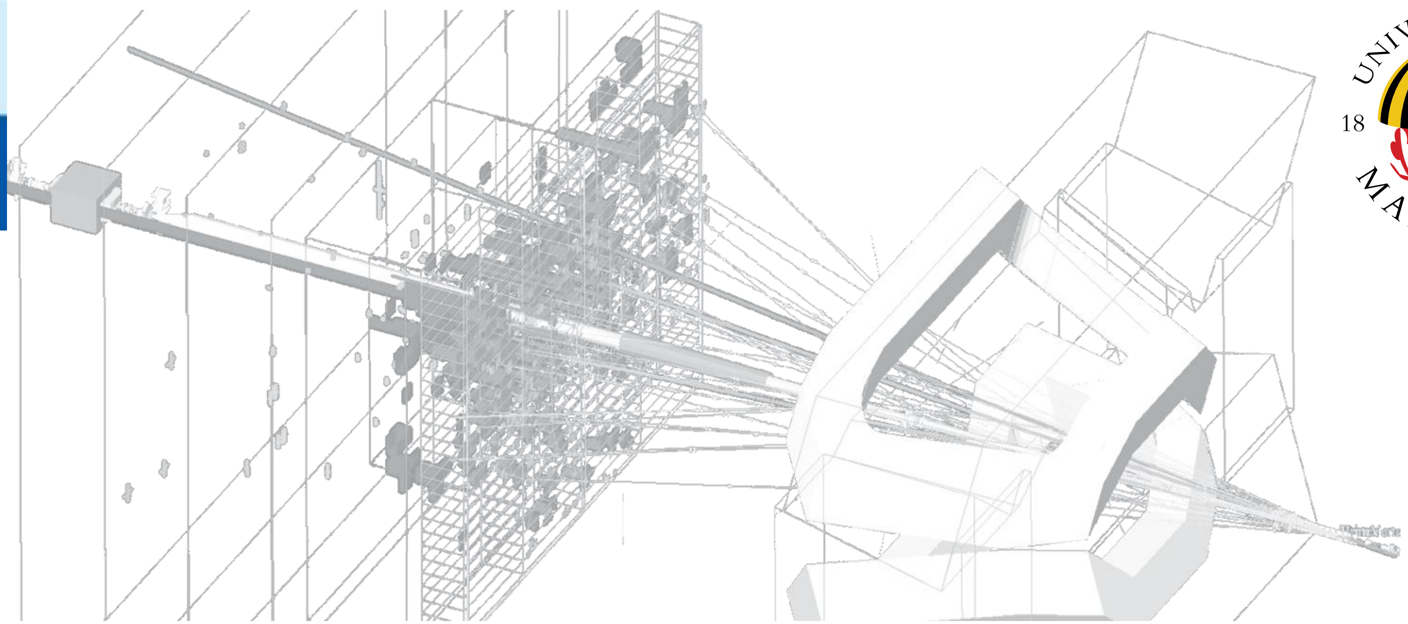


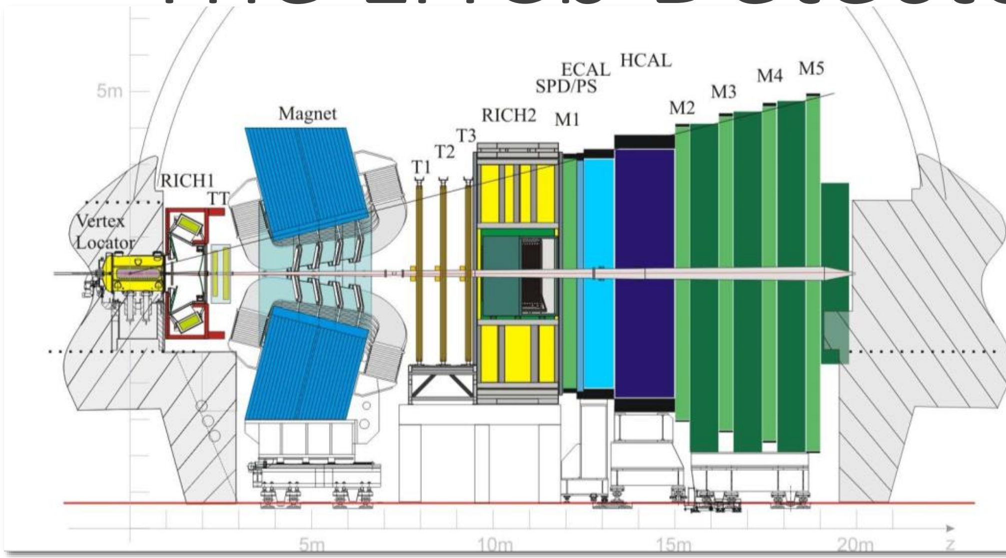
R(D) AND R(D*) MEASUREMENTS AT LHCb – MUONIC TAU CHANNELS

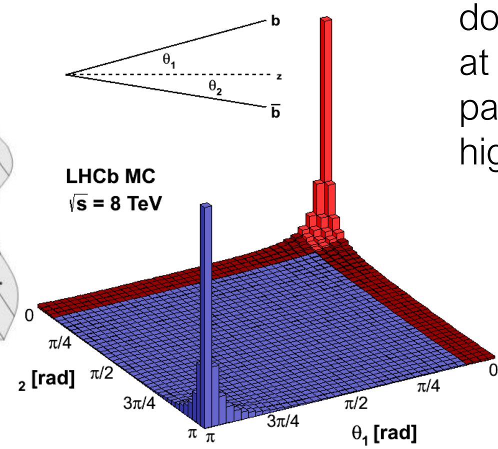
2ND LHCb OPEN SEMITAUONIC WORKSHOP

MONDAY 13 NOVEMBER 2017

BRIAN HAMILTON

The LHCb Detector





b$\bar{b}$ production dominantly at lower p_T: parton CM frame highly boosted

At 7 TeV:
σ_{inel} ~70 mb
$\sigma_{c\bar{c}}$ ~ 6 mb
$\sigma_{b\bar{b}}$ ~ 280 μb

- Focus on forward direction to exploit highly-boosted b quark production in multi-TeV collisions: *cover 27% (25%) of (pair) production while instrumenting < 3% of the solid angle*

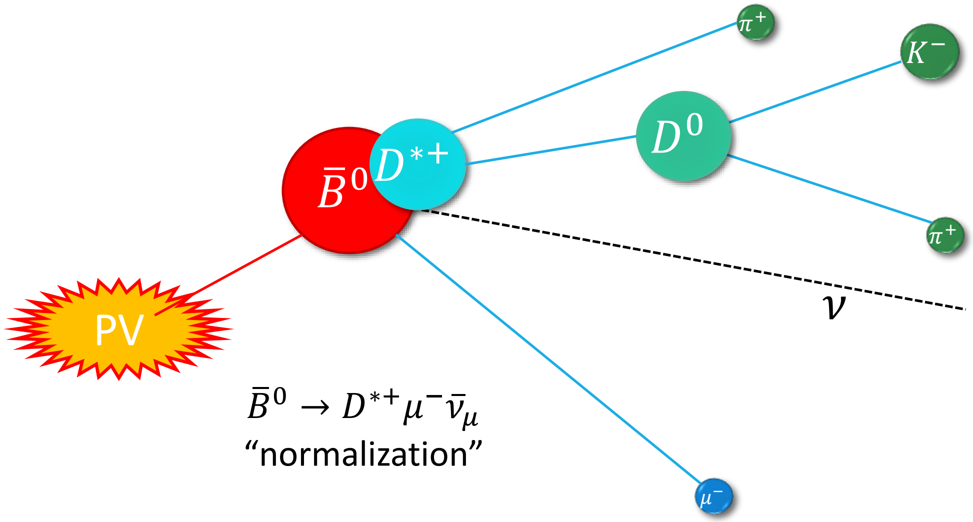
GREAT VALUE!

- Single arm spectrometer optimized for beauty and charm physics at large η:
  - Trigger: ~90% efficient for dimuon channels, ~30% for all-hadronic
  - Tracking: $\sigma_p/p \sim 0.4\%$–0.6% (p from 5 GeV to 100 GeV), $\sigma_{IP} < 20\ \mu m$
  - Vertexing: $\sigma_\tau \sim 45$ fs for $B_s \to J/\psi\phi$
  - PID: 97% μ ID for 1-3% π→μ misID
  - Dipole magnet polarity periodically flipped to change the sign of many reconstruction asymmetries

What we want to measure

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

- At LHCb, stick to muonic mode for denominator
  - Electron modes not strictly impossible, but $e^\pm$ reconstruction is lower efficiency, poorer p_e resolution
    - Both effects largely from Brem.

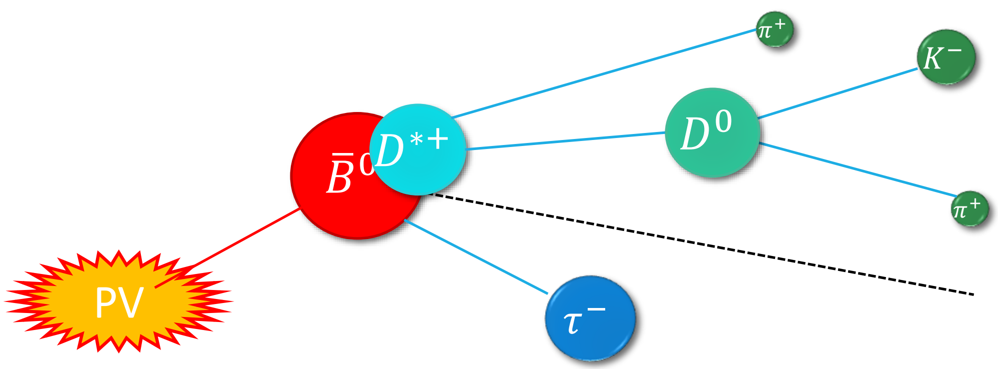


$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$
"normalization"

- Experimentally, we have a menu of options to choose from for reconstructing the tau:

- $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ *This talk*
  - Identical (visible) final state is optimal for cancelling systematic uncertainties in reconstruction
  - Automatic normalization at hadron colliders

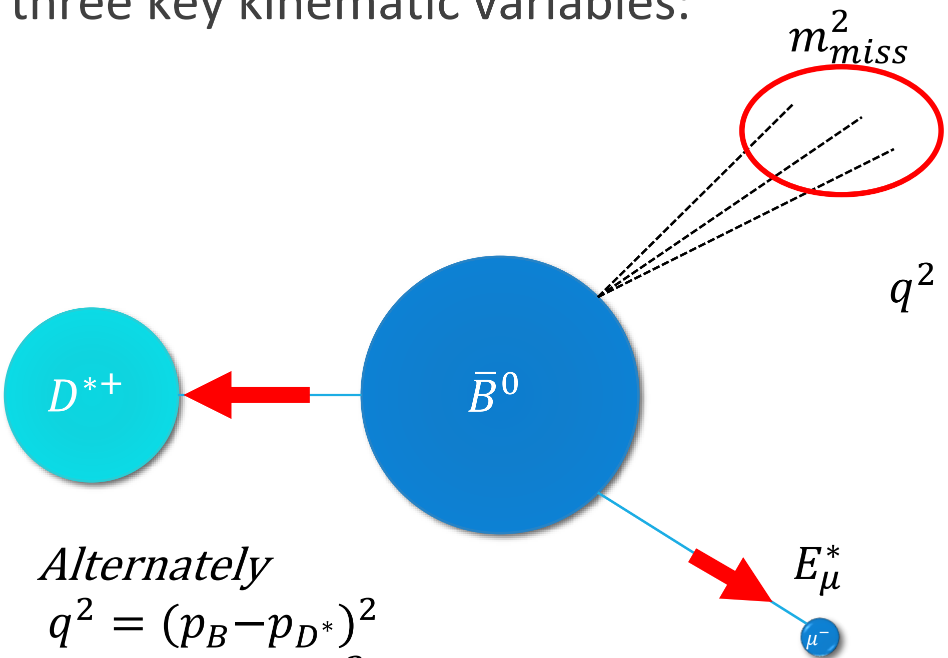
- $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ *Next Talk*
  - Reconstructible tau vertex, but short lifetime makes this hard to exploit in B factories
  - Normalization is difficult: either large systematics from reconstruction of additional tracks or have to measure relative to hadronic B decay



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

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

- In B rest frame, three key kinematic variables:



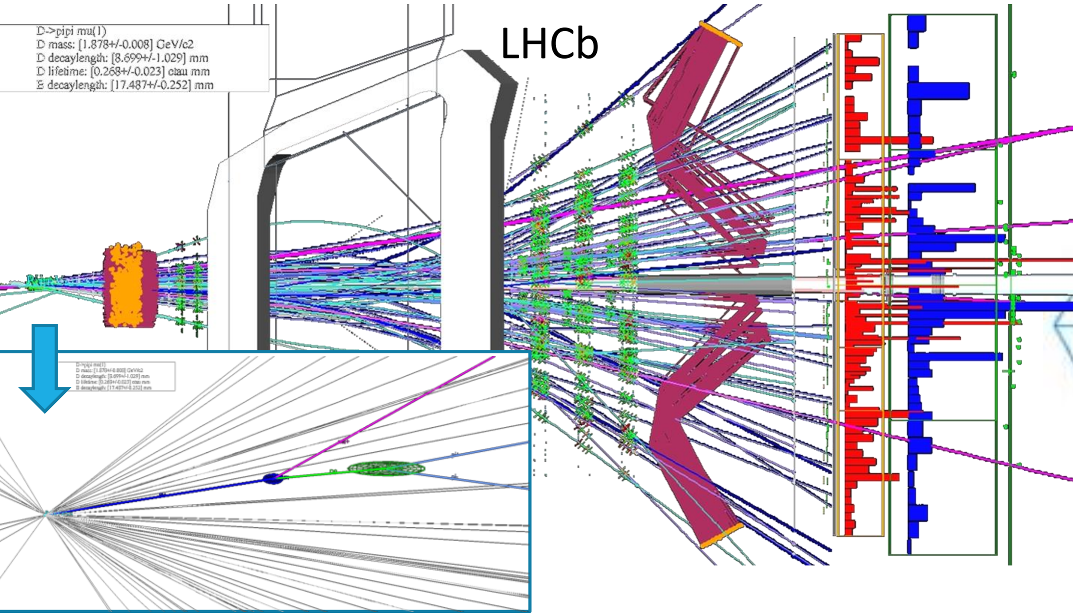
$$q^2 = (p_\ell + p_\nu)^2 = m^2_{W^*}$$

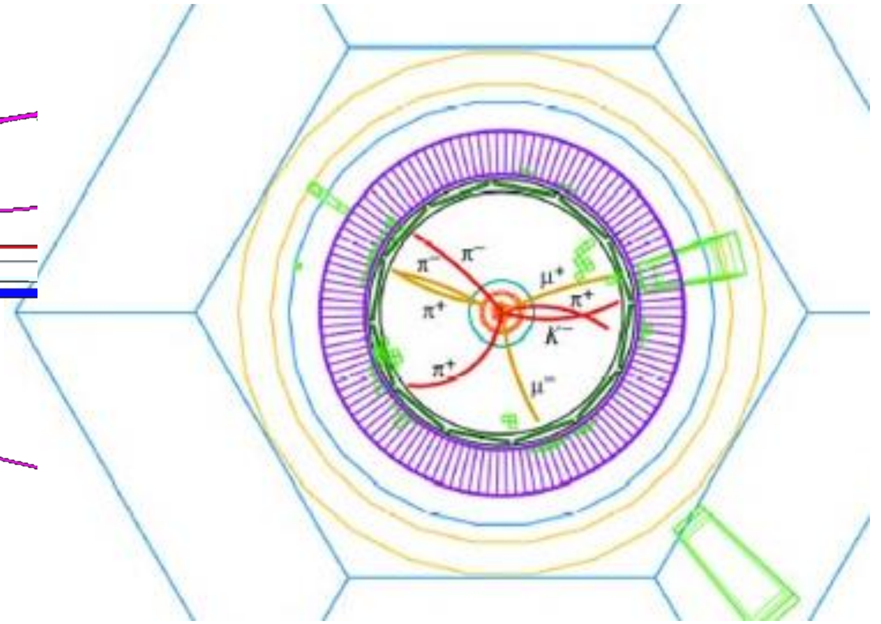
Alternately

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

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

Challenges in LHC data



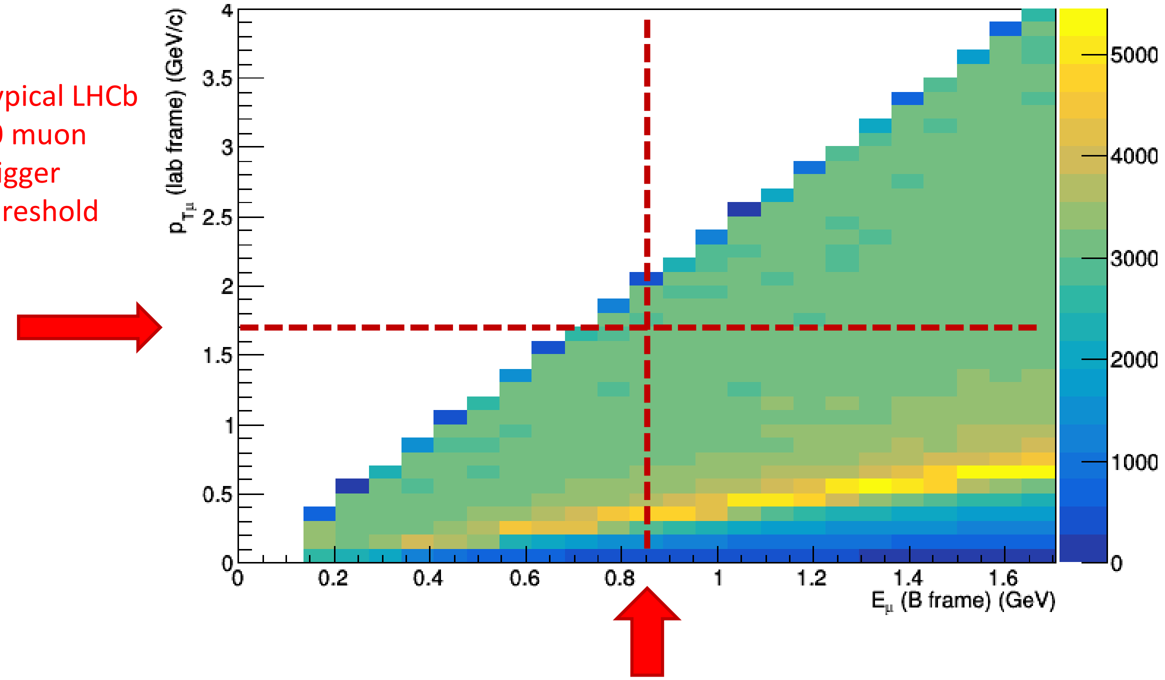


- In hadron collisions, things are not nearly as “nice” as in $\Upsilon(4S)$ decay at the B-factories
  - Unknown CM frame for $gg \to b\bar{b}$ production
  - Lots of additional particles in the event (showering, MPI etc)
  - Inclusive secondary vertex triggers are explicitly biased in missing mass
- Different handles are needed to deal with
  - Missing neutrinos → underconstrained kinematics
  - Partial reconstruction of signal decay →
    Large backgrounds from partially-reconstructed B decays with “missed” final state particles
    (e.g. $\bar{B} \to D^{*+}(n \geq 1\pi)\mu\nu, \bar{B} \to D^{*+}H_c(\to \mu\nu X)X$)

Additional Challenge: low p_T signal

$p_T(B) = 5\ \text{GeV}, \eta(B) = 3.0$

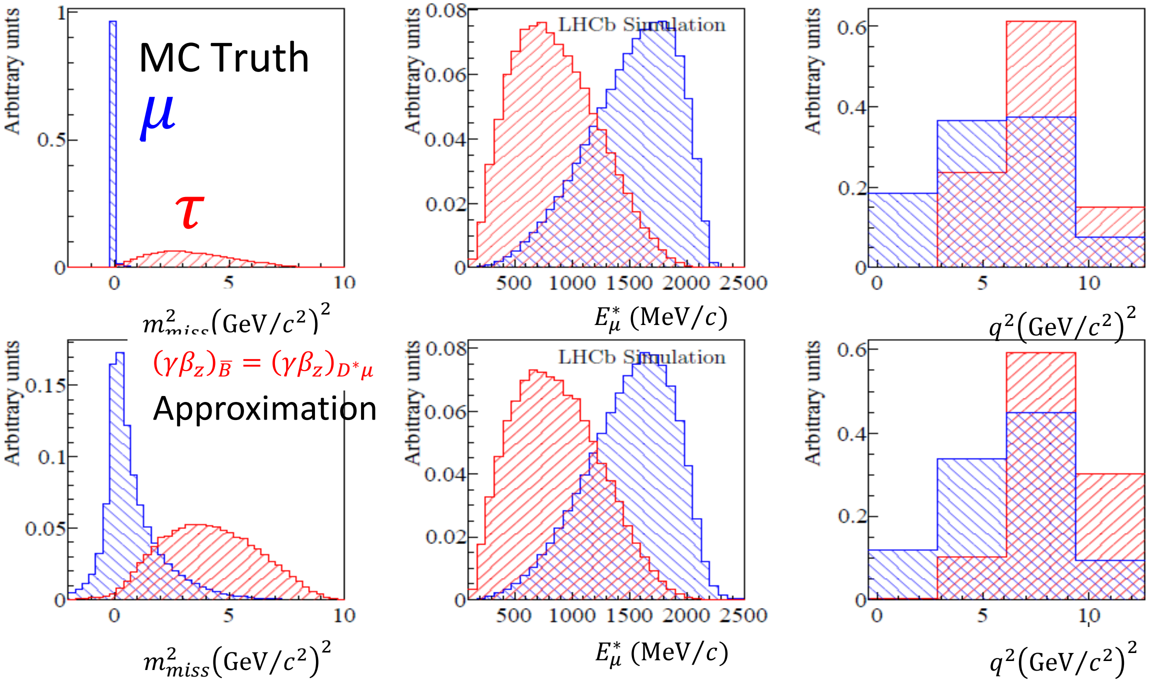
Typical LHCb L0 muon trigger threshold

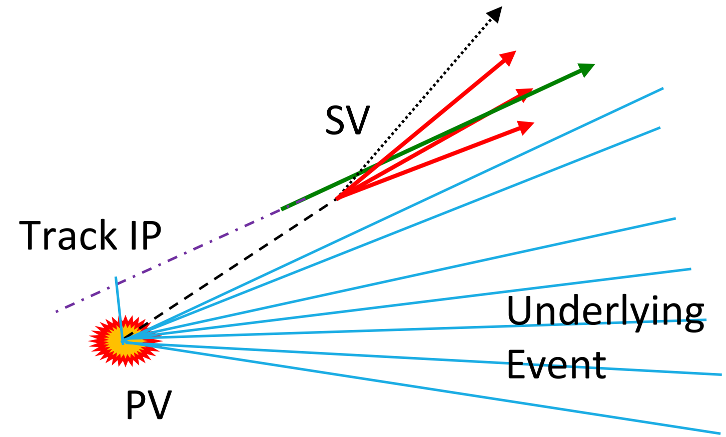


50% of signal below here

- Roughly speaking, average muon p_T in semileptonic decays is proportional to E_ℓ^*
  - Requires independence from harsh L0 muon trigger cuts
    - Rely on HCAL trigger or events tiggered independently of signal
  - Requires PID cuts be loose or custom-calibrated for flat efficiency in PT

Analysis Technique





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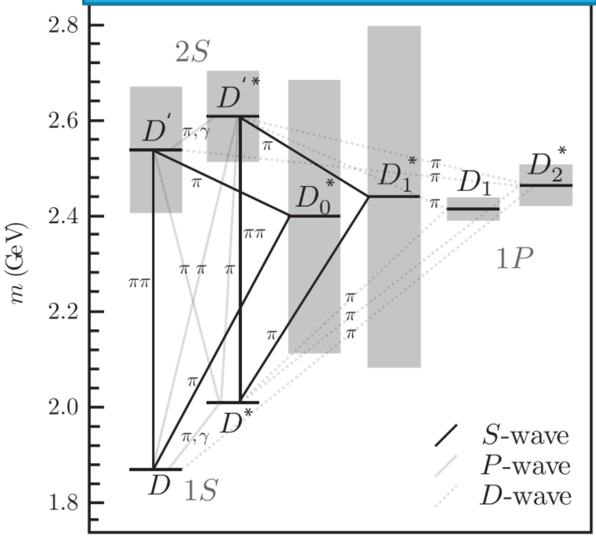
- No information on initial B momentum to reconstruct the discriminating variables
  - Key: Resolution on rest frame variables doesn’t matter much because distributions are broad to begin with -- well-behaved approximation will still preserve differences between signal, normalization and backgrounds

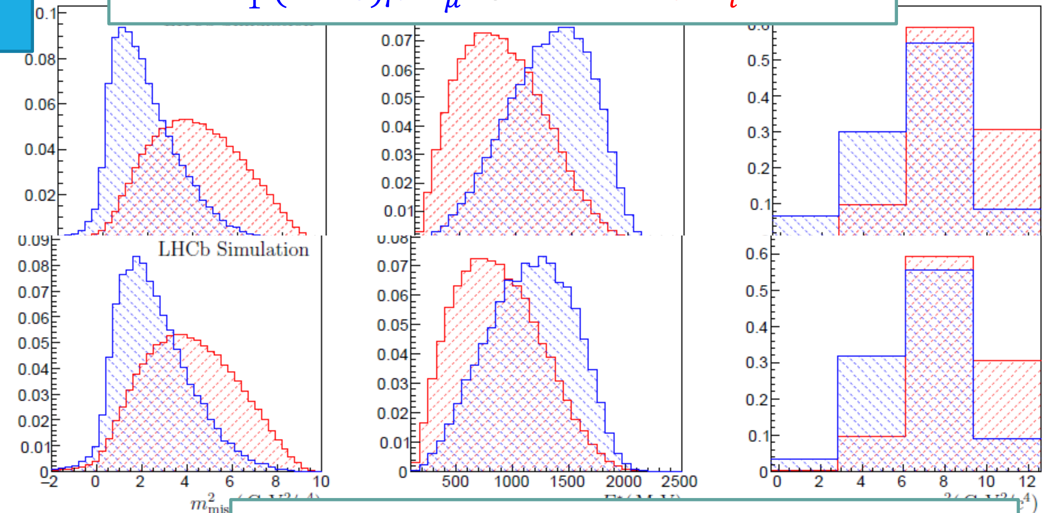
- Make use of superb tracking system to fight huge partially-reconstructed background
  - Scan over every reconstructed track and compare against $D^{*+}\mu^-$ vertex with machine-learning algorithm
  - Allows for cleaner signal sample *and* data control samples enriched in key backgrounds
    - Very important for the lower purity at LHCb vs B factory -- must model these backgrounds *in detail!*

Challenges: Semileptonic Backgrounds

Bernlochner et al, PRD 85 094033 (2012)



$\bar{B}^0 \to D_1^+(2420)\mu^-\bar{\nu}_\mu$ 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 $\approx (2)m_\pi$

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

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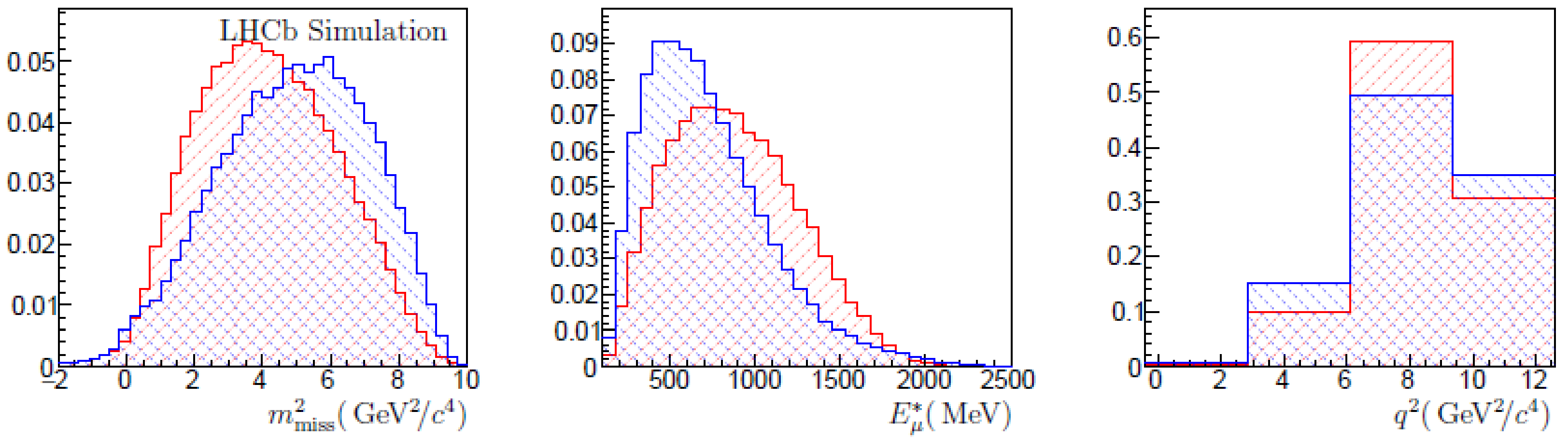
$B \to D^{*+} H_c (\to \mu\nu X') X$ background

- $b \to c\bar{c}q$ 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 $D^* D K (n \geq 0\ \pi)$ 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 $\bar{B}^0 \to D^{*+} \tau^- \nu_\tau$



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Control sample fit projections

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

Used for

$\bar{B} \to D^{**}(1P)\mu\nu$

Form Factors

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

Used to calibrate

$\bar{B} \to D^{*}\pi\pi\mu\nu$

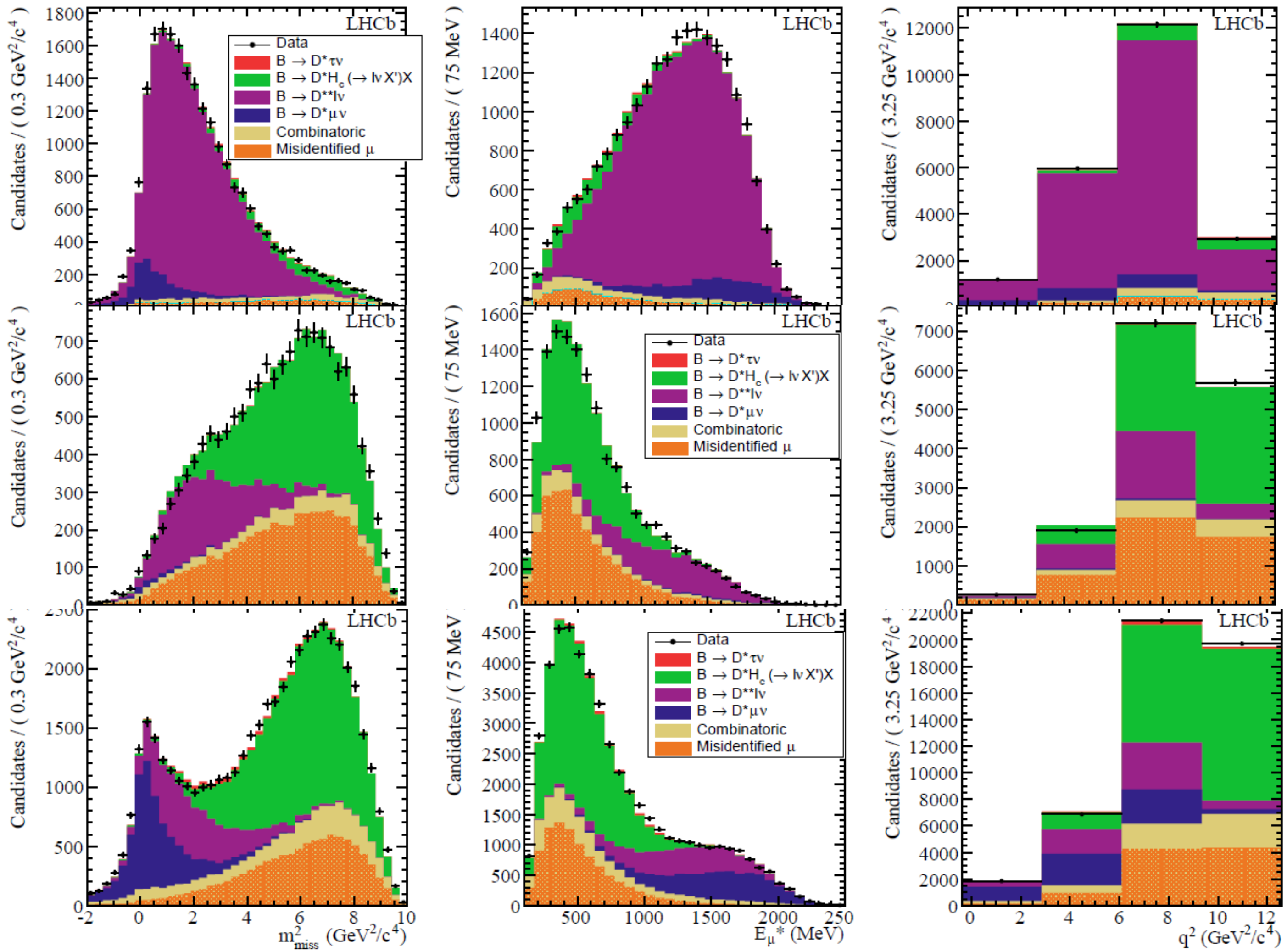
q^2 Shapes

$D^{*+}\mu^-K^{\pm}$

Used to calibrate

$\bar{B} \to D^{*}H_c[\to \mu\nu X]$

Shapes



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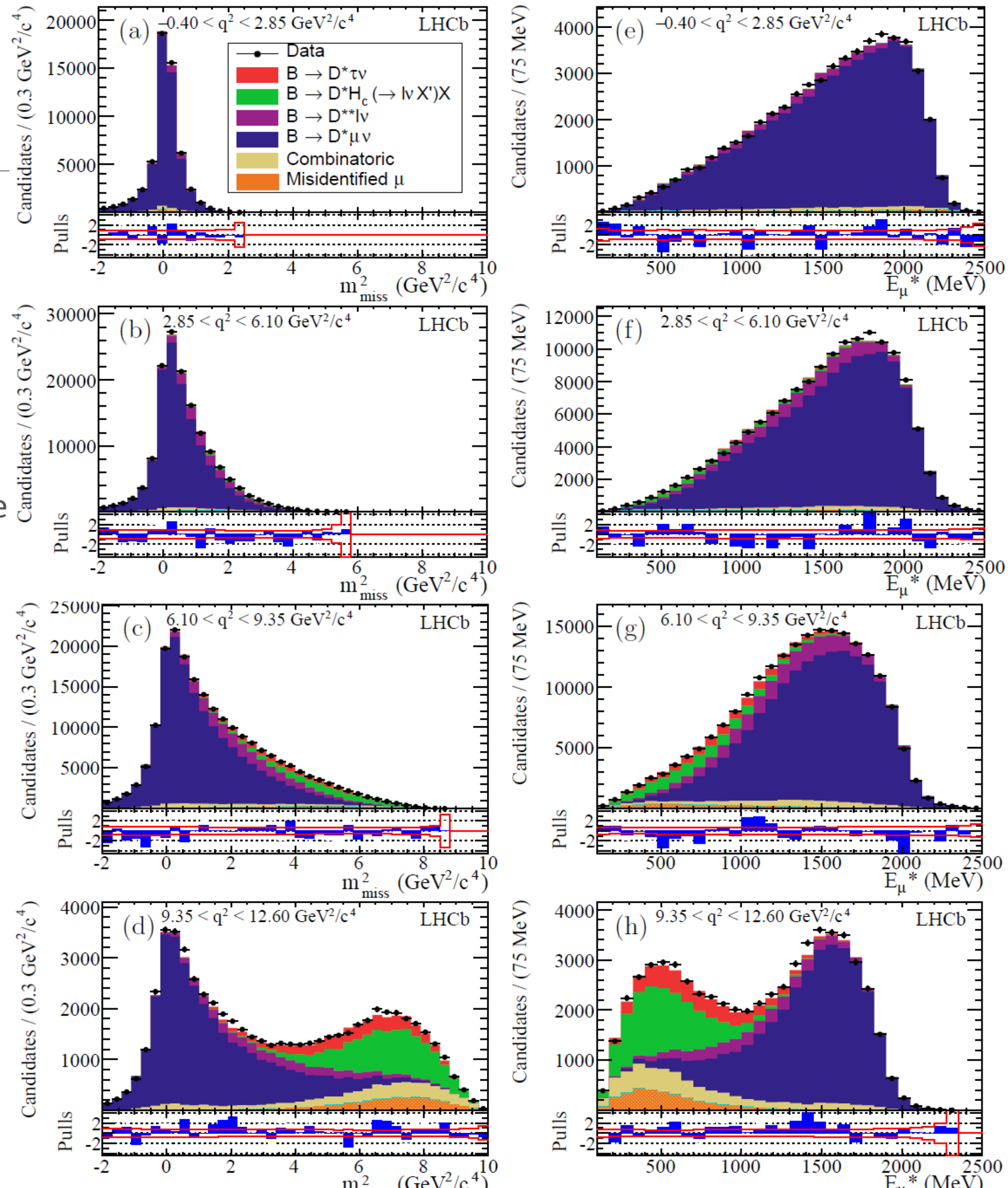
Detailed fit projections

- Projections of (left) m_{miss}^2 and (right) E_μ^* in bins of increasing q^2 from top to bottom
- Full range of q^2 important for verifying modeling of resolution effects
  - Requiring good fit for $D^*\mu\nu$ across the whole spectrum *and* consistency between fitted FFs and HFLAV average -> very strong constraint on simulation resolution & correlations
- Cross check: verify that simulation cocktail at best fit point reproduces data kinematics well
- Final result:
  $R(D^*) = 0.336 \pm 0.027 \pm 0.030$



PRL 115 111803 (2015)

Next steps in LHCb muonic $R(D^{(*)})$

Phase II

$R(D^0)$ vs $R(D^{*+})$ with $D^0 \to K^-\pi^+$ and $\tau \to \mu\bar{\nu}\nu$

$$\frac{B^- \to D^{*0}[\to D^0(\pi^0/\gamma)]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 2.5 \quad \frac{B^0 \to D^{*+}[\to D^0\pi^+_{missing}]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 0.75$$

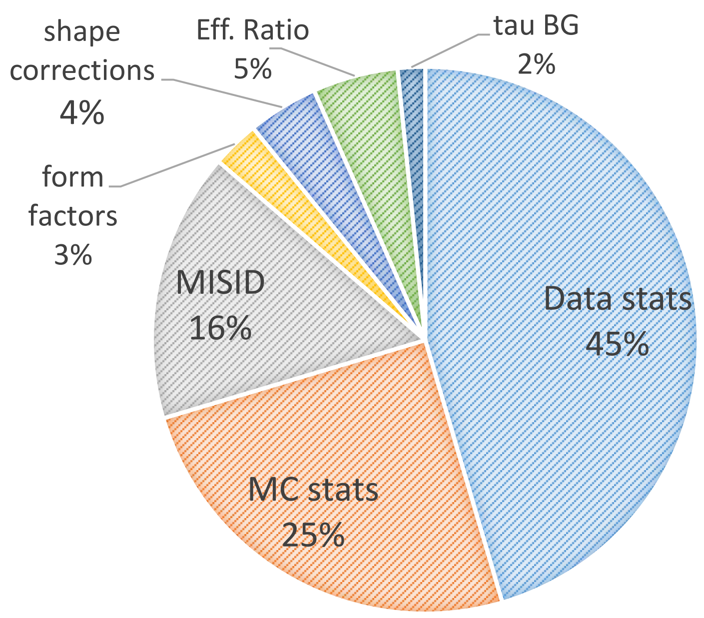
$$\frac{B_s^0 \to D_s^{**+}[\to D^0K^+_{missing}]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 0.06$$

- Muonic $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}$ served as a prototype due to simpler measurement structure, better handles on certain backgrounds

- $B^- \to D^0\tau^-\bar{\nu}$ perfectly possible at LHCb
  - Strategy: simultaneous fit to disjoint $D^0\mu^-$ and $D^{*+}\mu^-$ samples
    - Feed-down from D* always present in $D^0\mu^-$ sample → correlation in R(D) vs R(D*).
      - Simultaneously refitting $D^{*+}\mu^-$ sample helps control this
    - $D^0\mu^-$ sample is 5x larger than $D^{*+}\mu^-$
      - 75% is D* feed down → expect large reduction of statistical error
        - Additional data has more BG, so improvements will be more modest than simple $\sqrt{N_{D^*\tau\nu}}$, but still quite substantial
      - **Challenge:** template fit to such a huge dataset requires very careful evaluation and elimination of data/simulation differences everywhere possible

Improving on R(D*) systematics

Uncertainty breakdown from 2015 measurement:



Contribution of each source to the squared total measurement uncertainty

- Previous result was

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

- Systematic error dominates the pie, but is in turn mostly MC statistical error and uncertainty on the misID background
- Present status:
  - MC/data ratio improved dramatically
  - Improvements in low-momentum PID will dramatically decrease contamination from $h \to \mu$ misID
  - $R(J/\psi)$ analysis has led to better techniques to construct misID shapes
- ALSO: more signal data = more control data!
  - Form factors and shape corrections for backgrounds can be more precisely determined
  - Signal/normalization form factors will also be fitted more precisely

In-progress Run 2 Measurement

THE NEXT GENERATION

$R(D^{+})$ vs $R(D^{*+})$

- Frontline Run2 analysis on $R(D^{(*)})$ from LHCb
  - Why not Run1? No trigger!
    - Run1 analysis piggybacked on loose $D^0 \rightarrow K^-\pi^+$ charm trigger
    - Other (three+ body) Run1 exclusive charm triggers all cut tightly to *remove* charm from beauty
  - For Run2:
    - Dedicated trigger optimized around original R(D*) selection for $D^+ \rightarrow K^-\pi^+\pi^+$ and others (D^0, D_s^+, Λ_c^+)
      - Tests on $D^0 \rightarrow K^-\pi^+$ version showed 60% improvement in signal efficiency compared Run1 trigger strategy

- Other improvements being explored

- Result is expected to be of similar or better precision as existing measurements

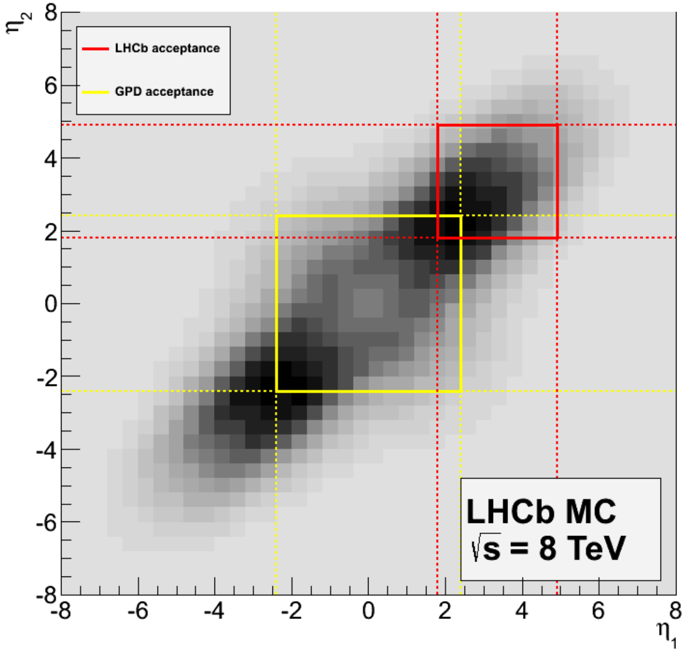
Summary

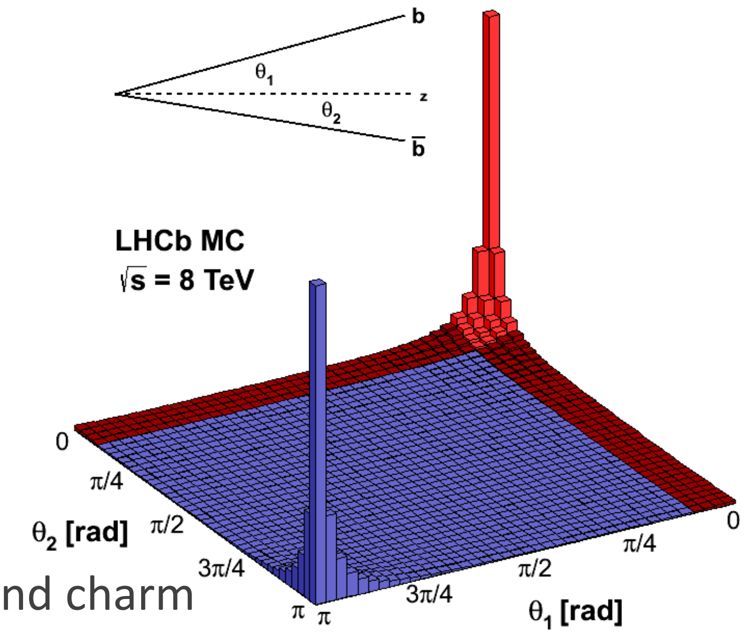
- LHCb is continuing efforts to expand its muonic R(D*) measurement to combined R(D) and R(D*)
  - Efforts underway both for a final/ultimate Run1 measurement in $D^0 \to K^- \pi^+$
    - Expecting large improvements in R(D*) in addition to adding R(D)
  - Run2 efforts underway using $D^+ \to K^- \pi^+ \pi^+$

- Other semitauonic measurements using muonic taus are also in progress – see other talks this workshop!

Backup

Heavy Flavor at LHC



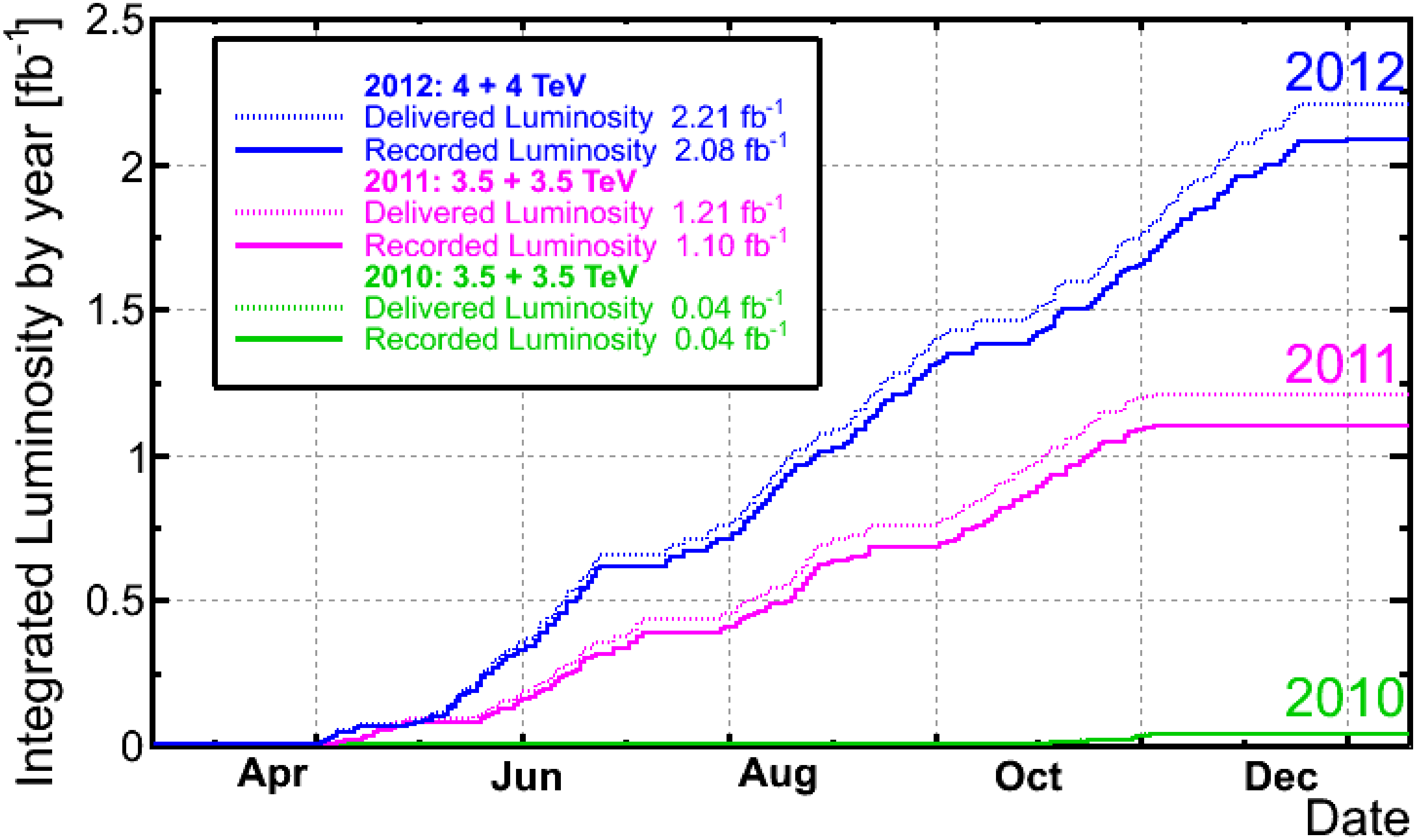


- LHC collisions produce copious amounts of beauty and charm
  - At 7 TeV: $\sigma_{c\bar{c}}$ ~ 6 mb
    $\sigma_{b\bar{b}}$ ~ 280 μb
  - Production dominantly occurs at high η with highly-boosted CM frame

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

- Alternate approach: focus on forward direction: cover 27% (25%) of (pair) production while instrumenting < 3% of the solid angle

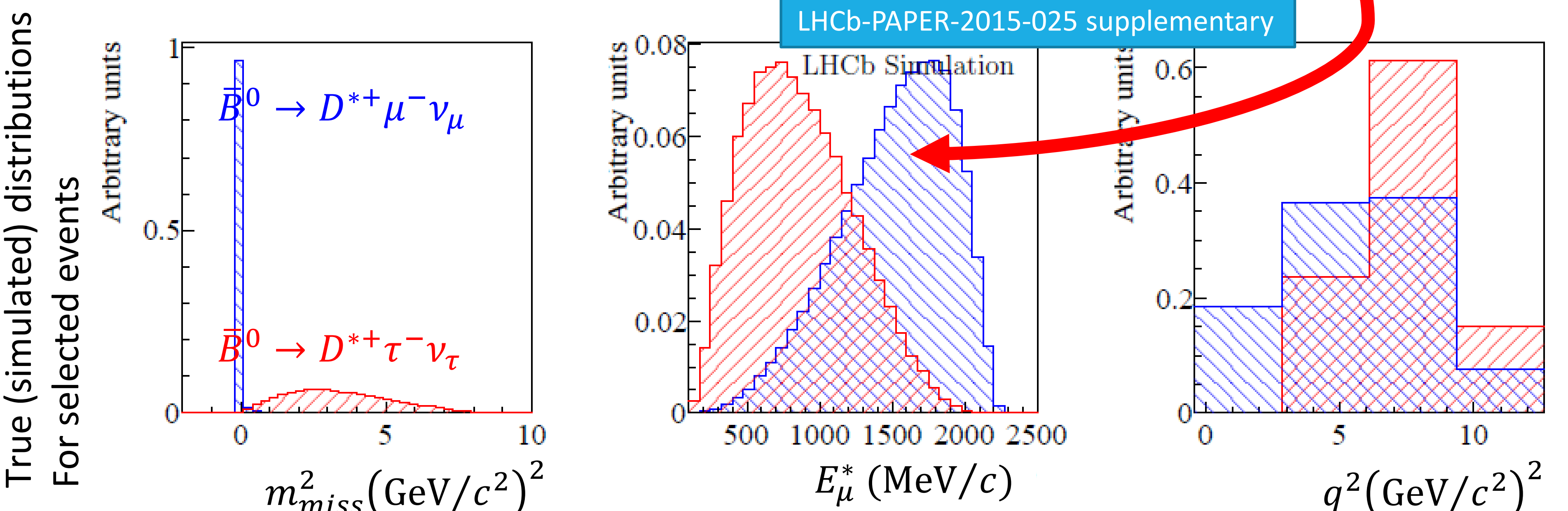
Run 1 Dataset



- >90% data taking efficiency with >99% of collected data good for analyses
- Lumi collected:
  $1\ fb^{-1}$ @ 7 TeV
  $2\ fb^{-1}$ @ 8 TeV

Rest-frame kinematics at LHCb

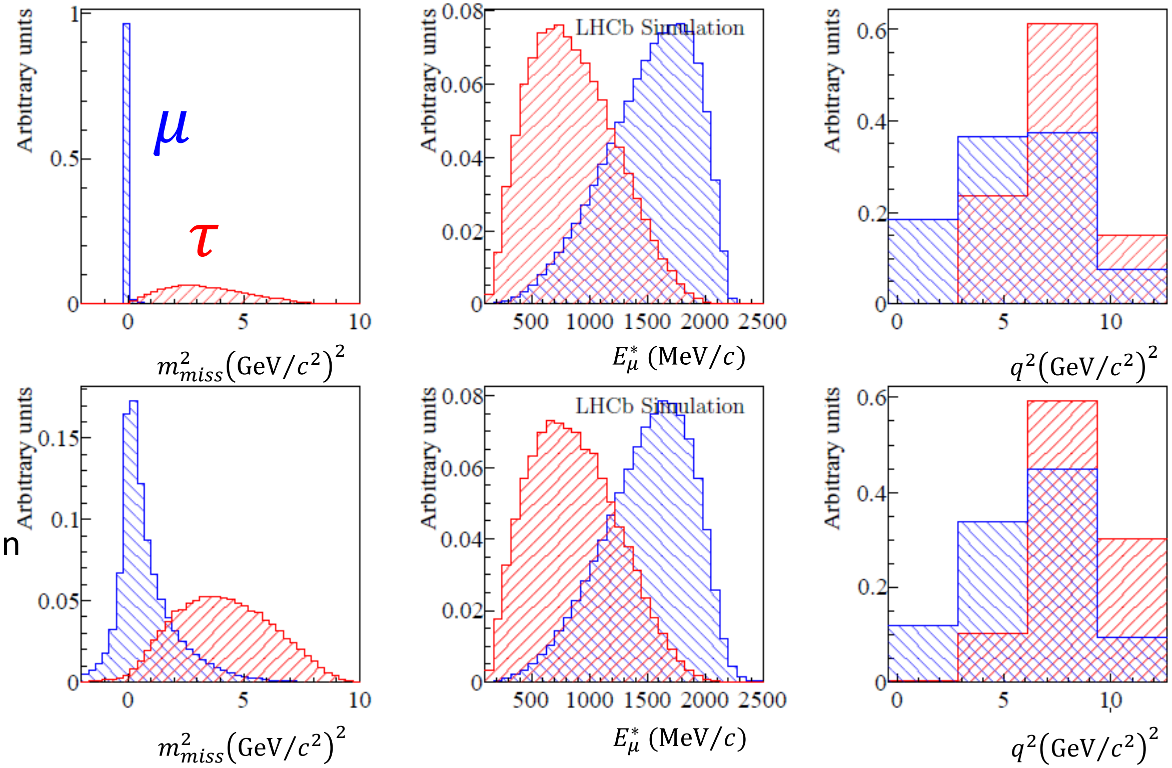
- How to compute the rest frame of the B in hadron collisions?
  - B flight direction is well-measured, but only provides enough constraints (with B mass) to solve for B momentum with single missing particle
    - Even then, 2-fold ambiguity remains
    - Exact solution impossible without more information
  - Important observation: resolution on rest frame variables not so critical because distributions are broad to begin with
    - well-behaved approximation will still preserve differences between signal, normalization and backgrounds



Rest frame approximation at LHCb

MC Truth

Our Approximation



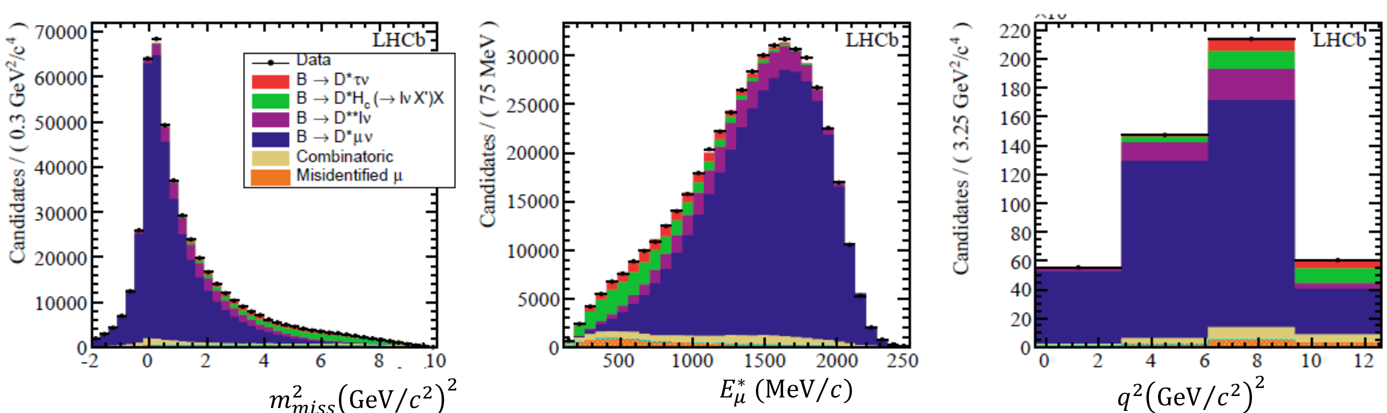
- Resolution on rest frame variables doesn't matter much because distributions are broad to begin with
  - A well-behaved approximation will still preserve differences between signal, normalization and backgrounds
  - Take $(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu} \implies (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$
- 18% resolution on B momentum approximation gives excellent shapes to use for fit

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

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



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Efficiency Ratio

From fit

Known (~17%)

$$R(D^*) = \frac{N(\bar{B}^0 \to D^{*+}\tau^-(\to \mu^-\bar{\nu}\nu)\bar{\nu})}{N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu})} \times \frac{1}{\mathcal{B}(\tau^- \to \mu^-\bar{\nu}\nu)} \times \frac{\epsilon_n}{\epsilon_s}$$

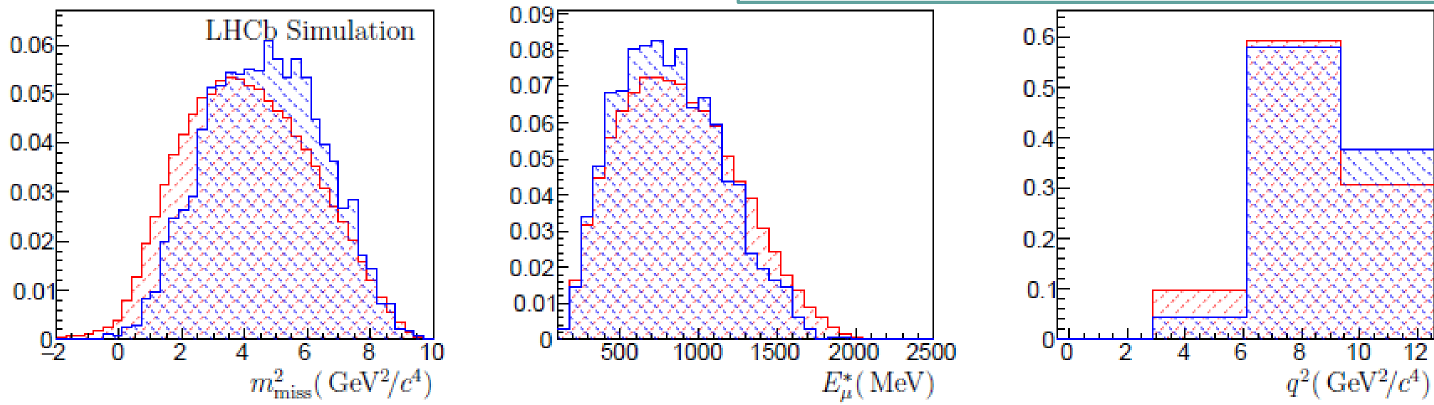
Computed in simulation (with corrections)

$$\frac{\epsilon_s}{\epsilon_n} = (77.6 \pm 1.4)\%$$

Deviation from 100% due to τ flight and lower Muon ID efficiency at low p_T

Tau backgrounds

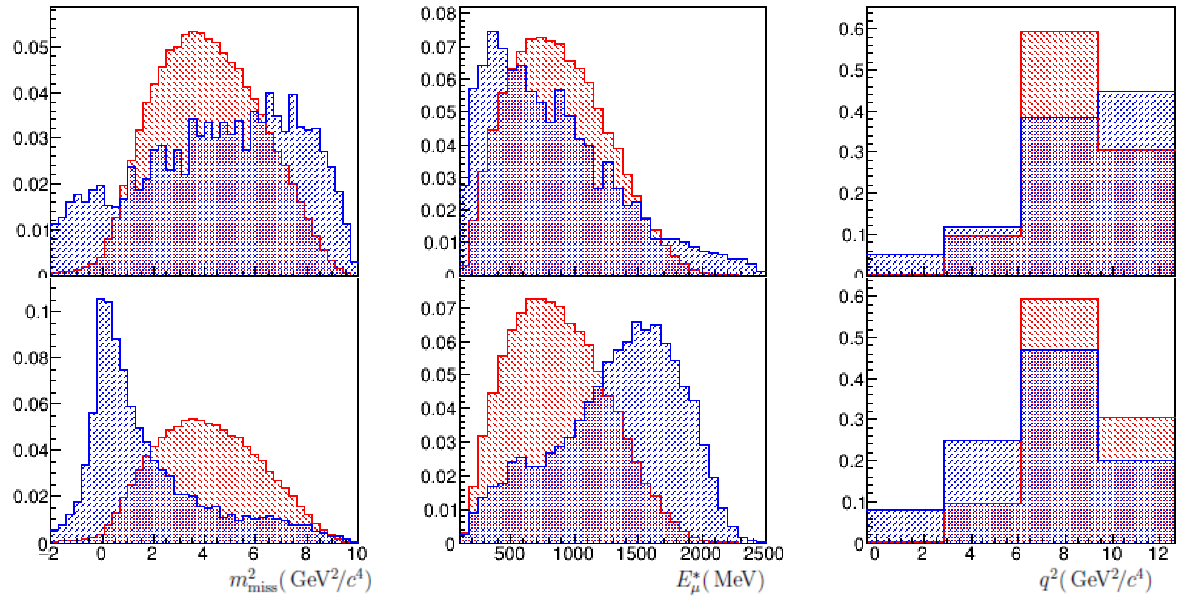
$\bar{B}^0 \to D_2^{*+}(2460)\tau^-\bar{\nu}_\tau$ vs $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$



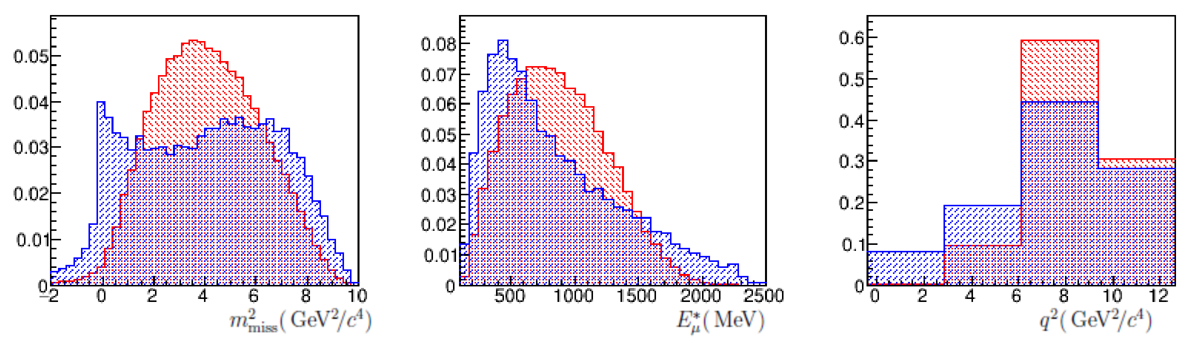
- All backgrounds with real $\tau \to \mu\bar{\nu}\nu$ decays are an order of magnitude (at least) smaller than the signal
  - Background contributions from $\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$ are considered to be fixed relative to the corresponding decay modes to muons
    - Very small component,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

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

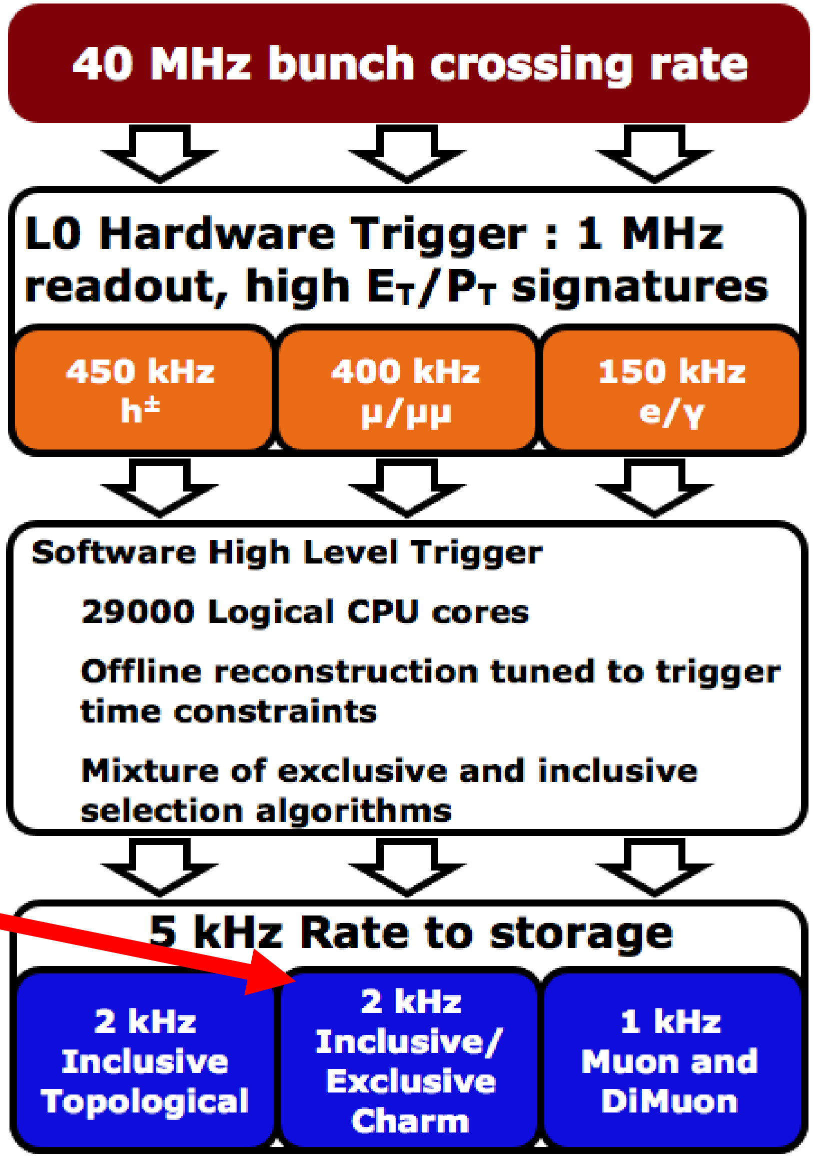


Triggering

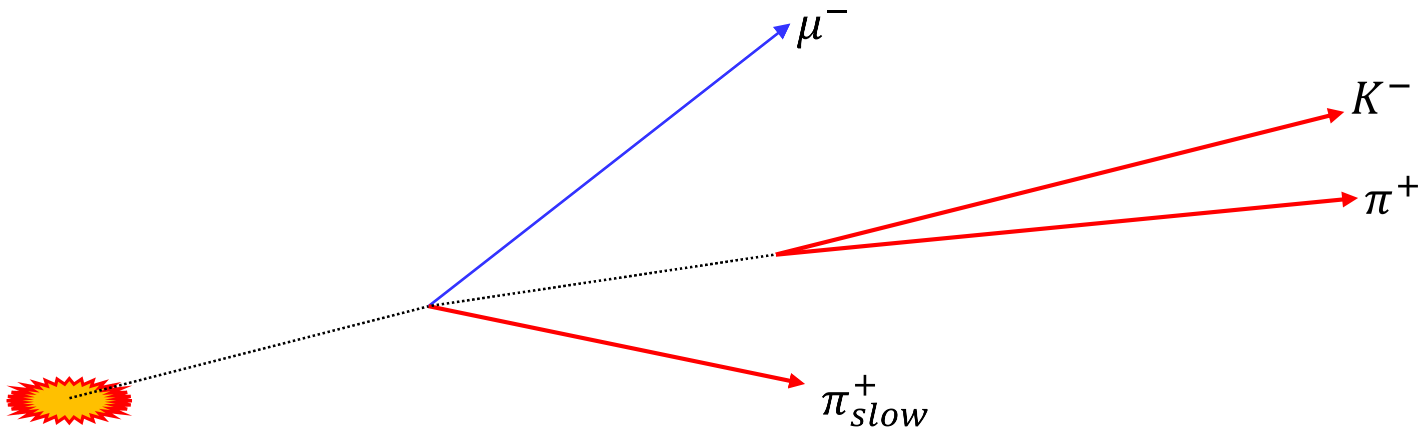
Performance paper:
JINST 8 P04022 (2013)

- Large cross section for heavy flavor production means a robust triggering system is needed
  - Triggering inclusively as possible is *essential* in order to not limit the physics program
  - Hardware trigger relies on muon and calorimetery
  - Software high-level trigger performs full event reconstruction for all tracks above 300 MeV of p_T

- For this measurement:
  - Trigger signal and normalization through the exclusive charm trigger path in software
    - Moderately high p_T $D^0 \rightarrow K^-\pi^+$ with well-separated vertex that loosely points to a PV in the event
  - No hardware muon trigger requirement



Event Selection



- Combine $D^0 \to K^-\pi^+$ candidate passing charm trigger with μ^- and π^+_{slow}
  - Require $D^0 \to K^-\pi^+$ decay vertex well-separated from PV
  - Require $\mu^-, K^-\pi^+$all to have significant impact parameter with respect to PV
  - Remove prompt charm background with impact parameter requirements on $D^0 \to K^-\pi^+$ (main background killed by full event reco at B-factories)