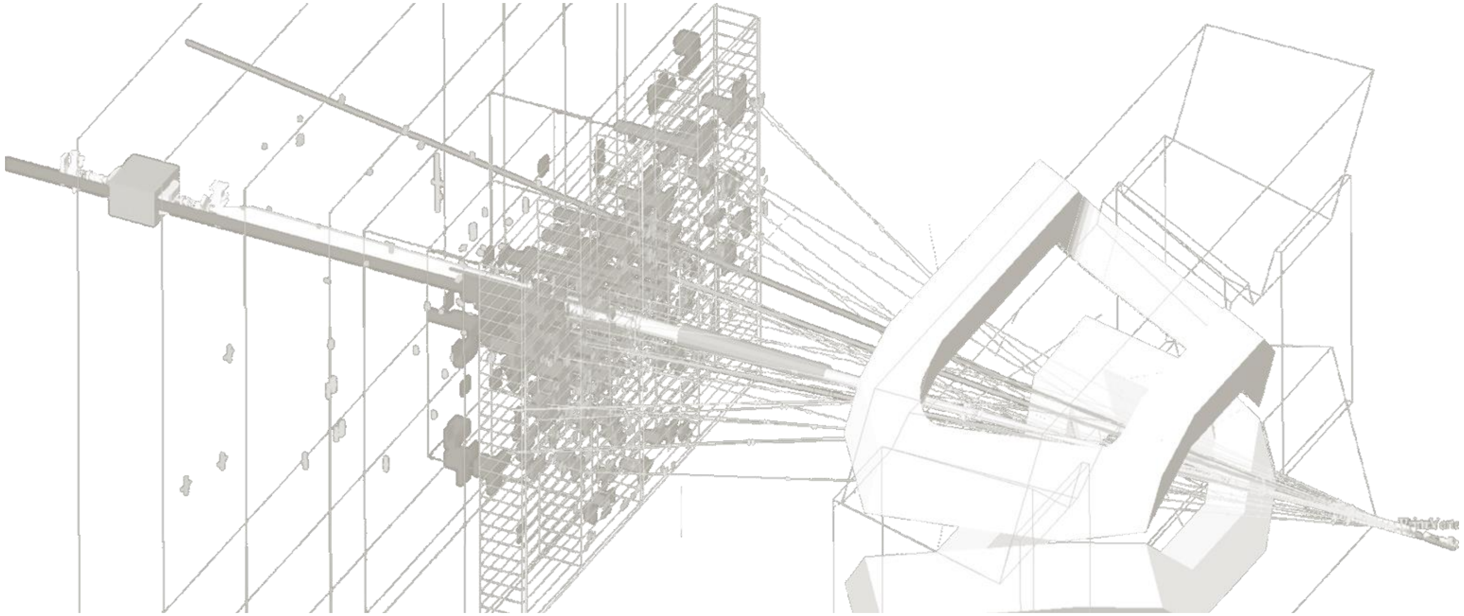


Test of lepton flavor universality with $b \to c$ semileptonic decays at LHCb

Physics Seminar
University of Maryland

Wednesday March 22nd 2023

Phoebe M Hamilton
(LHCb)
(University of Maryland)

LHCb: Heavy flavor at CERN's Large Hadron Collider

Some of LHCb's Big Questions

Does the standard model adequately explain all matter-antimatter asymmetry ("CP violation", "CPV") in hadrons?

- CP Violation studies in bottom and charm hadrons
- Search for CPT violation
- T-violating asymmetries

What are the dynamics that bind the hadrons like?

- Excited hadron spectroscopy
- Pentaquarks? Tetraquarks?
- Molecular hadron states?

Are there additional forces yet to be discovered? Do they distinguish the three generations of matter beyond the Higgs?

- Lepton Flavour Universality Tests
- Lepton Flavour Violation Searches

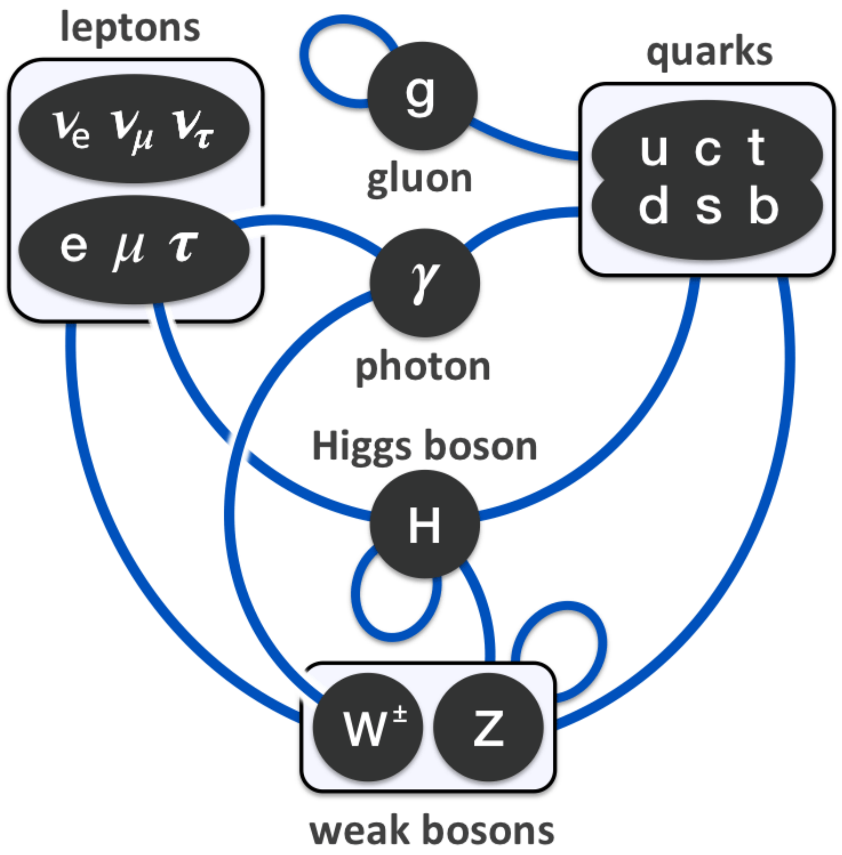
What is the nature of the 'dark' gravitating matter?

- Dark Photon Searches
- Hidden Sector/LLP searches

Standard Model Interactions

SM unifies the 3 non-gravitational forces into a single gauge theory – group= $U(1)_Y \otimes SU(2)_L \otimes SU(3)_C$

- Point-like matter fermions in pairs, mixed by weak bosons:
  - Leptons (neutral under strong force)
  - Quarks (charged under strong force)
    - Nonlinear strong force -> confinement
- Three copies of each matter field with different couplings to Higgs field
  - Charged Leptons: Mass eigenstates == weak eigenstates
  - Quarks: Mass eigenstates != weak eigenstates
    - Misalignment = CKM matrix



Basics of b physics

V_{CKM} hierarchical & nearly diagonal

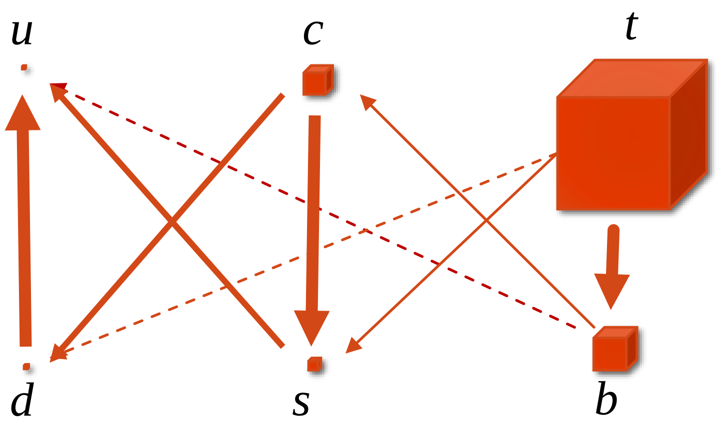
- Transitions mixing different generations suppressed
- 3rd generation especially "isolated"

-> Suppression of all tree-level b quark decay amplitudes

- $|V_{cb}|$~0.04
- Leads to long b quark lifetime: $c\tau_B \sim 400\mu m$! (= about 2x charm lifetime) – key to hadron collider studies
- Makes B physics quite sensitive to NP generically misaligned with CKM

Quarks spin =1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



Indirect Searches

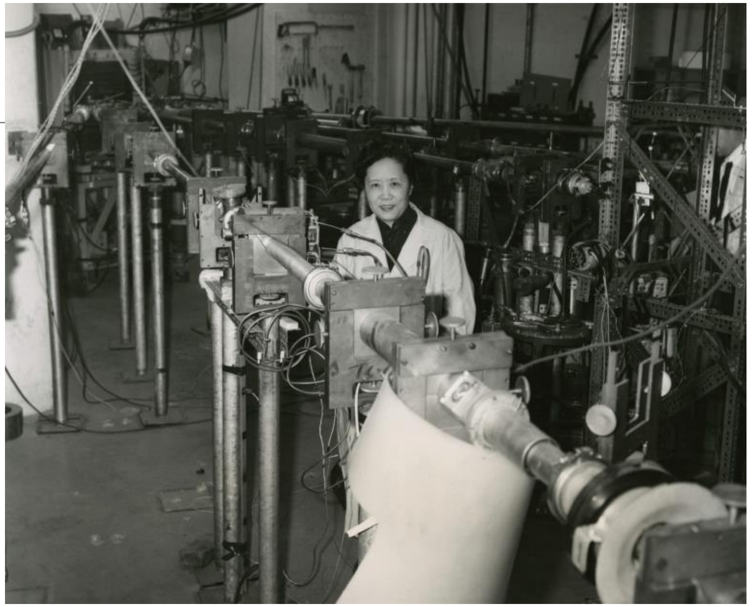
Nature of interacting quantum field theories is that physics at higher scales appears in low energy processes

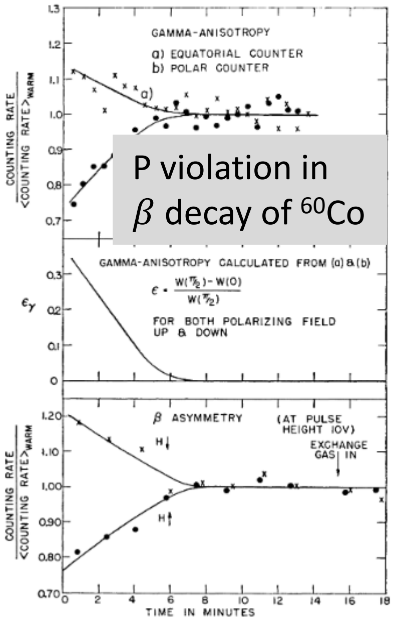
Long history of things being discovered (sometimes "discovered") before they were observed!

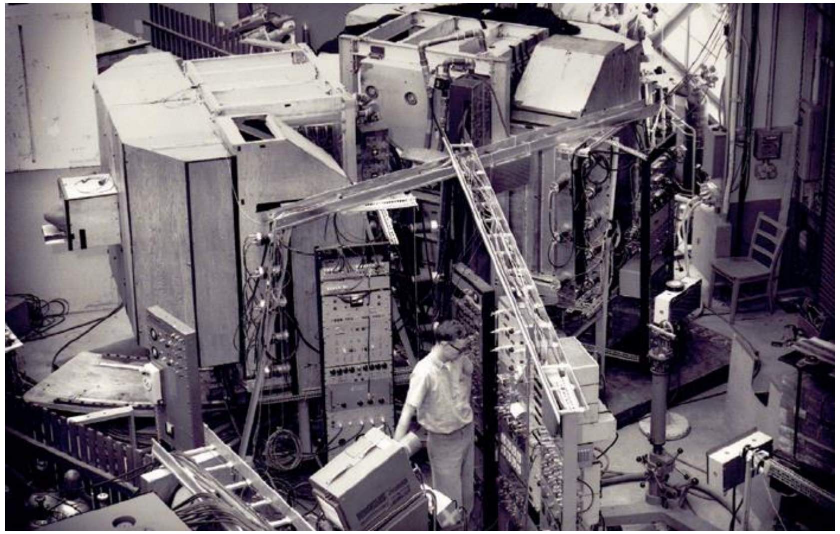
- β decay -> W boson
  - Charged current interaction
  - P violation
- $\nu N \rightarrow \nu N$ scattering
  - Neutral current interactions
  - Predates direct production of Z by a decade
- Forbidden K decays -> GIM mechanism -> c quark
- CP violation in K_L -> 3rd generation of quarks
- $B^0 \leftrightarrow \bar{B}^0$ mixing sets lower bound on m_{top}

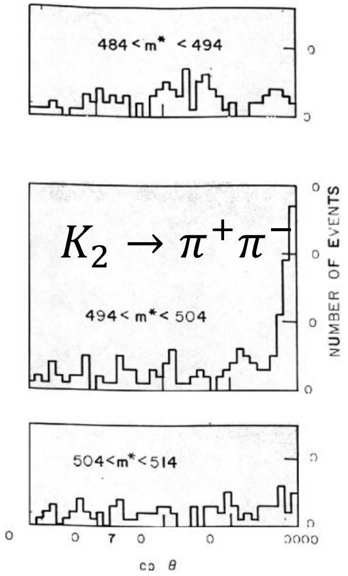
For best sensitivity to 'new' physics need:

- Well-understood predictions
- Good experimental precision
- (If possible) suppressed or absent 'known' physics contributions





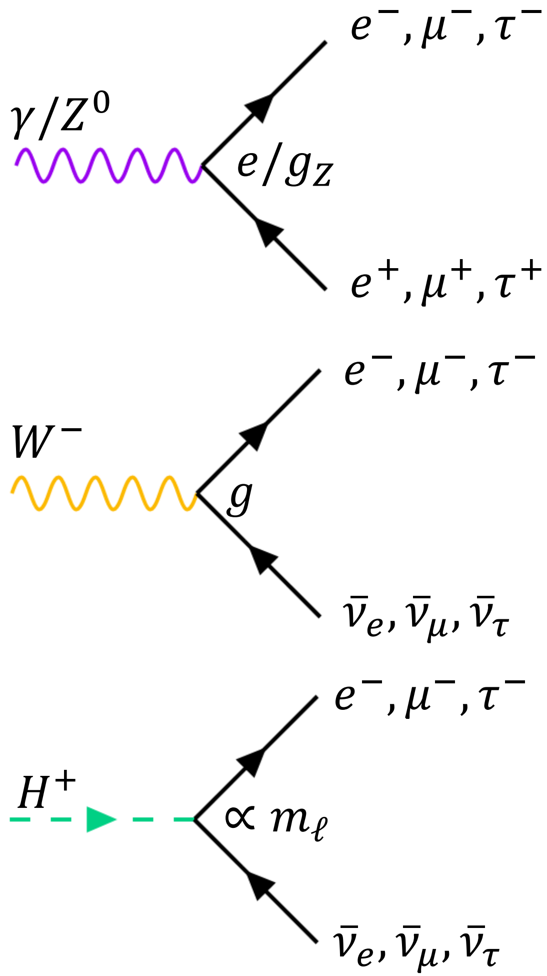




Lepton Flavor Universality (LFU)

In Standard Model (SM), charged lepton flavors are ***identical copies*** of one another

- Electroweak couplings are trivially equal for all three flavors by construction
- Amplitudes for processes involving e, μ, τ must all be identical up to explicit mass dependence (phase space, fermion helicity)
  - Examples:
    - $\mathcal{B}(Z \to e^+e^-) = \mathcal{B}(Z \to \mu^+\mu^-) = \mathcal{B}(Z \to \tau^+\tau^-)$
    - $\mathcal{B}(\psi(2S) \to e^+e^-) = \mathcal{B}(\psi(2S) \to \mu^+\mu^-) = 2.574 \times \mathcal{B}(\psi(2S) \to \tau^+\tau^-)$
      (P = 1840 MeV for e^+e^- vs 489 MeV for $\tau^+\tau^-$)
- Tests of SM LFU have been performed in a variety of systems
  - $Z \to \ell\ell, W \to \ell\nu, \tau \to \ell\nu\bar{\nu}, \pi \to \ell\nu, K \to \pi\ell\nu$, etc...



Universality of the SM does not necessarily imply universality of interactions beyond the SM (“new physics”)

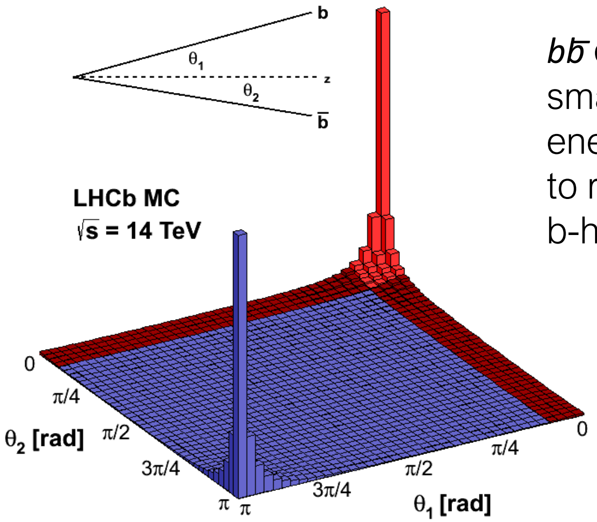
New physics preferentially coupling to the 3rd generation is usually less well-constrained, and can modify SM charged and neutral currents

- Examples: $A^0, H^\pm$, partial compositeness + W', leptoquarks

The LHCb experiment

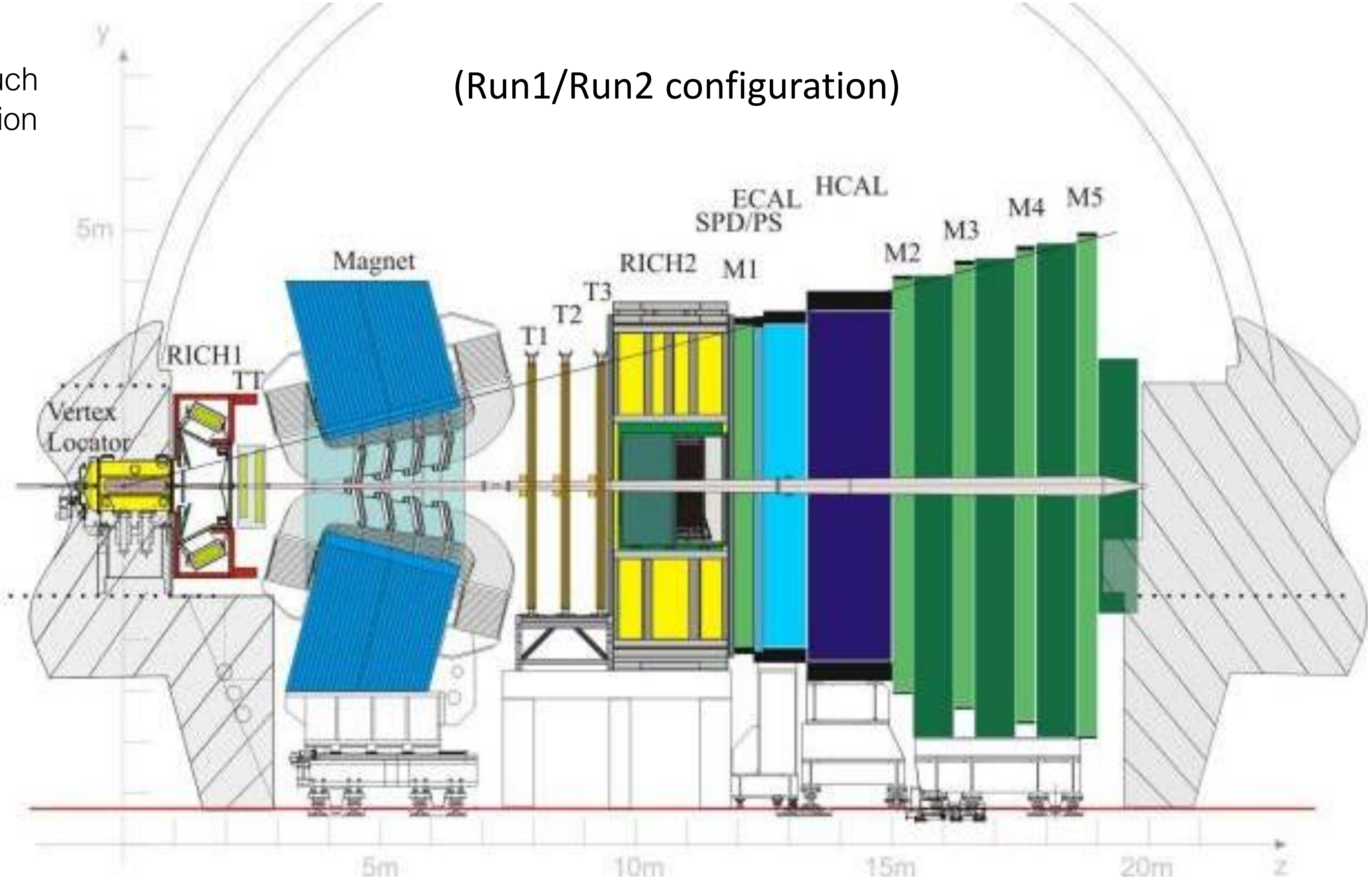
HEAVY FLAVOR AT THE LARGE HADRON COLLIDER

The LHCb Detector



$b\bar{b}$ quark mass much smaller than collision energy, leads to rapidly-moving b-hadrons

(Run1/Run2 configuration)



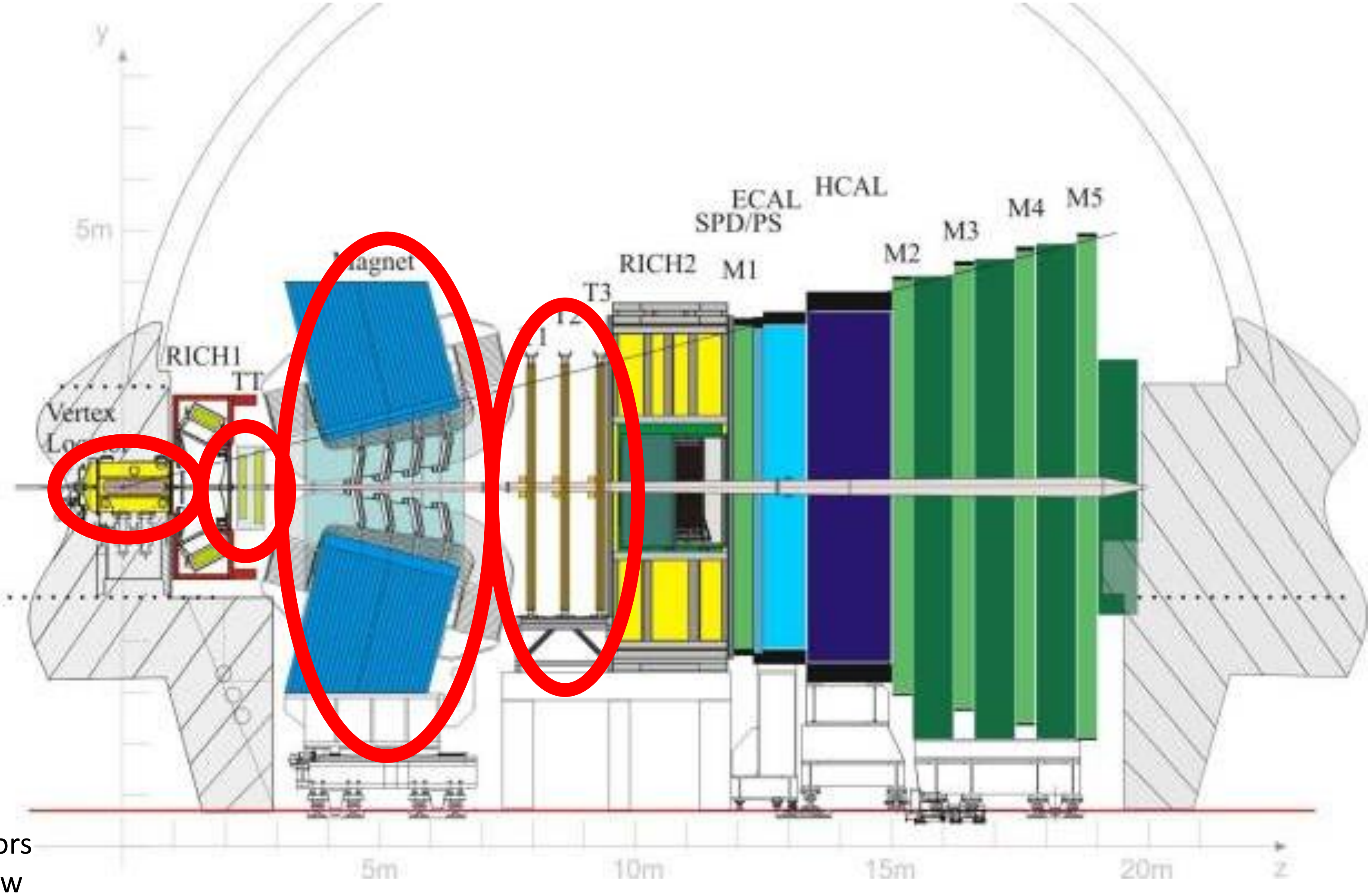
Forward detector exploits kinematics of b quark production in multi-TeV collisions:

cover 27% (25%) of b-hadron (pair) production while instrumenting < 3% of the solid angle

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



Aside: diagram shows Run1/2 configuration, currently installed detector is our Upgrade-1.

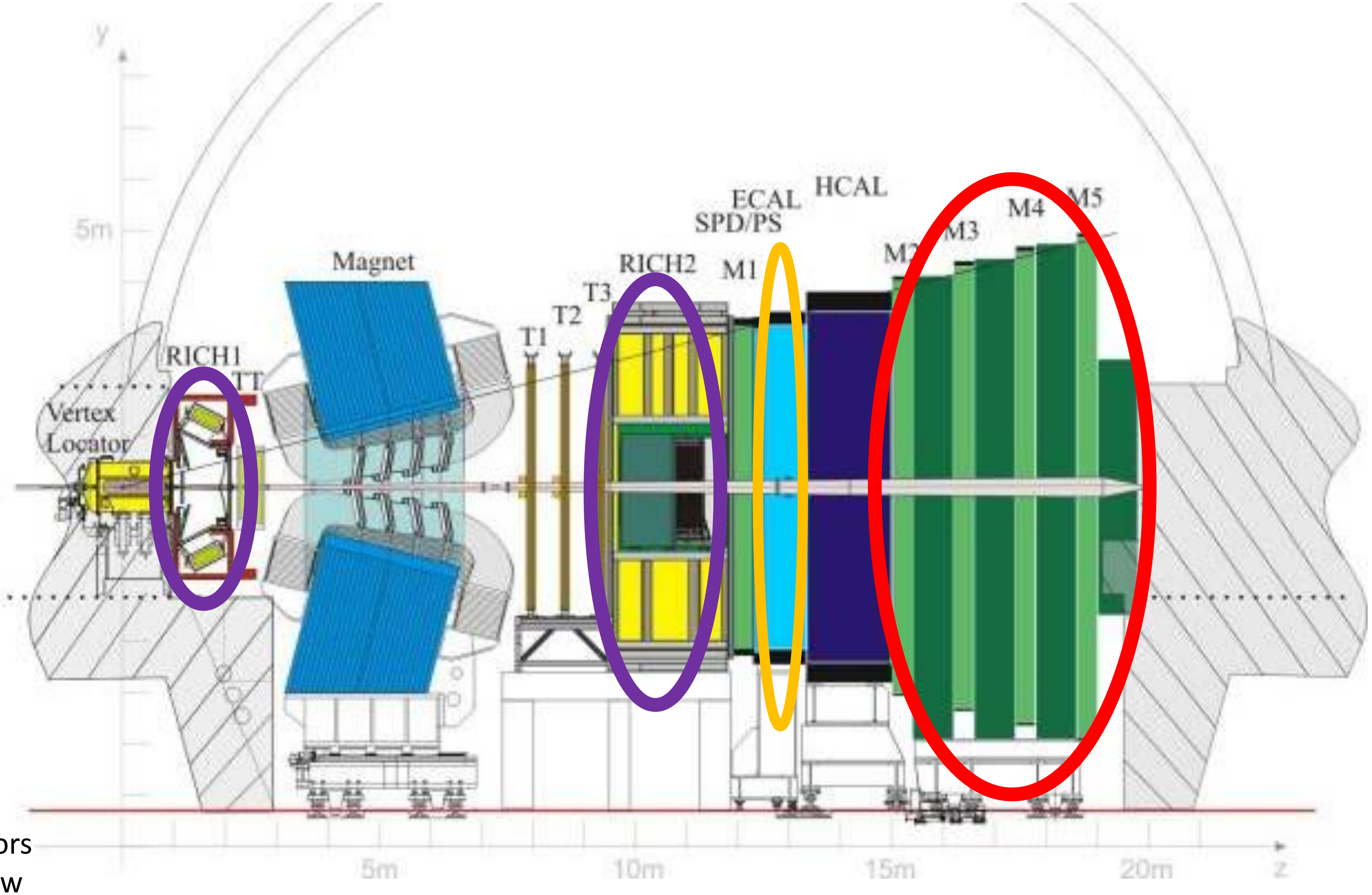
Locations and roles of subdetectors are largely the same, but with new technologies (later)

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



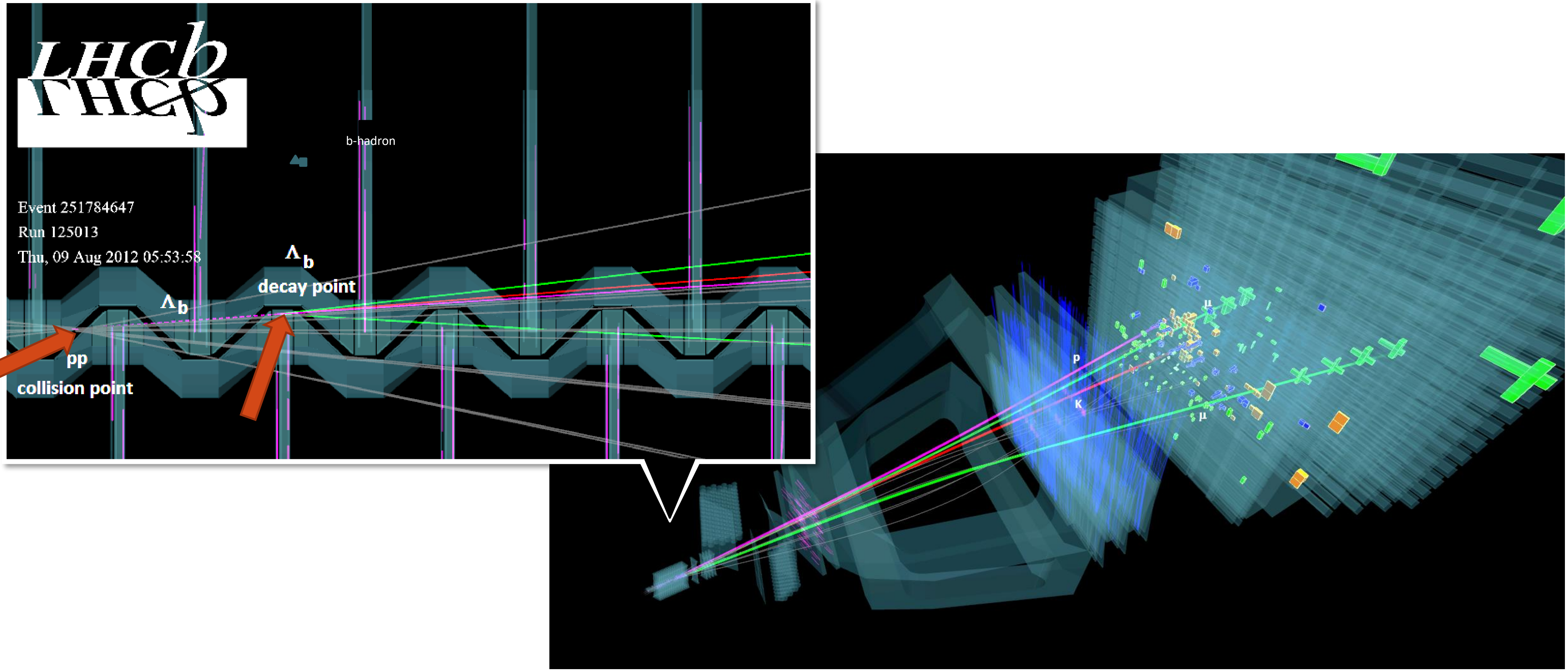
Aside: diagram shows Run1/2 configuration, currently installed detector is our Upgrade-1.

Locations and roles of subdetectors are largely the same, but with new technologies (later)

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

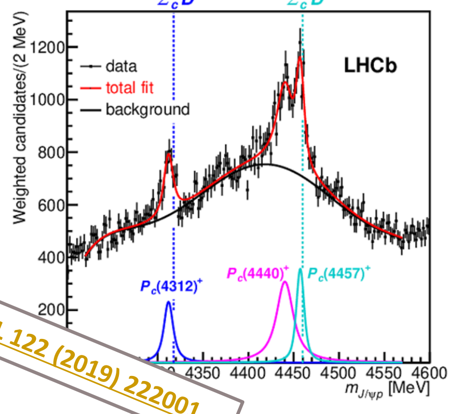
Muon Performance Paper:
JINST 8 (2013) P10020

A closer look



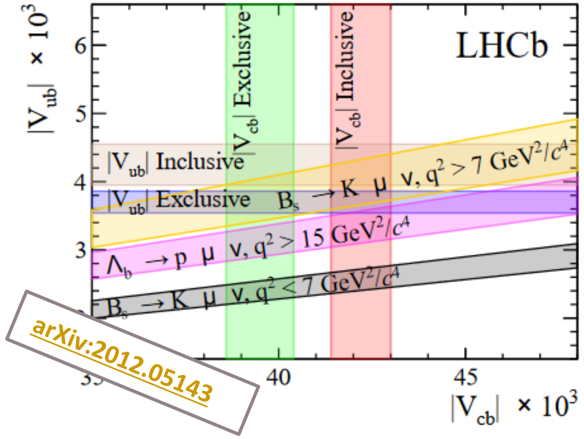
LHCb Physics Program

Pentaquark discovery



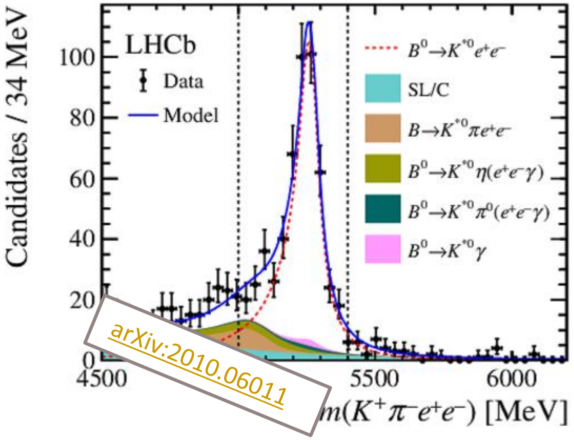
PRL 122 (2019) 222001

Vub with B_s^0



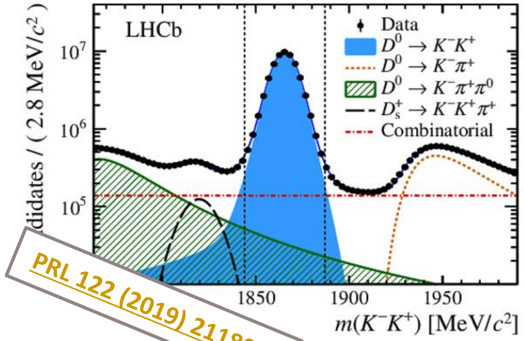
arXiv:2012.05143

$b \to s\gamma^*$ FCNC decays



arXiv:2010.06011

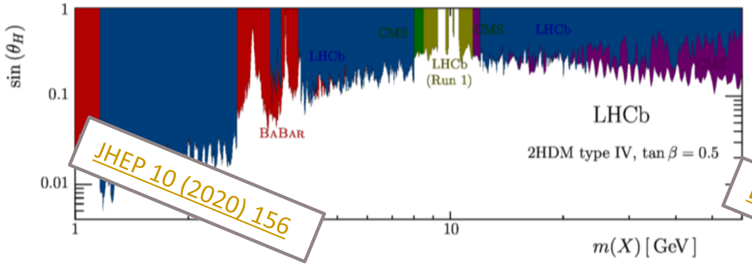
Discovery of Charm CPV



PRL 122 (2019) 211803

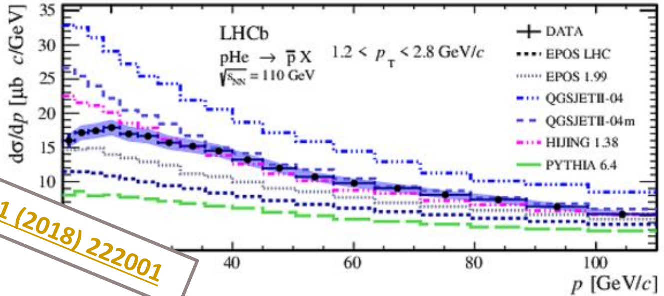
44 million prompt!

Light, weakly coupled $X \to \mu^+\mu^-$



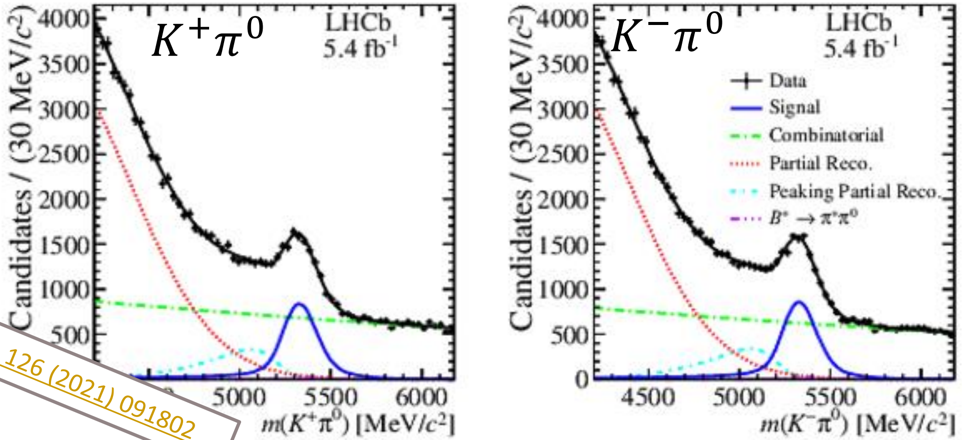
JHEP 10 (2020) 156

Antiprotons in p-on-He collisions



PRL 121 (2018) 222001

A_{CP} in $B^+ \to K^+\pi^0$ (no vertex!)



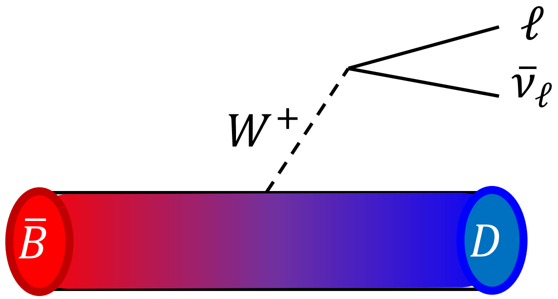
PRL 126 (2021) 091802

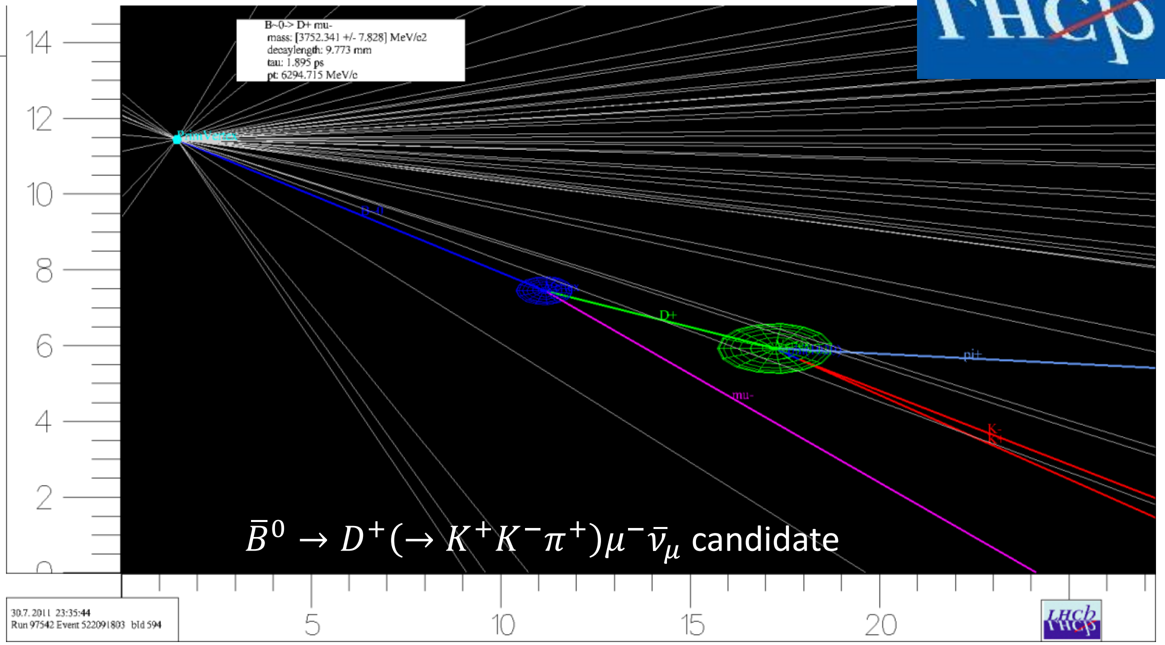
Many of these completed/submitted despite COVID-19 pandemic

Test of LFU in Semileptonic decays

ARXIV:2302.02886

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

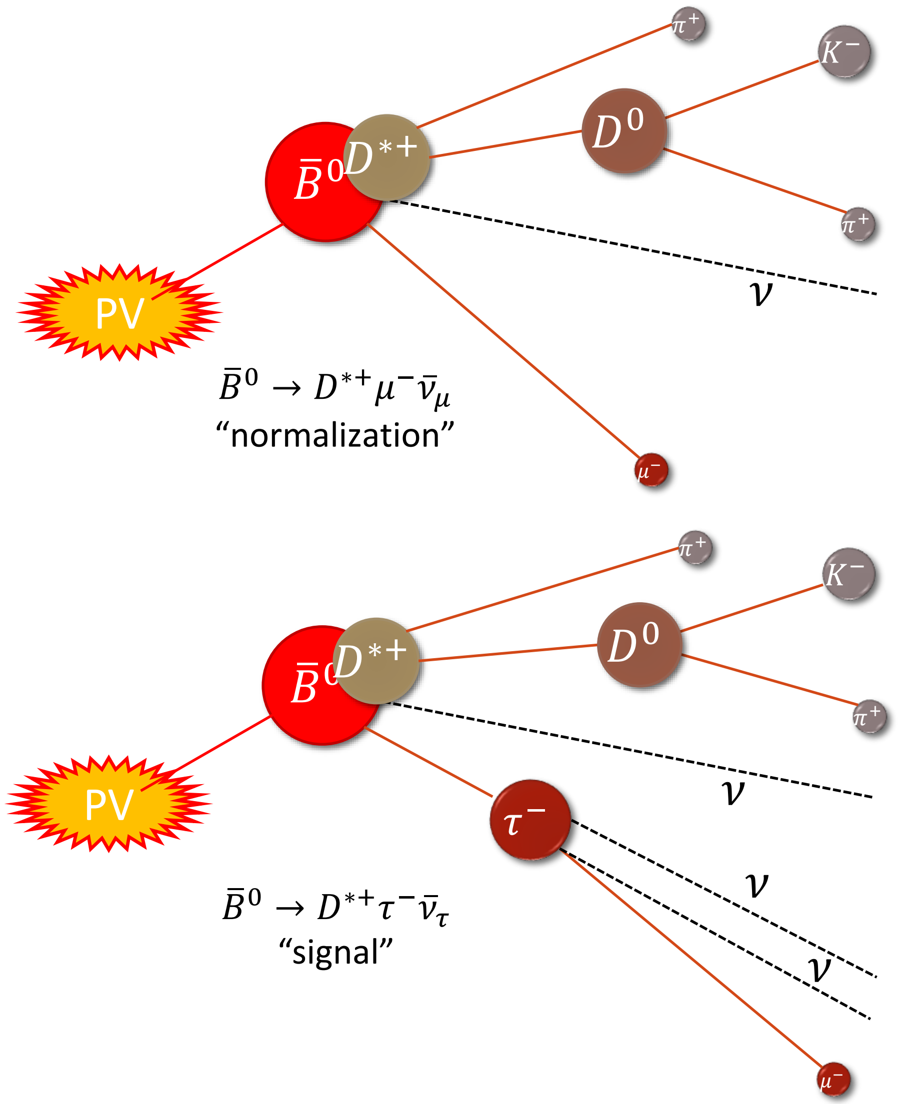
- Tree level virtual W emission – strong V-A structure
- No QCD interaction between the lepton-neutrino system and the recoiling hadron(s)
  - $\bar{B} \to W^{*\pm} D^{(*)}$ half of the decay still needs non-perturbative input

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

What we want to measure

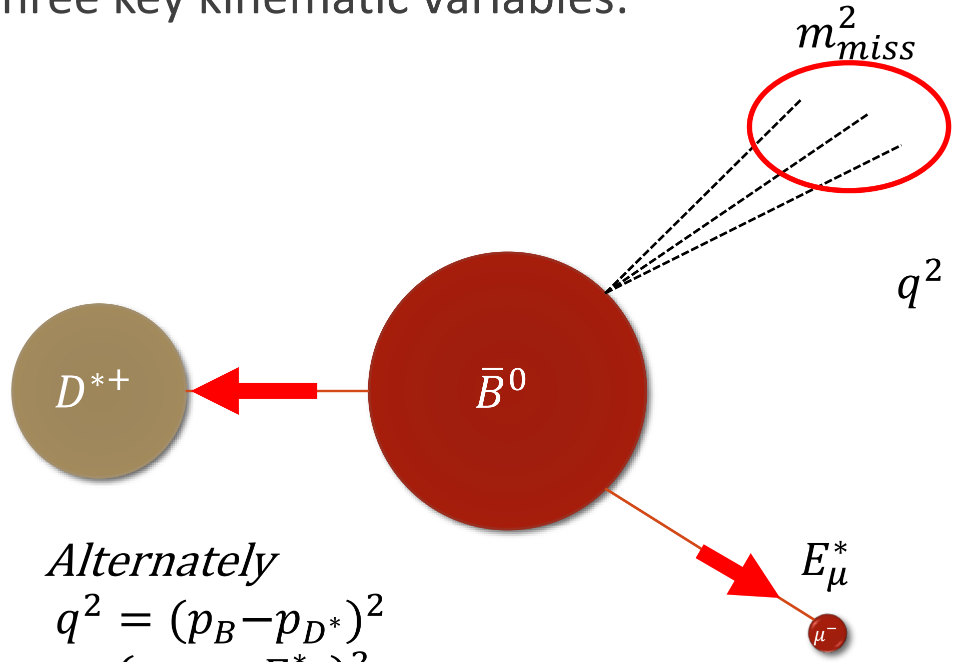
$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\ell)}$$

- Theoretically clean due to significant cancellation of form factor uncertainties
  - m_ℓ^2-suppressed contributions give dominant uncertainty
  - Unequal phase space spoils cancellation of helicity-favored part
  - SM: $R(D) = 0.299 \pm 0.003$ [PRD 94 (2016) 094008]
    $R(D^*) = 0.254 \pm 0.005$ [HFLAv average]
- $\tau^- \to \mu^-\bar{\nu}_\ell\nu_\tau$ channel
  - Automatic normalization from identical final state
  - Must be disentangled from $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ statistically
- Challenge: missing neutrinos with unknown energy
  - Don't have full B momentum
  - Large backgrounds from partially-reconstructed B decays



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

In B rest frame, 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
$\mathrm{m}^2_\tau \leq q^2 \leq 10.6\ \mathrm{GeV}^2$	$0 \leq q^2 \leq 10.6\ \mathrm{GeV}^2$

Previously….

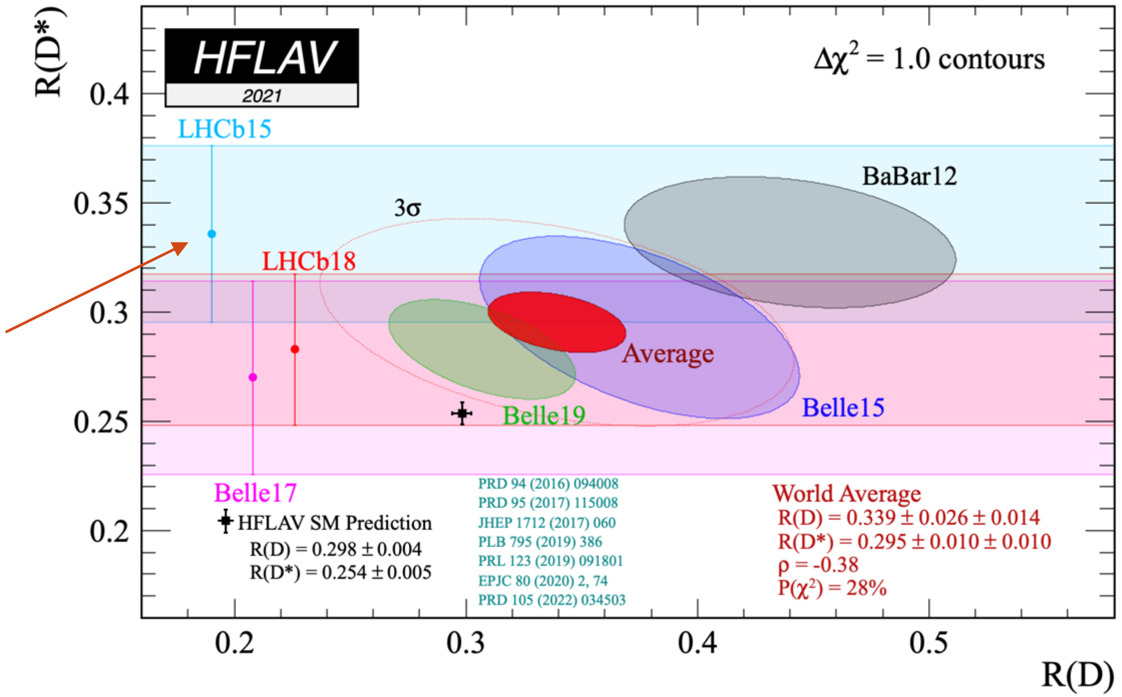
Situation with $\bar{B} \to X_c \tau \nu$ (“semitauonic”) decays evolving year by year since 2012

Two Run-1 measurements of R(D*) from LHCb so far

- $\tau^- \to \mu^- \nu \bar{\nu}$ and $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu$

This analysis: extend LHCb Run1 muonic measurement (‘LHCb15’) from 1D band to 2D ellipse via a simultaneous fit to disjoint $D^0 \mu^-$ and $D^{*+} \mu^-$ samples

- Joint R(D) v R(D*) measurement provides information about nature of enhancement
  - Example: equal enhancement in both (BaBar2012) *strongly* disfavors 2HDM charged Higgs contribution



As with 2015 measurement, have 2 fitters extensively cross-checked against one-another

A word of caution

Renato Quagliani
LHC Seminar

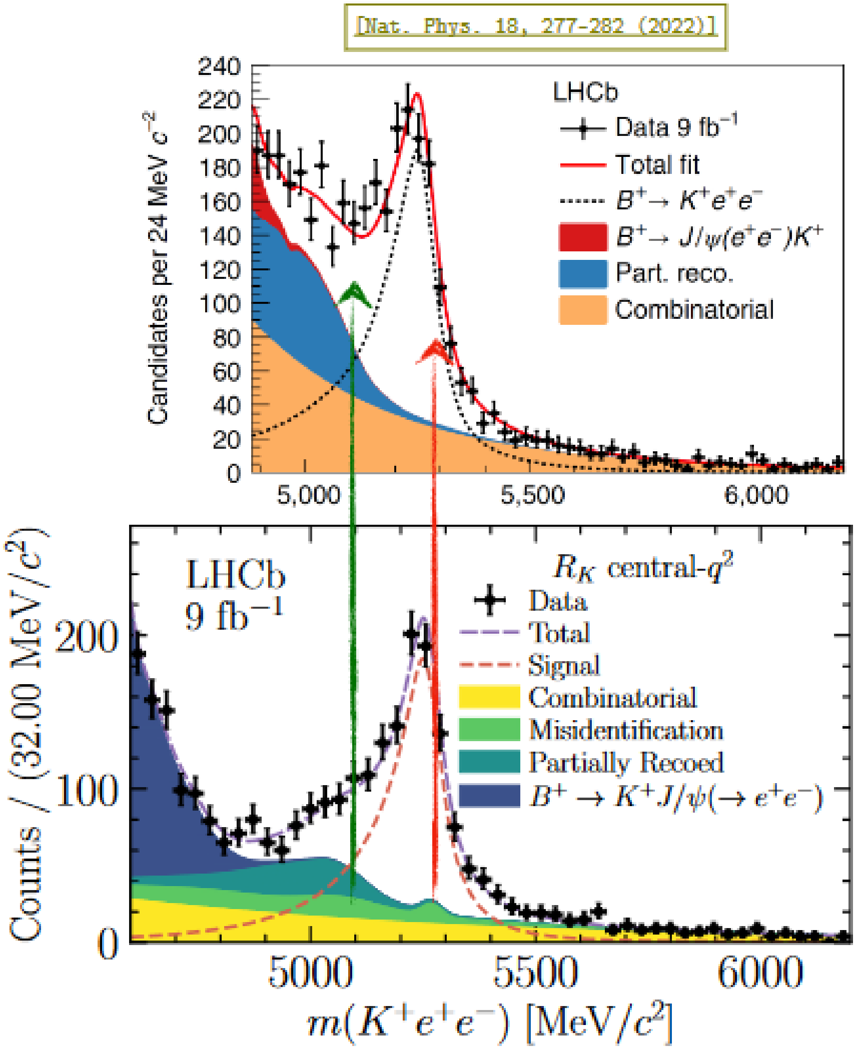
"Anomalies" can and do occasionally evaporate either under higher statistics or higher scrutiny

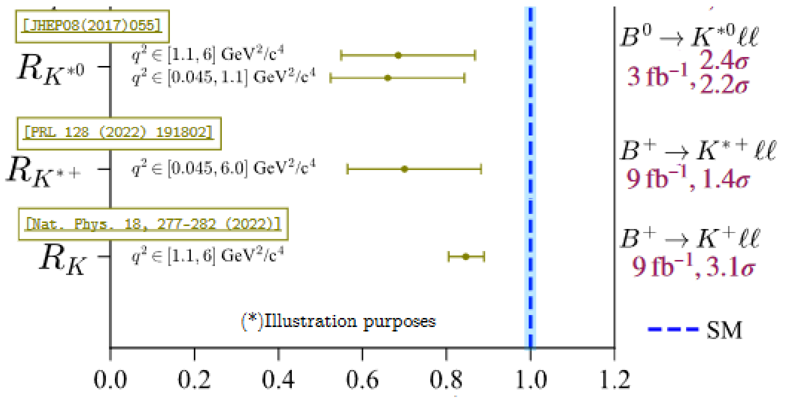
Recent example:

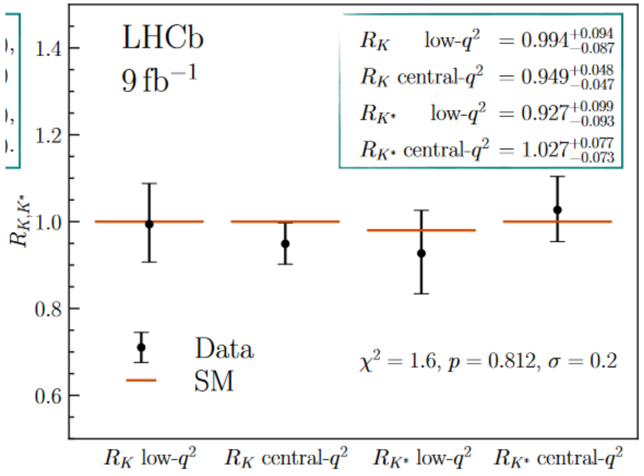
- Legacy combined analysis of $K^{(*)}\ell\ell$ found a funny trend in R_K vs PID on electrons. Subtle peaking background in fake electrons

Best we can do:

- compare different experiments with different purities / backgrounds / techniques
- Check for understanding of background everywhere possible

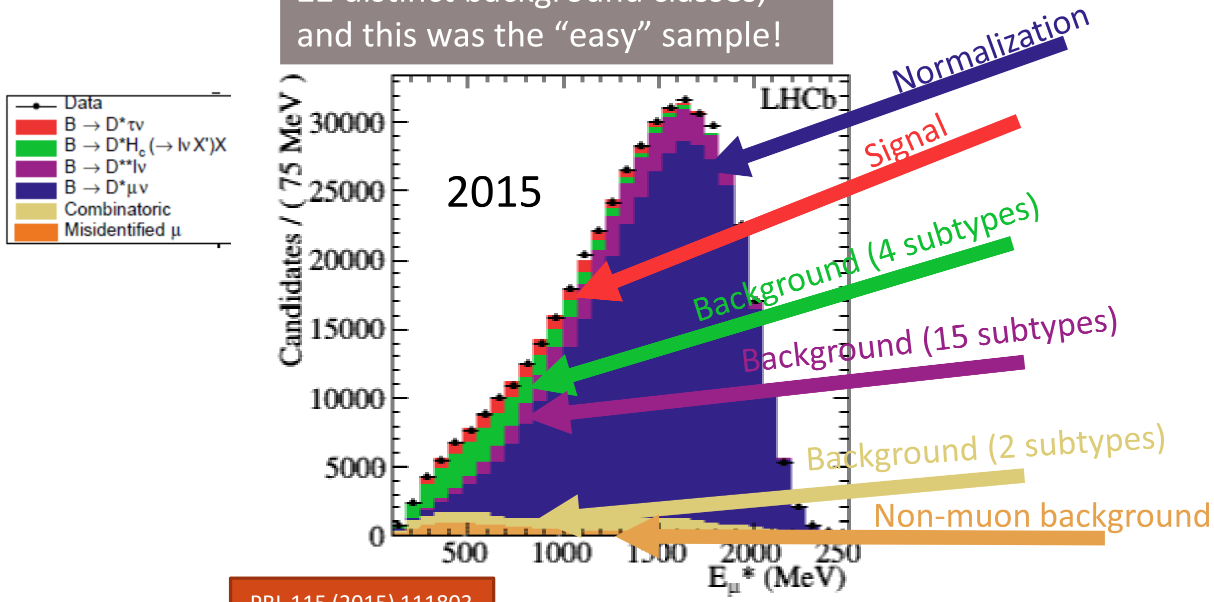






More data, more problems

22 distinct background classes, and this was the "easy" sample!



PRL 115 (2015) 111803

D^* feed-down *after* isolation, veto

$$\frac{B^- \to D^{*0}[\to D^0(\pi^0/\gamma)]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 2.5$$

$$\frac{B^0 \to D^{*+}[\to D^0\pi^+_{missing}]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 0.125,$$

Both a precision measurement and an inclusive analysis at high statistics

- Every background source must be understood in exacting detail to even see the signal

$D^0\mu^-$ sample is 5x larger than $D^{*+}\mu^-$

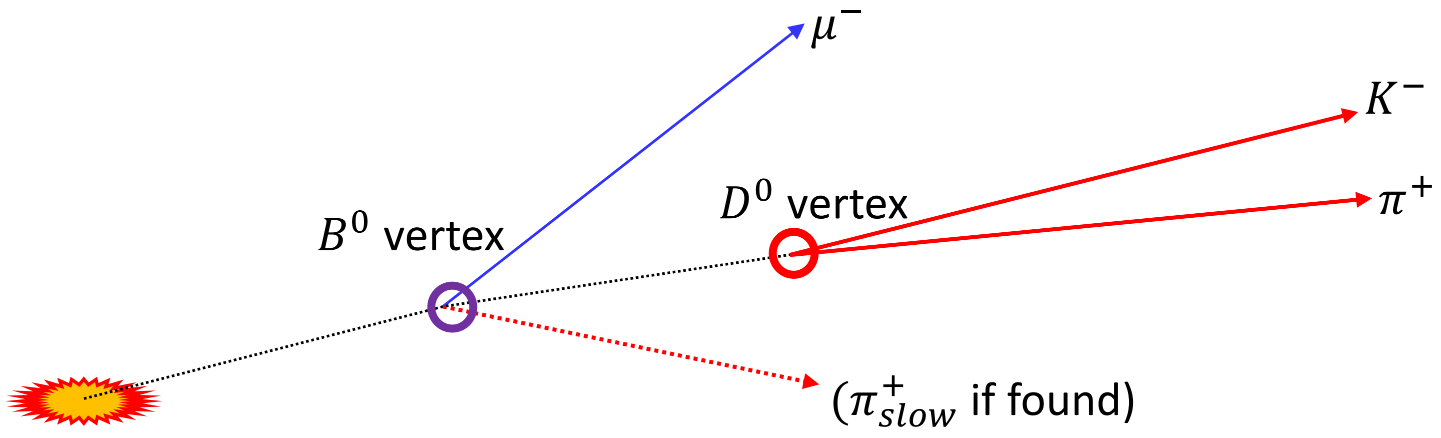
- Already as big a jump as Run1->Run2 for many analyses

$B^- \to D^0\tau^-\bar{\nu}$ background structure much more complicated

- $\bar{B} \to D^{*0}\mu X$ always present in $D^0\mu^-$ sample (75% of the sample!)
  - Triplicated background modes
- Three separate "signal" categories all kinematically similar!

Procedure

What’s reconstructed



Combine $D^0 \to K^-\pi^+$ candidate passing charm trigger with μ^- and π^+_{slow}

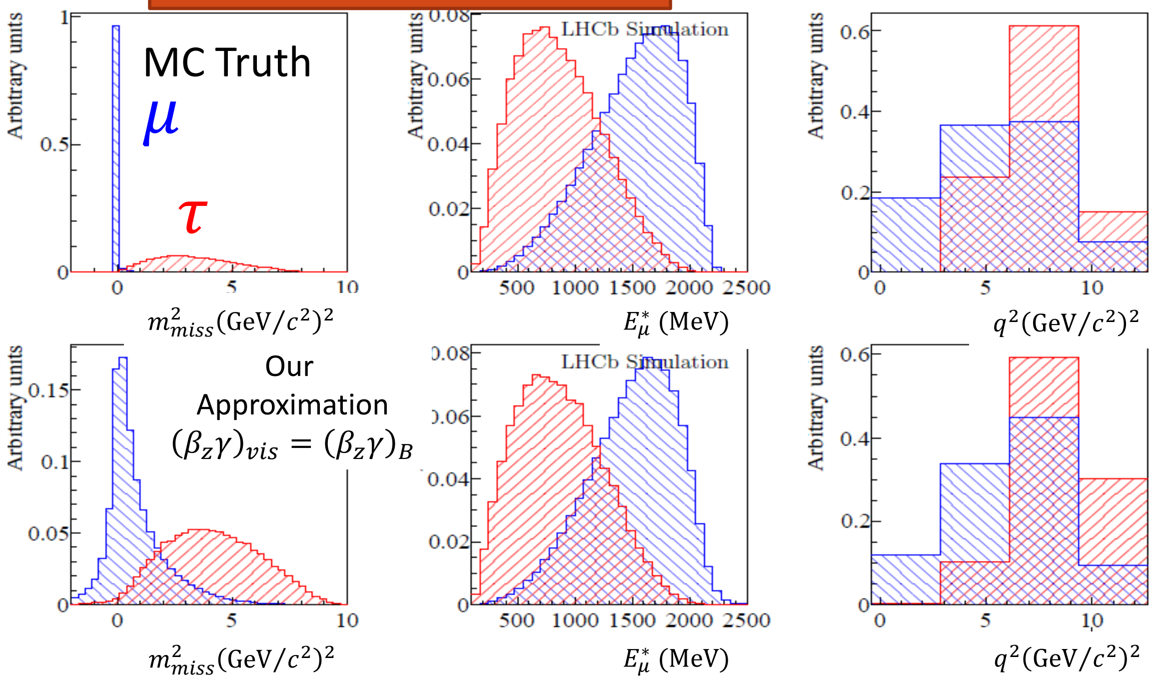
- Inclusive single-muon triggers biased in missing mass
- Require $\mu^-, K^-\pi^+$all to have significant impact parameter with respect to PV
- Impact parameter requirements on $D^0 \to K^-\pi^+$ remove prompt charm pollution

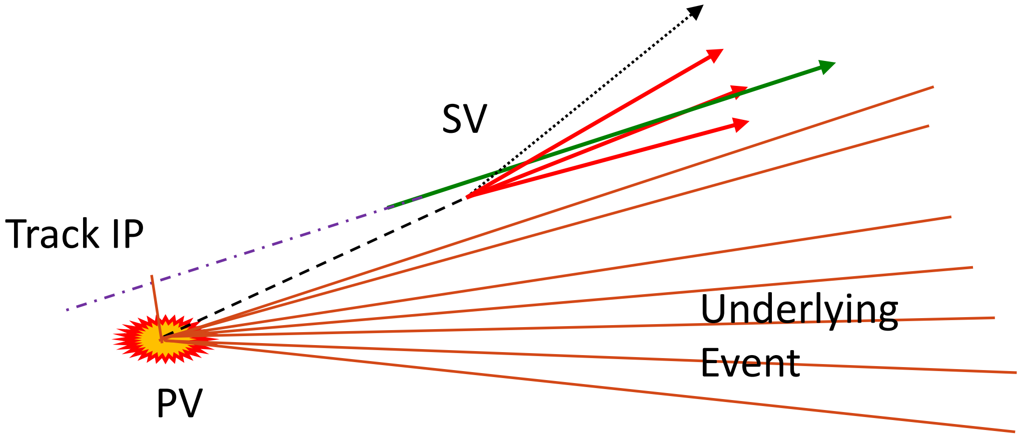
Flight direction of B hadron allows transverse (to B) components of missing momentum to be inferred from visible decay momentum (2 constraints)

- One additional input plus a total mass constraint would be enough to know the initial B momentum…

LHCb Technique

LHCb-PAPER-2015-025 supplemental





No information on initial B momentum to reconstruct the discriminating variables

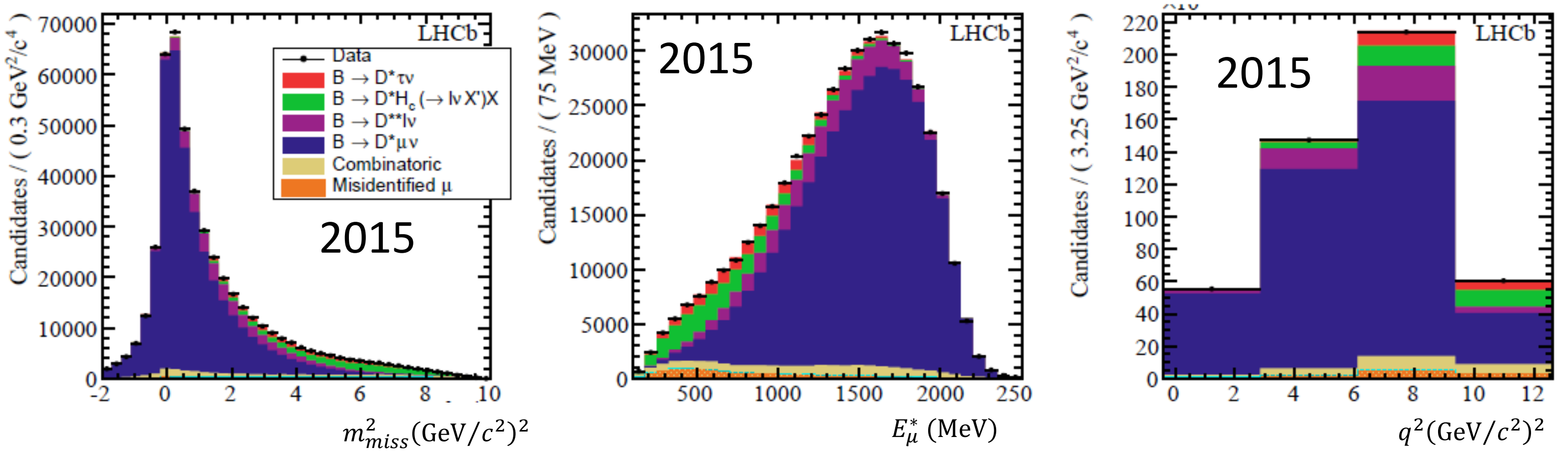
- Key: Resolution on rest frame variables doesn't matter much because distributions are broad to begin with -- well-behaved approximation will still preserve differences for fit
- Approximation + knowledge of direction from PV to SV => solve for full B momentum

Use superb tracking system to fight huge partially-reconstructed background

- Scan over every track and compare against $D^{*+}\mu^-$ vertex with machine-learning alg.
- Allows for cleaner signal sample *and* data control samples enriched in key backgrounds

EXTRA TRACKS

Fitting the data



LHCb-PAPER-2015-025 supplementary

3D “template” histograms for each process contributing to $D^{*+}\mu^-$ or $D^0\mu^-$

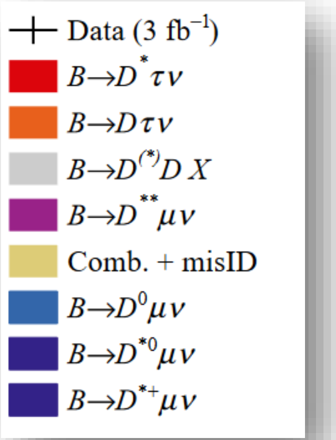
- Signal, normalization, and partially reconstructed backgrounds use simulated events, other backgrounds use control data
- Model parameters included in templates and explicitly part of likelihood

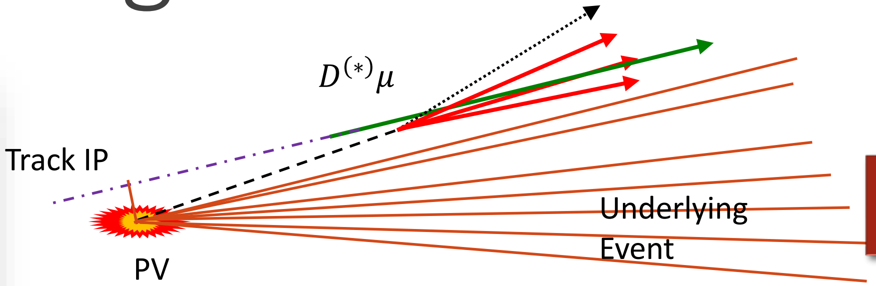
Simultaneous maximum-likelihood fit to isolated signal regions, anti-isolated control regions

- Shape parameters shared, yields independent in each sample
- Alternate strategy of finding background shapes then fitting signal region first gives excellent agreement with simultaneous treatment

LHCb-PAPER-2022-039 supplementary

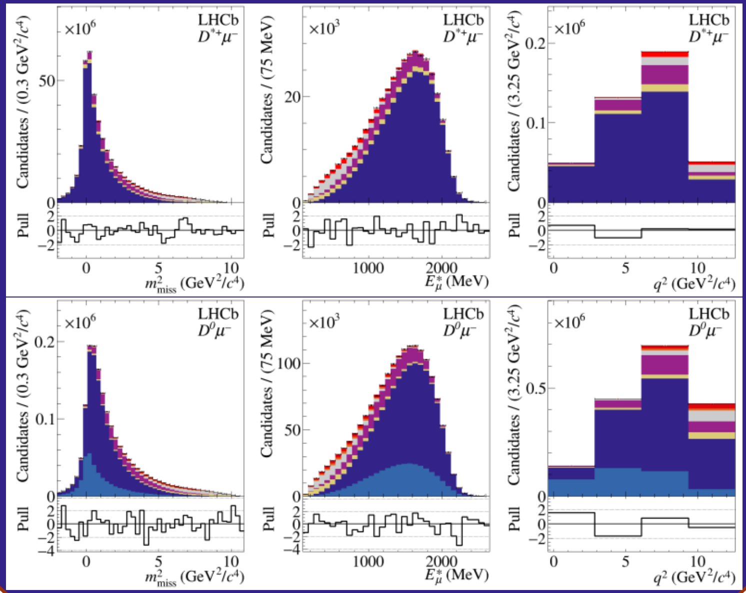
Fit Regions





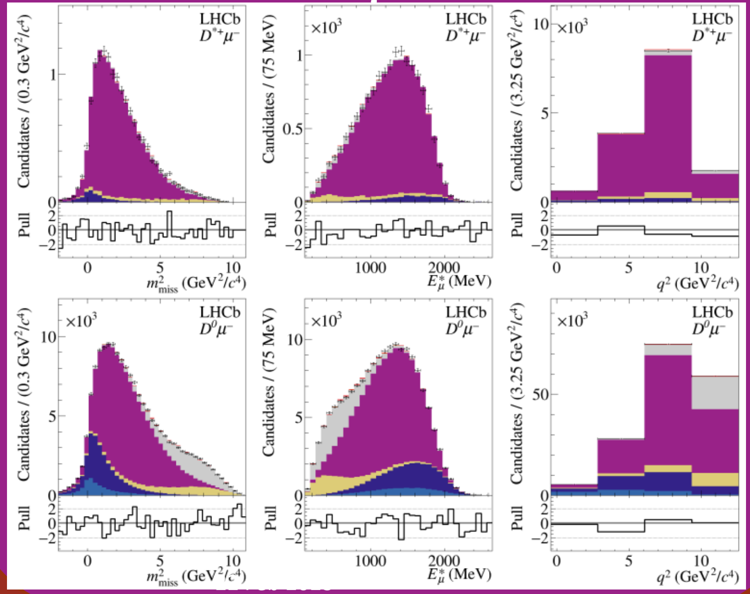
No other SV-like tracks

Isolated signal

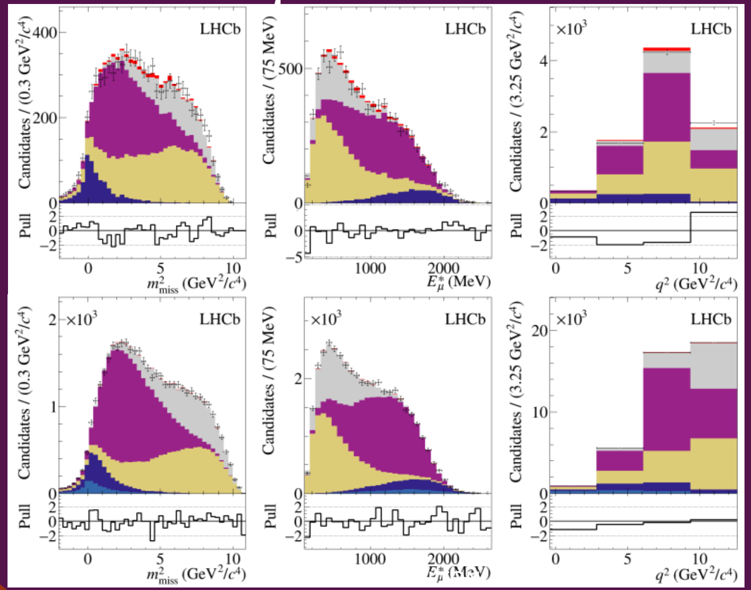


$\geq$ 1 SV-like track(s)

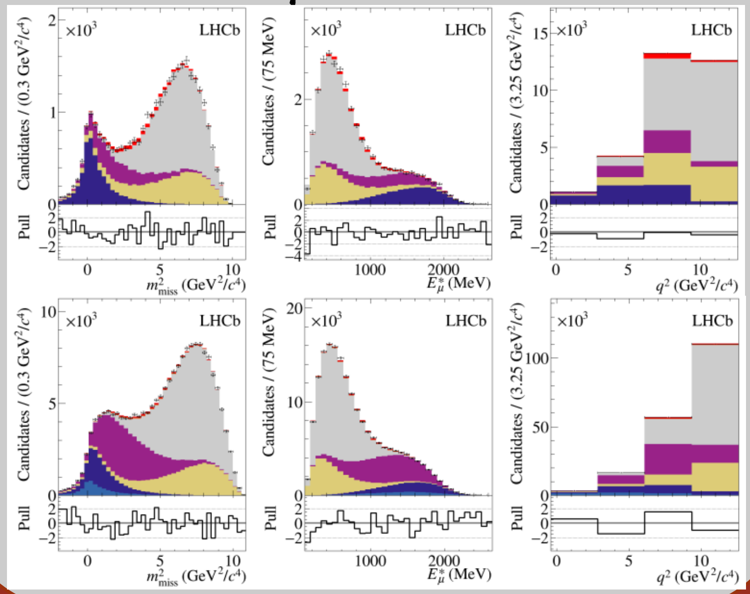
$D^{(*)}\mu + \pi$



$D^{(*)}\mu^- + \pi^-\pi^+$



$D^{(*)}\mu + K + X$

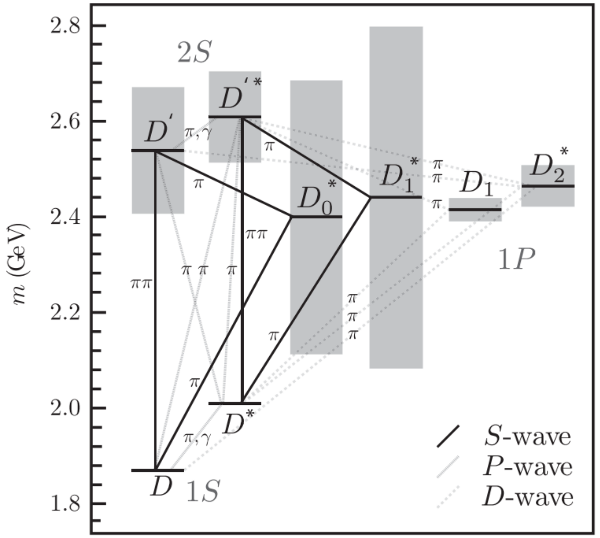


Background classes

Bernlochner et al, PRD 85 094033 (2012)

Semileptonic feed-down backgrounds:

- $\bar{B} \to D^{**}[\to D^{(*)}\pi]\ell\bar{\nu}$
- $\bar{B} \to D^{**}[\to D^{(*)}\pi\pi]\ell\bar{\nu}$

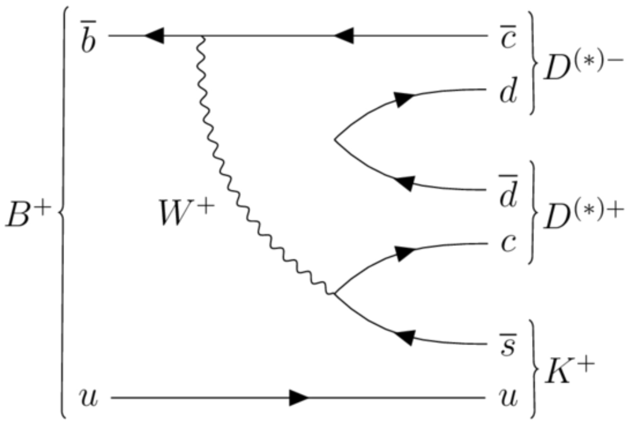


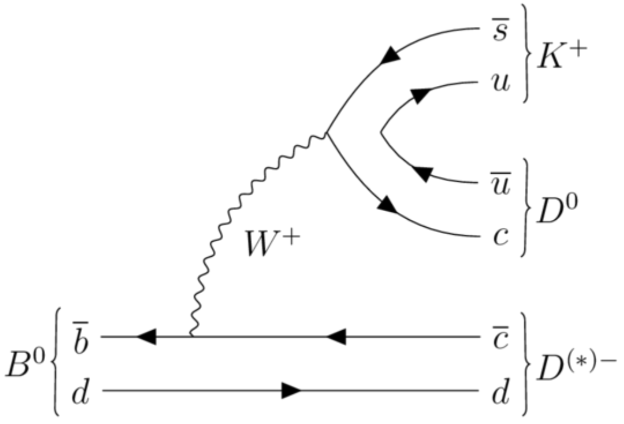
Semileptonic cross-feed:

- $\bar{B}_s^0 \to D_s^{**+}[\to D^{(*)}K]\ell\bar{\nu}$

"Double-charm"

- $\bar{B} \to D^{(*)}\bar{D}_{(s)}^{(*)}[\to X\ell\bar{\nu}]$
  - $\bar{B} \to D^{(*)}\bar{D}_s^{(*)}[\to \tau\bar{\nu}]$
- $\bar{B} \to D^{(*)}\bar{D}^{(*)}[\to X\ell\bar{\nu}]K$





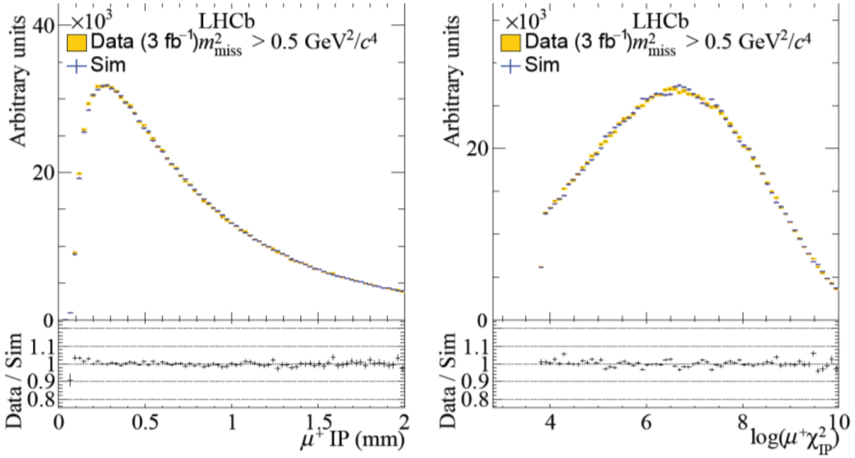
Other "junk" backgrounds:

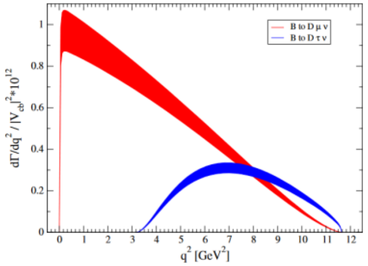
- Combinatorial background
- Fake muon background

Improvements/New Technology

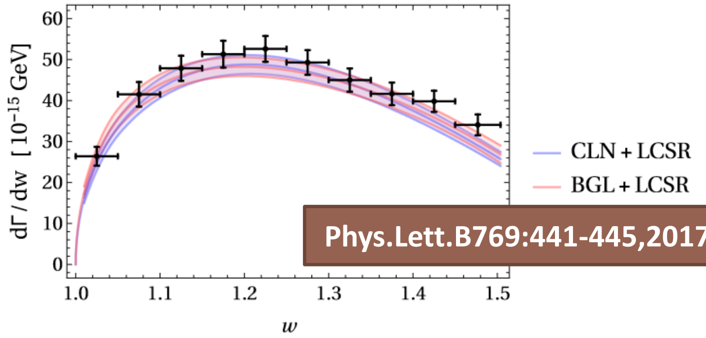
A number of improvements in the modeling of the signal, normalization, and backgrounds have been introduced for this analysis

- Exhaustive data/simulation correction procedure
- New theory parameterizations for all semileptonic decays in model
- Improved rejection of fake muons and modeling of residual fake muon background
- Extensive tests in other anti-isolated selections to check for add’l backgrounds not degenerate with existing model

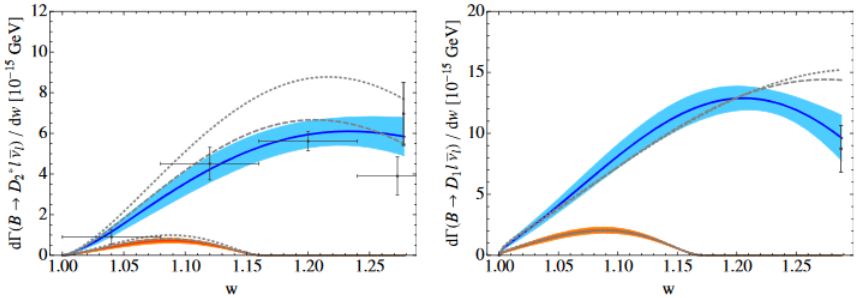




PRD 92 (2015) 054510



Phys.Lett.B769:441-445,2017



Phys. Rev. D 95, 014022

Fake Muon background

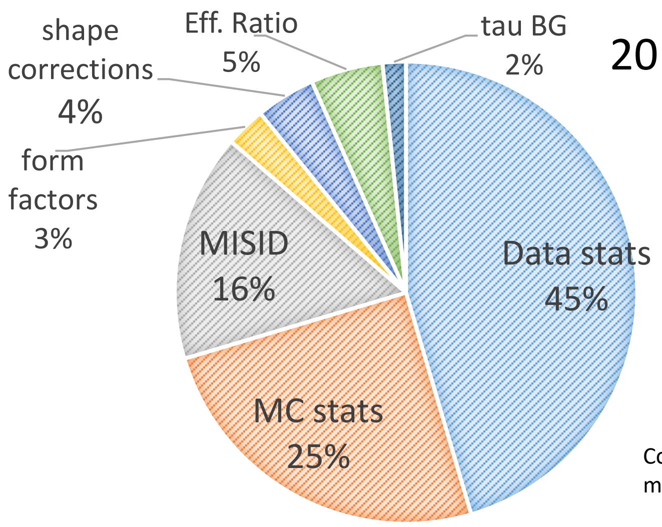
Hadrons misidentified as muons present an important challenge to the effort to move to larger datasets and higher precision

- 2nd Largest systematic uncertainty in 2015 analysis after MC stats

Twofold approach:

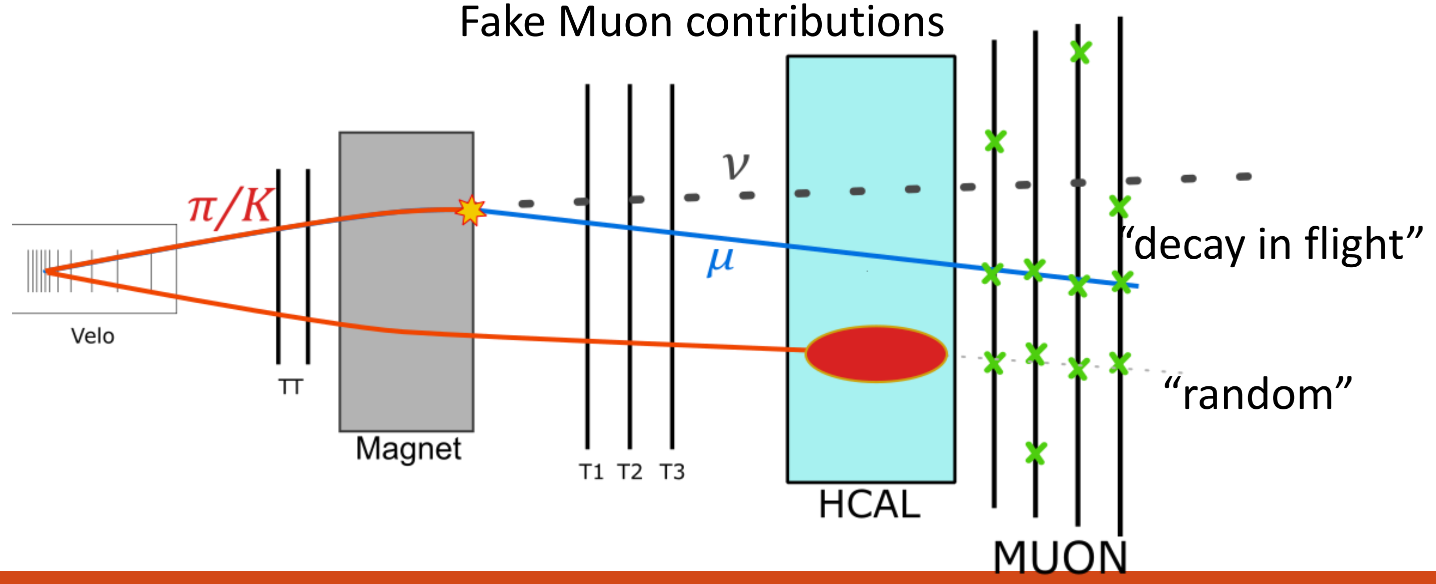
- Reduce background with improved BDT PID
  - Constrained to be flat vs muon momentum, pT
  - Removes ~1/2 of fakes selected by old criteria
- Improved techniques to estimate background shape based on $D^{(*)} + track$ data
  - +modeling of decay-in-flight momentum smearing on data-driven input

2015 Uncertainty budget



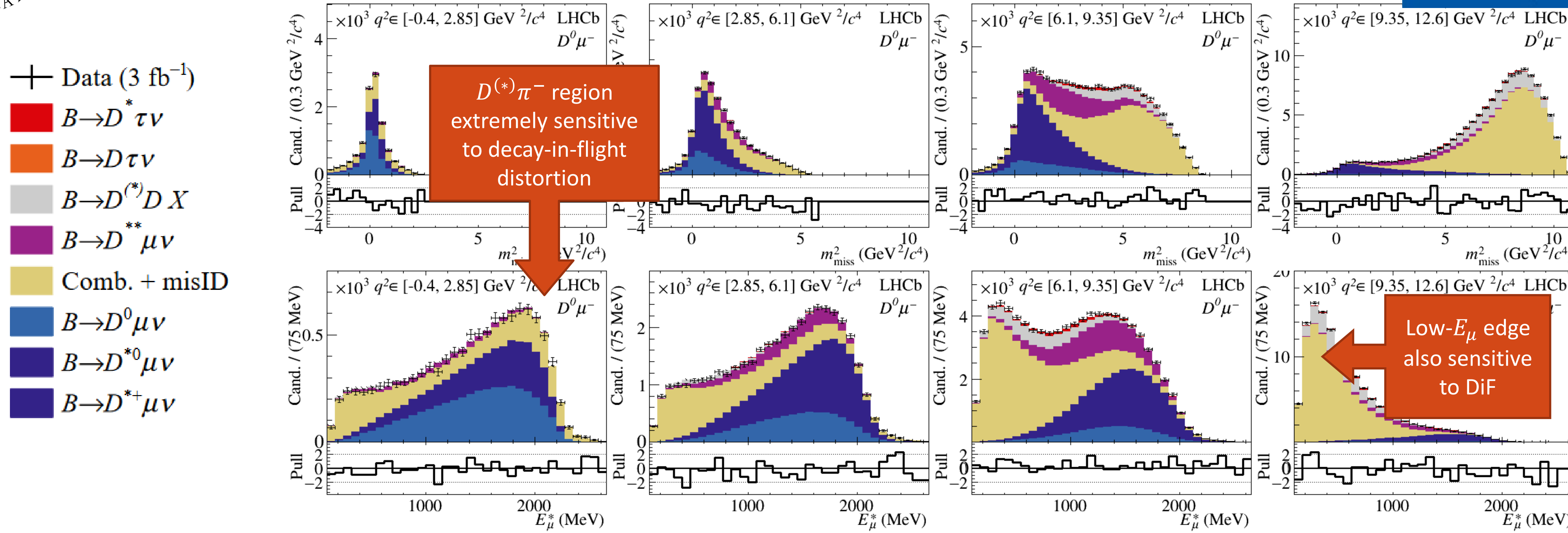
Contribution of each source to the squared total measurement uncertainty

Fake Muon contributions



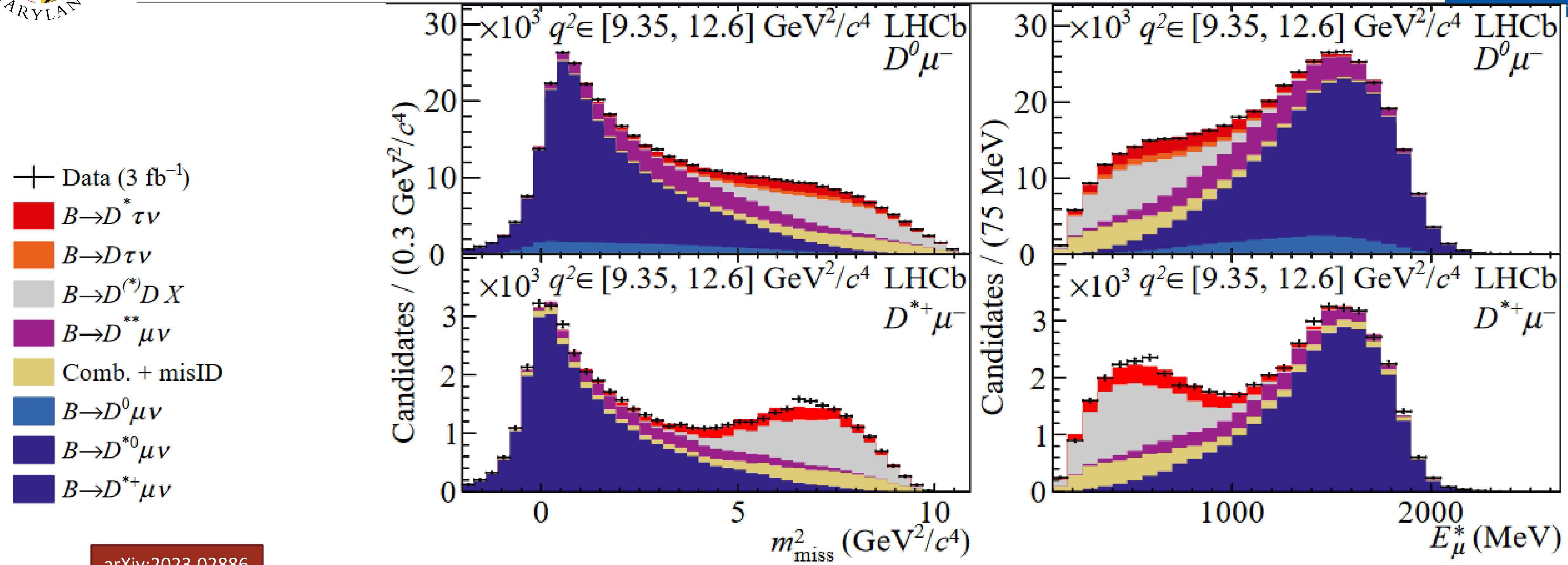
MisID validation

LHCb-PAPER-2022-039 supplementary



Background shape validated against data *rejected* by new selection but *retained* by old

Results



arXiv:2023.02886

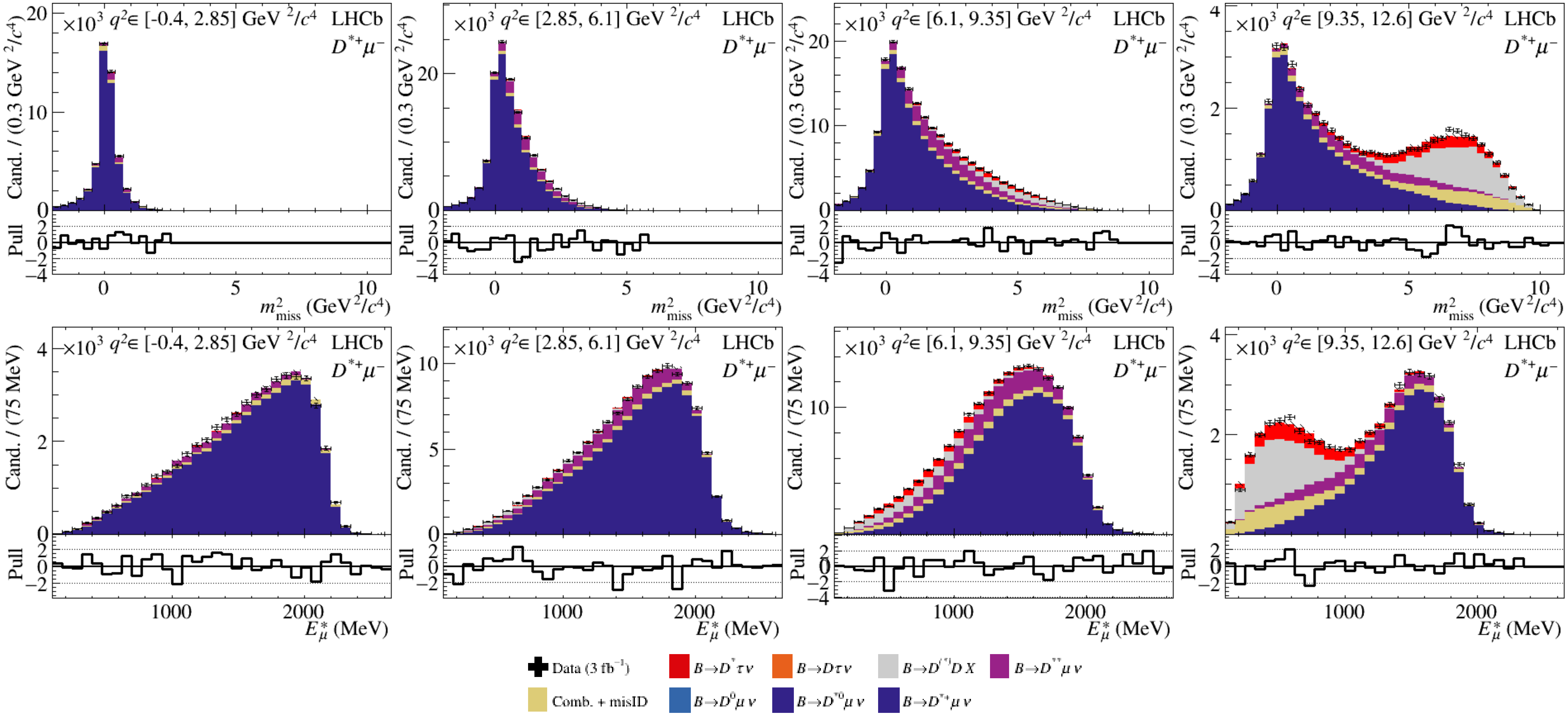
$$R(D^0) = 0.441 \pm 0.060(stat) \pm 0.066(sys)$$

$$R(D^*) = 0.281 \pm 0.018(stat) \pm 0.023(sys)$$

$$\rho = -0.49(stat)/-0.40(sys)/-0.43(tot)$$

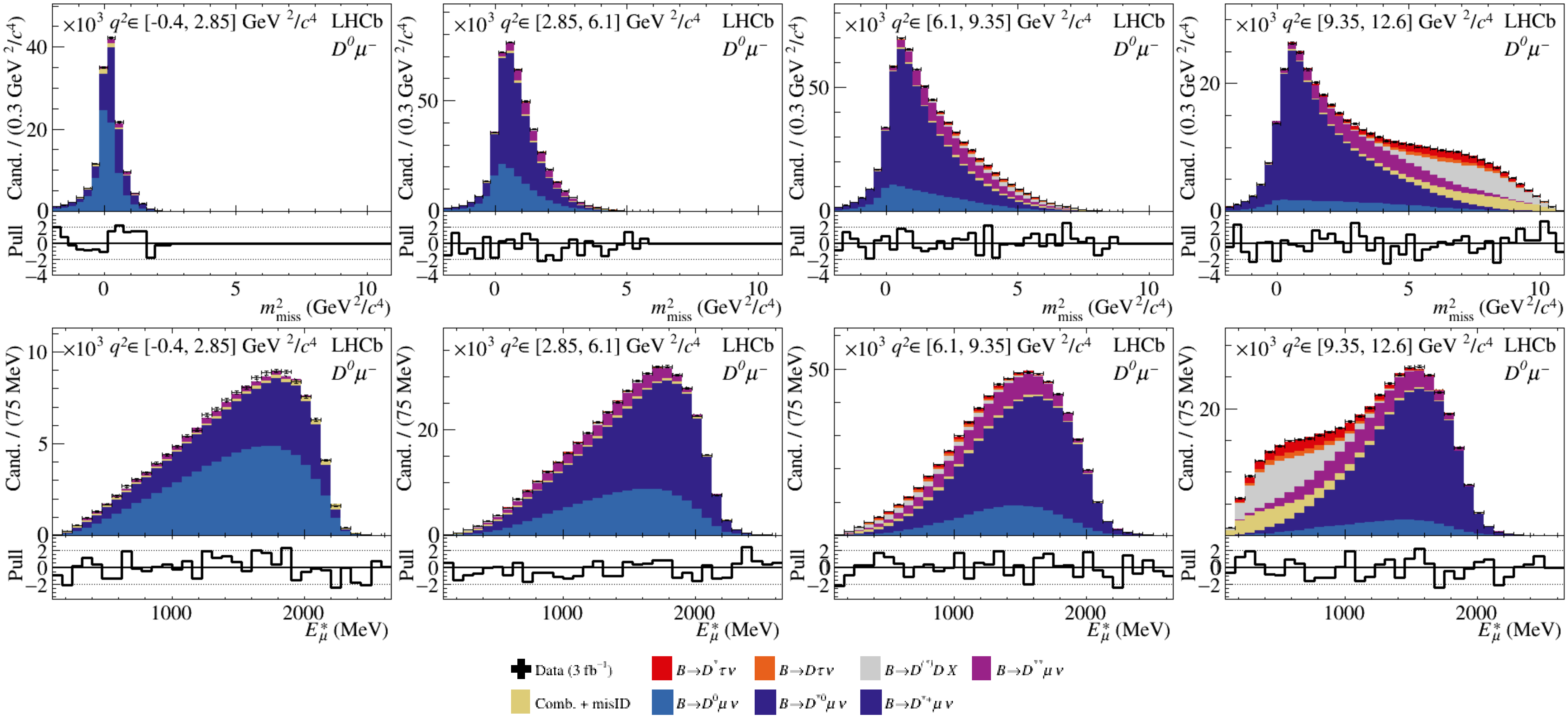
Results-$D^{*+}\mu^-$ sample

LHCb-PAPER-2022-039 supplementary

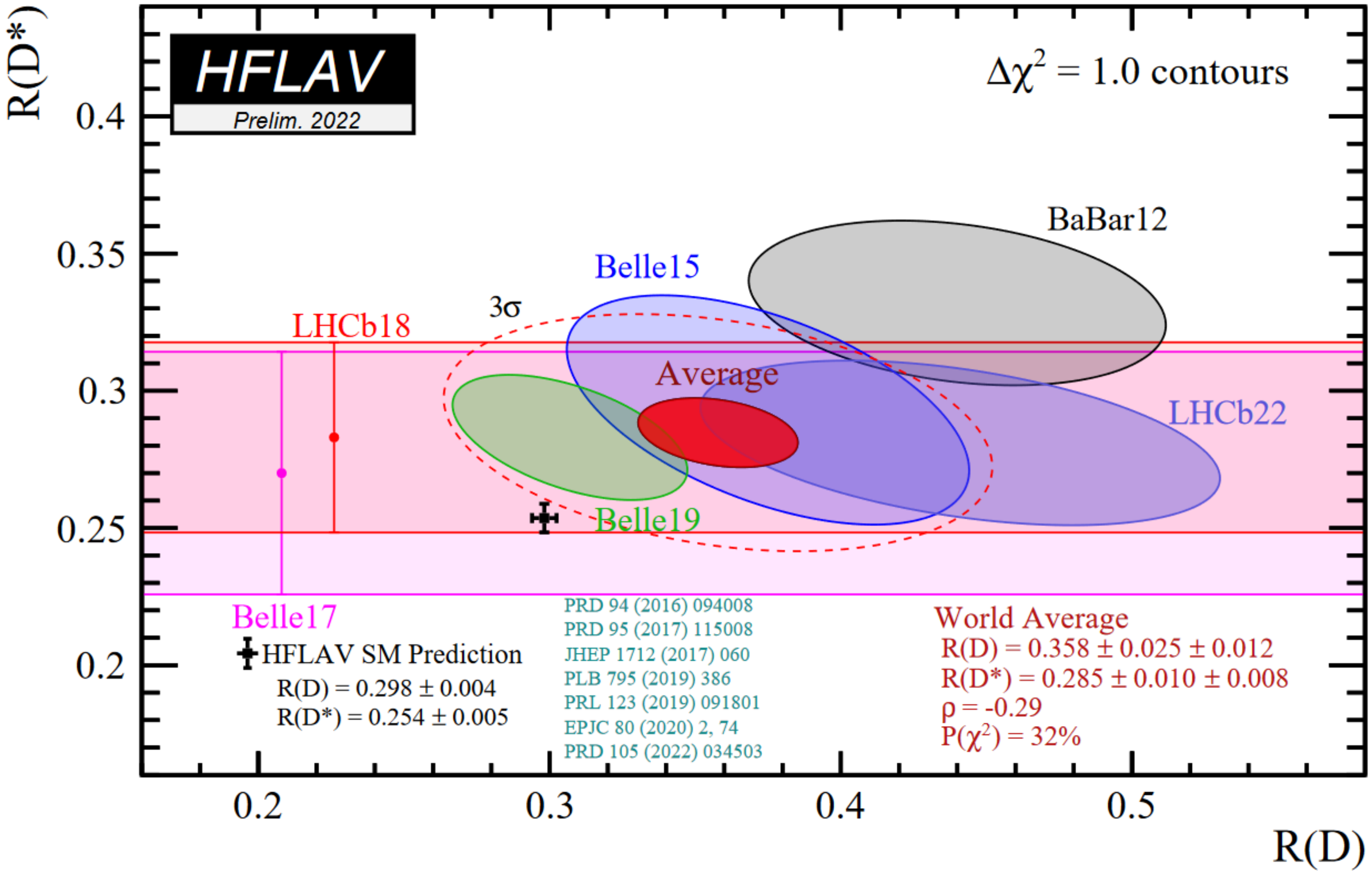


Results-$D^0\mu^-$ sample

LHCb-PAPER-2022-039 supplementary



Results in Context



arXiv:2023.02886

$$R(D) = 0.441 \pm 0.060(stat) \pm 0.066(sys)$$
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$$\rho = -0.49(stat)/-0.40(sys)/-0.43(tot)$$

2021 HFLAv (previous)

HFLAV

World Average
R(D) = 0.339 ± 0.026 ± 0.014
R(D*) = 0.295 ± 0.010 ± 0.010
ρ = -0.38
P(χ²) = 28%

Syst. Table

arXiv:2023.02886

Internal to fit likelihood
-> Scale roughly with size of control data

External to fit likelihood. Will require more than just more control data to improve

Multiplicative uncertainties small in $\tau \to \mu\nu\bar{\nu}$

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	**Correlation**
Statistical uncertainty	1.8	6.0	−0.49
Simulated sample size	1.5	4.5	
$B \to D^{(*)}DX$ template shape	0.8	3.2	
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\,(\overline{B} \to D^* D_s^-(\to \tau^-\overline{\nu}_\tau)X)$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\,(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	0.5	0.5	
Combinatorial	<0.1	0.1	
Resolution	<0.1	0.1	
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7	
$\overline{B}{}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.8	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
MisID template unfolding	0.7	1.2	
Baryonic backgrounds	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
Data/simulation corrections	$0.4\times\mathcal{R}(D^*)$	$0.6\times\mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ branching fraction	$0.2\times\mathcal{R}(D^*)$	$0.2\times\mathcal{R}(D^0)$	
Total systematic uncertainty	2.4	6.6	−0.39
Total uncertainty	3.0	8.9	−0.43

Validation test fits

FIX SHAPE PARAMETERS TO NOMINAL BEST FIT, TRY TO FIT OTHER POSSIBLE ANTI-ISOLATED REGIONS WITH ONLY YIELDS FREE

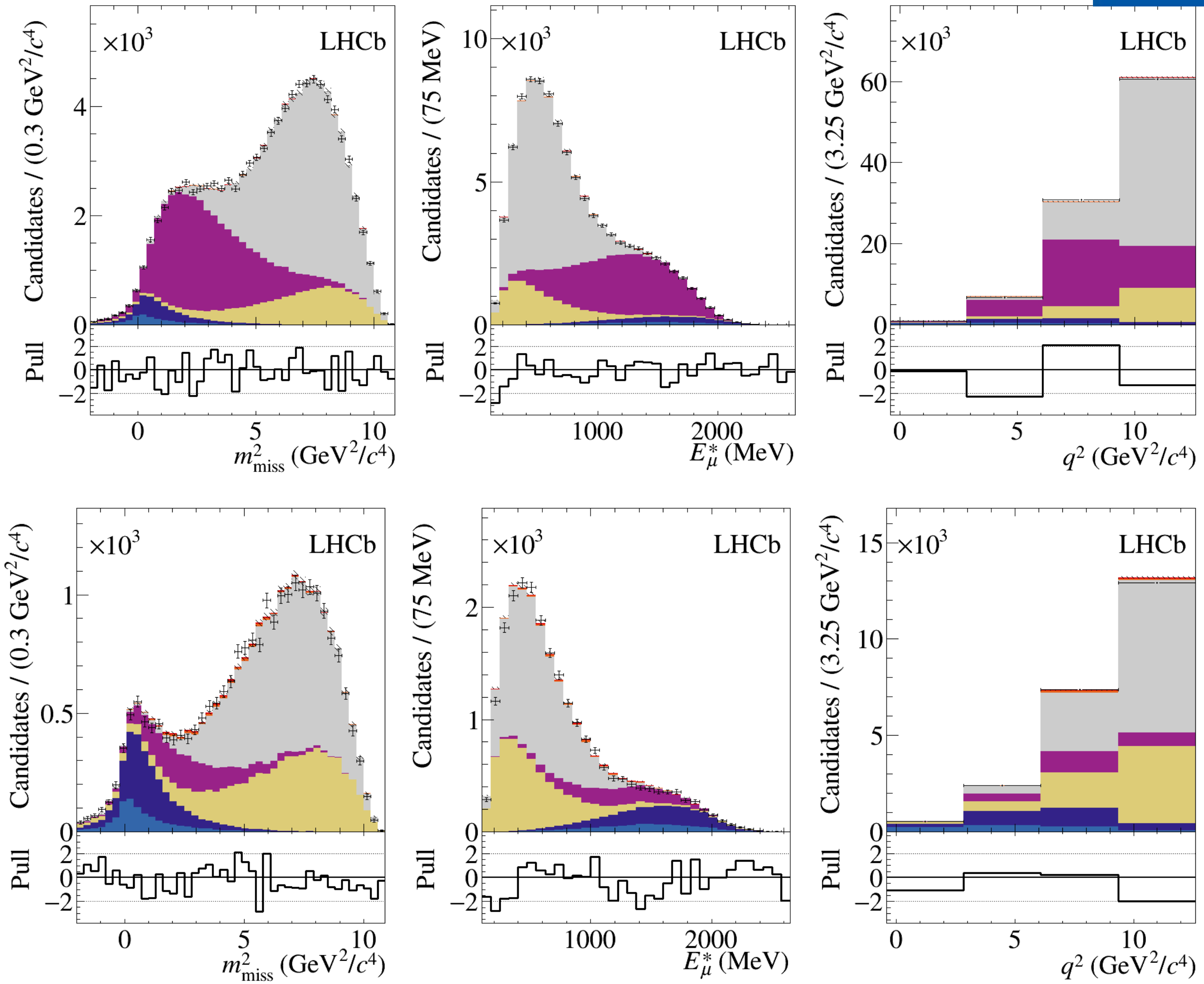
K split

$\bar{B} \to D^{(*)}\bar{D}_q^{(*)}X$ with $\bar{D}_q \to \mu\bar{\nu}X'$ (including $D_s^+ \to \tau\bar{\nu}$) is the most signal-like background

- Check our understanding by splitting our $D^{(*)}\mu^- K^\pm$ by kaon charge
  - Top: $D^0\mu^- K^+$
  - Bottom: $D^0\mu^- K^-$

Schematically,

$$\bar{B} \to D\bar{D}[\to K^+\mu^- X']X$$
$$\bar{B} \to D\bar{D}[\to \mu^- X']K^-$$
$$\bar{B} \to D[\to \mu^+ X']\bar{D}K^-$$
$$\bar{B} \to D_s^{**+}[\to D^0 K^+]\mu^-\bar{\nu}$$

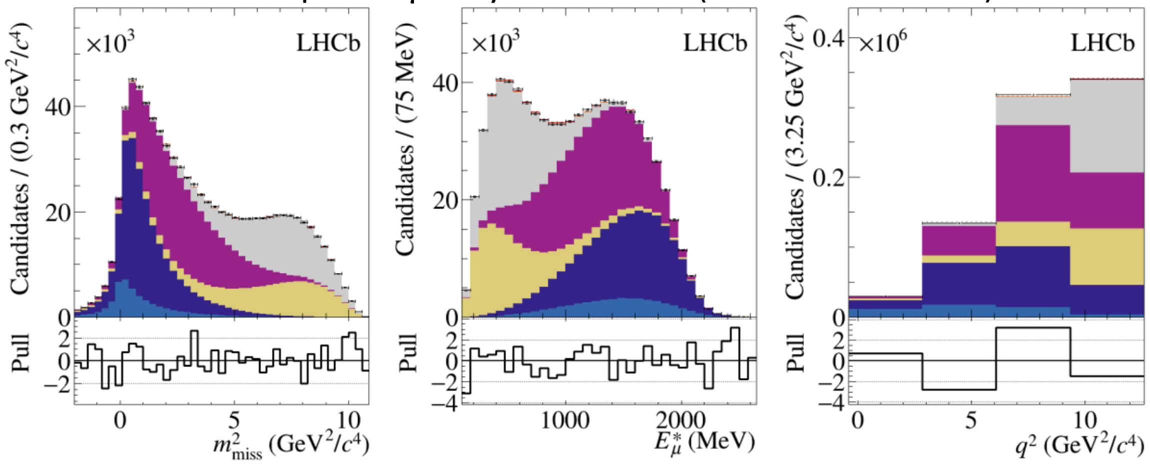


Inclusive samples

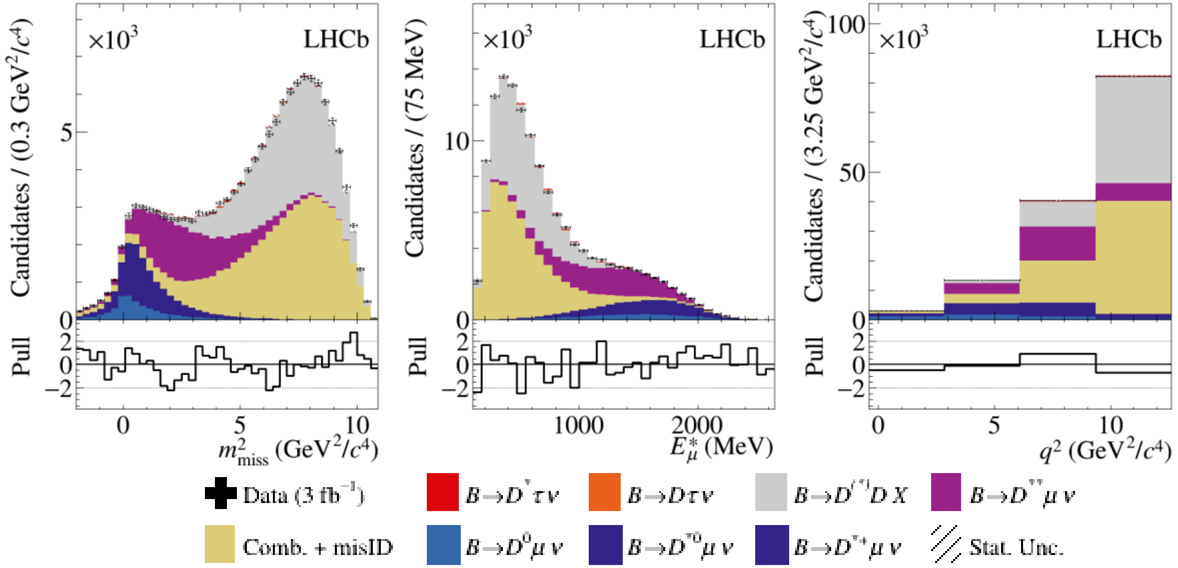
Punchline: model seems to give good description of data everywhere (including literally “everywhere” – summed anti-isolated data)

NOTE: This is not a claim that the model includes all possible processes, but rather that anything else is not distinguishable from the summed sources in our present model

Example: $D^0\mu$+any extra tracks (inclusive selection)



Example: $D^0\mu$+3 extra tracks (higher multiplicity B background)

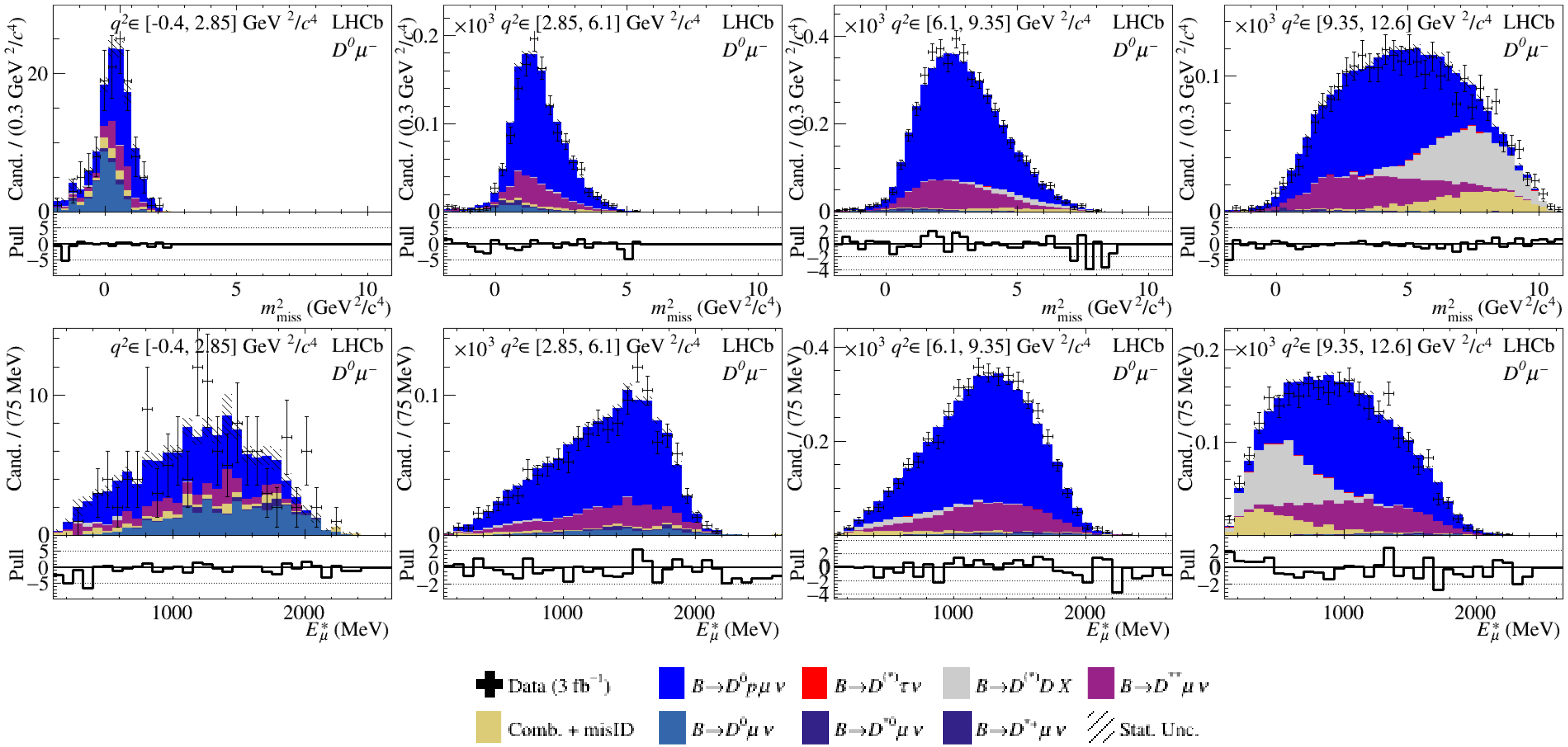


Baryonic backgrounds

$\Lambda_b \rightarrow D^0 p \mu \bar{\nu}$ poorly understood and difficult to model

Measure shapes in $D^0\mu^- + p$ sample, refit nominal samples with constrained contribution from this background to estimate sensitivity of to this missing source

- Resulting systematic uncertainty under good control
- Better understanding of this will be important with larger datasets



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Total systematic uncertainty	2.4	6.6	-0.39
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Next steps

Run2 The Next Generation

Dedicated B2Xtaunu trigger lines added for $D^0\mu X$ as well as $D^+\mu X,\ \Lambda_c^+\mu X,\ D_s^+\mu X$

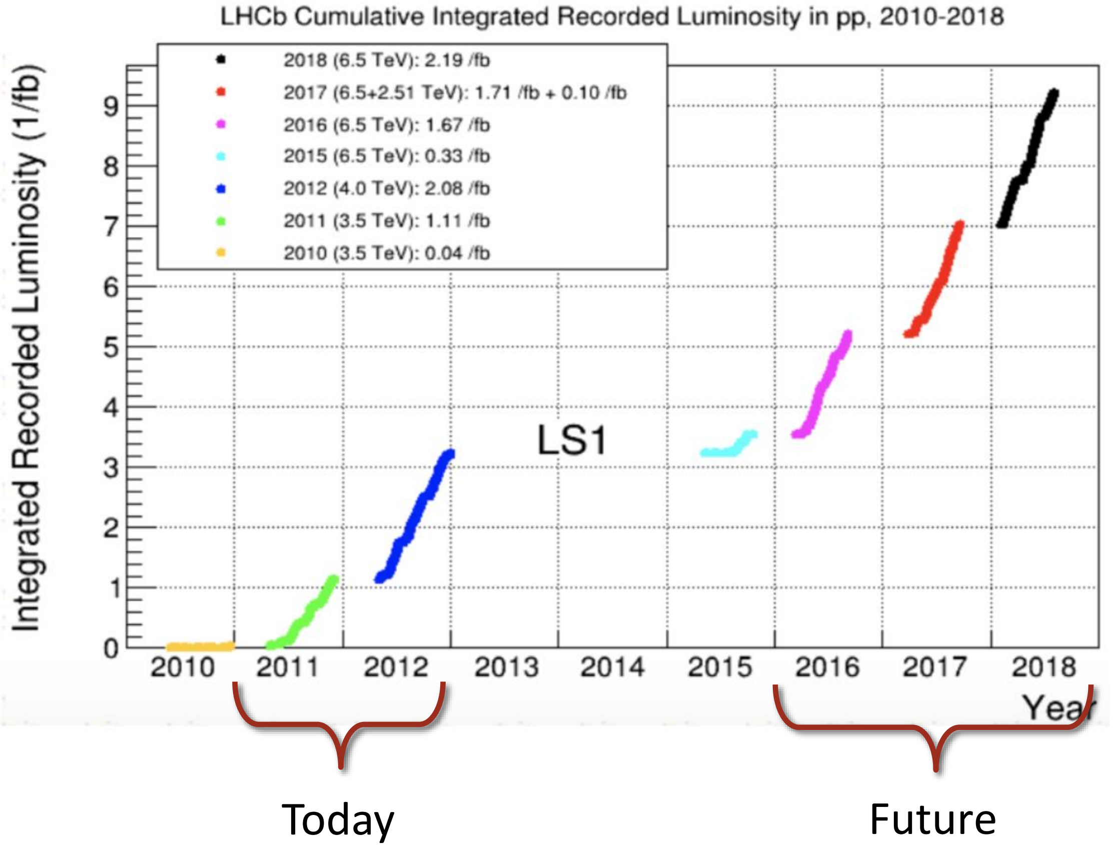
- Large efficiency gain compared to Run1 "piggyback" trigger path

Large statistics gain independent of efficiency as well

- 1.9x more luminosity, 1.8x $\sigma\left(b\bar{b}\right)$

But "more data more problems" – simulation statistics and corrections must be precise to fully use this data

- FastMC techniques essential, but introduce new complications in Hardware (L0) trigger modeling
- How consistent is 2016/2017/2018 data? Separate corrections may be needed – more complications



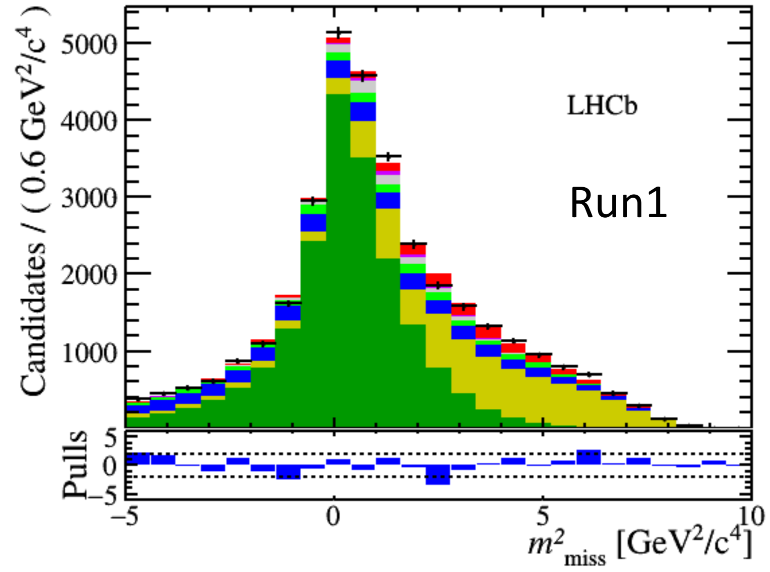
$R(J/\psi)$

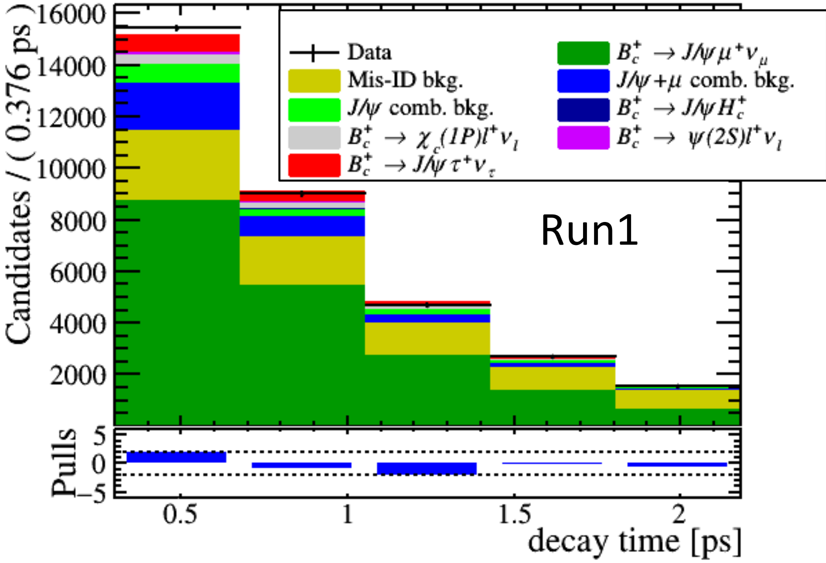
Advantage: striking tri-muon signature in $\tau \to \mu\nu\nu$, $J/\psi \to \mu\mu$ decay chain

- Disadvantage: lighter b hadrons 100x more common – large background from inclusive J/ψ+fake muon
- Efficient triggering and event selection even at higher pileup

Big improvement expected in Run2 data

- More data
- Improved fake muon treatment based on $R(D^0) vs\ R(D^*)$ experience
- Lattice input on form-factors now available





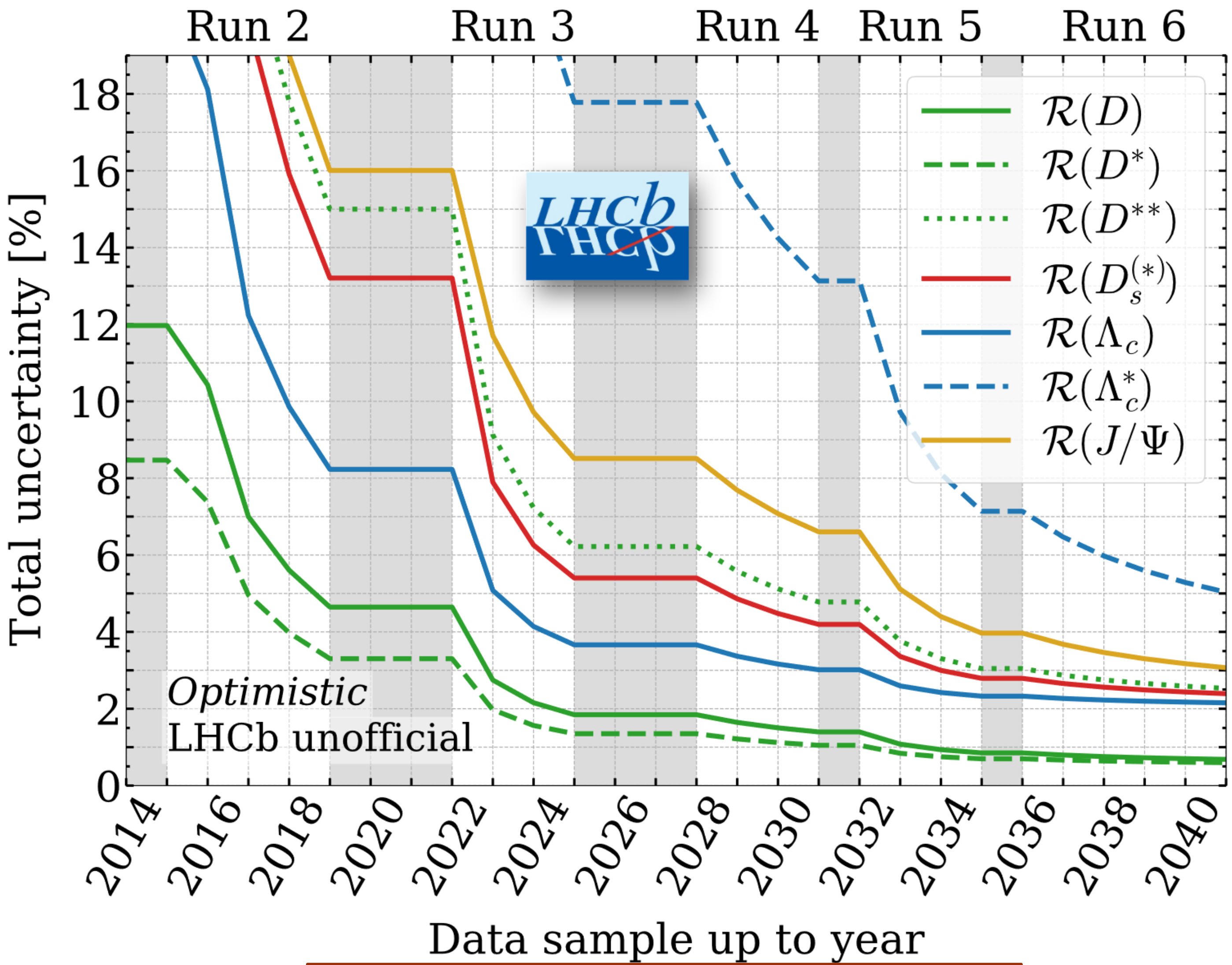
$$R(J/\psi) \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi \tau\nu)}{\mathcal{B}(B_c^+ \to J/\psi \mu\nu)} = 0.71 \pm 0.17 \pm 0.18$$

arXiv:1711.05623

Goals for $b \to c$ semileptonic LFU

- Broad program of related measurements underway
  - Larger control data will help bring down some uncertainties, but many challenges remain in order to realize these improvements!

Zeroth-order question to ask: “where is this data coming from?”



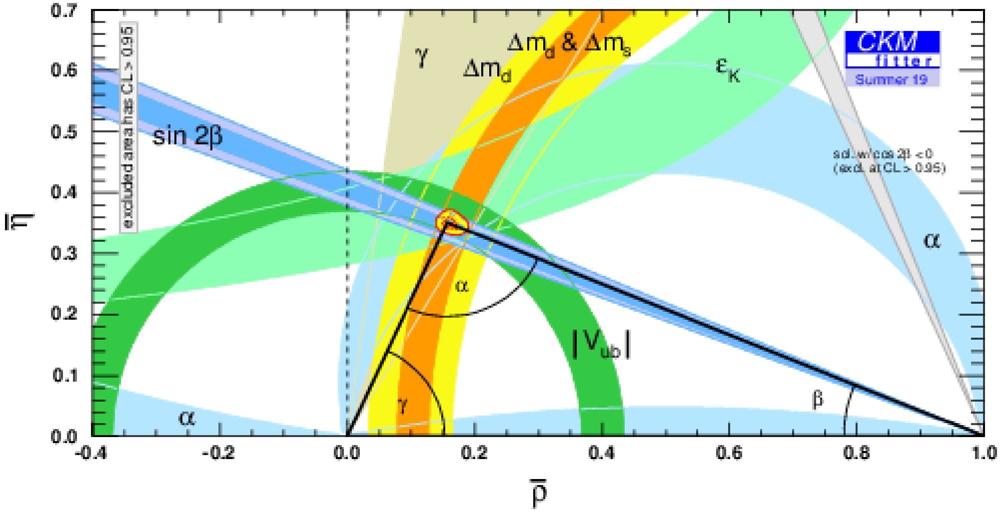
From Manuel’s joint JHU/UMD seminar

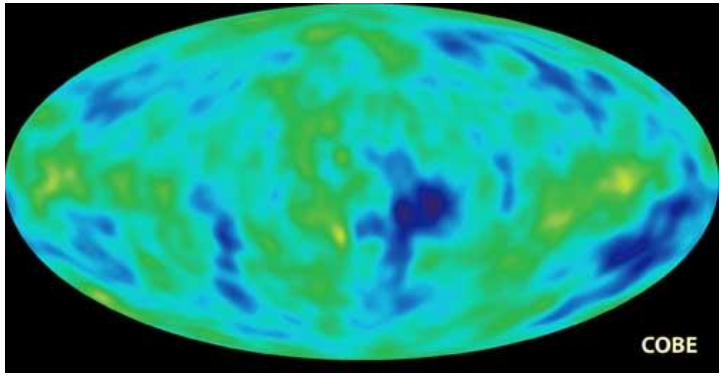
Getting to larger datasets

HEAVY FLAVOR IN RUN3 AND BEYOND

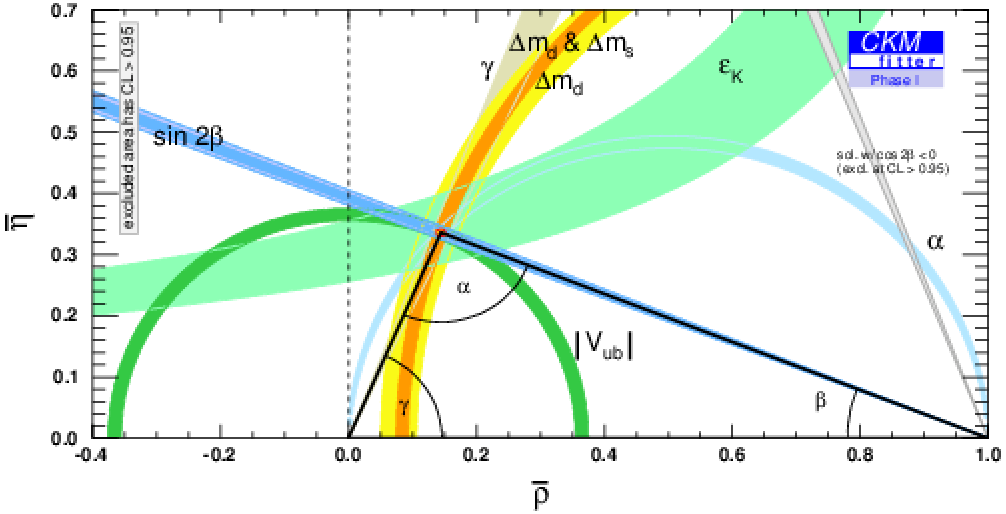
Next decade: leap forward in flavor precision

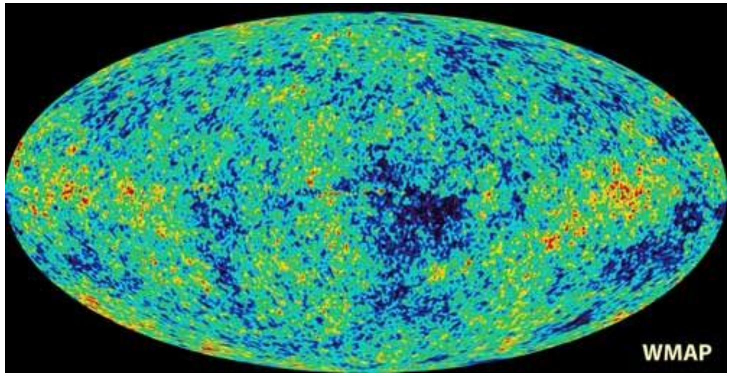
2019





2030





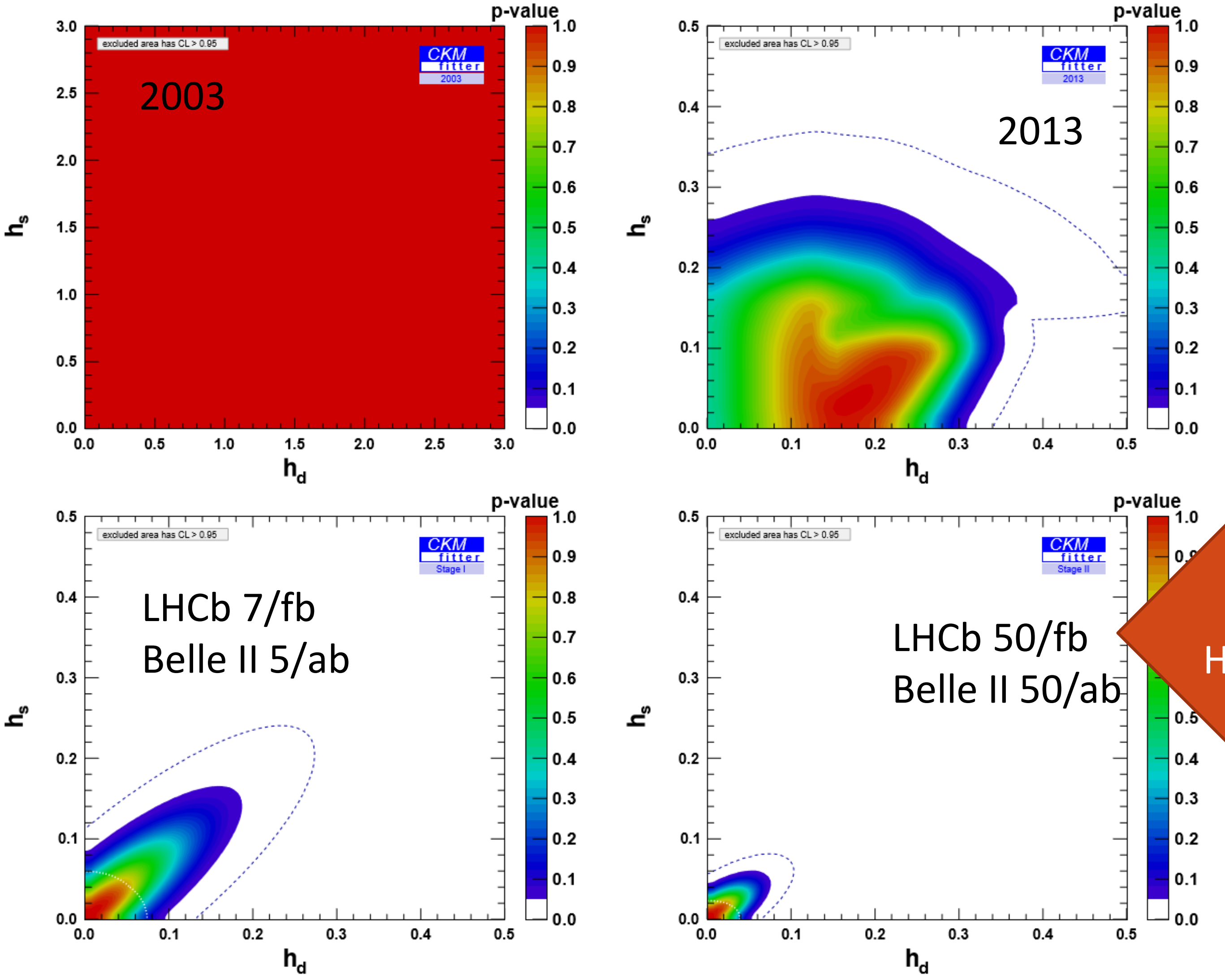
Example: Constraining NP in B mixing

J. Charles, S. Descotes-Genon, Z. Ligeti, S. Monteil, M. Papucci, K. Trabelsi
arxiv 1309.2293

Older but illustrative case study:

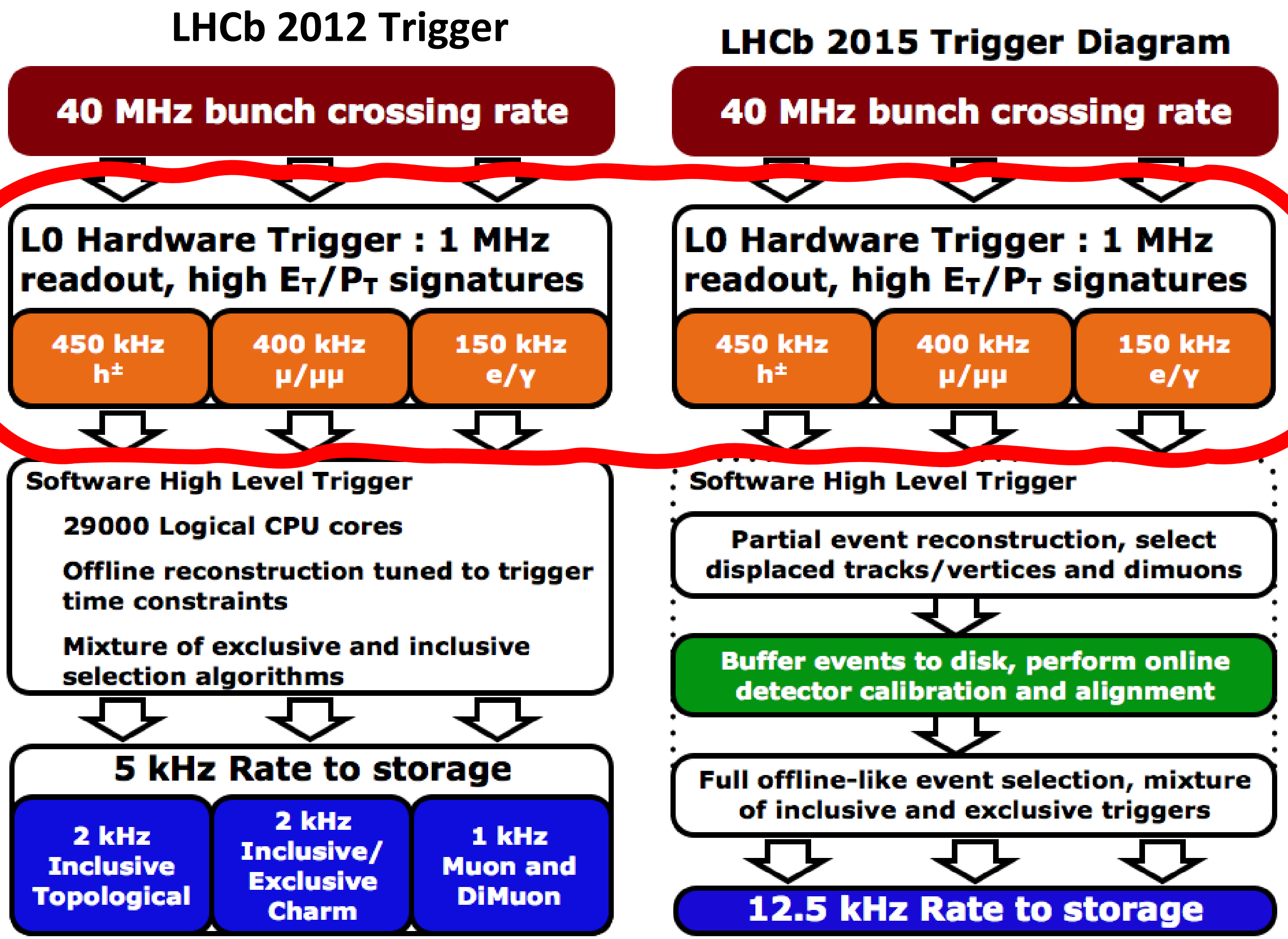
Constraints on model-independent parametrization of new physics in B mixing

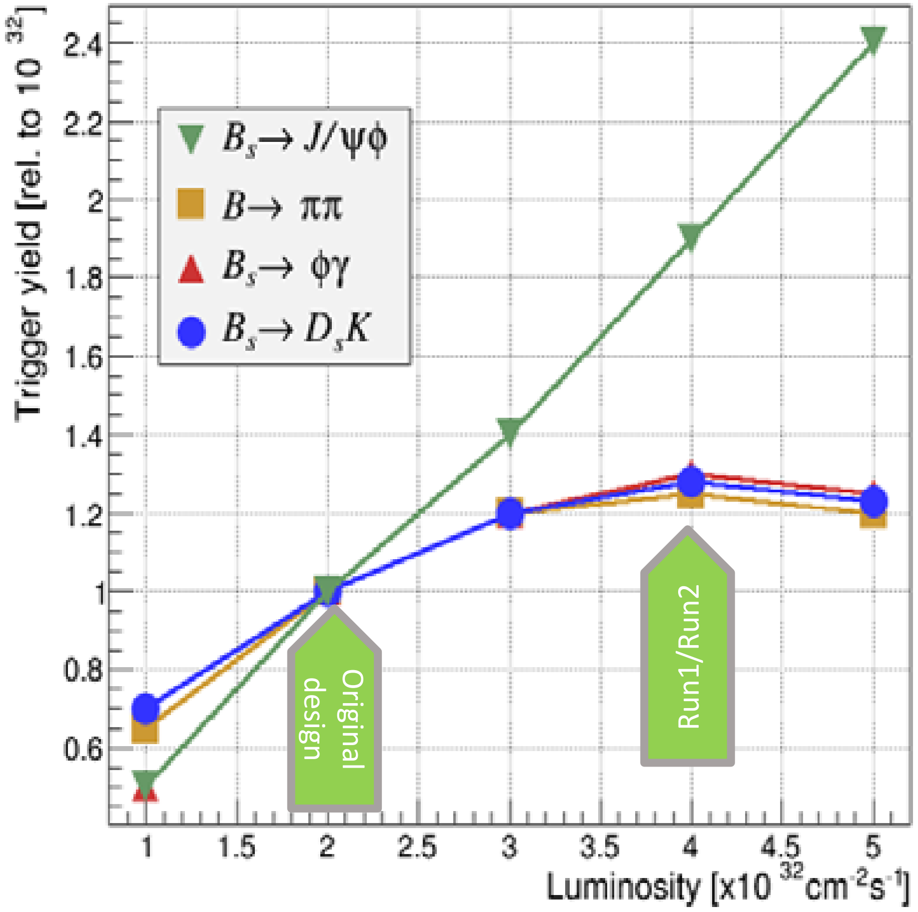
Take $M \sim M_{SM}(1 + he^{i\sigma})$ and look at sensitivity to new physics amplitude h



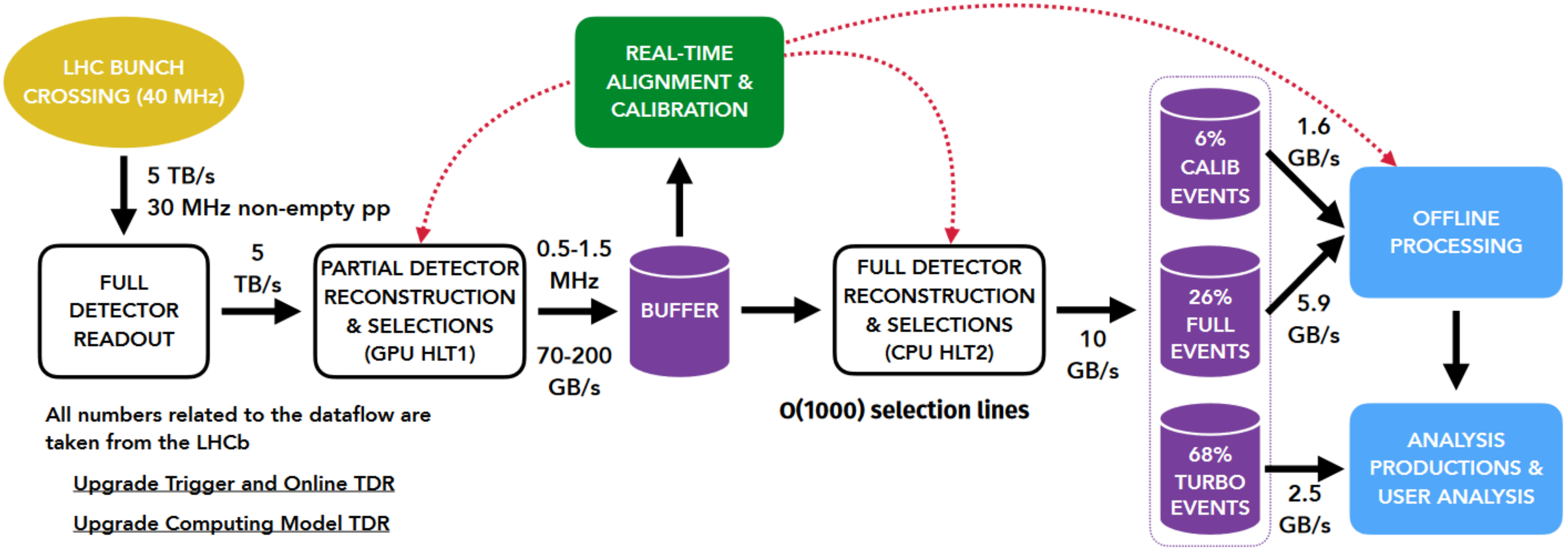
≈ 10 × Run2.
How to get there?

Triggering on Heavy Flavor





Rebuilt and reoptimized



All numbers related to the dataflow are taken from the LHCb

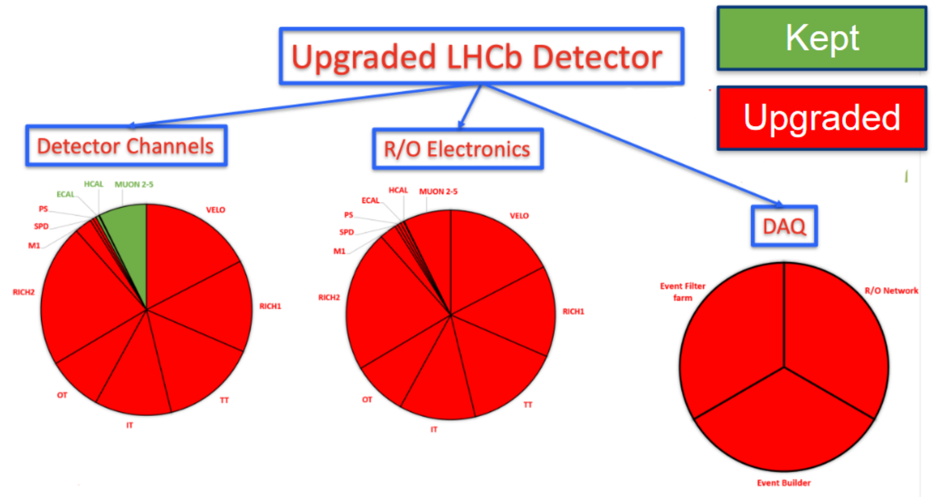
[Upgrade Trigger and Online TDR]

[Upgrade Computing Model TDR]

Result: Order-of-magnitude increase in dataset

Require significant increase in segmentation to deal with ~5 pp collisions per event

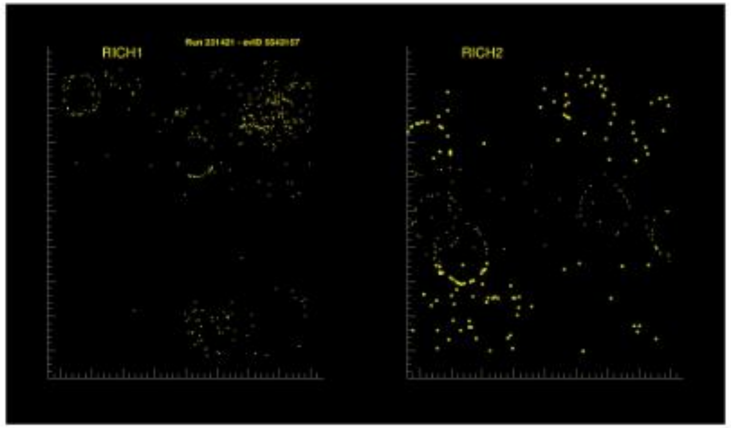
- All new charged-particle trackers
- Re-optimized and rebuilt particle identification subdetectors

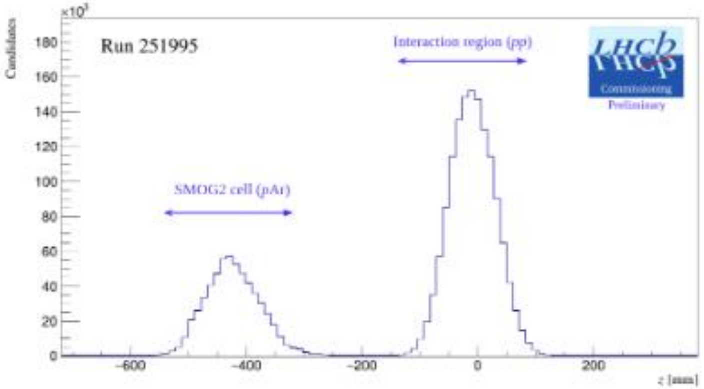


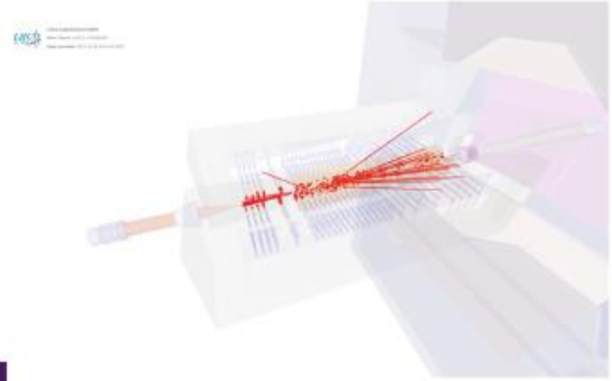
Upgrade I: major project

Upgrade I | 2022-2032

- Major project achieved **on budget**
- Commissioning of detector proceeding well

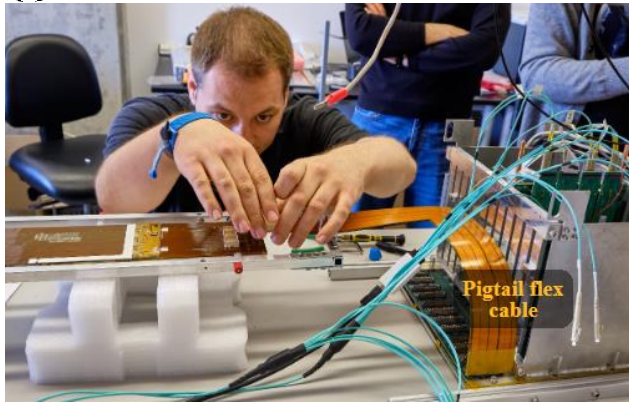


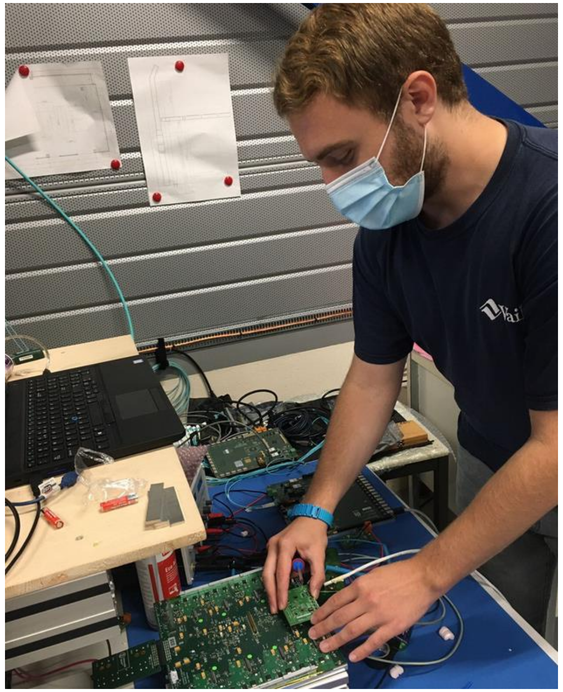


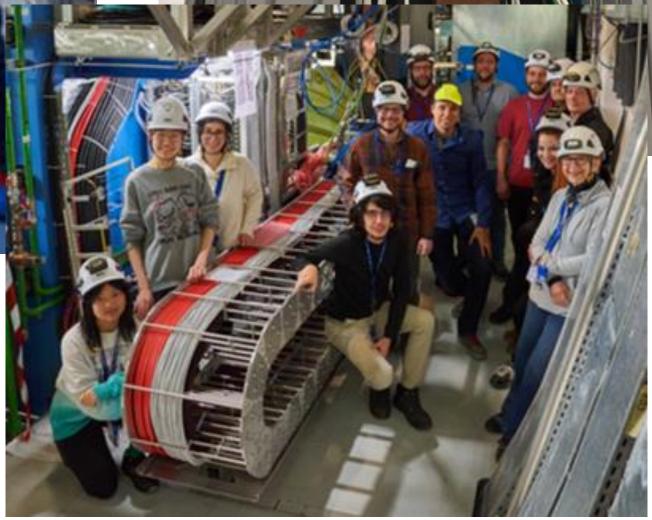


Chris Parkes
11th ECFA plenary meeting
Nov 18, 2022

UMD Upstream Tracker Effort







VELO vacuum incident

The VELO detector is installed in a secondary vacuum inside the LHC primary vacuum.

The primary and secondary volumes are separated by two thin walled Aluminium boxes, the RF foils

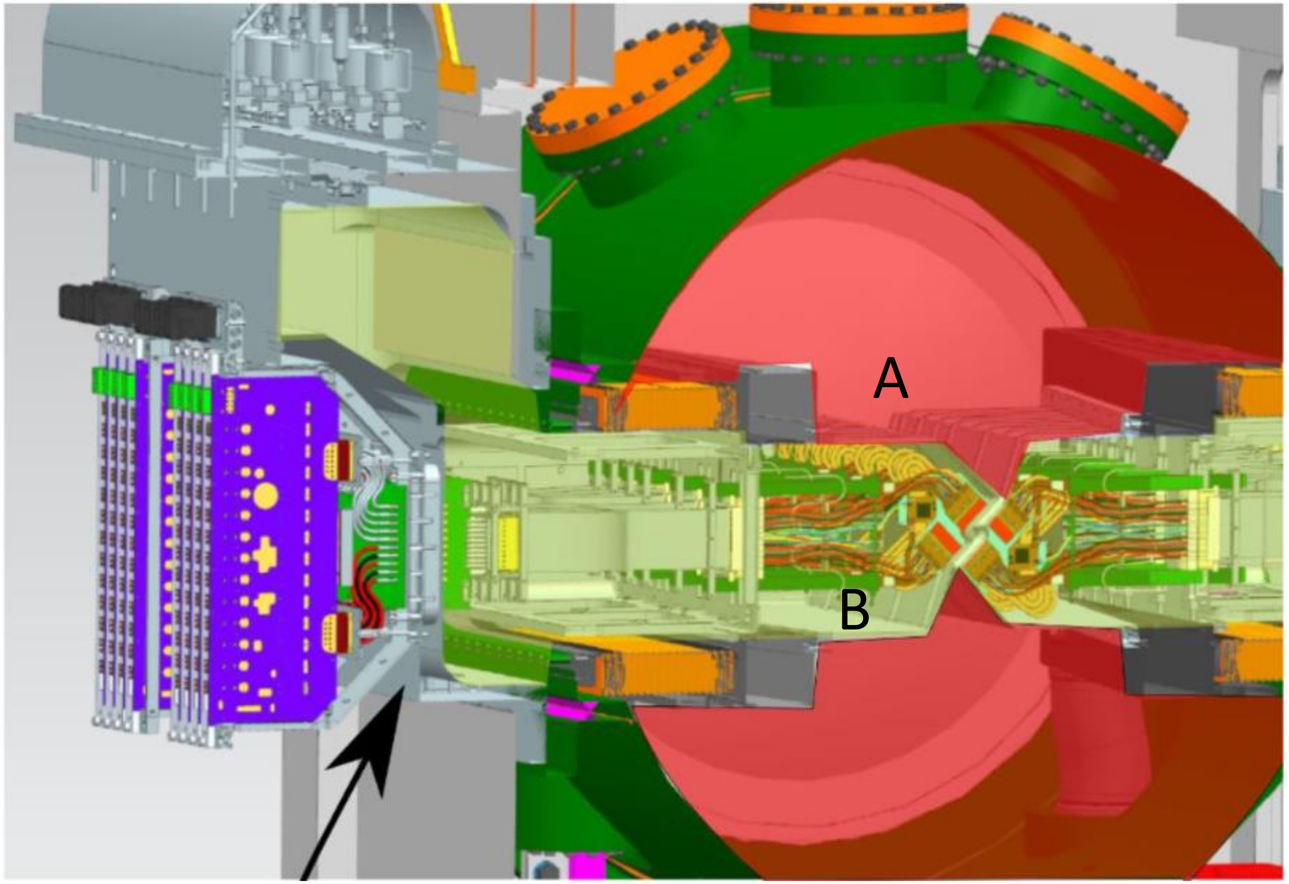
On 10th January 2023, during a VELO warm up in neon, there was a loss of control of the protection system

A pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only

Initial investigations show no damage to the VELO modules; sensors show correct leakage currents, microchannels show no leaks

RF foils have suffered plastic deformation up to 14 mm and have to be replaced.

View of the inside of the VELO tank

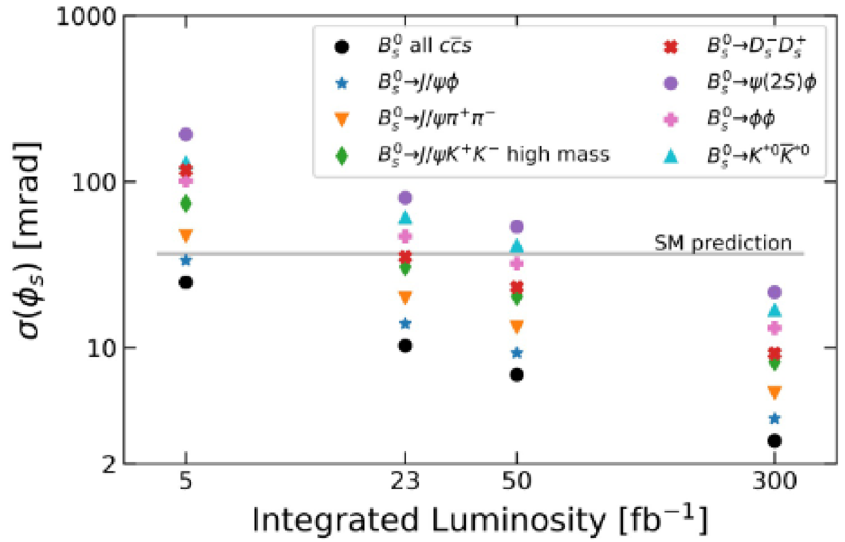


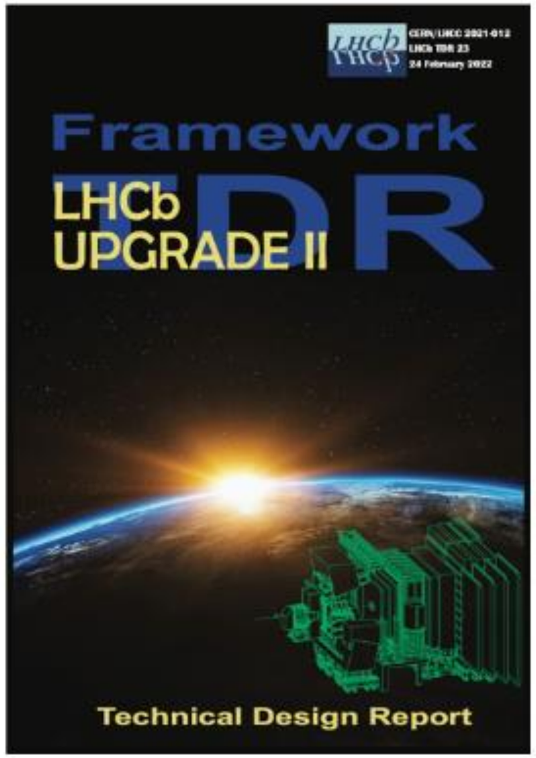
Flavor frontiers beyond LS4

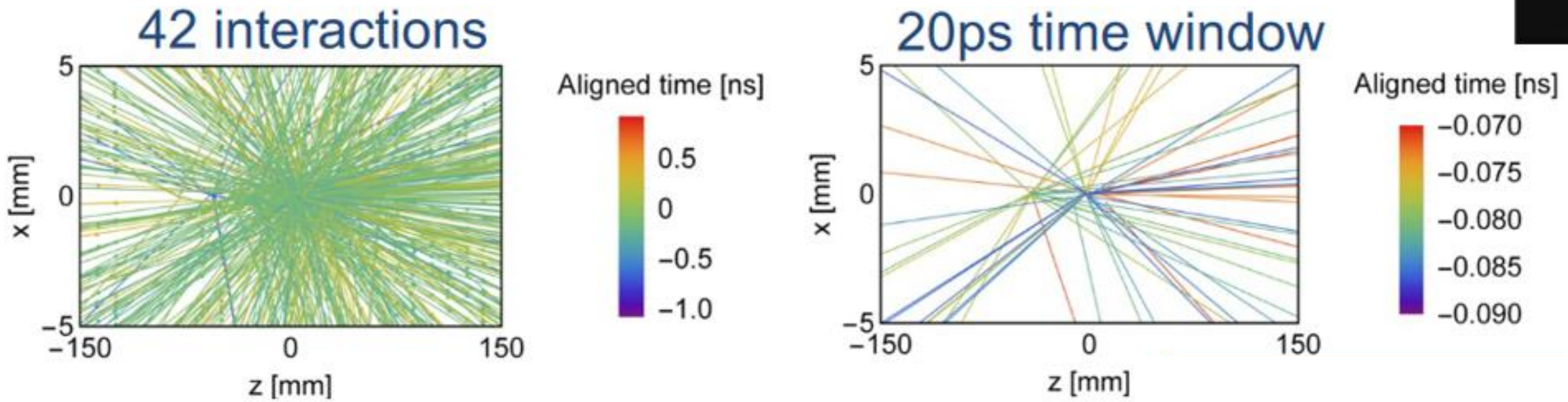
LHCb ‘phase-II’ upgrade currently under study to record 300/fb

- Physics reach still limited by detector, not collider
- Maximizing reach will require coping with pileup in the forward region
    - Granularity, timing

Plans maturing rapidly, some commitments already in place





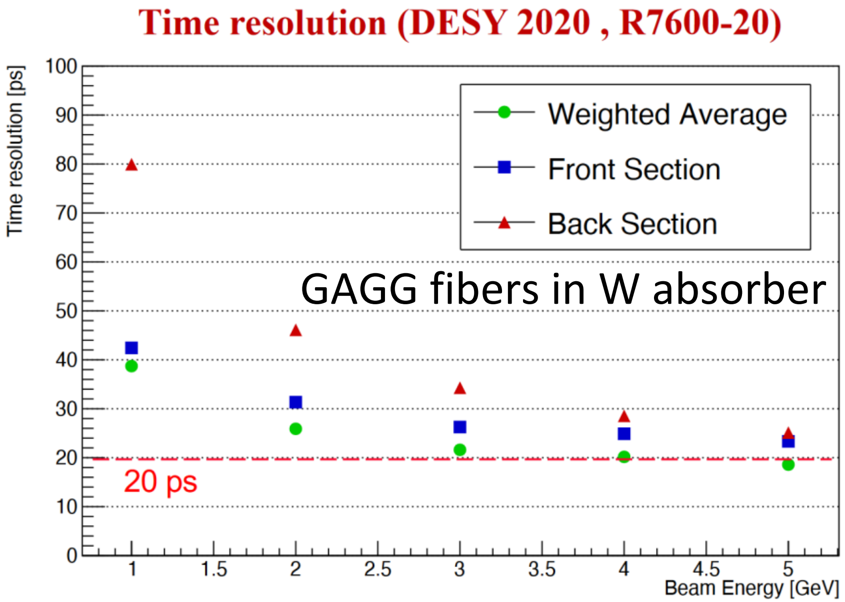


“4d” vertex finding

Upgrade II Caorimetery

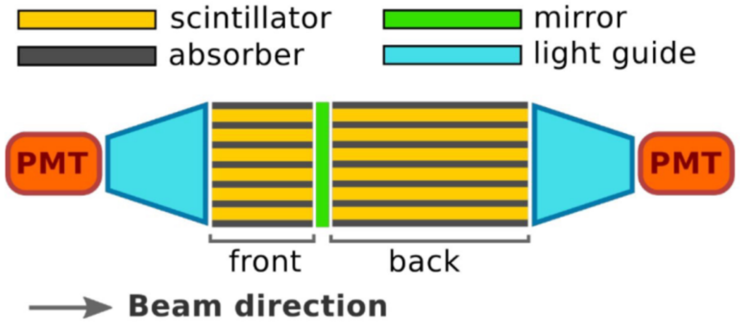
Current ECAL design unworkable at $L = 1.5 \times 10^{34}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

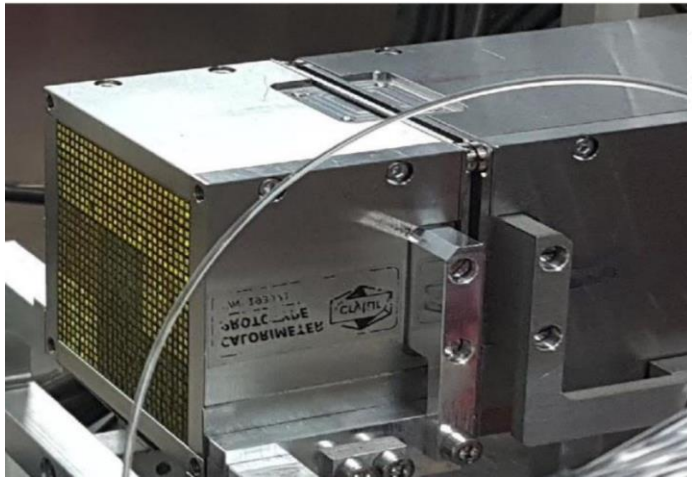
- Occupancy extremely high
- Need radiation hardness to ~ MGy in central region
- Need fast timing to associate clusters with PV within a beam crossing

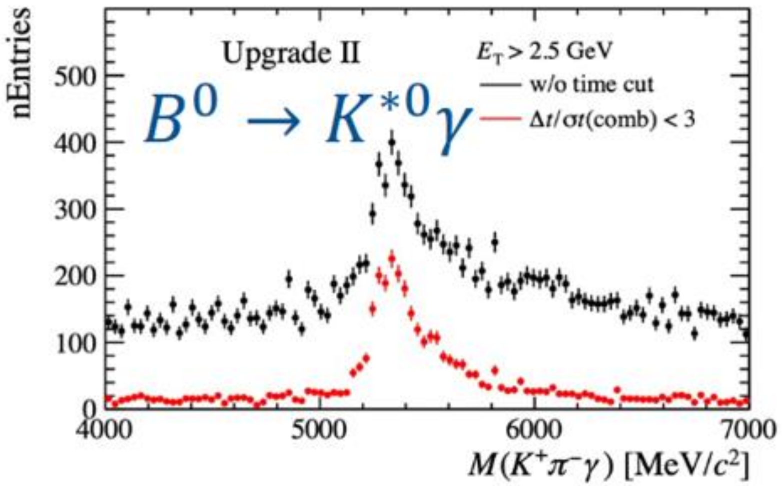


New modules planned using SpaCal concept, with garnet-in-tungsten for innermost region (200 kGy+) and plastic scintillator-in-lead for middle (40-200 kGy)

- Double-sided readout, fast timing -> "5D calorimetery"
- R&D program underway on electronics, PMTs, doped GAGG crystal timing, 3d printing of W absorber







Summary

LHCb Run1 R(D*) measurement extended and refined into a full ellipse

- Result:
$$R(D^0) = 0.441 \pm 0.060(stat) \pm 0.066(sys)$$
$$R(D^*) = 0.281 \pm 0.018(stat) \pm 0.023(sys)$$
$$\rho = -0.49(stat)/-0.40(sys)/-0.43(tot)$$
- Excellent agreement with world average, 1.9σ from standard model
- First measurement of R(D) at a hadron collider 🏆

Pathfinder analysis: much of the procedure already at the level of precision needed for (much!) bigger datasets

- Follow-up in Run2 dataset already well underway with many more B hadron decays on disk and a dedicated trigger to make life easier
- New challenges ahead integrating fast simulation

Much other work also underway on this mode using techniques inherited from or inspired by this work

Backup

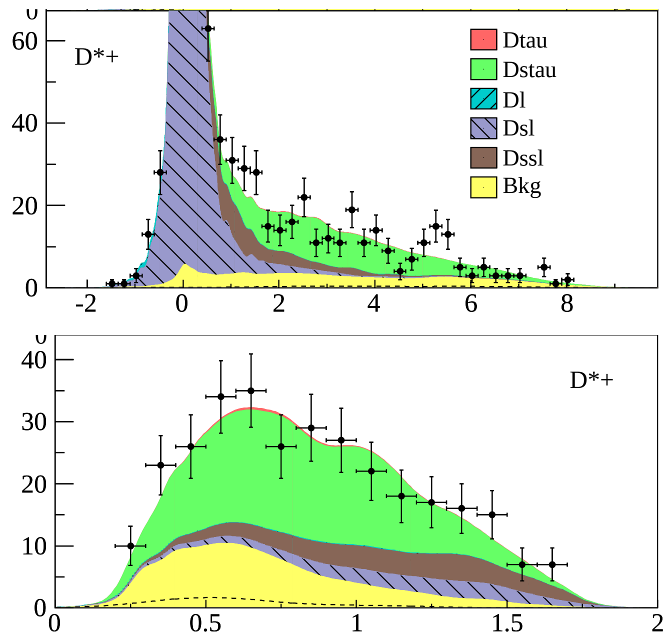
2012 *BaBar* result

In 2012 *BaBar* fit to E_ℓ vs m^2_{miss} and found tension with the SM

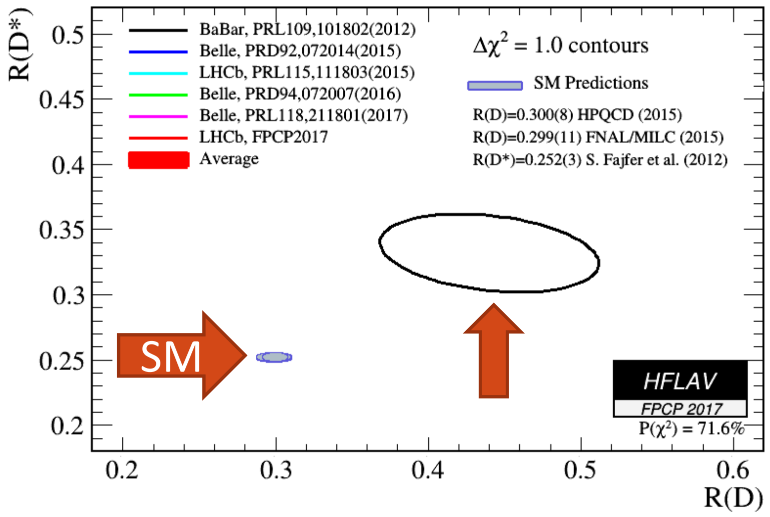
- Two Higgs doublet models (2HDM-TypeII) can naturally effect $R(D^{(*)})$, but are strongly disfavored
- Other possibilities:
  - Non-universal leptoquark? W'? More exotic 2HDM?

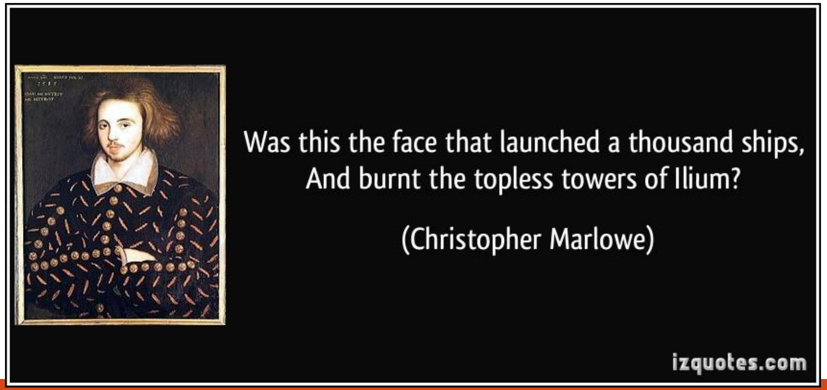
First priority for experimenters: confirm or rule out the excess

Our challenge: How can we bring LHCb to bear on this very difficult mode without full event reconstruction?

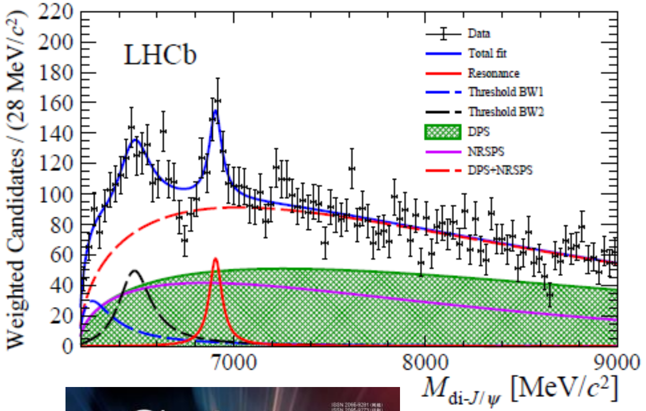


$$R(D) = 0.440 \pm 0.058 \pm 0.042$$
$$R(D^*) = 0.332 \pm 0.024 \pm 0.018$$



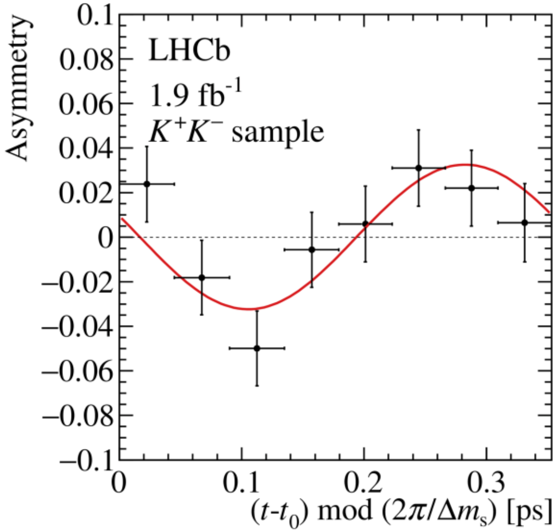


Notable Recent(ish) Breakthroughs



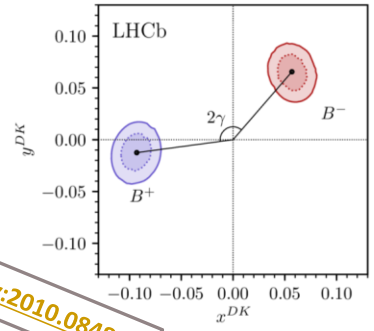
Observation of tetraquark $T_{cc\bar{c}\bar{c}}$ enhancement

Science Bulletin 2020 65(23)1983-1993

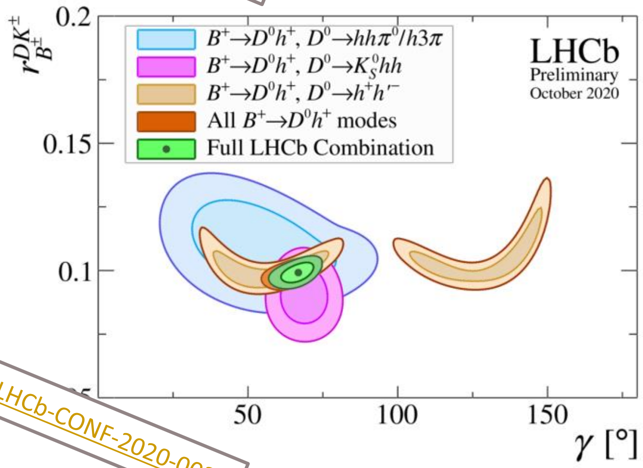


Discovery of time-dependent matter-antimatter asymmetries in Bs mesons

LHCb-PAPER-2020-029



arXiv:2010.08483



LHCb-CONF-2020-003

Best determination of matter-antimatter asymmetry parameter γ

Backgrounds

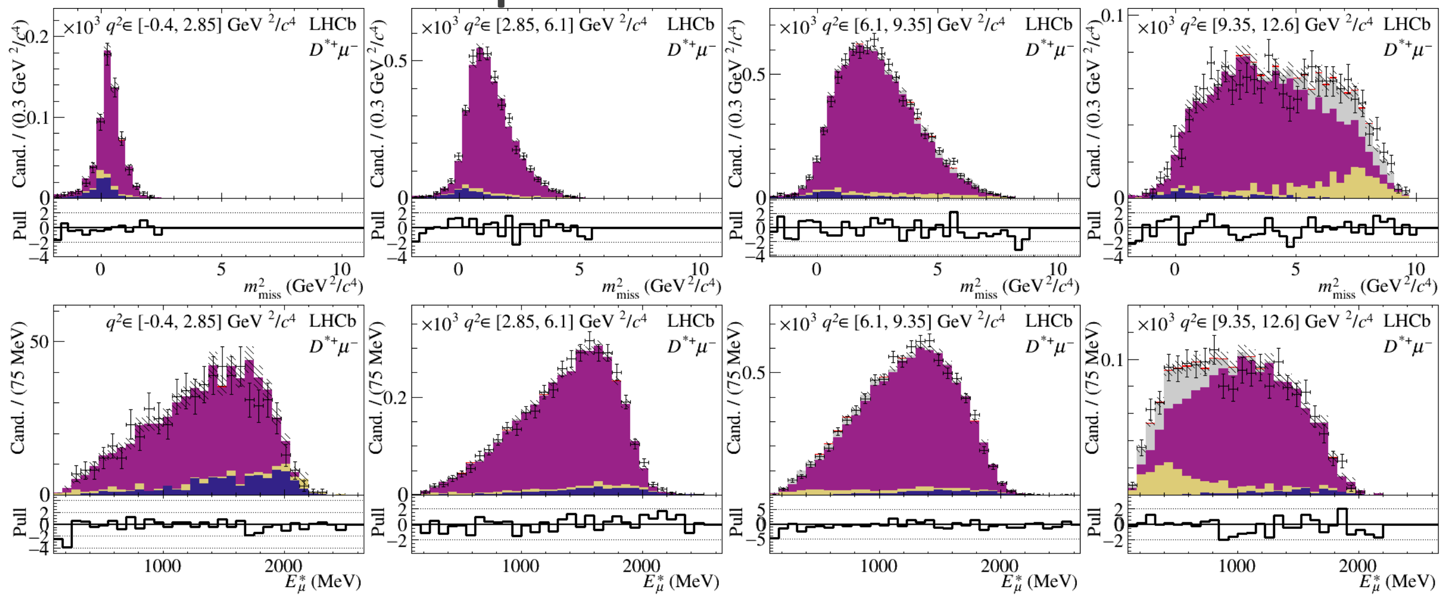
$D^{*+}\mu^-$ sample

- $\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}$
  $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}$
- $\bar{B} \rightarrow (D^{**} \rightarrow D^{*+}\pi)(\mu,\tau)\nu\ (\bar{B}^0\ and\ B^-)\ (\times 12)(D_1, D_1', D_2)$
  $\bar{B}_s \rightarrow (D_s^{**} \rightarrow D^{*+}K^0)\mu\nu$ $(\times 2)$
  $\bar{B} \rightarrow (D^{**} \rightarrow D^{*+}\pi\pi)\mu\nu\ (\bar{B}^0\ and\ B^-)$
- $B \rightarrow D^{*+}[X_c -\!\!\rightarrow \mu\nu X]Y\ \left(B^0, \bar{B}^0\ \ and\ B^{+/-}\right)(\times 2)$
  $B \rightarrow D^{*+}[Ds -\!\!\rightarrow \tau\nu]X\ \left(B^0, \bar{B}^0\ and\ B^{+/-}\right)\ (\times 2)$
- $D^{*+}\mu$ Combinatoric (template from wrong-sign μ)
- $D^0\pi_s^+$ Combinatoric (template from wrong-sign π_{slow})
- Partially reconstructed hadronic decays

$D^0\mu^-$ sample

- $B^- \rightarrow D^0\mu^-\bar{\nu}$
  $\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}$
  $B^- \rightarrow D^{*0}\mu^-\bar{\nu}$
  $B^- \rightarrow D^0\tau^-\bar{\nu}$
  $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}$
  $B^- \rightarrow D^{*0}\tau^-\bar{\nu}$
- $\bar{B} \rightarrow \left(D^{**} \rightarrow D^{(*)}\pi\right)(\mu,\tau)\nu\ (B^0\ and\ B^+)(\times 16)(D_1, D_1', D_2, D_0)$
  $\bar{B}_s \rightarrow \left(D_s^{**+} \rightarrow D^{(0,*0/*+)}K^{+/0}\right)\mu\nu$ $(\times 2)$
  $B \rightarrow (D^{**} \rightarrow D^*\pi\pi)\mu\nu\ (B^0\ and\ B^+)$ $(\times 2)$
  $B \rightarrow (D^{**} \rightarrow D\pi\pi)\mu\nu\ (B^0\ and\ B^+)$
- $B \rightarrow D^*[X_c \rightarrow \mu\nu X]Y\ \left(B^0, \bar{B}^0\ \ and\ B^{+/-}\right)(\times 2)$
  $B \rightarrow D^*[D_s \rightarrow \tau\nu]X\ \left(B^0, \bar{B}^0\ \ and\ B^{+/-}\right)\ (\times 2)$
- $D^0\mu$ Combinatoric (template from wrong-sign μ)
  Partially reconstructed hadronic decays

Semileptonic feed-down detail

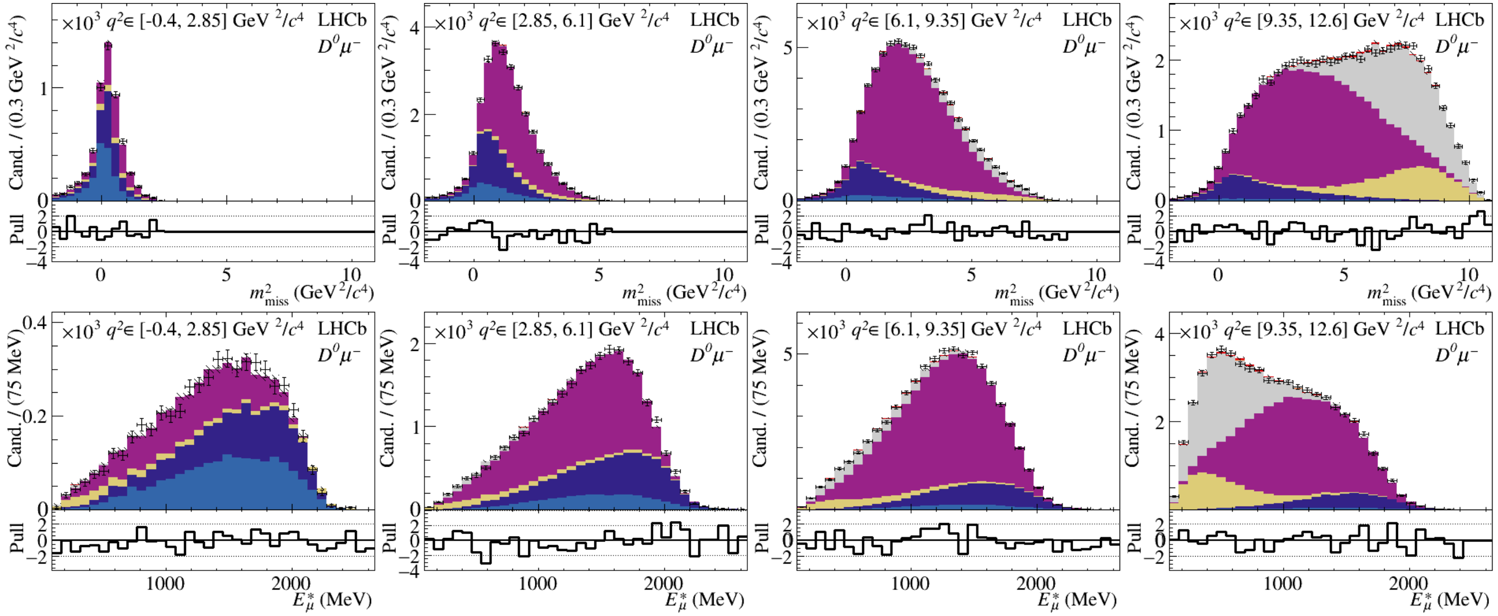


<- Has Δm selection on extra pion

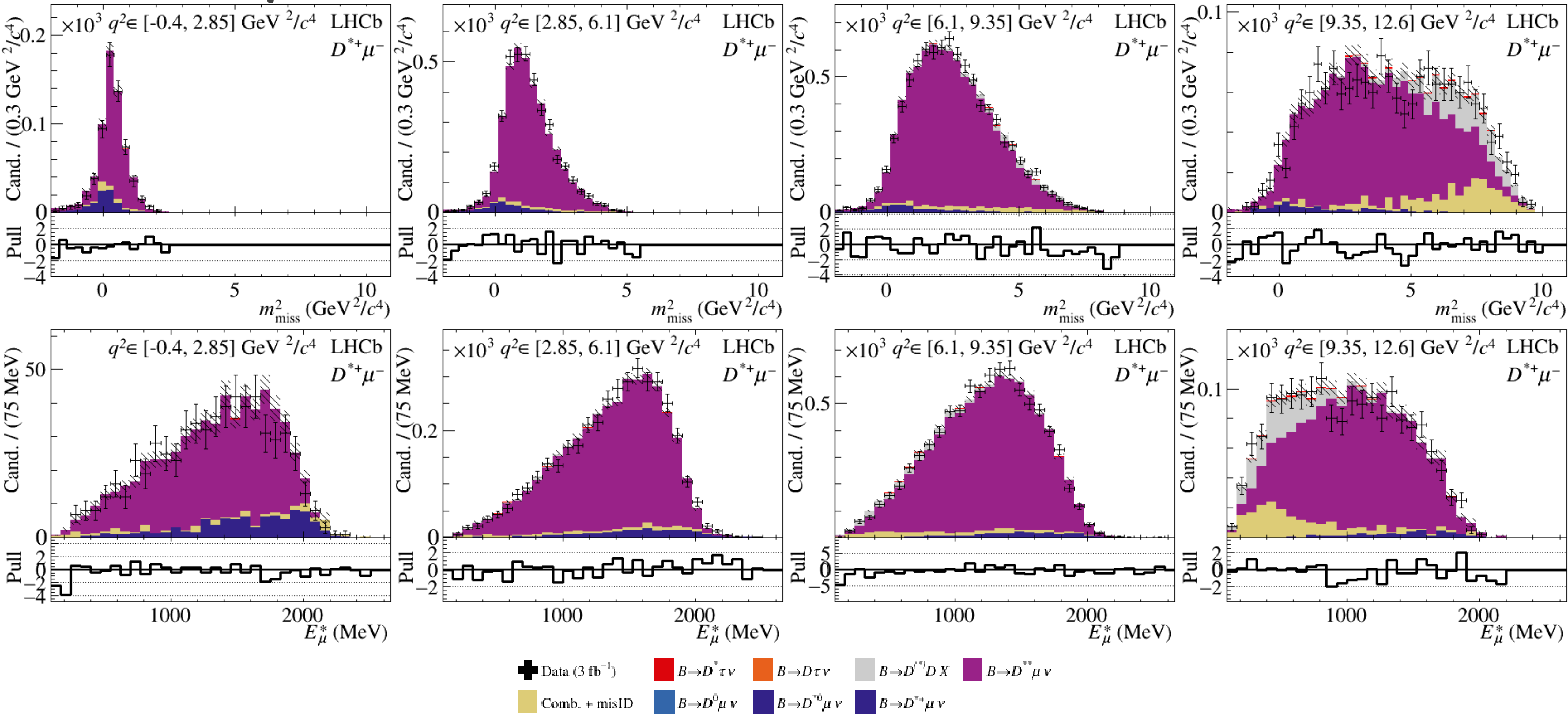
Provides tight constraint on form-factors of decays to the known light excited charm resonances

No requirements on kinematics of extra pion->

Fully inclusive, vacuums up backgrounds with $D^0\pi^+\mu^-\nu$ +anything. Constrains the amount of unknown background that *isn't* degenerate with things already in feed-down model

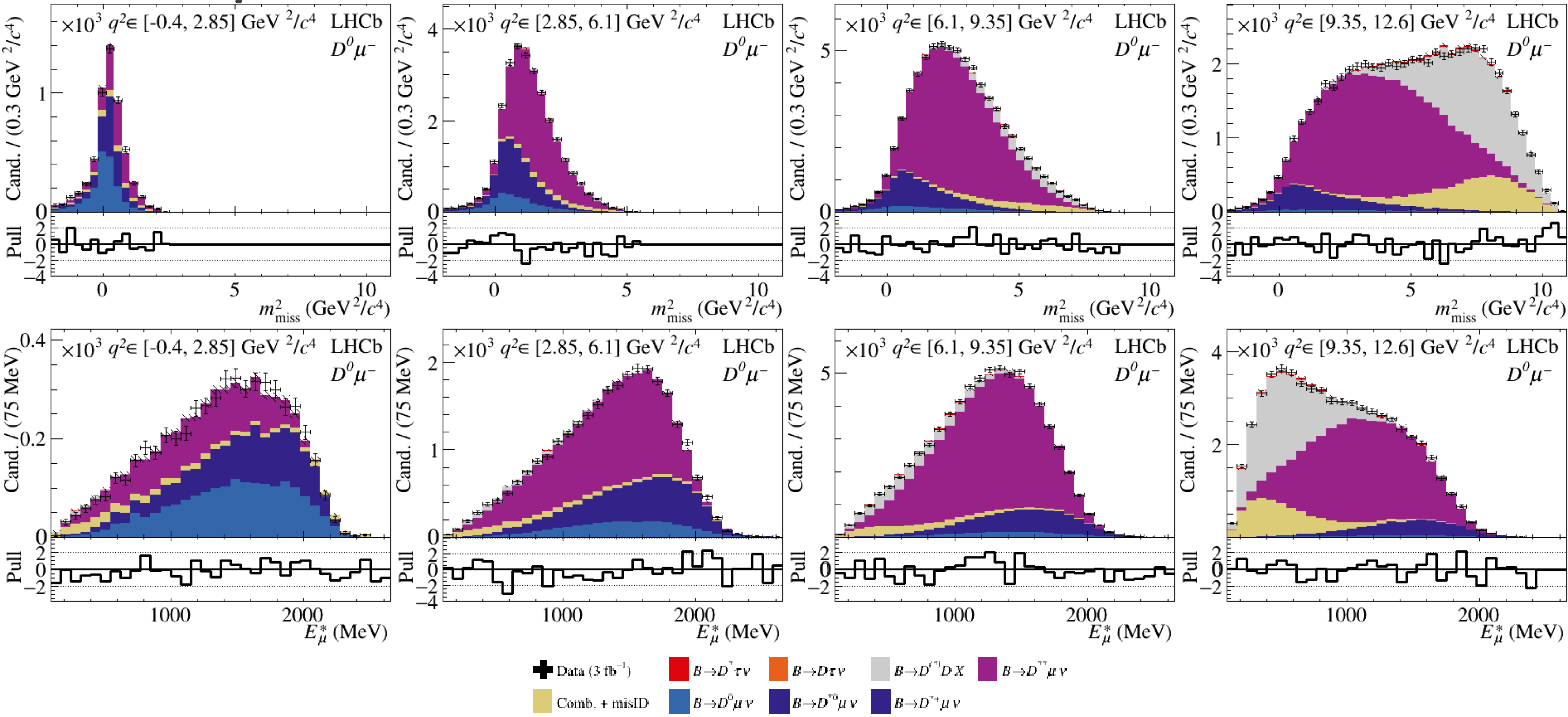


$D^{*+}\mu^-$ 1OS



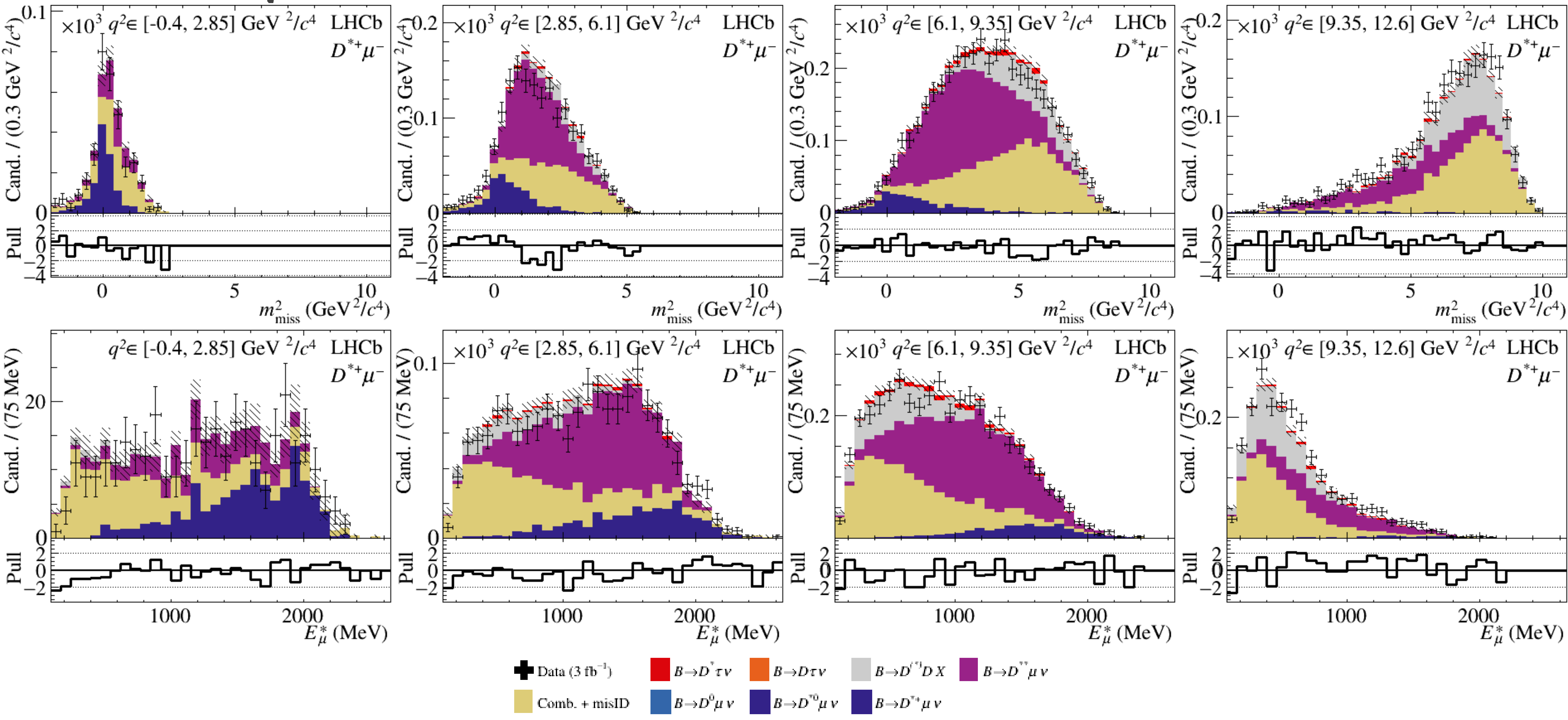
$\times10^3$ $q^2\in$ [-0.4, 2.85] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
$\times10^3$ $q^2\in$ [2.85, 6.1] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
$\times10^3$ $q^2\in$ [6.1, 9.35] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
$\times10^3$ $q^2\in$ [9.35, 12.6] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
Cand. / (0.3 GeV $^2/c^4$)
Pull
m^2_{miss} (GeV$^2/c^4$)
$q^2\in$ [-0.4, 2.85] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
Cand. / (75 MeV)
E^*_μ (MeV)
Data (3 fb^{-1})
$B\to D^*\tau\nu$
$B\to D\tau\nu$
$B\to D^{(*)}D X$
$B\to D^{**}\mu\nu$
Comb. + misID
$B\to D^0\mu\nu$
$B\to D^{*0}\mu\nu$
$B\to D^{*+}\mu\nu$

$D^0\mu^-$ 1OS



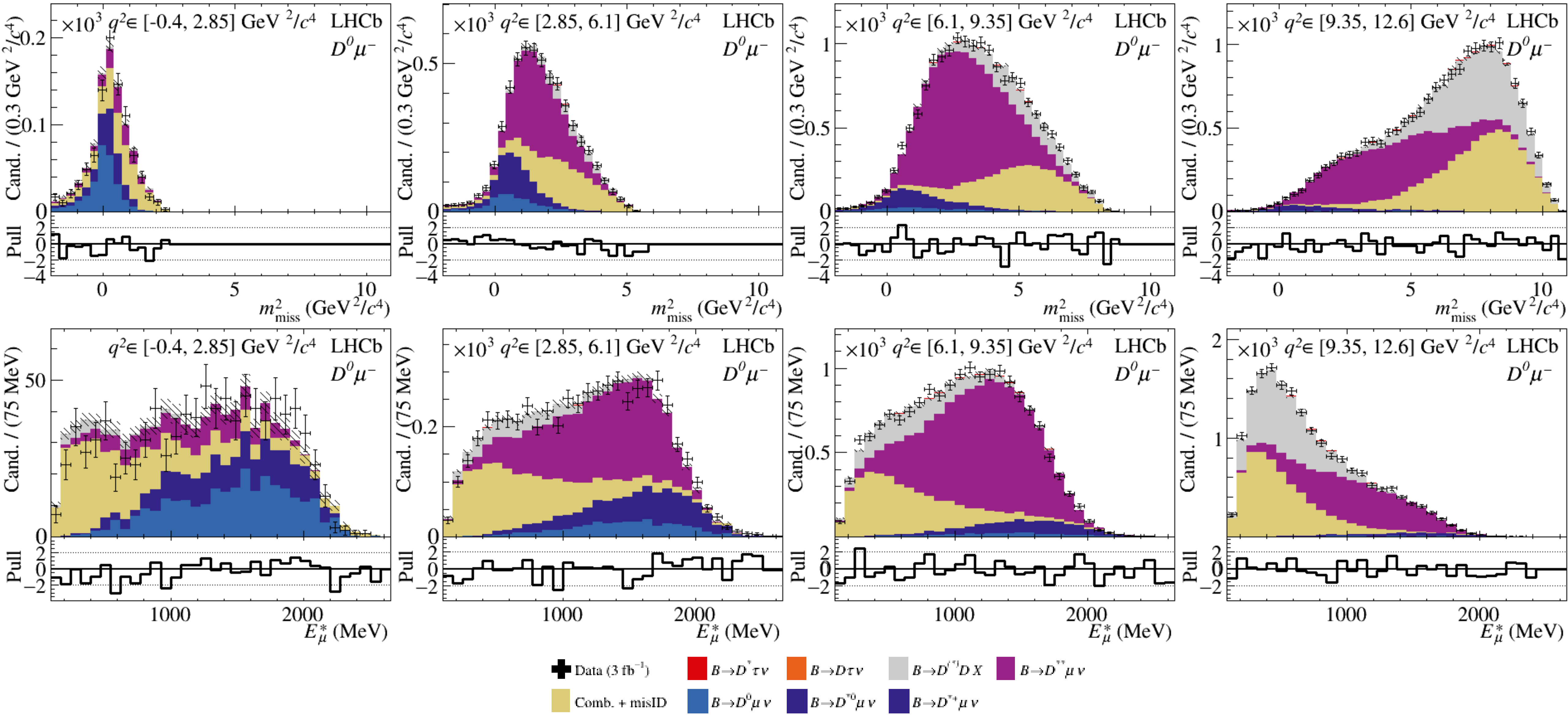
×10³ q²∈ [-0.4, 2.85] GeV ²/c⁴ LHCb D⁰μ⁻
×10³ q²∈ [2.85, 6.1] GeV ²/c⁴ LHCb D⁰μ⁻
×10³ q²∈ [6.1, 9.35] GeV ²/c⁴ LHCb D⁰μ⁻
×10³ q²∈ [9.35, 12.6] GeV ²/c⁴ LHCb D⁰μ⁻
Cand. / (0.3 GeV ²/c⁴)
Cand. / (75 MeV)
Pull
m²miss (GeV²/c⁴)
E*μ (MeV)
Data (3 fb⁻¹)
B→D*τν
B→Dτν
B→D(*)D X
B→D**μν
Comb. + misID
B→D⁰μν
B→D*⁰μν
B→D*⁺μν

$D^{*+}\mu^-$ 2OS



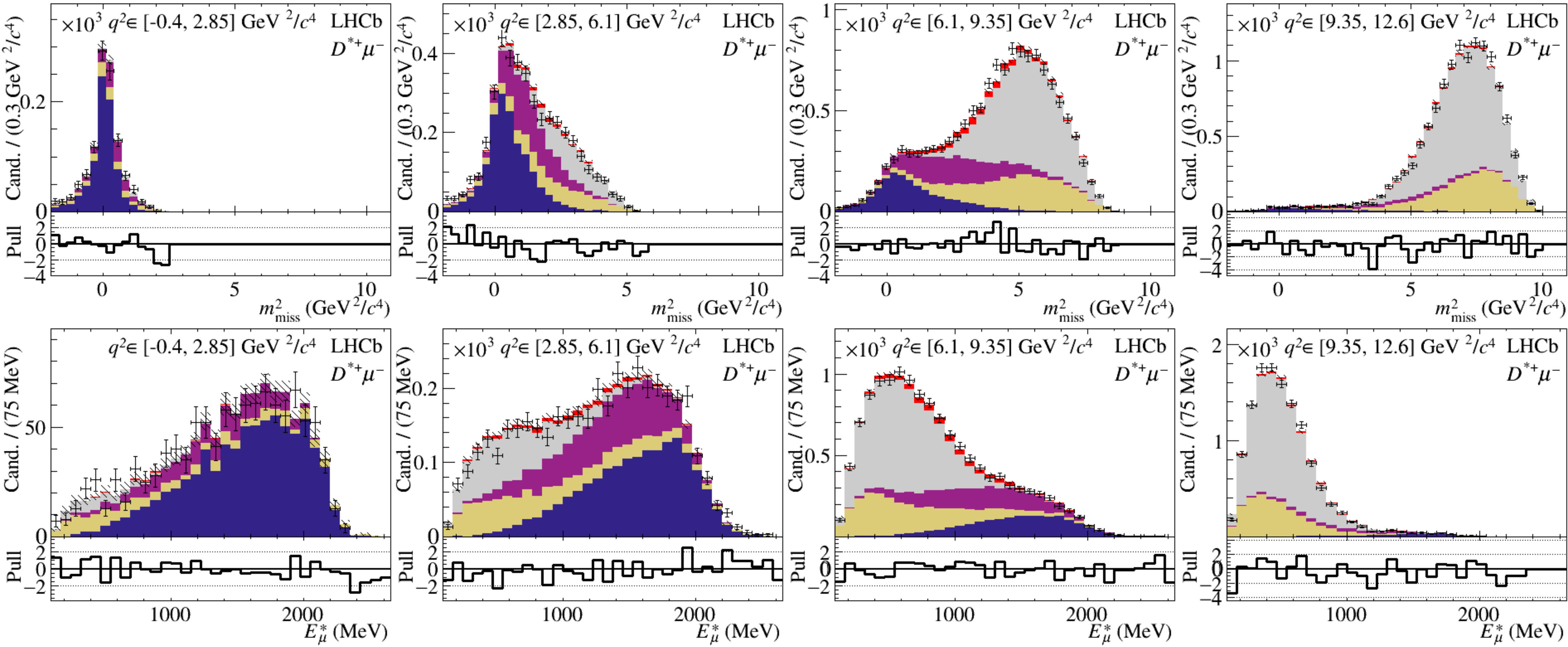
LHCb
$D^{*+}\mu^-$
$\times10^3$ $q^2\in$ [-0.4, 2.85] GeV $^2/c^4$
$q^2\in$ [2.85, 6.1] GeV $^2/c^4$
$q^2\in$ [6.1, 9.35] GeV $^2/c^4$
$q^2\in$ [9.35, 12.6] GeV $^2/c^4$
Cand. / (0.3 GeV $^2/c^4$)
Cand. / (75 MeV)
Pull
$m^2_{\rm miss}$ (GeV$^2/c^4$)
E^*_μ (MeV)
Data (3 fb^{-1})
$B\to D^*\tau\nu$
$B\to D\tau\nu$
$B\to D^{(*)}D X$
$B\to D^{**}\mu\nu$
Comb. + misID
$B\to D^0\mu\nu$
$B\to D^{*0}\mu\nu$
$B\to D^{*+}\mu\nu$

$D^0\mu^-$ 2OS



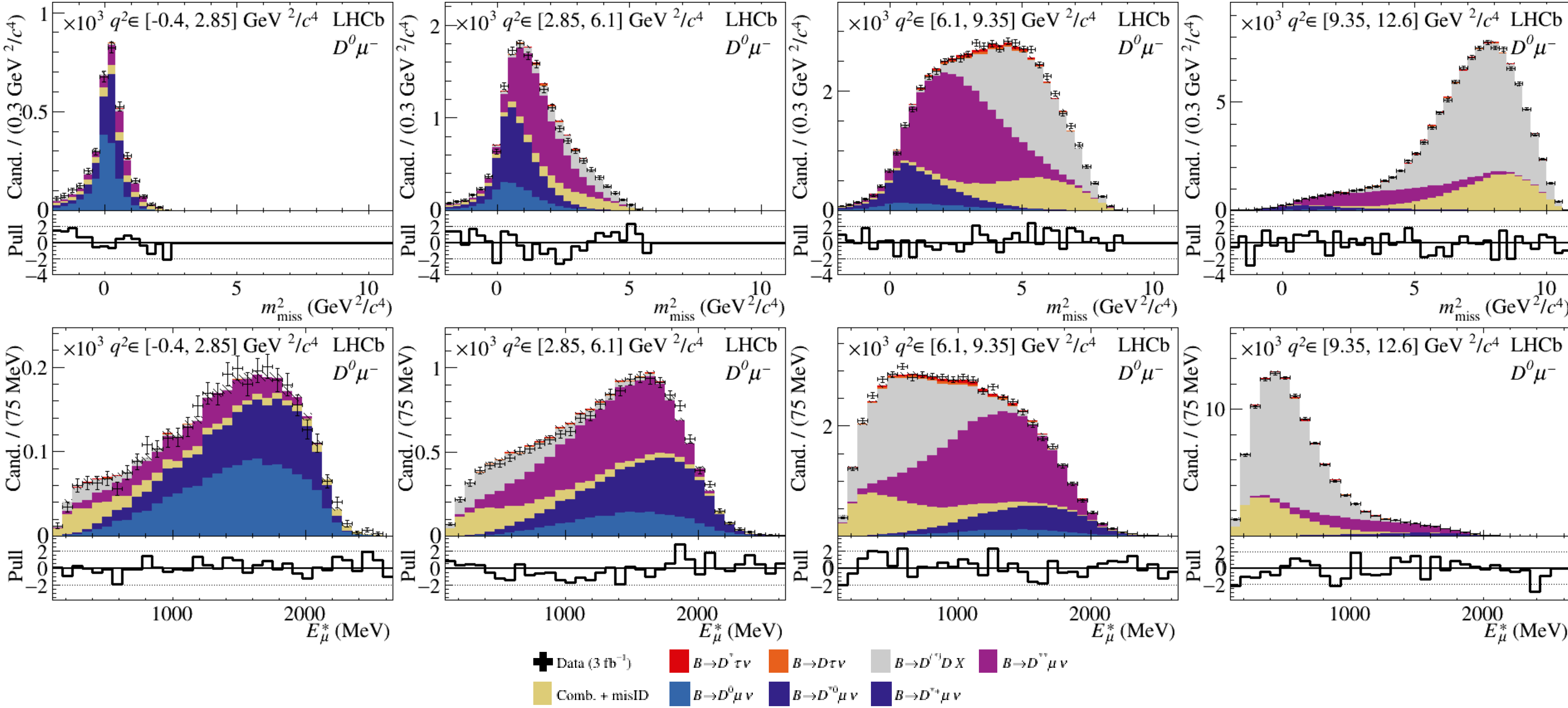
$\times10^3$ $q^2\in$ [-0.4, 2.85] GeV $^2/c^4$ LHCb $D^0\mu^-$
$\times10^3$ $q^2\in$ [2.85, 6.1] GeV $^2/c^4$ LHCb $D^0\mu^-$
$\times10^3$ $q^2\in$ [6.1, 9.35] GeV $^2/c^4$ LHCb $D^0\mu^-$
$\times10^3$ $q^2\in$ [9.35, 12.6] GeV $^2/c^4$ LHCb $D^0\mu^-$
Cand. / (0.3 GeV $^2/c^4$)
Pull
$m^2_{\rm miss}$ (GeV$^2/c^4$)
$q^2\in$ [-0.4, 2.85] GeV $^2/c^4$ LHCb $D^0\mu^-$
Cand. / (75 MeV)
E^*_μ (MeV)
Data (3 fb^{-1})
$B\to D^*\tau\nu$
$B\to D\tau\nu$
$B\to D^{(*)}DX$
$B\to D^{**}\mu\nu$
Comb. + misID
$B\to D^0\mu\nu$
$B\to D^{*0}\mu\nu$
$B\to D^{*+}\mu\nu$

$D^{*+}\mu^-$ DD



$\times 10^3$ $q^2 \in$ [-0.4, 2.85] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
$\times 10^3$ $q^2 \in$ [2.85, 6.1] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
$\times 10^3$ $q^2 \in$ [6.1, 9.35] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
$\times 10^3$ $q^2 \in$ [9.35, 12.6] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
Cand. / (0.3 GeV $^2/c^4$)
Pull
$m^2_{\rm miss}$ (GeV$^2/c^4$)
$q^2 \in$ [-0.4, 2.85] GeV $^2/c^4$ LHCb $D^{*+}\mu^-$
Cand. / (75 MeV)
E^*_μ (MeV)

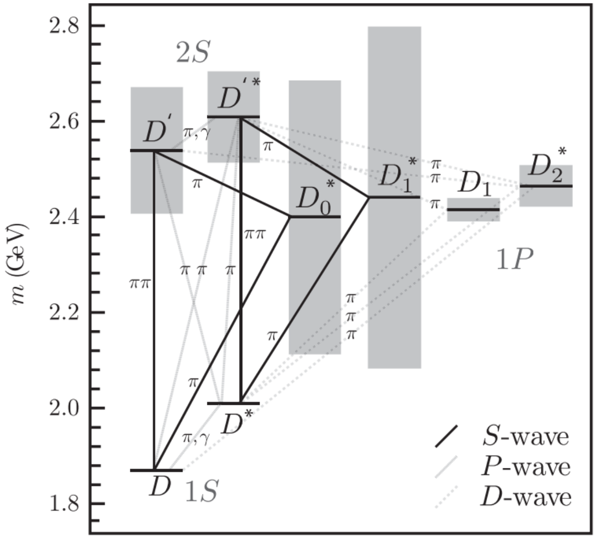
$D^0\mu^-$ DD



$\times10^3$ $q^2\in$ [-0.4, 2.85] GeV $^2/c^4$ LHCb
$D^0\mu^-$
$\times10^3$ $q^2\in$ [2.85, 6.1] GeV $^2/c^4$ LHCb
$\times10^3$ $q^2\in$ [6.1, 9.35] GeV $^2/c^4$ LHCb
$\times10^3$ $q^2\in$ [9.35, 12.6] GeV $^2/c^4$ LHCb
Cand. / (0.3 GeV $^2/c^4$)
Cand. / (75 MeV)
Pull
$m^2_{\rm miss}$ (GeV$^2/c^4$)
E^*_μ (MeV)
Data (3 fb^{-1})
$B\to D^*\tau\nu$
$B\to D\tau\nu$
$B\to D^{(*)}D X$
$B\to D^{**}\mu\nu$
Comb. + misID
$B\to D^0\mu\nu$
$B\to D^{*0}\mu\nu$
$B\to D^{*+}\mu\nu$

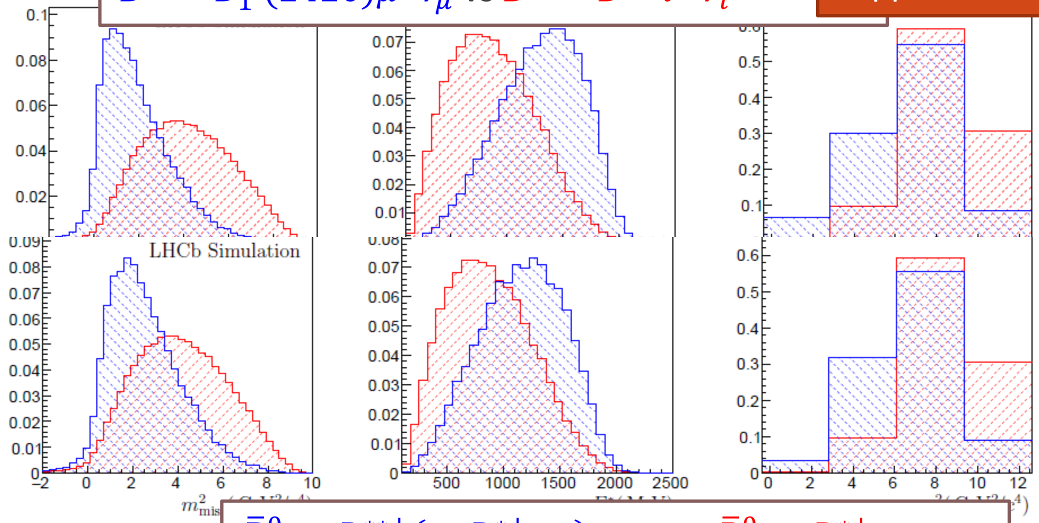
Semileptonic Backgrounds

Bernlochner et al, PRD 85 094033 (2012)



LHCb-PAPER-2015-025 supplementary

$\bar{B}^0 \to D_1^+(2420)\mu^-\bar{\nu}_\mu$ vs $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$



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

Contributions of excited charm states in the $B^{\pm,0} \to (c\bar{q})\mu\nu$ transition are large

- **We directly fit for contributions of 1P states constrained and unconstrained**
  - Excellent consistency of resulting R(D*) with and without external measurements as input
  - $D^{*+}\mu^-\pi^-$ control sample sets nonperturbative shape parameters for input to signal fit ~ 1.8% relative systematic
- States decaying as $D^*\pi\pi$ less well-understood, fit insensitive to exact composition.
  - $D^{*+}\mu^-\pi^+\pi^-$ control sample used to correct q^2 spectrum to match data ~ 1.2% relative systematic

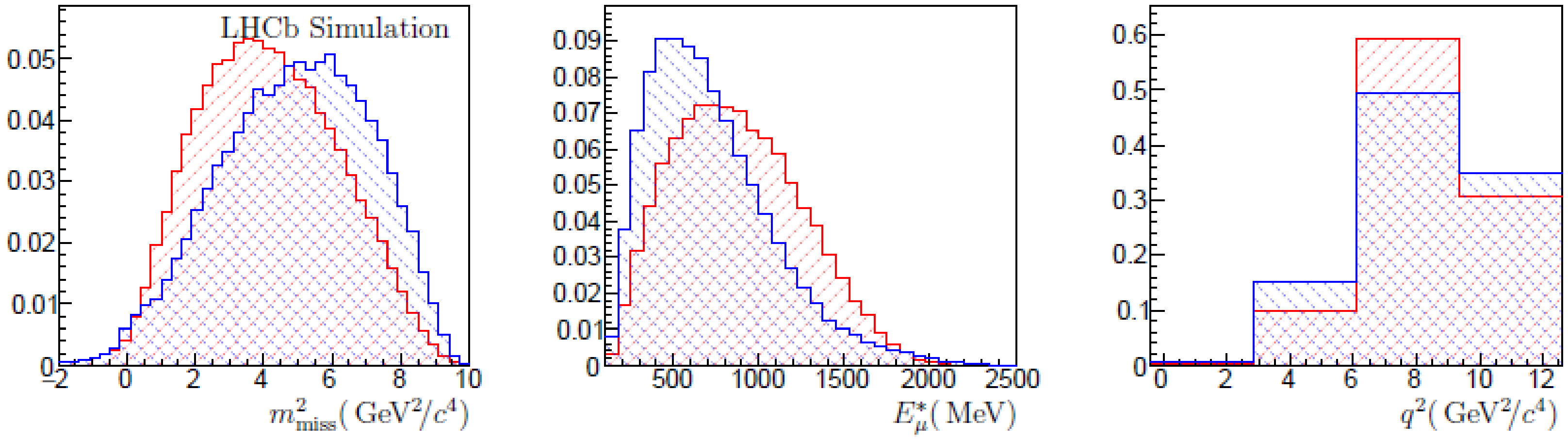
Distinguishable by “edge” at missing mass ≈ $(2)m_\pi$

Use mu component plus reasonable guess (with large error bars) on R(D**) to constraint tau component (only adds 1.5% relative systematic)

$B \to D^{*+} H_c(\to \mu \nu X')X$ background

- $b \to c\bar{c}q$ decays can lead to very similar shapes to the semitauonic decay (e.g. $\bar{B}^0 \to D^{*+} D_s^- (\to \phi\mu\nu)$ +many others)
- Branching fractions well-cataloged, but detailed descriptions of the $D^* DK (n \geq 0\ \pi)$ final states are not simulated using full Dalitz plot description
  - Dedicated $D^{*+}\mu^- K^\pm$ control sample used to improve the template to match data
  - (1.5% relative systematic)
- Nastiest background – unconstrained in fit (major contributor to statistical uncertainty)

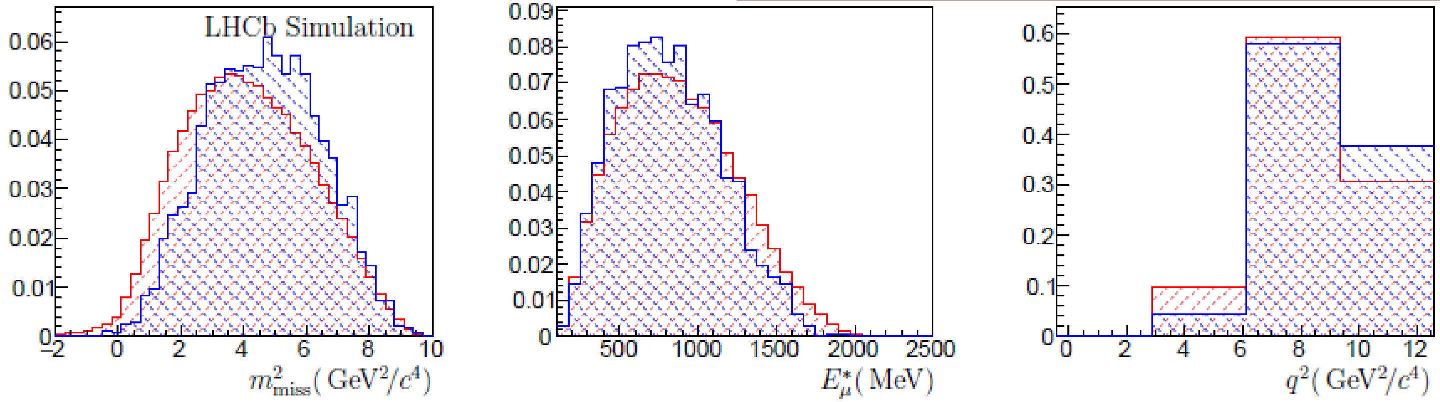
$\bar{B}^0 \to D^{*+} H_c(\to \mu\nu X')X$ vs $\bar{B}^0 \to D^{*+}\tau^-\nu_\tau$



LHCb-PAPER-2015-025 supplementary

Tau backgrounds

$\bar{B}^0 \rightarrow D_2^{*+}(2460)\tau^-\bar{\nu}_\tau$ vs $\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau$

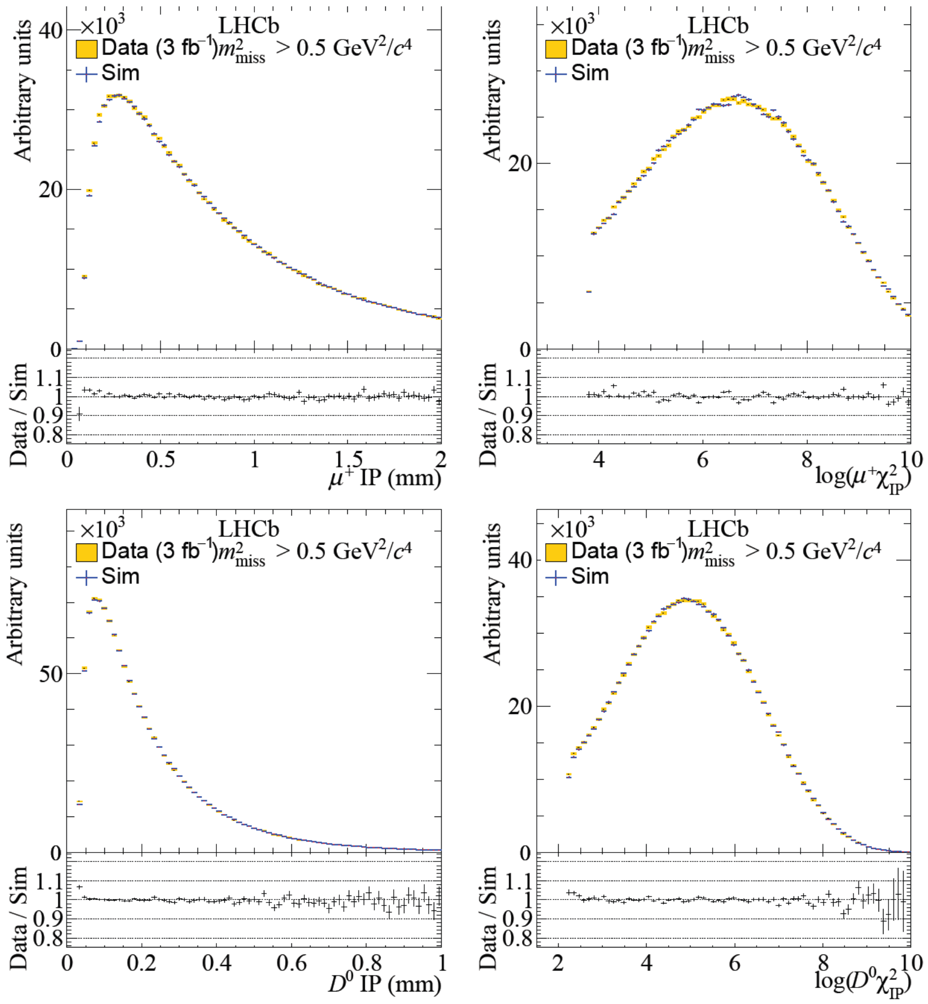


All backgrounds with real $\tau \rightarrow \mu\bar{\nu}\nu$ decays are an order of magnitude (at least) smaller than the signal

- Background contributions from $\bar{B} \rightarrow D^{**}\tau^-\bar{\nu}_\tau$ are considered to be fixed relative to the corresponding decay modes to muons
  - Very small component, varying this contribution by 50% only moves R(D*) by 0.005
- Similarly, $\bar{B} \rightarrow D^{*+}D_s^-(\rightarrow \tau^-\nu)X$ are fixed to a known fraction of the $\bar{B} \rightarrow D^{*+}H_c(\rightarrow \mu\nu X')X$ background
  - Again, these have a negligible effect on R(D*)

New technology: data/simulation corrections

LHCb-PAPER-2022-039 supplementary



New Data/MC correction recipe:

- B hadron kinematics correction from $J/\psi K$ control samples
- Final correction from normalization-rich isolated data

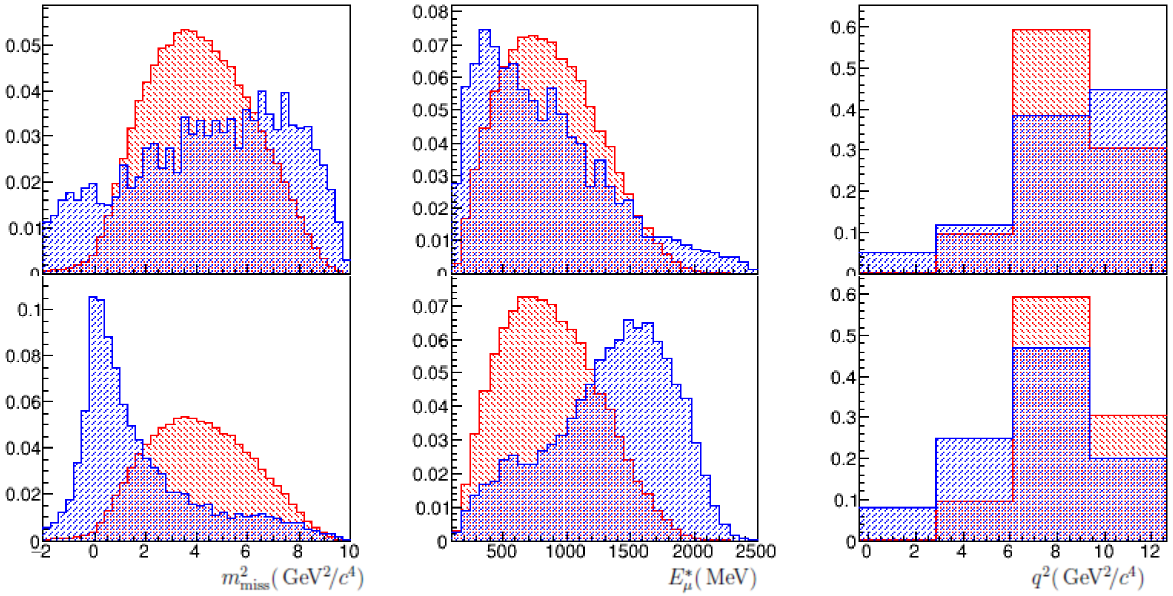
Extensively tested

- Checked by correcting deliberately-broken MC vs nominal MC
  - single correction at low missing mass fixes both normalization and double-charm MC

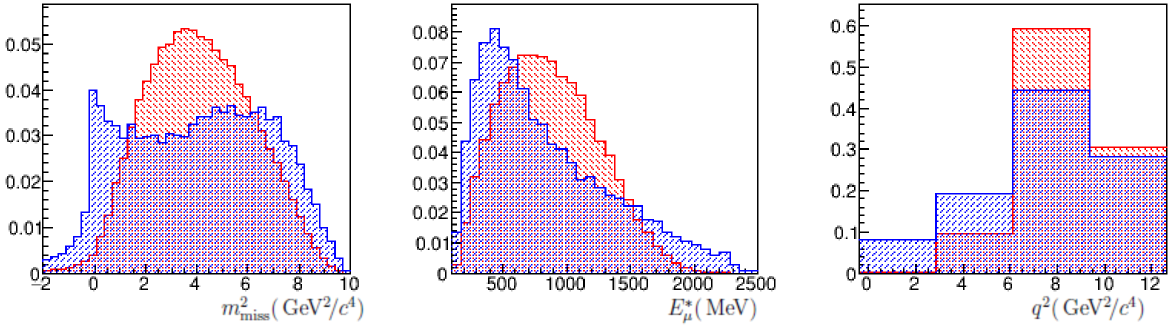
Other backgrounds

Other backgrounds from "junk" reconstructed as $D^{*+}\mu^-$

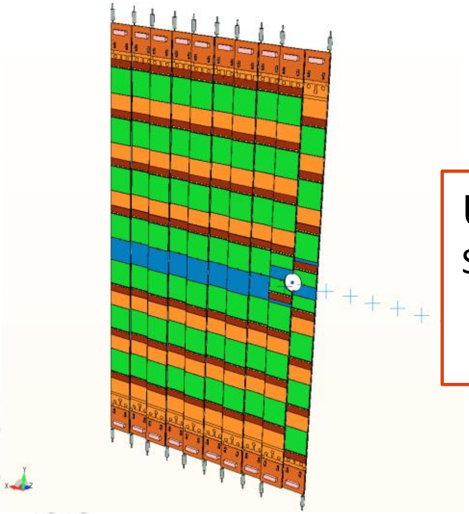
- combinatorial (top), fake D^{*+} candidates (middle), hadrons misidentified as muons (bottom), all derived from control samples



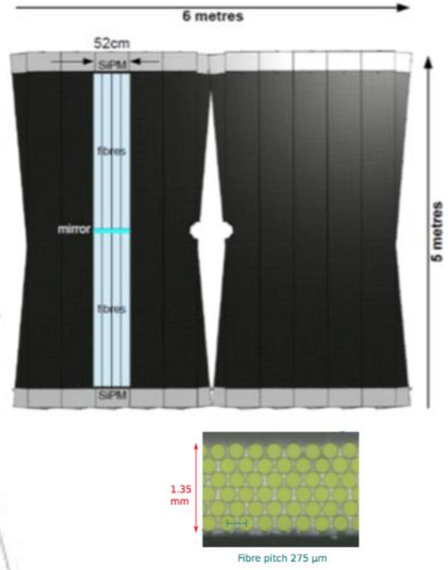
Misidentification background particularly troublesome due to ambiguities in deriving fit shapes from the control sample



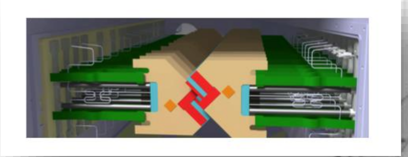
LHCb Upgrade Hardware

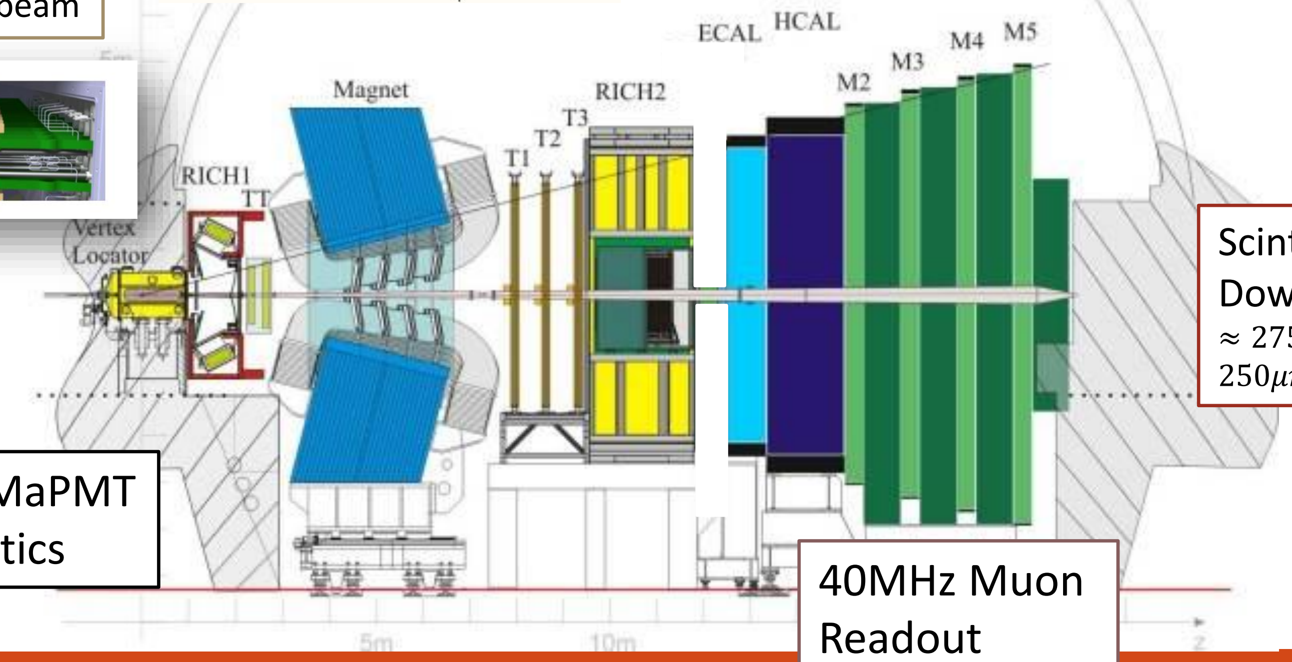


Upstream Tracker
Silicon Strips
$\approx 190\mu m$ outer,
$95\mu m$ inner



Pixel Velo
$55\mu m$ square
@ 3.5mm from beam





Scintillating Fibre Downstream Tracker
$\approx 275\mu m$ fiber pitch,
$250\mu m$ pitch SiPM sensors

New RICH MaPMT sensors+optics

40MHz Muon Readout