Unexpected LHCb

Neutrals, Neutrinos, Taus, and all that

2021 Belle II physics week
December 2, 2021

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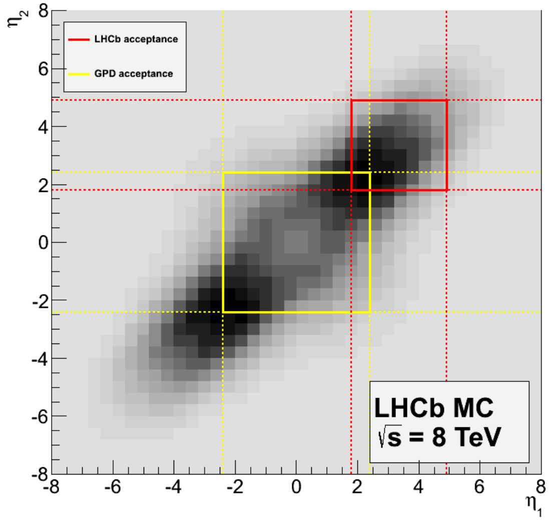
Goals today:

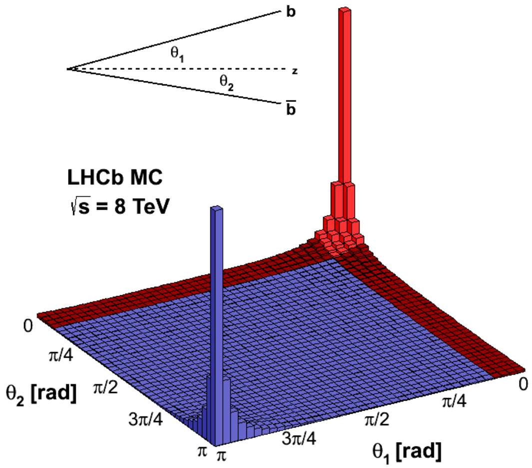
- This talk:
  - Show how LHCb uses the strengths of its detector to overcome the limitations of the environment
  - Focus on *key techniques* -- not a complete "analysis seminar"
- Beyond this talk:
  - Stimulate thinking about new ways to use the information you have to approach analyses in new ways and unlock "impossible" signals
  - Prevent you from being locked into "conventional" analysis paradigms as the only way to do things

Outline

- Introduction to LHCb & our “environment” in data
- Hadronic B decays
  - LHCb standard technique overview
  - New technology in $B^+ \to K^+\pi^0$
  - Extensions
- Semileptonic B decays
  - General LHCb approaches
  - Tau analyses
    - Muonic
    - 3-prong
- Upgrade preview

Heavy Flavor at LHC





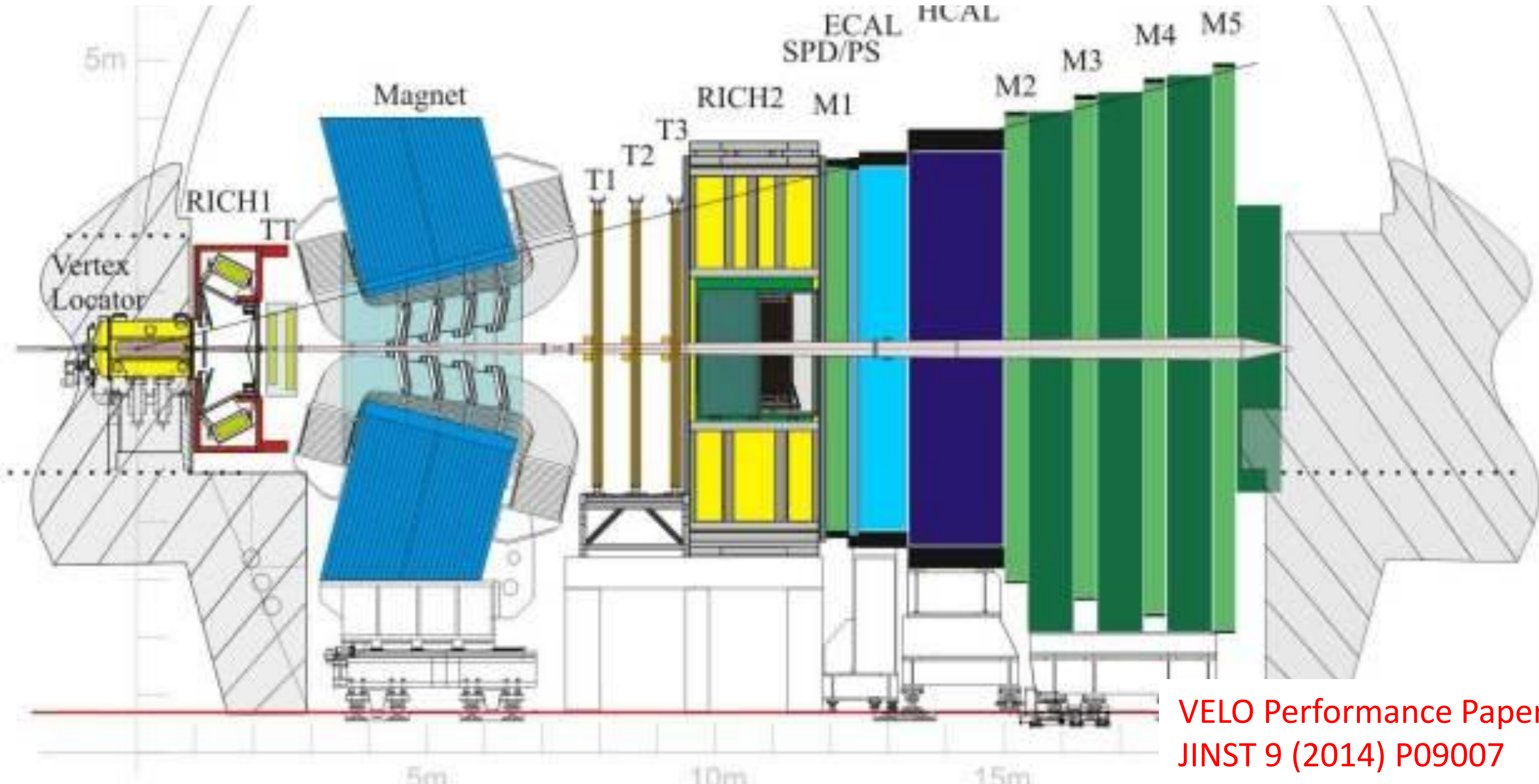
- LHC collisions produce copious amounts of beauty and charm
  - At 7 TeV: $\sigma_{b\bar{b}}$ ~ 250 μb
  - At 13 TeV: $\sigma_{b\bar{b}}$ ~ 530 μb
  - Production dominantly occurs at high η with highly-boosted CM frame
  - Fragmentation (averaged in acceptance): 62% B, 12% Bs, 26% baryon

- Central detector ($|\eta| < 2.5$) scheme covers only 52% (45%) of b quark (pair) production despite surrounding >98% of the solid angle

The LHCb Detector

- LHCb approach: focus on forward direction: cover 27% (25%) of (pair) production while instrumenting < 3% of the solid angle
  - Lumi @ LHCb ~ $3 \times 10^{32}/cm^2/s \rightarrow 40{,}000\ b\bar{b}/s$ produced in acceptance (~400 billion per snowmass standard year)

- Coverage is from $\approx$ 15 mrad - 300(250)mrad in the horizontal (vertical)
  - $\approx$ 1°-17° (very roughly)



VELO Performance Paper:
JINST 9 (2014) P09007

The LHCb Detector

Charged particles ($e, \mu, p\ \pi^{\pm}, K^{\pm}$) are bent into/out of the page and their charge, momentum, and trajectory are measured (dipole spectrometer)

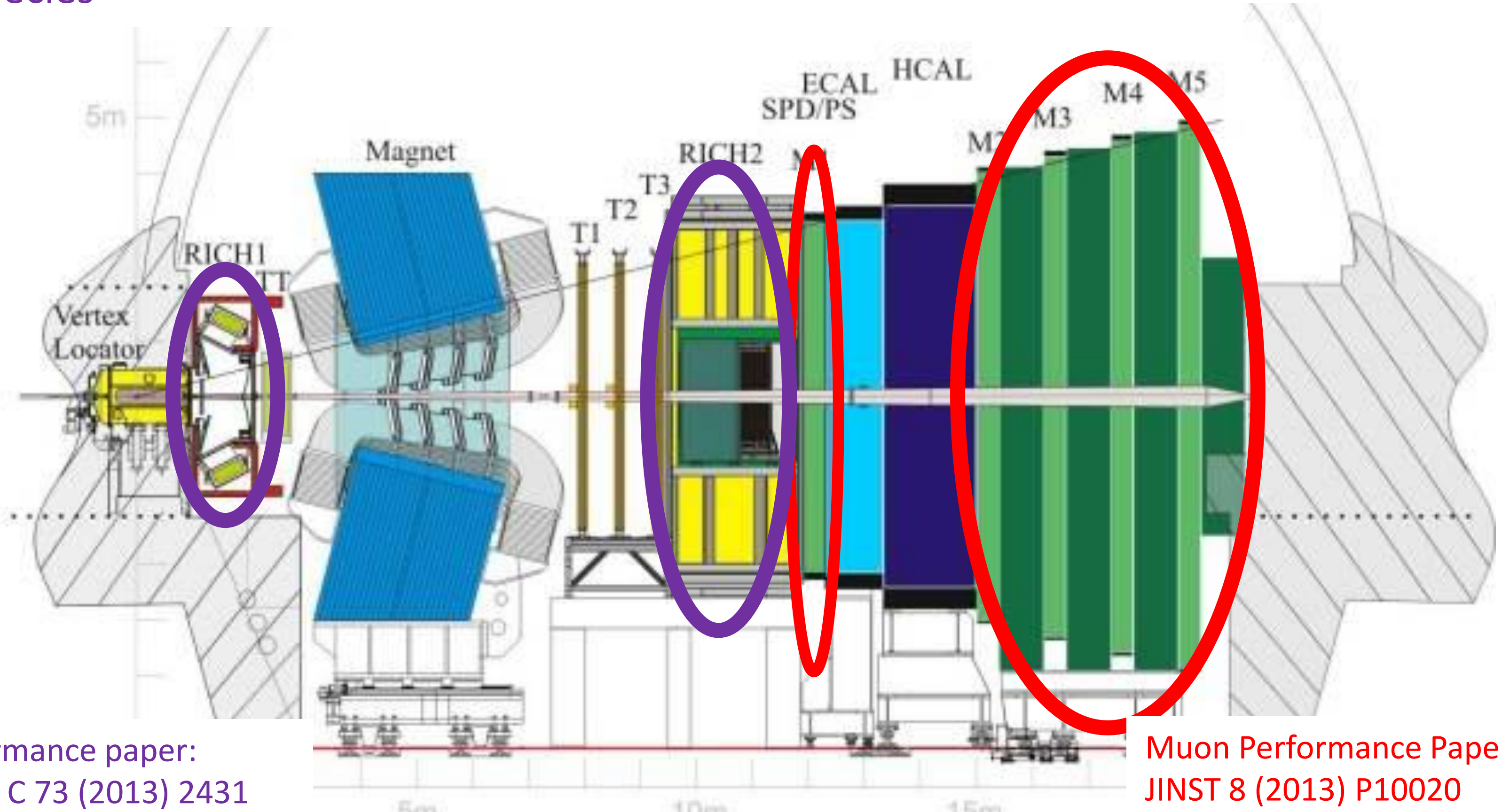
b-hadron decay products are distinguished from proton-proton collision fragments via their impact parameter with respect to reconstructed pp vertices

VELO Performance Paper: JINST 9 (2014) P09007

The LHCb Detector

Dedicated Gas Cherenkov detectors provide measurements of $\theta_c = \theta(v/c)$ to separate different particle species

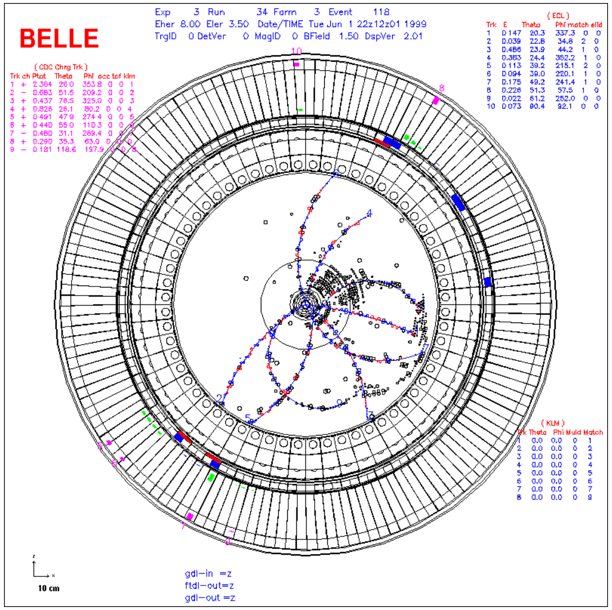
High-energy muons are not easily stopped by material and are identified by their exiting out the back of the detector

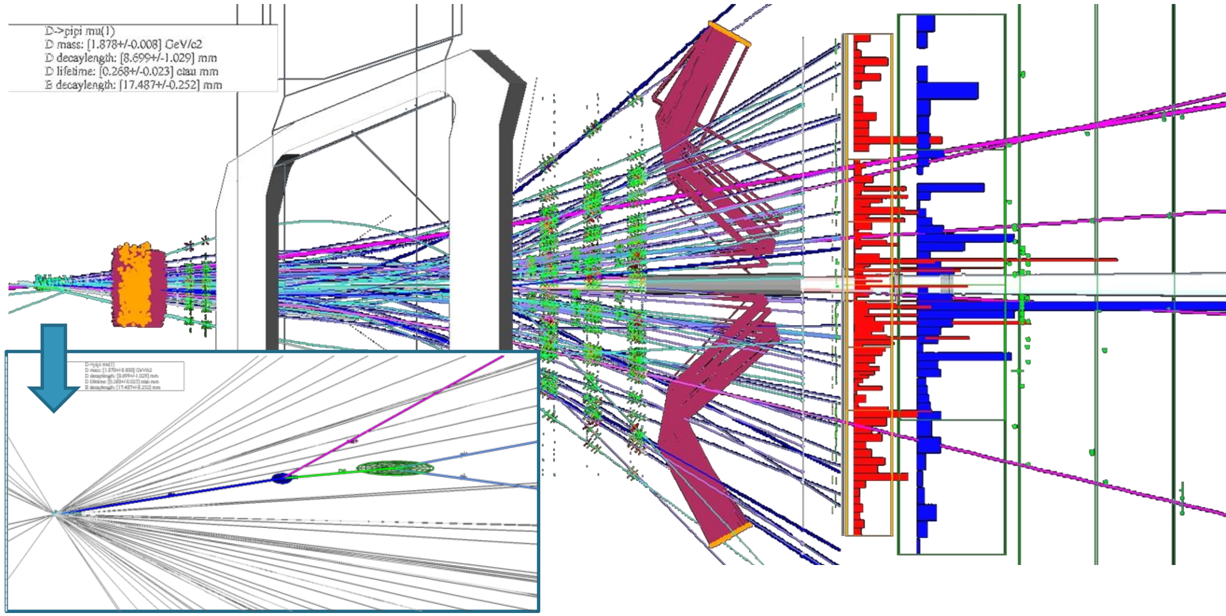


RICH Performance paper:
Eur. Phys. J. C 73 (2013) 2431

Muon Performance Paper:
JINST 8 (2013) P10020

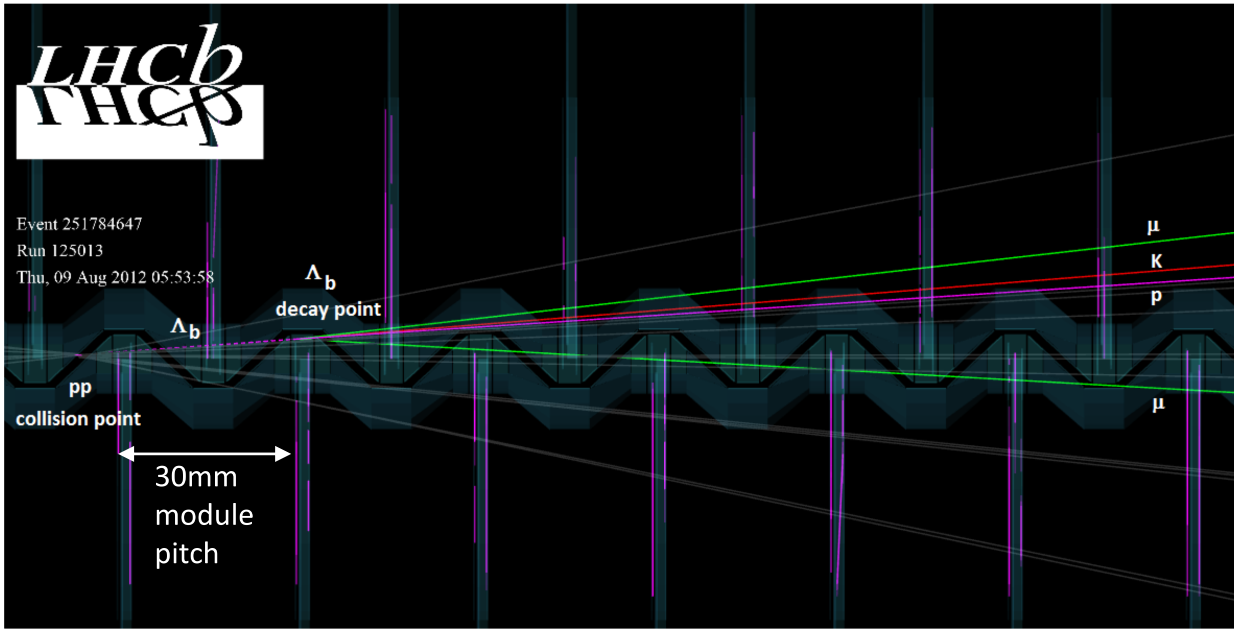
Experimental Environments

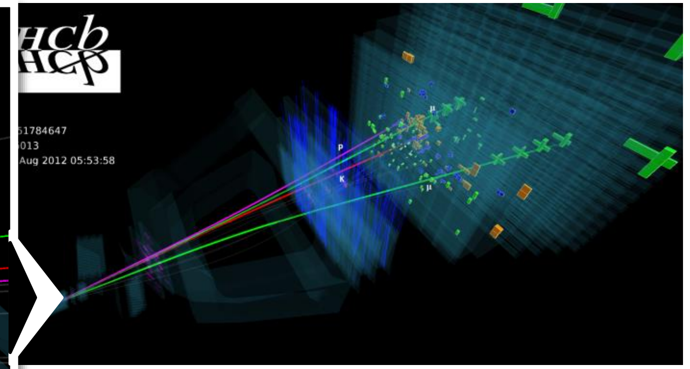




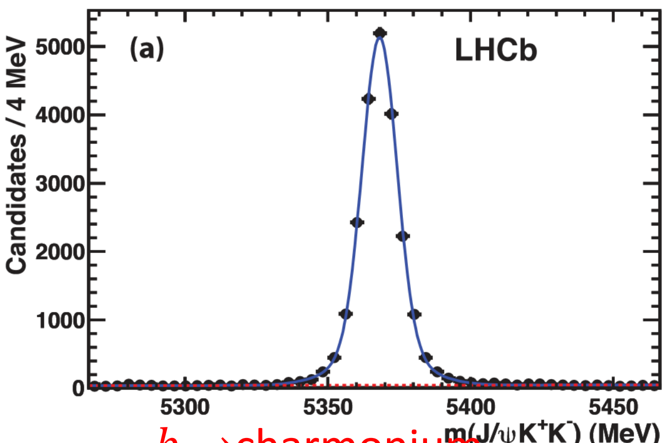
- B-factories: exploit clean BB ***production*** from $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ $(Q = 20\ \mathrm{MeV})$
  - *A priori* knowledge of B energy and collision CM, no extra particles in signal events
  - Easy to cross-feed tracks due to low CM momentum of B mesons
    Event shape needed to separate $B\bar{B}$ vs more frequent $e^+e^- \to q\bar{q},\ q = u, d, s, c$
- LHCb: exploit clean B hadron ***decay vertex***
  - At LHC energies, b hadrons fly macroscopic distances before decay: use displaced vertex, large impact parameter of charged tracks, etc
  - Production is $gg \to b\bar{b} + MPI + showering + ISR + \cdots$, many extra tracks, very large background for neutrals

LHCb Events

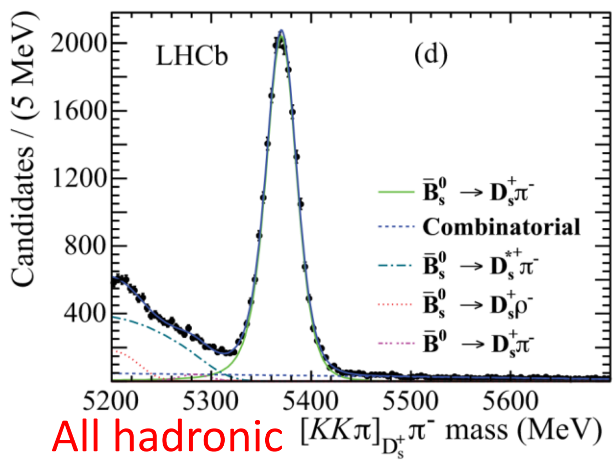




- Reconstruction of secondary vertex *extremely* clean
  - Flight distance up to ~cm scale
  - Impact parameter resolution (15 +29/pT[GeV]) μm
- Dominant background is other (partially-reconstructed) B decays & combinatorial, misID



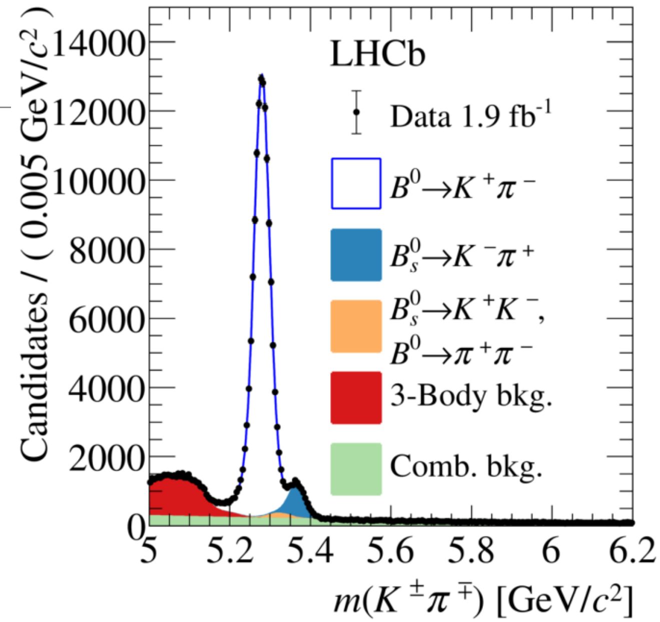
b →charmonium
[PRD 86, 052006 (2013)]

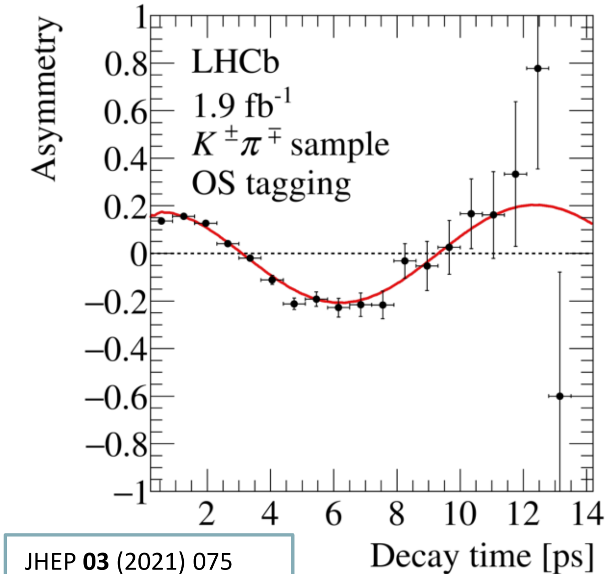


All hadronic
[PRL 113, 172001(2014)]

Example

- Excellent example of a mode that plays to LHCb strengths: $B^0 \to K^+\pi^-$
  - Only two tracks to reconstruct (high efficiency)
  - Kaon in final state (most PV tracks are pions)
  - 2×10^{-5} branching fraction is large (enough) given $10^4 b\bar{b}$/s
  - Momentum and vertex (~ lifetime) resolution allows clear separation of B^0, B_s^0

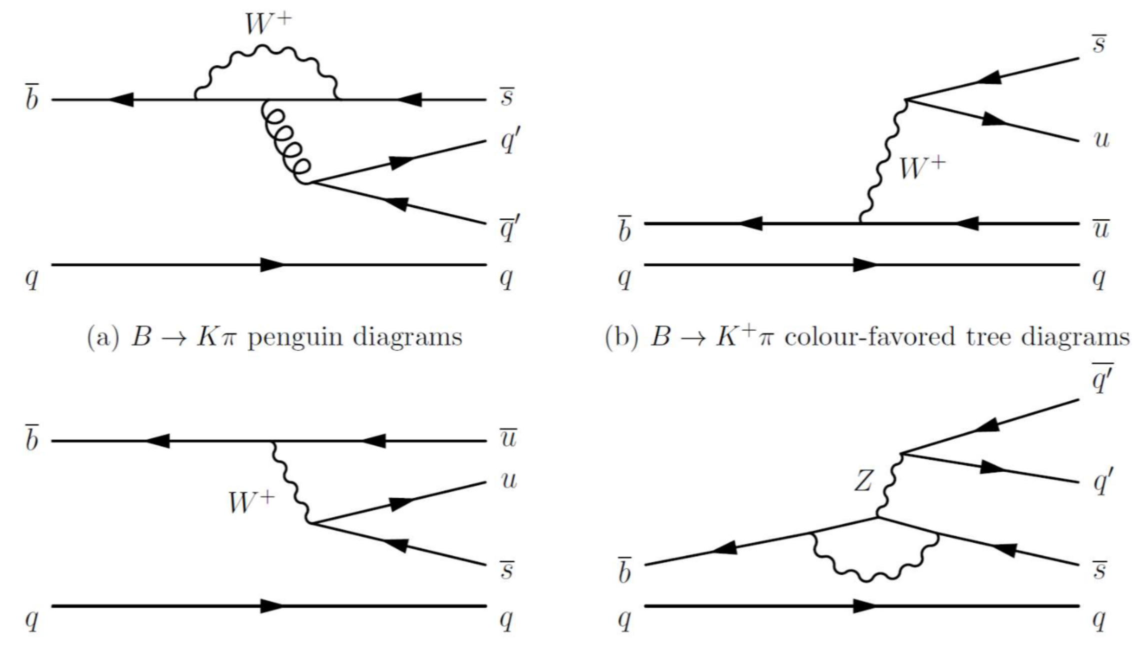




JHEP **03** (2021) 075

The $B \rightarrow K\pi$ System

- $B^0 \rightarrow K^+\pi^-$, $B^0 \rightarrow K^0\pi^0$, $B^+ \rightarrow K^+\pi^0$, $B^+ \rightarrow K^0\pi^+$
- Dominated by QCD penguin diagrams
  - Suppressed by loop
  - Tree suppressed by V_{ub}
- Different $K\pi$ decays have contributions from different diagrams
- Potentially sensitive to new physics through massive virtual particles in loops



(a) $B \rightarrow K\pi$ penguin diagrams

(b) $B \rightarrow K^+\pi$ colour-favored tree diagrams

(c) $B \rightarrow K\pi^0$ color-suppressed tree diagrams

(d) $B \rightarrow K\pi^0$ electroweak penguin diagrams

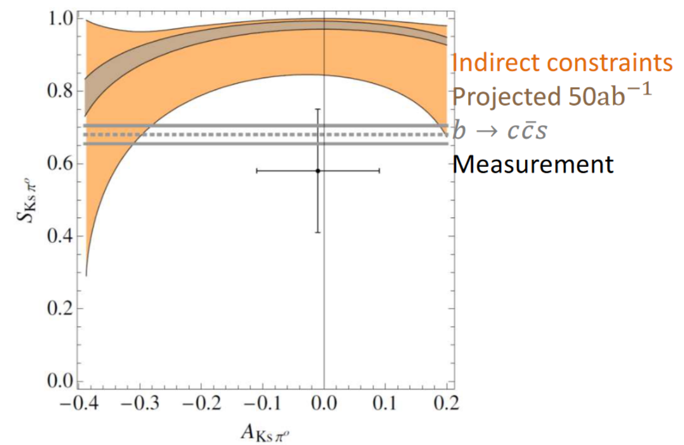
- Skipping many details…

Will Parker, CERN LHC seminar, 1Dec2020

The $K\pi$ Puzzle Continued

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\mathrm{B}(K^0\pi^+)}{\mathrm{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\mathrm{B}(K^+\pi^0)}{\mathrm{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\mathrm{B}(K^0\pi^0)}{\mathrm{B}(K^+\pi^-)}$$

- All $K\pi$ CP asymmetries and branching fractions can be incorporated in more precise equivalence
- Current measurements (HFLAV 2018) predict $A_{CP}(K^0\pi^0) = -0.150 \pm 0.032$, value measured by B factories: 0.01 ± 0.10
- Fits to $K\pi$ observables show some tension
- Can be resolved by enhancement of color-suppressed trees or NP in penguins
- $B^0 \to K^0_S\pi^0$ is a key component of Belle II physics program



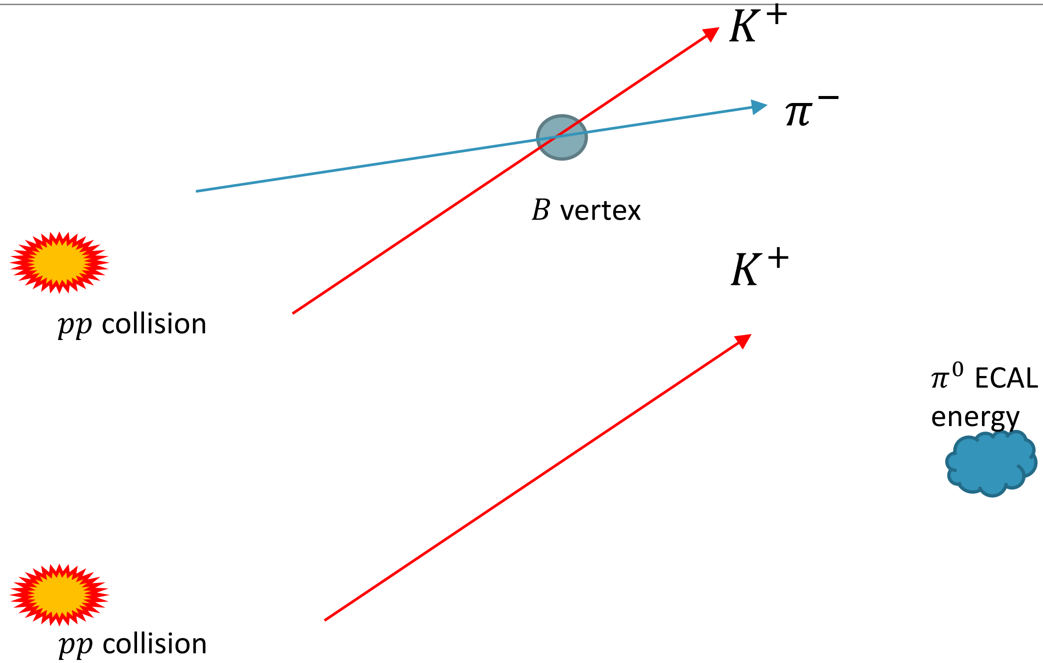
Phys. Rev. D 78, 111501(R)

Buras et al., Eur. Phys. J. C 32 (2003) 45, Phys. Rev. Lett. 92 (2004) 101804, Nucl. Phys. B 697 (2004) 133;
S. Baek et al., Phys. Rev. D 71 (2005) 057502, Phys. Lett. B 653 (2007) 249, Phys. Lett. B 675 (2009) 59;
M. Gronau, Phys. Lett.B 627 (2005) 82; N. B. Beaudry et al., JHEP01(2018) 074; R. Fleischer et al., Phys. Lett. B 785 (2018) 525

01/12/2020 9

- “impossible” 1-track mode $B^+ \to K^+\pi^0$ is also of clear interest to check consistency of sum rule
  - Covered by B-factories, but bringing LHCb statistics to bear is tantalizing (bf ~ 1.3×10^{-5})

LHCb Events & $B \to K^+\pi^{-/0}$



- Have only a single track and a blob in the calorimeter, no conventional vertex is possible!
  - *Is there a way to identify the signal without knowing the trajectory of the 2nd daughter particle?*

- Before we talk about the answer, lets look back in time a bit…

Some Time Travel

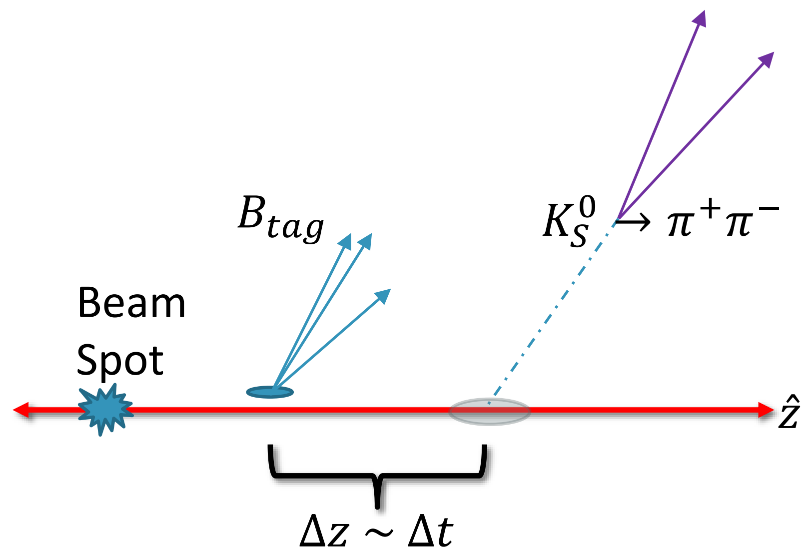
- LHCb's problems in this mode look unique, but in reality *they are not*!
- A similar difficulty exists at the B-factories: Want to do time-dependent A_{CP} in $K_S^0\pi^0$, $K_S^0\pi^0\gamma$, etc
  - B-tagging can yield clean signal peaks, but no secondary vtx = no decay time info!
- Their solution: compute a vertex between the K_S^0 trajectory and the beam axis
  - Underlying approximation is that $\Delta x, \Delta y \ll \Delta z$

arXiv:hep-ex/0403001 (hep-ex)

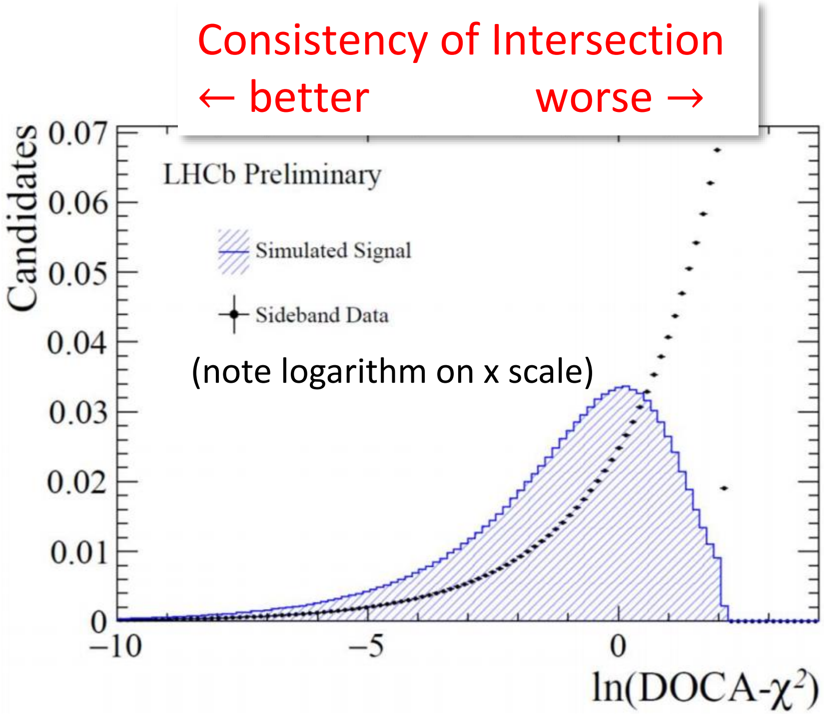
[Submitted on 27 Feb 2004]

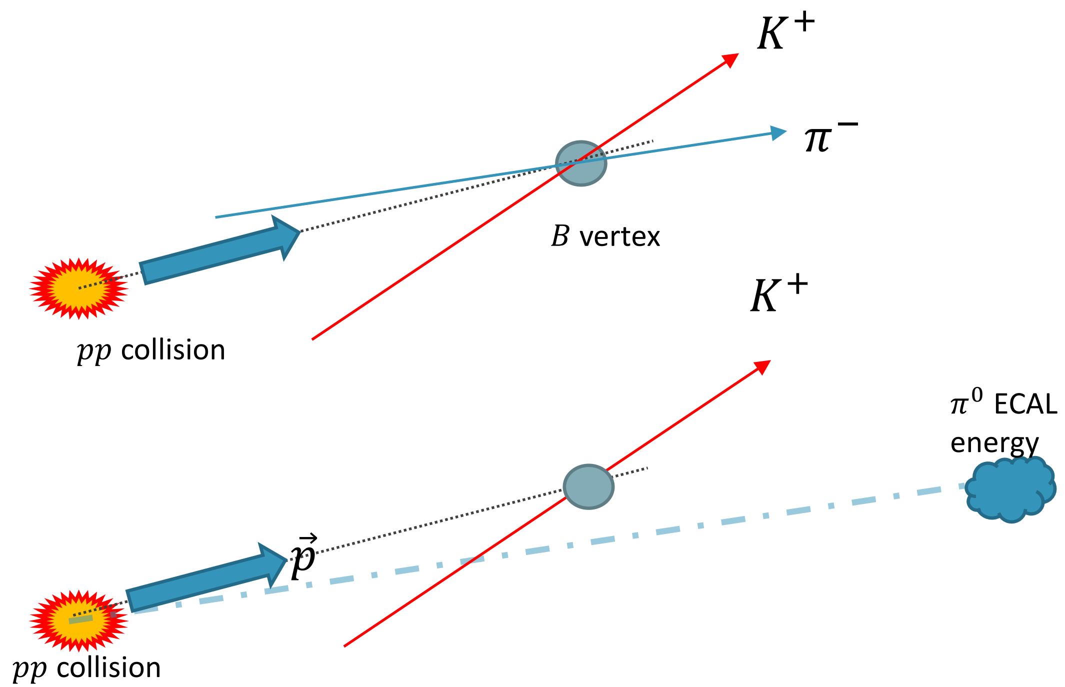
Measurements of CP-violating Asymmetries in $B^0 \to K_s^0\pi^0$ Decays

The BABAR Collaboration, B. Aubert, et al



Mother-trajectory approach



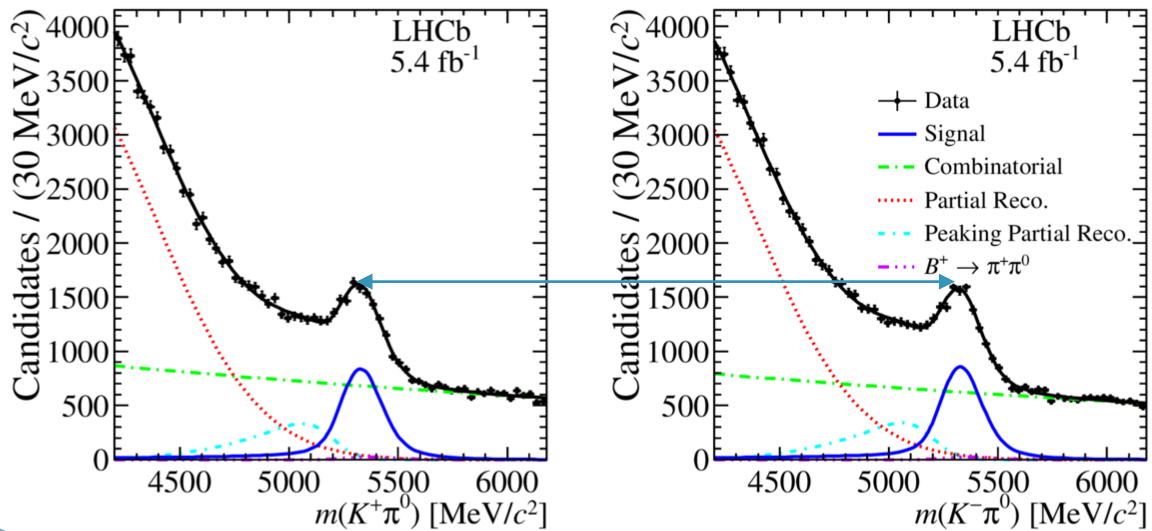


- *Construct intersection of 3-momentum vector (origin at PV) and Kaon flight trajectory!*
  - Usual LHCb analysis place selection on the consistency of the reconstructed momentum and displacement vectors -- here we require the same consistency but with different information

- BDT combines isolation and kinematics to do remainder of background suppression, but this really is the secret sauce-- without MT DOCA we couldn’t even trigger this!

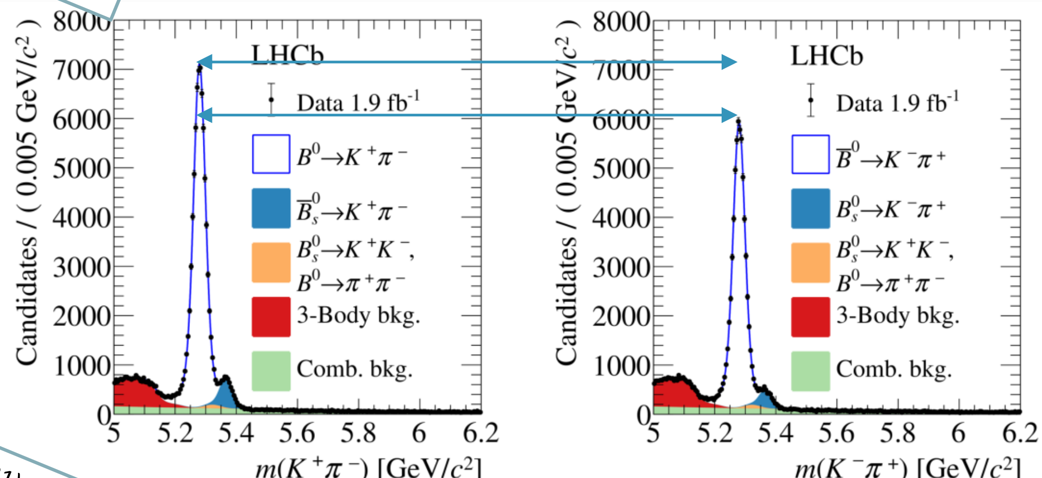
Result: A Clear Signal!

- With combination of the new technique and efficient selection of events *without additional nearby tracks* ("isolation")
- Word-leading measurement of the asymmetry in this "impossible" mode!
- Note the much-smaller asymmetry here compared to all-charged mode (lower)
  - Naively should be similar. Something to learn here!



PRL **126** (2021) 091802

- $A_{raw} = 0.005 \pm 0.022$ (Magnet Up), 0.019 ± 0.021 (Magnet Down)



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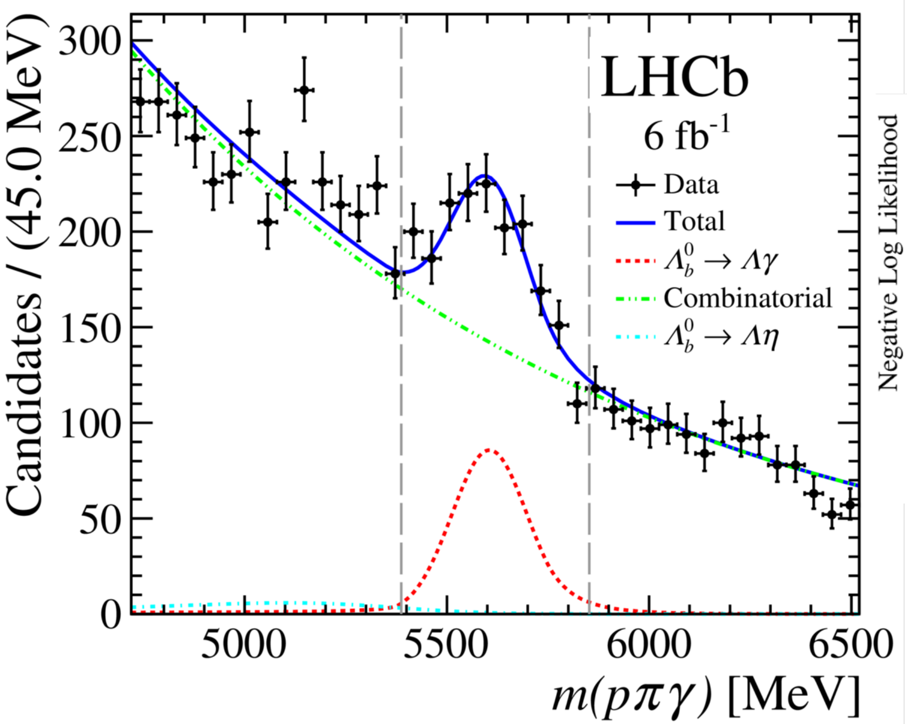
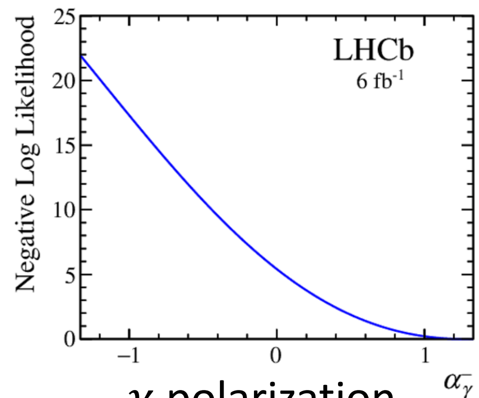
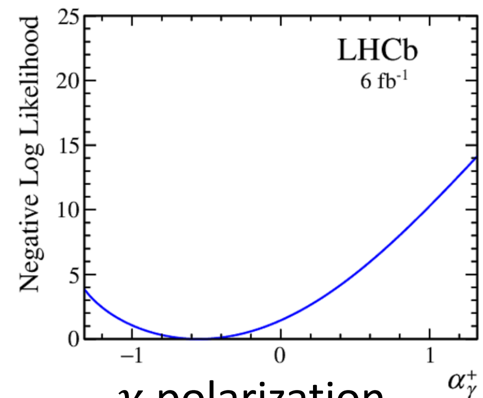
Extensions to other modes

- Mother-trajectory approach can be applied in a straightforward way to intermediate lifetime neutrals as well (K_s^0, Λ^0)
- New result: photon polarization & CP asymmetry in $\Lambda_b^0 \to \Lambda^0\gamma$
  arXiv:2111.10194, Submitted to PRL



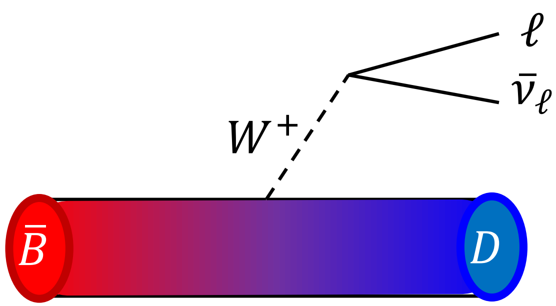


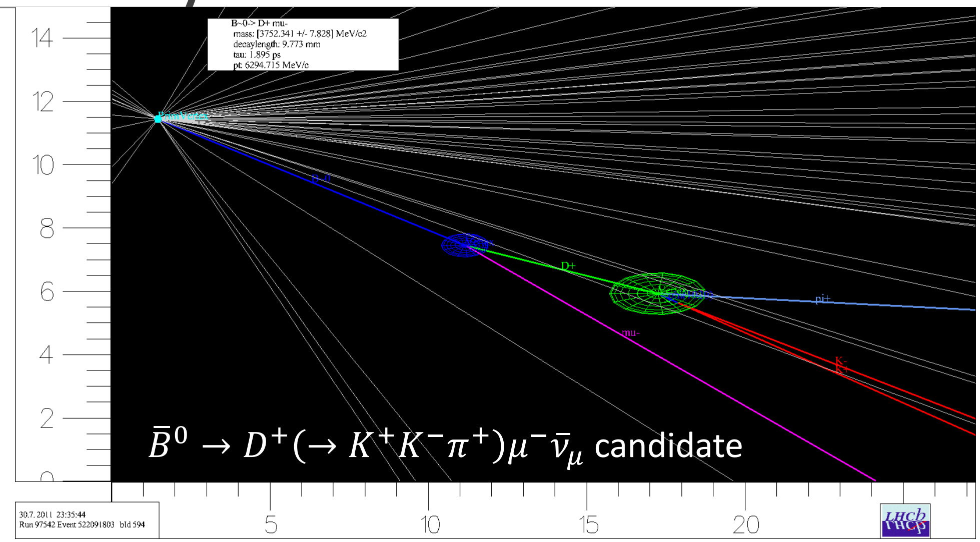
γ polarization in Λ_b^0



γ polarization in $\overline{\Lambda}_b^0$

Semileptonic B decays





- "Beta decay" of B hadrons – signature is lepton (μ or e (or τ!)) , recoiling hadronic system, and missing momentum

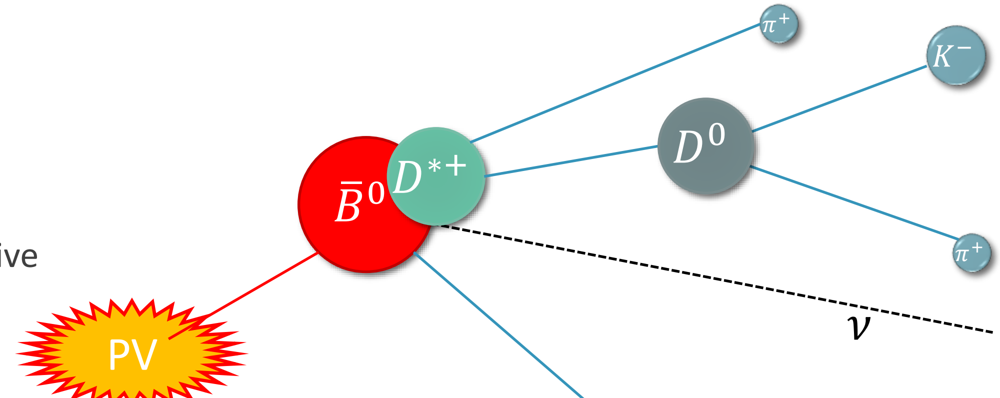
- Theoretically well-understood in the SM
  - Tree level virtual W emission – strong V-A structure
  - No QCD interaction between the lepton-neutrino system and the recoiling hadron(s)
    - $\bar{B} \to W^{*\pm} D^{(*)}$ half of the decay still needs non-perturbative input

- Charged lepton universality implies branching fractions for semileptonic decays to e, μ, τ differ only phase space and helicity-suppressed contributions

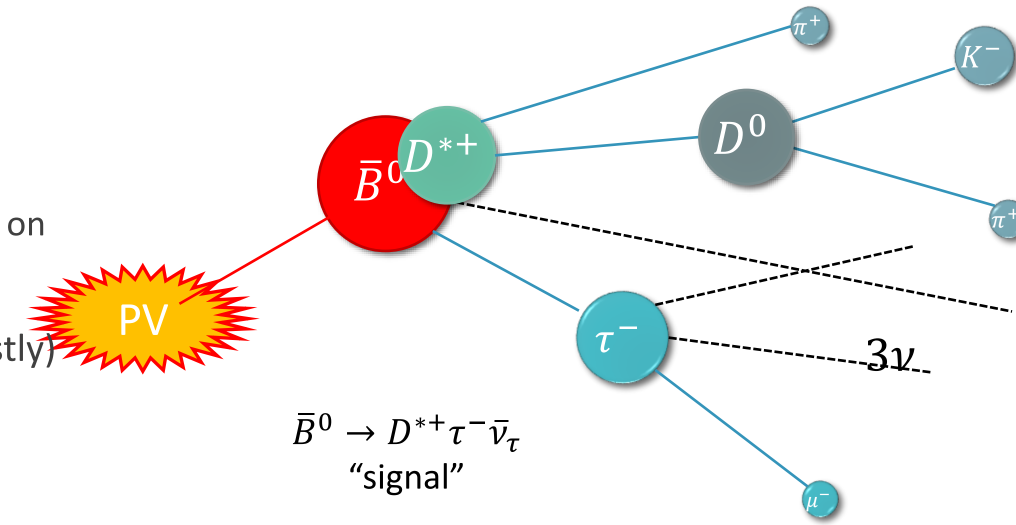
What we want to measure

$$R(D^{*+}) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\ell)}$$

- Theoretically clean due to cancellation of form factor uncertainties
  - Poorly-measured helicity suppressed amplitudes give dominant uncertainty
  - SM (HFLAv): $R(D^*) = 0.252(5)$
- $\tau^- \to \mu^-\bar{\nu}_\ell\nu_\tau$
  - Automatic normalization from identical final state
  - Must be disentangled from $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ using decay kinematics
- $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
  - Potentially higher signal purity
  - Must be normalized to hadronic B decays (reliant on external measurements to get R(D*)
- Common Challenges: missing neutrinos with (mostly) unconstrained momentum
  - Don't have full B momentum
  - Large backgrounds from other partially-reconstructed B decays



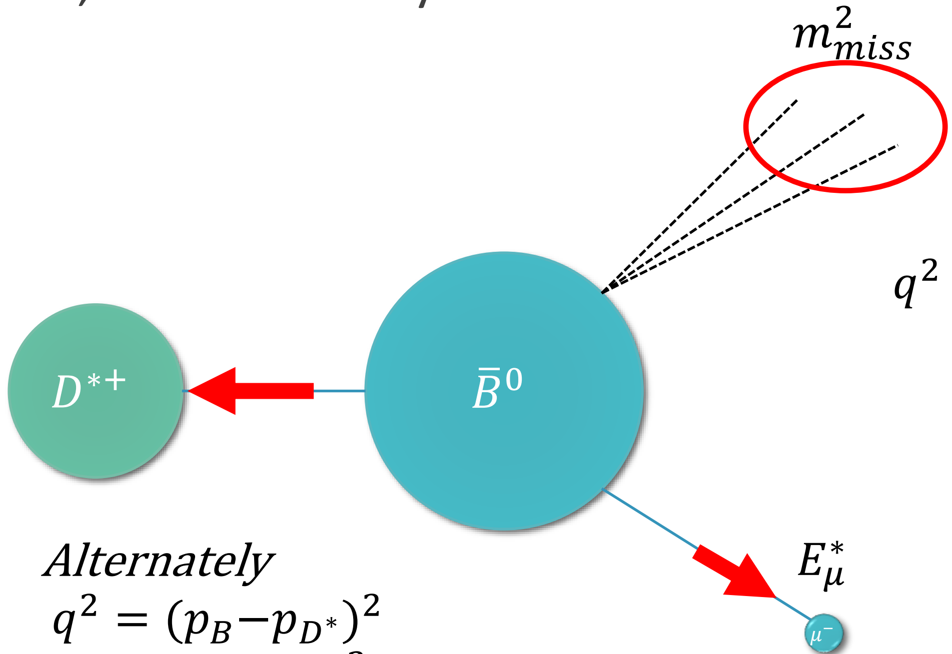
$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$
"normalization"



$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
"signal"

Distinguishing $b \to c\tau(\to \mu\nu\nu)\nu$ from $b \to c\mu\nu$

- Starting in $\tau \to \mu\nu\nu$, have three key kinematic variables:



$$q^2 = (p_\ell + p_\nu)^2 = m^2_{W^*}$$

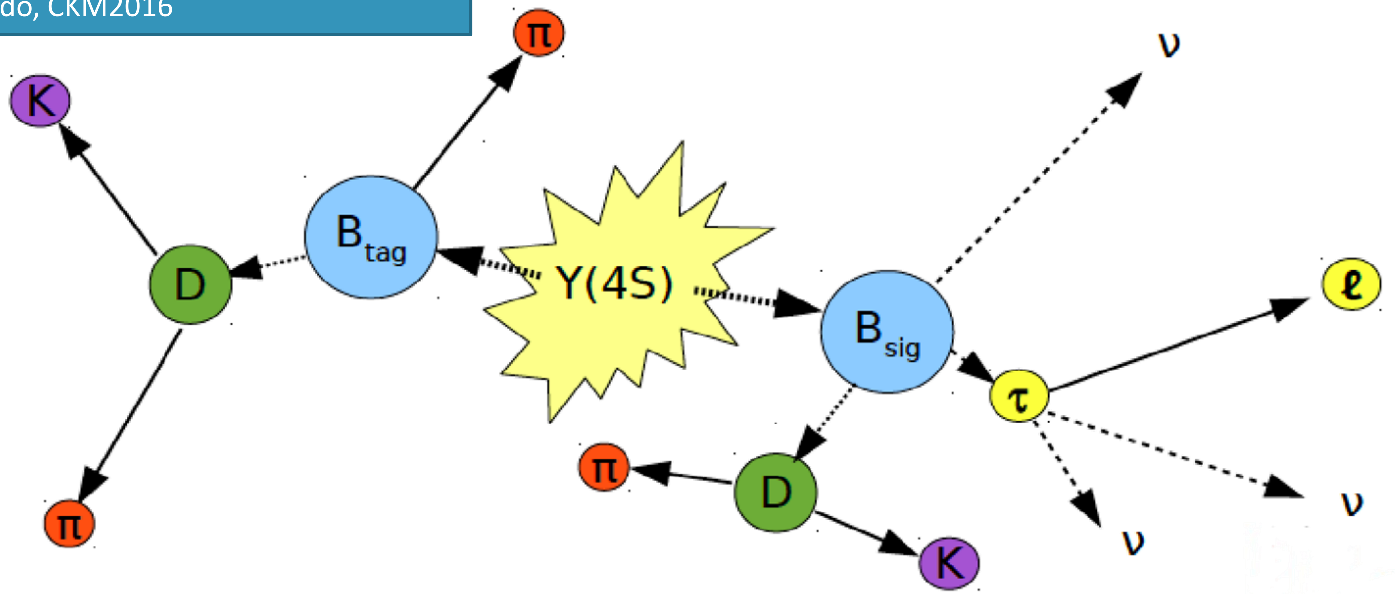
Alternately

$$q^2 = (p_B - p_{D^*})^2 = (m_B - E^*_{D^*})^2$$

$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}$	$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}$
$m^2_{miss} > 0$	$m^2_{miss} = 0$
E^*_l spectrum is soft	E^*_l spectrum is hard
$m^2_\tau \leq q^2 \leq 10.6\ \mathrm{GeV}^2$	$0 \leq q^2 \leq 10.6\ \mathrm{GeV}^2$

In a more perfect world…

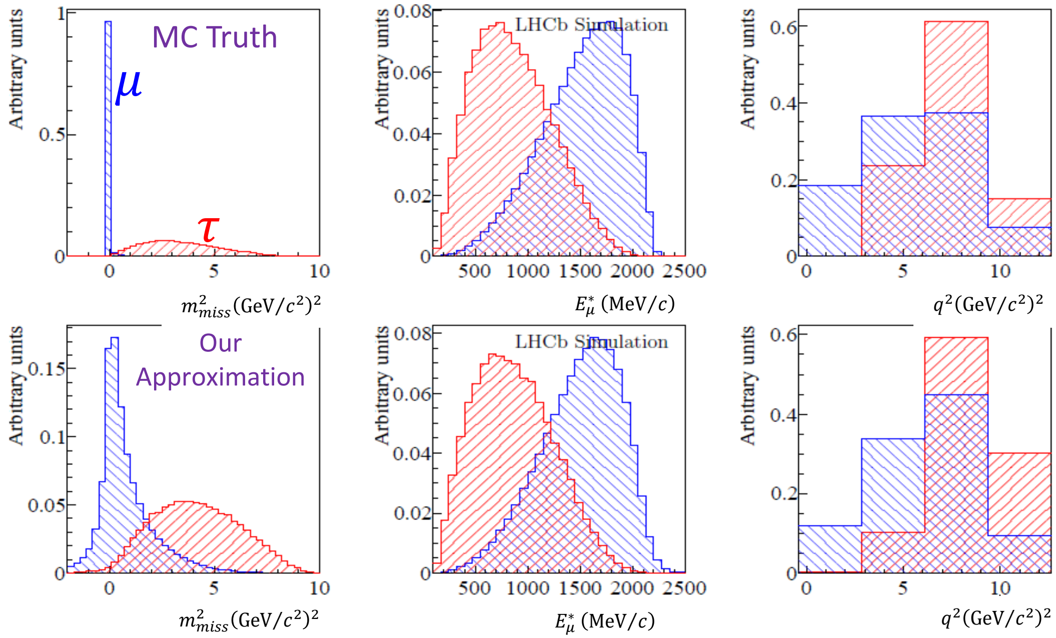
Cartoon from M. Rotondo, CKM2016



- By fully reconstructing the event, the missing energy (or alternately the signal B initial momentum) can be constrained and the missing mass directly computed
- But at LHCb we lack the information needed to close the kinematics!
  - Unknown hard interaction energy, many underlying event particles, etc…
  - We know the *direction* of p_B, but not the *magnitude*… need a constraint!

Rest frame approximation

LHCb-PAPER-2015-025 supplementary



- Key observation: Distributions are broad to begin with – a well-behaved approximation will still preserve differences between signal, normalization and backgrounds

Take $(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu}$

$$\Longrightarrow \quad (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

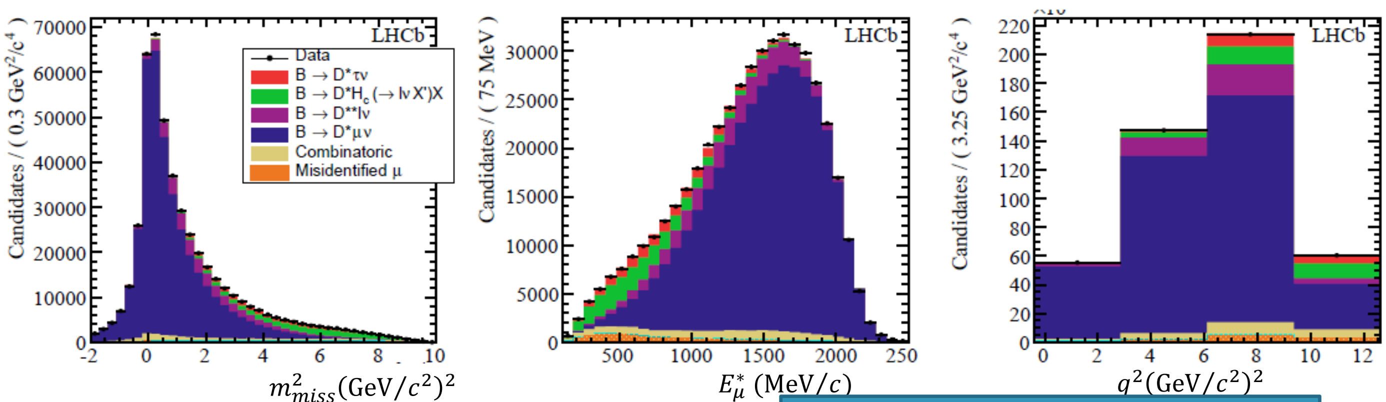
- The problem of large nontrivial resolutions is by no means unique to us, and it should not be daunting
  - See, e.g., neutron spectrometry
  - If resolution/approximations in reconstruction are *reliably simulated*, then you can get away with a lot!

Fit

- Using rest frame approximation, construct 3D "template" histograms for each process contributing to $D^{*+}\mu^-$
  - Signal, normalization, and partially reconstructed backgrounds use simulated events, other backgrounds use control data
  - Templates are functions of any relevant model parameters via interpolation between histograms generated with different fixed values of those parameters

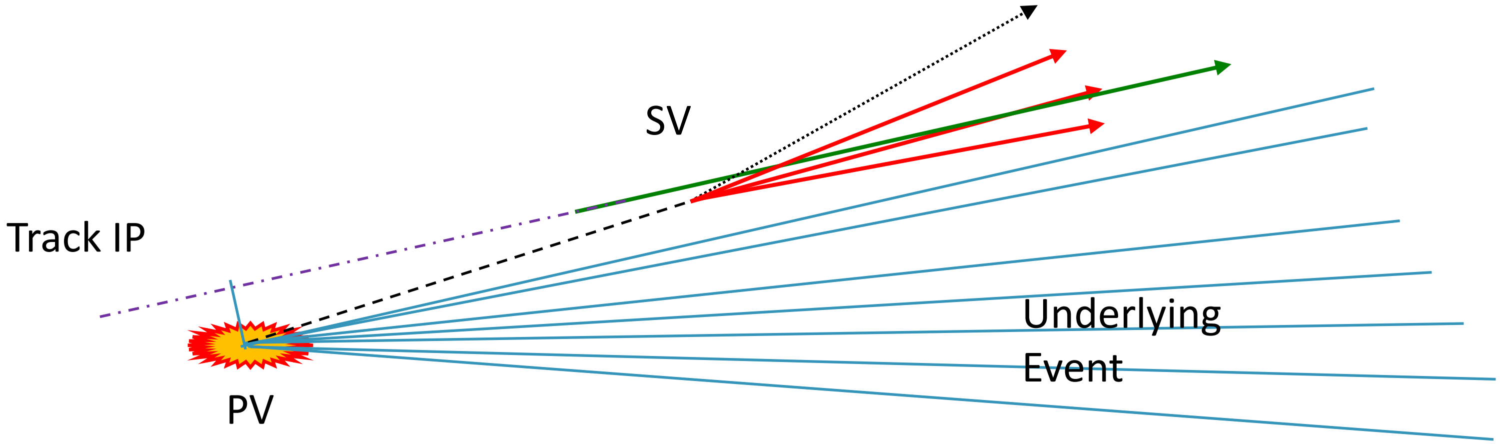
- These templates are then used as PDFs for a maximum likelihood fit to data
  - ~Inclusive spectral unfolding in multiple dimensions

- -> distributions shown previously directly translate to one-dimensional projections of the 3D templates for signal and normalization



LHCb-PAPER-2015-025 supplementary

Reducing partially reconstructed backgrounds



- Make use of superb tracking system
  - Scan over every reconstructed track and compare against $D^{*+}\mu^-$ vertex
    - Check for vertex quality with PV and SV, change in displacement of SV, p_T, alignment of track and $D^{*+}\mu^-$ momenta
    - Our equivalent tool to requiring no more reconstructed physics objects after signal and tag are selected

- Each track receives BDT score as "SV-like" (high) vs "PV-like" (low)
  - Cut on most SV-like track below threshold: get signal sample enriched in exclusive decays. Rejects 70% of events with 1 additional slow pion
  - Cut on most SV-like track(s) being above threshold: get control samples enriched in interesting backgrounds - $B \to D^{*+}\pi\mu\nu, B \to D^{*+}\pi\pi\mu\nu, B \to D^{*+}H_c(\to \mu\nu X')X$ (very analogous to high E_{ECL} control regions in, e.g. $B \to \tau\nu$)

Other Major Tool: *Control Samples*

$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ (normalization)

$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
(signal)

$\bar{B}^0 \to D^{**+}\mu^-\bar{\nu}_\mu + \bar{B}^0 \to D^{**+}\tau^-\bar{\nu}_\tau$
$\bar{B}^- \to D^{**0}\mu^-\bar{\nu}_\mu + \bar{B}^- \to D^{**0}\tau^-\bar{\nu}_\tau$
$D^{**} \to D^{*+}\pi$ (3 states each, 6 PDFs)

$\bar{B}_s^0 \to D_s^{**+}\mu^-\bar{\nu}_\mu$
$D_s^{**+} \to D^{*+}K_S^0$, (2 states, 1 free param)

$B^{+,0} \to \bar{D}^{**}\mu^+\nu_\mu$
$\bar{D}^{**} \to D^{*-}\pi\pi$, (cocktail)

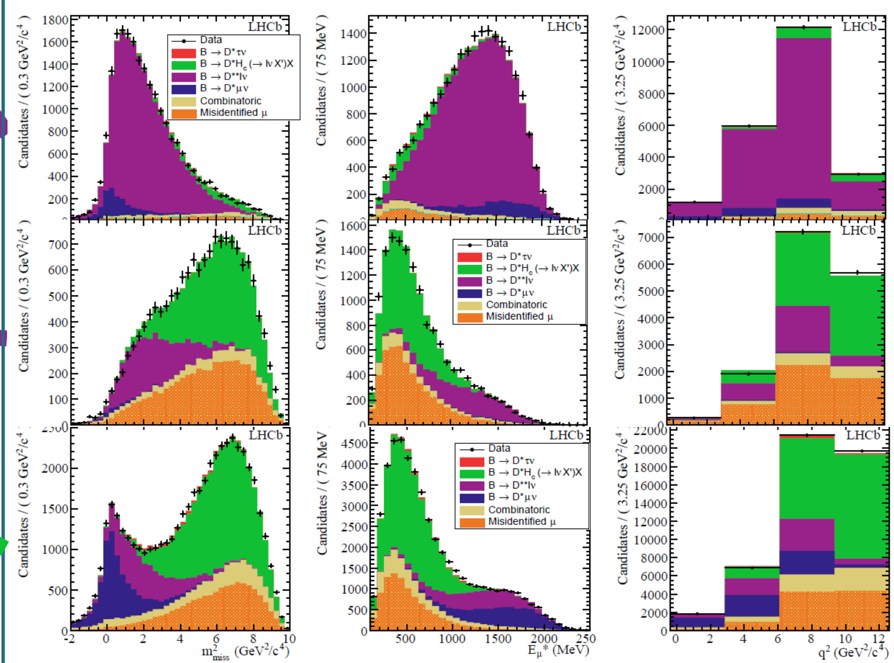
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$
$+\bar{B} \to D^{*+}D_s^-(\to \tau^-\bar{\nu}_\tau)X$

$h \to \mu$
misidentification

combinatorial

Corrections applied to double-charm dalitz plots, form factors of semileptonic backgrounds (excited charm) *measured*

Control sample fits to constrain shapes



LHCb-PAPER-2015-025 supplementary

Other Major Tool: *Control Samples*

$\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu$ (normaliza

$\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$
(signal)

$\bar{B}^0 \rightarrow D^{**+}\mu^-\bar{\nu}_\mu + \bar{B}^0 \rightarrow D^{**}$
$\bar{B}^- \rightarrow D^{**0}\mu^-\bar{\nu}_\mu + \bar{B}^- \rightarrow D^{*}$
$D^{**} \rightarrow D^{*+}\pi$ (3 states each, 6

$\bar{B}_s^0 \rightarrow D_s^{**+}\mu^-\bar{\nu}_\mu$
$D_s^{**+} \rightarrow D^{*+}K_S^0$, (2 states, 1 free param)

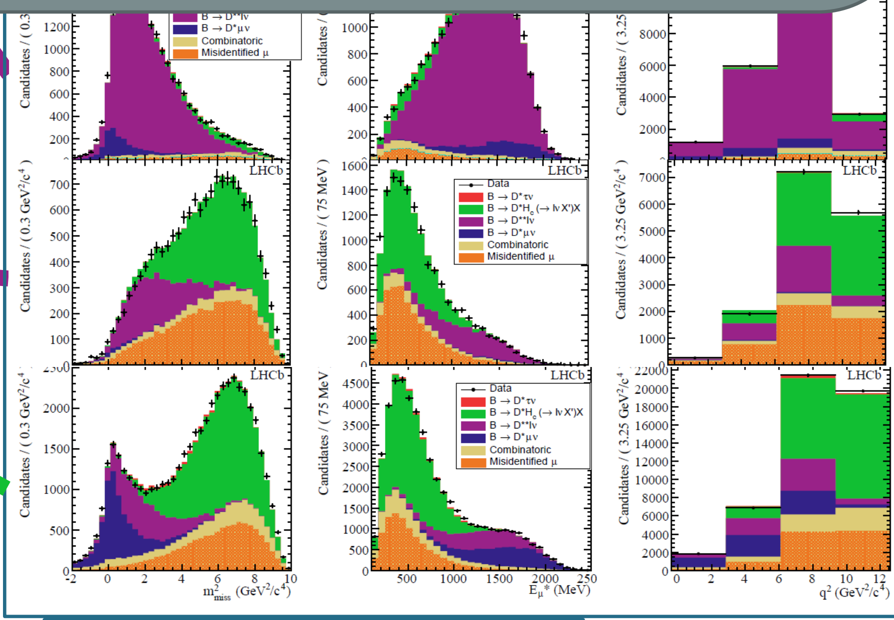
$B^{+,0} \rightarrow \bar{D}^{**}\mu^+\nu_\mu$
$\bar{D}^{**} \rightarrow D^{*-}\pi\pi$, (cocktail)

$\bar{B} \rightarrow D^{*+}H_c(\rightarrow \mu\nu X')X$
$+\bar{B} \rightarrow D^{*+}D_s^-(\rightarrow \tau^-\bar{\nu}_\tau)X$

$h \rightarrow \mu$
misidentification

combinatorial

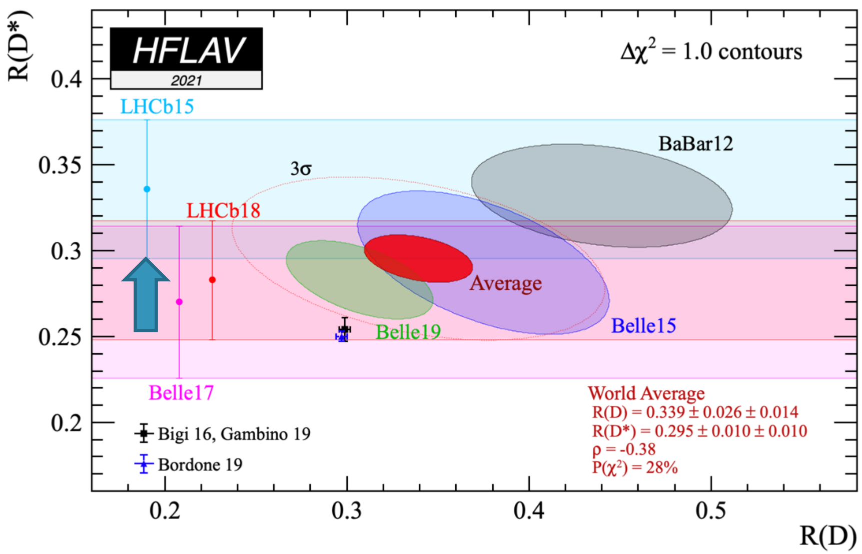
Johnathan Frakes
on simulated B
background samples
"out of the box"

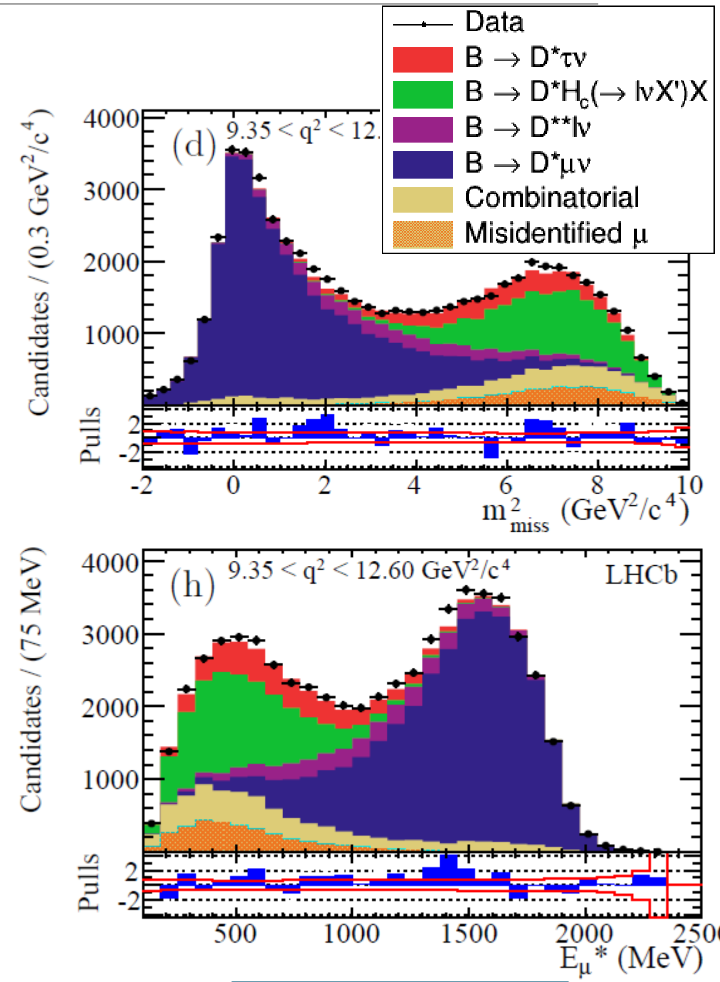


LHCb-PAPER-2015-025 supplementary

LHCb result

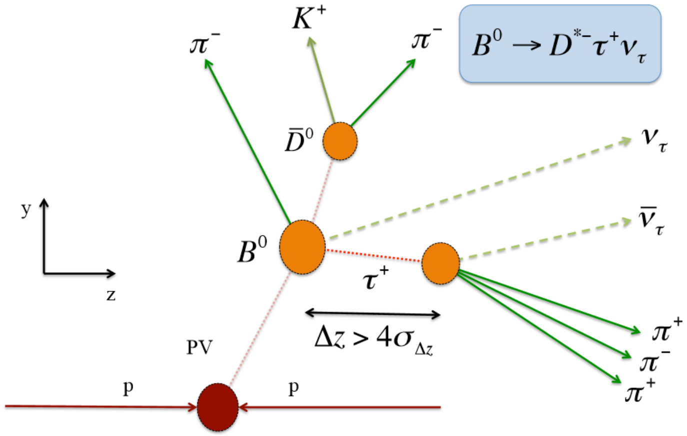
- 3D fit to m_{miss}^2, E_μ^*, q^2
- Result: $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
  - (2.1 sigma from CLN prediction)
  - First measurement of a $b \to X\tau\nu$ decay at a hadron collider
- Dominant systematics from MC statistical uncertainty and background from hadrons misidentified as muons

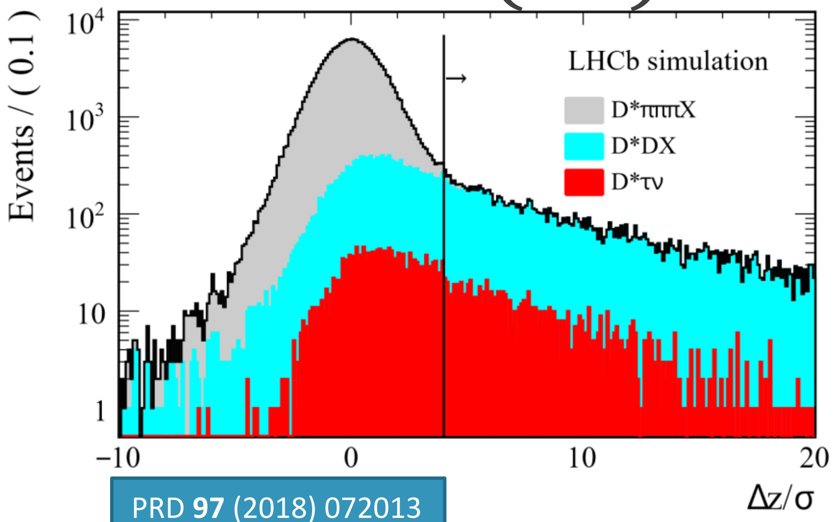




PRL 115 111803(2015)

$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$





PRD **97** (2018) 072013

- This signal mode is historically very challenging due to the large inclusive $\bar{B} \to D^{*+}3\pi_{direct}X$ branching fraction (includes normalization mode)
  - Size is 100x expected signal
- Very large boost yields a tertiary vertex and additional handles at LHCb
  - Requiring 4σ separation of vertices along $\hat{z}$ removes 99.9% of non-flying background
  - Signal efficiency is ~34%

Reconstruction of Fit Variables

- Again, we make use of alignment of flight direction and total momentum, except now we have a tau vertex to play with!
  - Know: $p_{3\pi}, p_{D^*}$, B flight vector from PV, 3π flight vector from D^*
  - Using known B and τ mass to solve results in 2 × 2-fold quadratic ambiguities

$$|\vec{p}_{B^0}| = \frac{(m^2_{D^*\tau} + m^2_{B^0})|\vec{p}_{D^*\tau}|\cos\theta_{B^0,D^*\tau} \pm E_{D^*\tau}\sqrt{(m^2_{B^0} - m^2_{D^*\tau})^2 - 4m^2_{B^0}|\vec{p}_{D^*\tau}|^2\sin^2\theta_{B^0}}}{2(E^2_{D^*\tau} - |\vec{p}_{D^*\tau}|^2\cos^2\theta_{B^0,D^*\tau})}$$

$$|\vec{p}_\tau| = \frac{(m^2_{3\pi} + m^2_\tau)|\vec{p}_{3\pi}|\cos\theta_{\tau,3\pi} \pm E_{3\pi}\sqrt{(m^2_\tau - m^2_{3\pi})^2 - 4m^2_\tau|\vec{p}_{3\pi}|^2\sin^2\theta_{\tau,3\pi}}}{2(E^2_{3\pi} - |\vec{p}_{3\pi}|^2\cos^2\theta_{\tau,3\pi})}$$

- Choose θ, θ' such that the ambiguity vanishes
  - Provides $\approx 10\%$ resolution on q^2

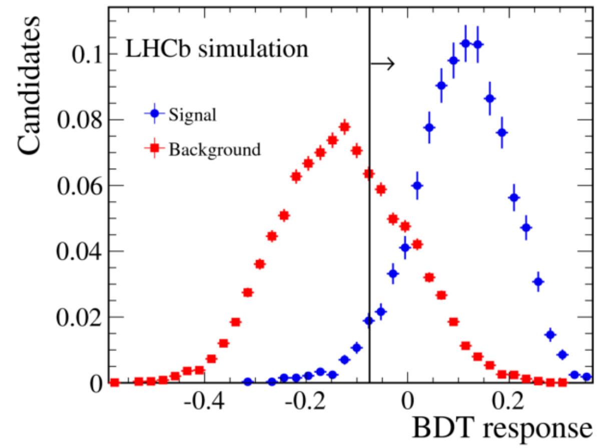
- 2nd reconstruction hypothesis: assume no neutinos at B vertex, unknown mass neutral system at 3pi vertex – obtain estimate for mass m(3pi+N) which peaks for Ds bkgnd

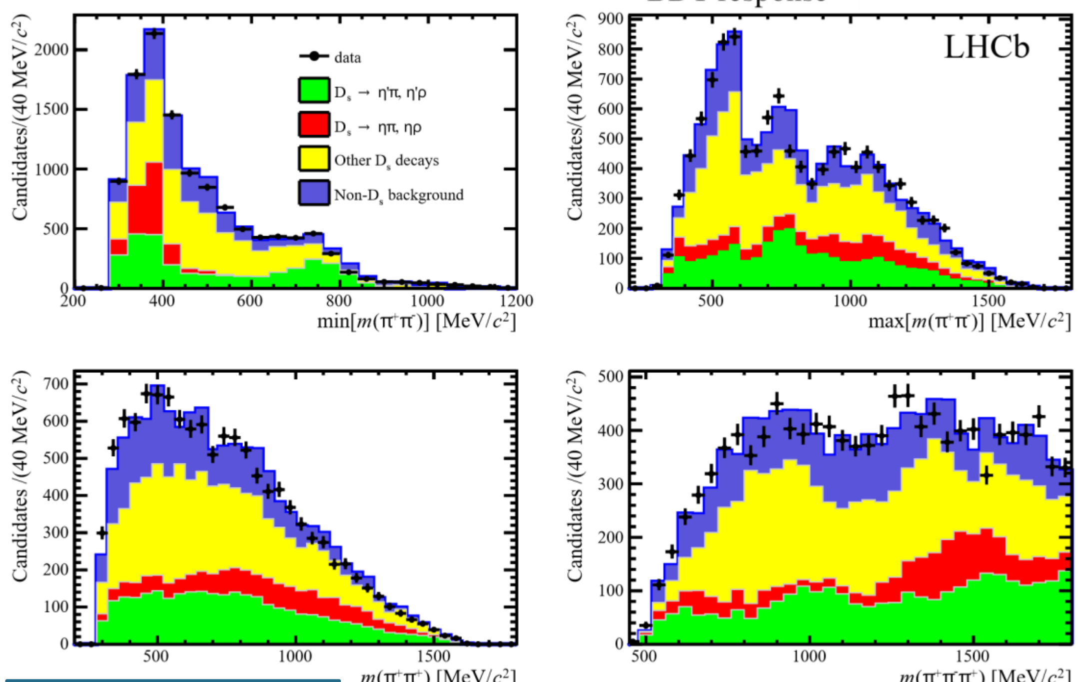
- using strengths of detector to overcome difficulties of environment/final state!

Controlling Ds backgrounds

- Largest background is from $B \to D^* D_s[\to 3\pi X]$
  - Train BDT to distinguish the two decays using (mainly) 3π dynamics
  - BDT used both as selection and fit variable

- D_s decay simulation is untrustworthy at best (don't blindly trust decay.dec!). 3 Step process to calibrate background simulation:
  - Train BDT on "vanilla" (uncorrected) simulation
  - use to select pure D_s sample
  - correct D_s simulation modelling by comparison of BDT inputs in background-like region
  - Apply corrections to background template in signal fit





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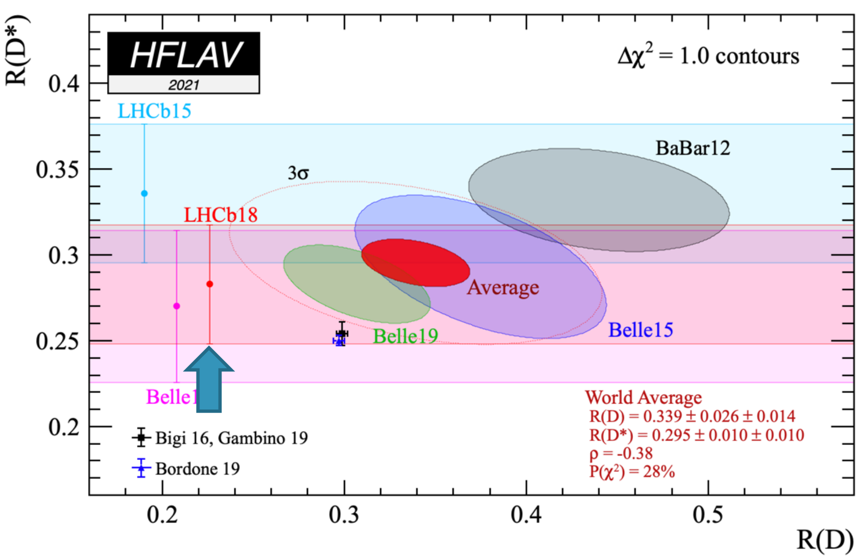
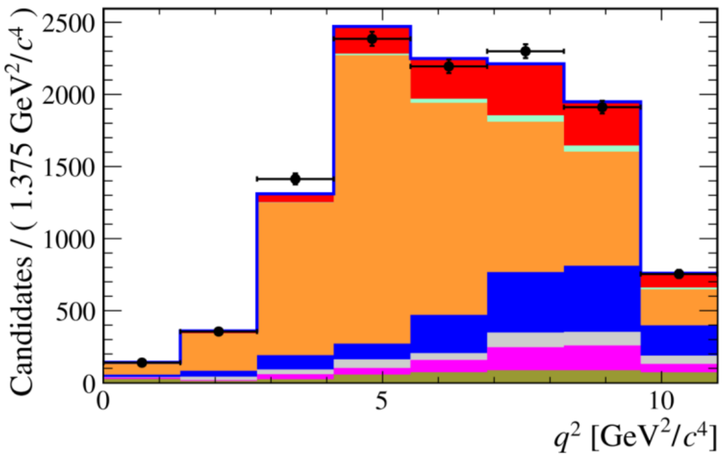
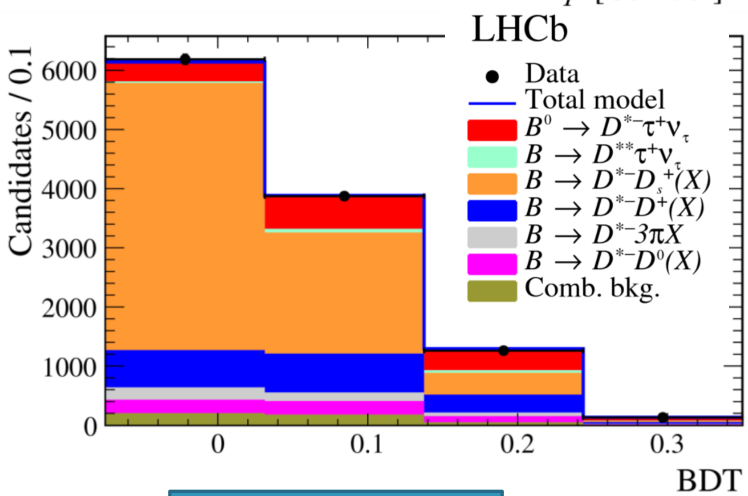
Fit

- 3D fit in q^2, τ decay time (not shown), BDT
- Exclusive $\bar{B} \to D^{*+}3\pi_{direct}$ provides normalization for measurement
  - $K(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}$

    $R(D^*) = K(D^*) \times \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\tau)}$
- **Result:** $0.286 \pm 0.019 \pm 0.025 \pm 0.021$







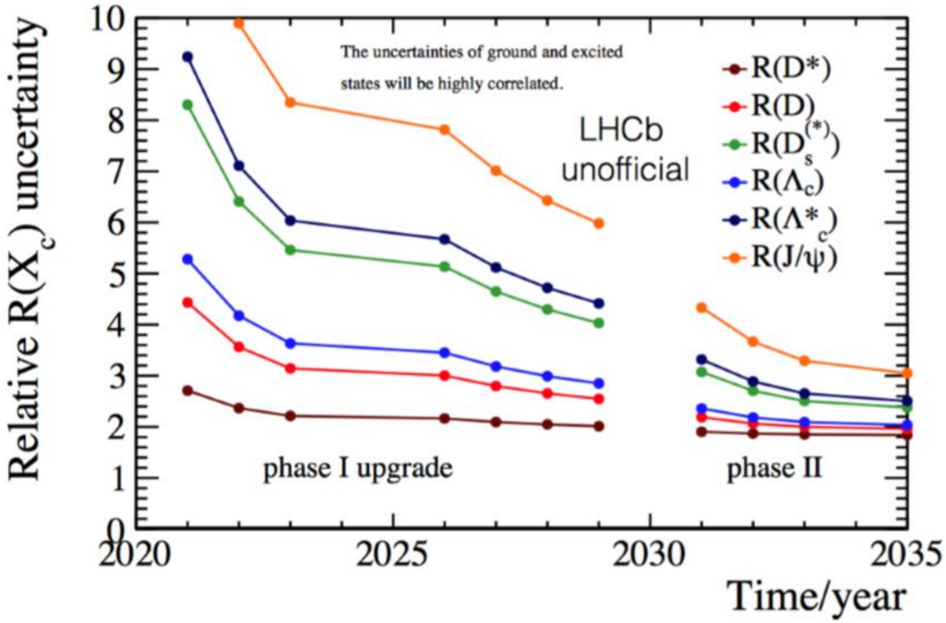
PRD **97** (2018) 072013

Next Steps for LHCb

HEAVY FLAVOR IN RUN3 AND BEYOND

LFU Ratio prospects

- General prospects for increasing precision of core observables ($R(X_c)$) are relatively well-established
  - Ultimate sensitivity depends on what systematics become limiting
  - Large datasets -> large control samples -> most systematics can be reduced



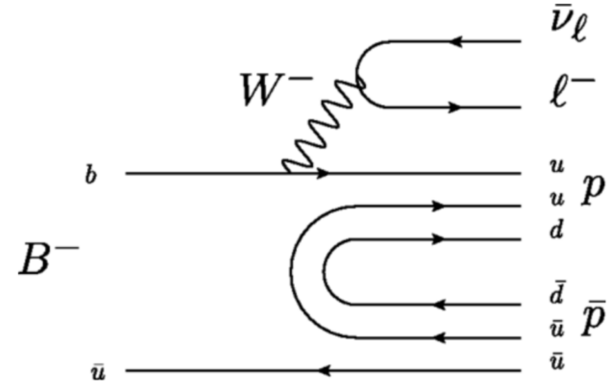
- Right: projections if limiting systematics become combinatorial background shapes, PID efficiencies, data/MC corrections

- Absolutely crucial that computing keep up with data (need simulation ~4x data to keep up)
  - Raw power/architecture improvements?
  - Improved FastMC? (systematics?)

$b \to u\tau\nu$

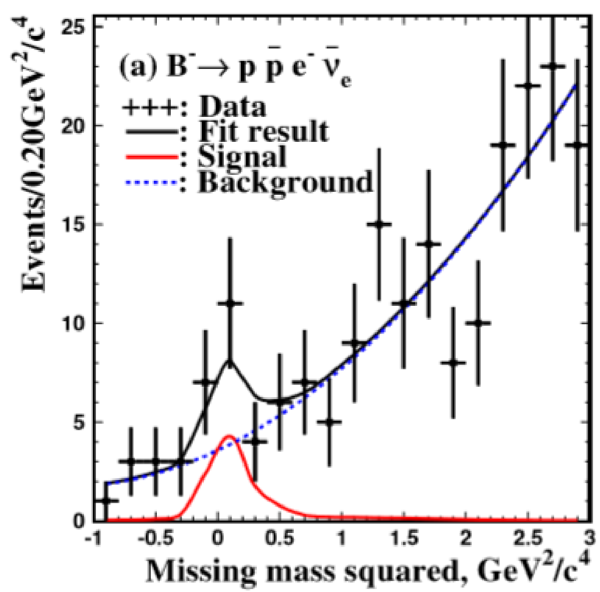
- $b \to u$ semileptonics are challenging due to very large combinatoric backgrounds
  - Low daughter multiplicity, no tertiary vertex
  - One handle: rarer X_u systems (p, K instead of π)
  - Example: Existing LHCb result on $|V_{ub}|$ in $\Lambda_b^0 \to p\mu\nu$ is already systematics limited with just Run1
    - External inputs dominate – form factors, $\Lambda_c^+ \to pK\pi$

- Targets for LFU: $B^- \to p\bar{p}\tau\nu$
  - Expect O(1000) normalization in first search for this mode at LHCb, by Run5 could have similar stats to 2015 LHCb R(D*) measurement
  - Many challenging partially reconstructed bkgds



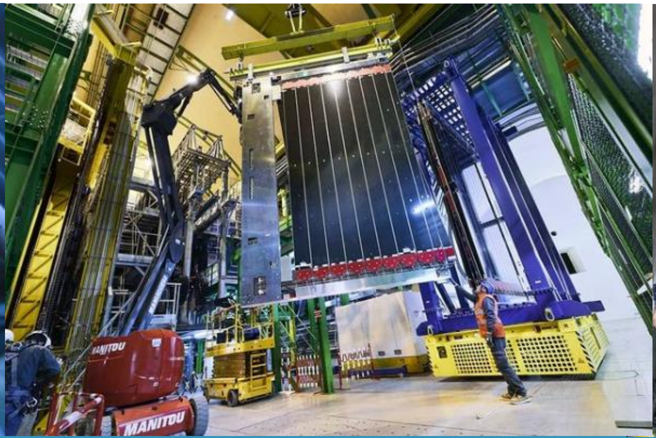
Belle - PRD 89, 011101 (2014)

$$\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (3.1^{+3.1}_{-2.4} \pm 0.7) \times 10^{-6}$$



Farewell to a Superb Detector

- LHCb remains diverse and vibrant experimental collaboration during long shutdown:
  - ~1400(!!!) members across 85 institutions in 18 countries working on Run1&2 data, upgrade construction, upgrade software, planning for further future, etc.
- LHCb as we knew it has been disassembled to make room for the Phase-I upgrade detector
  - Fast readout for real-time software decision-making
  - More granular subdetectors to cope with ‘busier’ events
- Photos: LHCbExperiment on Instagram



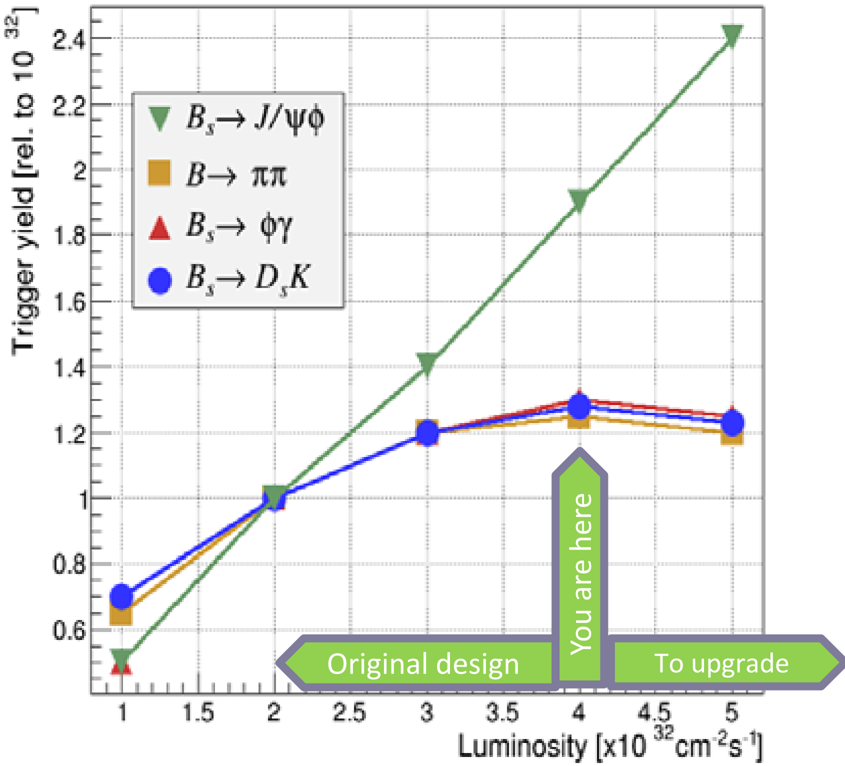
LHCb Upgrade in a Nutshell

- Cannot increase luminosity any further in Run2 trigger scheme
  - Fixed-bandwith hardware decisions limit output rate and only access limited event info
  - Increasingly strict requirements select *against* heavy-flavour events

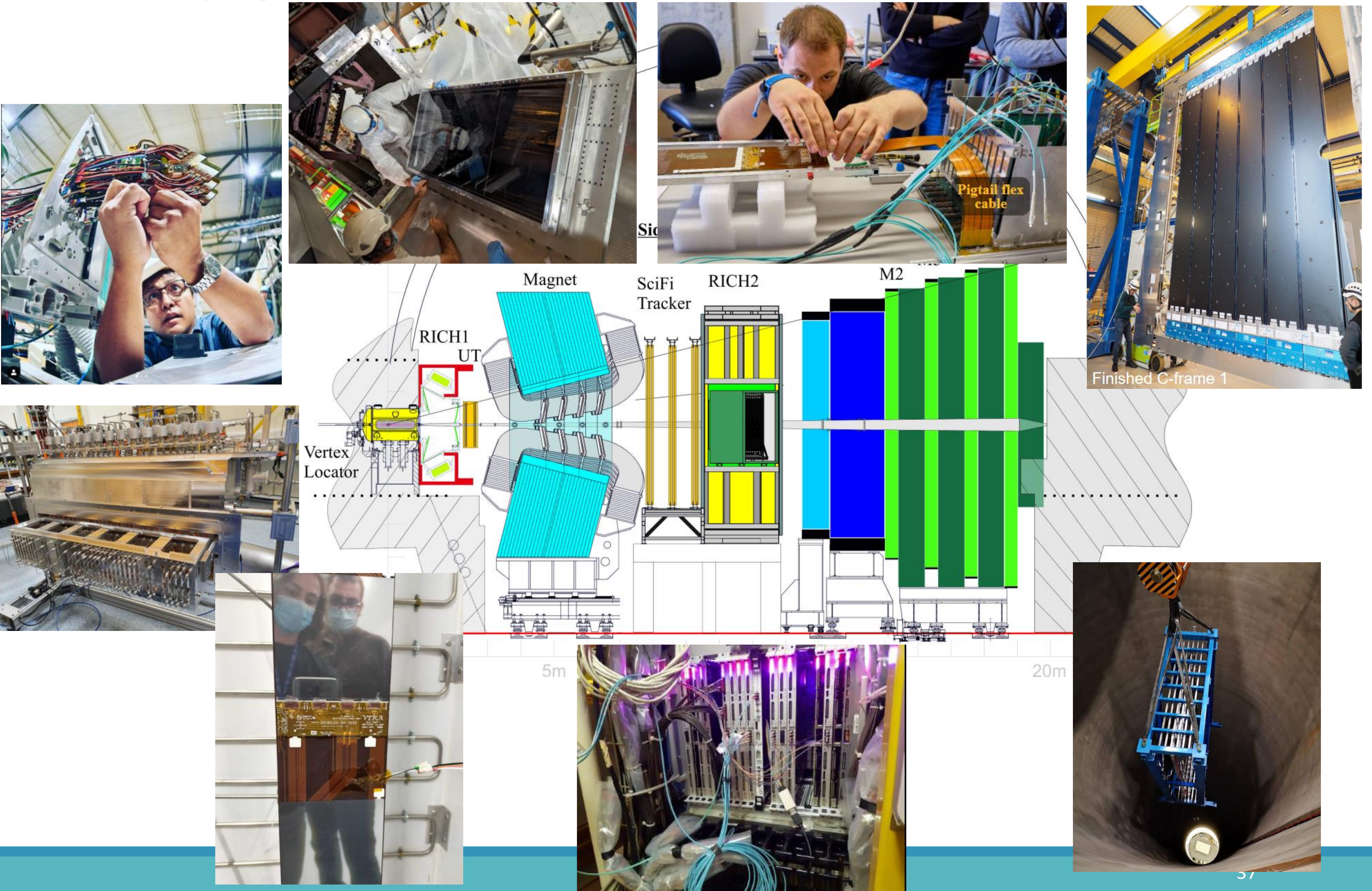
- LHCb Upgrade Concept:
  - Completely rebuilt detector readout to be synchronous with LHC beam crossings
  - Real-time analysis style event selection
    - Fast event reconstruction with GPU technology
    - Can identify candidate B hadrons and interesting tracks *before* making the decision!

- Result: Order-of-magnitude increase in dataset

- Require significant increase in segmentation to deal with $\sim 5\ pp$ collisions per event
  - All new charged-particle trackers
  - Re-optimized and rebuilt particle identification subdetectors



Upgrade outside the nutshell

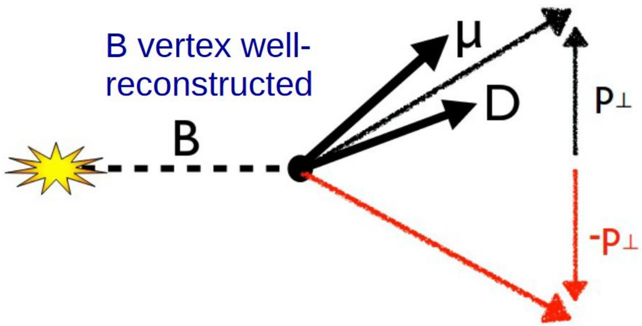


Summary

- LHCb groups have been hard at work finding ways to move beyond the applications envisioned in the physics case and design work
  - Many of the techniques have spiritual (if not direct) analogs in the B factories – we don't work in a vacuum and neither do you!
- Not every possibility for Belle-II has been done already, nor possibly even imagined yet!
  - Keep your eyes open and look for connections between your problems and others, you never know where a breakthrough will come from!

Backup Slides

Aside: Semileptonics with light leptons



- With a single missing neutrino, there exists a very nice tool:
  - $m_{corr} = \sqrt{m_{vis}^2 + p_\perp^2} + |p_\perp|$
  - Signal peaks at B mass, shape well-described by MC, not very sensitive to form factors
- This tool is surprisingly general however:
  - Exactly equivalent to "transverse mass" variable used for energy frontier searches involving missing energy
  - Also appears in some partial-reconstruction techniques with single missing neutral particles
  - Used in LHCb inclusive triggering to find B decays with daughters below HLT tracking threshold and/or neutrals
  - Good to keep in your toolbox!