MAY 30, 2023

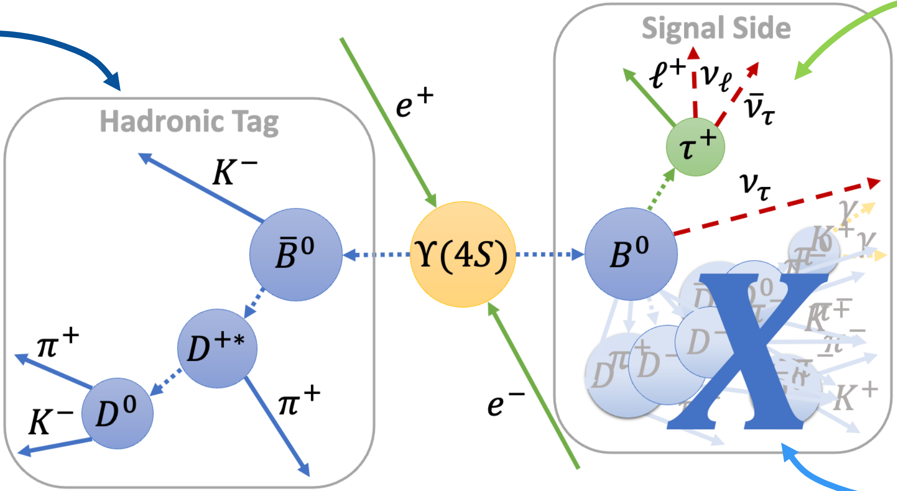
UNDERESTIMATION OF "$D \rightarrow K_L^0$-LIKE" DECAYS IN SEMILEPTONIC B-MESON DECAYS @ GENERATOR-LEVEL

Henrik Junkerkalefeld

* = junkerkalefeld@physik.uni-bonn.de

EVENT SELECTION

- Hadronically tagged
- Very tight constraint of $\mathcal{P}_{\rm sig}^{\rm had.FEI} > 0.1$
- Very pure tag-side, good kinematic control



- Lepton with $p_\ell^{\rm T} > 0.3/0.4$ GeV
- Very inclusive sample

- Beam bkg. & had. splitoff rejection
- No KLM clusters used for ROE! (only for muons)

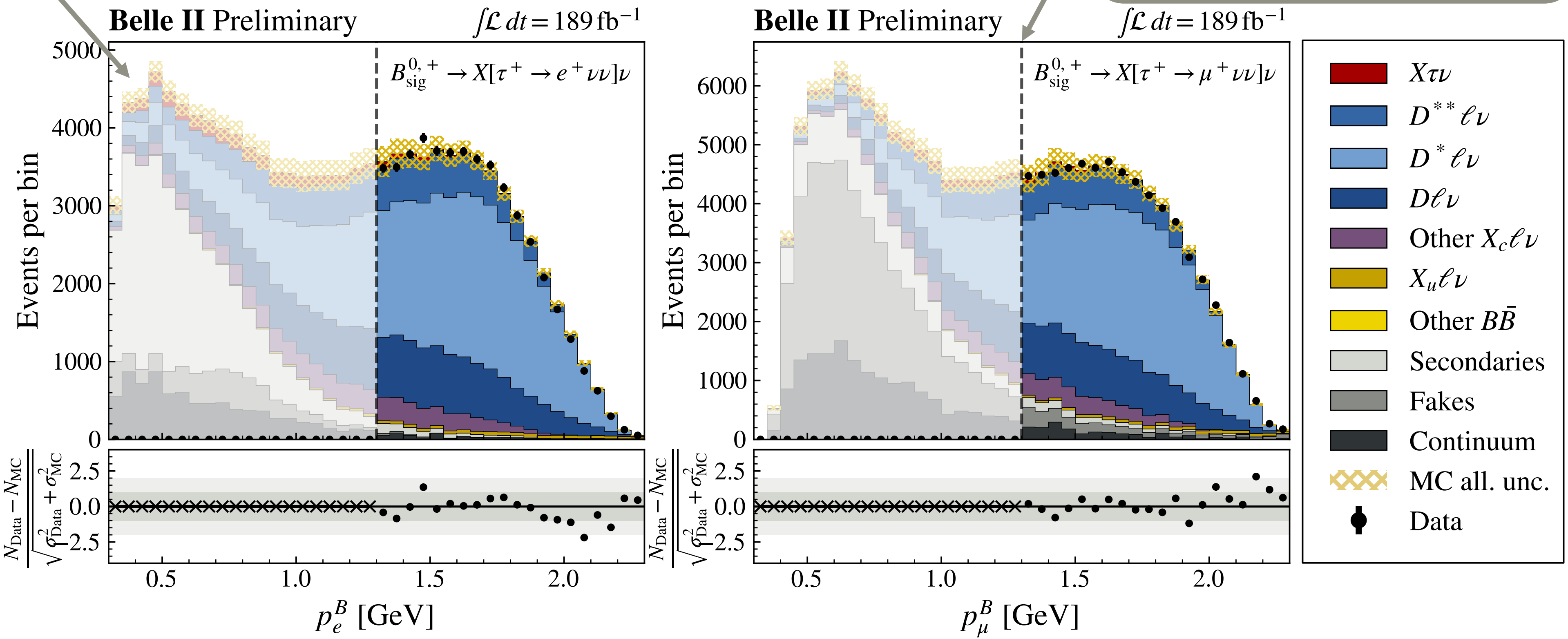
MC14, 189 fb^{-1}

$D \to K_L^0$ decay modeling basically unchanged in MC15 (cf. backup).
So everything that follows is expected to be **equally relevant for MC15**.

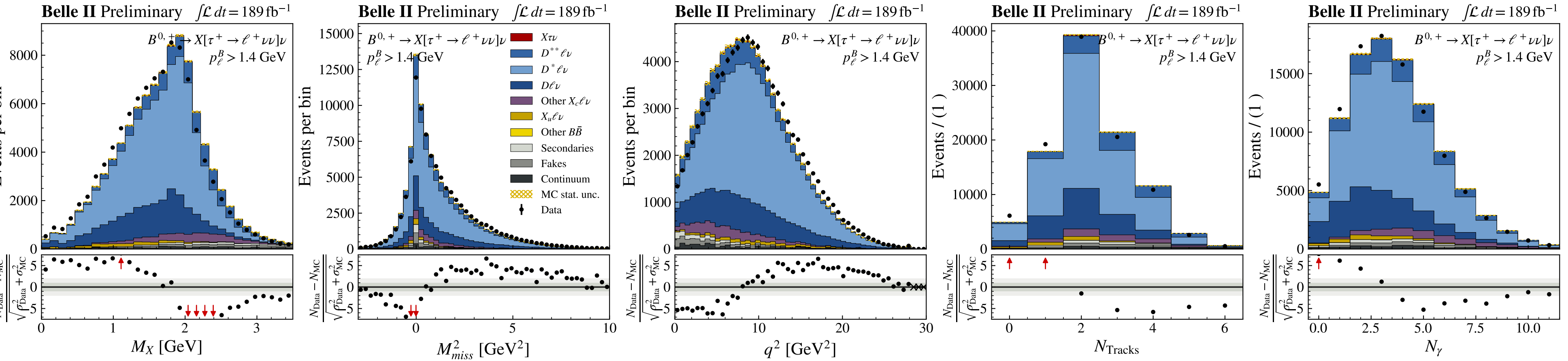
HIGH p_ℓ^B: A PURE $X\ell\nu$ SIDEBAND

Low p_ℓ^B issue that currently limits $R(X_{\tau/e})$ does not matter here.

Tight p_ℓ^B cut to suppress
- hadrons faking leptons ("**fakes**")
- secondary leptons from $b \to c \to (\ell, s)$ cascades ("**secondaries**")
- $B \to X\tau\nu$



FACTS ABOUT OUR CURRENT $X\ell\nu$ MODELING



- Our **inclusive**, semileptonic $B \to X_c \ell\nu$ modeling only **poorly agrees with data.**
- Data has a higher fraction of events with: **low M_X, high M^2_{miss}, and low multiplicities**
- This effect is **mode dependent** (see following slides) and does not correlate to suspicious phase spaces w.r.t. detector efficiency mismodeling (not exclusive to low momentum tracks or low energy clusters).

➢ **Assumption: Generator level issue caused by mismodeling of (hadronic) D decays**

FACTS ABOUT D DECAY MODELING

- The **inclusive** $D \to K_L^0 + X$ decays are
  - **not known** in the PDG (only $D \to K^0$, but high unc.)
  - **NOT just the sum of exclusive** $D \to K_L^0$ …, they include stuff like $D \to [K^* \to K^0 \ldots] \ldots$
  - **underrepresented in our MC(14&15).** It's on the lower edge or below their sizeable uncertainty.
    - An **increase of $D \to K^0$ decays of 20-25%** (D^0: $40 \to 50\%$, $D^+: 57.5 \to 66\%$) is **covered by the PDG uncertainties.**
- **Branching fractions** are a big piece of the puzzle (particularly $D \to K_{\mathrm{L}}^0 X$), but cannot solve it entirely
- The **phase-space modeling** used in $\approx 40\%$ of the 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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We derived an **iterative, data-driven reweighting** of the inclusive components $D \to \ell, K^\pm, K_S^0, K_L^0, K^{*\pm}, K^{*0} + X$ to find **sweet spot suggested by data**:

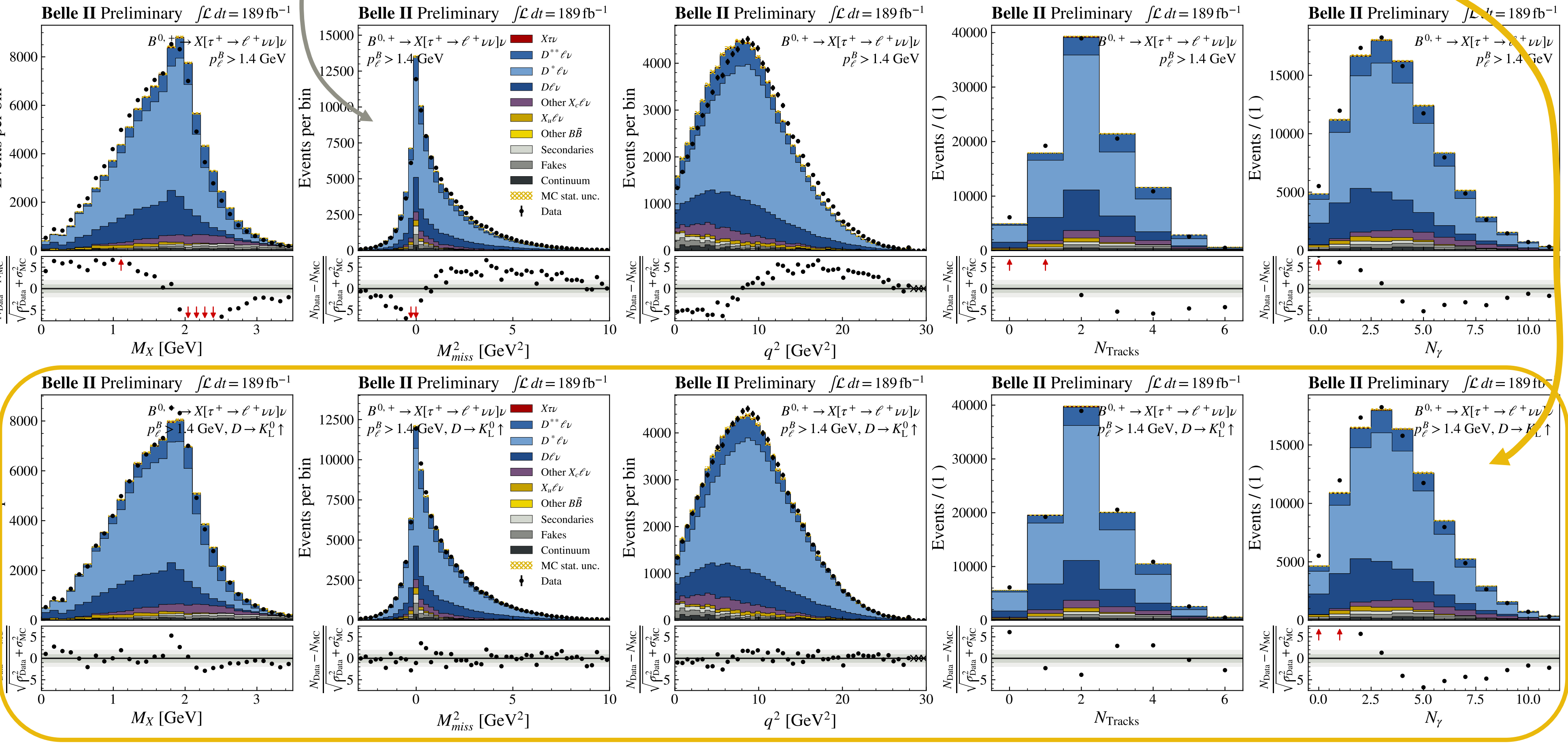
$D^0 \to K_L^0$: $20.6 \to 28.8$ % (39% increase)

$D^+ \to K_L^0$: $30.1 \to 40.8$ % (36% increase)

(obviously unreliable, but it's a fact that data can best be described by our MC if this is done)

Very untrivial to fix M^2_{miss}.
Simple energy shift is insufficient.

$X\ell\nu$ MODELING WITH 36-39% $D \to K^0_L$ UPSCALING



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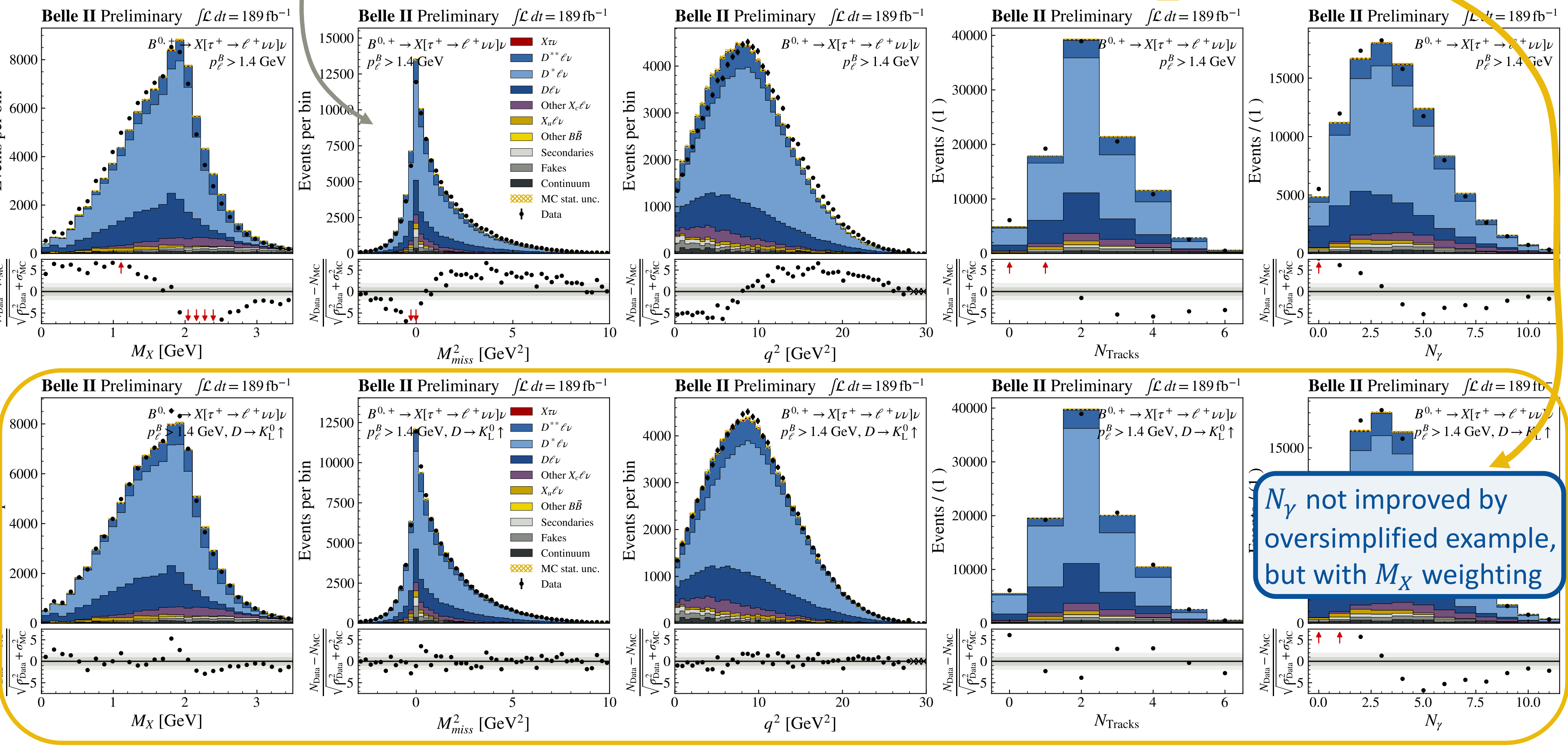
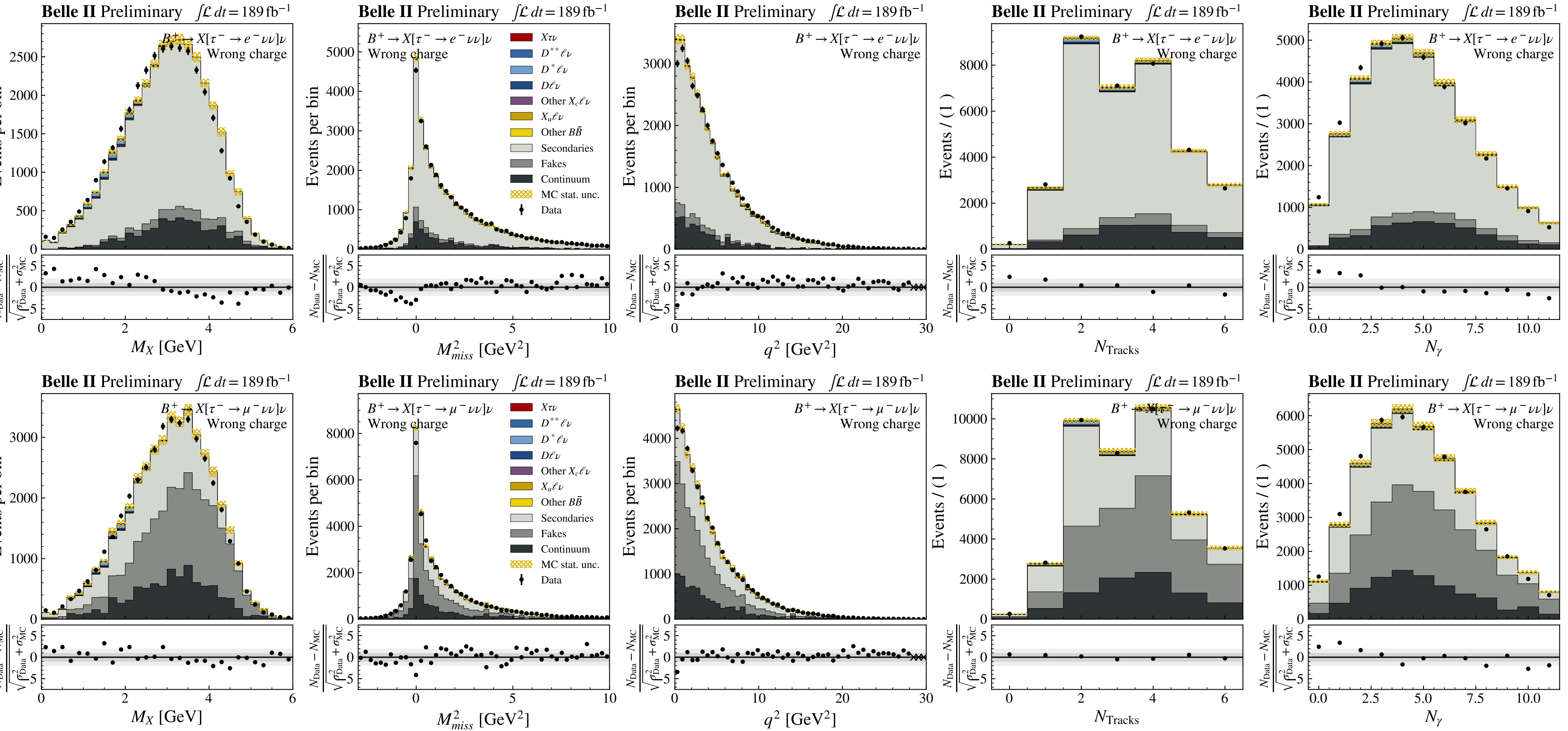


MODE DEPENDENCY OF MISMODELING



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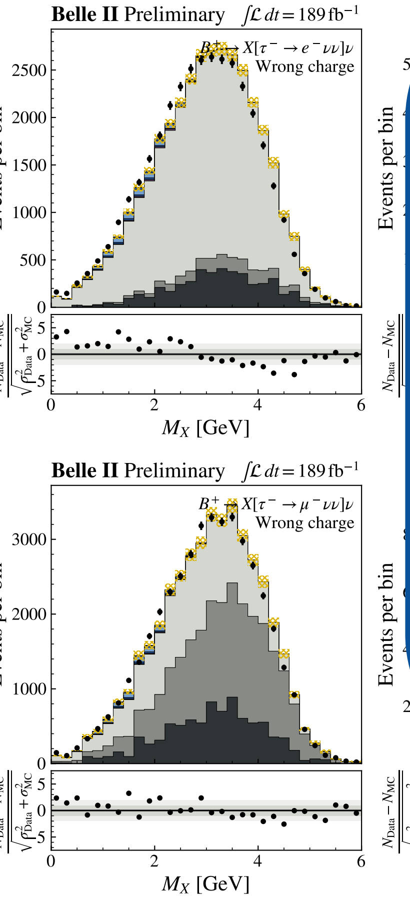
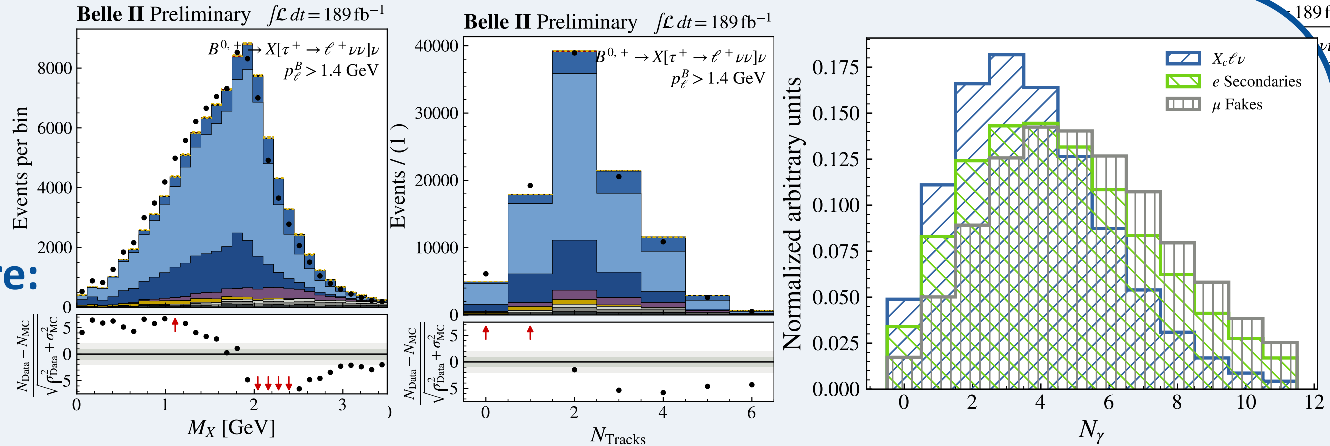
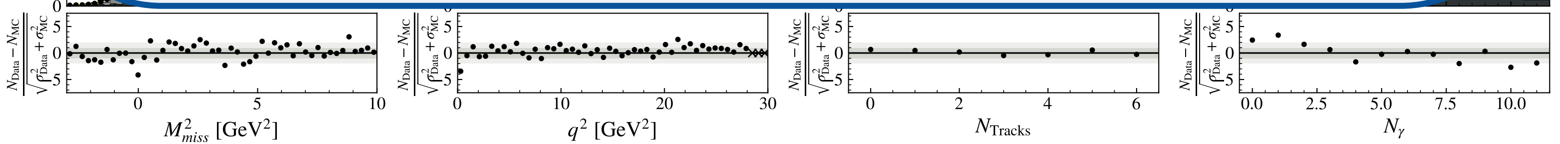


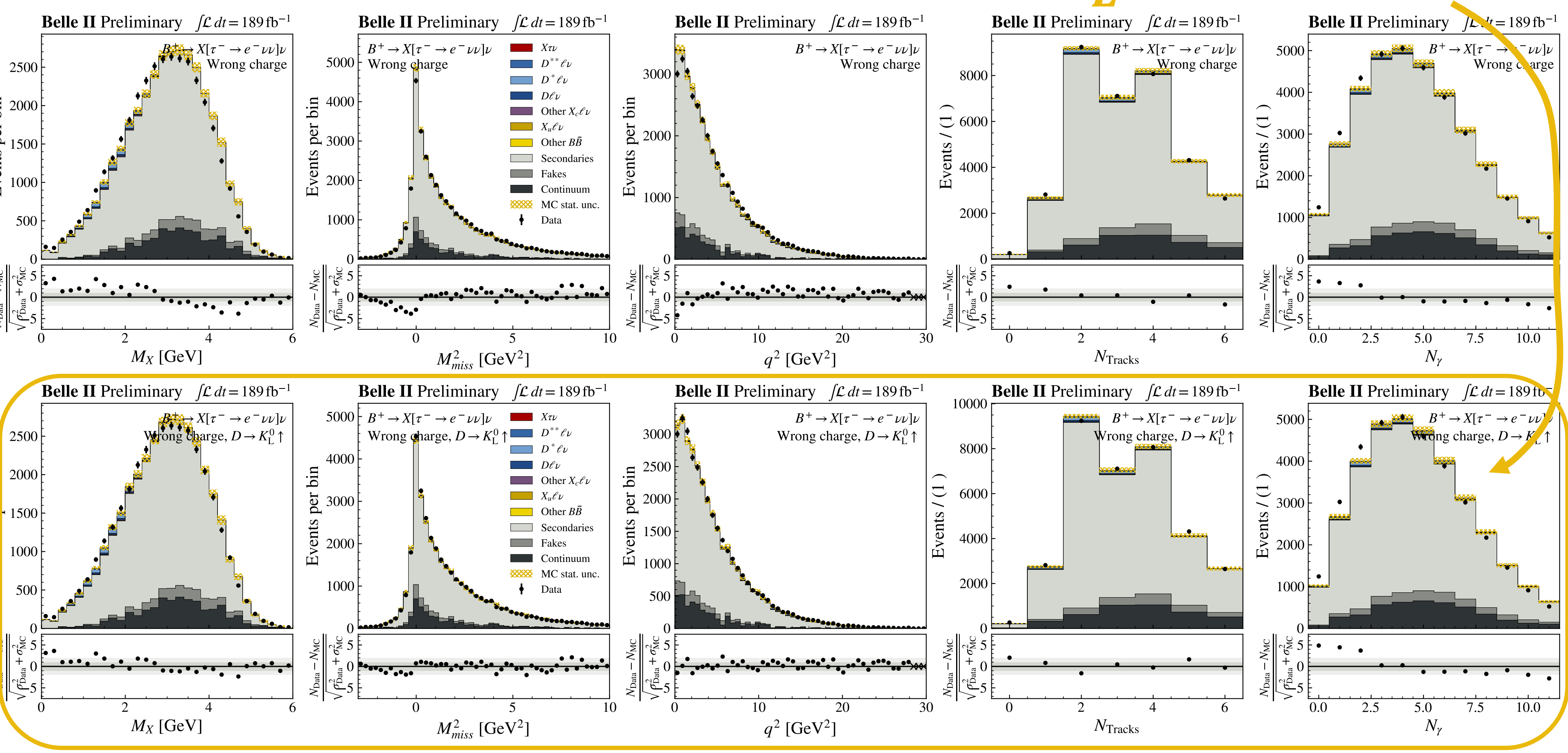
Compare:



- Secondaries and fakes do have **more reco. photon clusters on average** than $X\ell\nu$
- **If** problem was (mainly) **caused by fake cluster mismodeling**, I'd expect it to be **strongest in fake-enriched sideband**. **The opposite is true!**
- In fact, in very pure sidebands for $\pi \to e/\mu$ & $K \to e/\mu$ fakes, $\gamma \to e^+e^-$ & $J/\Psi \to \ell^+\ell^-$, no mismodeling at all is observed.



SIDEBANDS WITH 36-39% $D \to K_L^0$ UPSCALING



SUMMARY AND CONCLUSION

- **Data** of inclusive $X_c\ell\nu$ modeling is **best described** when **increasing relative $D \to K_L^0$** events of our generic MC(14) to **136-139%**! If the $K\nu\nu$ excess is completely explained by a similar increasement, this is in agreement with the $X_c\ell\nu$ mismodeling.
- These numbers won‘t be the final truth. It’s probably overshooting to **account for additional D-meson decay kinematic mismodeling** (40% modeled only with phase space)
- Mismodeling is **strongly mode-dependent**. It washes out when hadronic B decays & $B \to X_c X_c$ dominate and it’s mainly related to the X system (not the $B \to \ell$ part).

➢ **Fake cluster assumption insufficient.** Their adjustment does not change N_{track} and unclear why it would not show up for fakes or secondaries (it can additionally be true, but it’s effect is probably comparably small)

- Data compared to our MC has more **high M^2_{miss}, low M_X** and **low multiplicity (including N_π & N_K, not only N_γ)** events! This looks just like $D \to K_L^0 + \text{X}$ (or $B \to K\nu\nu/[\tau \to \ell\nu\nu]\nu$)
  - ➢ Be aware if $X_c\ell\nu$ dominates backgrounds and you are looking for such signatures

BACKUP

MC14 VS MC15: D DECAY MODELING

Final charm meson is D^0 for

- 77% of my reconstructed $B \to X_c \ell \nu$ (majority)
  - 93% of FEI tagged $B^+_{\mathrm{FEI}} \to X_c \ell \nu$
  - 52% of FEI tagged $B^0_{\mathrm{FEI}} \to X_c \ell \nu$

Final charm meson is D^+ for

- 23% of my reconstructed $B \to X_c \ell \nu$ (minority)
  - 7% of FEI tagged $B^+_{\mathrm{FEI}} \to X_c \ell \nu$
  - 48% of FEI tagged $B^0_{\mathrm{FEI}} \to X_c \ell \nu$

Any altered decay that contains either a K^0_L or something that can decay into it ($K^*, K_1 \ldots$):

```
### MC14 D0:
0.005600000    K_L0   eta   pi0                       PHSP;
0.035300000    K_L0   pi+   pi-   pi0                 PHSP;
0.000237000    K*+   pi-                              SVS;
```

```
### MC15 D0:
# changed BR 0.0056 to:
0.010100000    K_L0   eta   pi0                       PHSP;
# changed BR 0.0353 to these ones (several new modes):
0.006000000    K_L0   pi+   pi-   pi0                 PHSP;
0.008560000    K_L0   pi0   pi0   pi0                 PHSP;
0.008560000    K_L0   pi+   pi-   pi0   pi0           PHSP;
0.008655500    K_L0   pi+   pi-   pi0   pi0   pi0     PHSP;
# changed B*+ BR (0.000237) to:
0.000113000    K*+R   pi-
```

Total $D^0_{\mathrm{MC14}} \to K^0_L/K^*/K_1 \ldots$: 37% (direct $\to K^0_L$: 13%)

All changes combined increase $D^0 \to K^0_L/K^* \ldots$ BR by 0.08% (negligible!)

```
### MC14 D+:
0.003851000    anti-K0   omega   pi+                  PHSP;
0.003040000    K_L0   K+                              PHSP;
0.000770000    K+   anti-K0   pi0                     PHSP;
```

```
### MC15 D+:
# replaced anti-K0 by 50-50% K_S0 & K_L0:
0.001925500    K_L0   omega   pi+                     PHSP;
# added!:
0.013100000    K_L0   eta   pi+                       PHSP;
# changed BR 0.00304 to:
0.003120000    K_L0   K+                              PHSP;
# changed BR drastically from 0.00077/2. to:
0.005240000    K_L0   K+   pi0                        PHSP;
```

Total $D^+_{\mathrm{MC14}} \to K^0_L/K^*/K_1 \ldots$: 56% (direct $\to K^0_L$: 24%)

All changes combined increase $D^+ \to K^0_L/K^* \ldots$ BR by 1.77% (no game changer)

(Semi)leptonic modes are biased as any time the lepton is picked, the final event is not classified as $X_c\ell\nu$ any more. **Hadronic modes** are unbiased and were tested independently.

DATA SUGGESTED D DECAY COMPOSITIONS

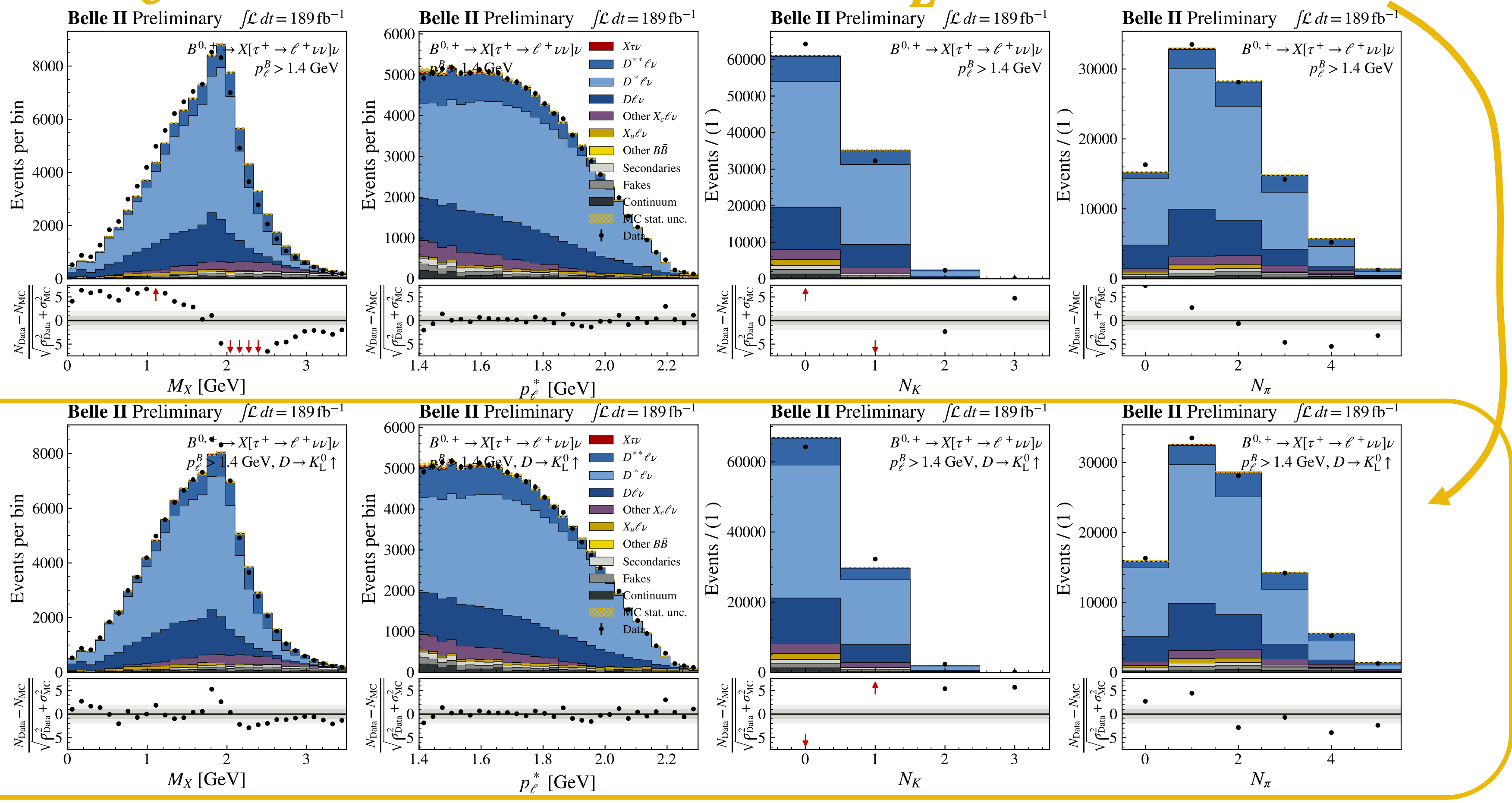
- These distributions are NOT more realistic
- BUT they are the ones needed if one wanted to have a **good shape description of $X_c\ell\nu$ without reweighting any kinematic distributions**
- They result in an **upscaling of $D \to K_L^0$ of 39/36%**
- The procedure is not **sensitive to all effects**, it just upscales stuff with missing energy (K_L^0, ν). This is why K^- or K_S^0 become so unrealistic

Decay mode	D^0 generic MC	D^0 data suggested	D^+ generic MC	D^+ data suggested
$e + X$	4.9%	**6.9%**	9.7%	**11.4%**
$\mu + X$	3.6%	**5.3%**	8.3%	**10.0%**
$K^- + X$	56.4%	**47.9%**	30.8%	**18.4%**
$K^+ + X$	3.6%	3.4%	6.9%	6.0%
$K^0 + X$	39.7%	48.5%	57.3%	69.5%
$K_S^0 + X$	19.6%	20.3%	29.0%	31.5%
$K_L^0 + X$	**20.6%**	**28.8%**	**30.1%**	**40.8%**
$K^{*\pm} + X$	12.6%	19.5%	4.6%	6.3%
$K^{*0} + X$	9.2%	6.7%	19.5%	12.7%

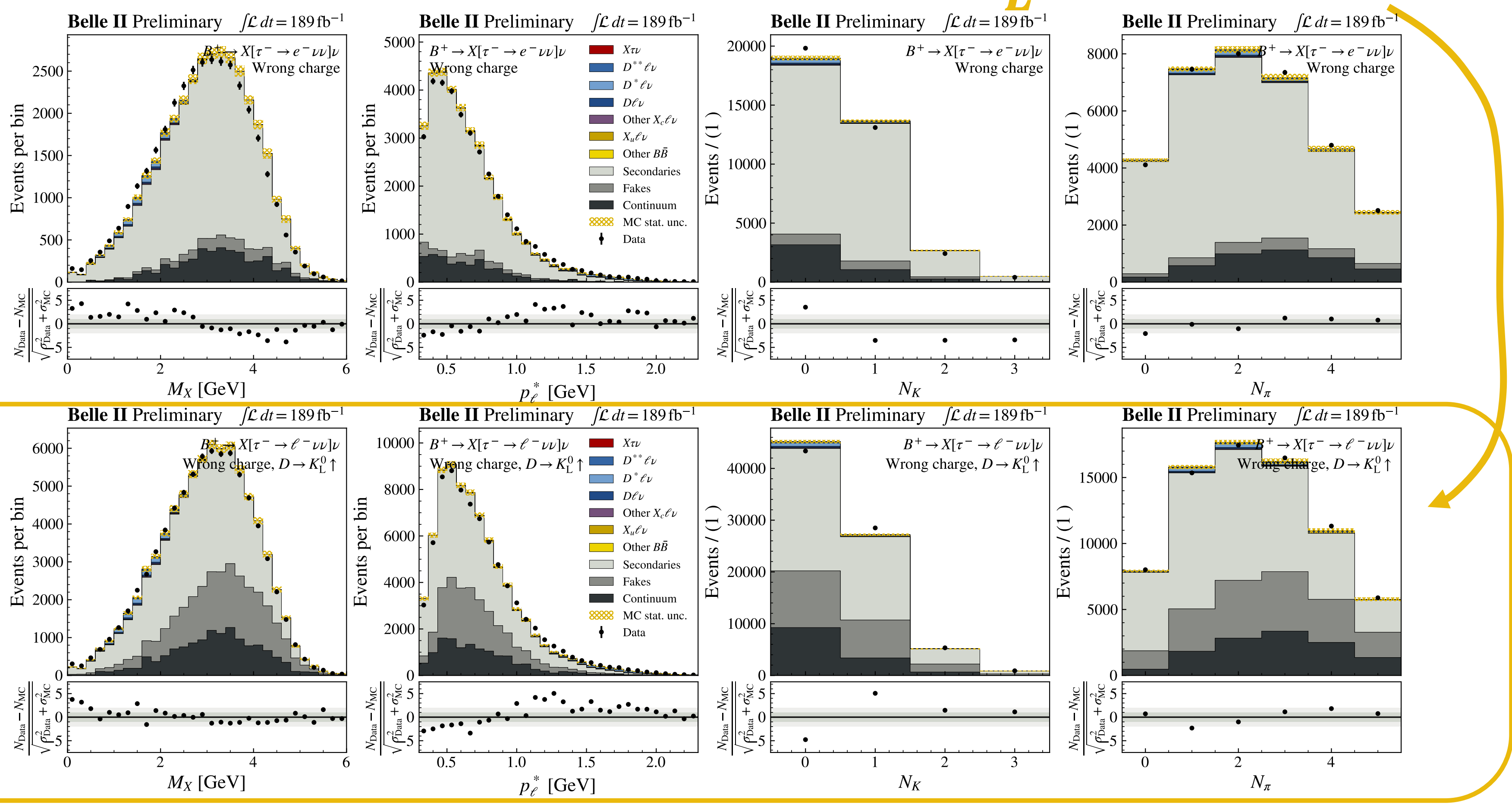
PDG:

		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	$(3.4 \pm 0.4)\%$	$(5.9 \pm 0.8)\%$

$X_c \ell \nu$ WITH 36-39% $D \to K_L^0$ UPSCALING



SIDEBANDS WITH 36-39% $D \to K_L^0$ UPSCALING



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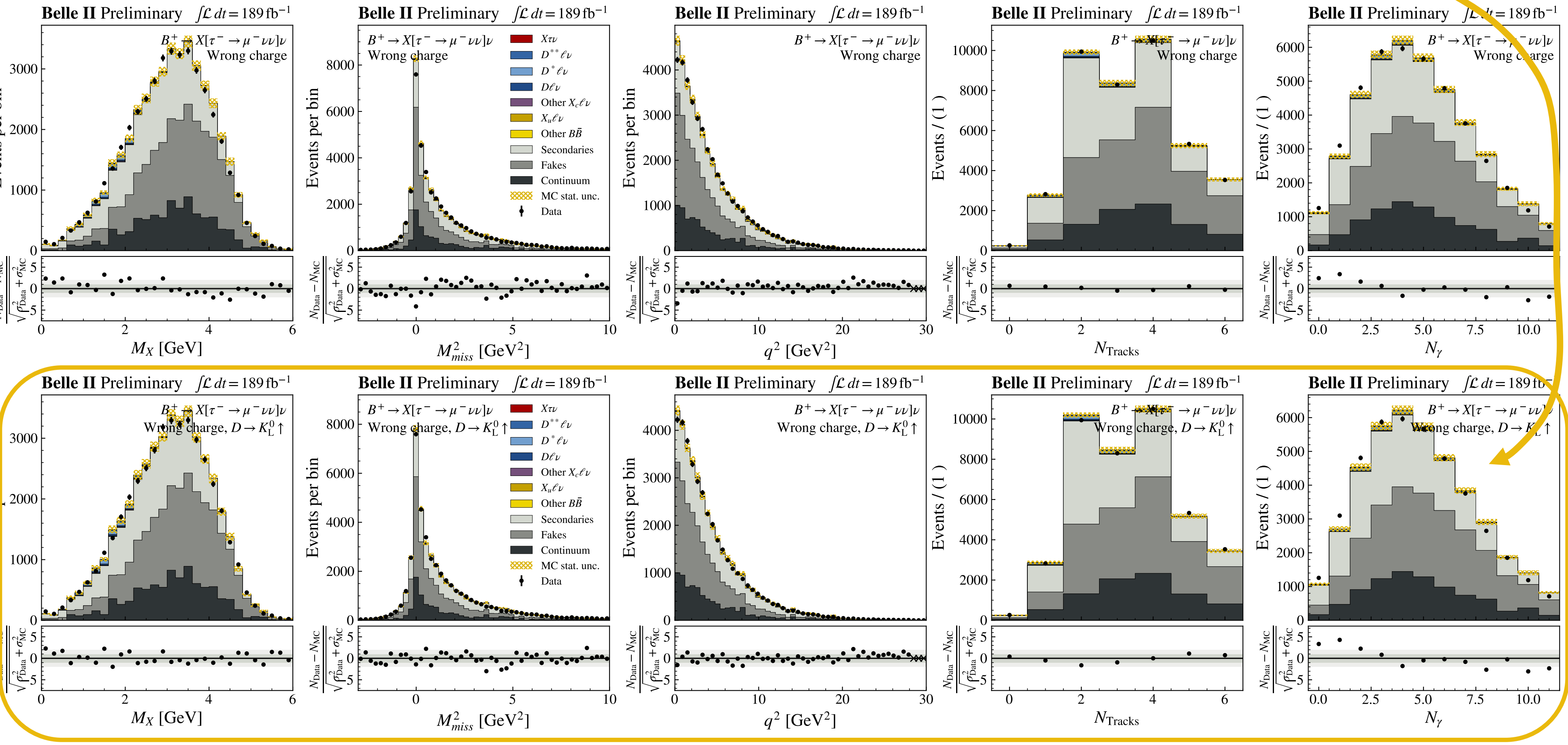

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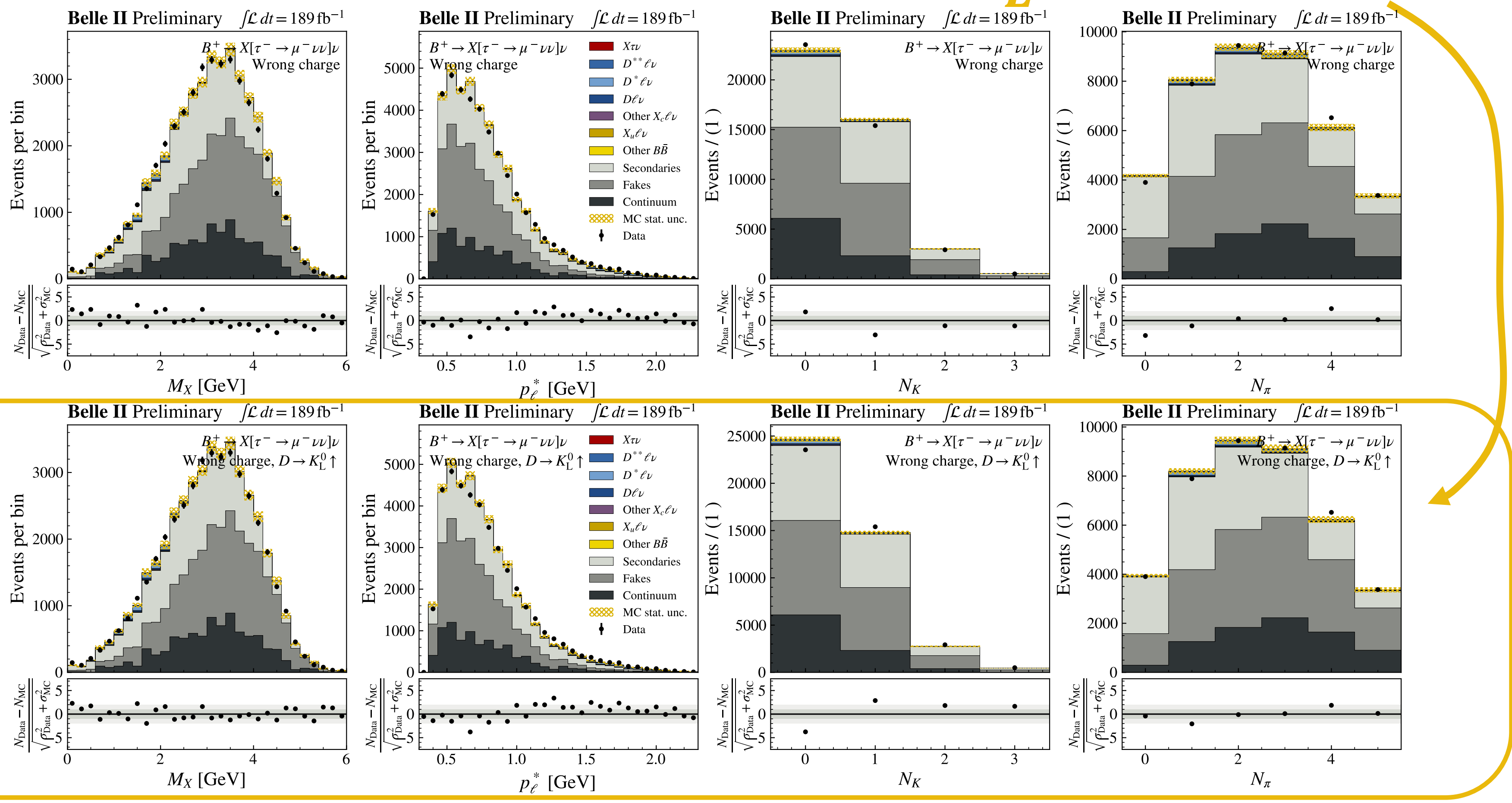
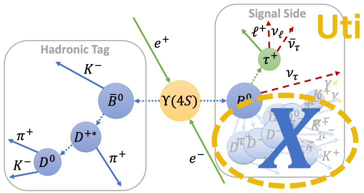
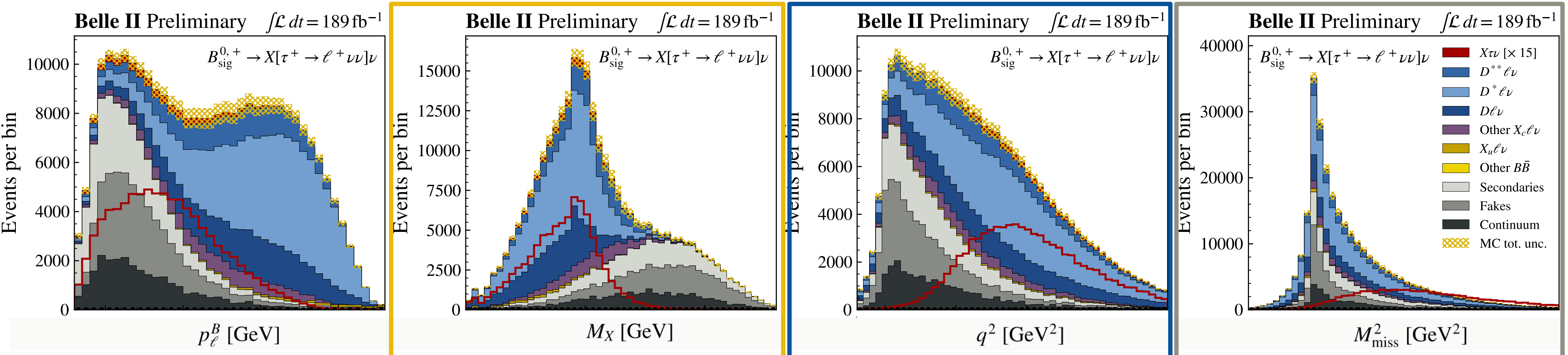


TARGETING $R(X_{\tau/\ell})$



Utilize the X!

- More details in the BELLE2-NOTE, sections 5.6, A.3 and A.4



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

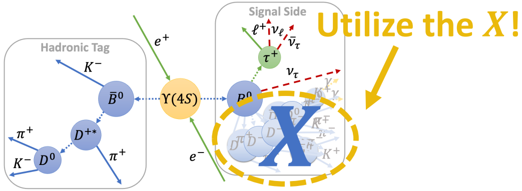
$$q^2 = \left[\begin{pmatrix} E_{\mathrm{CMS}}/2 \\ -\vec{p}_{B_{\mathrm{tag}}} \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2$$

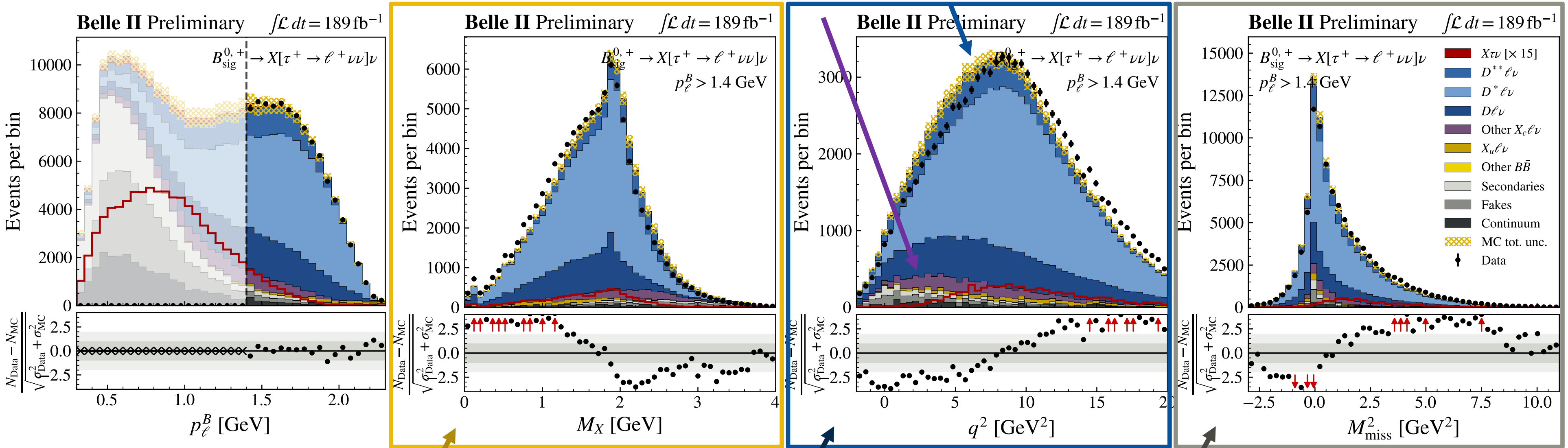
$$M^2_{\mathrm{miss}} = \left[\begin{pmatrix} E_{\mathrm{CMS}} \\ \vec{p}_{\mathrm{CMS}} \end{pmatrix} - \begin{pmatrix} E_{\mathrm{CMS}}/2 \\ -\vec{p}_{B_{\mathrm{tag}}} \end{pmatrix} - \begin{pmatrix} E_\ell \\ \vec{p}_\ell \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2$$

TARGETING $R(X_{\tau/\ell})$

Must be caused by something that is **present in all $X_c\ell\nu$, but not equally in secondaries & fakes**: **Single hadronic D decays!**

Controversial **non-resonant $B \to D^{(*)}\eta\ell\nu$ & $B \to D^{**}\ell\nu$ are** too small to cause the problem!





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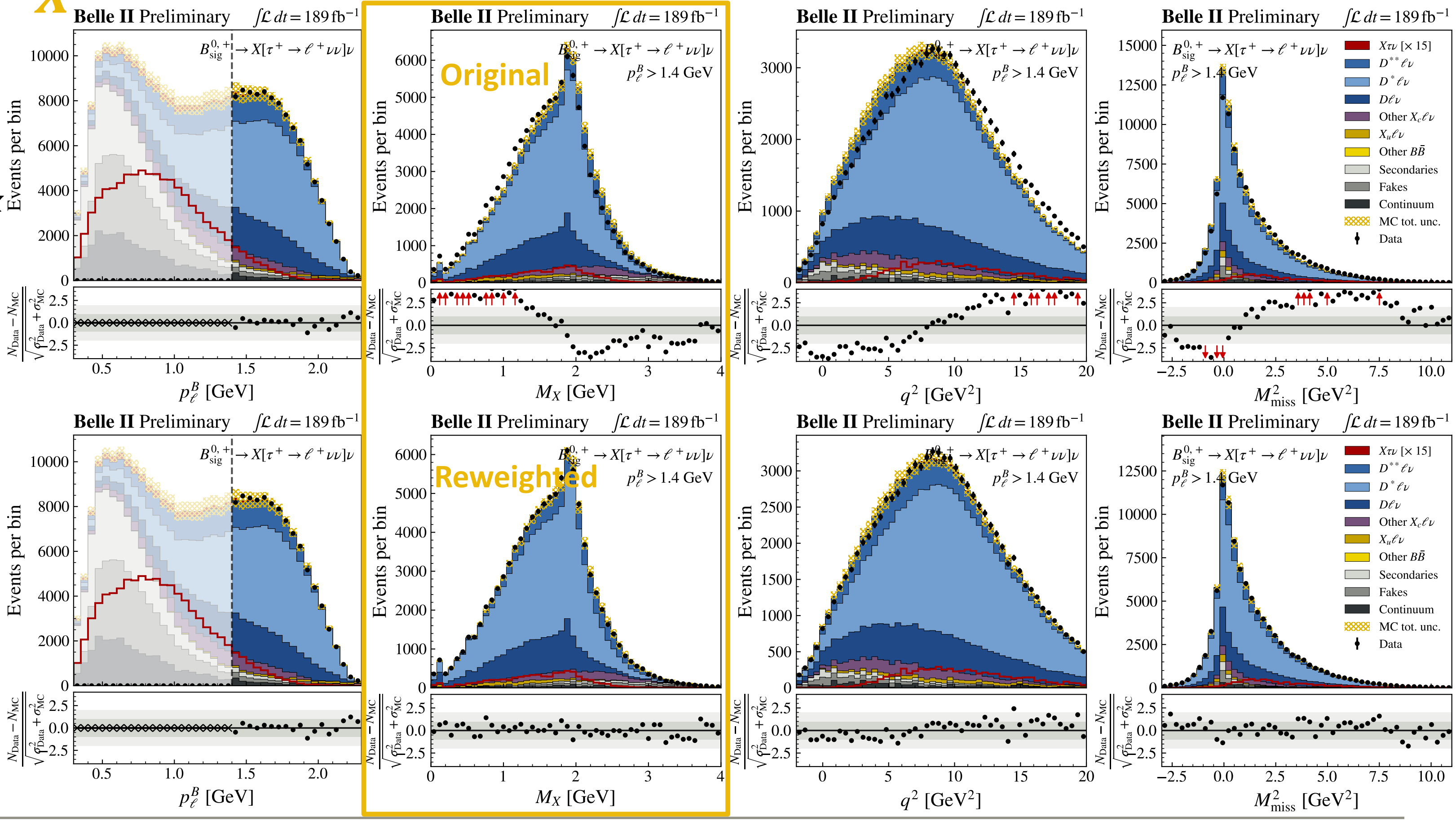
Very reliably modeled and controlled

- M_X controls the part of the reconstruction that we know the least about!

M_X BASED REWEIGHTING OF $X\ell\nu$

Event weights from data/MC ratio in $\boldsymbol{M_X}$ (high p_ℓ^B sideband)



Mismodeling is fixed in **all other variables!**

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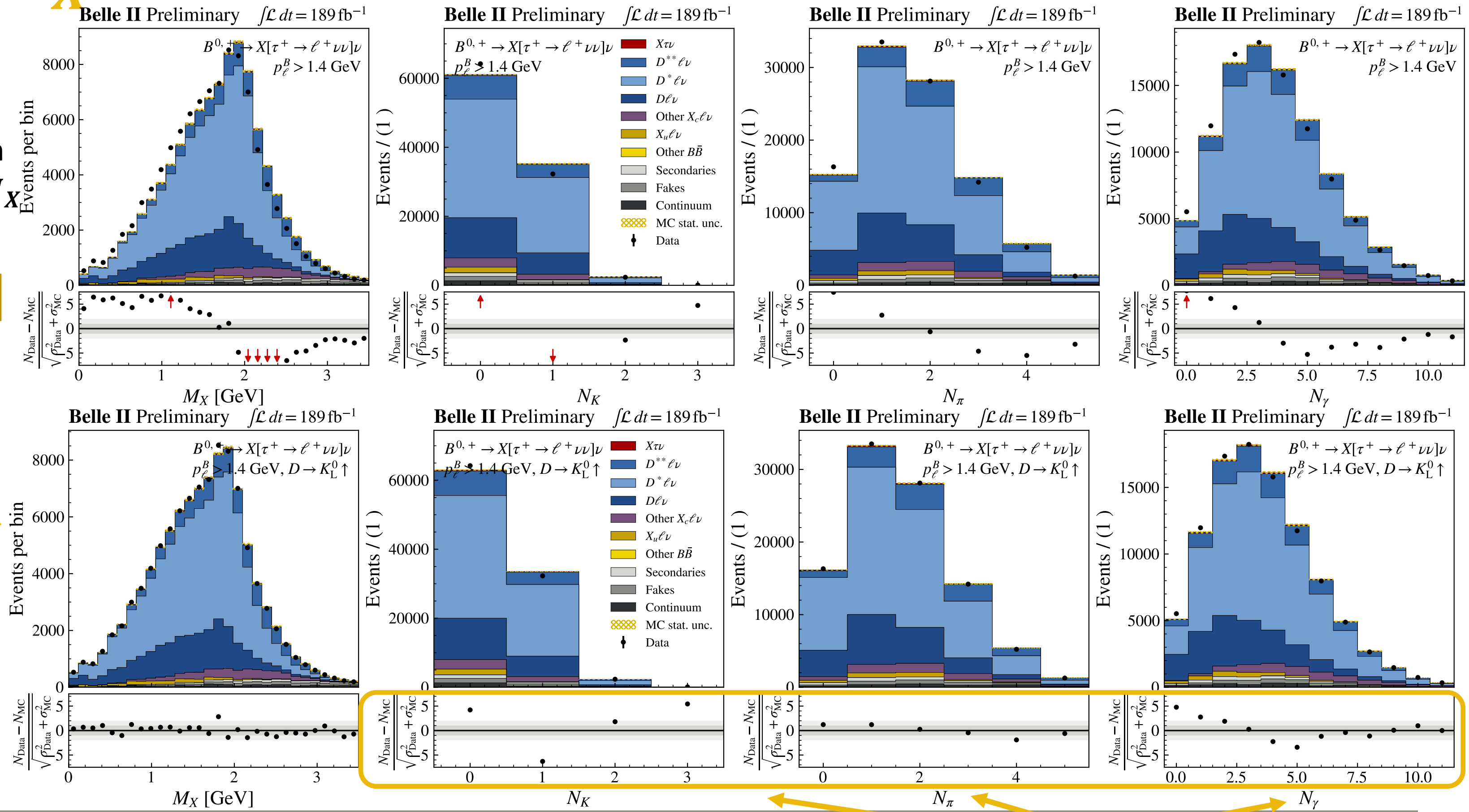

Mismodeling is fixed in **all other variables!**

All multiplicities improve!

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REWEIGHTED D DECAY COMPOSITIONS

- These distributions **do reweight kinematic distributions** (40% of D decays are just phase space modeled)
- Thus, they are **less severe** than the data suggested results (cf. other slide)
- But they **cannot directly be derived** by simply up- and downscaling certain existing events

Decay mode	D^0 generic MC	D^0 M_X reshaped	D^+ generic MC	D^+ M_X reshaped
$e + X$	4.9%	**5.2%**	9.7%	**10.3%**
$\mu + X$	3.6%	**3.8%**	8.3%	**8.9%**
$K^- + X$	56.4%	**55.1%**	30.8%	**29.2%**
$K^+ + X$	3.6%	3.6%	6.9%	6.6%
$K^0 + X$	39.7%	41.1%	57.3%	59.4%
$K_S^0 + X$	19.6%	19.5%	29.0%	28.9%
$K_L^0 + X$	**20.6%**	**22.1%**	**30.1%**	**32.5%**
$K^{*\pm} + X$	12.6%	13.0%	4.6%	4.5%
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PDG:

		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	$(3.4 \pm 0.4)\%$	$(5.9 \pm 0.8)\%$

D DECAY MODELING

N_K uncertainty of 5-10% natural

$K_S^0 \to \pi^{0,\pm}\pi^{0,\mp}$ extends this to an **N_π** and **N_γ uncertainty**

Why not just fix the modeling instead?

- The M_X shape is sensitive to the **types of modeling that are not well known** (inclusive K_L^0 BF, D^{**} and nonres. BF, modeling of high multiplicity D decays)
- **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** used in $\approx 40\%$ of the D decays is significant/unfixable
- The PDG inclusive and exclusive BFs cannot be reconciled

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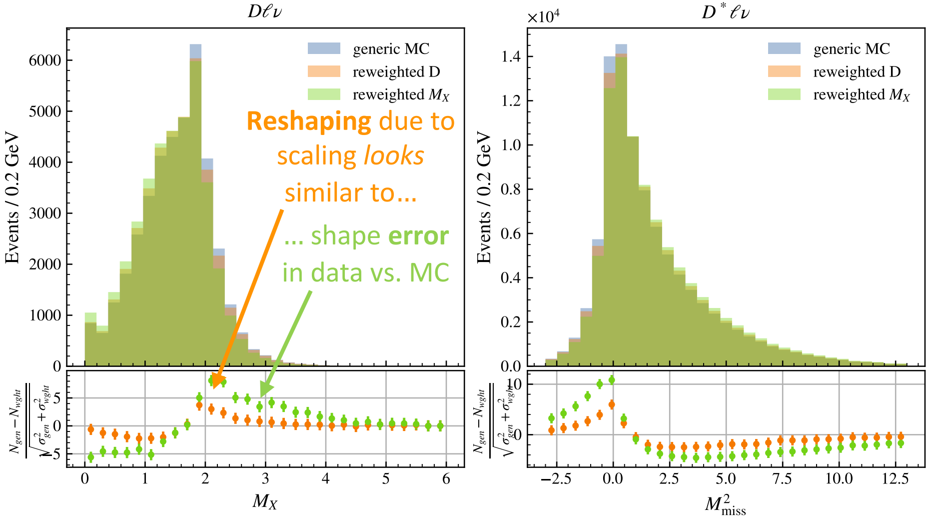


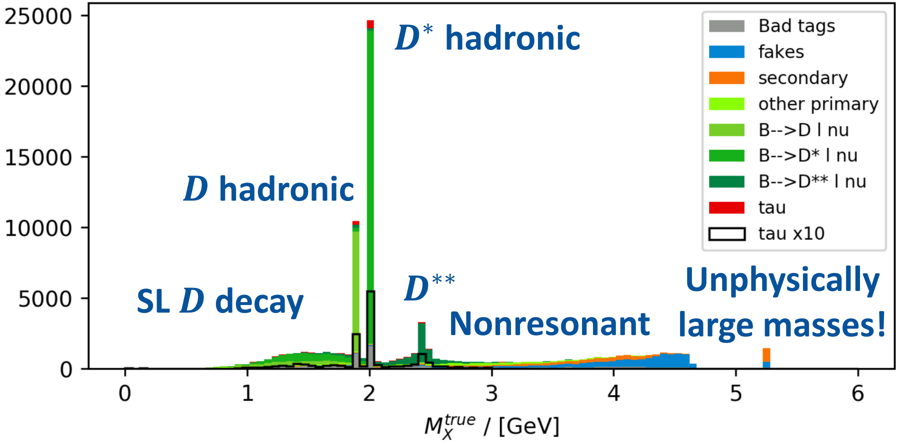
Fixing this at generator level is not feasible; instead, use M_X to reweight our MC in a data-driven way!

Success can be evaluated in non-trivial improvements in **several quantities** ($M^2_{\rm miss}$, q^2, $N_{K^\pm}$, $N_{\pi^\pm}$, N_γ) **at the same time** while keeping other unchanged (p^B_ℓ).

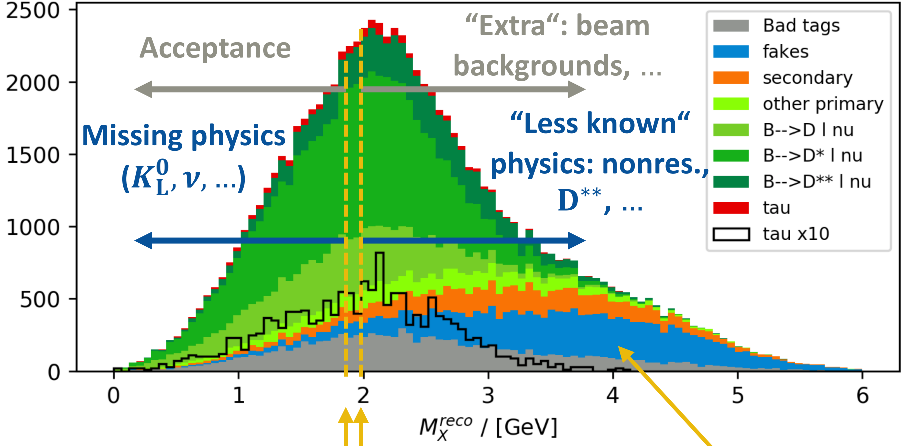
M_X RECONSTRUCTION

Ideally reconstructed M_X, if we made **no reconstruction errors in the X system** except missing neutrinos.

Dennis Benterbusch, Masterthesis, Uni Bonn (2020)



Real M_X distribution (in MC)



Minimum X_c mass (M_D, M_{D^*}); $\approx {}^2/_3$ of events

Not-$X\ell\nu$ is separable

		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	$(3.4 \pm 0.4)\%$	$(5.9 \pm 0.8)\%$