LHCb-PAPER-2022-039 (in preparation)

Joint Measurement of $R(D)$ $vs.$ $R(D^*)$ using $\tau \to \mu\nu\bar{\nu}$ at LHCb

Implications of LHCb measurements and future prospects

Wednesday 19 October 2022

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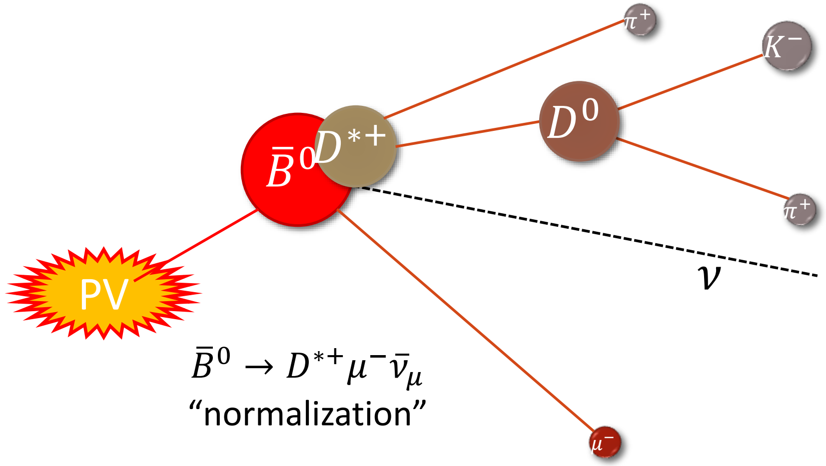
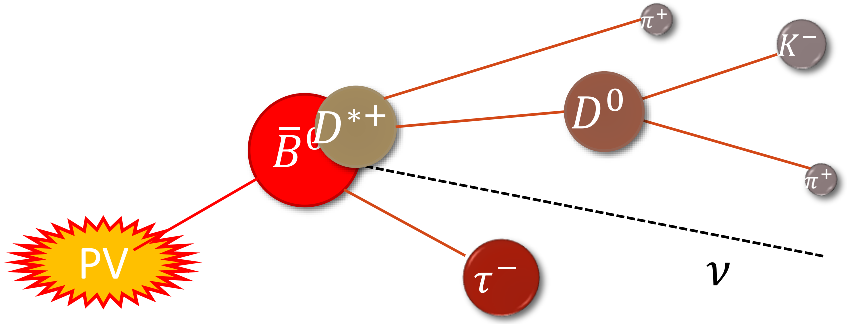
University of Maryland/LHCb

LFU in Semileptonic B Decays

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



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



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

- Theoretically clean due to substantial cancellation of form factor uncertainty
  - Helicity-suppressed amplitudes as well as the FFs in the low q^2 normalization region don't cancel
- $\tau^- \rightarrow \mu^-\bar{\nu}_\ell\nu_\tau$ submode
  - Direct normalization from identical (visible) final state
  - Must disentangle from $\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu$ in fit
- $\tau^- \rightarrow \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ submode
  - Clear signature at LHCb: higher signal purity, more kinematic constraints
  - Reliant on external measurements to get back R(D*)
- Challenges: missing neutrinos
  - Don't know full momentum -> unknown rest frame
  - Large partially-reconstructed B backgrounds

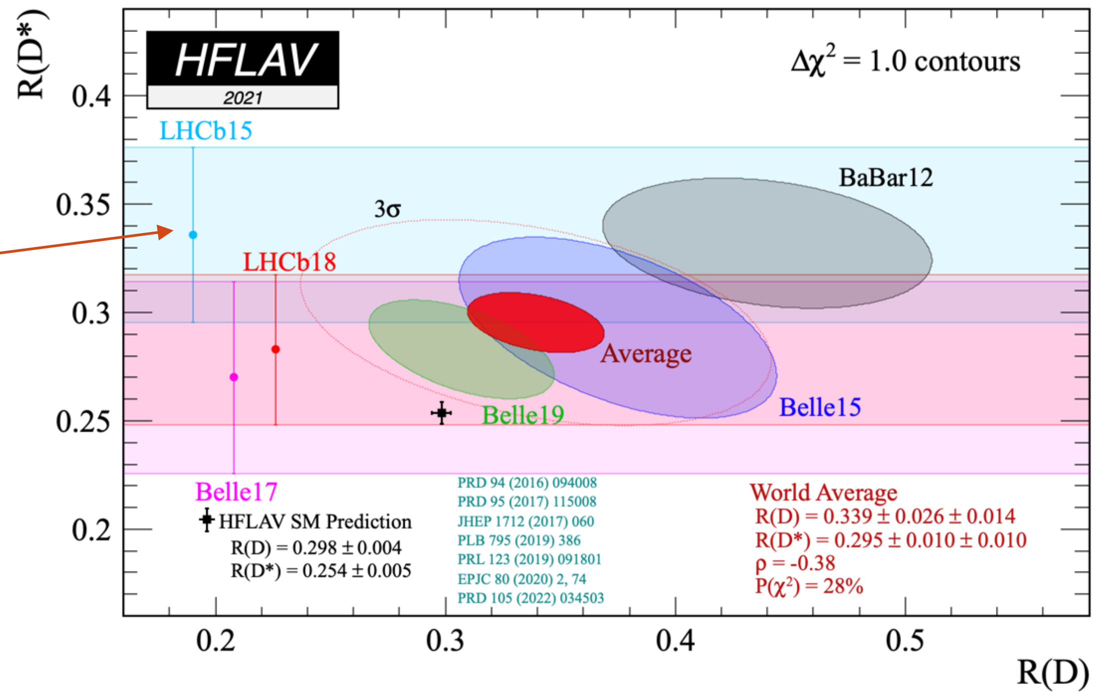
Background

- Situation with $\bar{B} \to X_c \tau \nu$ ("semitauonic") decays evolving year by year

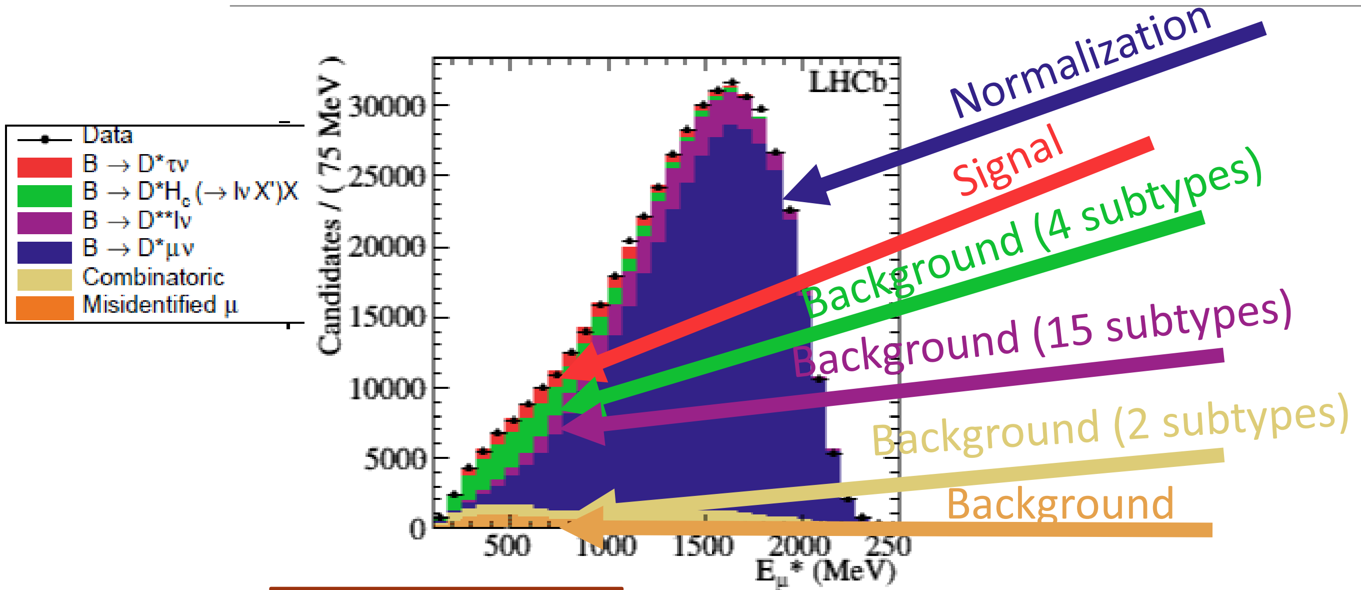
- Two Run-1 measurements of R(D*) from LHCb so far
  - $\tau^- \to \mu^- \nu \bar{\nu}$ and $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu$

- 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
  - $D^{*+} \mu^-$ same data sample (+ new tricks) as 2015 -> old measurement to be superseded
  - Pathfinder analysis on Run1
    - Procedure ready for larger datasets without significant new machinery

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



Challenges



PRL 115 (2015) 111803

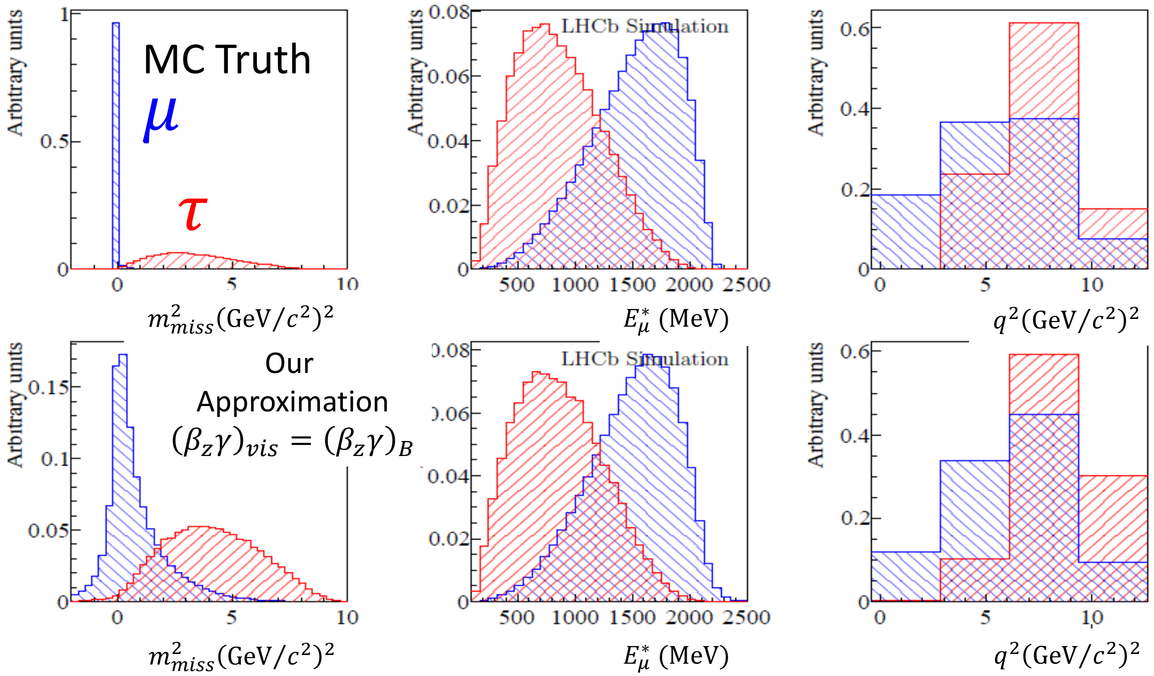
D^* feed-down after isolation, veto

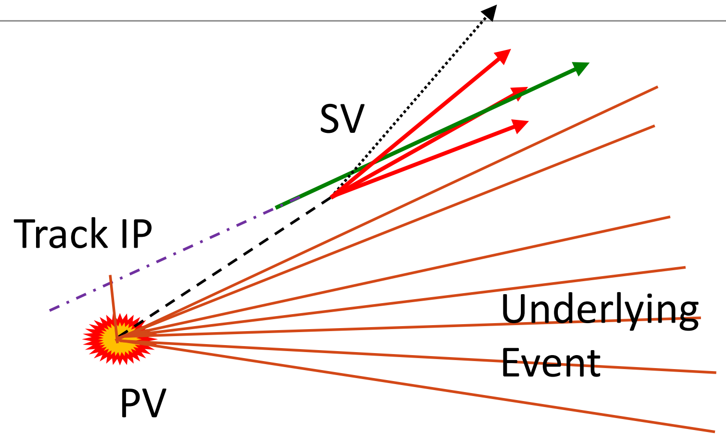
$$\frac{B^- \to D^{*0}[\to D^0(\pi^0/\gamma)]\mu\bar{\nu}}{B^- \to D^0\mu\bar{\nu}} \approx 2.5$$

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

- 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
- $B^- \to D^0\tau^-\bar{\nu}$ background structure much more complicated
  - $\bar{B} \to D^{*0}\mu X$ always present in $D^0\mu^-$ sample (75% of the sample!)
  - Three separate "signal" categories all kinematically similar!
- $D^0\mu^-$ sample is 5x larger than $D^{*+}\mu^-$
  - Already as big a jump as Run1->Run2 for many analyses

LHCb Technique





LHCb-PAPER-2015-025 supplemental

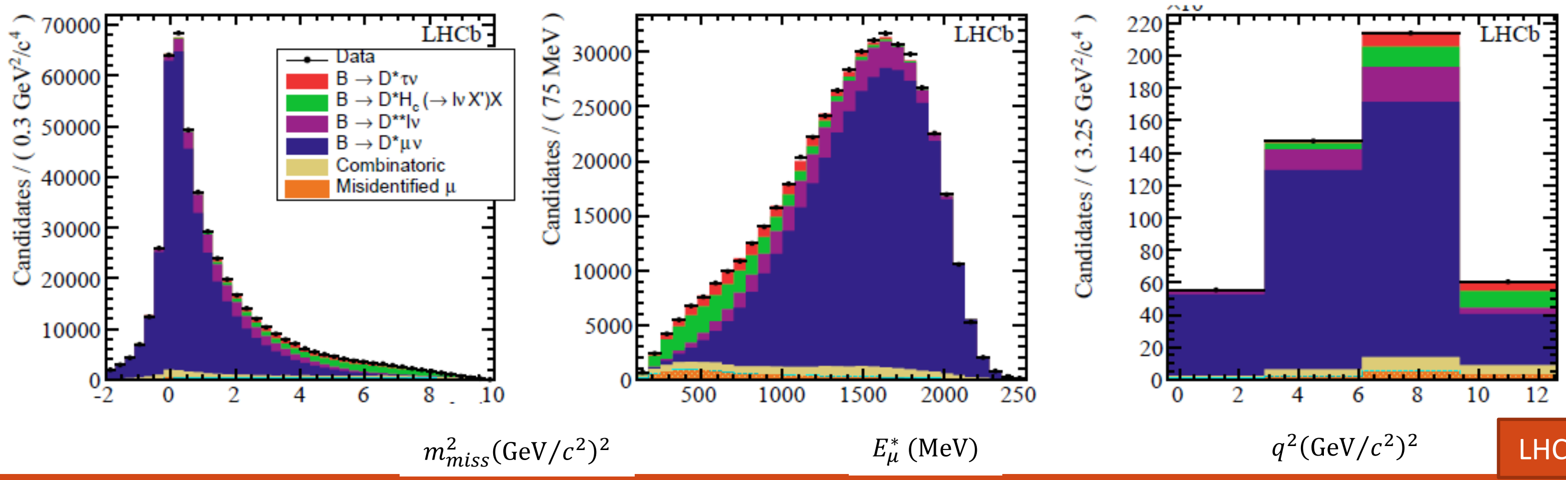
- No information on initial B momentum to reconstruct the discriminating variables
  - Key: Resolution on rest frame variables doesn't matter much because distributions are broad to begin with -- well-behaved approximation will still preserve differences for fit
  - Approximation + knowledge of direction 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

1 EXTRA TRACKS

Fitting the data

- Using rest frame approximation, construct 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
  - Templates are functions of any relevant model parameters via interpolation between histograms generated with different fixed values of those parameters

- 8-way simultaneous maximum-likelihood fit to (2x) isolated signal regions, (2x3x) anti-isolated control regions
  - Shape parameters shared, yields independent in each sample



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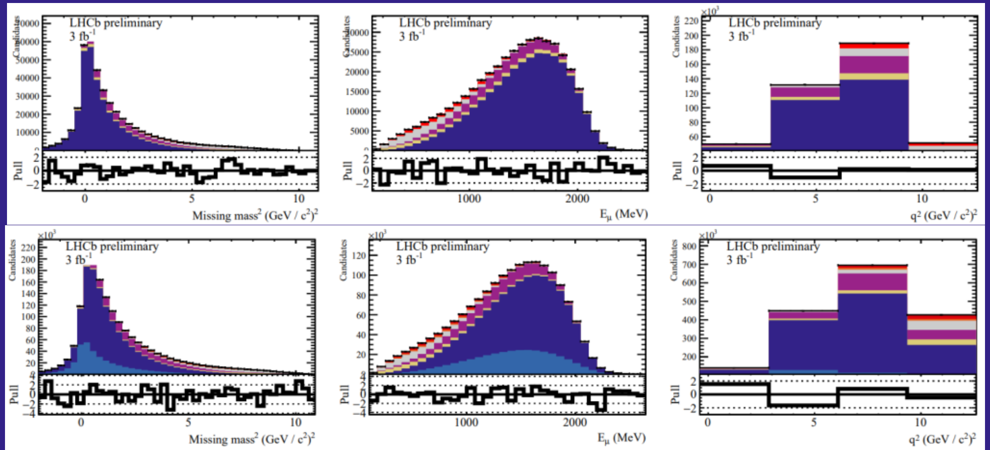
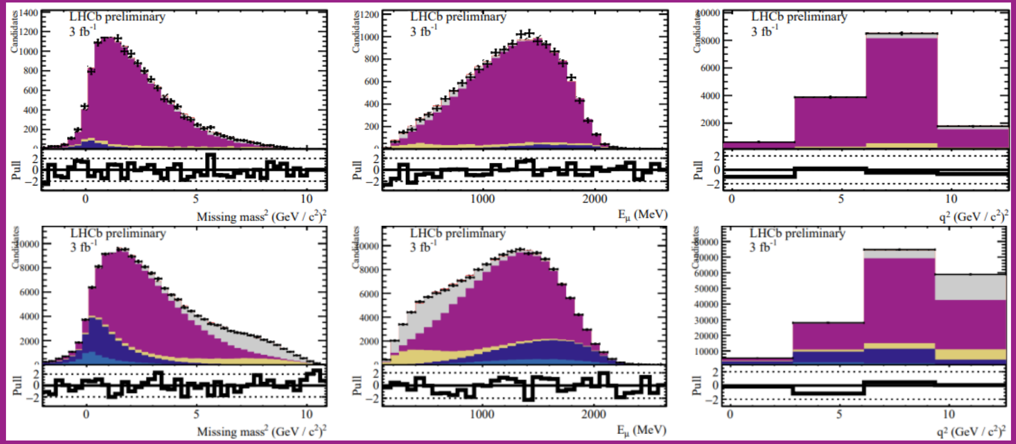
Isolation Fit Categories

Signal - ISO



$D^{(*)}\mu + \pi - 1\text{OS}$



- $B \to D^0 \mu \nu$
- $B \to D^{*0} \mu \nu$
- $B \to D^{*+} \mu \nu$
- Comb. + Fake
- $B \to D^{**} \mu \nu$
- $B \to D^0$ D X
- $B \to D \tau \nu$
- $B \to D^* \tau \nu$
- Template stats

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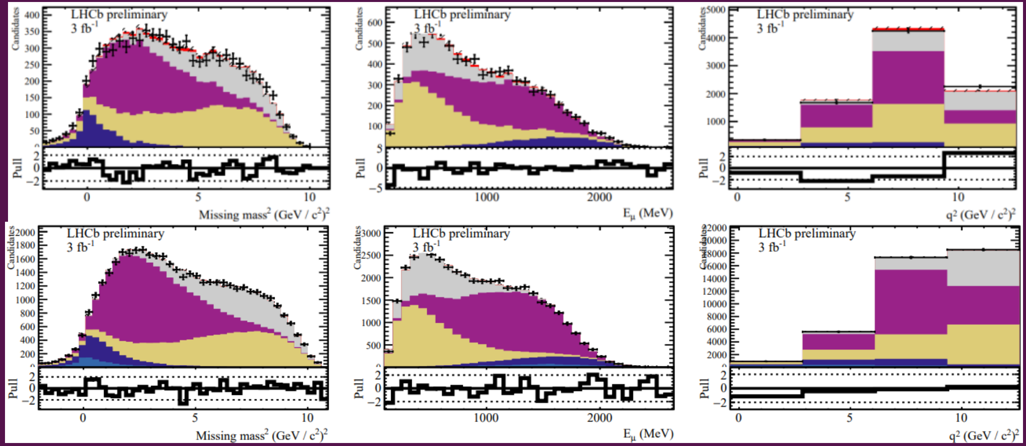
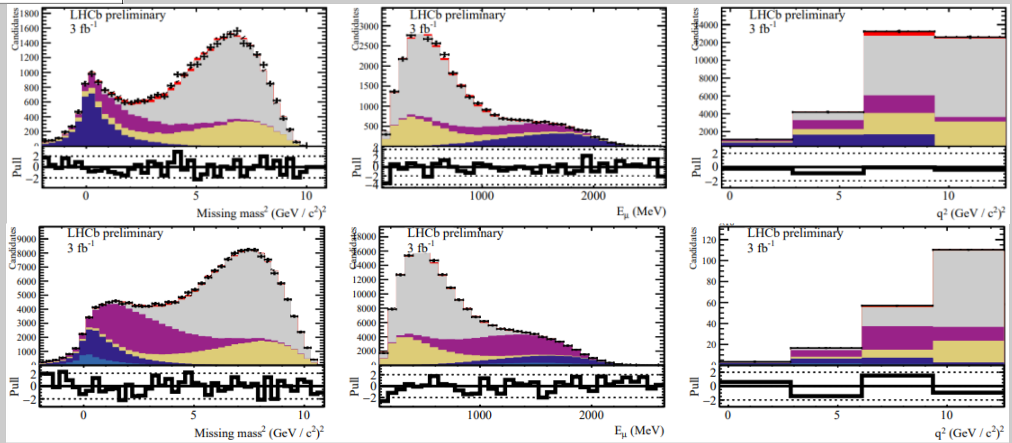
$D^{(*)}\mu^- + \pi^-\pi^+ - 2\text{OS}$



$D^{(*)}\mu + K(X)$ – “DD”



New Technology

New technology: data/simulation corrections

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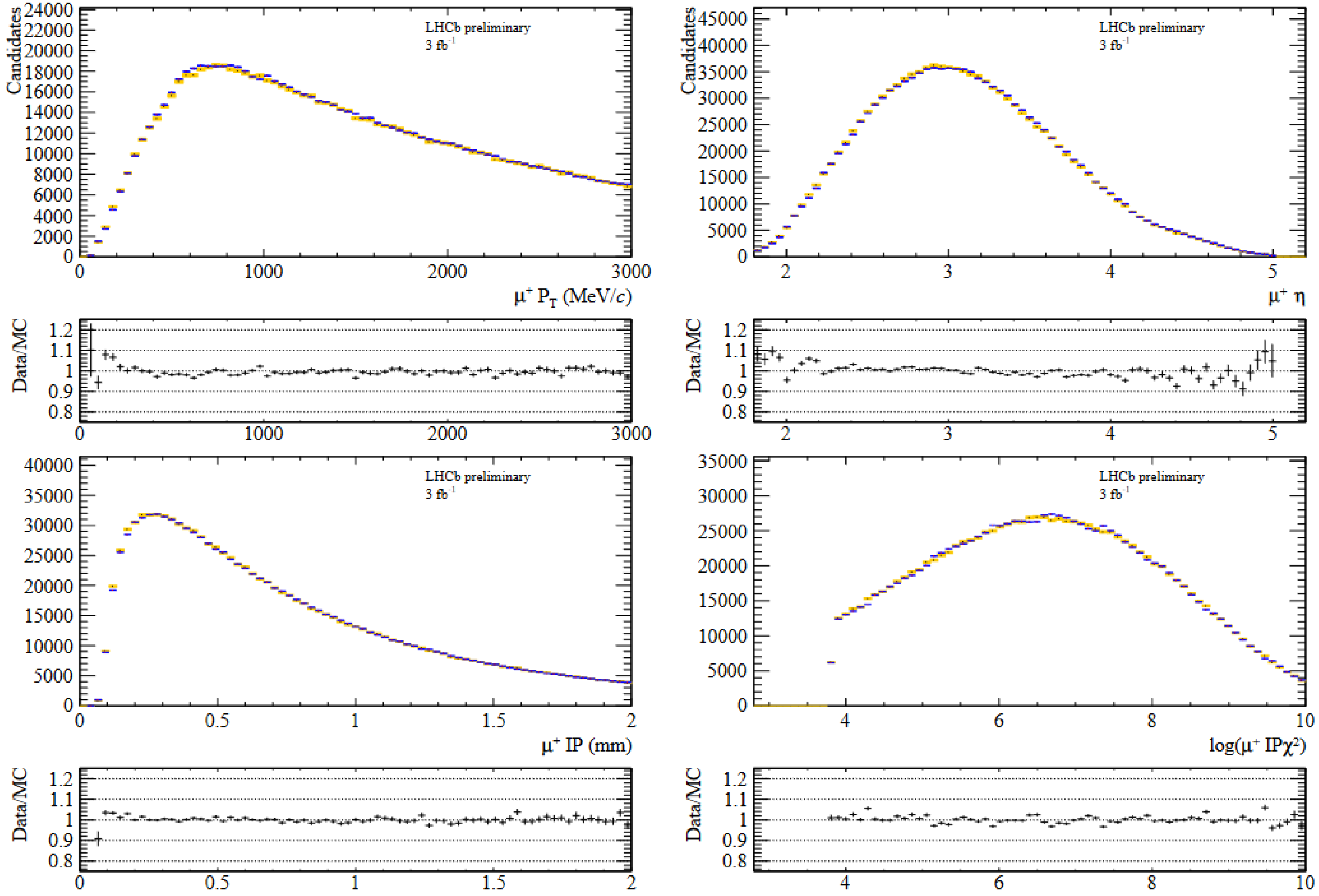
- New Data/MC correction recipe:
  - B hadron kinematics correction from $J/\psi K$ control samples
  - Final correction from normalization-rich isolated data

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

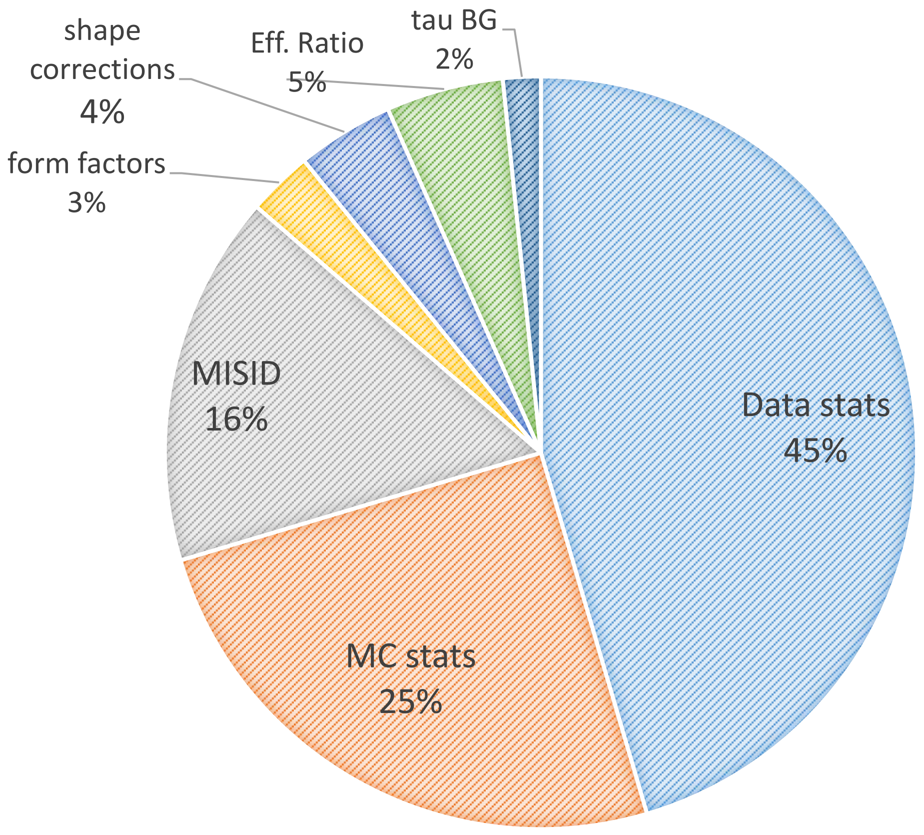


New Technology: misID

- Two-prong approach to reduce systematic from hadron to muon misidentification ("misID background")
  - Reduce contamination
  - Improve modeling

- Dedicated multivariate selector trained using uBoost for flatness in muon P/PT
  - ANN PID tends to learn PT bias in training samples and strongly reject low-PT candidates (our signal!)
  - Rapidly-varying PID efficiencies difficult to model with finite control samples
  - Rejects 50% of background retained by the 2015 muon PID

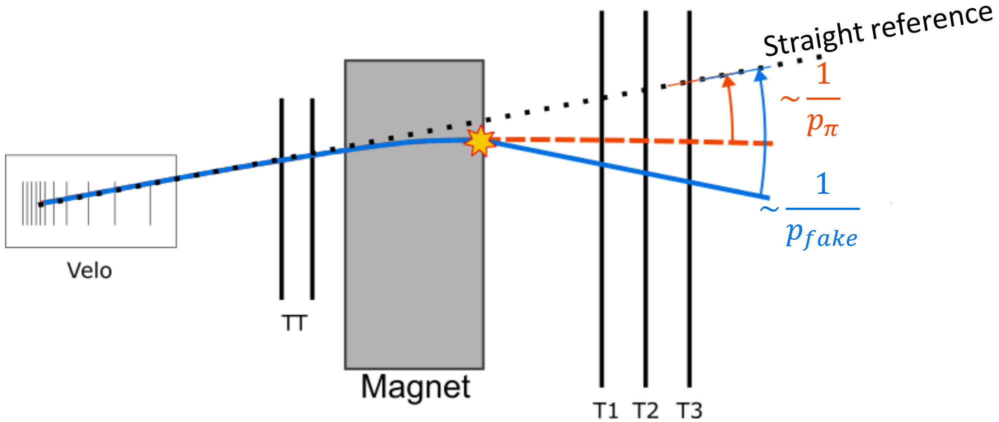
- "Waste not want not" – use the rejected data to study this background



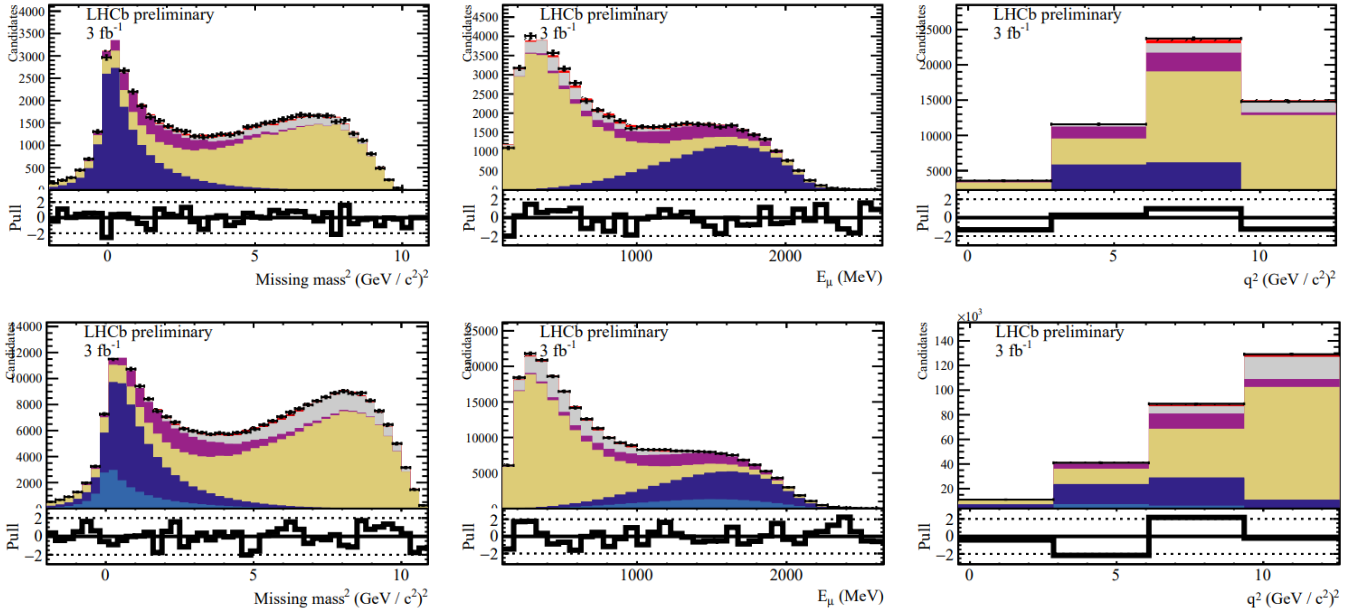
2015 Measurement uncertainty budget (squared contributions)

New Technology: misID

- MisID background modelled with improved data-driven approaches using MUON-vetoed control data
  - Compute per-track weight combining known $h \to \mu$ misID fake rates $(h = \pi, K, p, e, \text{fake})$ with probability $P(h)$ for each species
  - New techniques combine statistical unfolding with per-track PID classification to get best estimate of $P(h)$
- Add decay-in-flight effect on "muon" momentum resolution with statistical smearing
  - Essential for best fit quality!



Decay in flight -> mismeasure track deflection in magnet



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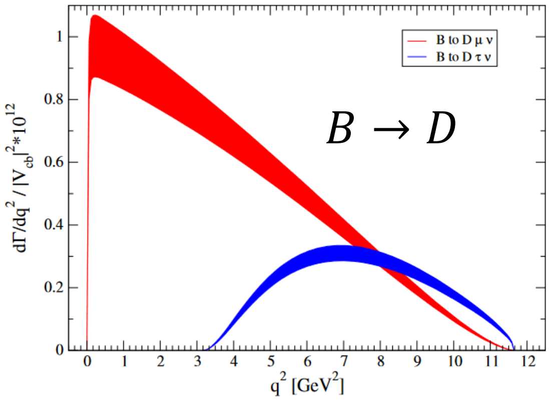
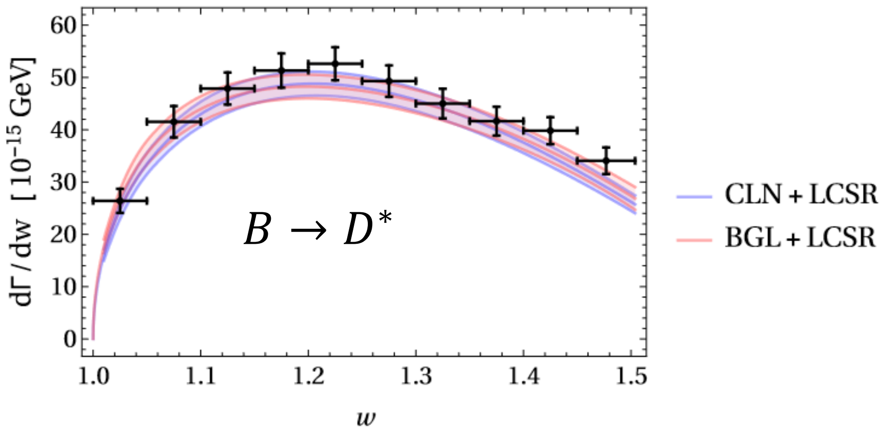
New Technology: Form-factor models

- Using updated form-factor models for semileptonic backgrounds
  - D* from CLN to BGL
    [JHEP 11 (2017) 061], [JHEP 12 (2017) 060]
    D using BCL ala HPQCD
    [PRD 92 (2015) 054510]
  - D** from LLSW to Bernlochner & Ligeti
    [PRD 95 (2017) 014022]

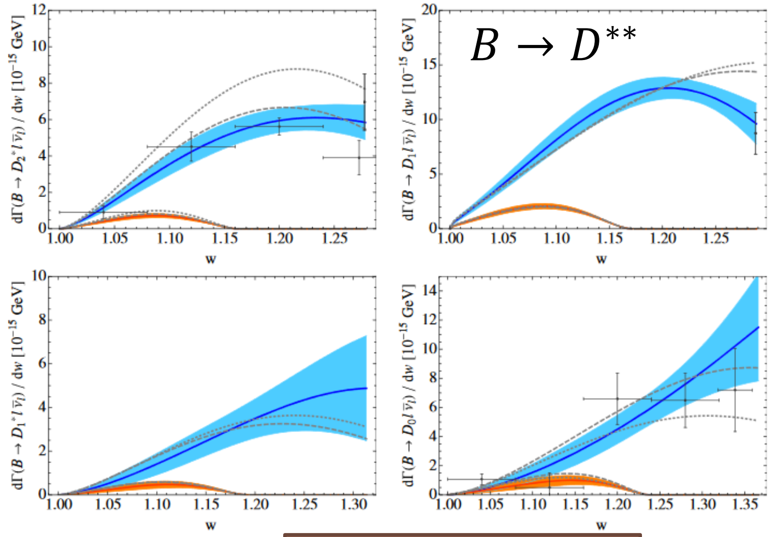
- Parameters free to vary in nominal fit, only helicity-suppressed terms constrained from external input
  - Alternate fitter: likelihood constraint on normalization/signal form factors
  - Constraint makes little difference in extracted value of RD/RDst – fit can compensate with degenerate degrees of freedom



PRD 92 (2015) 054510

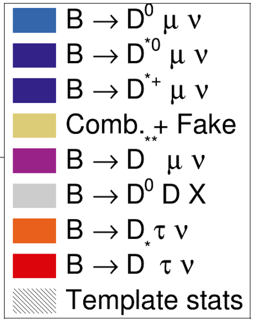


Phys.Lett.B769:441-445,2017



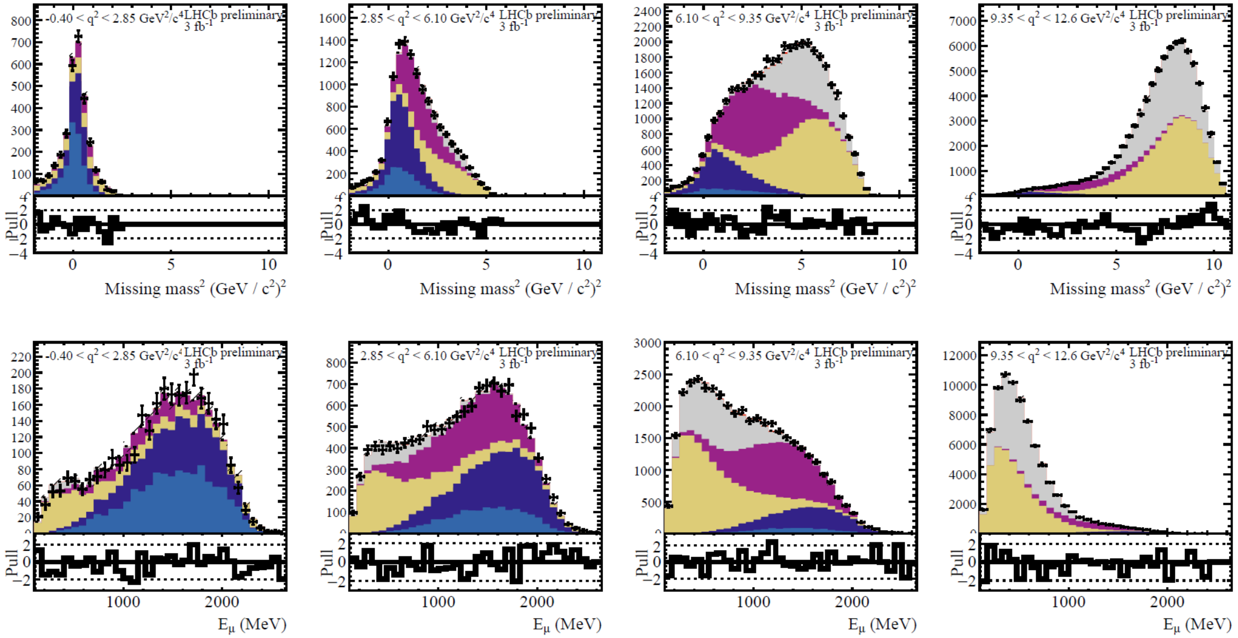
Phys. Rev. D 95, 014022

Auxilliary fits



- Fix shape parameters to nominal best fit, try to fit other possible anti-isolated regions with only yields free
  - Exhaustive list of possibilities (see Greg's seminar)

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



- 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

Results

Results!

- $R(D) = 0.441 \pm 0.060(stat) \pm 0.066(sys)$
  $R(D^*) = 0.281 \pm 0.018(stat) \pm 0.023(sys)$

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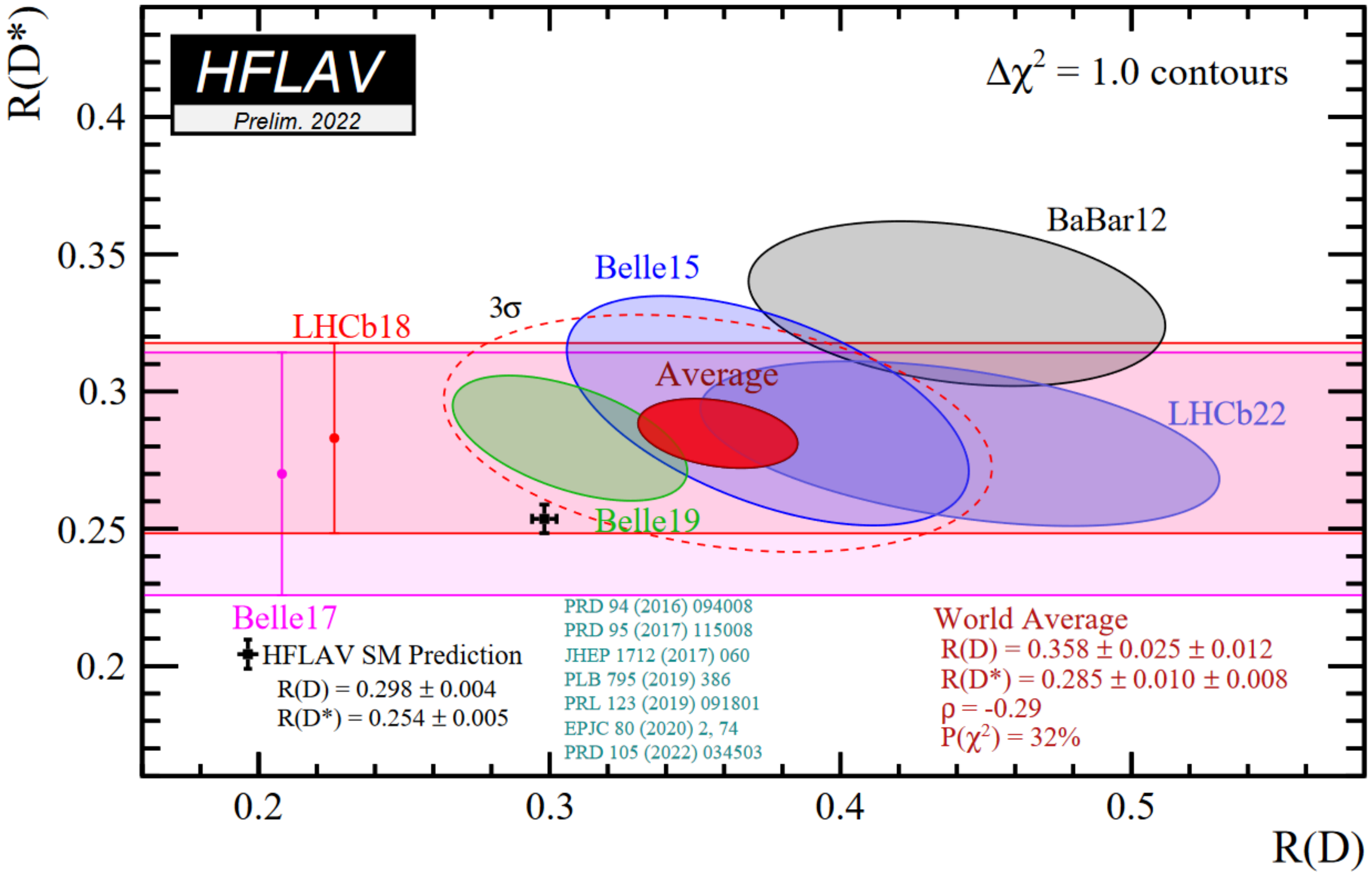
- $\rho = -0.49(stat)/-0.40(sys)/-0.43(tot)$



2021 HFLAv (previous)

World Average
$R(D) = 0.339 \pm 0.026 \pm 0.014$
$R(D^*) = 0.295 \pm 0.010 \pm 0.010$
$\rho = -0.38$
$P(\chi^2) = 28\%$

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

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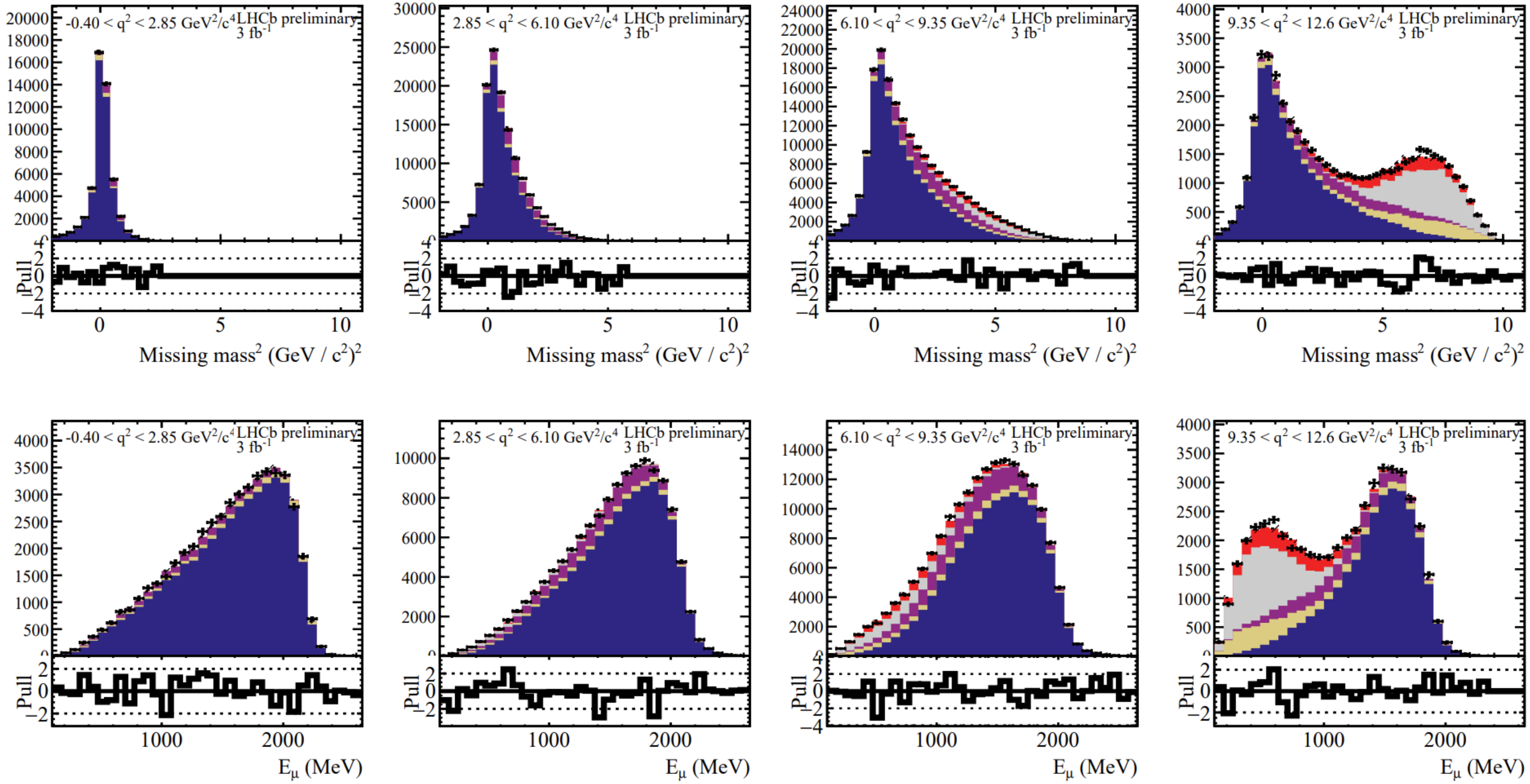

Results-$D^0\mu^-$ sample

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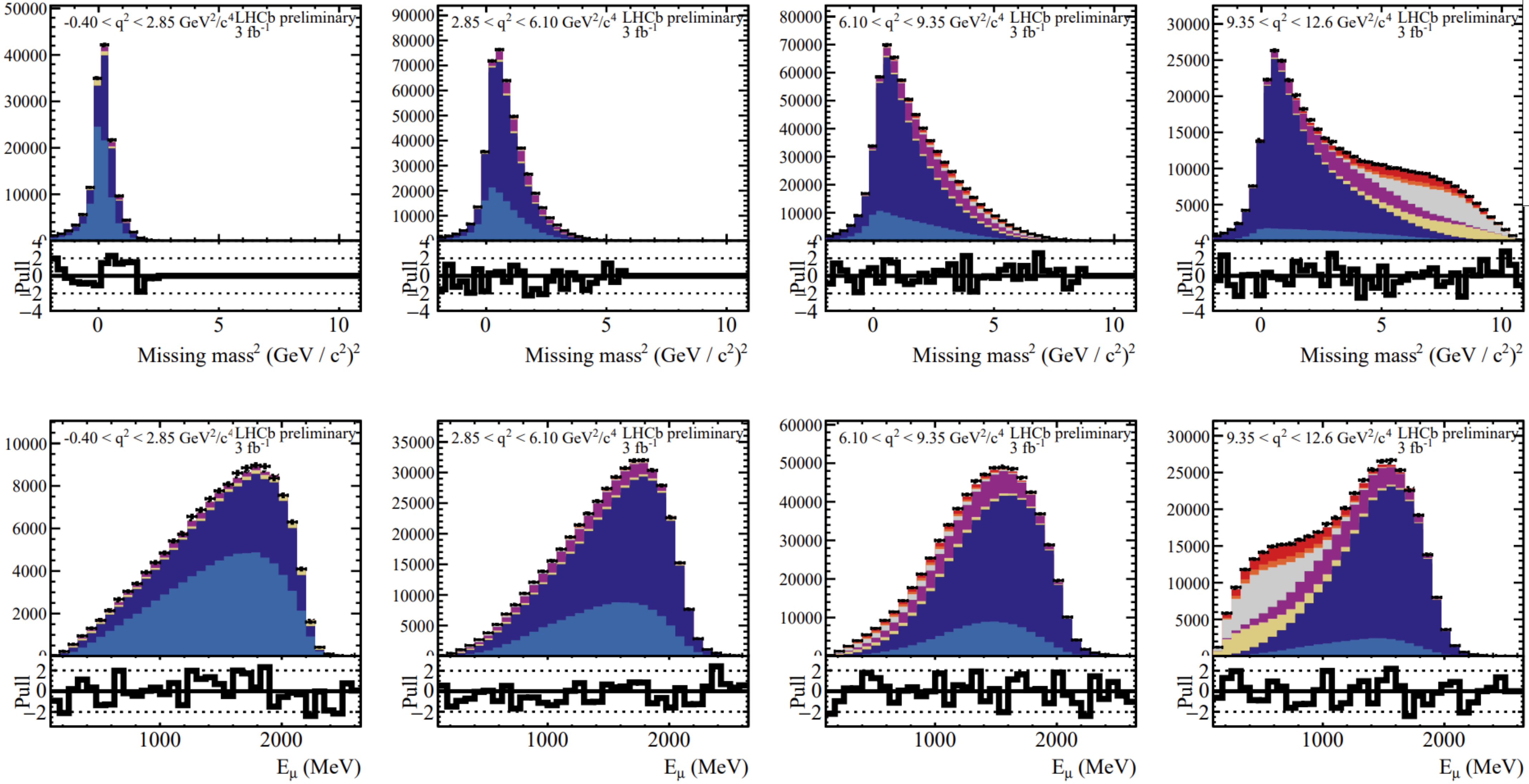
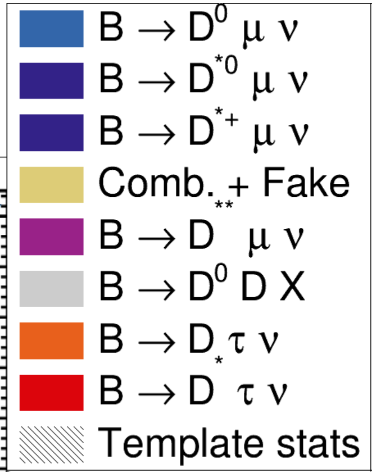
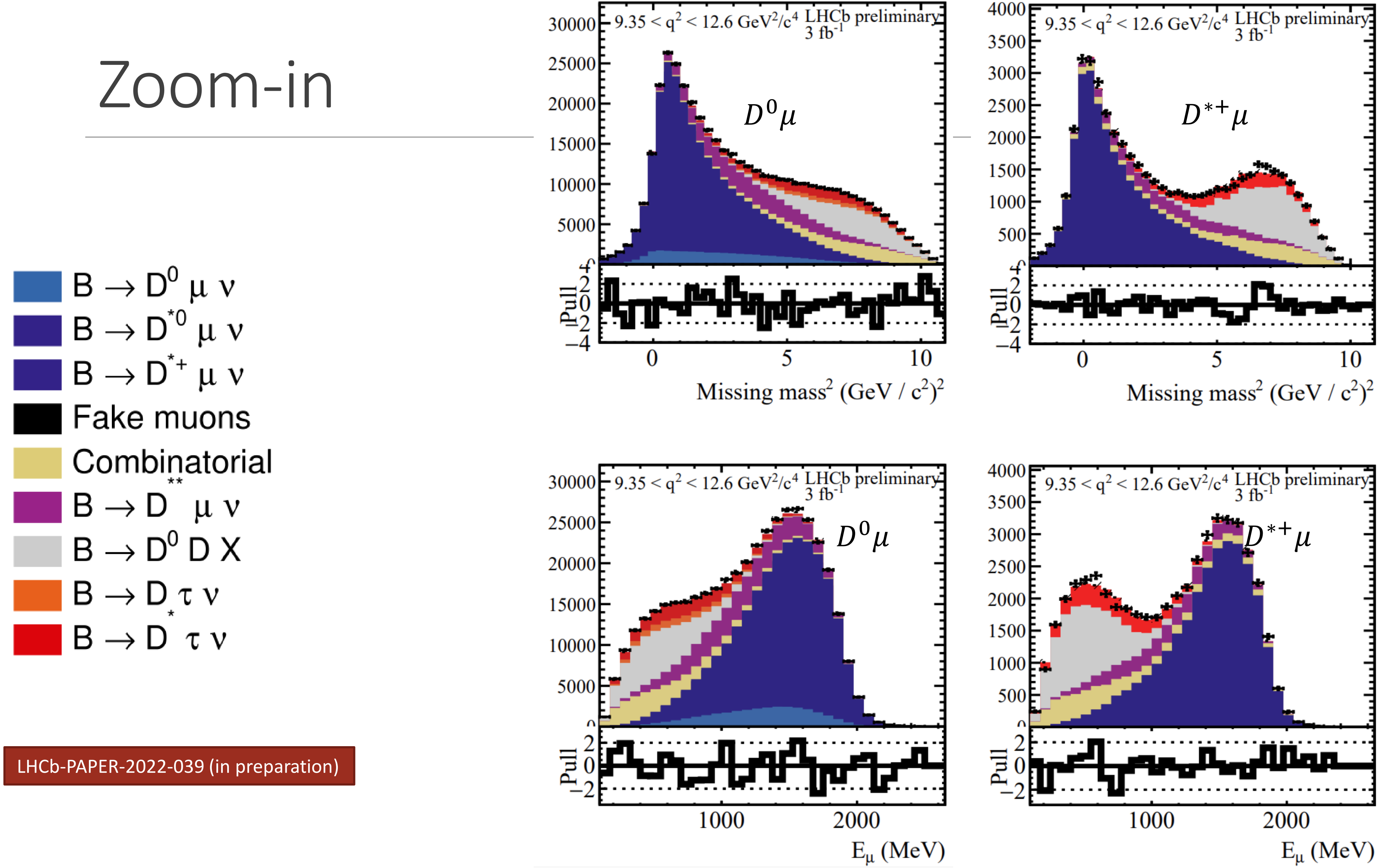




Zoom-in



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Syst. Table

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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 $\tau \to \mu\nu\bar{\nu}$

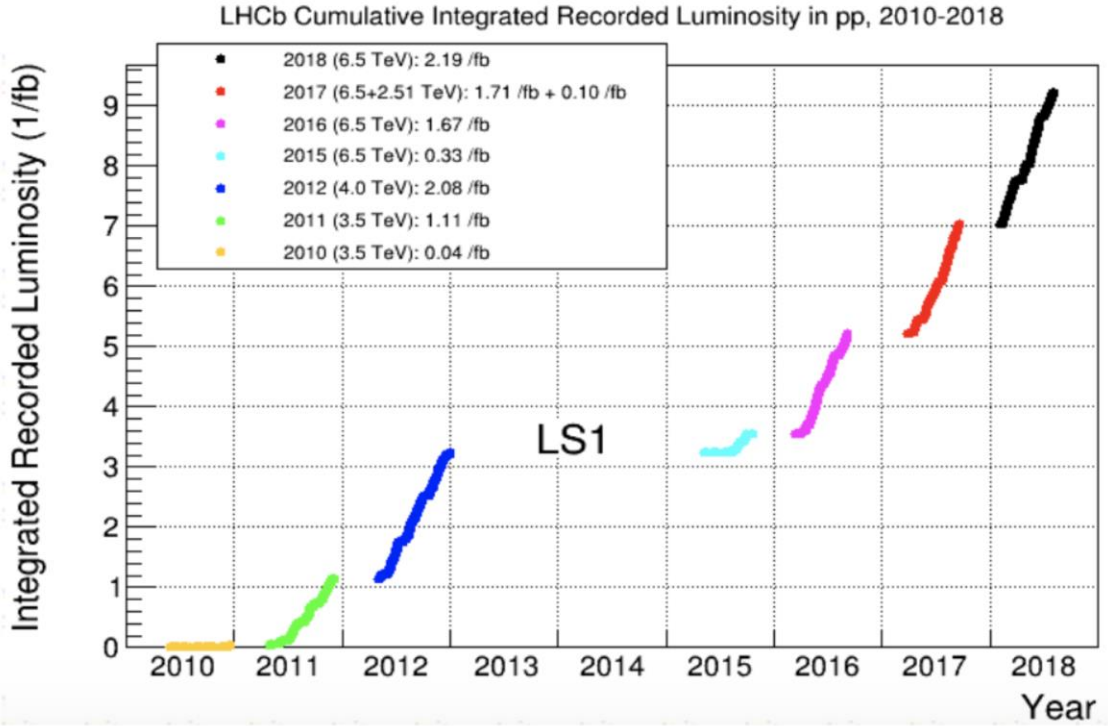
Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$	**Correlation**
Statistical uncertainty	1.8	6.0	-0.49
Simulated sample size	1.5	4.5	
$B \to D^* DX$ template shape	0.8	3.2	
$\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (B \to D^* D_s(\to \tau\nu)X)$	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	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$	
$B \to D^{(*)} DX$ model uncertainty	0.6	0.7	
$\overline{B}^0_s \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.75	
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	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$	
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D)$	
Total systematic uncertainty	2.4	6.6	-0.39
Total uncertainty	3.0	8.9	-0.43

Run2 The Next Generation

- Run2 introduced a suite of dedicate B2Xtaunu trigger lines in the $\tau \to \mu\nu\bar{\nu}$ submode 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" on charm triggers

- Large statistics gain independent of efficiency as well
    - 1.9x more luminosity, 1.8x $\sigma(b\bar{b})$

- But "more data more problems" – MC statistics and corrections must be more precise to exploit this data
    - FastMC techniques essential, but introduce complications in Hardware (L0) trigger modeling
    - How consistent is 2016/2017/2018 data? Separate corrections may be needed – more complications



Summary

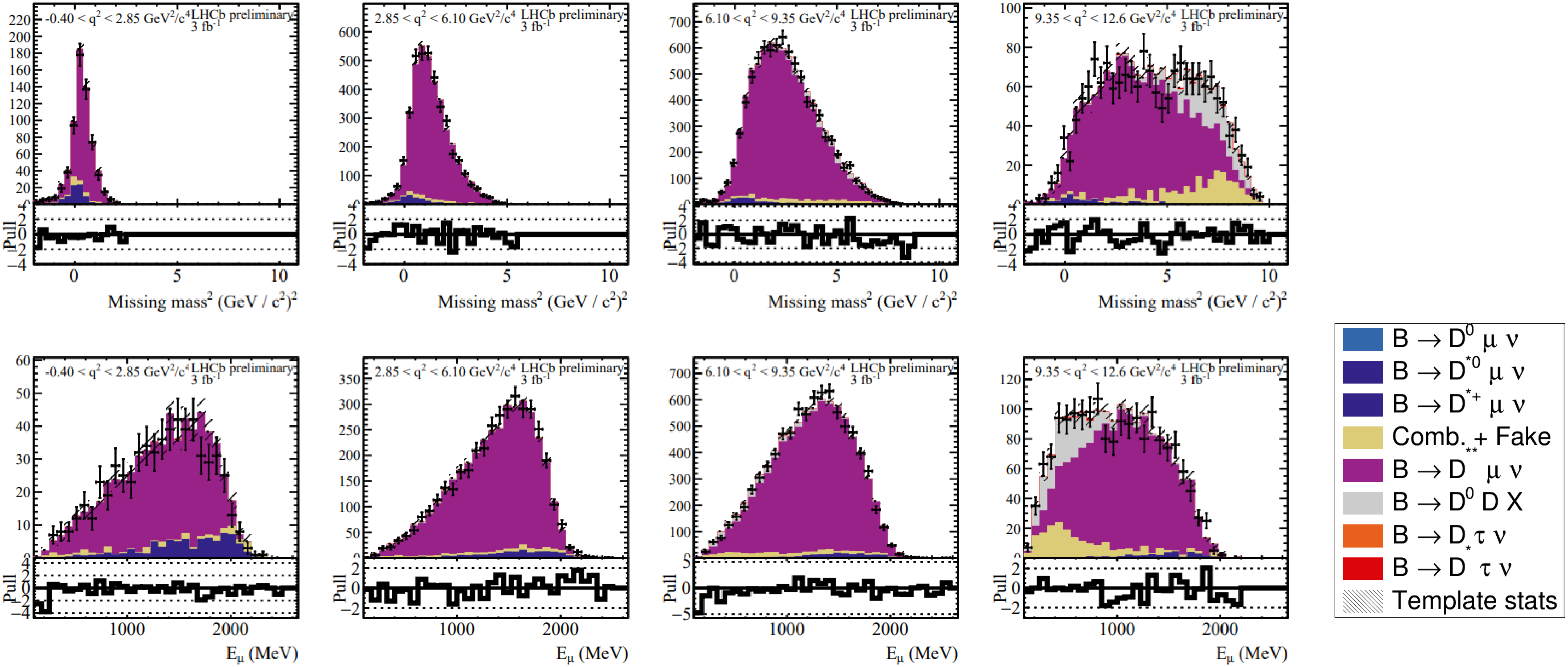
- LHCb Run1 R(D*) measurement successfully extended to joint R(D), R(D*) ellipse
  - Result: $$\begin{aligned} R(D) &= 0.441 \pm 0.060(stat) \pm 0.066(sys) \\ R(D^*) &= 0.281 \pm 0.018(stat) \pm 0.023(sys) \\ \rho &= -0.49(stat)/-0.40(sys)/-0.43(tot) \end{aligned}$$
  - Excellent agreement with world average, 1.9σ from standard model

- 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

- Much more exciting work also underway on this mode using techniques inherited from or inspired by this work

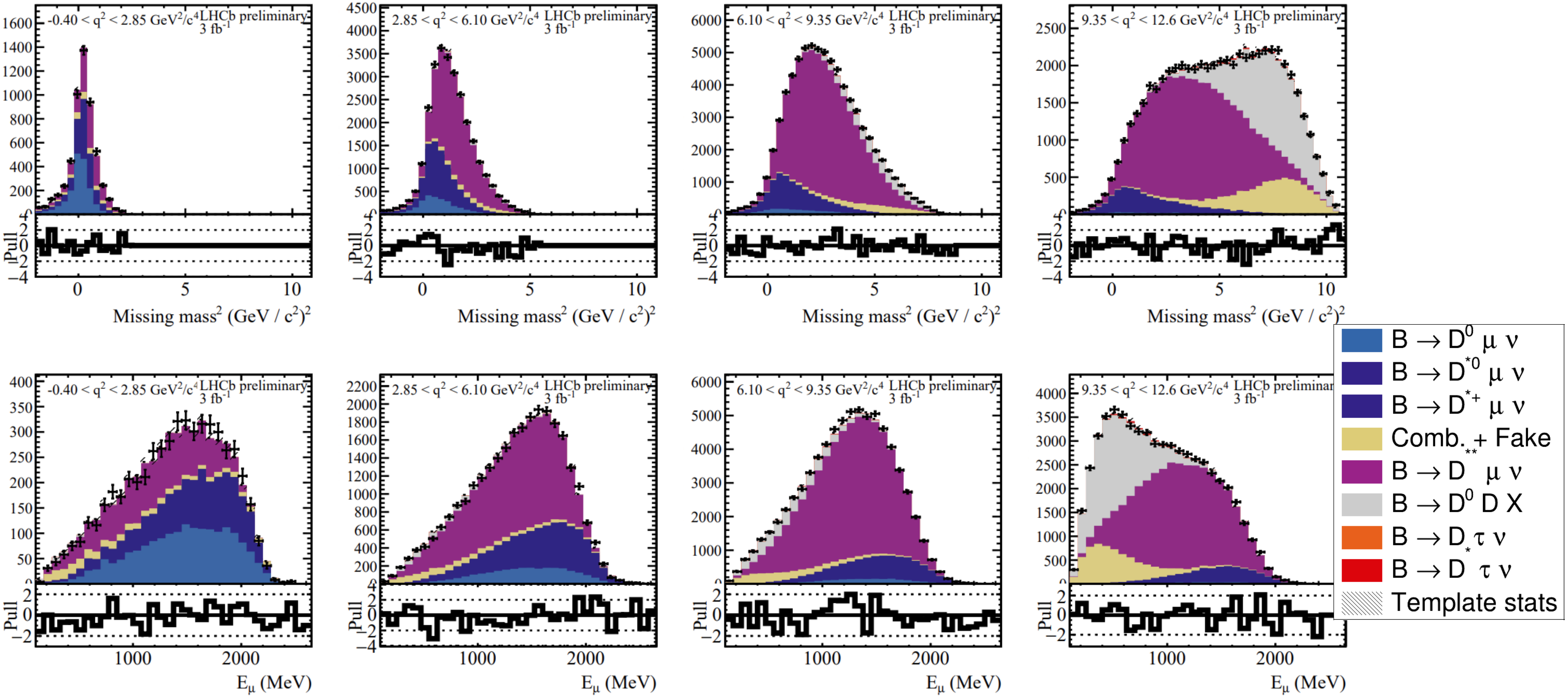
Backup

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



-0.40 < q² < 2.85 GeV²/c⁴ LHCb preliminary 3 fb⁻¹
2.85 < q² < 6.10 GeV²/c⁴ LHCb preliminary 3 fb⁻¹
6.10 < q² < 9.35 GeV²/c⁴ LHCb preliminary 3 fb⁻¹
9.35 < q² < 12.6 GeV²/c⁴ LHCb preliminary 3 fb⁻¹
Pull
Missing mass² (GeV / c²)²
Eμ (MeV)
B → D⁰ μ ν
B → D*⁰ μ ν
B → D*⁺ μ ν
Comb. + Fake
B → D** μ ν
B → D⁰ D X
B → D τ ν
B → D* τ ν
Template stats

$D^0\mu^-$ 1OS



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B → D⁰ μ ν
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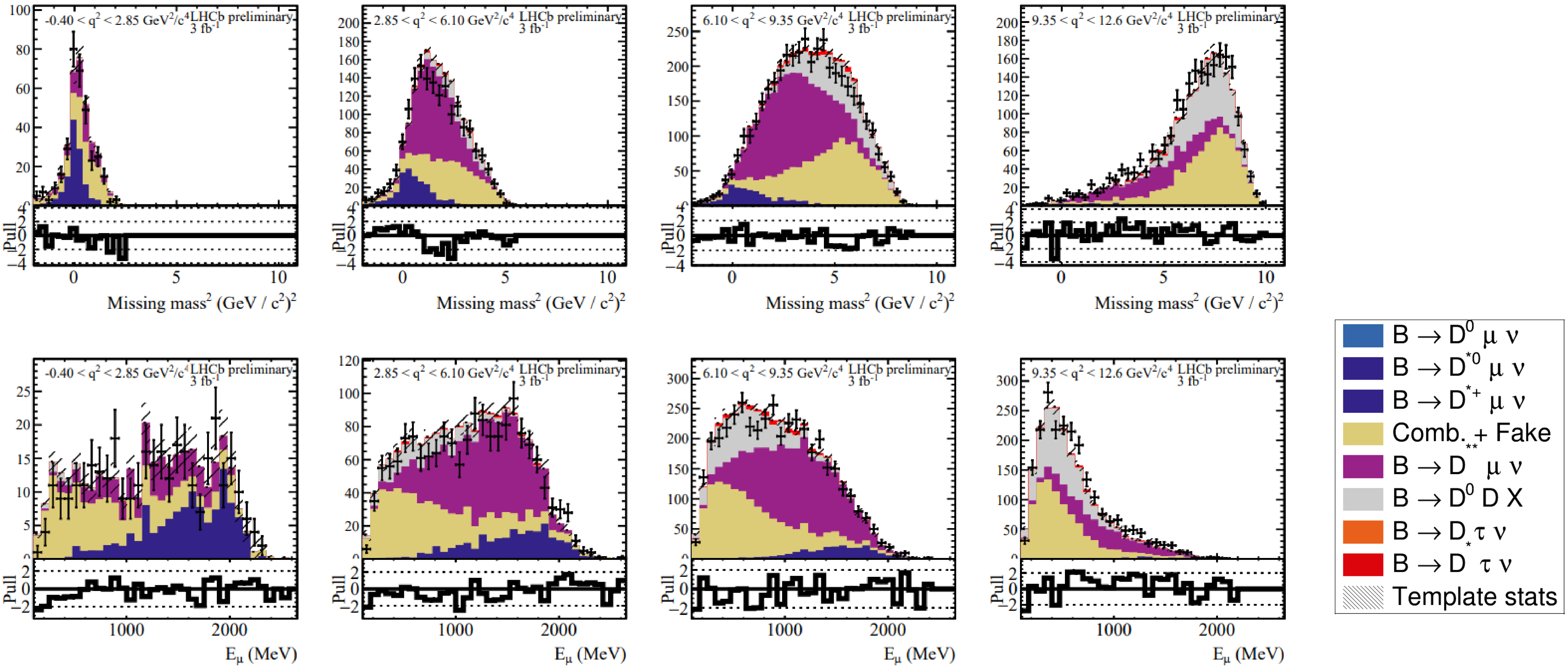
Comb. + Fake
B → D** μ ν
B → D⁰ D X
B → D* τ ν
B → D τ ν
Template stats

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



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LHCb preliminary
3 fb⁻¹
Pull
Missing mass² (GeV / c²)²
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B → D⁰ μ ν
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B → D** μ ν
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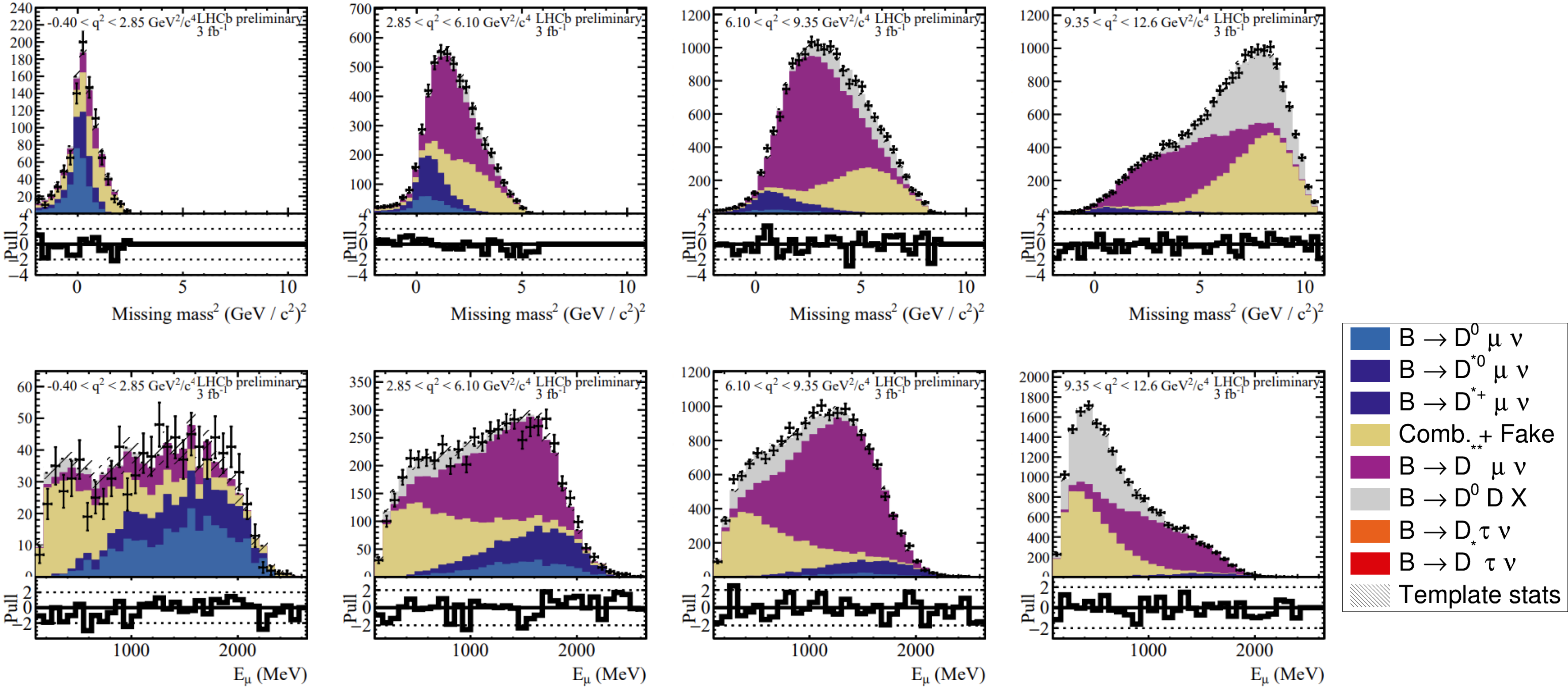
B → D* τ ν
Template stats

$D^0\mu^-$ 2OS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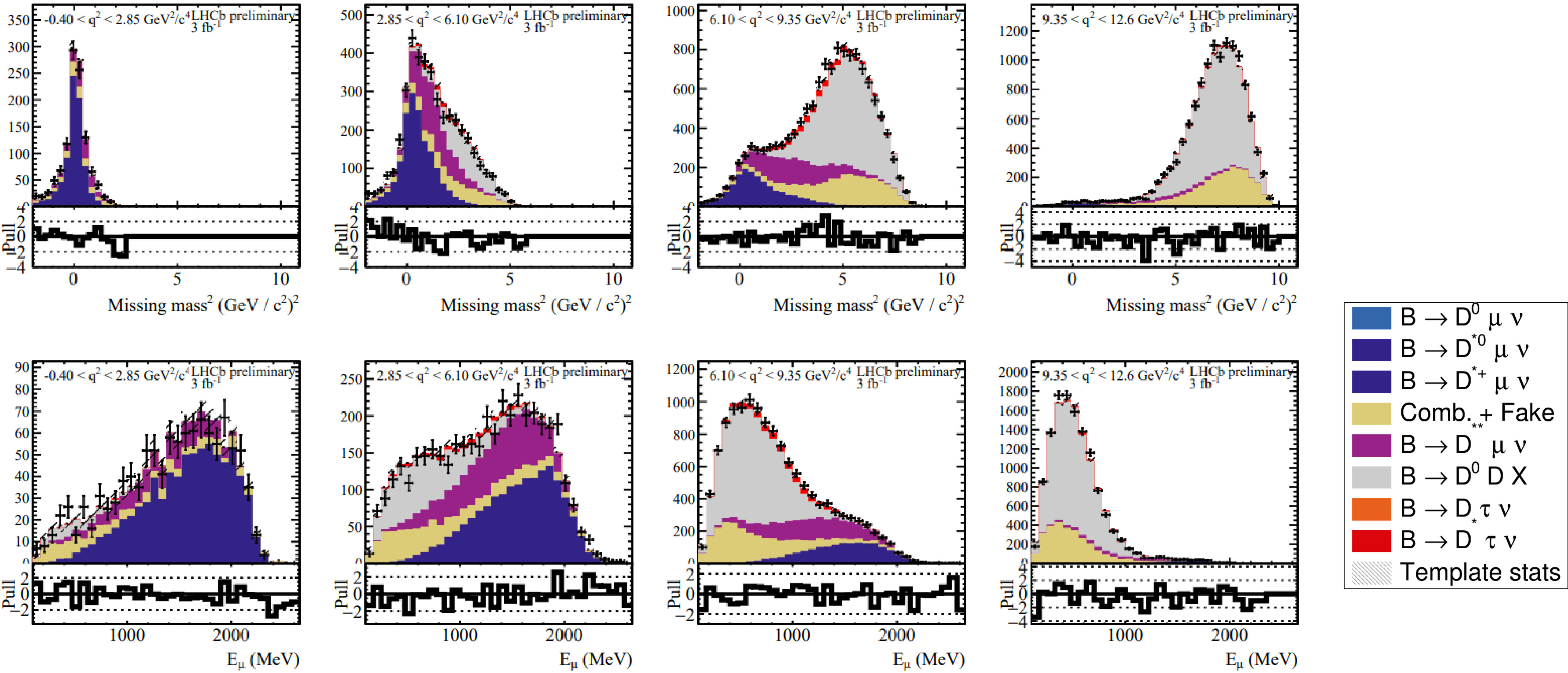
9.35 < q² < 12.6 GeV²/c⁴ LHCb preliminary 3 fb⁻¹
Missing mass² (GeV / c²)²
Pull
E_μ (MeV)
B → D⁰ μ ν
B → D*⁰ μ ν
B → D*⁺ μ ν
Comb. + Fake
B → D** μ ν
B → D⁰ D X
B → D* τ ν
B → D τ ν
Template stats

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



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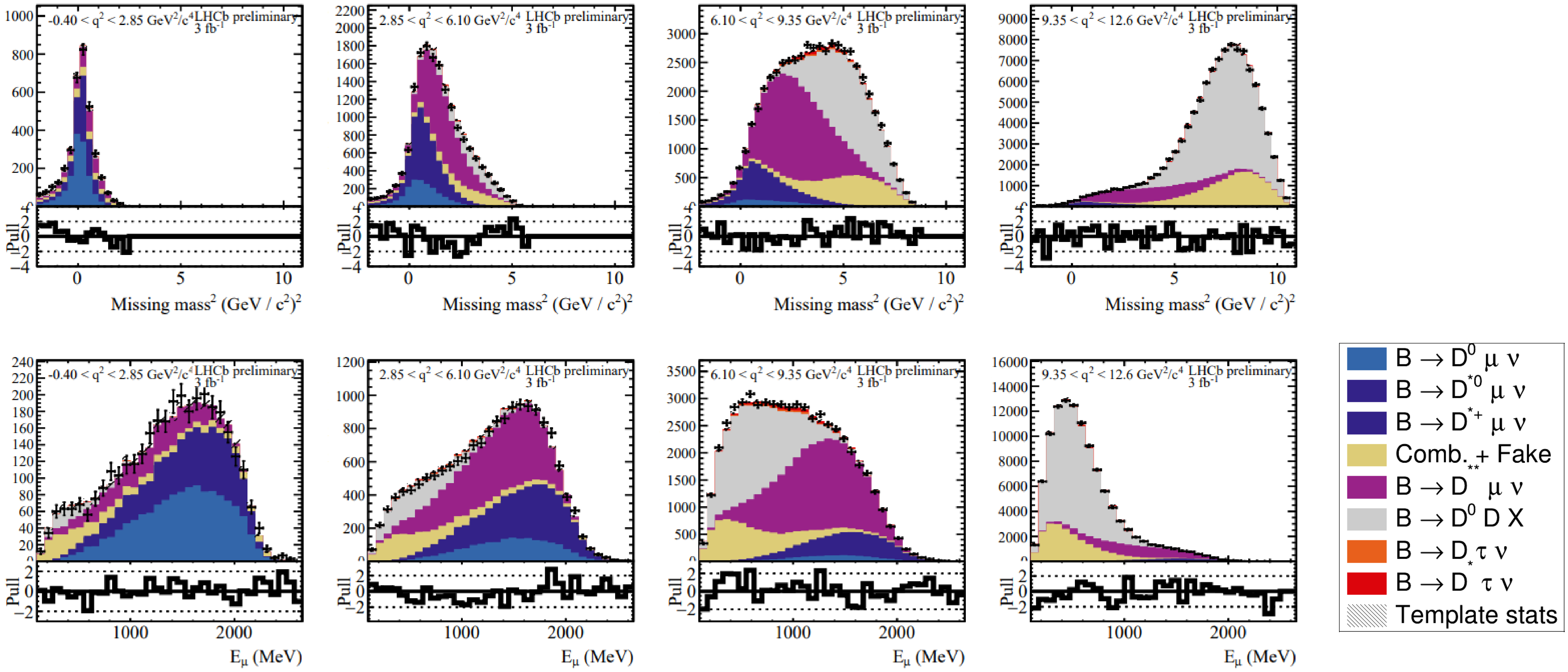
LHCb preliminary
3 fb⁻¹
Missing mass² (GeV / c²)²
Eμ (MeV)
Pull
B → D⁰ μ ν
B → D*⁰ μ ν
B → D*⁺ μ ν
Comb. + Fake
B → D** μ ν
B → D⁰ D X
B → D τ ν
B → D* τ ν
Template stats

$D^0\mu^-$ DD



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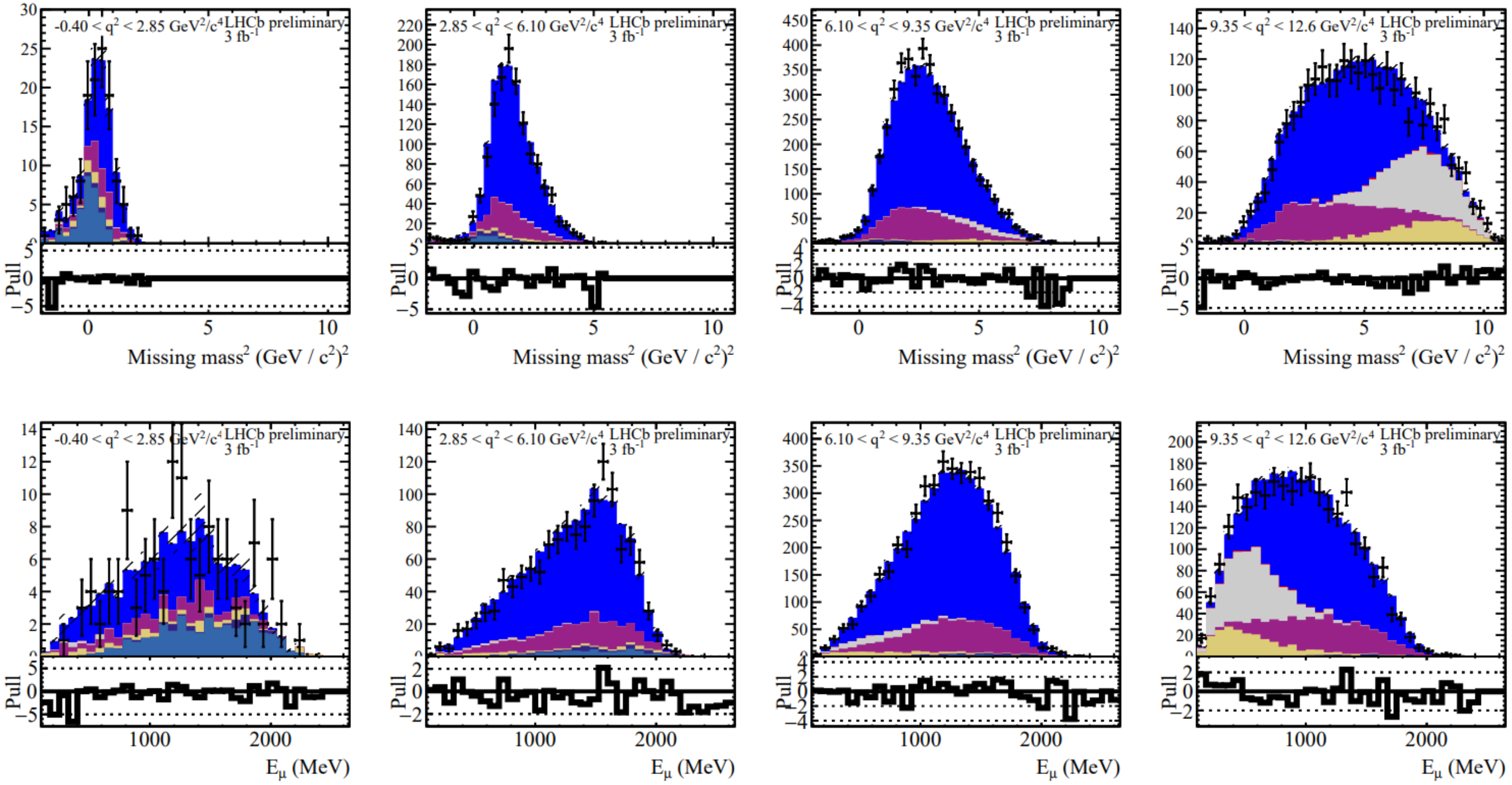
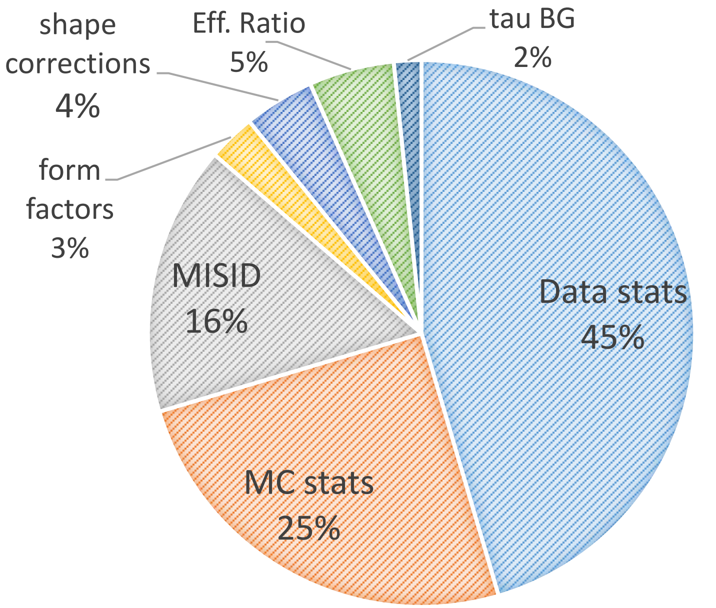
Missing mass² (GeV / c²)²
E_μ (MeV)
B → D⁰ μ ν
B → D*⁰ μ ν
B → D*+ μ ν
Comb. + Fake
B → D** μ ν
B → D⁰ D X
B → D τ ν
B → D* τ ν
Template stats

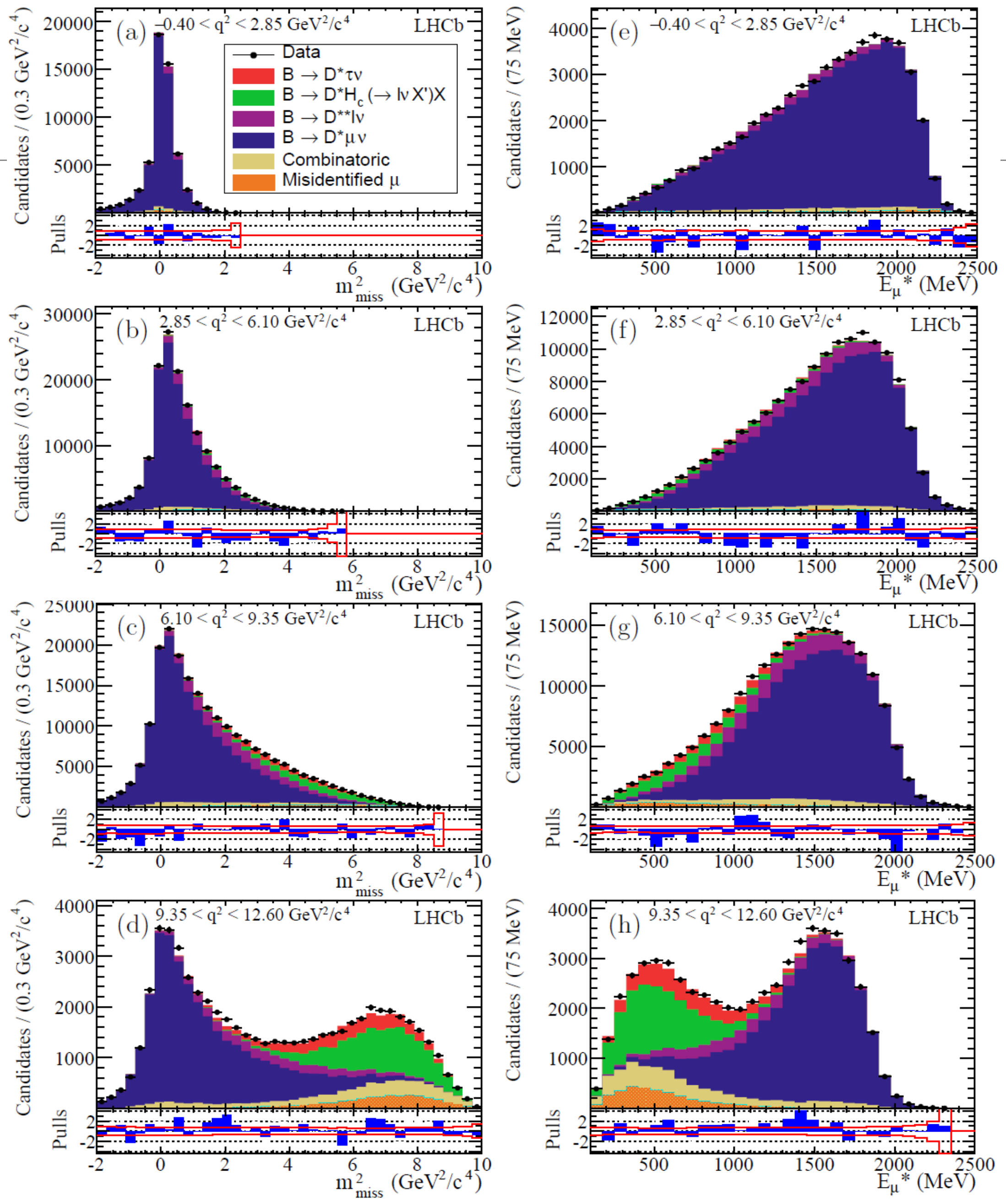
Baryonic backgrounds

- $\Lambda_b \to D^0 p\mu\bar{\nu}$ poorly understood and difficult to model
  - Question: Can our existing $D^{**}\mu\bar{\nu}$ background model represent this component?
  - Answer: Yes! Measure shapes in $D^0\mu^- + p$ sample, refit simultaneous data with constrained contribution from this background to estimate sensitivity of R(D(*)) to this missing source



2015 R(D*) fit result and systematics





Contribution of each source to the squared total measurement uncertainty