R(D) and R(D*) measurements at LHCb

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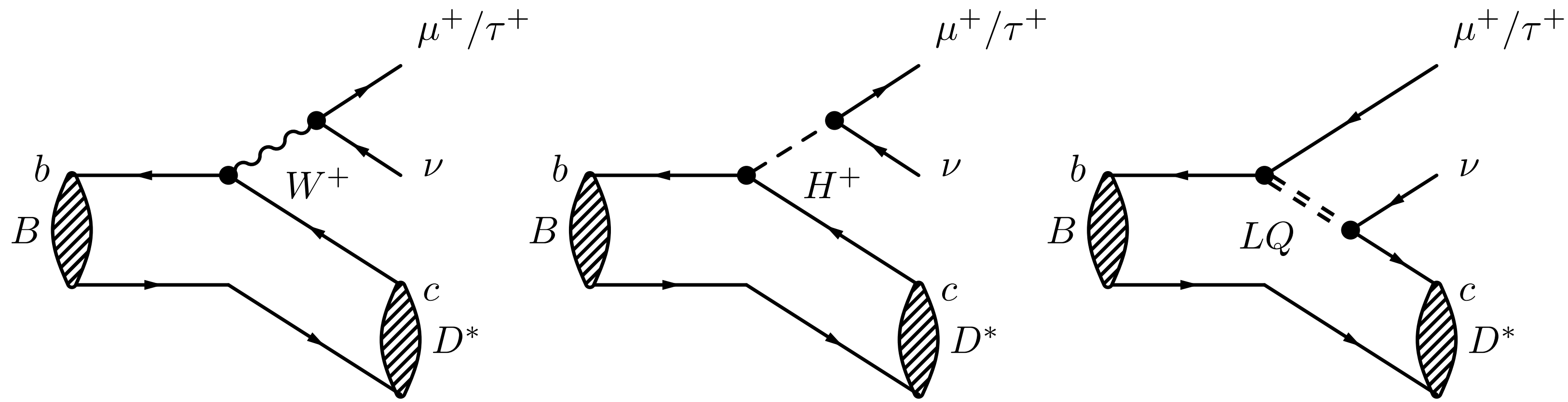
On behalf of the LHCb collaboration

Semi-tauonic decays

- B → D(*)τν are tree level decays mediated by a W in SM
- Lepton universality in SM, might be broken by mass-dependent couplings

→ Probe SM extensions to models with e.g. enlarged Higgs sector, leptoquarks



→ Test SM by measuring ratios

theoretically and experimentally cleaner

$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

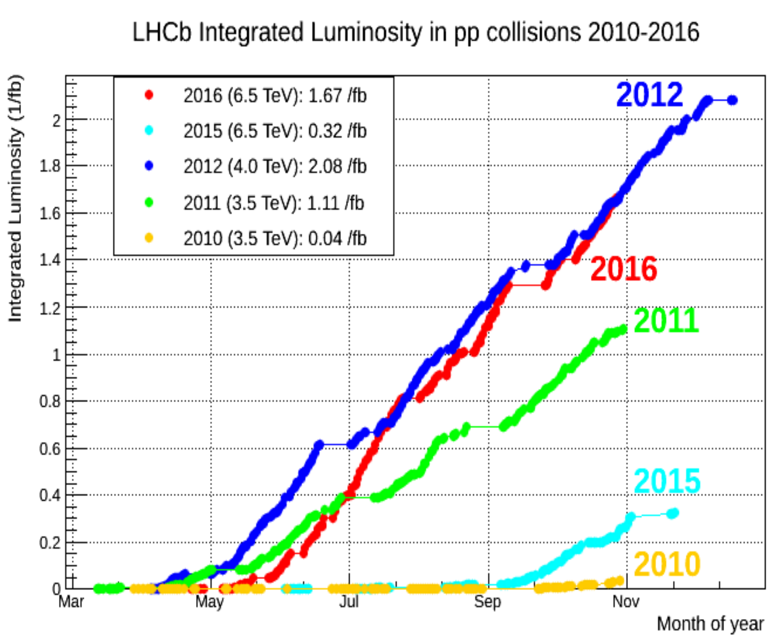
→ Renewed interest in this area, after anomalous result of Babar (next talk)

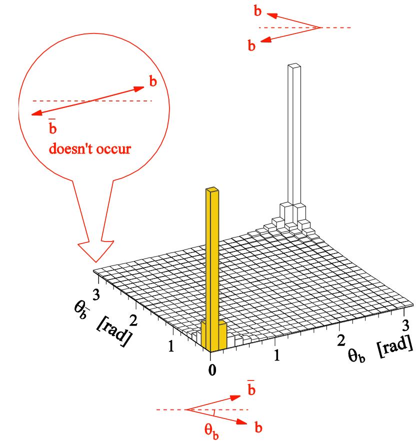
PRL109, 101802 (2012)

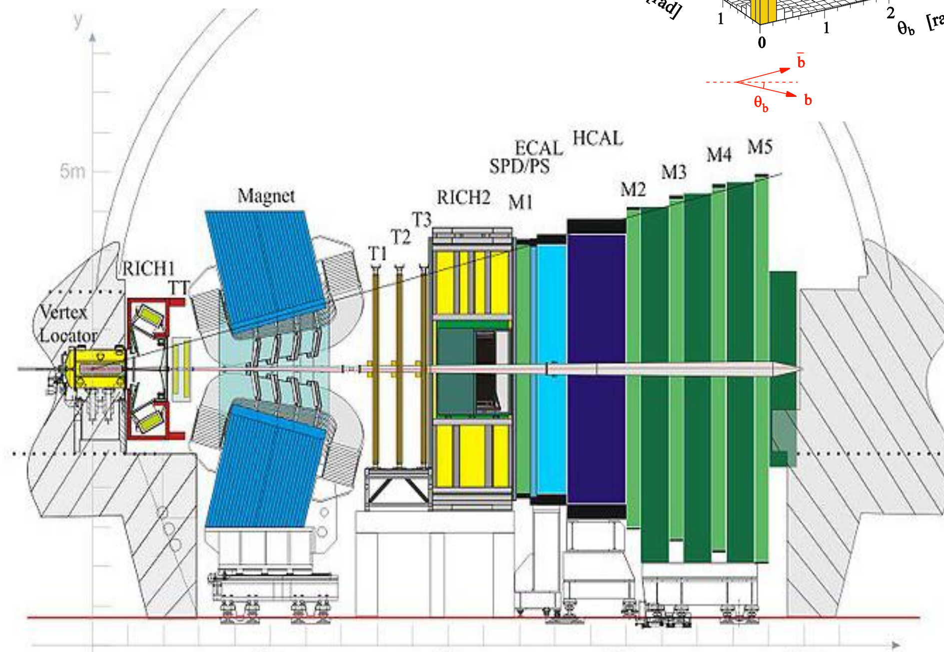
The LHCb experiment

Forward spectrometer optimised for heavy flavour physics at the LHC

- Large acceptance 2<η<5
- Low trigger thresholds
- Precise vertexing
- Efficient particle identification
- Running at a constant luminosity of 4×10^{32} cm^{-2}s^{-1}, <μ>~1.7, 4x design

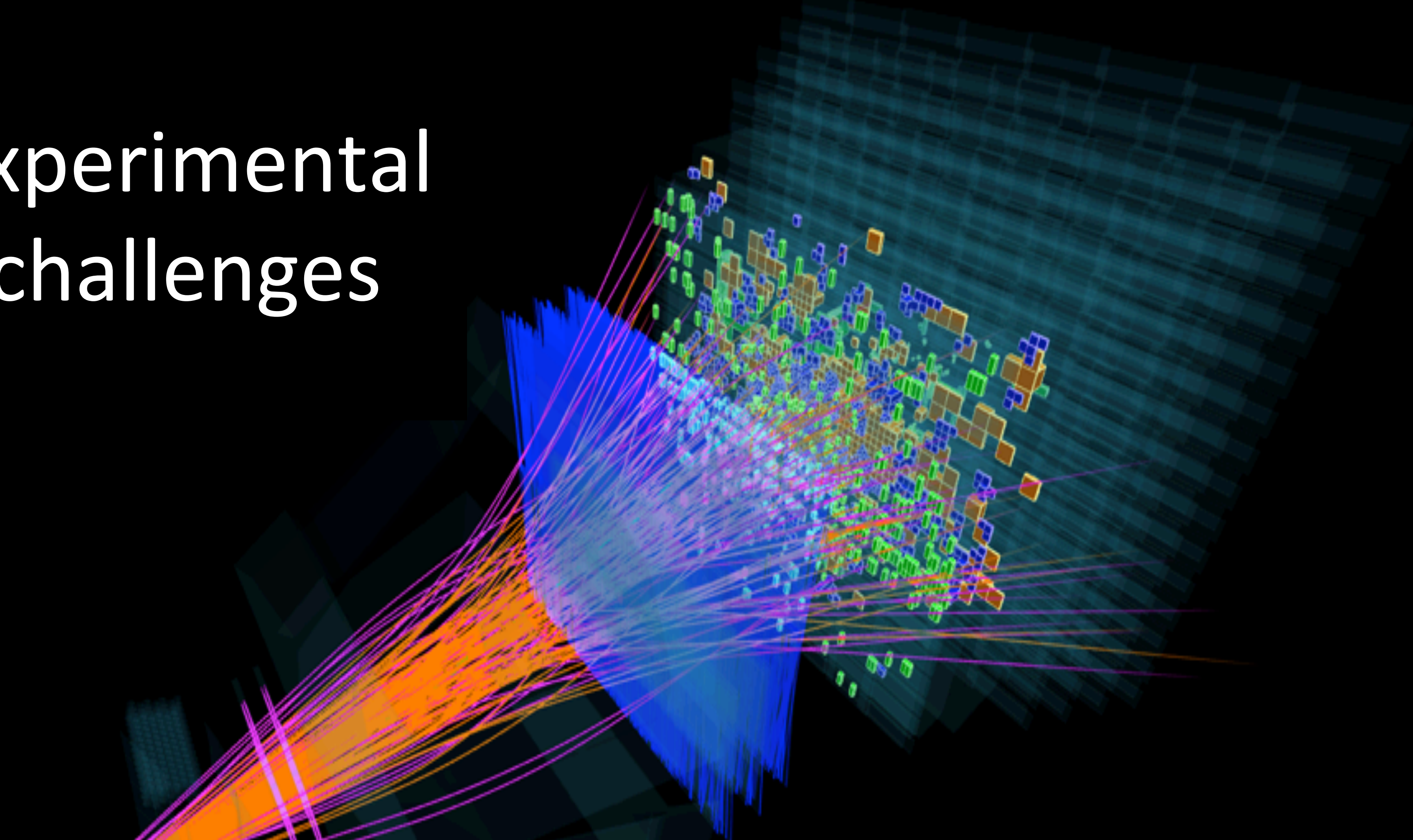






- Large boost (B mesons flight ~1cm)
- Huge production cross section (~300μb)
- Small S/B ratio

Experimental challenges

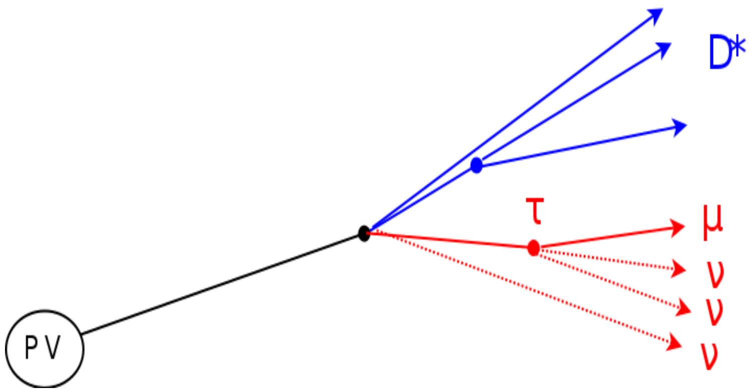


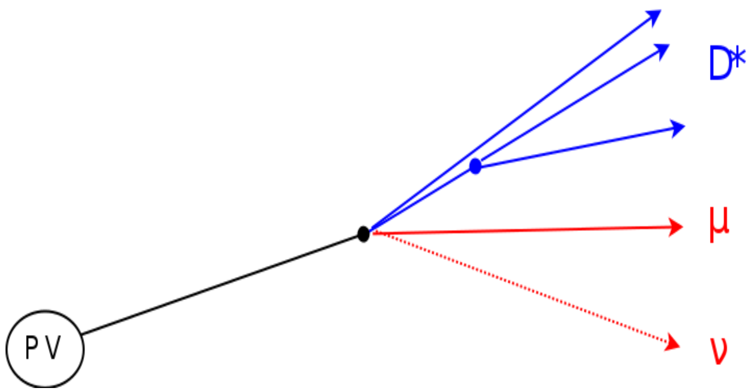
- Neutrinos in the final state → unconstrained kinematics
- Extra particles in the event → large backgrounds from partially reconstructed B decays
  - $B \to D^{*}\mu\nu$, $B \to D^{**}\mu\nu$, $B \to D^{*}D(\to \mu X)X$ ...
  - $B \to D^{*}\pi\pi\pi X$, $B \to D^{*}D(\to \pi\pi\pi X)X$ ...

LHCB-PAPER-2015-025
PRL 115 11803 (2015)

R(D*) measurement with $\tau \rightarrow \mu\nu_\tau\nu_\mu$

- Same final state particles
- Favourable, well-measured BF for τ decay (17.41+/- 0.04)%





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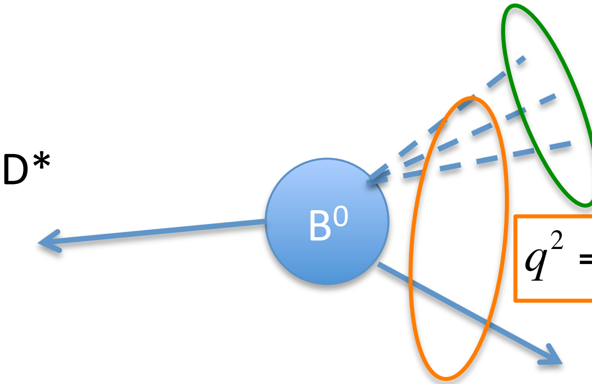
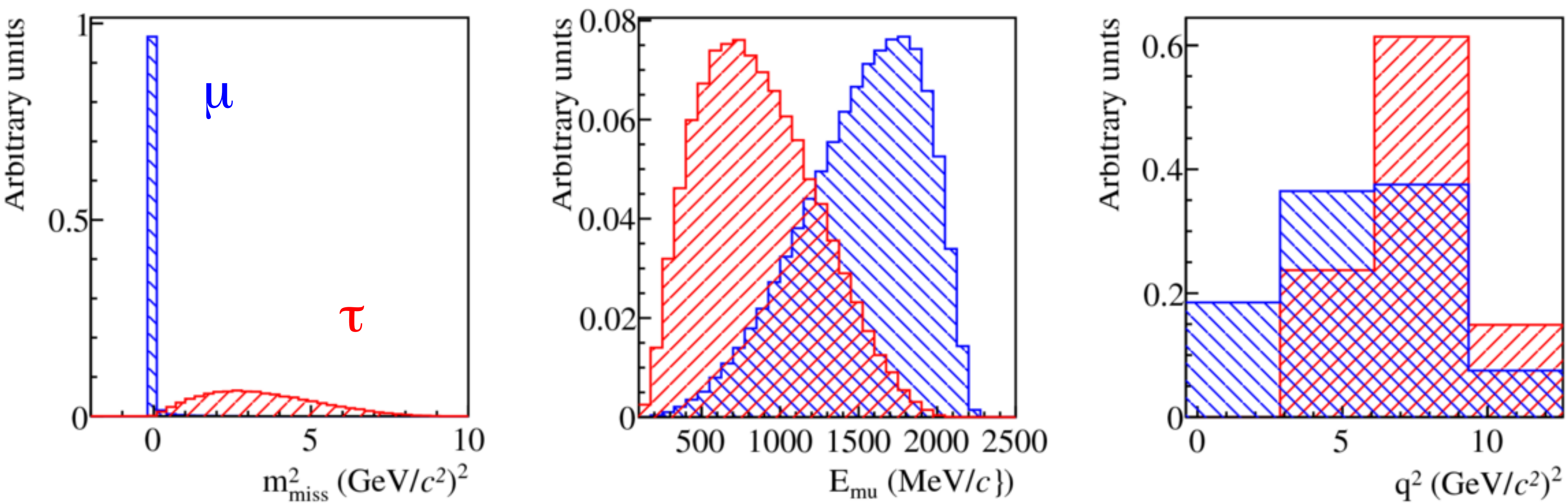


$$m^2_{miss} = (p_B - p_{D^*\mu})^2$$

$$q^2 = (p_\mu + p_\nu)^2 = (p_B - p_{D^*})^2$$



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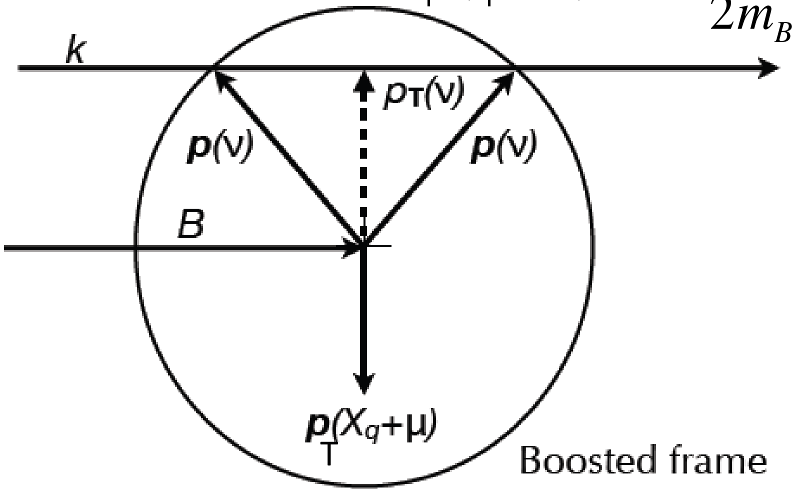
- Signal $B \rightarrow D^* \tau \nu$ and normalization $B \rightarrow D^* \mu \nu$ best separated through rest-frame variables
- Using well-measured B flight direction gives momentum with 2-fold ambiguity

$$R = |\vec{p}_\nu| = E_\nu = \frac{m_B^2 - m_{X_q+\mu}^2}{2m_B}$$



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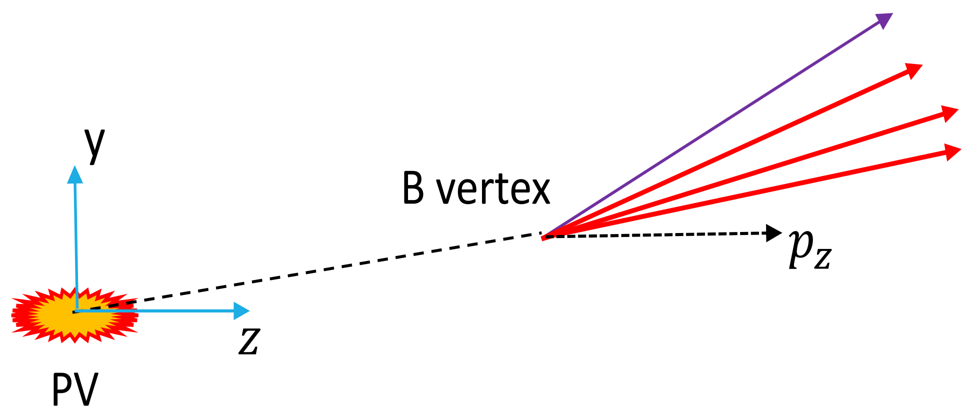

$$(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu} \quad \Longrightarrow \quad (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

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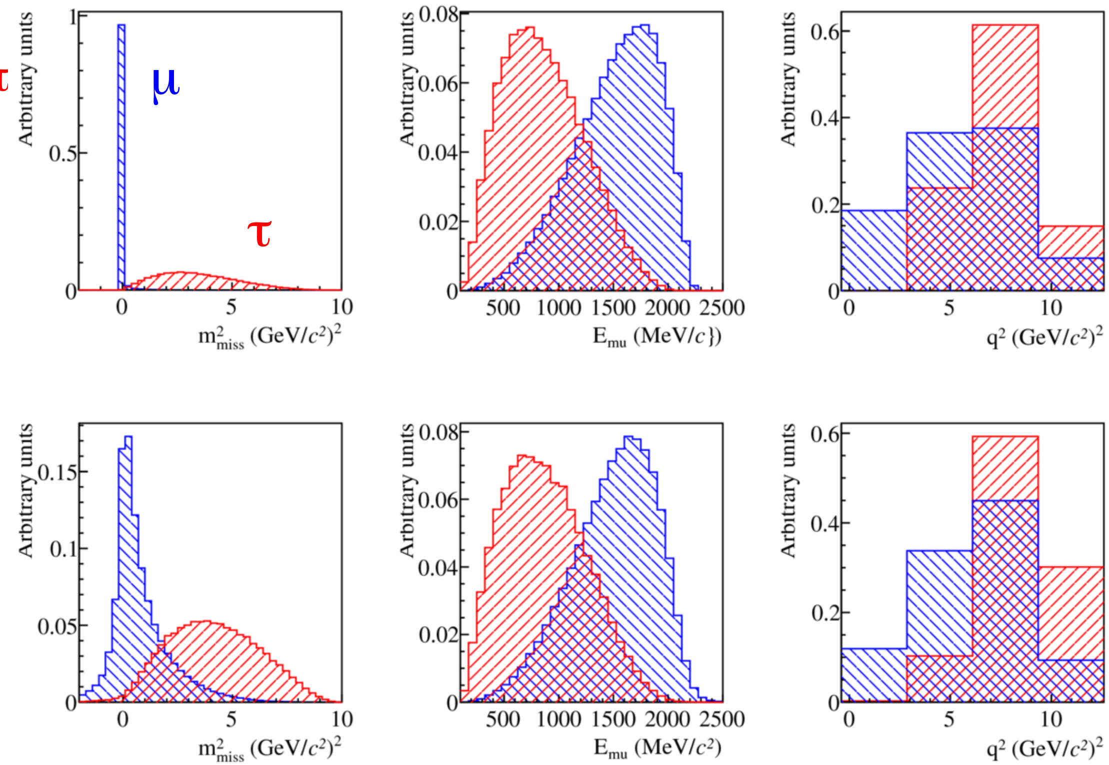
- Avoid ambiguity by assuming B boost along z >> boost of decay products in the rest frame
- 18% resolution on B momentum approximation **preserves differences between signal, normalization and backgrounds**



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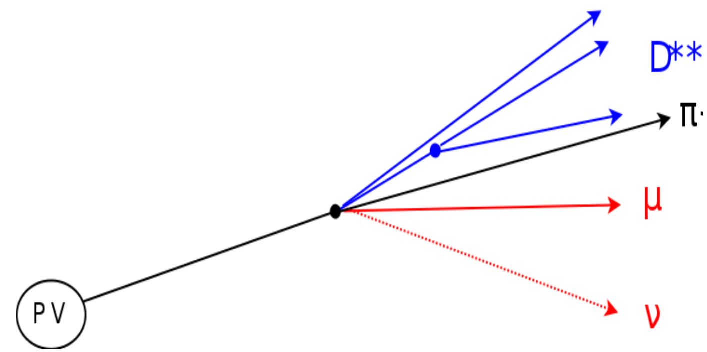
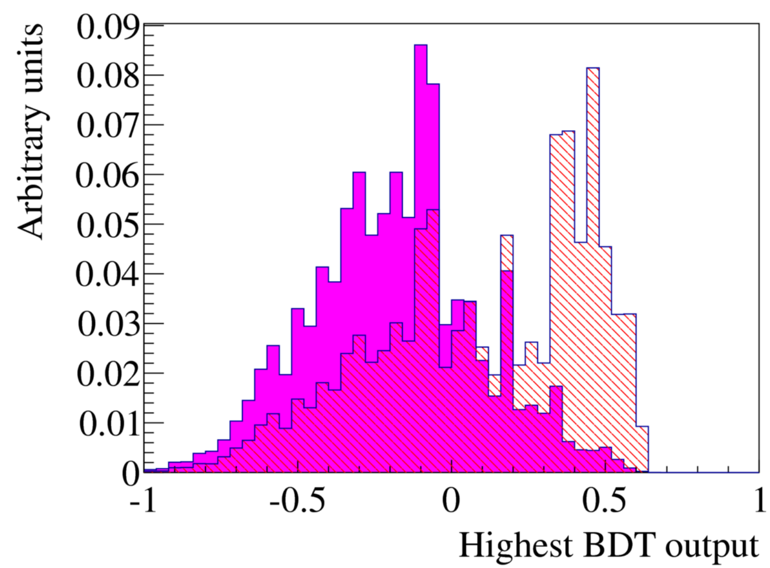
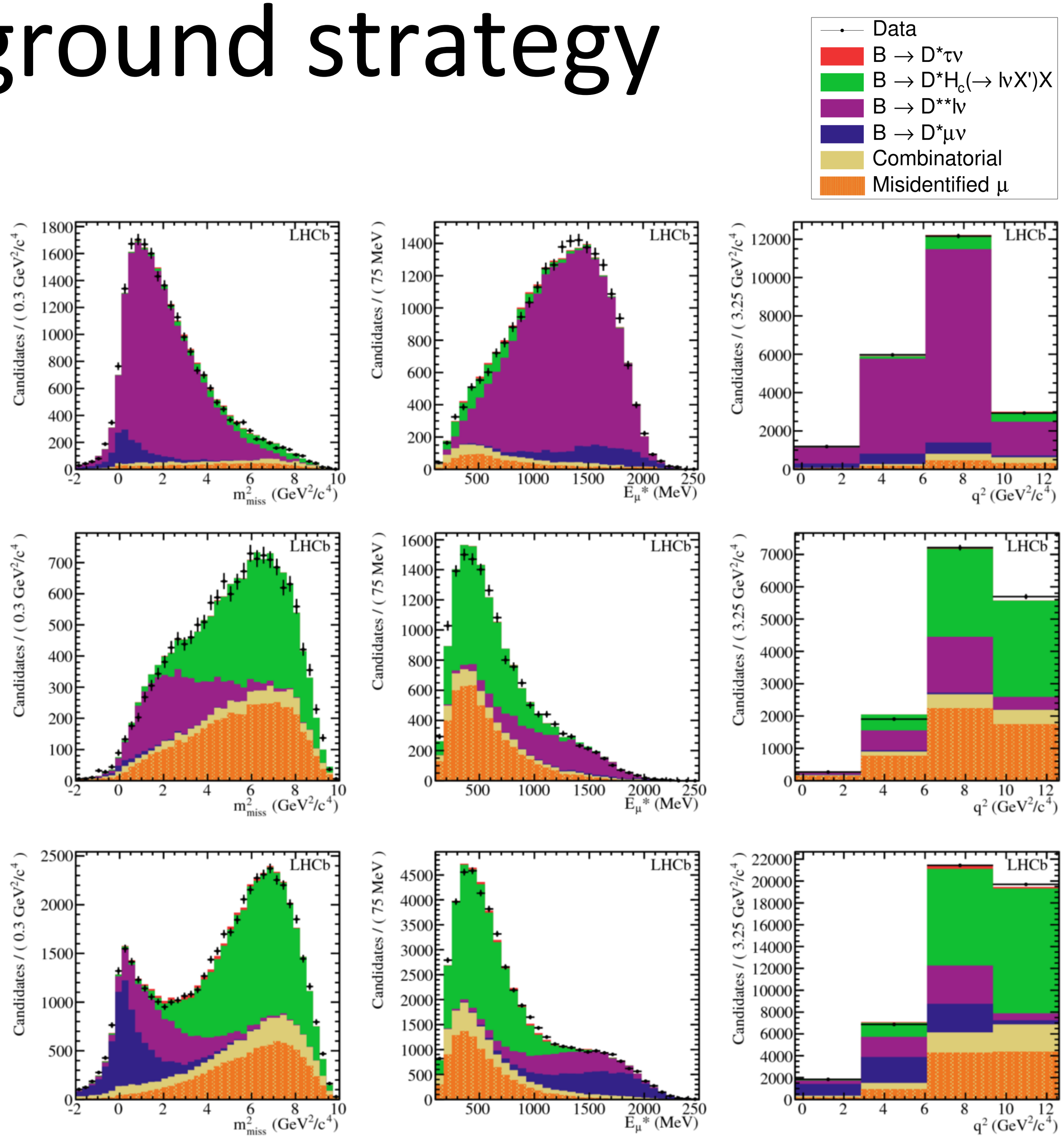
Background reduction

- Scan over every reconstructed track and assess compatibility with $D^{*+}\ \mu^-$ vertex
  - vertex quality with PV and SV, change in displacement of SV, p_T, alignment of track and $D^{*+}\ \mu^-$ momenta
- Build BDT to classify tracks as “SV-like” or “PV-like”
- Cut on most SV-like track below threshold to select signal-enriched sample.
  - 70% of events with 1 additional slow pion are rejected
- Reverse cut to get background-enriched samples
  - One or two extra pions ($D^*\mu\pi$, $D^*\mu\pi\pi$) as proxy for $B\to D^{**}\mu\nu$
  - kaon PID ($D^*\mu K$) as proxy for $B\to D^* H_c(\to\mu\nu X')X$





Background strategy



- All major backgrounds modelled using control samples in data
- **Isolation MVA gives one or two extra tracks→ sample enhanced in B → D**μν**
- **Isolation MVA gives an extra track with loose kaon ID → sample enhanced in B → D*DX**
- Combinatorial or misID backgrounds taken from data

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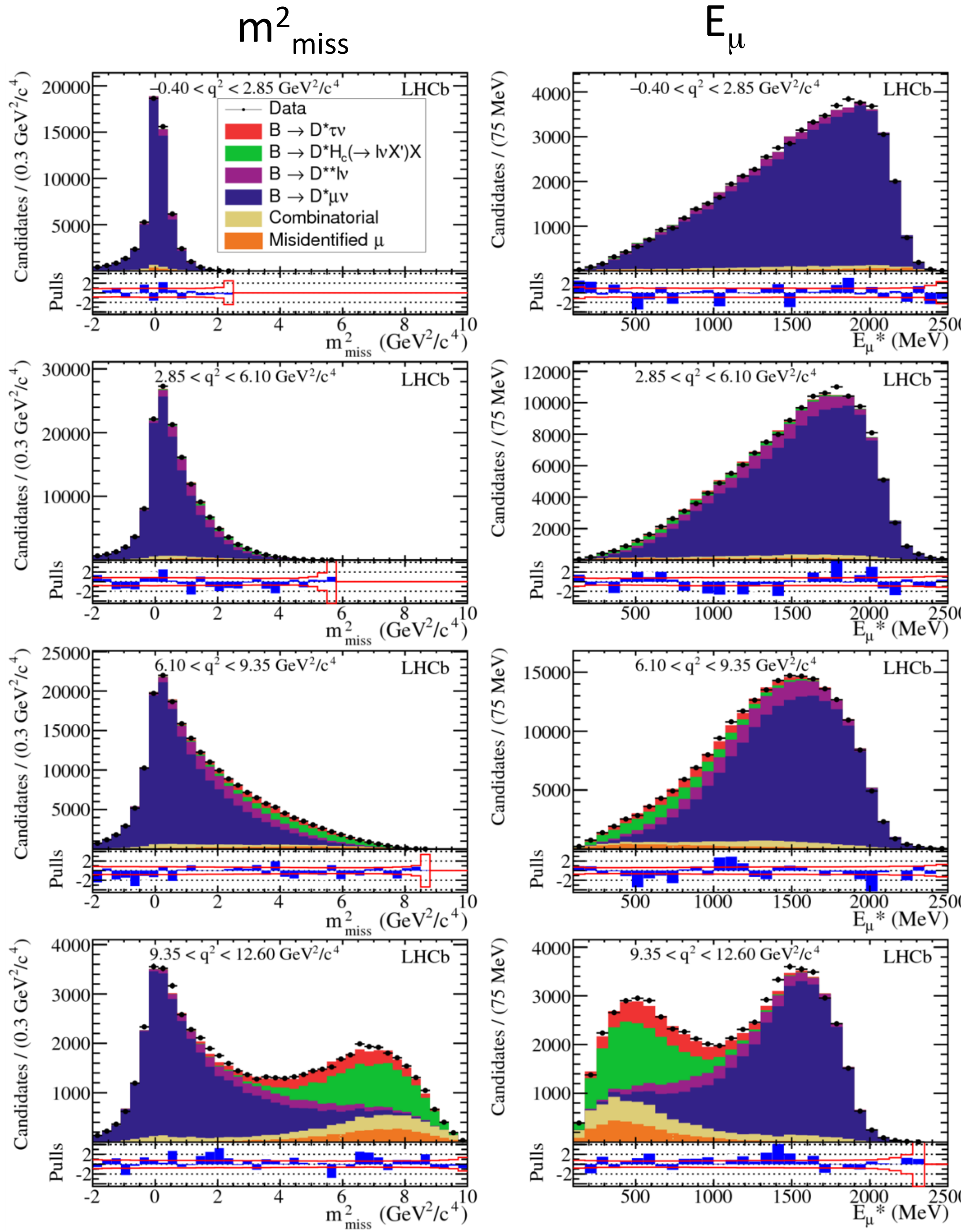
Fit results

- No additional particles
- 3D fit to m^2_{miss}, E_μ, in 4 bins of q^2.
- Simultaneously fit 3 control regions defined by isolation criteria
- Signal yield: 16500 events

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

- In agreement with Babar and Belle
- 2.1σ higher than the SM



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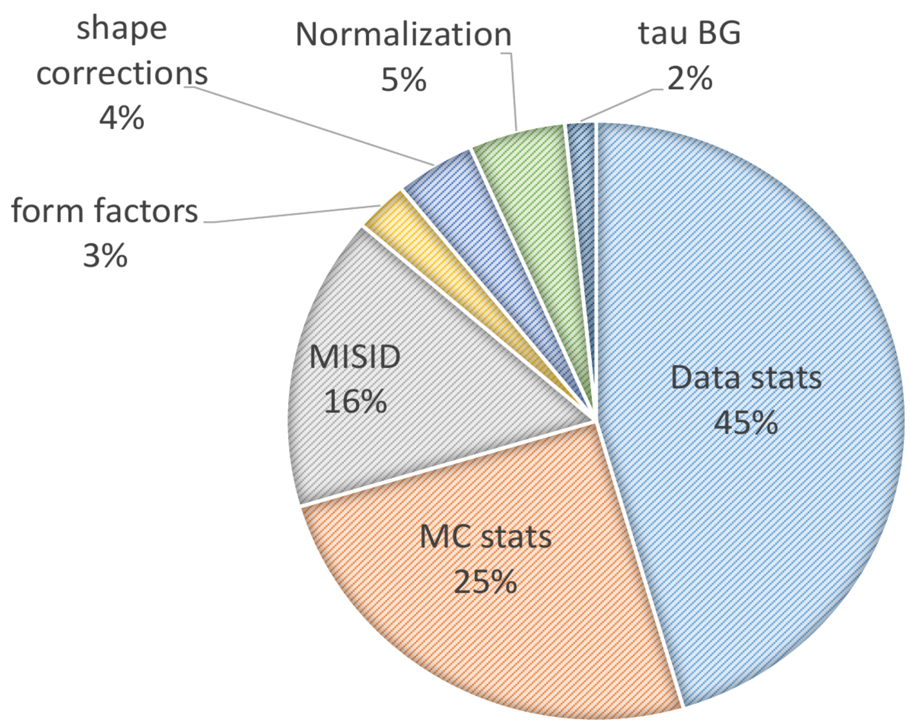
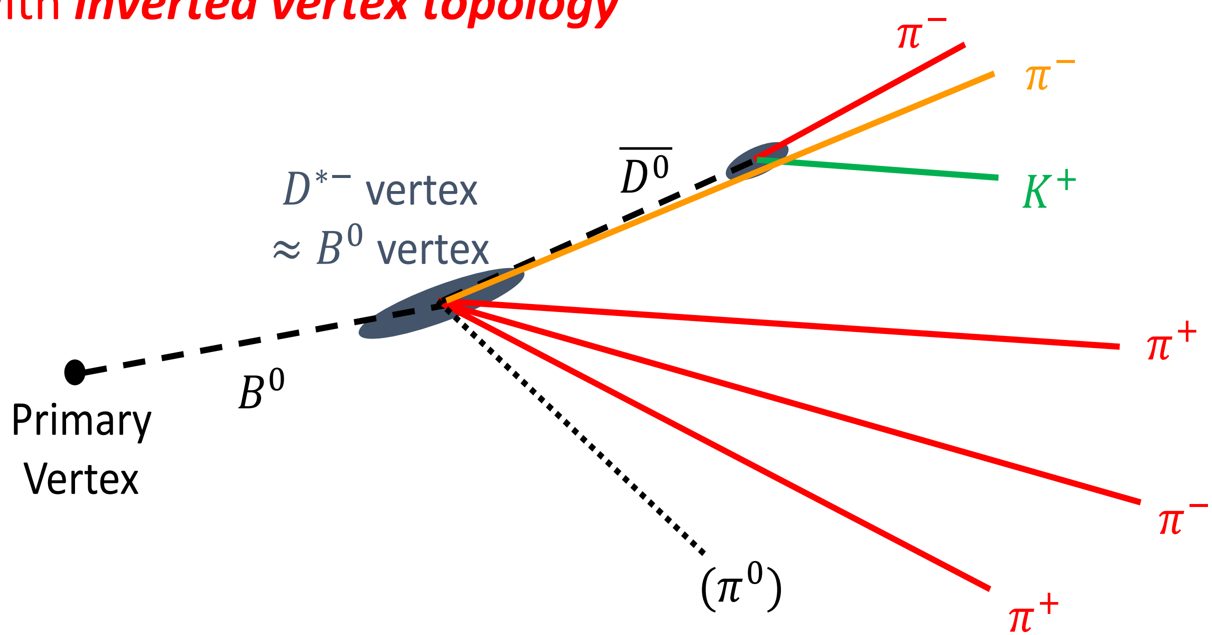
R(D*): Error budget

- Total uncertainty at the 10% level
- Largest systematics from MC statistics and non-muon component
- They can both be reduced by
  - generating more MC samples
  - improved methods, smarter use of PID
- Expect to reduce the total uncertainty to the levels of
  - 4% with the addition of Run2 data and the $\tau \rightarrow 3\pi(\pi^0)$ decay
  - 2% by using also Run3 data and the upgraded LHCb detector



$B \to D^* \tau \nu$, with $\tau \to 3\pi(\pi^0)$

- Doing semileptonic physics **without leptons in the final state!**
- The $B \to D^* \tau \nu$ decay, with $\tau \to 3\pi(\pi^0)$ leads to a ***$D^*3\pi(X)$* final state**
- Nothing is more common than this final state in a typical B decay
- $Br(B \to D^* 3\pi(X)) \,/\, Br(B \to D^* \tau \nu;\, \tau \to 3\pi(\pi^0)\nu)_{SM}$ **~100**
- Suppress with ***inverted vertex topology***



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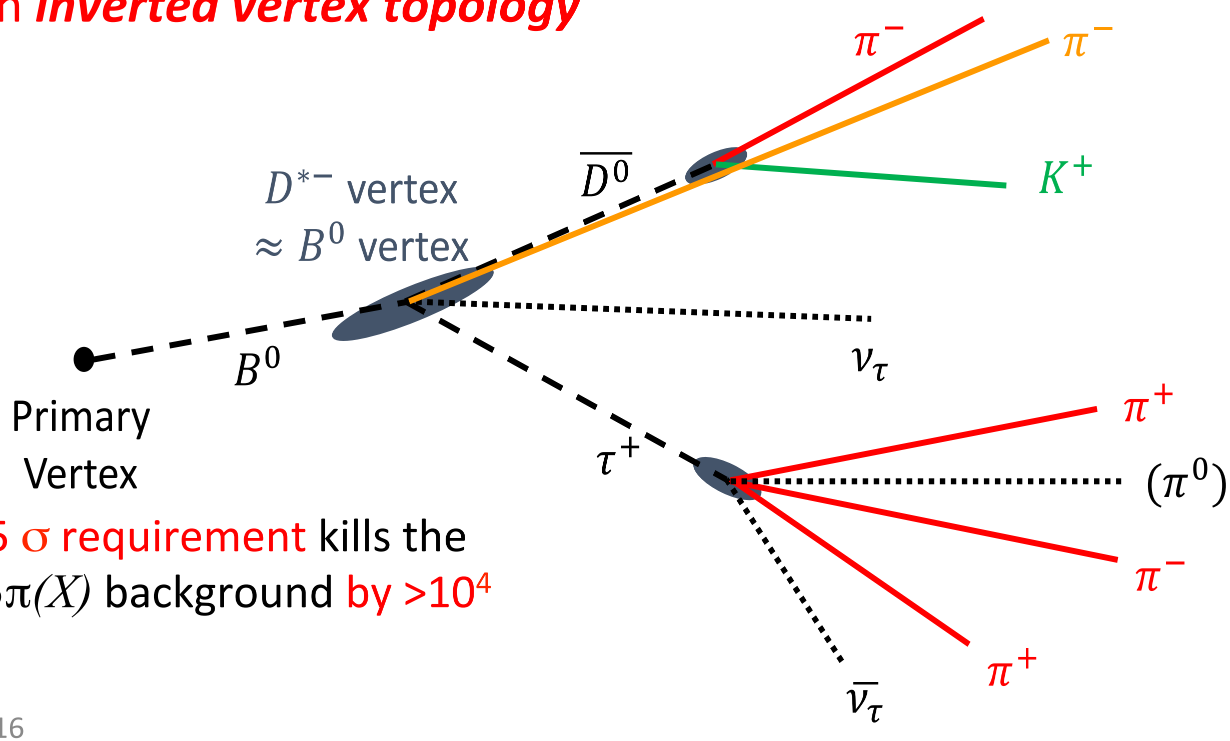

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- Suppress with ***inverted vertex topology***
- A 5 σ requirement kills the $D^*3\pi(X)$ background by $>10^4$
- Remaining background from B^0 decays where the 3π vertex is transported away by a **charm carrier:** D_s, D^+ or D^0 (in order of importance)
- $Br(B \to D^*\text{'}D\text{'};\ \text{'}D\text{'} \to 3\pi)$ / $Br(B \to D^*\tau\nu;\ \tau \to 3\pi(\pi^0)\nu)_{SM}$ **~10**
- LHCb has **good 'weapons'** to suppress this background: Partial background reconstruction, dynamics of 2π, 3π system, track and neutral isolation

Other decays?

- $R(D^{*+})$ measurement chosen as proof-of-concept due to simpler feed-downs and structure, not any limitations in purity or technique
- $R(D^0)$ requires statistical separation of D* feed-down; expect x5 more events
- $O(10^{4\text{-}5})$ semileptonic decays into exclusive narrow p-wave D mesons would make $R(D_1)$, $R(D_2^*)$ also possible
- LHCb has unique access to B_s, B_c , and Λ_b production
  - $R(D_s)$: $B_s \to D_s \tau\nu$ is challenging, many excited states with feed-down emitting unreconstructed neutrals
  - $R(J/\psi)$: $B_c \to J/\psi\tau\nu$ has spectacular signature, and "high" BF($J/\psi \to \mu\mu$) could compensate lower B_c production rate
  - $R(\Lambda_c^{(*)})$: $\Lambda_b \to \Lambda_c^{(*)}\tau\nu$ has a different spin structure → different physics sensitivity, would help discriminate tensor contributions
- What about charmless decays? E.g. $B \to pp\tau\nu$, $\Lambda_b \to p\tau\nu$ …

Conclusion

- First ever measurement of a $b \rightarrow \tau$ decay at a hadron collider
- R(D*) is the beginning of a vast exploration
  - Several channels
  - Two τ decay modes
- The addition of Run2 and Run3 data will eventually lead to samples of $O(10^5\text{-}10^6)$ events
  - Not only R, but also angles, polarizations, form factors…
  - …and charmless semi-tauonic decays!
- LHCb will compete with final Belle-II measurements

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