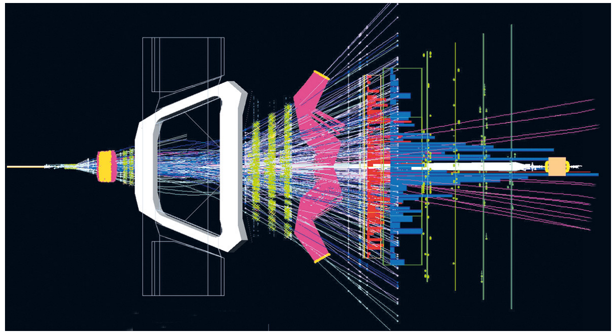


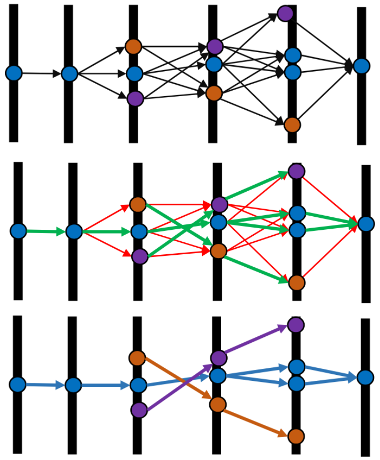
If data has NP and we fit with SM templates this leads to a bias. Not good for global fits!

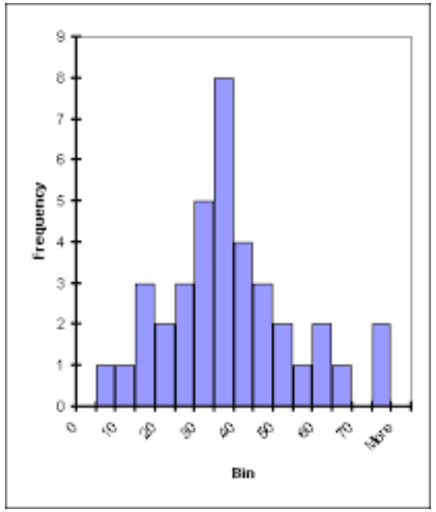
How to solve the model dependence?

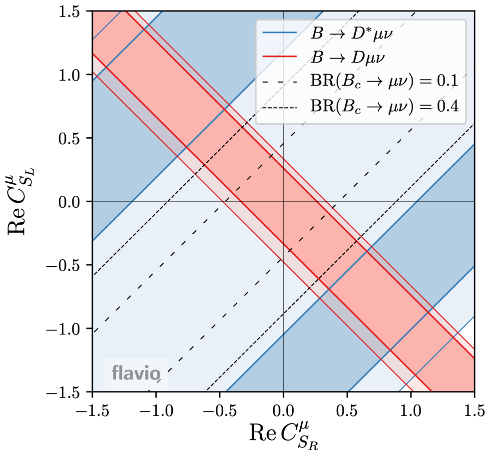
Correct thing to do is at **each fit iteration**:

Generate MC according to model → Reconstruct and apply selection → Model signal/bkg template → Extract parameters









This is not pragmatic!

How to solve the model dependence?

Assume reconstruction and selection are not heavily model dependent

Generate MC according to model → Reconstruct and apply selection → Model signal/bkg template → Extract parameters

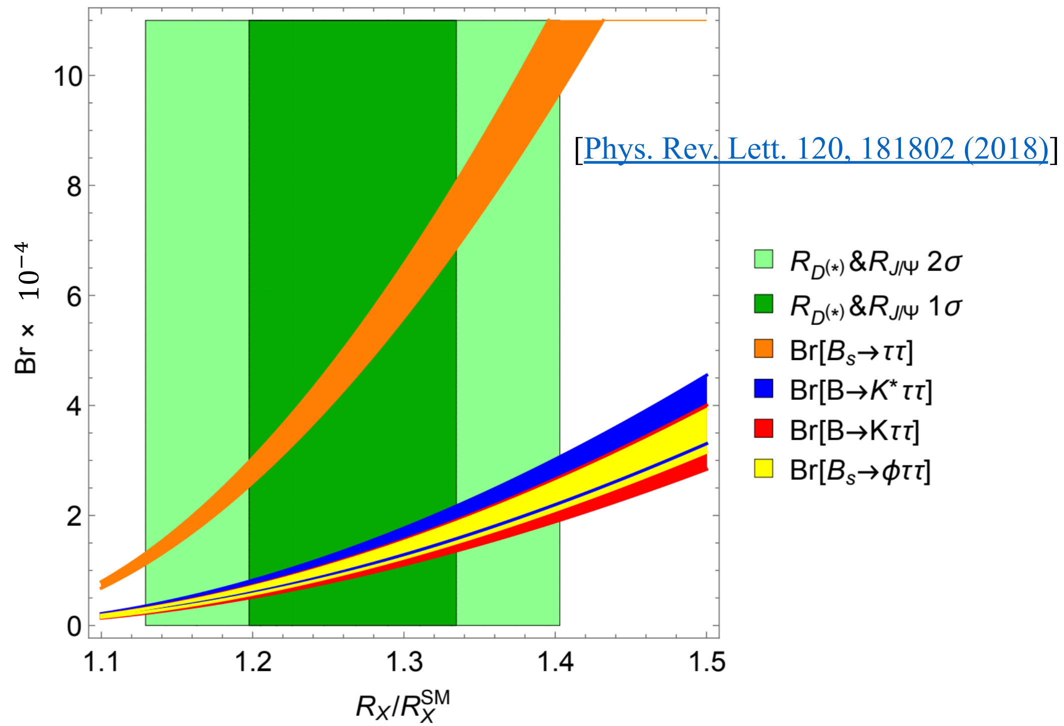
At each fit iteration, reweight truth information to a different NP model

Techniques developed:

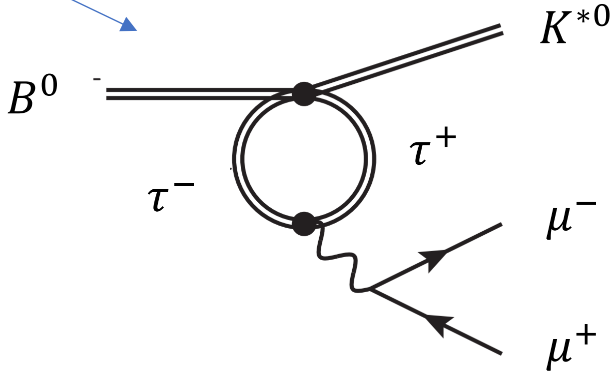
- RoHammerModel (see paper)
- ReDist + EOS (See paper)
- **ReDist + HAMMER (Prospects for LHCb + Belle II combination, paper soon)**

Searches for $B^0 \to K^+\pi^-\tau^+\tau^-$ and $B_s^0 \to K^+K^-\tau^+\tau^-$

- BF of these channels $O(10^{-7})$.
- BSM models explaining $R(D^*)$ can enhance them by $O(100)$.
- Previously Belle-II: $BF(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$ (90% CL)
- Previously LHCb: Indirect Wilson coefficient $C_9^{\tau\tau} < 600$ (95% CL).
- Can we improve with Run 2 data (2016-2018)?



[Phys. Rev. Lett. 120, 181802 (2018)]



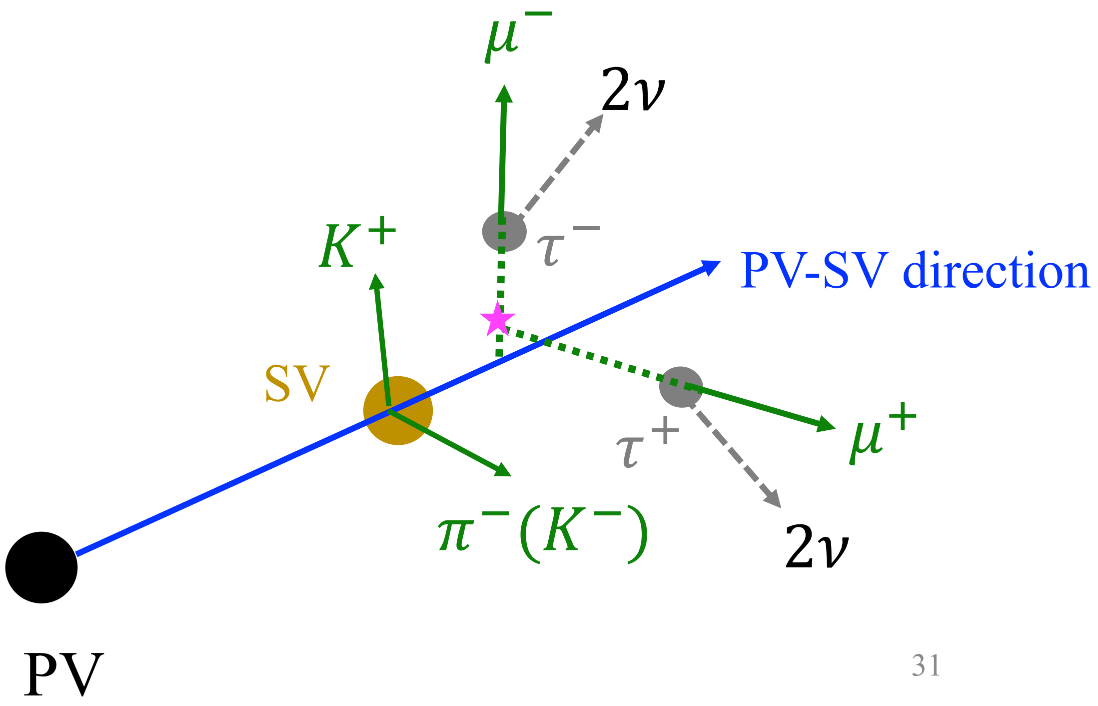
Produces cusp in q^2 of $B^0 \to K^{*0}\mu^+\mu^-$[arXiv]

Topology and bins in di-hadron mass spectra

[LHCb-PAPER-2025-048]

Mass range (MeV/c^2)	Mass range (MeV/c^2)
$792 \leq m_{K^+\pi^-} < 992$	$980 \leq m_{K^+K^-} < 1060$
$992 \leq m_{K^+\pi^-} < 1330$	$1060 \leq m_{K^+K^-} < 1200$
$1330 \leq m_{K^+\pi^-} < 1530$	$1200 \leq m_{K^+K^-} < 1400$
$1530 \leq m_{K^+\pi^-} < 1726$	$1400 \leq m_{K^+K^-} < 1600$
–	$1600 \leq m_{K^+K^-} < 1813$

- Search caried out in bins of $m(h^+h^-)$ spectra taking resonant (e.g. $K^*(892)$, $\phi(1020)$) into account.
- Large PV-SV distance → beats combintatorial bkg.
- Muon intersection downstream of SV → beats $b \to s\,\mu^+\mu^-$ bkg.



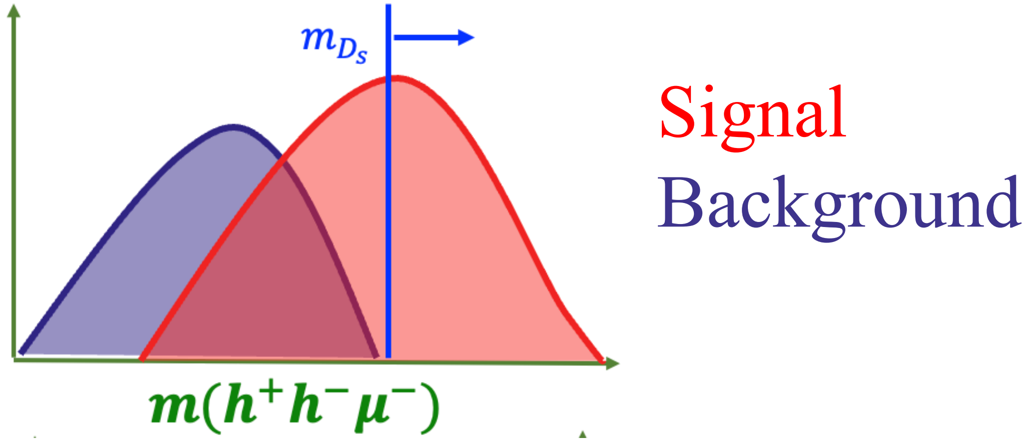
Background rejection

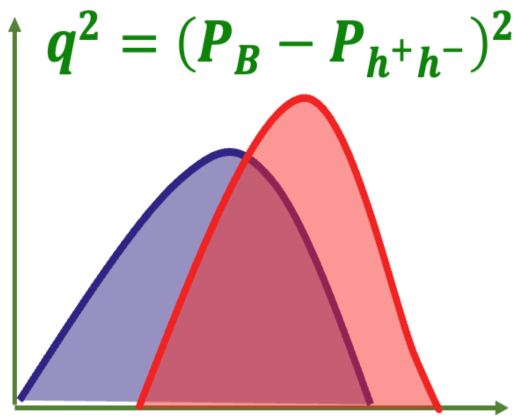
[LHCb-PAPER-2025-048]

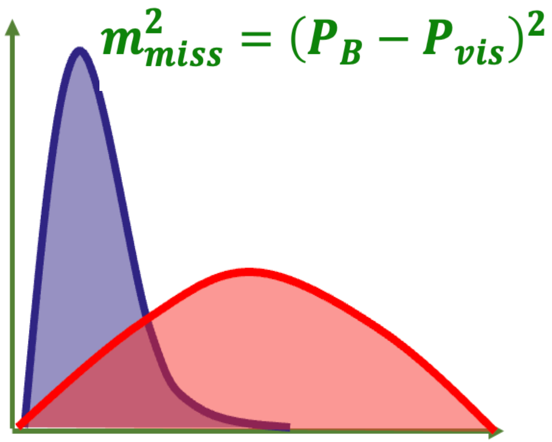
- Bkg $B \to D_s(\to h^+h^-\mu^+\nu)\,\mu^-\nu$ removed with $m(h^+h^-\mu^+) > m_{D_s}$.
  - Halves the eff. but larger bkg. rej.

- Bkg $B \to D\bar{D}h^+h^-$ with each SL D decaying, apply 2D cut:
  - q^2 (used rest frame approximation)
  - m^2_{miss} as signal has more missing particles.

- Feed down from higher K^* negligible.



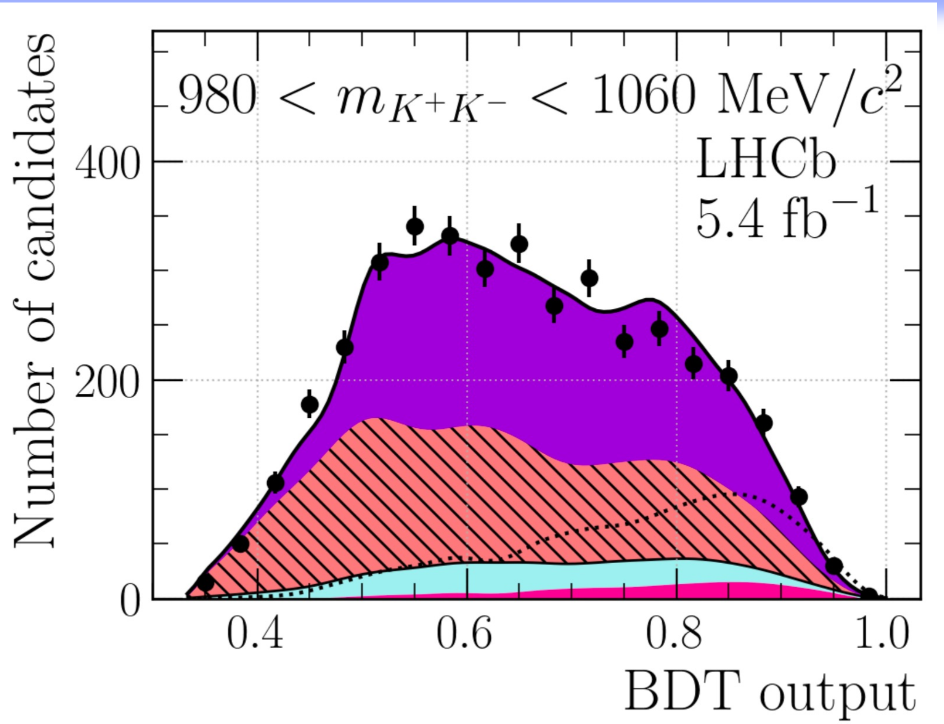


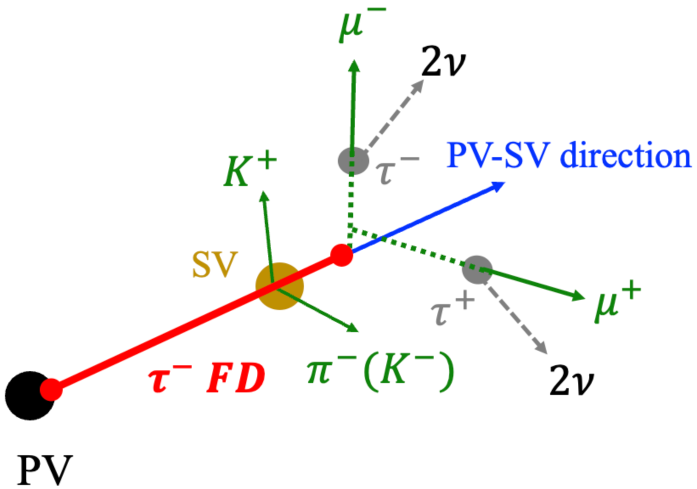


BDT training

[LHCb-PAPER-2025-048]

- Three-class BDT: Combinatorial bkg., Semileptonic $B \to D^0(\to h^-\mu^+X)h^+\mu^-X$ and signal.
- BDT features: $\tau^\pm$ FD and isolation vars.
- Candidate with highest BDT for the signal category retained and fitted.
- MisID: Four control regions used for yield and shape determination.
- SL bkg & signal modelled using MC, comb. bkg. via data (same muon sign).

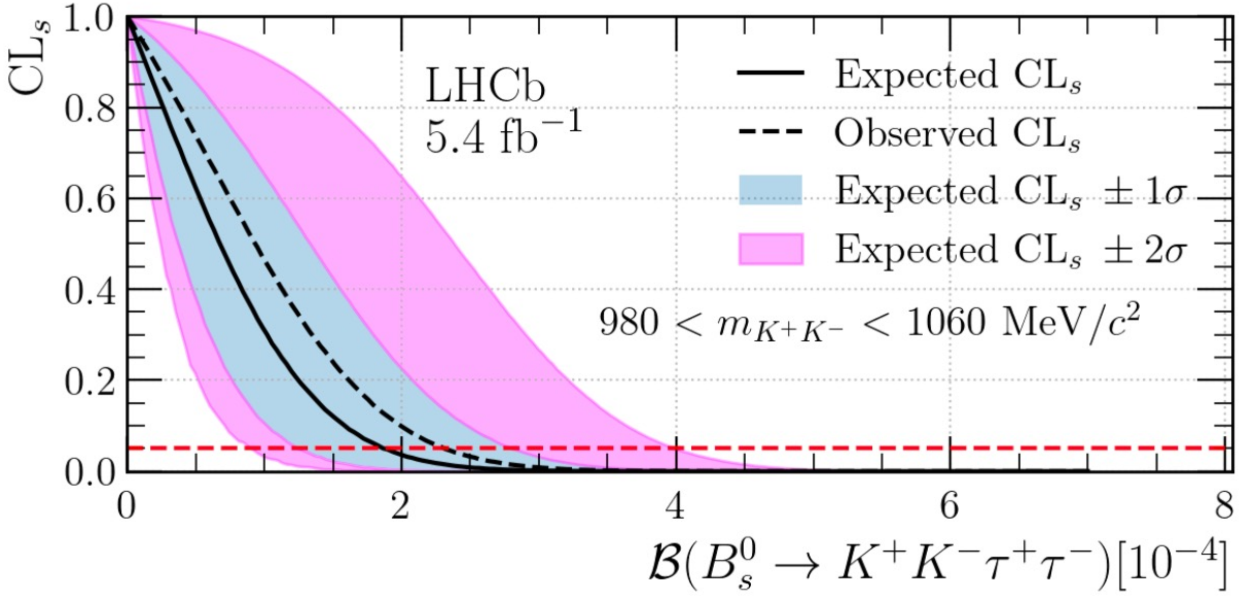




Results

[LHCb-PAPER-2025-048]

- Normalisation channels: $B^0 \to J/\psi K^*$ and $B_s^0 \to J/\psi\phi$.
- Limits obtained in all bins of $m(K^+K^-)$ and $m(K^+\pi^-)$.
- **Dominant systematics: Modelling of the bkg shapes.**



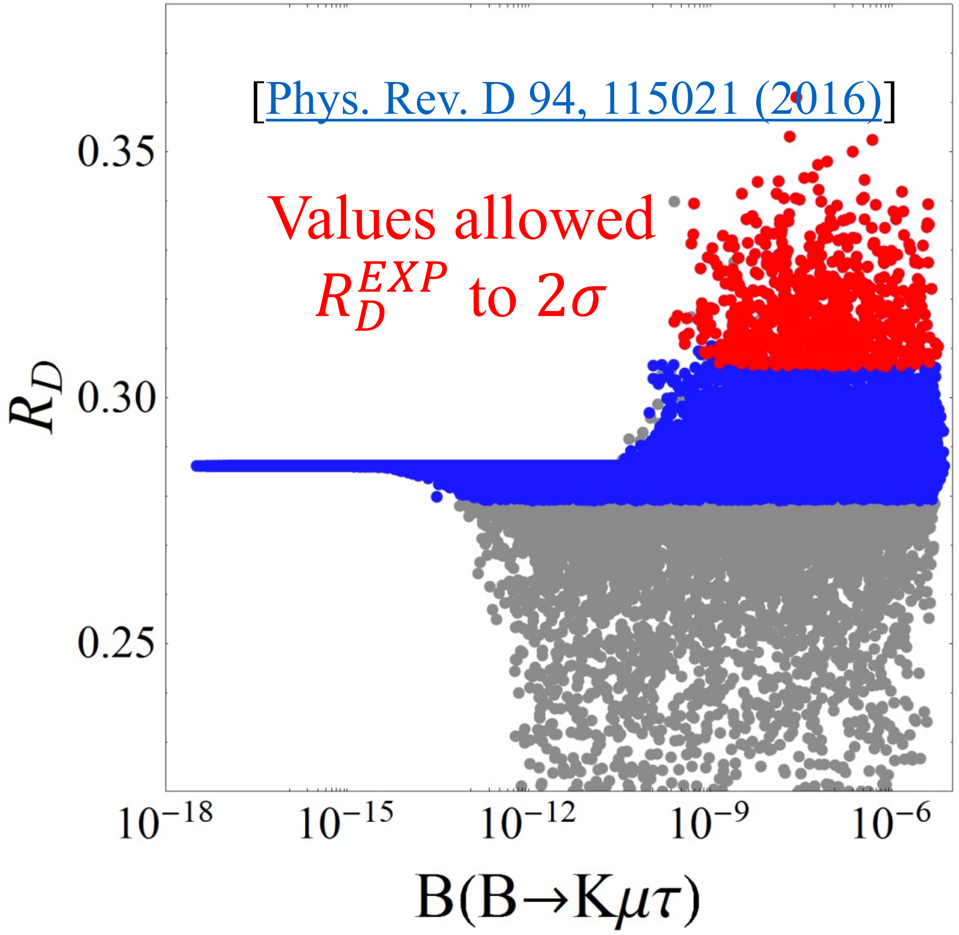
$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.8 \times 10^{-4}\ (2.5 \times 10^{-4}) \text{ at } 95\%\ (90\%) \text{ CL},$$
$$\mathcal{B}(B_s^0 \to \phi\tau^+\tau^-) < 4.7 \times 10^{-4}\ (4.1 \times 10^{-4}) \text{ at } 95\%\ (90\%) \text{ CL}.$$

Limit 10x better than Belle-II!

Limits 3x better on $|C_9^{\tau\tau}|$ than prev. LHCb limit.

Search for Lepton Flavour Violation (LFV) in $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$

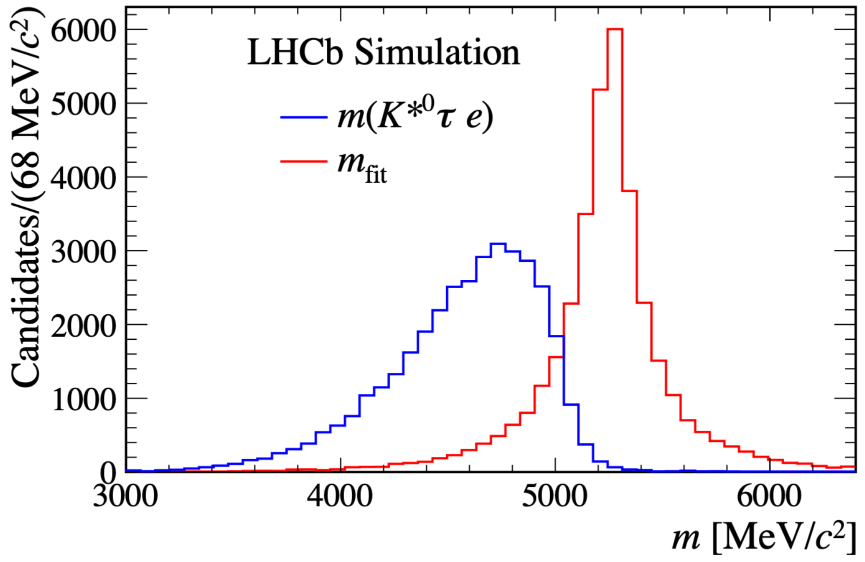
- Even with neutral LFV in SM, charged LFV (cLFV) highly suppressed $O(10^{-50})$.
- NP models of $R(D^*)$ can enhance them.
- Most stringent τe coupling Belle: $BF(B^+ \to K^+\tau e) < 1.5 \times 10^{-5}$ @ 90% CL.
- First τe probe by LHCb with Run 2 data ($\sim 5.4\ fb^{-1}$).
- Both τ^+e^- & τ^-e^+ samples analyzed independently, with hadronic τ decay.

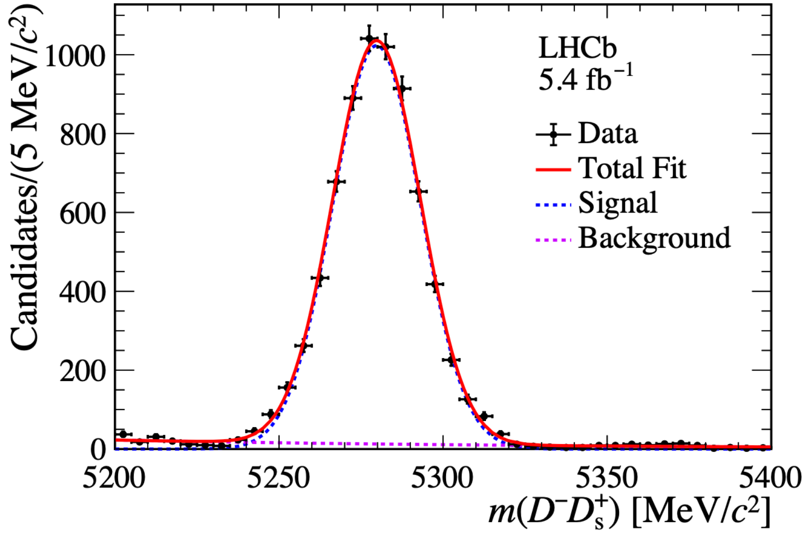


Event selection

[LHCb-PAPER-2025-048]

- Use vertex and mass constraints to reconstruct full decay chain.
- Normalisation: $B^0 \to D^-(\to K\pi\pi)\, D_s(\to K K\pi)$.
- **Event selection:**
  - Multiple L0 triggers to offset low e⁻ L0 eff.
  - MVA to reject comb. bkg, partially reco., and mis-ID charm bkg.
  - Optimized PID selection.
  - D-meson vetoes to suppress physics backgrounds.



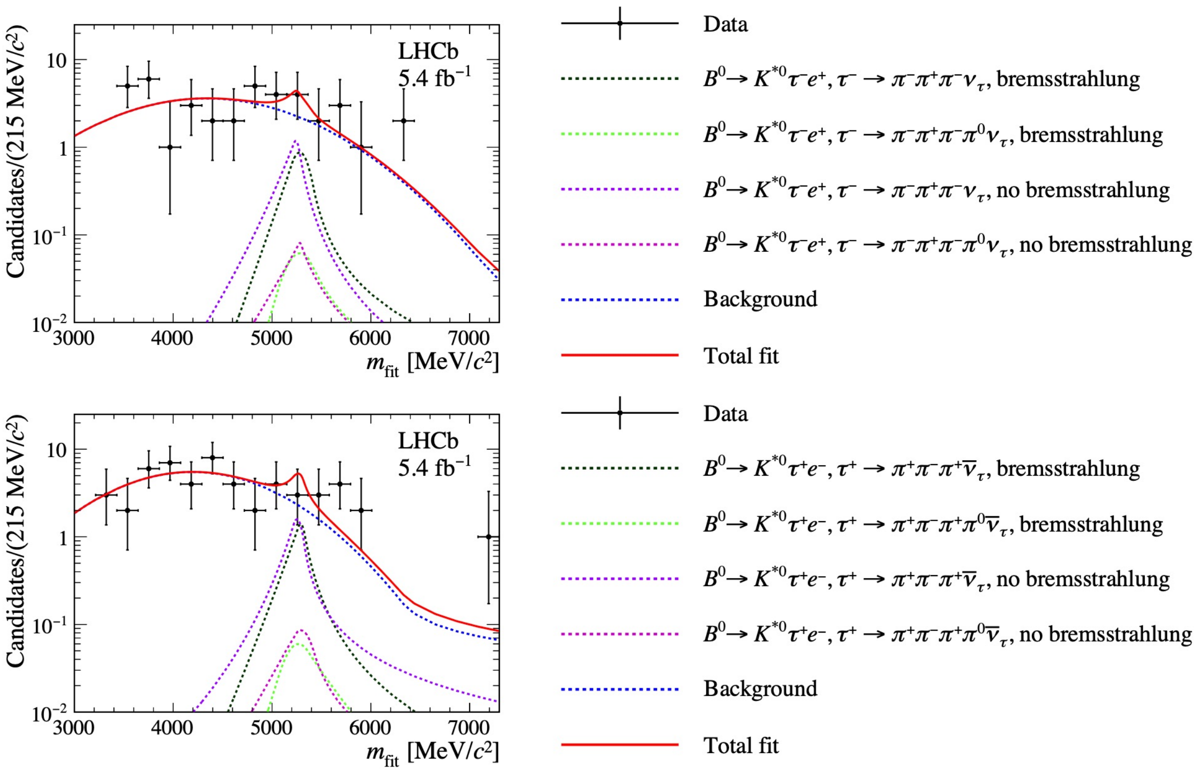


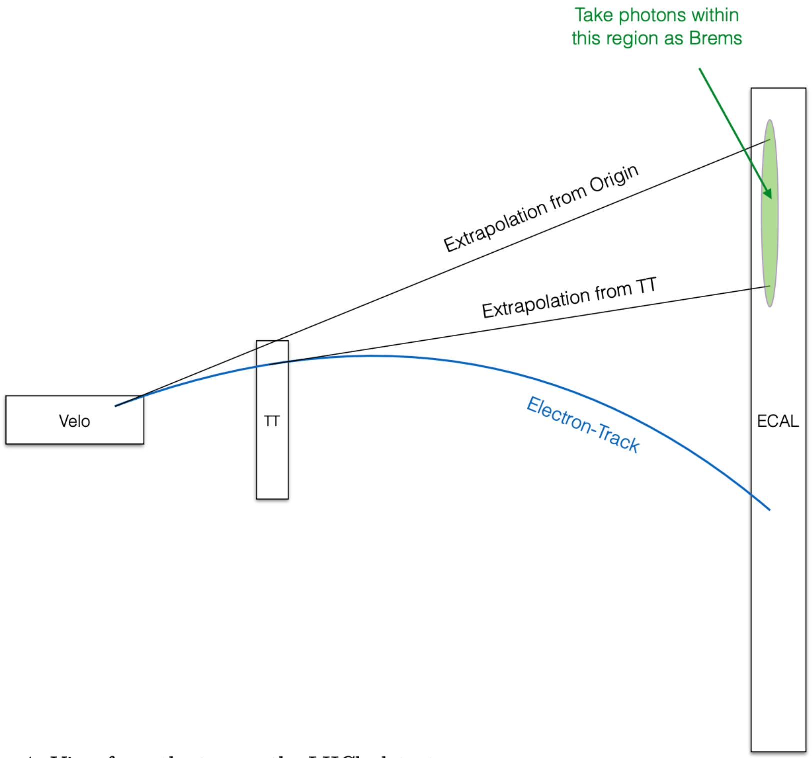
Backgrounds and fit

[LHCb-PAPER-2025-048]

- Main backgrounds: combinatorial and $b \to cl\nu$ decays.
- Electrons with and without bremsstrahlung considered.

$B^0 \to K^{*0}\tau^- e^+$





$B^0 \to K^{*0}\tau^+ e^-$

Results

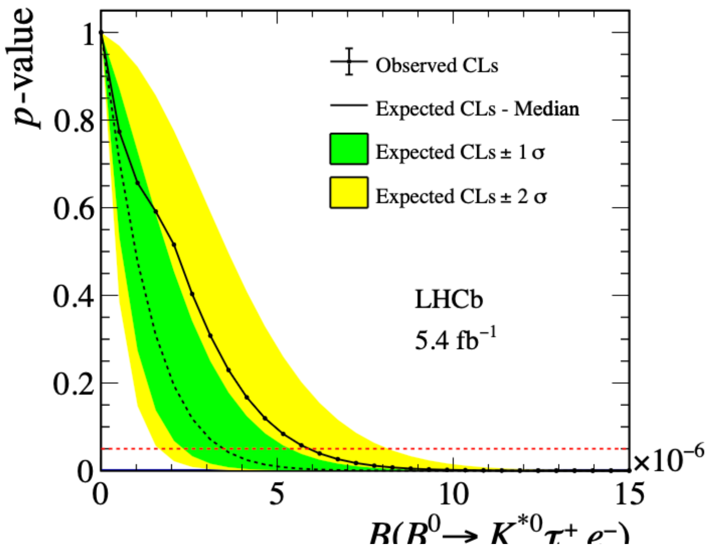
[LHCb-PAPER-2025-048]

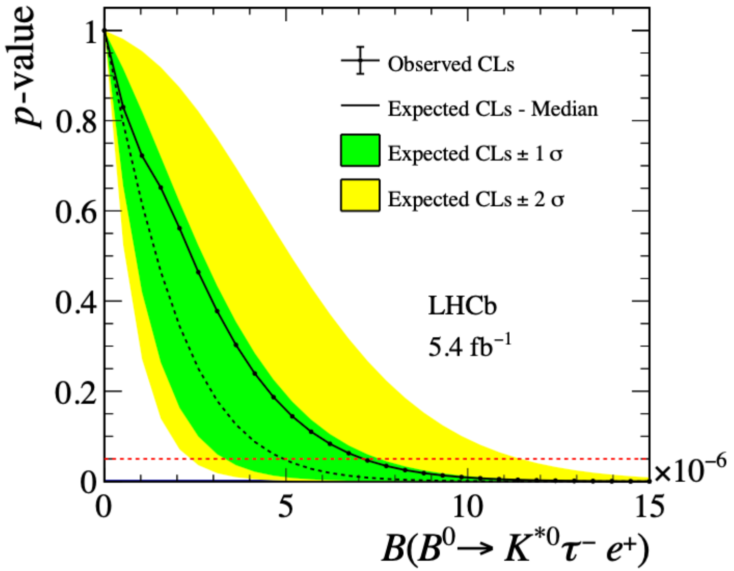
- **Most stringent limits to date on $b \rightarrow s\tau l$.**
- Upper limits on NP scenarios: accounting for variation selection efficiency.

Model	Upper limit $[10^{-6}]$	
	$B^0 \to K^{*0}\tau^- e^+$	$B^0 \to K^{*0}\tau^+ e^-$
Phase space (PHSP)	5.9 (7.1)	4.9 (5.9)
Left-handed ($C_9^{\tau e} = -C_{10}^{\tau e} \neq 0$)	6.3 (7.7)	5.4 (6.4)
Scalar ($C_S^{\tau e} \neq 0$)	6.6 (8.0)	5.7 (6.8)

90 (95) % CL

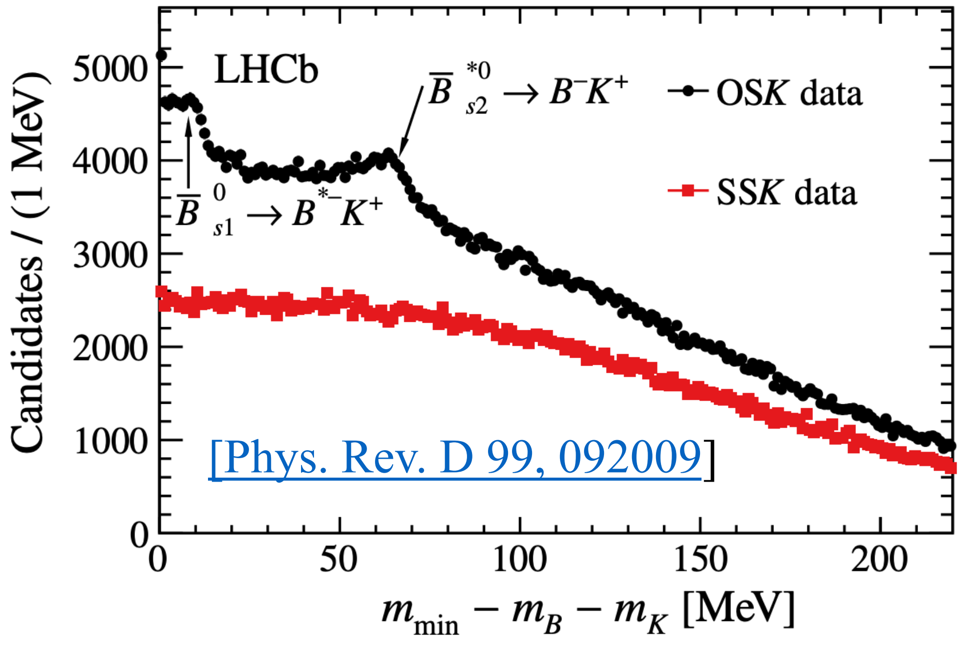
Systematic effect	Upper limit increase [%]	
	$B^0 \to K^{*0}\tau^+ e^-$	$B^0 \to K^{*0}\tau^- e^+$
Input branching fractions	2.3	2.5
Normalisation yields	<0.1	<0.1
Efficiencies	1.2	1.0
Background model	4.7	5.2
Signal model	1.2	0.5
Total	9.7	9.5

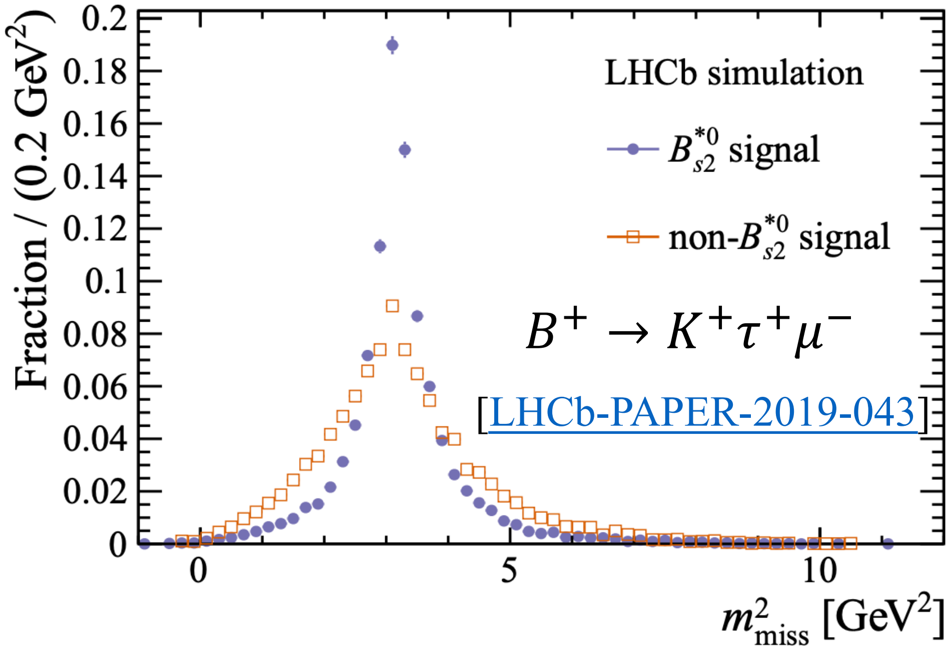




Other tricks with missing energy decays at LHCb

Exploit the fact that B_{s2}^{*} is narrow and decays to $B_{s2}^{*} \to B^{-}K^{+}$ to constrain the missing momentum.

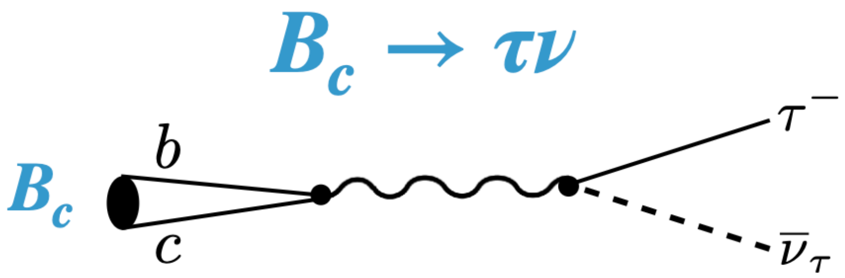




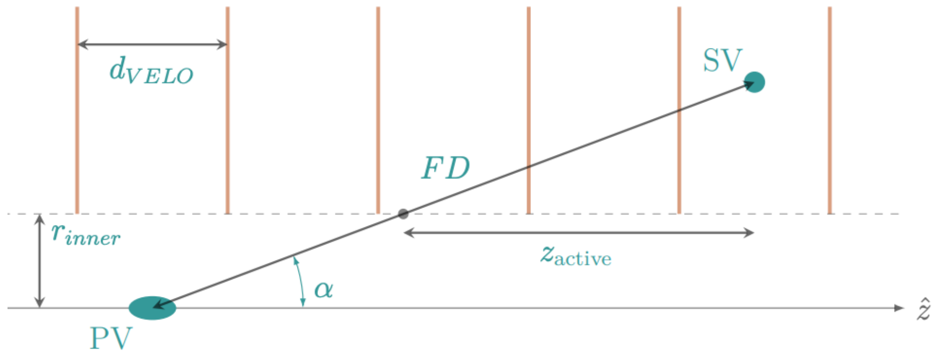
Used in BF analysis of $B^{-} \to D^{*,**,0}\mu^{-}\nu$ and LFV in $B^{+} \to K^{+}\tau^{+}\mu^{-}$.

FCC-ee decays @ LHCb?

Probe $B_c^- \to \tau^-\nu$ @ LHCb?
A clean probe of NP in $b \to c\tau\nu$

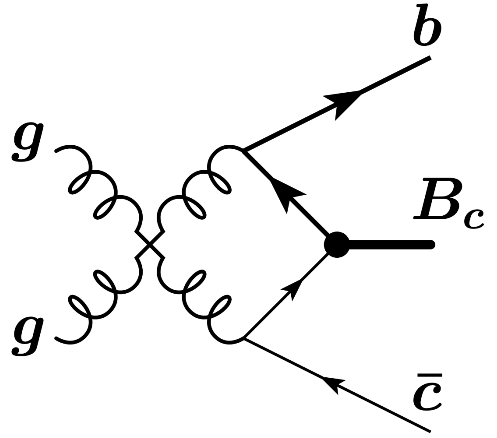


Idea I: Exploit B_c^+ hits in VELO



[Master's Thesis]

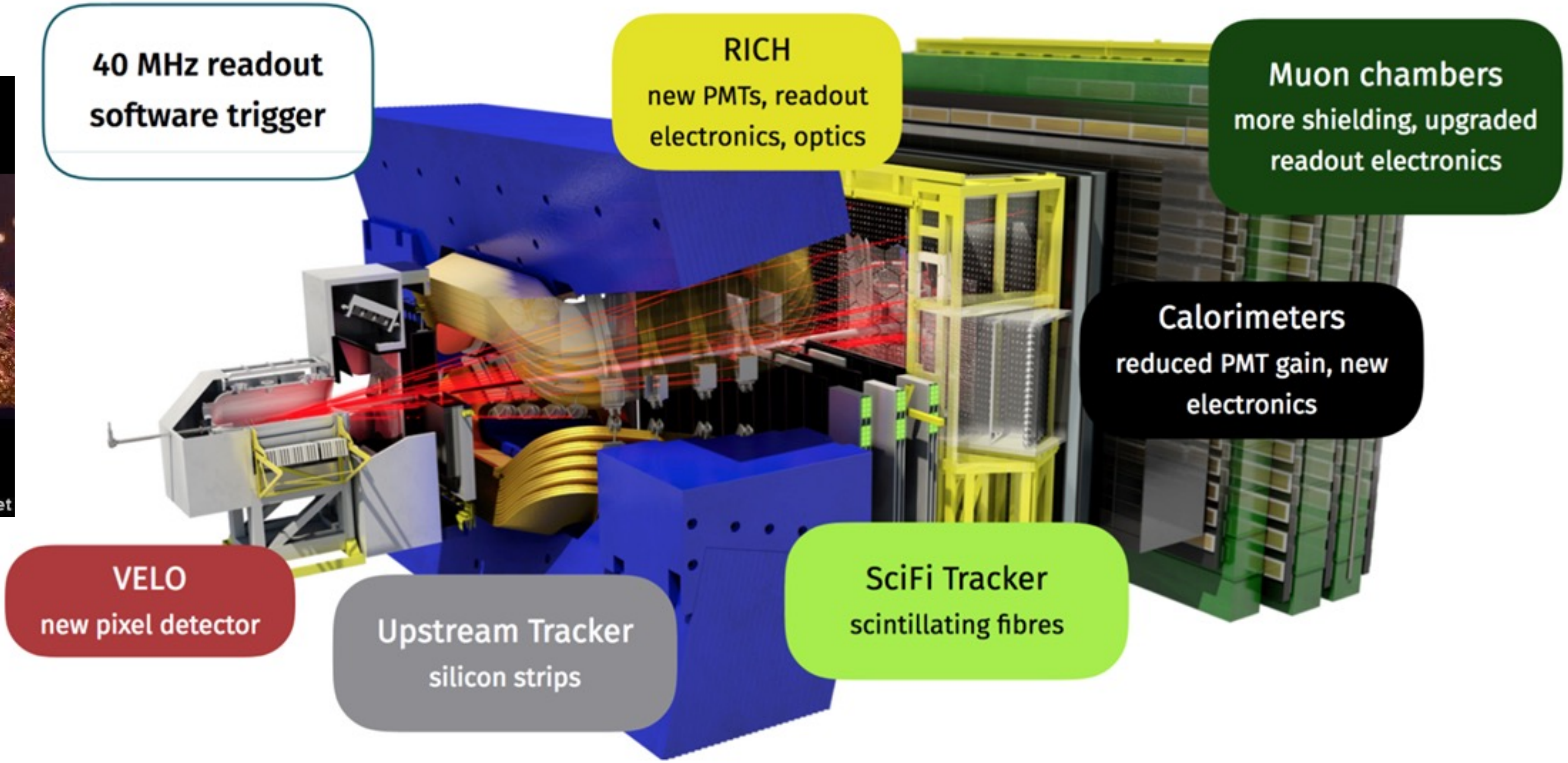
Idea II: Exploit Bc-D associated production



Production property measurement ongoing…

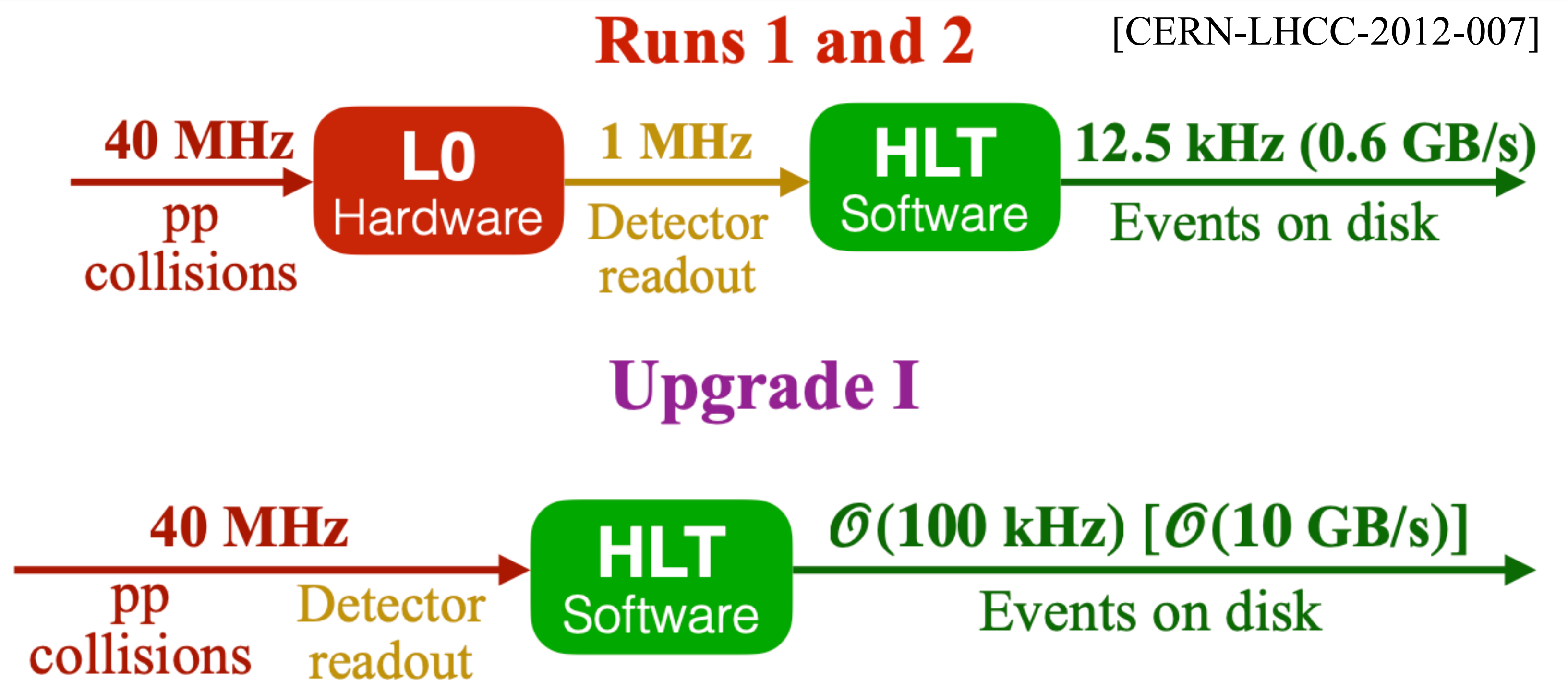
Brand new detector for Run 3

Luminosity increased by a factor 5. New tracking system: VELO, UT, SciFi



Brand new software for Run 3

For more Manuel's talk



First hadron detector with no hardware trigger!

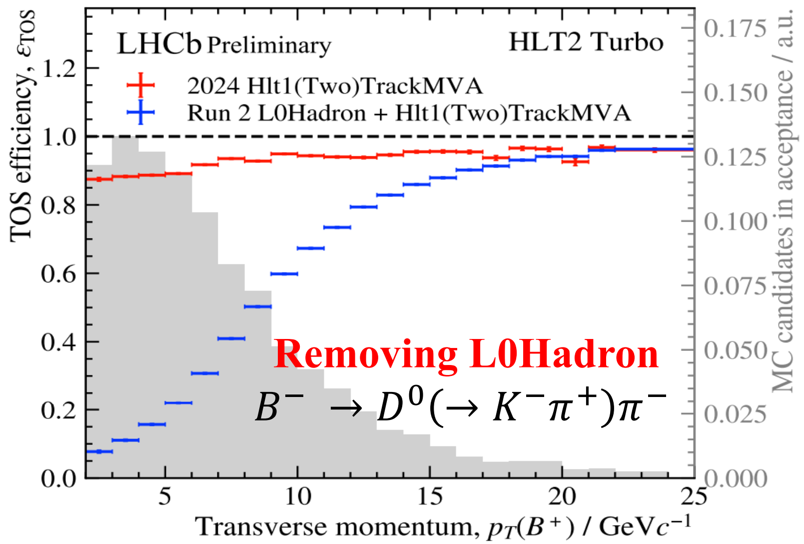
Run 3 Performance and new physics results

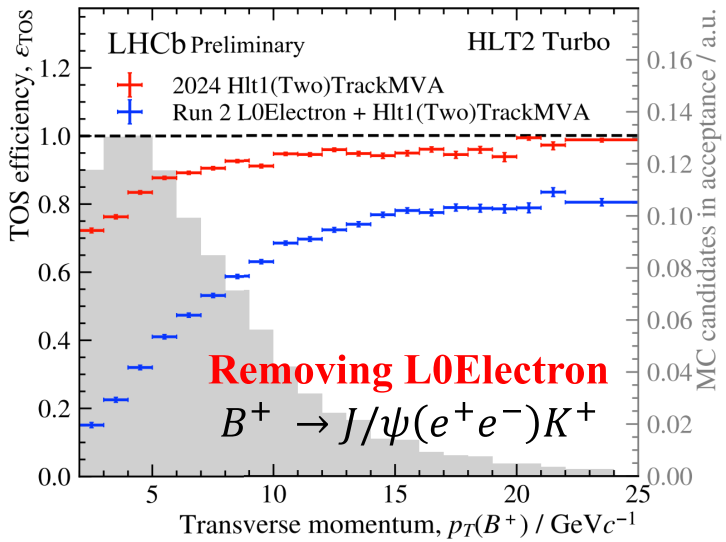
Much higher efficiency for "soft" B decays!

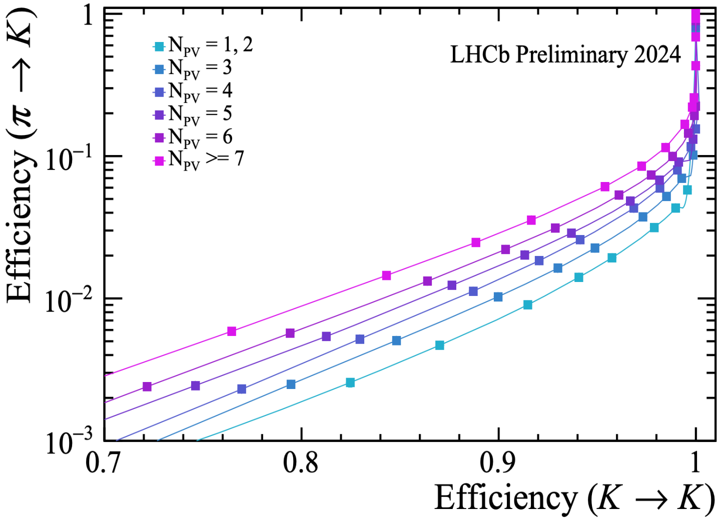
Particle ID performing well in harsher Run 3 environment!

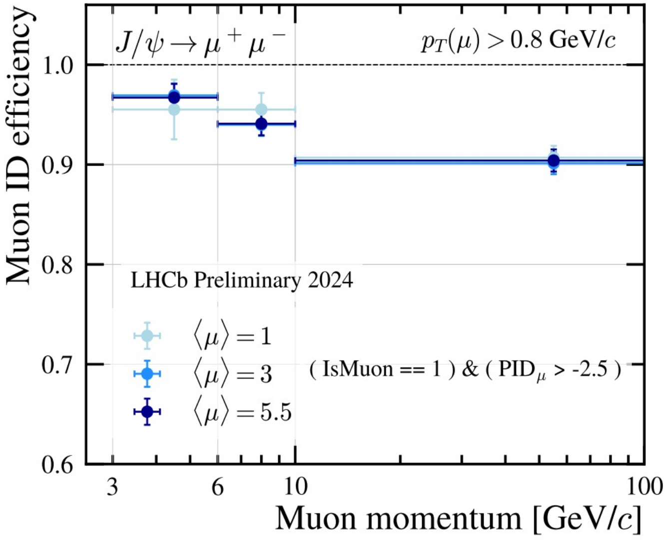
Two charm physics results: Production asym. and $A_{CP}(D^0 \to K_S K_S)$

[LHCb-PAPER-2024-052, CERN Seminar]

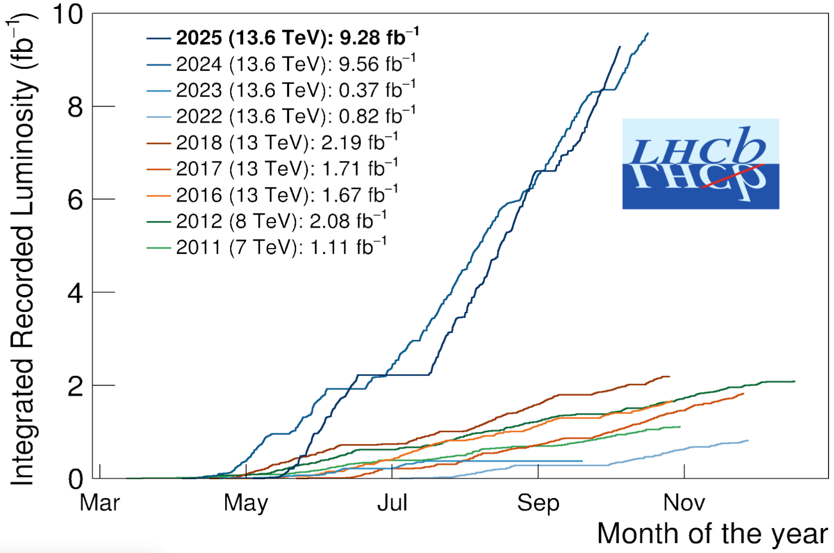






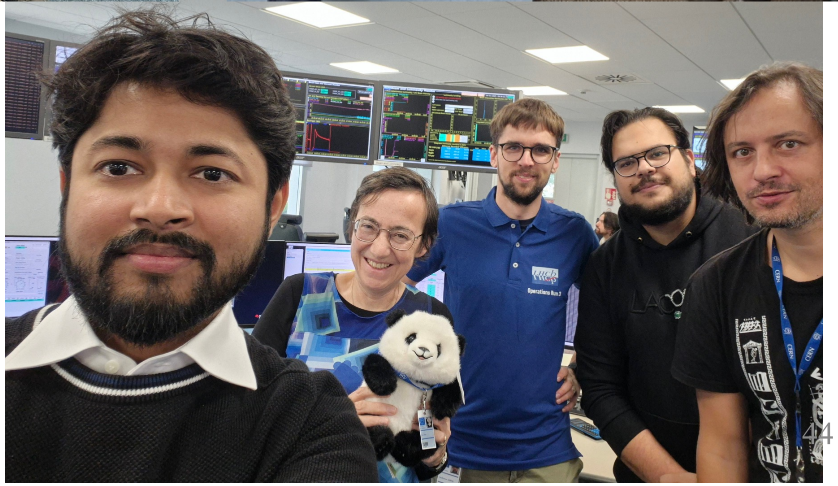


Incredible Run 3 data taking!



More than 20 fb^{-1} Run 3 pp data collected.
More than twice that Run 1-2 (pp)!

More to collect in 2026…



LHCb Future (Upgrade II)

9 fb^{-1} (Run 1 – Run 2) | 50 fb^{-1} (Run 3 – Run 4) | 250 fb^{-1} (Run 5)

Upgrade I (LS2) | Enhancement (LS3) | Upgrade II (LS4)

Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024 2025 2026	2027 2028 2029	2030 2031 2032 2033	2034 2035	2036 2037 2038 2039 2040 2041

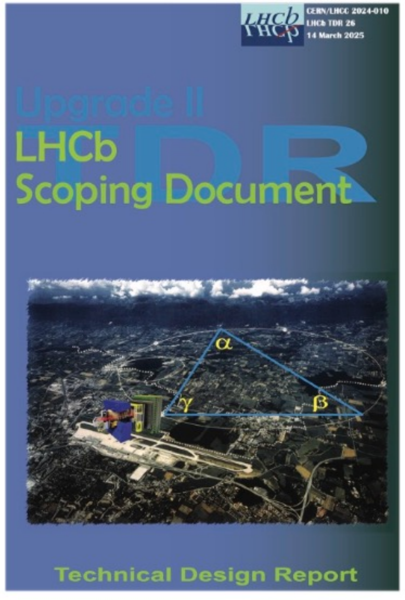
Data rate ~ 4 TB/s
Pile-up ~ 5

We are here

Data rate ~ 12.5 x Upgrade I
Pile-up ~ 8 x Upgrade I

bridge to future accelerators

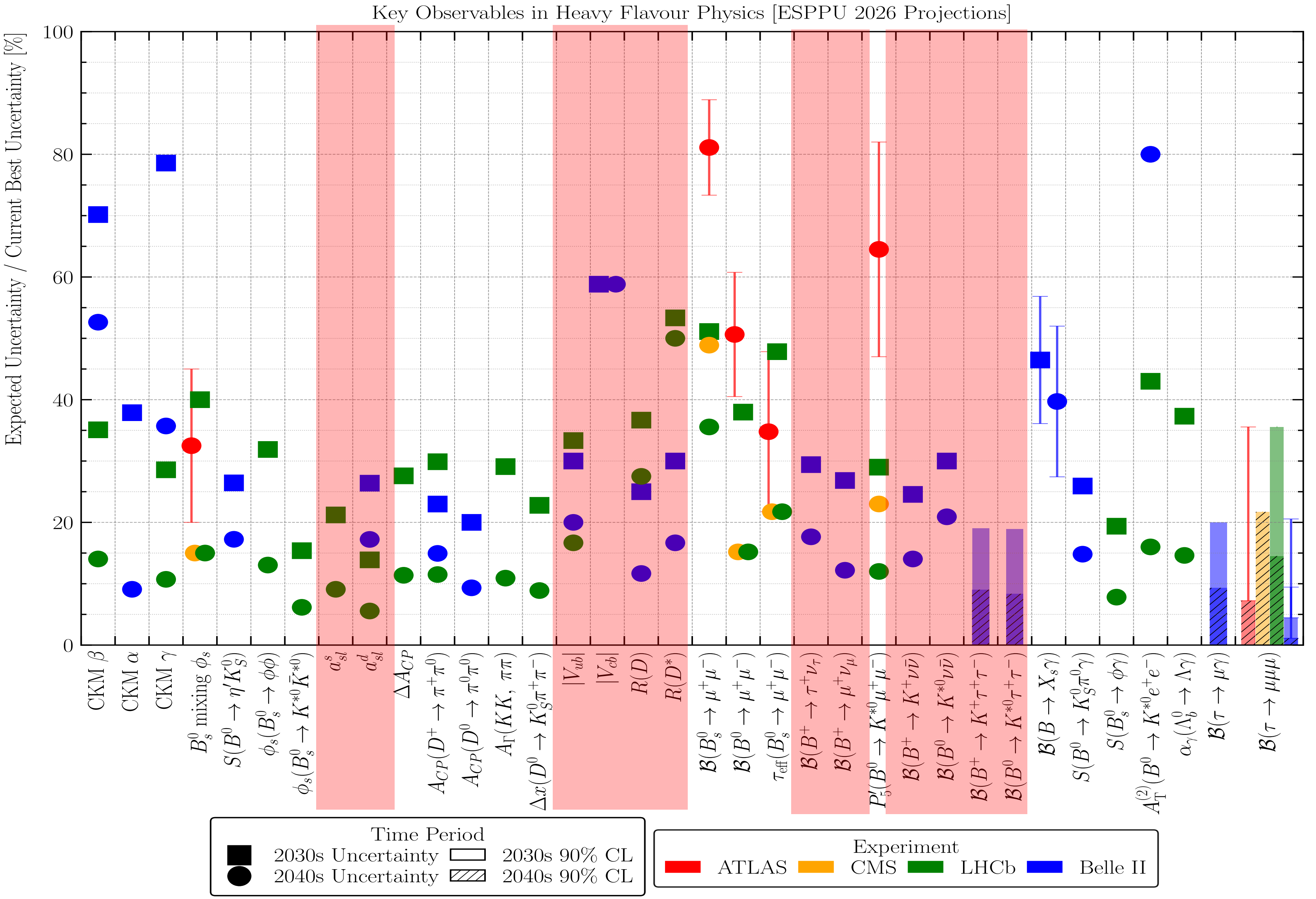
- Starting R&D phase of new technologies
  - precision timing for tracking and PID
  - extreme radiation hardness
  - low-cost monolithic pixels
  - cryogenic cooling (for SiPMs)



Endorsed by CERN Research board (April 2025)!

Towards the TDR in one year!

Future of missing energy decays



LHCb will strive to deliver competitive results to Belle II's missing-energy programme well into the 2040s.

Conclusions

Best experiment (for missing-energy decays)?

For a dynamic heavy-flavour programme,

LHCb <u>needs</u> Belle II and Belle II <u>needs</u> LHCb.

ありがとうございました

Back-up

Need for speed: Simulation

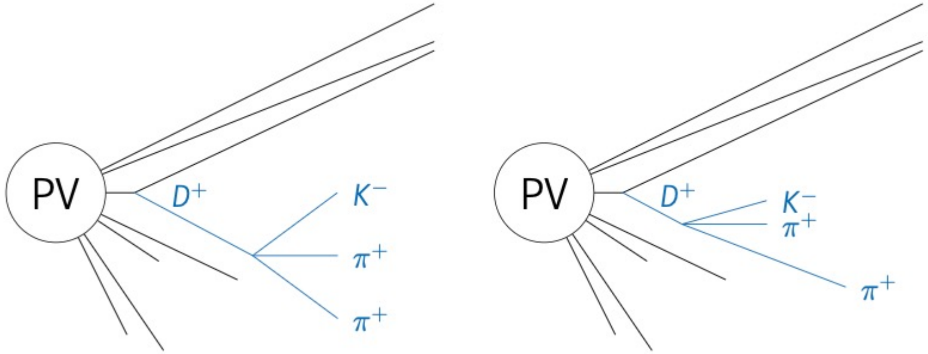
- Tree-level missing-energy decays are abundant → form background to rare modes.
- Need equally large simulated samples.
- **Data vs. MC**
  - Signal $B \rightarrow D^{*}\tau\nu$: once every $1.7{\times}10^{7}$ bunch crossings (or every 0.6 s at LHC).
  - Simulation: ~1 min per event → 1M events ≈ **2 years** (sequential, but in really production parallel).

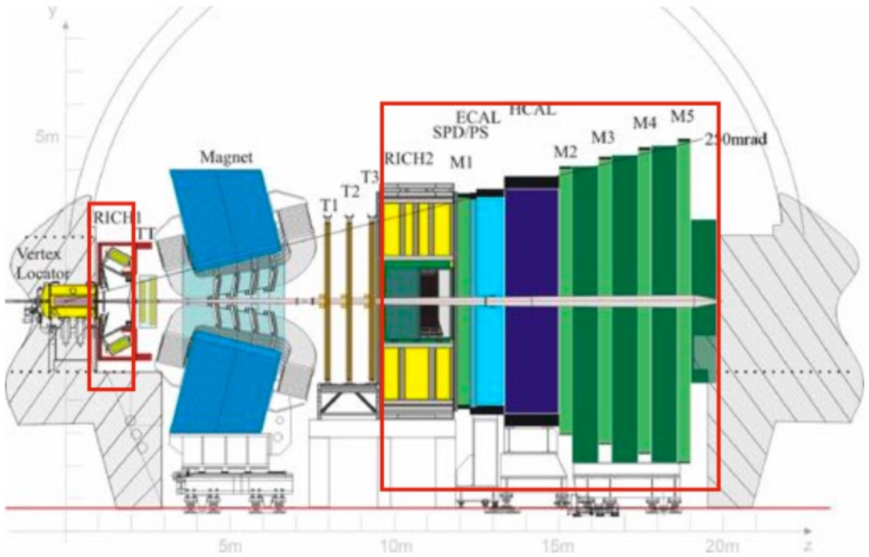
→ **Fast simulation is essential!**

Need for speed: Simulation

See Patrick O's talk

Redecay	Tracker only simulation
Reuse underlying event for different decays. arXiv:1810.10362	Turn off parts of the detector response (shower development, photon propagation in RICH).





Speed up 10-100, same disk space.

Speed up by factor 8, disk space down by 40%

Systematics relative to statistical uncertainty

[LHCb-PAPER-2025-048]

Source of uncertainty	Percentage uncertainty for $\mathcal{B}(B^0 \to K^+\pi^-\tau^+\tau^-)$			
$m_{K^+\pi^-}$ (MeV/c^2)	[792, 992]	[992, 1330]	[1330, 1530]	[1530, 1726]
Combinatorial shape	74%	128%	125%	124%
Misidentified shape	39%	85%	78%	116%
Semileptonic shape	45%	42%	28%	19%
Signal shape	15%	12%	9%	11%
Reweighting	21%	11%	6%	4%
Known quantities	11%	5%	5%	4%
Efficiency	11%	4%	5%	4%

Source of uncertainty	Percentage uncertainty for $\mathcal{B}(B_s^0 \to K^+K^-\tau^+\tau^-)$				
$m_{K^+K^-}$ (MeV/c^2)	[980, 1060]	[1060, 1200]	[1200, 1400]	[1400, 1600]	[1600, 1813]
Combinatorial shape	111%	140%	160%	141%	175%
Misidentified shape	44%	33%	40%	44%	35%
Semileptonic shape	69%	64%	53%	33%	17%
Signal shape	25%	13%	11%	10%	19%
Reweighting	15%	16%	14%	11%	12%
Known quantities	11%	5%	9%	18%	25%
Efficiency	9%	4%	8%	15%	21%

Dominant due to low background statistics for modelling!

Limits in all $m(K^+K^-)$ and $m(\pi^+\pi^-)$ bins

[LHCb-PAPER-2025-048]

Confidence level	Upper limit on $\mathcal{B}(B^0 \to K^+\pi^-\tau^+\tau^-)$				
$m_{K^+\pi^-}$ (MeV/c^2)	[792, 992]	[992, 1330]	[1330, 1530]	[1530, 1726]	
90%	1.4×10^{-4}	2.7×10^{-5}	1.0×10^{-5}	2.7×10^{-6}	
95%	1.6×10^{-4}	3.4×10^{-5}	1.1×10^{-5}	3.3×10^{-6}	
Confidence level	Upper limit on $\mathcal{B}(B_s^0 \to K^+K^-\tau^+\tau^-)$				
$m_{K^+K^-}$ (MeV/c^2)	[980, 1060]	[1060, 1200]	[1200, 1400]	[1400, 1600]	[1600, 1813]
90%	2.0×10^{-4}	1.3×10^{-4}	1.2×10^{-4}	6.8×10^{-5}	3.2×10^{-5}
95%	2.3×10^{-4}	1.5×10^{-4}	1.4×10^{-4}	7.6×10^{-5}	3.6×10^{-5}
Confidence level	Upper limit on $\mathcal{B}(B_s^0 \to K^-\pi^+\tau^+\tau^-)$				
$m_{K^+\pi^-}$ (MeV/c^2)	[792, 992]	[992, 1330]	[1330, 1530]	[1530, 1726]	
90%	6.5×10^{-4}	1.2×10^{-4}	5.1×10^{-5}	1.7×10^{-5}	
95%	7.3×10^{-4}	1.5×10^{-4}	6.2×10^{-5}	2.1×10^{-5}	

Limits of $|C_9^{\tau\tau}|$

[LHCb-PAPER-2025-048]

the-SM effects may be introduced via a shift, Δ, in the Wilson coefficients $C_9^{\tau\tau} = C_9^{\mathrm{SM}} - \Delta$ and $C_{10}^{\tau\tau} = C_{10}^{\mathrm{SM}} + \Delta$, where C_9^{SM} is 4.1 and C_{10}^{SM} is -4.3 [23]. If $\Delta \gg C_{9,10}^{\mathrm{SM}}$ the branching

In this particular case four unknowns must be fixed, which are the components of the τ momentum p_τ^μ. This can be done by exploiting the information on the τ flight direction $\hat{p}_\tau$ (which fixes two unknowns), the mass shell condition for the τ $p_\tau^2 = M_\tau^2$ (one unknown) as well as the momentum conservation in the $\tau \to 3\pi + \nu$ decay, *i.e.* $(p_\tau - p_{3\pi})^2 = p_\nu^2 = 0$ (one unknown), where $p_{3\pi} \equiv (E_{3\pi}, \vec{p}_{3\pi})$ and p_ν are the four-momenta of the 3π system and the ν respectively. With these constraints the modulus p of the τ space momentum is defined up to a twofold ambiguity, being the solution of the following second degree equation (see *e.g.* Ref.[112]):

$$p^2\left(1 - \frac{|\vec{p}_{3\pi}|^2}{E_{3\pi}^2}\right) - p\left(\frac{\vec{p}_{3\pi}}{E_{3\pi}} \cdot \hat{p}_\tau\right)\frac{M_\tau^2 + p_{3\pi}^2}{E_{3\pi}} + M_\tau^2 + \left(\frac{M_\tau^2 + p_{3\pi}^2}{2E_{3\pi}}\right)^2 = 0\,. \qquad (4.12)$$

Confidence level	$B^0 \to K^+\pi^-\tau^+\tau^-$	$B_s^0 \to K^+K^-\tau^+\tau^-$
90%	2.5×10^4	4.5×10^4
95%	2.9×10^4	5.2×10^4

Ambiguities in B momentum reconstruction

LHCb-INT-2011-039

The B_s^0 decay vertex must lie within the plane spanned by the three vertices pV, dV_1 and dV_2. The vectors between the primary vertex and the first or second decay vertex are denoted by $\vec{v}$ and $\vec{w}$ respectively. The B_s^0 and τ momentum vectors are colinear with the spacial vectors between their origin and decay vertices. Scale factors, $L_{1\tau}$, $L_{2\tau}$ and L_B, are used to relate the topological direction vectors to the particle momenta. The basic geometry of the plane in which the B_s^0 and τ momenta lie is depicted in Figure 1.

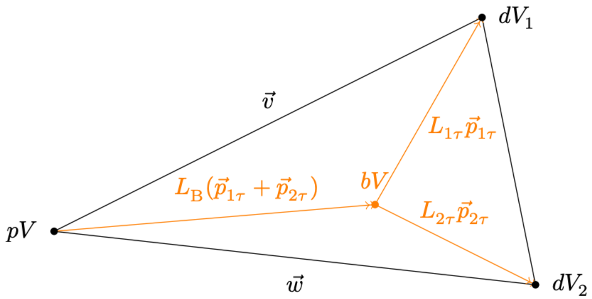


Figure 1 Geometry of the plane containing the B_s^0 and both τ momentum vectors.

L1, L2 and LB are parameters that are found empirically!

The three relations linking the directional vectors to the momenta using scale factors are

$$dV_1 - bV = L_{1\tau}\vec{p}_{1\tau} \quad (1)$$

$$dV_2 - bV = L_{2\tau}\vec{p}_{2\tau} \quad (2)$$

$$bV - pV = L_B(\vec{p}_{1\tau} + \vec{p}_{2\tau}) \quad (3)$$

These relations can be rewritten to a single formula, eliminating the factors $L_{1\tau}$, $L_{2\tau}$ and L_B, as

$$\vec{v} \times \vec{p}_{1\tau} = -\vec{w} \times \vec{p}_{2\tau} \quad (4)$$

The second relation occurs through the fixing of the B_s^0 mass: $(p_{1\tau} + p_{2\tau})^2 = m_B^2$

$$E_{1\tau}E_{2\tau} - \vec{p}_{1\tau} \cdot \vec{p}_{2\tau} = \frac{1}{2}m_B^2 - m_\tau^2 \quad (5)$$

And finally two relations due to the fixing of the neutrino mass

$$(p_{1\tau} - p_{13\pi})^2 = (p_{2\tau} - p_{23\pi})^2 = 0 \quad (6)$$

and two from fixing the τ mass

$$p_{1\tau}^2 = p_{2\tau}^2 = m_\tau^2 \quad (7)$$

The system to be solved thus consists of 8 equations and 8 unknowns, which are the two τ 4-momenta $\{p_{1\tau}, p_{2\tau}\}$. To simplify the algebra, the plane is rotated such that its norm aligns with the z-axis. By doing this the z-components of the two τ momenta as well as the vectors $\vec{v}$ and $\vec{w}$ are set to 0. From this point onwards this will be assumed to be the case.

The $B_s^0 \to \tau^\pm\tau^\mp$ decay with $\tau^\pm \to \pi^\pm\pi^\pm\pi^\mp\nu_\tau$ is theoretically reconstructable up to an 8^{th} order polynomial. In order to find the B_s^0 and τ momenta solutions, the roots of this polynomial need to be determined. These roots are limited to a specified interval and can be calculated by scanning this interval in a certain number of steps.

Ambiguities in B momentum reconstruction

$B^0 \rightarrow K^-\pi^+\tau^+\tau^-$ Case

https://repository.cern/records/k8s3d-gf870

In this particular case four unknowns must be fixed, which are the components of the τ momentum p^μ_τ. This can be done by exploiting the information on the τ flight direction $\hat{p}_\tau$ (which fixes two unknowns), the mass shell condition for the τ $p^2_\tau = M^2_\tau$ (one unknown) as well as the momentum conservation in the $\tau \to 3\pi + \nu$ decay, *i.e.* $(p_\tau - p_{3\pi})^2 = p^2_\nu = 0$ (one unknown), where $p_{3\pi} \equiv (E_{3\pi}, \vec{p}_{3\pi})$ and p_ν are the four-momenta of the 3π system and the ν respectively. With these constraints the modulus p of the τ space momentum is defined up to a twofold ambiguity, being the solution of the following second degree equation (see *e.g.* Ref.[112]):

$$p^2\left(1 - \frac{|\vec{p}_{3\pi}|^2}{E^2_{3\pi}}\right) - p\left(\frac{\vec{p}_{3\pi}}{E_{3\pi}} \cdot \hat{p}_\tau\right)\frac{M^2_\tau + p^2_{3\pi}}{E_{3\pi}} + M^2_\tau + \left(\frac{M^2_\tau + p^2_{3\pi}}{2E_{3\pi}}\right)^2 = 0\,. \qquad (4.12)$$

LHCb-INT-2011-039

$B^0_s \rightarrow \tau^+\tau^-$ Case

https://arxiv.org/pdf/1703.02508

The unknown quantities are

- the decay vertex of the B^0_s meson: bV,
- the momentum of the B^0_s meson: $\vec{p}_B$,
- the momenta of the two τ leptons: $\vec{p}_{1\tau}$ and $\vec{p}_{2\tau}$,
- the momenta of the two neutrinos: $\vec{p}_{1\nu}$ and $\vec{p}_{2\nu}$.

of the $B \to \tau^+\tau^-$ decay chain, described in detail in Refs. [35, 36], has been developed. It combines geometrical information about the decay and mass constraints on the particles (B, τ and ν) in the decay chain to calculate the τ momenta analytically. The possible solutions for the two τ momenta are found as solutions of a system of two coupled equations of second degree with two unknowns. The finite detector resolution and approximations made in the calculation prevent real solutions being found for a substantial fraction of the signal events. However, several intermediate quantities associated with the method are exploited to discriminate signal from background.

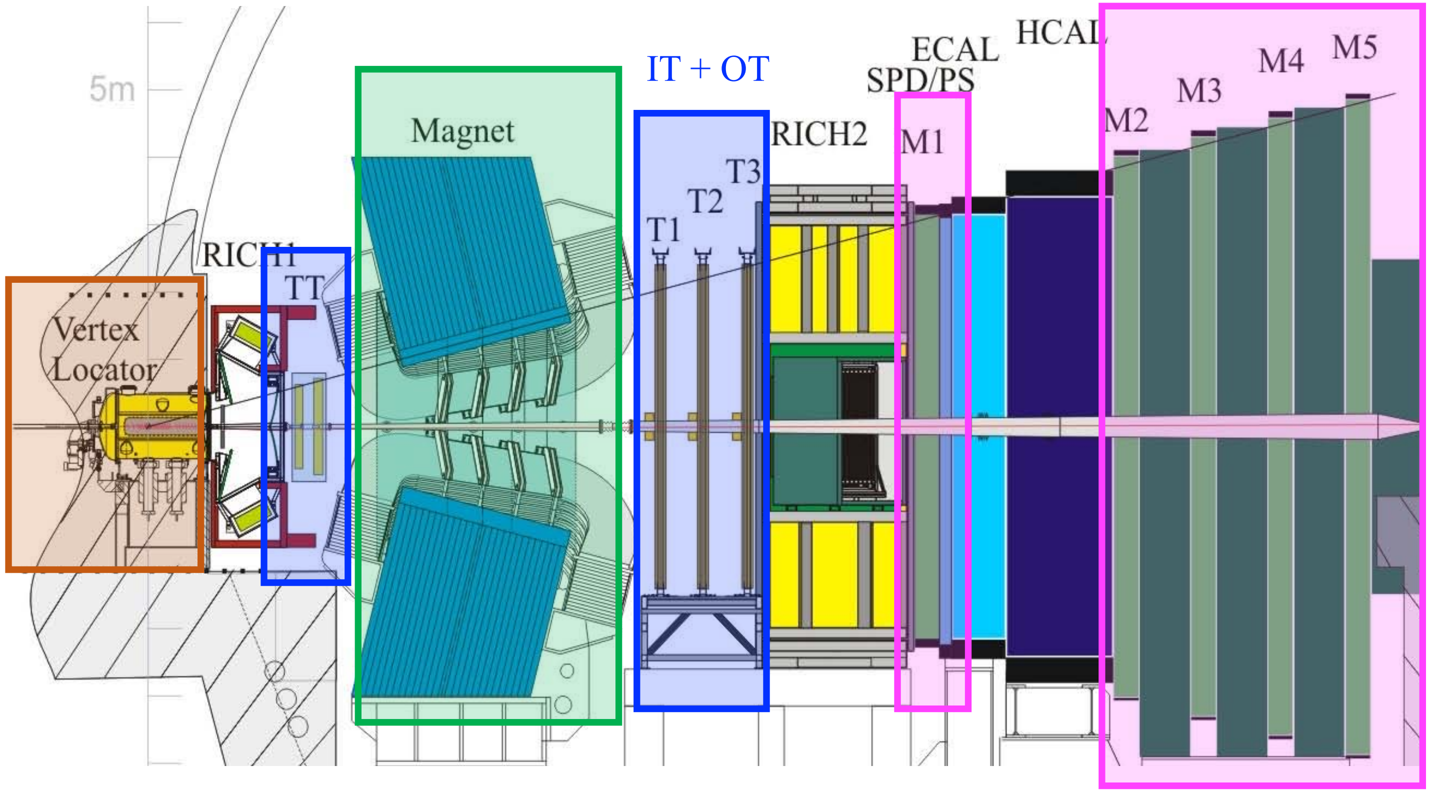
Track and Vertex reconstruction [LHCb-DP-2014-002]

Vertex locator
- 42 silicon modules provide r and ϕ coord.
- Retractable halves
- 8mm from beam in data taking

Tracking stations
- TT and IT: silicon microstrips
- OT: Straw-tube modules

Dipole magnet
- 4 Tm magnetic field
- Polarity inverted every few weeks

Muon stations
- Consists of 5 stations (M1-M5)
- MWPCs + triple GEM



- Good decay time res. $\sigma_{\tau} \sim 45\ fs\ wrt\ \tau_B \sim 1.5\ ps$
- Good momentum res. $\frac{\delta p}{p} \sim 0.5\% - 1\%\ (5 - 200\ GeV)$

Particle identification (PID)

[LHCb-DP-2014-002]

Ring imaging Cherenkov detectors

- PID for kaons, pion and protons
- Covers a wide momentum range

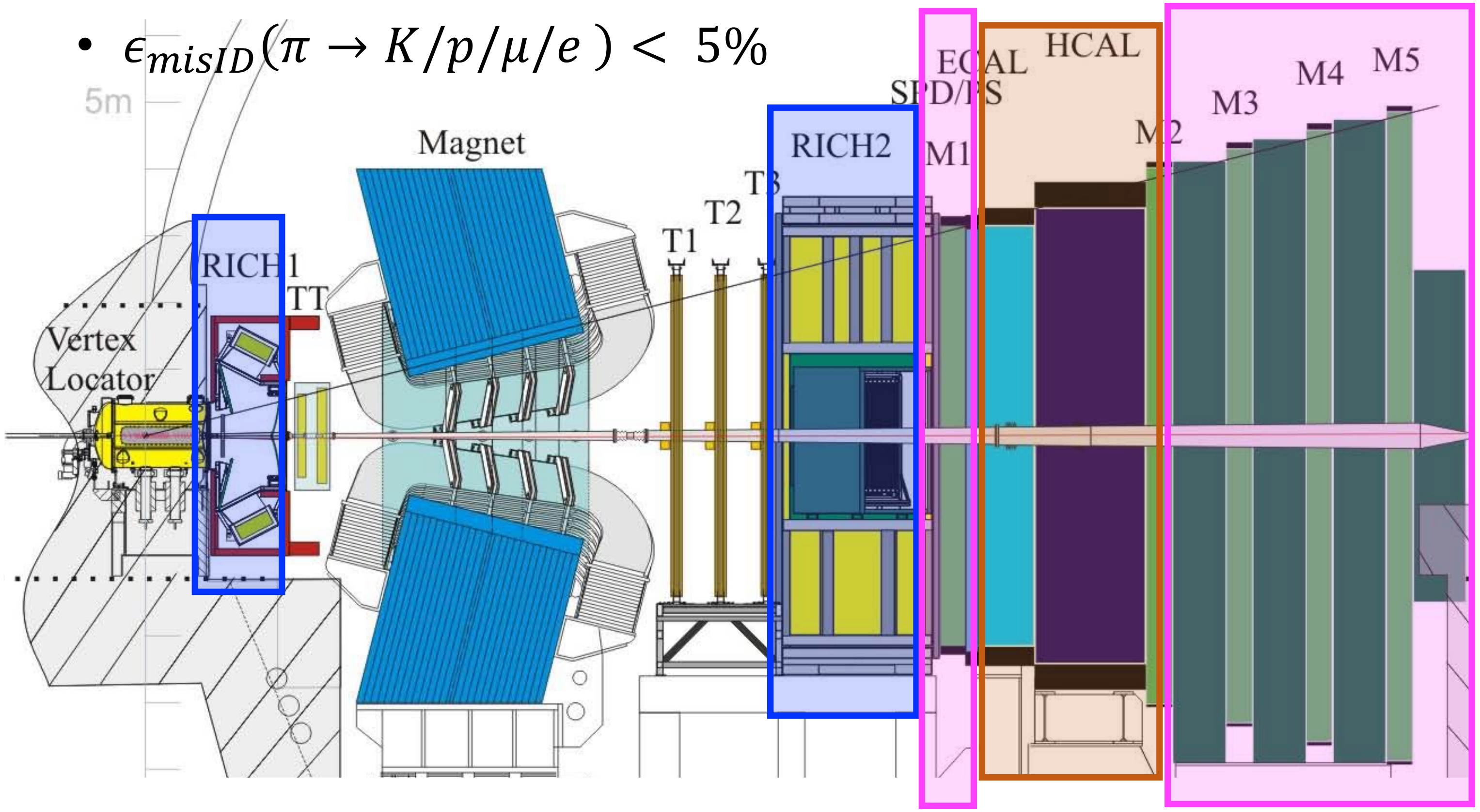
Calorimeters

- SPD,PS,ECAL,HCAL
- PID for e, γ, π^0
- Energy and position for neutral objects and trigger for e, γ

Muon stations

- 5 stations (M1-M5) have high purity PID for muons

- $\epsilon_{PID}(K \to K) > 95\%.$
- $\epsilon_{misID}(\pi \to K/p/\mu/e) < 5\%$

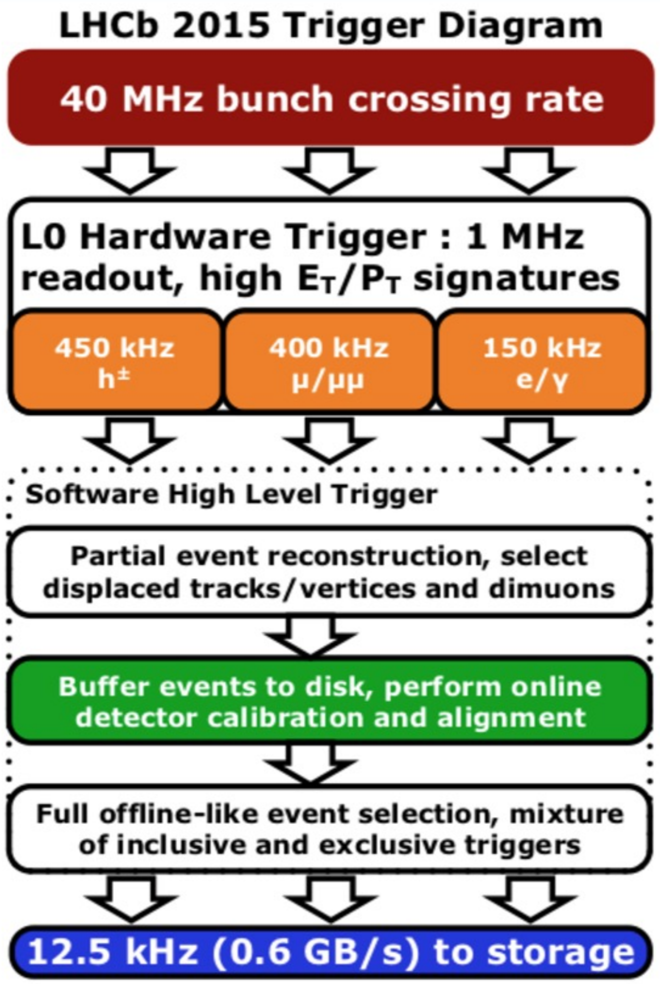


SPD: Scintillating pad detector
PS: Preshower

LHCb trigger (2015-2018)

[2019 JINST 14 P04006, Comput.Phys.Commun. 208 (2016) 35-42]

- Trigger needed to **reduce storage and readout costs with good signal to background ratio**.
- Consists of three stages:
  - **L0**: Hardware, E_T/p_T thresholds.
    40 MHz → 1 MHz.
  - **HLT1**: Software, partial reconstruction,
    1 MHz → 150 kHz.
  - **HLT2**: Full event reconstruction,
    100 kHz → 12.5 kHz.

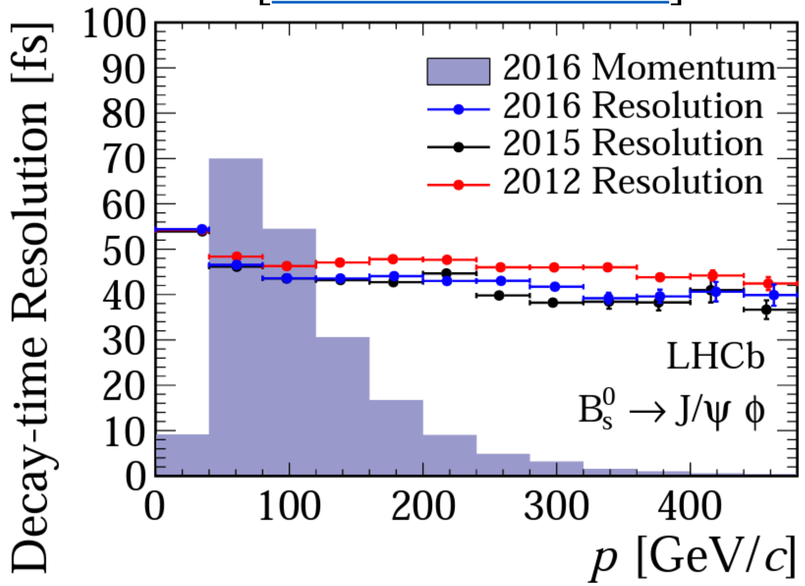


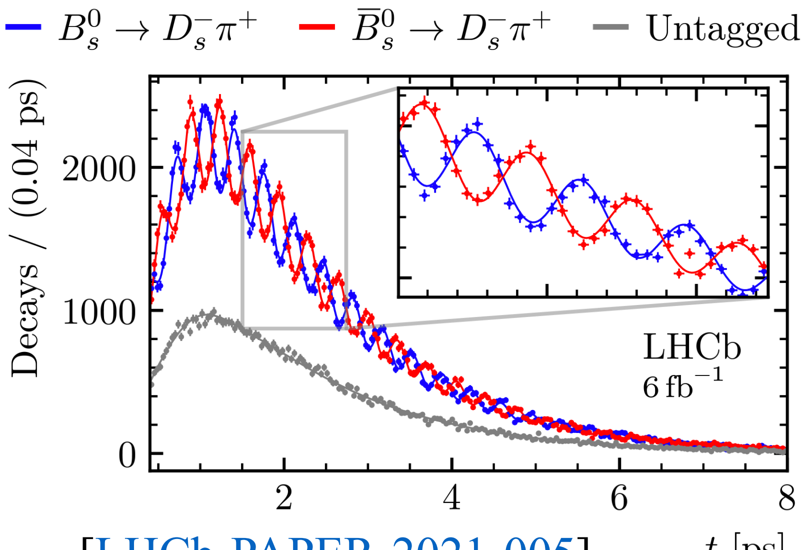
L0: Level 0 trigger
HLT: High level trigger

Vertex reconstruction

Excellent vertexing in VELO! Can still reconstruct downstream decays (K_S, Λ).

[LHCb-DP-2019-001]





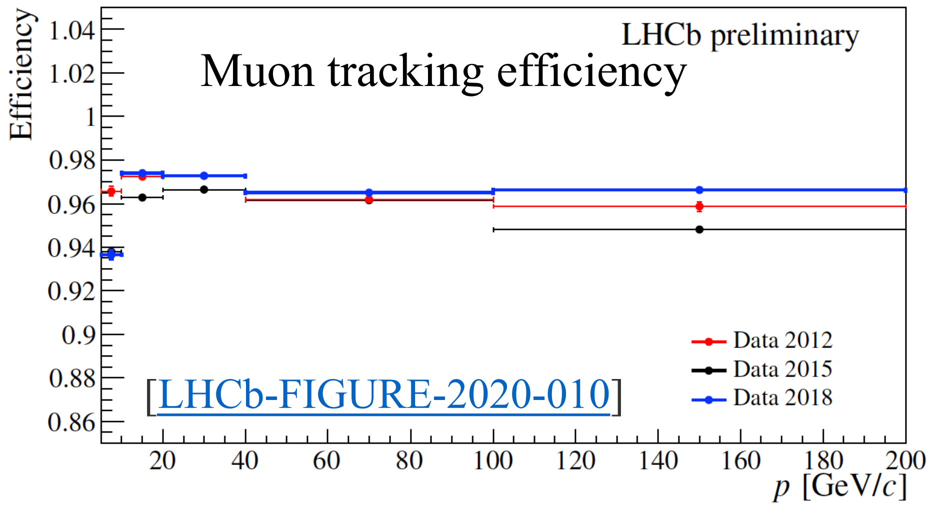
[LHCb-PAPER-2021-005]

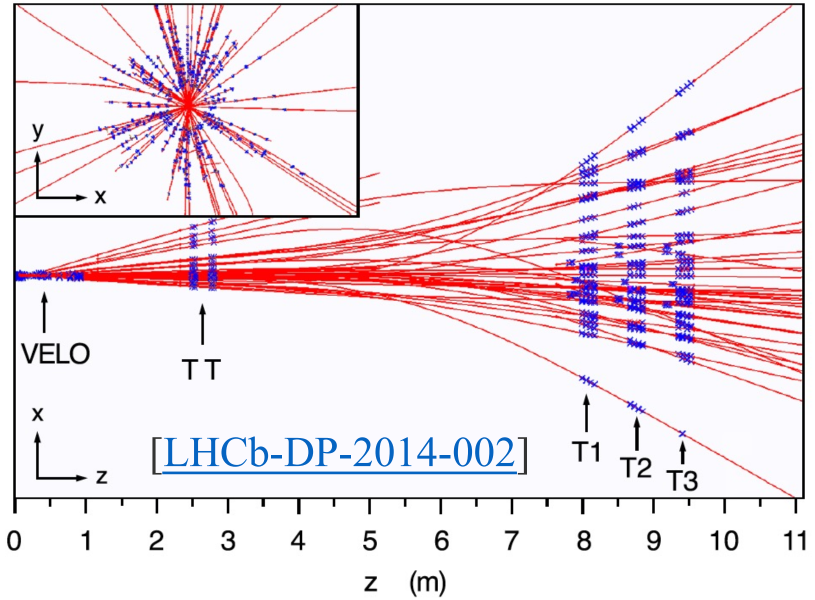
- Good resolution on **Impact Parameter** (IP) required for efficiently selecting B decays: $\sigma_{IP} \sim 20\ \mu m$ for high p_T tracks.
- Good resolution on **decay time** crucial for time-dependent CP violation analyses: $\sigma_\tau \sim 45\ fs\ wrt\ \tau_B \sim 1.5\ ps$

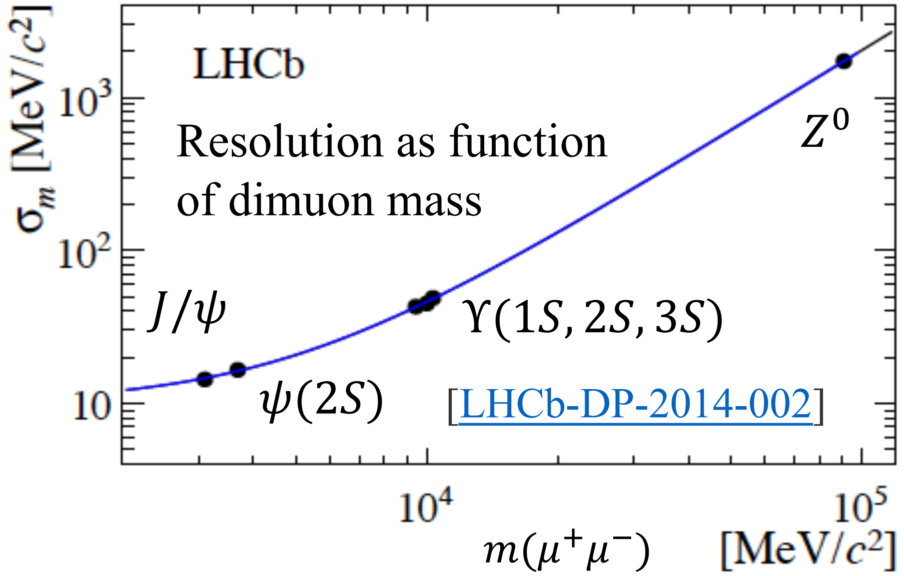
Track reconstruction

Excellent track reconstruction!

- $\epsilon(tracking) \sim 96\%$
- $\frac{\delta p}{p} \sim 0.5\% - 1\%\ (5 - 200\ GeV)$
- $\sigma(m_{J/\psi}) \sim 15\ MeV$

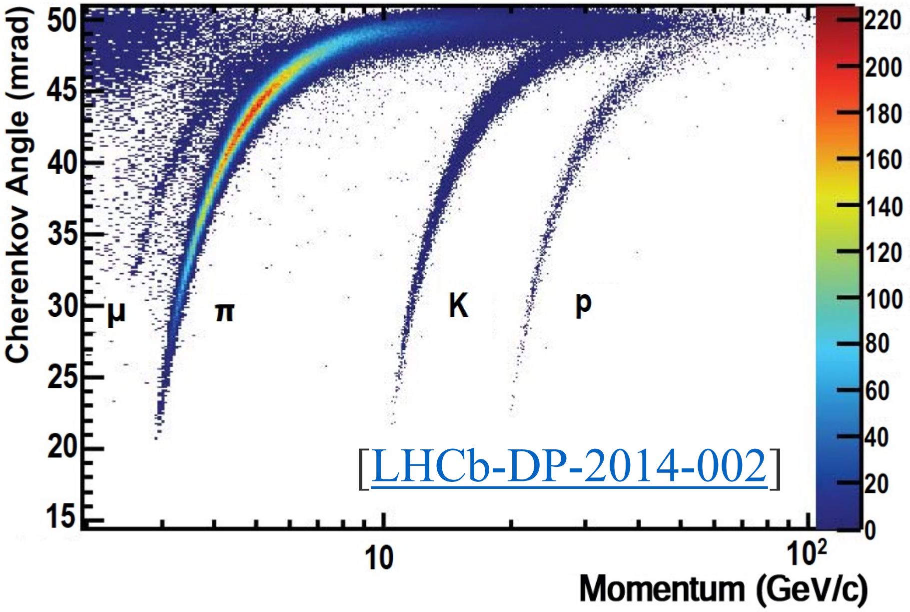


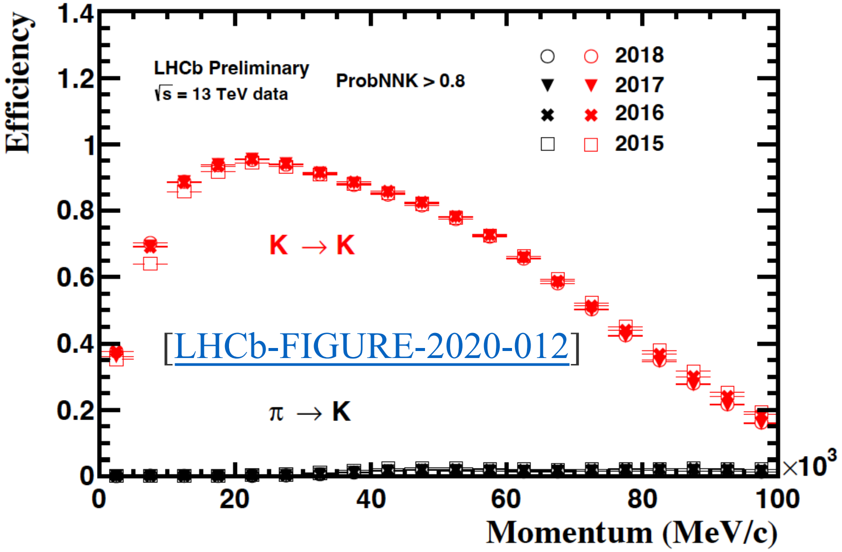


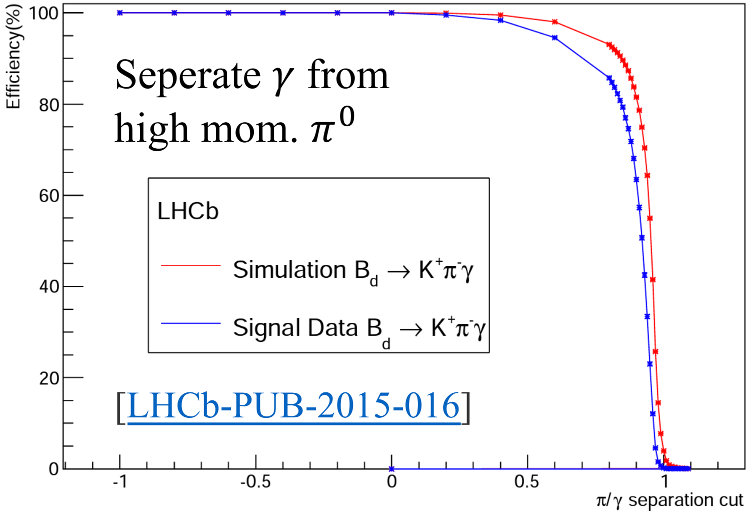


Particle identification performance

- Charged: Combine info from RICH, CALO, MUON.
  - $\epsilon_{PID}(K \rightarrow K) > 95\%$ (same for μ and lower for e)
  - $\epsilon_{misID}(\pi \rightarrow K/p/\mu/e) < 5\%$
- Neutral: Dedicated NN for identifying deuterons and separating γ from hadrons, $e^{\pm}$ and high-energy π^0s.

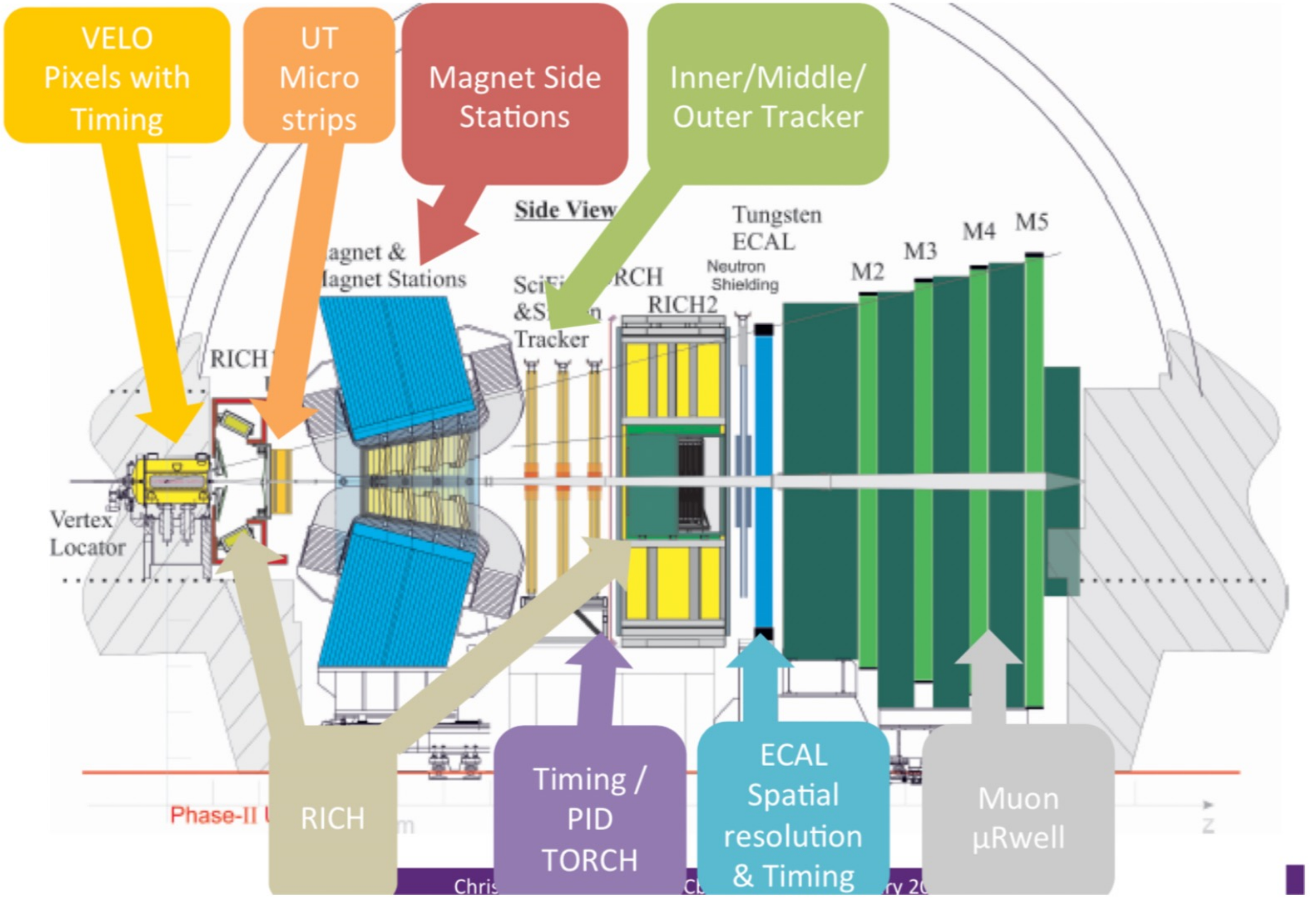






π/γ

Upgrade II



VELO
Pixels with
Timing
UT
Micro
strips
Magnet Side
Stations
Inner/Middle/
Outer Tracker
Side View
Tungsten
ECAL
Neutron
Shielding
M2
M3
M4
M5
RICH2
Tracker
Vertex
Locator
RICH
Timing /
PID
TORCH
ECAL
Spatial
resolution
& Timing
Muon
µRwell