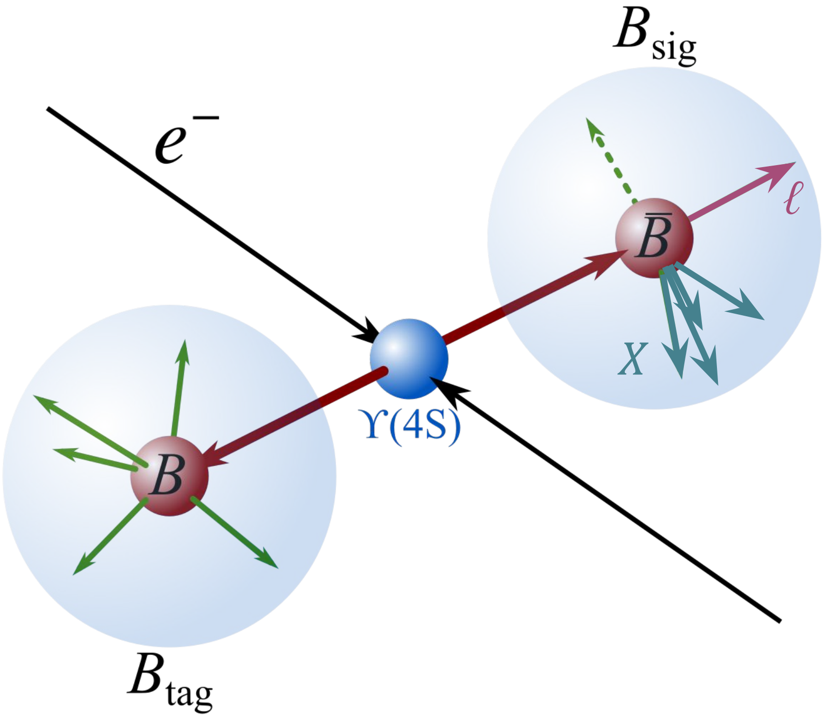


Feasibility of $R(\boldsymbol{X})$ at Belle II

Searching for lepton universality violation in **inclusive** semileptonic B decays

Peter Lewis | University of Bonn

KEK-FF | 10 Feb 2023

Disclaimer

This talk contains public material from **PhD/Masters theses**

These results are **unpublished** and **unapproved** and should *not* be considered official collaboration results

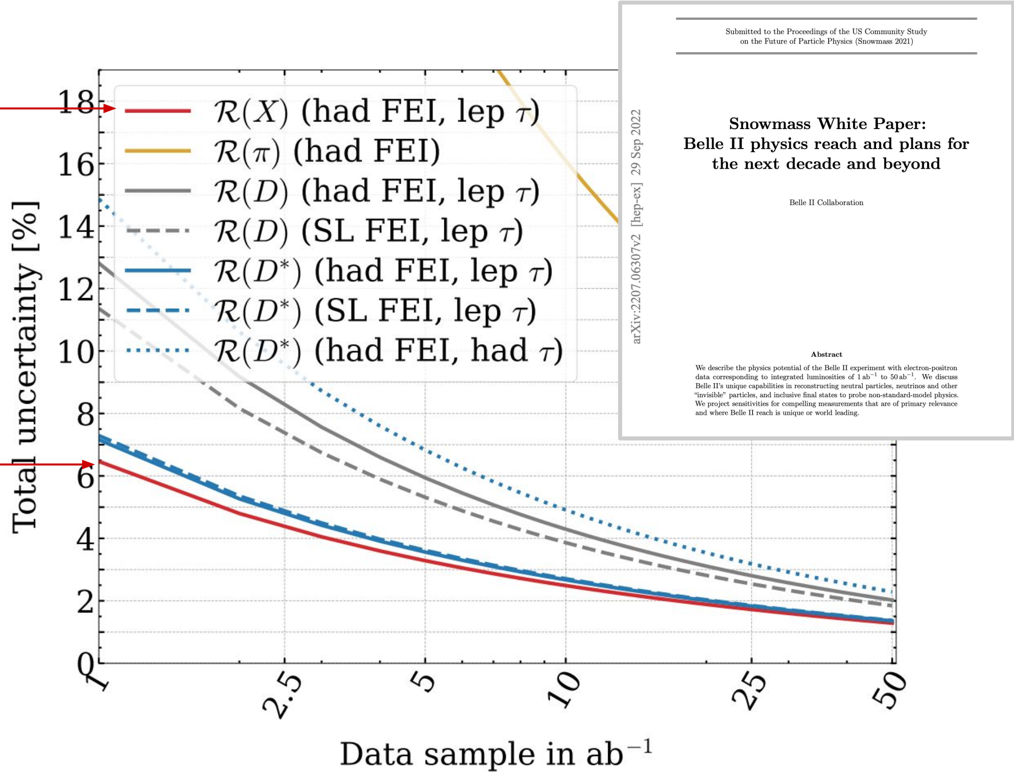
Only plots with the “Belle II” label are Belle II plots!

An intriguing claim…

The **strongest** test of $\boldsymbol{\tau/\ell}$ **universality** will come from the *inclusive* measurement:

$$\mathcal{R}(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$$

This has **never*** been measured. Why? What makes us think that *we* can?



Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

arXiv:2207.06307v2 [hep-ex] 29 Sep 2022

Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond

Belle II Collaboration

Abstract

We describe the physics potential of the Belle II experiment with electron-positron data corresponding to integrated luminosities of 1 ab^{-1} to 50 ab^{-1}. We discuss Belle II's unique capabilities in reconstructing neutral particles, neutrinos and other "invisible" particles, and inclusive final states to probe non-standard-model physics. We project sensitivities for compelling measurements that are of primary relevance and where Belle II reach is unique or world leading.

*(there are two near-exceptions)

First: why $R(X)$?

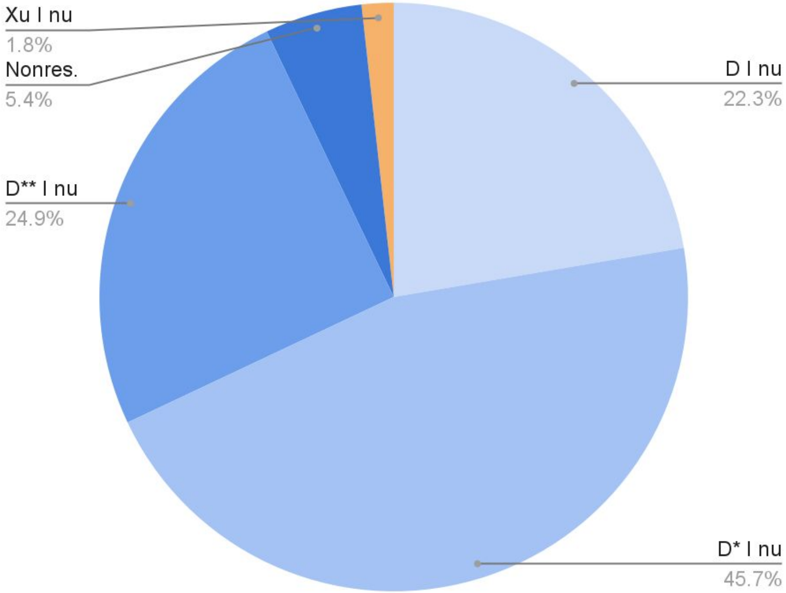
Fully inclusive B decays:

- **~2/3** overlap with D and D^*
- **~1/3** contribution from D^{**} and nonresonant X_c

Fully inclusive D decays:

- **~1/4** overlap with typical list of exclusive D modes
- The rest: *ugly stuff*! ν, K_L^0, $N\pi^0$…

Breakdown of $B \to X\ell\nu$ branching fractions (assume $B \to X\tau\nu$ is similar)



$R(X)$ is critical **cross-check** of $R(D(^*))$ *and* a partially **complementary** test of LU

LEP measurements

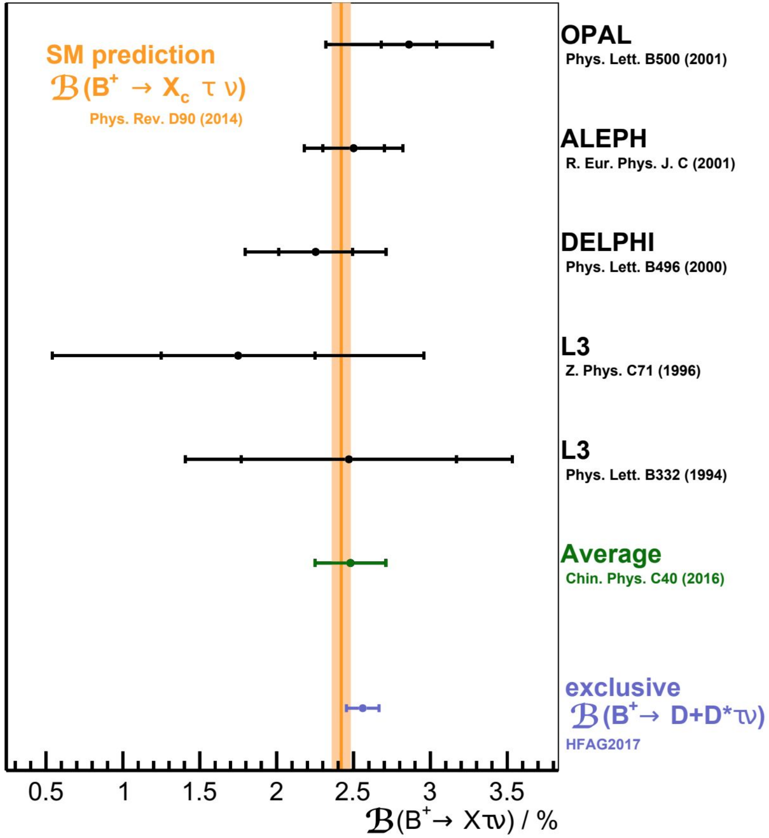
Multiple LEP experiments measured

$$\mathcal{R}(X) = \frac{\mathcal{B}(b \to X\tau\nu)}{\mathcal{B}(b \to X\ell\nu)}$$

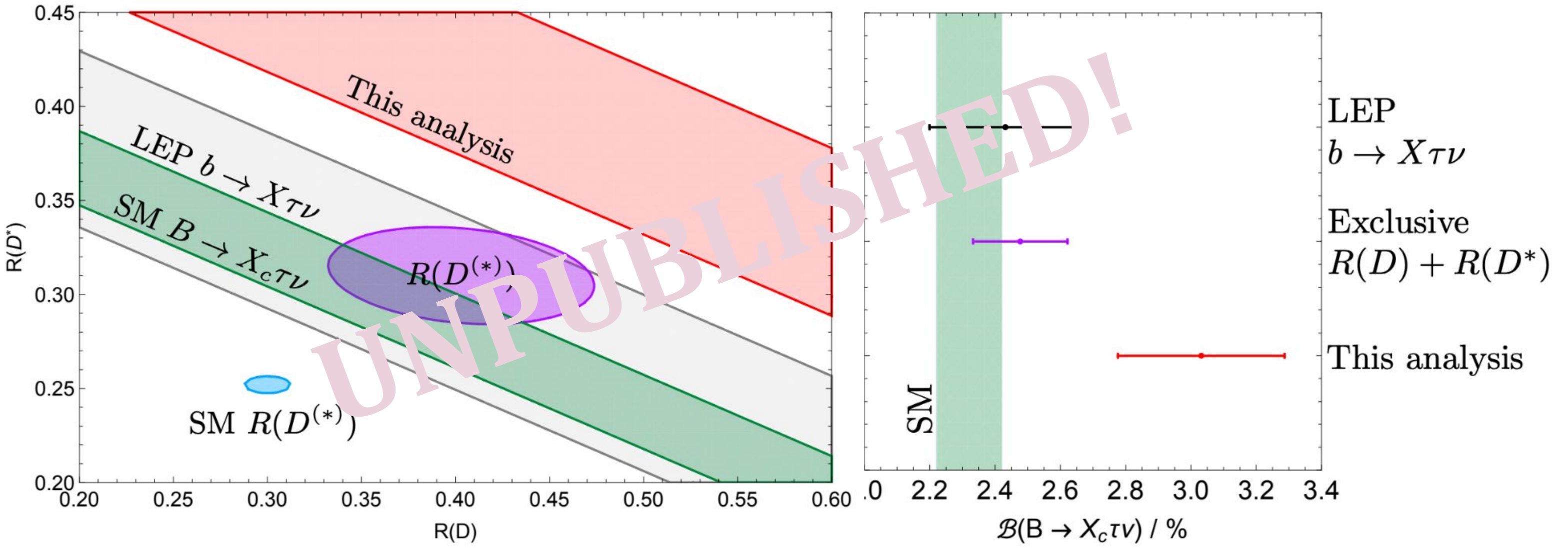
From which $R(X)$ can be *inferred*

A puzzle: their measurements of $\mathcal{B}(b \to X\tau\nu)$ are completely **saturated** by current D/D^* BFs

An update is urgently needed



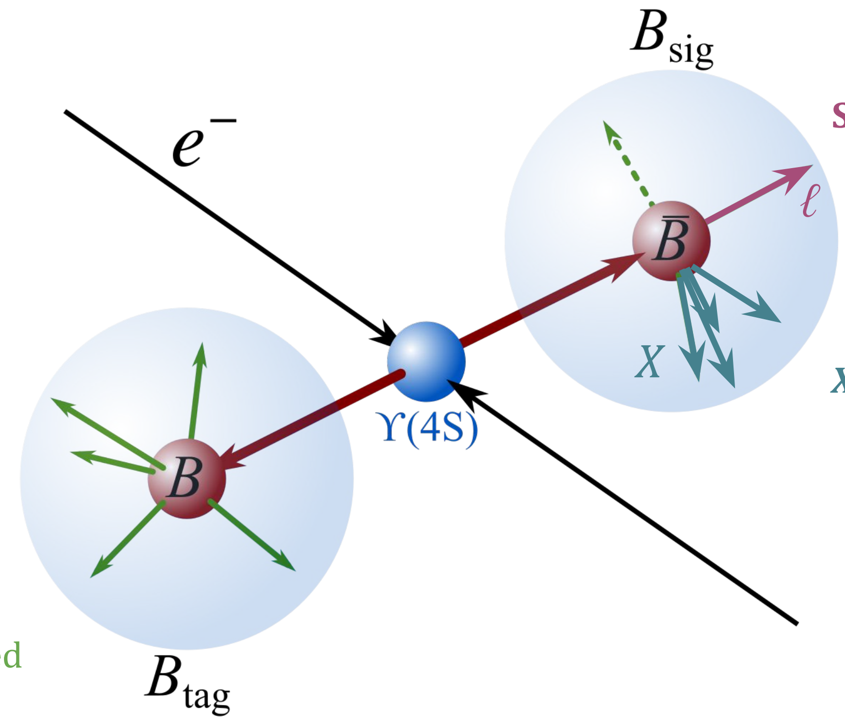
A recent, intriguing analysis at Belle…



[Jan Hasenbusch PhD thesis
U. Bonn, 2017]

…was **not published**. *Why?*

Here's how this analysis works…



Signal lepton:

- High electron or muon likelihood

***X* system:**

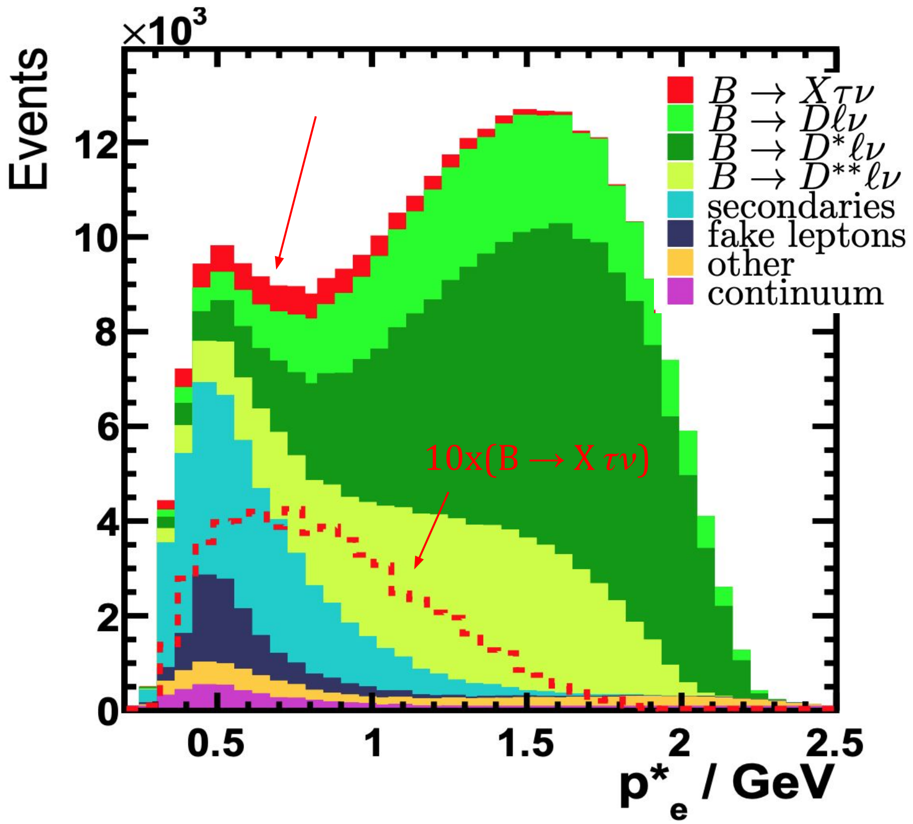
- **Everything else in the event…**
- (passing quality criteria)

Tag-side *B* meson

- Fully reconstructed (hadronic FEI)
- Tight tag quality selections

How can we identify $X\tau\nu$?

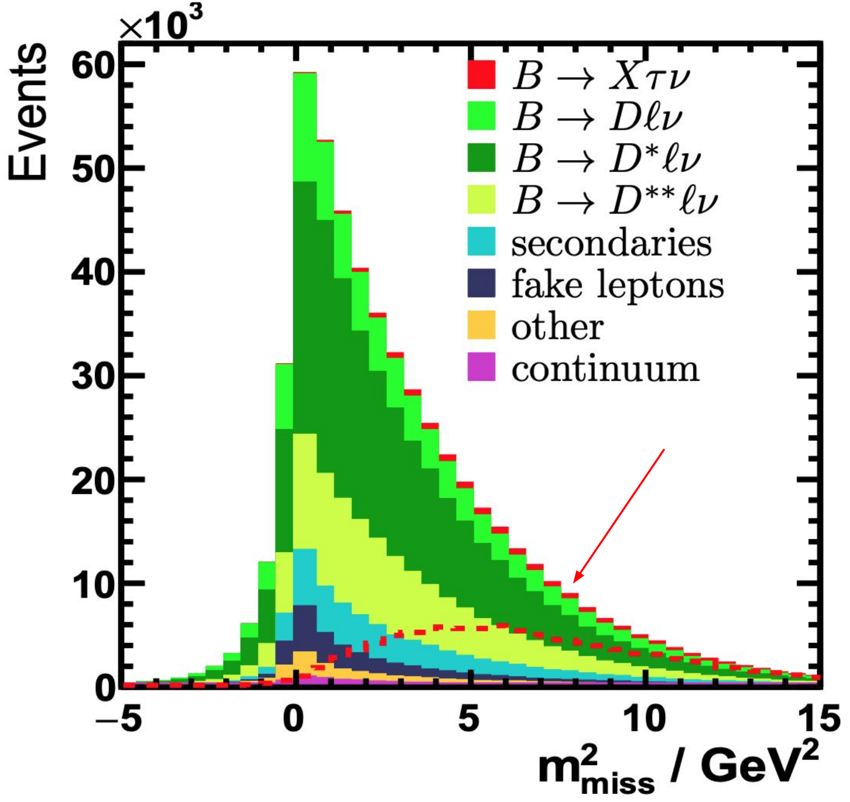
- p_l: lepton momentum distribution (insufficient by itself)



Jan Hasenbusch PhD thesis
U. Bonn, 2017

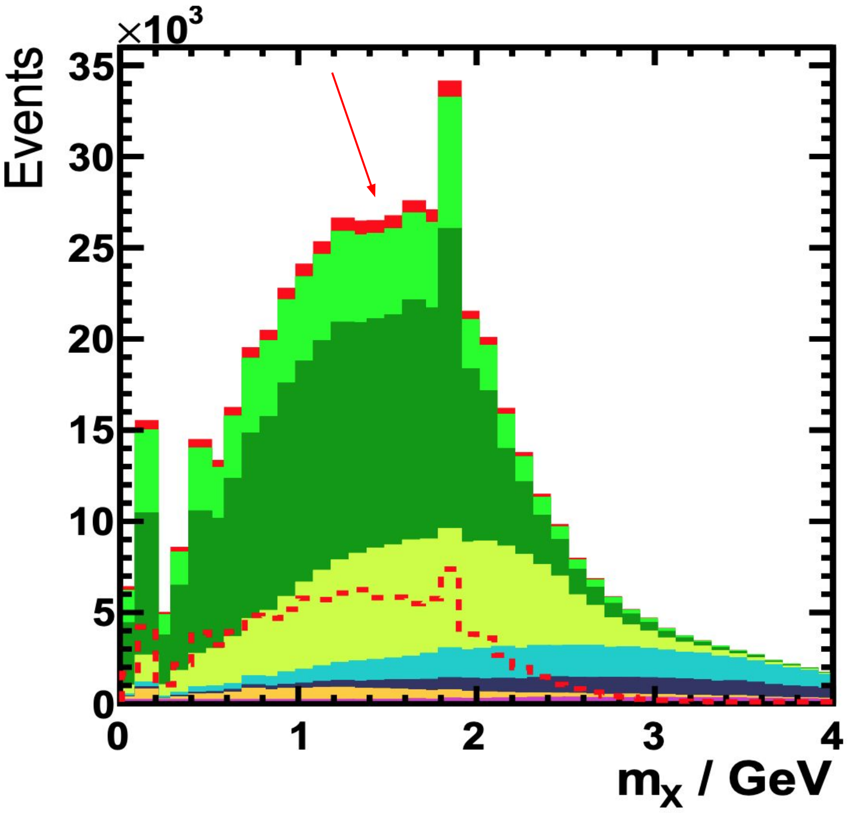
How can we identify $X\tau\nu$?

- p_l: lepton momentum distribution
- m_{miss}^2: missing mass (adds information but is also insufficient)



How can we identify $X\tau\nu$?

- p_l: lepton momentum distribution
- m_{miss}^2: missing mass
- M_X: invariant mass of "X" (adds some orthogonal information)



So, just use a 3D fit?

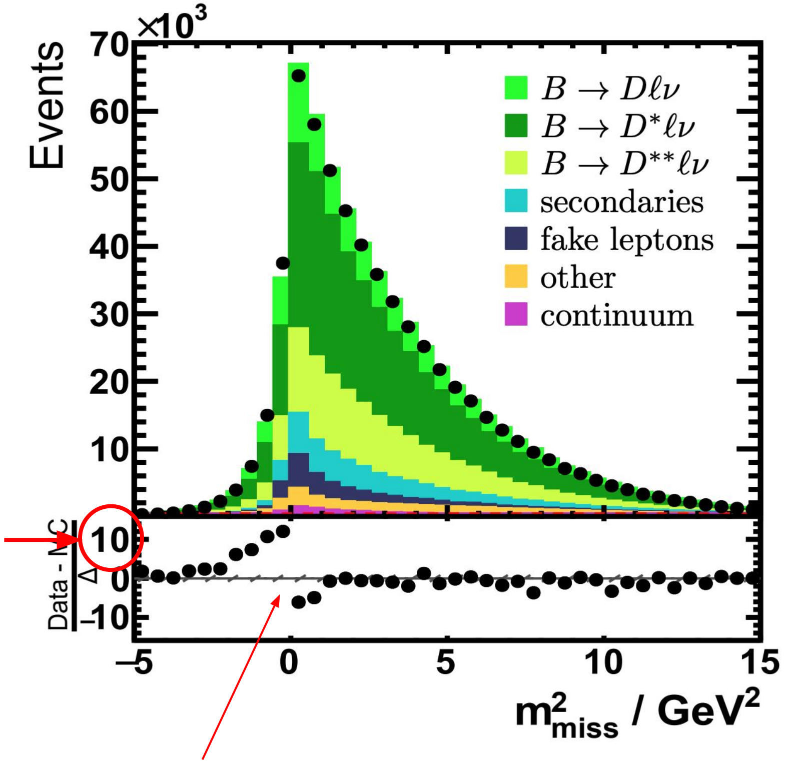
It's not that simple… inclusive *modeling* is ***hard***

What modeling do we depend on?

- **All** $B \to X\ell\nu$ decays
- (all other B decays)
- **All** X decays
- All continuum processes
- All detector effects (acceptance, efficiency, backgrounds, etc…)

What could be the culprit?

Data/MC agreement in sideband



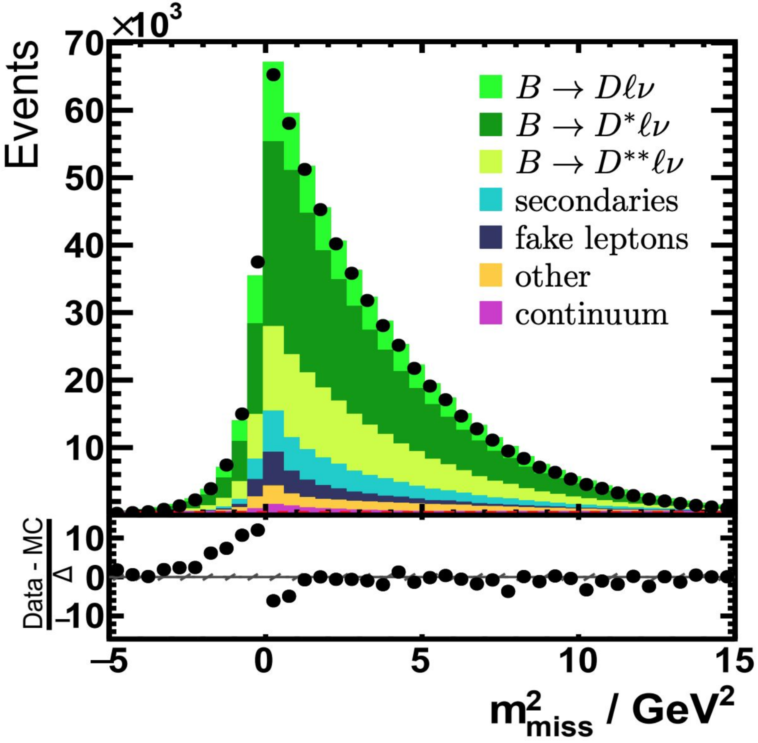
Belle attempt

Conclusions The discrepancy between data and MC at $m^2_{\text{miss}} < 0\,\text{GeV}$ has a complex origin.

Extensive work to understand mismodeling

Important insights:

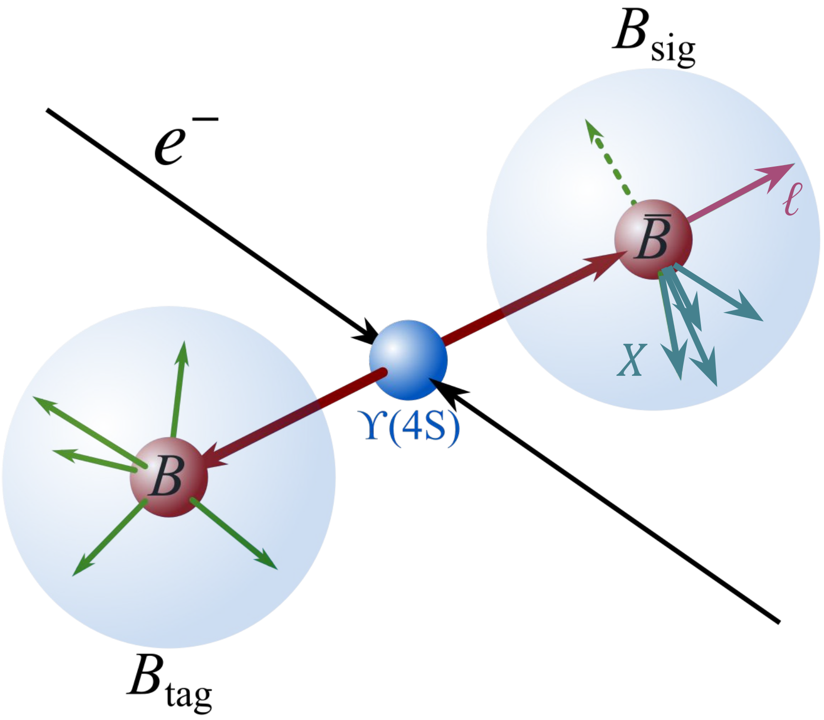
- Detector effects are far too small
- Beam backgrounds are far too small
- The culprit appears to be somewhere in the ***physics simulation***



Ultimately not approved because solution couldn't be found…

Belle II approach:

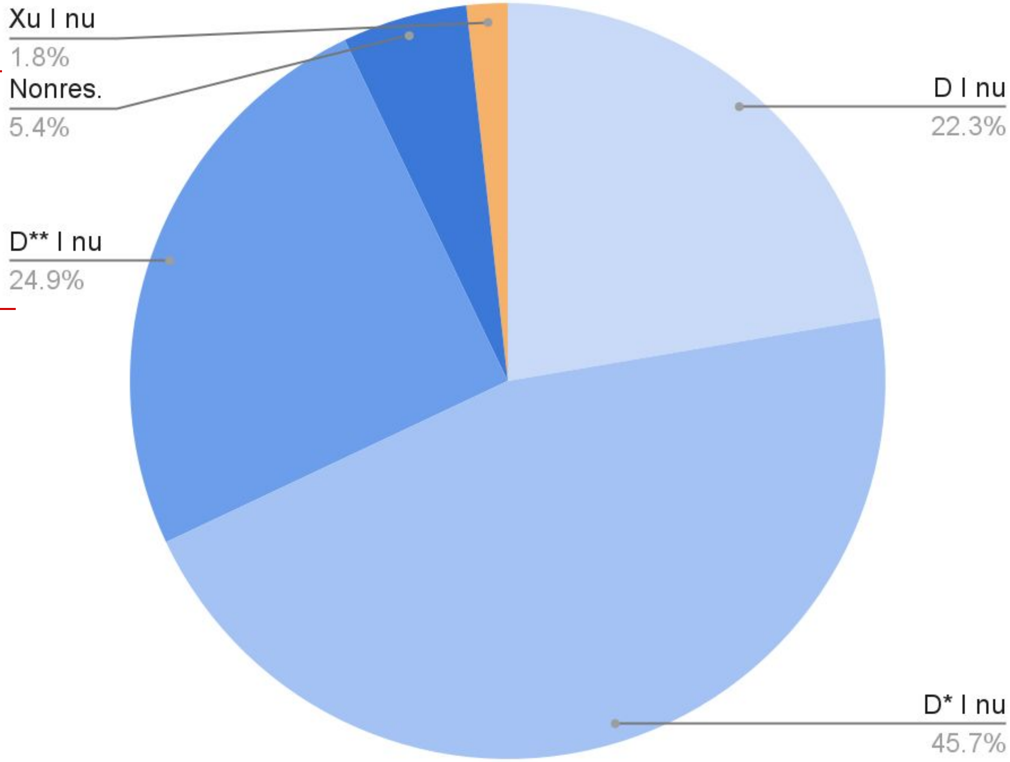
1. First learn **everything we can** about ***X***
   a. What's **in** there?
   b. What determines the **shape**?
   c. What's **modeled** well/poorly?
2. Only then do we attempt extraction



Let's talk about *X*…

Dennis Benterbusch Master's thesis, U. Bonn, 2020

X: what's in there?



Poorly measured, poorly described

Well-known exclusive modes

Almost all of this includes **exactly one *D* decay**…

X: what's in there?

$D \to$? (*overlapping* contributions):

		D^0	$D^{+/-}$
Neutrinos	e^+ anything [4]	$(6.49 \pm 0.11)\%$	$(16.07 \pm 0.30)\%$
	μ^+ anything	$(6.8 \pm 0.6)\%$	$(17.6 \pm 3.2)\%$
	K^- anything	$(54.7 \pm 2.8)\%$	$(25.7 \pm 1.4)\%$
1/2 K_L^0	$\overline{K}^0$ anything + K^0 anything	$(47 \pm 4)\%$	$(61 \pm 5)\%$
	K^+ anything	$(3.4 \pm 0.4)\%$	$(5.9 \pm 0.8)\%$

A large fraction of the time the D **cannot** be fully reconstructed.

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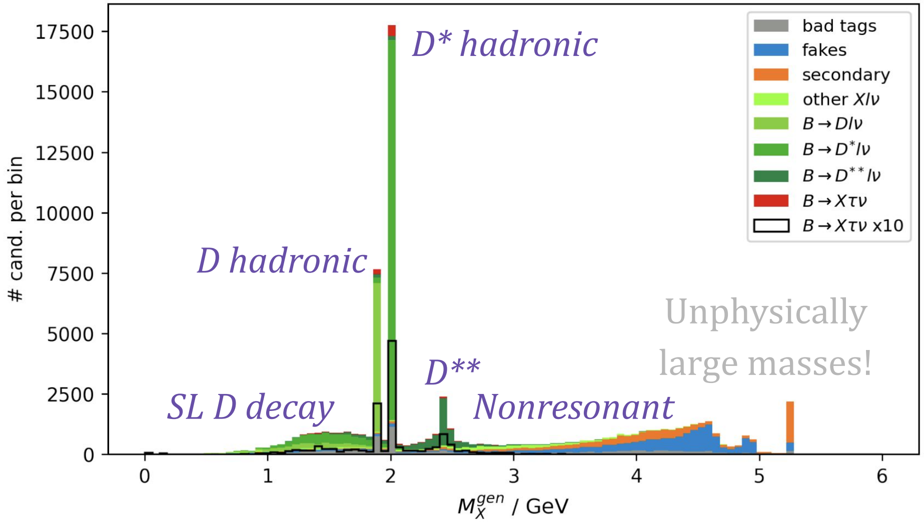
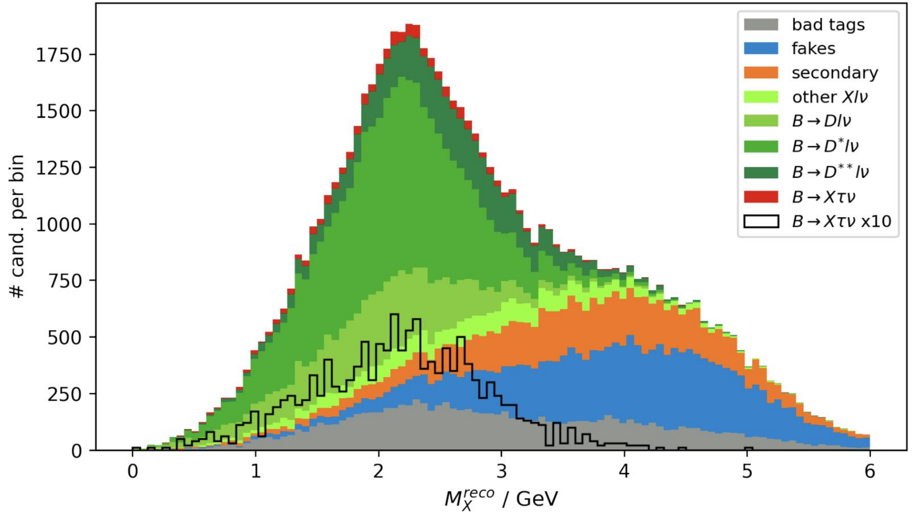




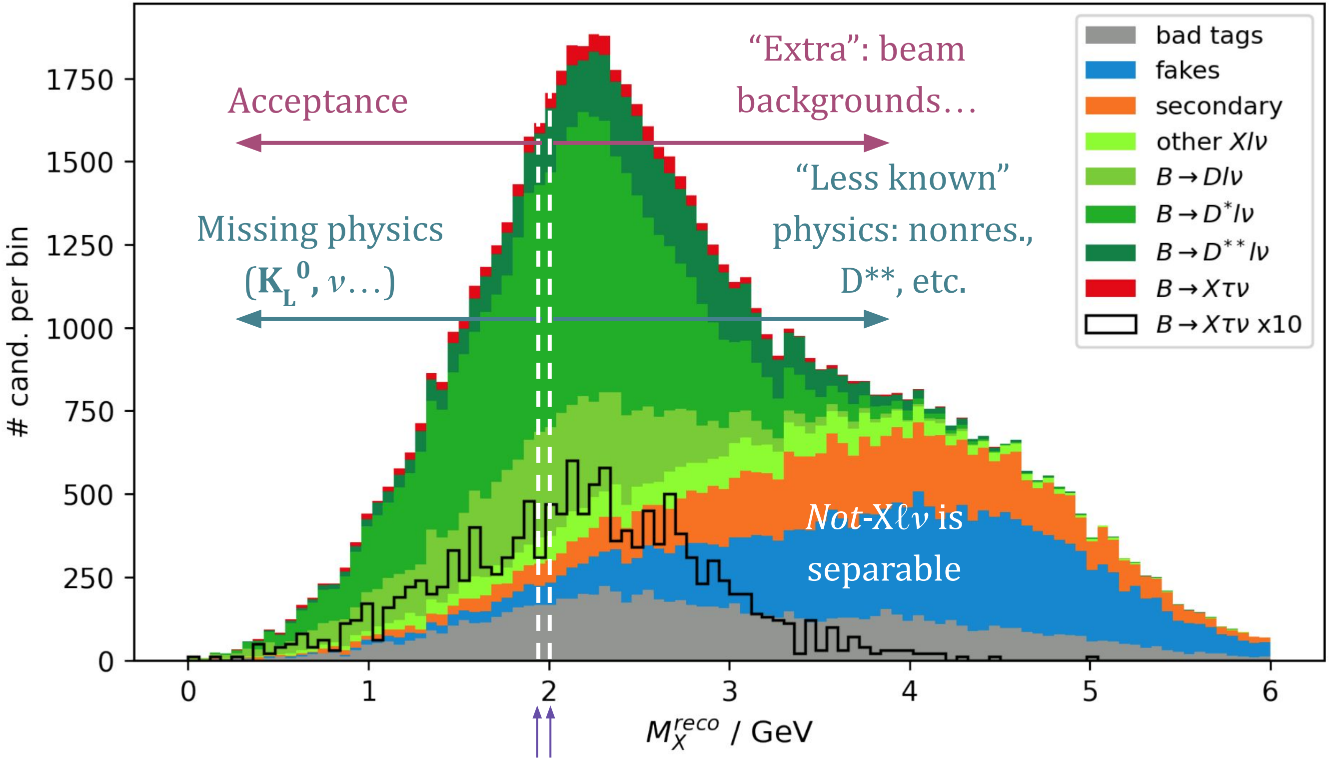
What M_X (invariant mass) *would* look like if we made no **reconstruction errors in the *X*** (except *neutrinos*)

What it *really* looks like (in MC)…

… how does this shape arise?

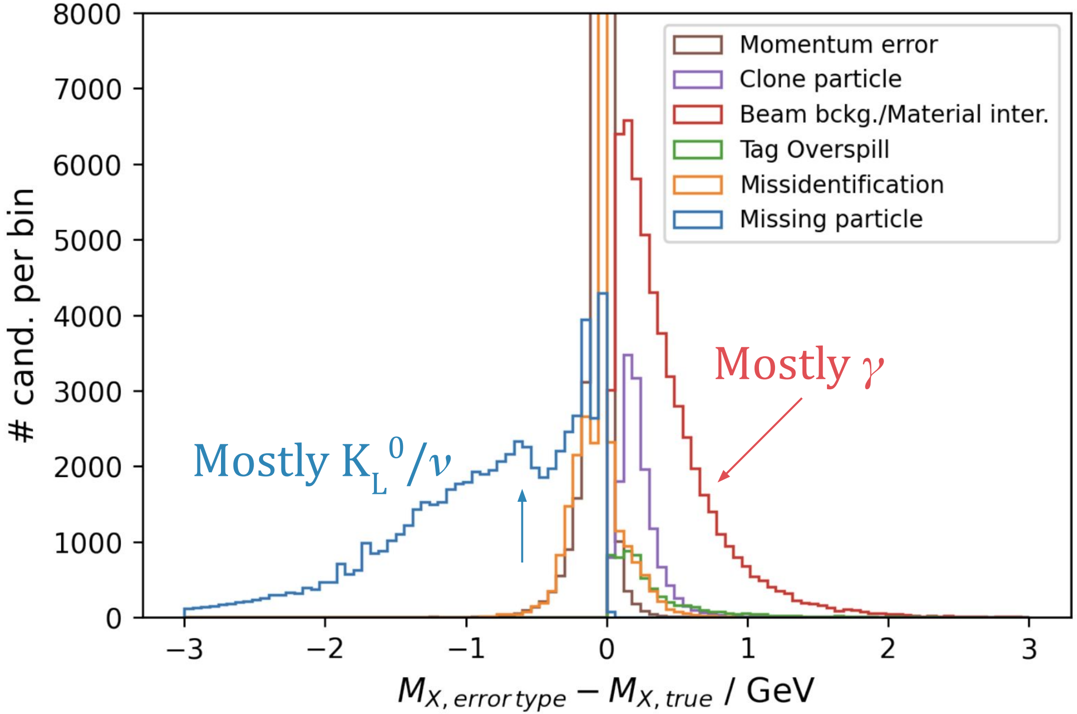
X: what determines the shape?

M_X shape describes the **underlying physics**… smeared out by (*relatively* well-modeled) **detector effects**



Minimum X_c mass (m_D, m_{D^*});
~2/3 of events

Contributions to M_X misreconstruction by **error type**



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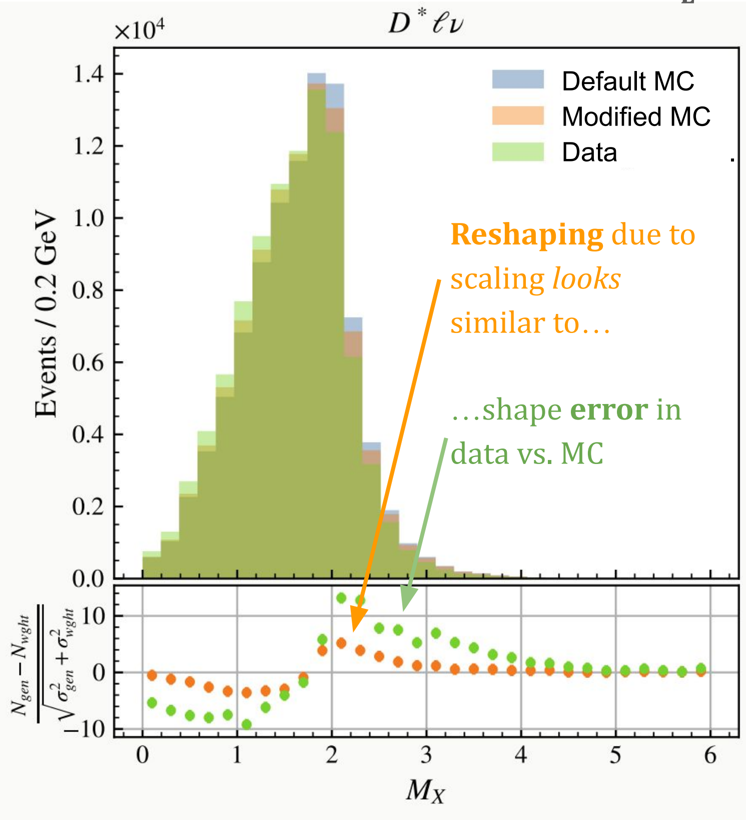
Note: one event can have several of these errors at once

Mostly *missing* and *extra*, which are **largely irreducible**

The M_X shape is sensitive to the types of modeling that are hardest to do right:

- Inclusive K_L^0 BF
- D^{**} and nonres. BF
- Modeling of high-multiplicity D decays

Effect of manually **scaling up K_L^0**



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Implication: M_X gives us a handle on all of the physics modeling that impacts m_{miss}^2 + …

Why not just fix the modeling instead?

Conclusions from extensive work by current team:

- **Branching fractions** are a big piece of the puzzle (particularly $D \to K_L^0 X$) but *cannot solve it entirely*
- The **phase-space modeling** using in ~40% of D decays is significant/unfixable
- The PDG inclusive and exclusive BFs cannot be reconciled

	PDG		MC	
Decay	D^0 BF / %	D^+ BF / %	D^0 BF / %	D^+ BF / %
K^-	54.7 ± 2.8	25.7 ± 1.4	56.1	30.5
K^0 / $\bar{K}^0$	47 ± 4	61 ± 5	40.0	57.5
K^+	3.4 ± 0.4	5.9 ± 0.8	3.7	7.0
$K^{*,-}$	15 ± 9	6 ± 5	12.7	4.6
$\bar{K}^{*,0}$	9 ± 4	23 ± 5	9.1	19.3
$K^{*,0}$	2.8 ± 1.3	< 6.6		

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Fixing this at generator level is not feasible; instead, use M_X to **reweight** our MC…

Why is M_X so nice for this?

It controls the **part** of the reconstruction that we know the least about …

Very reliable

$$M_X{}^2 = \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}^2$$

$$q^2 = \left[\begin{pmatrix} E_{\mathrm{CMS}}/2 \\ -\vec{p}_{B_{\mathrm{tag}}} \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2$$

$$m_{\mathrm{miss}}^2 = \left[\begin{pmatrix} E_{\mathrm{CMS}} \\ \vec{p}_{\mathrm{CMS}} \end{pmatrix} - \begin{pmatrix} E_{\mathrm{CMS}}/2 \\ -\vec{p}_{B_{\mathrm{tag}}} \end{pmatrix} - \begin{pmatrix} E_\ell \\ \vec{p}_\ell \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2$$

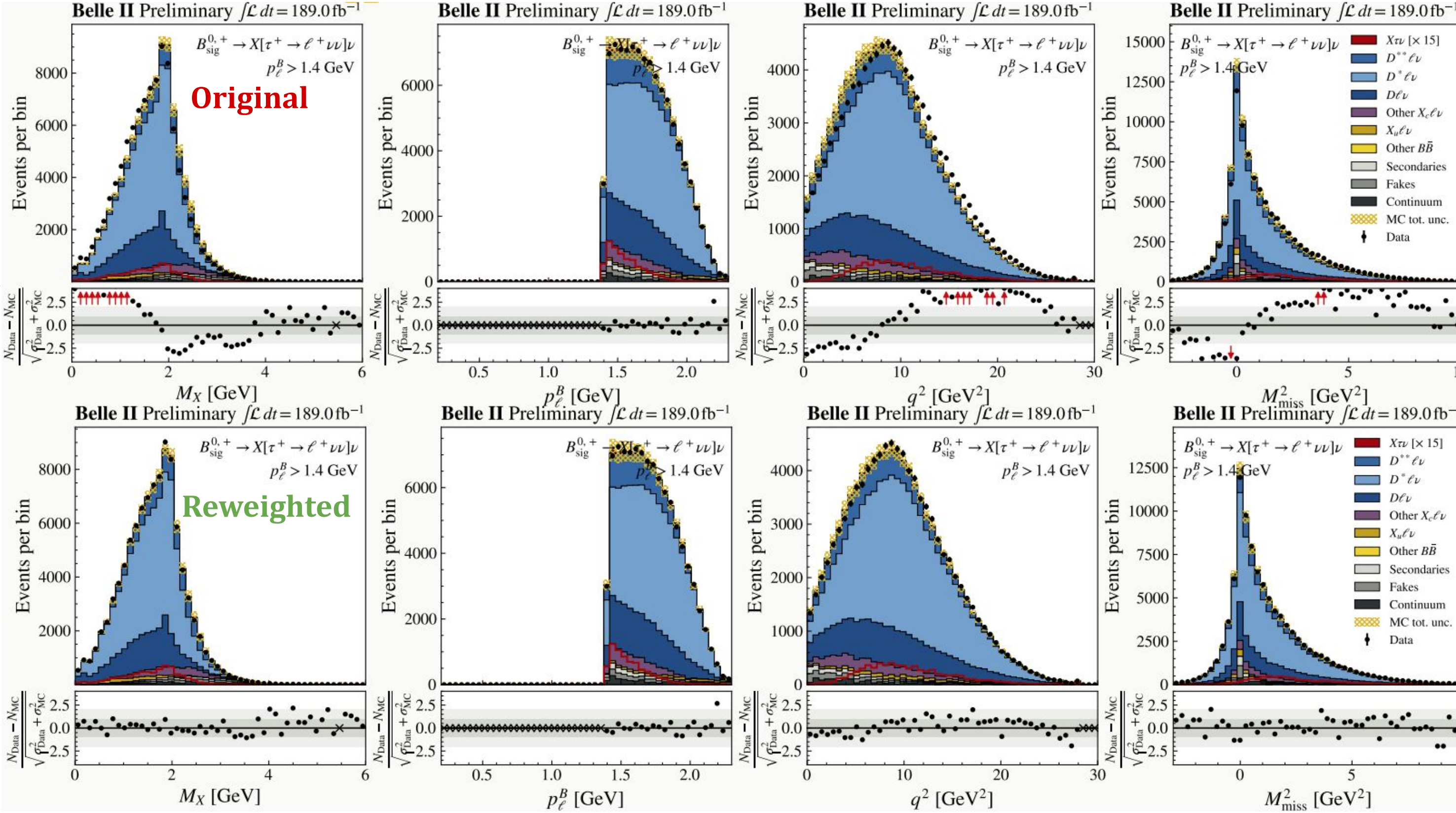
Does it work?

M_X reweighting

Event weights from data/MC ratio in M_X (high-p_l sideband)

Applied to all events

Mismodeling is **magically** "healed" in *all other variables!*



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The end

A path forward

- M_X reweighting unlocks $R(X)$ at Belle II…
- …but a huge amount remains to be learned about inclusive modeling of the D decays

Look for $R(X)$ in La Thuile!