Semi-tauonic Measurements at Belle II

Snowmass 2021: Lepton flavor violation and lepton universality violation in meson and baryon decays

Florian Bernlochner | Snowmass 2021

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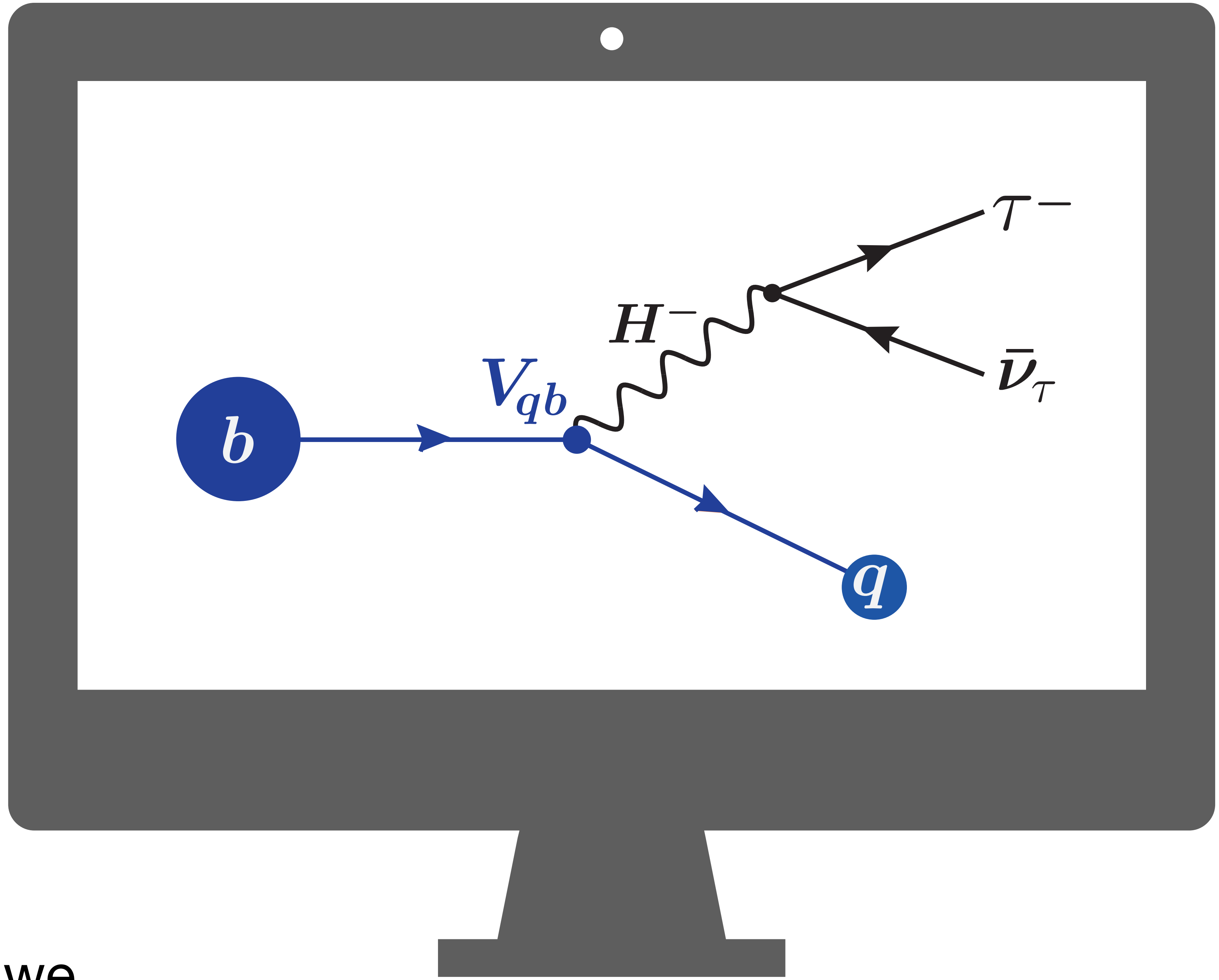
$$\mathscr{R} = \frac{b \to q\,\tau\,\bar{\nu}_\tau}{b \to q\,\ell\,\bar{\nu}_\ell}$$

$$\downarrow \qquad \ell = e, \mu$$

$$\mathscr{R}(D^{(*)}, D_s^{(*)}, X, \pi, \ldots)$$



1. How do we measure today?

2. Extrapolating to Belle II

3. Novel Ideas

4. Going Wilson

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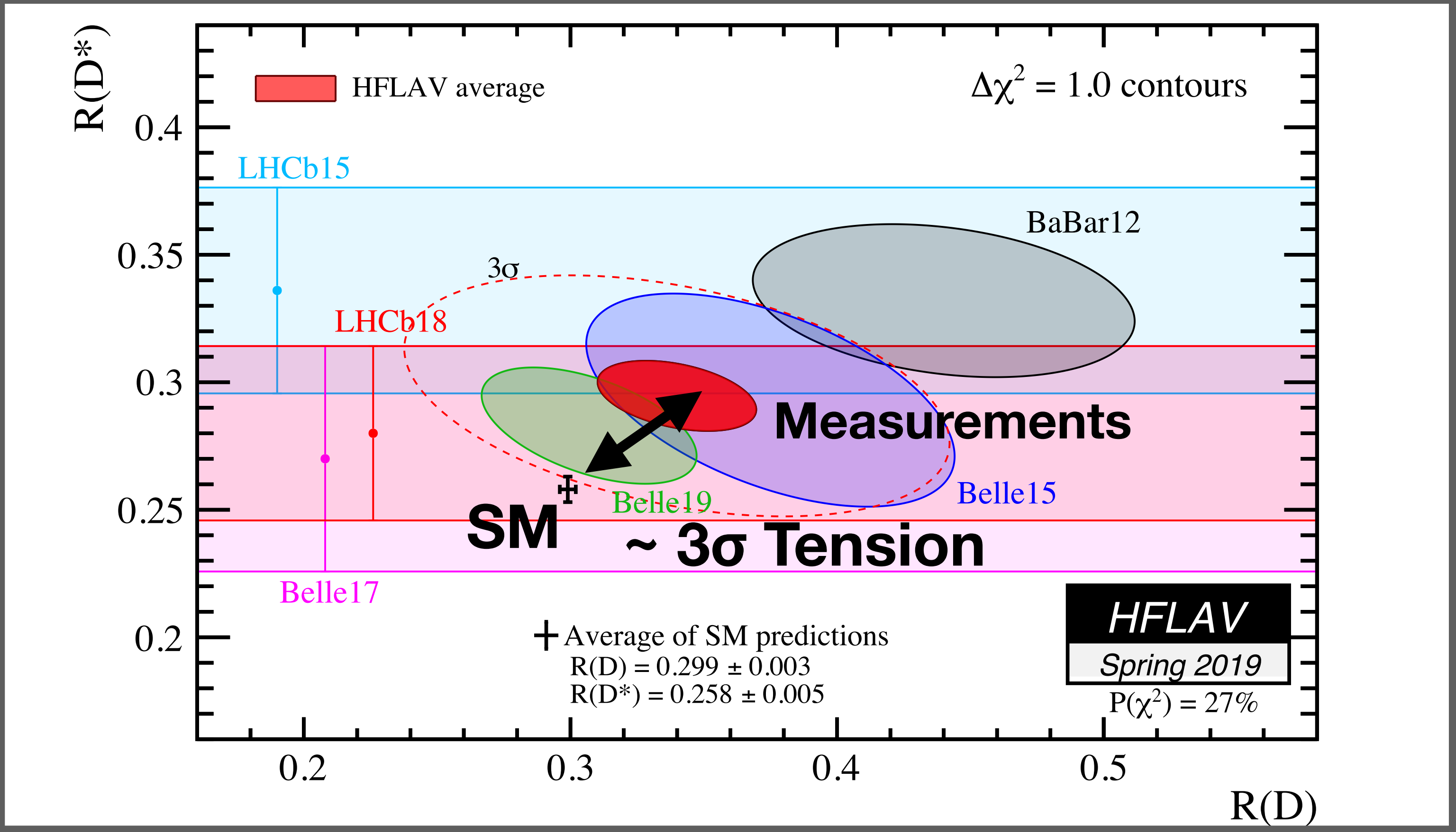

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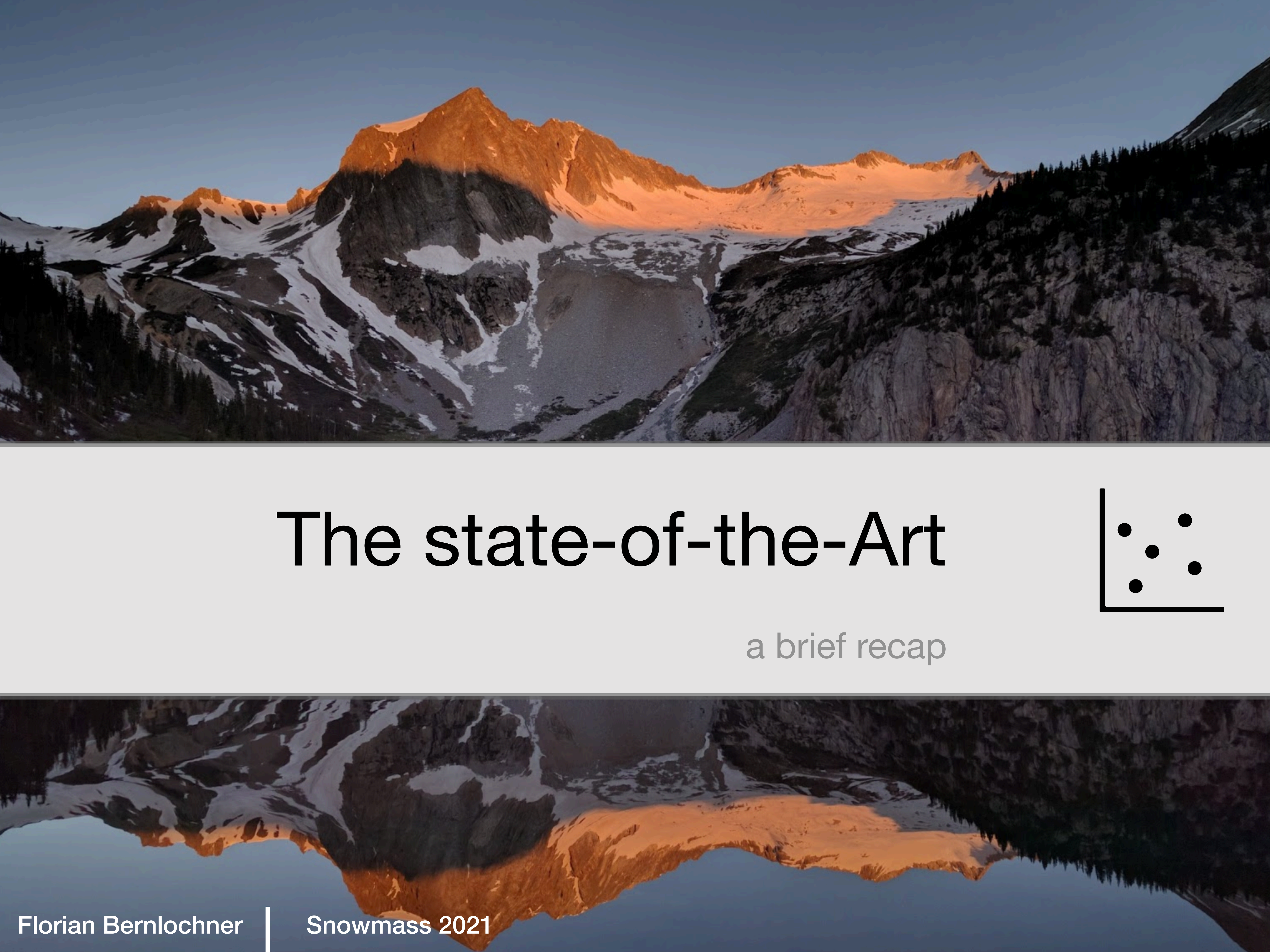


The state-of-the-Art

a brief recap

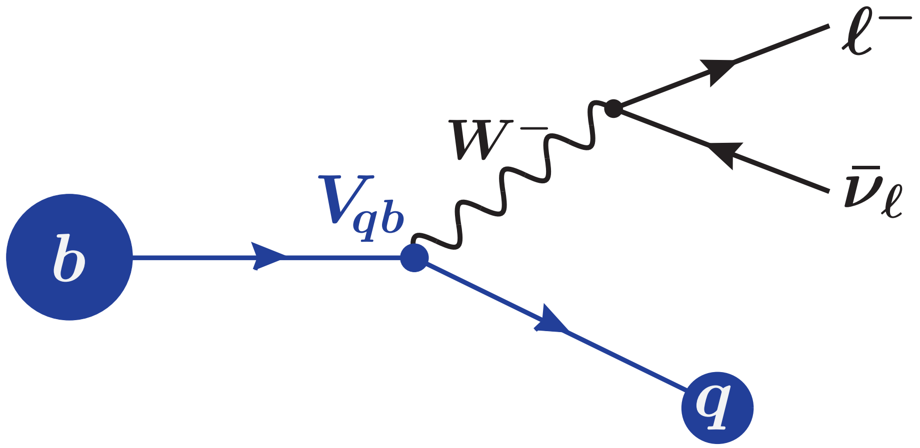
How do we measure $\mathscr{R}(D^{(*)})$ at B-Factories?

$$\mathscr{R} = \frac{b \rightarrow q \, \tau \, \bar{\nu}_\tau}{b \rightarrow q \, \ell \, \bar{\nu}_\ell}$$

$\ell = e, \mu$

1. **Leptonic or Hadronic τ decays?**

Some properties (e.g. τ **polarisation**) **only accessible** in **hadronic decays.**



2. **Albeit not necessarily a rare decay of O(%) in BF, TRICKY to separate from normalisation and backgrounds**

LHCb: **Isolation** criteria, **displacement** of τ, **kinematics**

B-Factories: Full reconstruction of event (**Tagging**), **matching topology, kinematics**

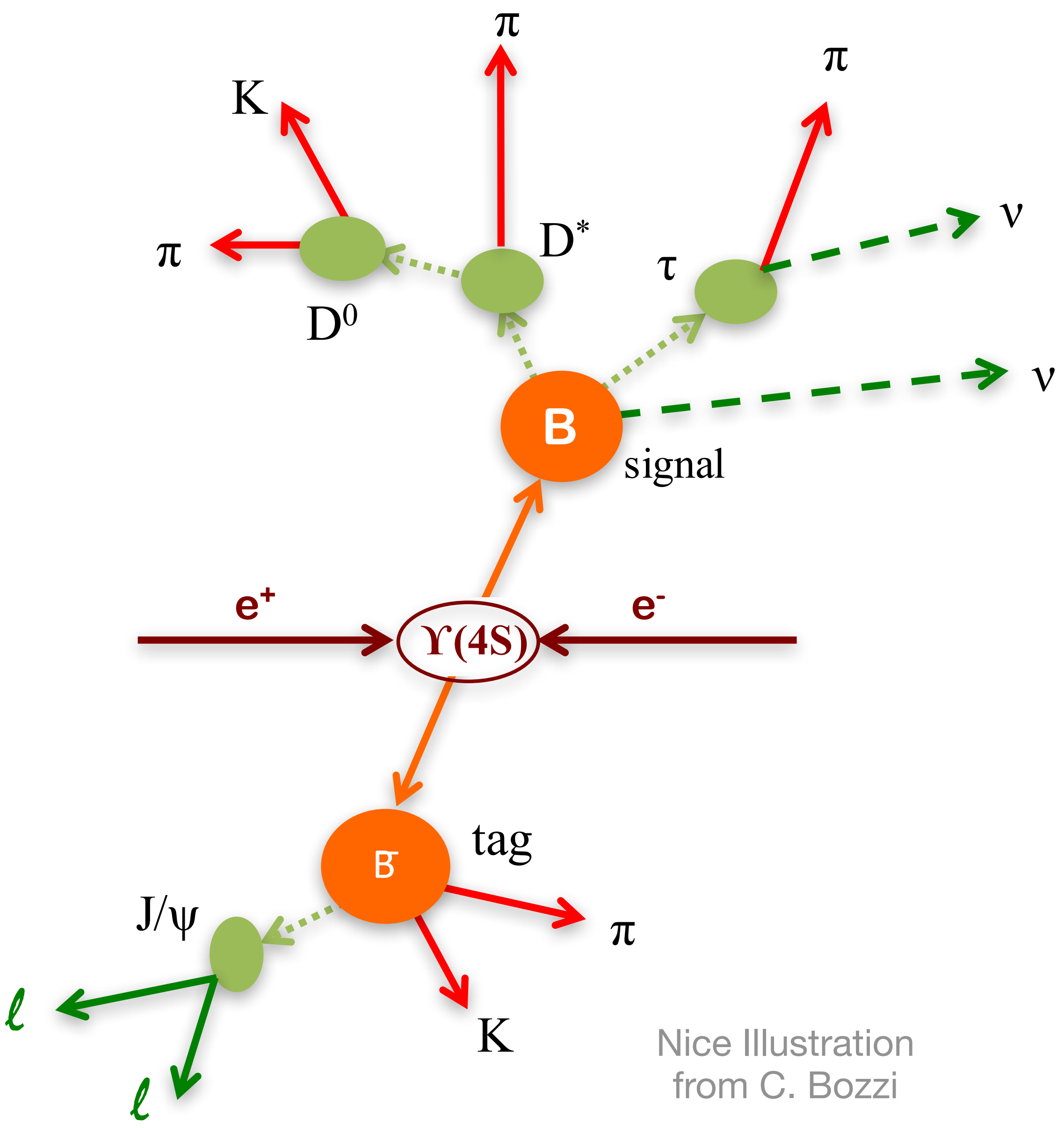
How do we measure $\mathscr{R}(D^{(*)})$ at B-Factories?

3. Semileptonic decays at B-Factories

- e+/e- collision produces ***Y(4S)*** → $\boldsymbol{B\overline{B}}$
- Fully reconstruct one of the two B-mesons ('tag') → **possible** to measure **properties** of signal B

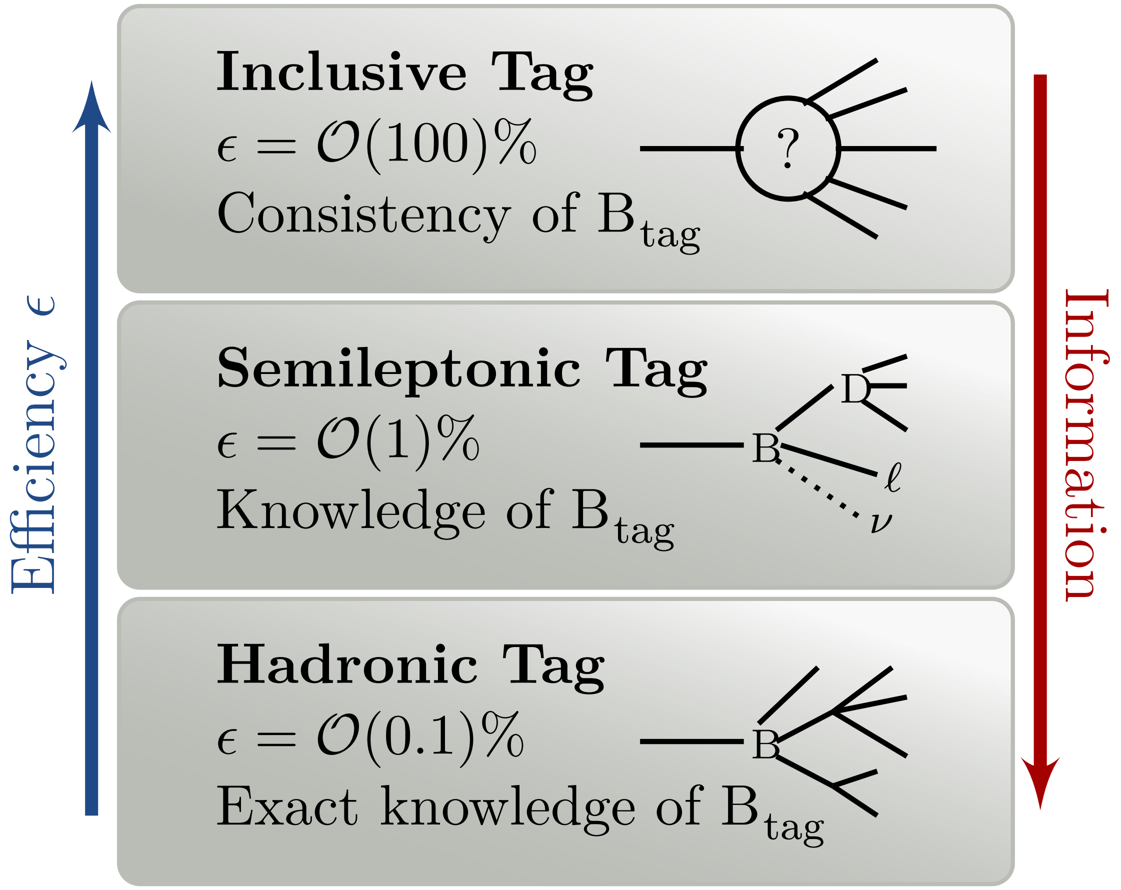
If reconstruction happens in e.g. **fully hadronic modes**: $\mathscr{B} \sim 10^{-3}$

✓ **Small efficiency (~0.2-0.4%) compensated by large integrated luminosity**



Nice Illustration from C. Bozzi

How do we measure $\mathscr{R}(D^{(*)})$ at B-Factories?



Efficiency ϵ

Inclusive Tag
$\epsilon = \mathcal{O}(100)\%$
Consistency of $\mathrm{B}_{\mathrm{tag}}$

Semileptonic Tag
$\epsilon = \mathcal{O}(1)\%$
Knowledge of $\mathrm{B}_{\mathrm{tag}}$

Hadronic Tag
$\epsilon = \mathcal{O}(0.1)\%$
Exact knowledge of $\mathrm{B}_{\mathrm{tag}}$

Information

Belle: BELLE-CONF-1805 [arXiv:1903.03102] + others

Belle: Phys. Rev. Lett. 124, 161803 (2020), [arXiv:1910.05864]

BaBar: Phys.Rev.Lett. 109,101802 (2012) [arXiv:1205.5442_[hep-ex]] Phys.Rev.D 88, 072012 (2013) [arXiv:1303.0571_[hep-ex]]

Belle: Phys.Rev.D 92, 072014 (2015) [arXiv:1507.03233 [hep-ex]]

Belle: Phys.Rev.Lett.118,211801 (2017) [arXiv:1612.00529 [hep-ex]] Phys.Rev.D 97, 012004 (2018) [arXiv:1709.00129_[hep-ex]]

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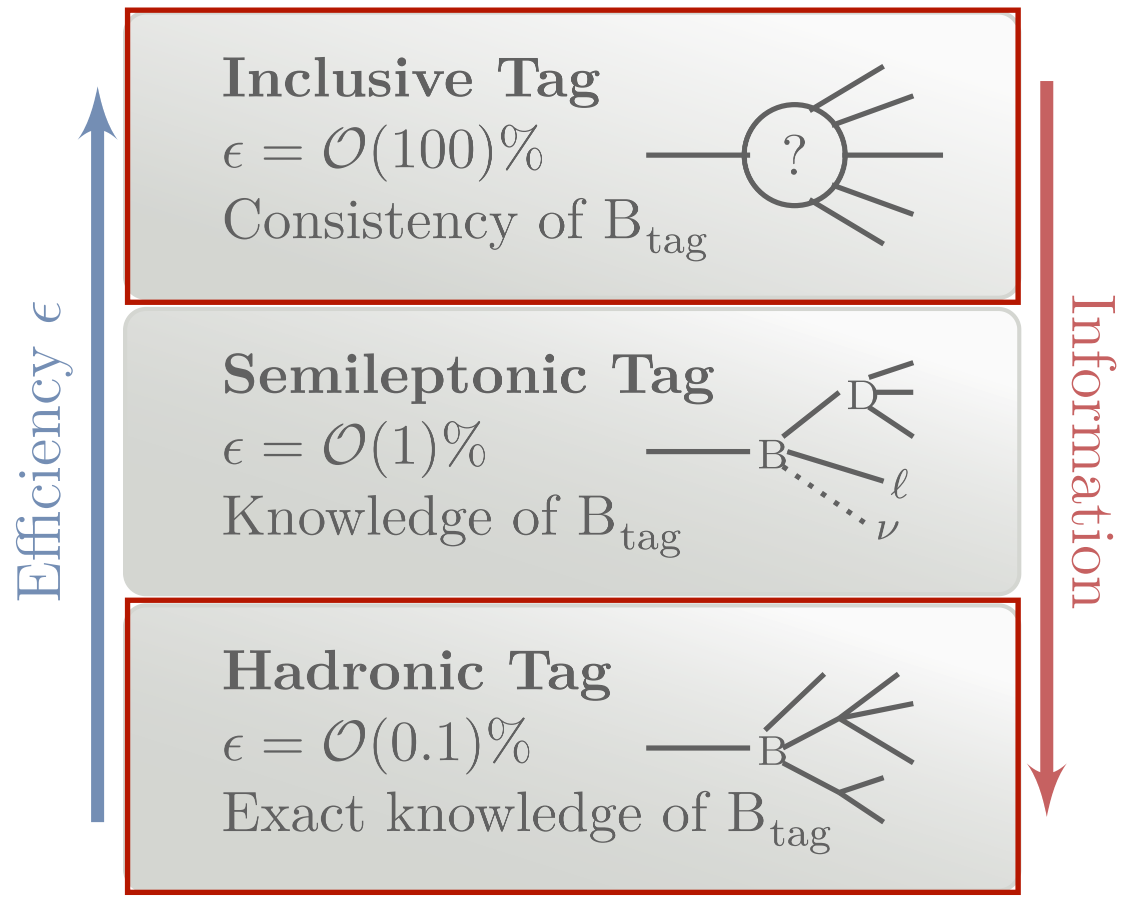

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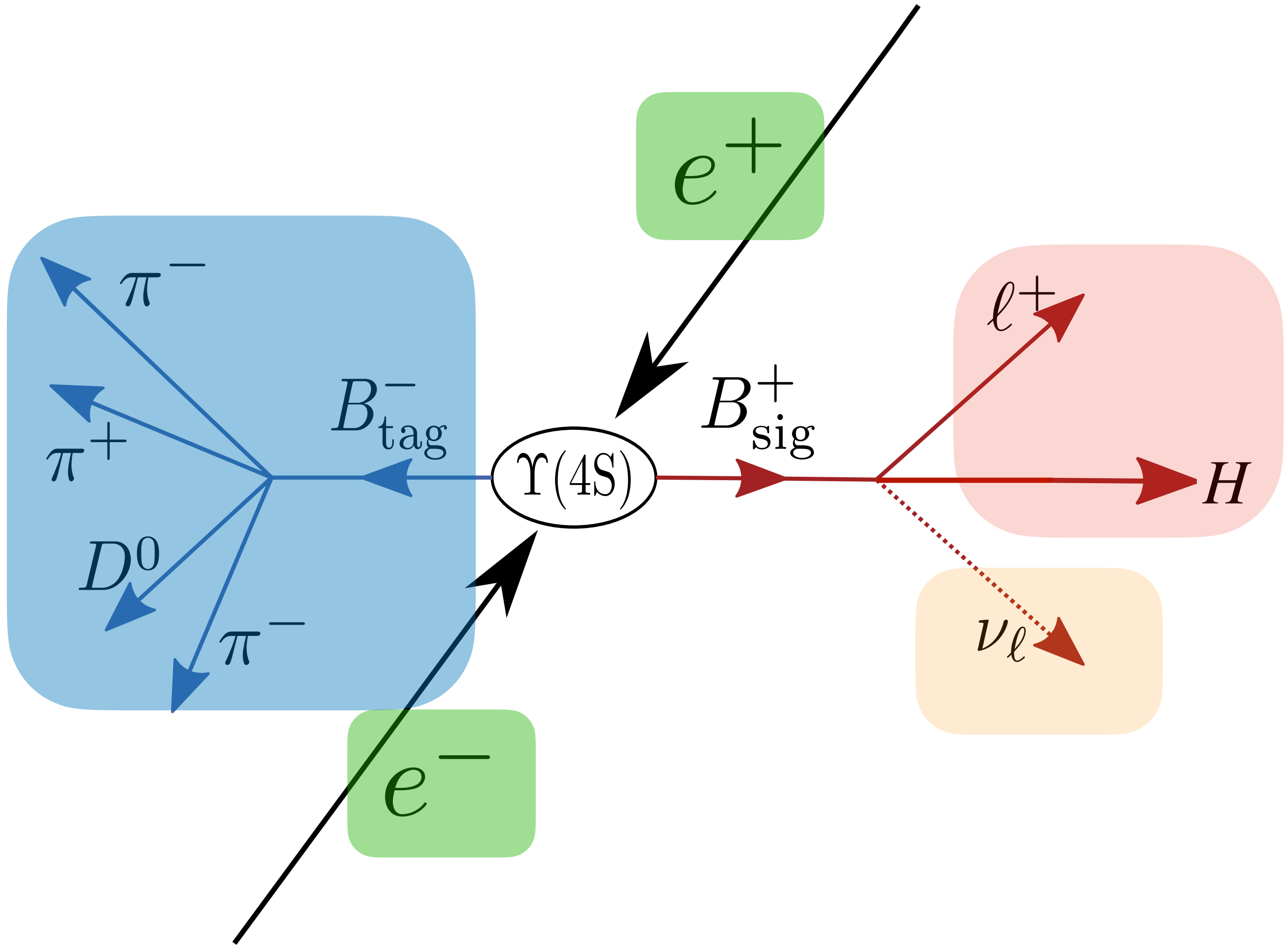


Benefit #1

$$p_\nu = \left(p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_\ell - p_H \right)$$

invisible signal particles

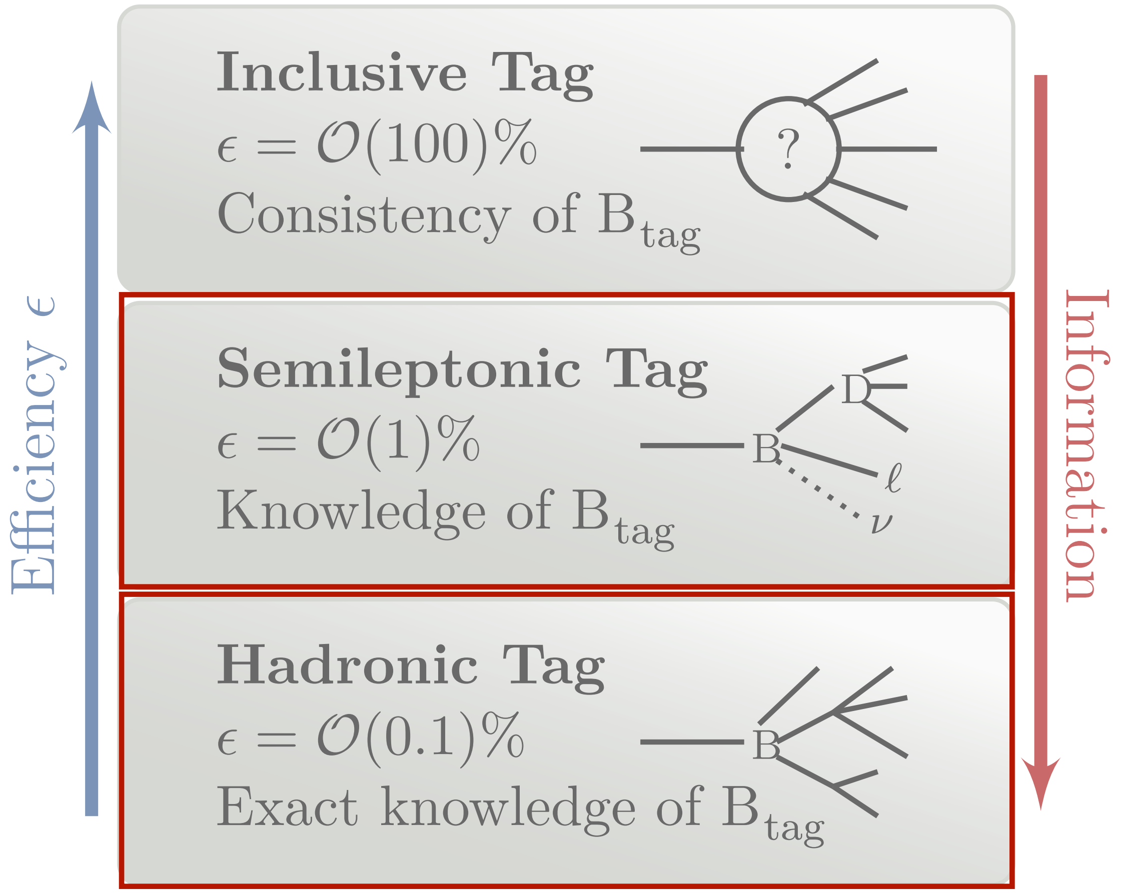
known collision energy

tag w/o neutrinos

visible signal particles

also:
access to $\mathrm{B}_{\mathrm{sig}}$ frame

How do we measure $\mathscr{R}(D^{(*)})$ at B-Factories?



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$\epsilon = \mathcal{O}(100)\%$
Consistency of B_{tag}

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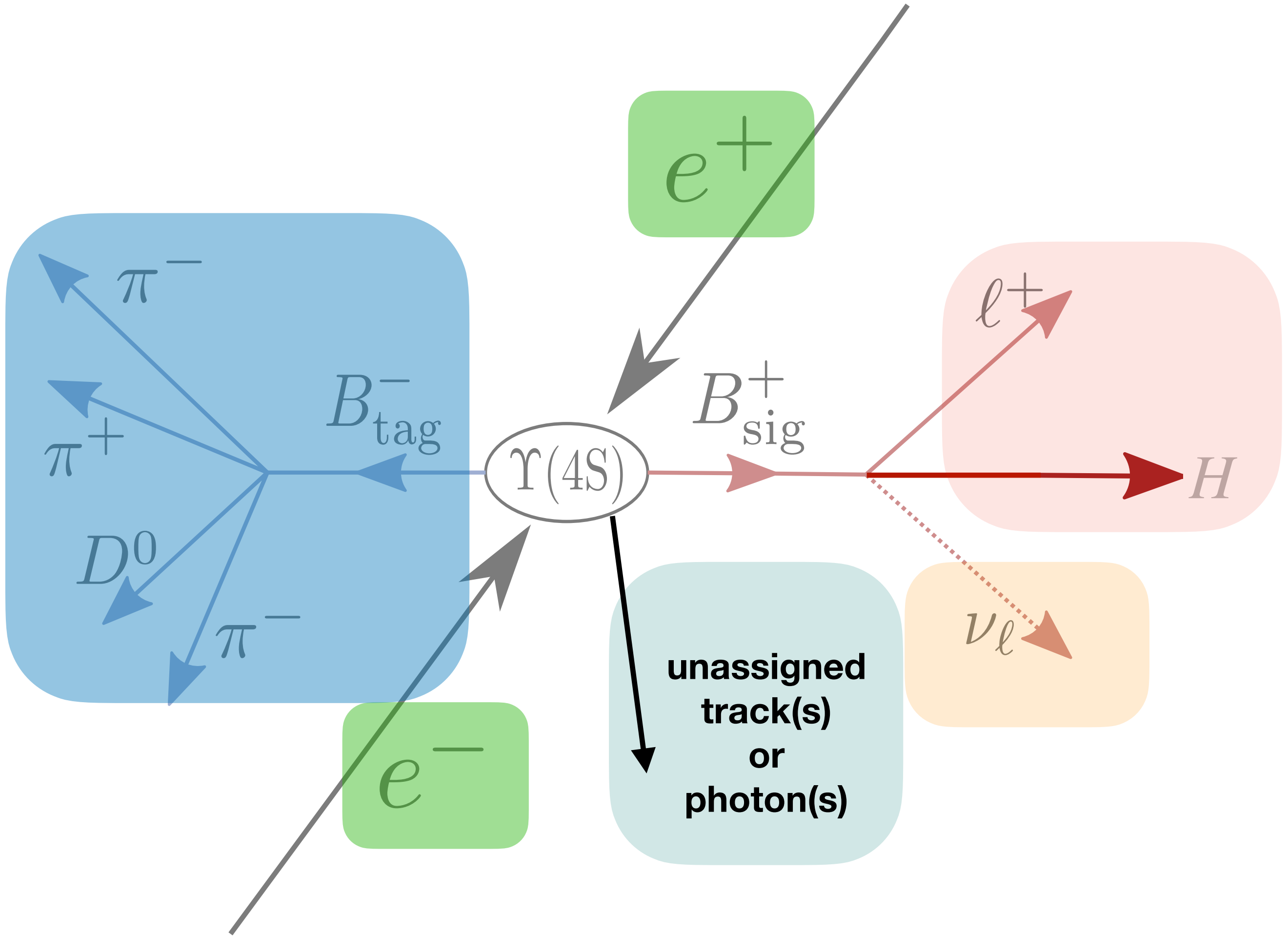
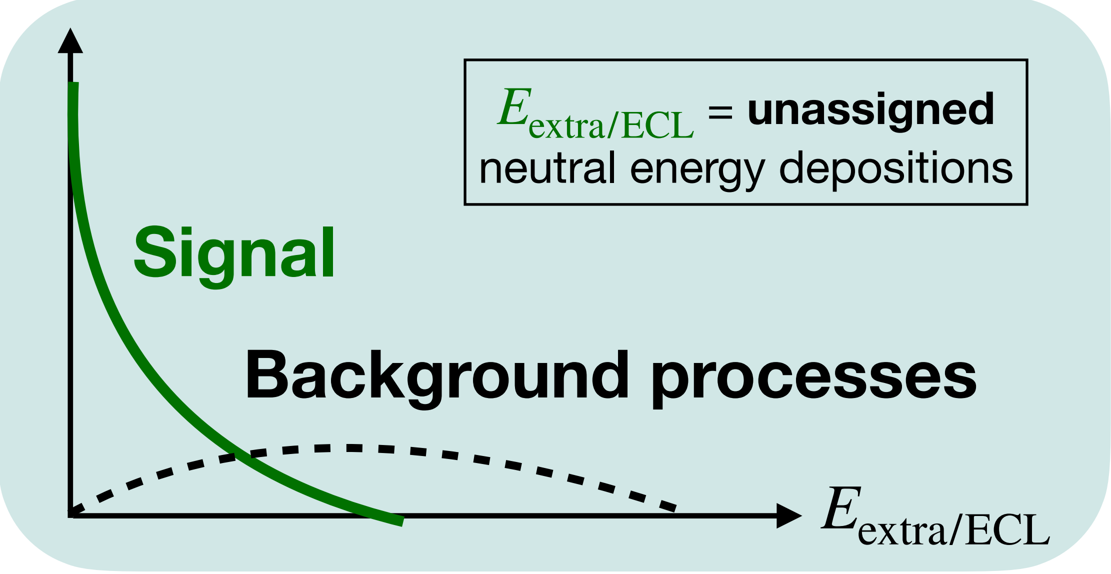


$E_{extra/ECL}$ often directly fitted or used in BDT to agregate signal

Benefit #2

Demand matching topology

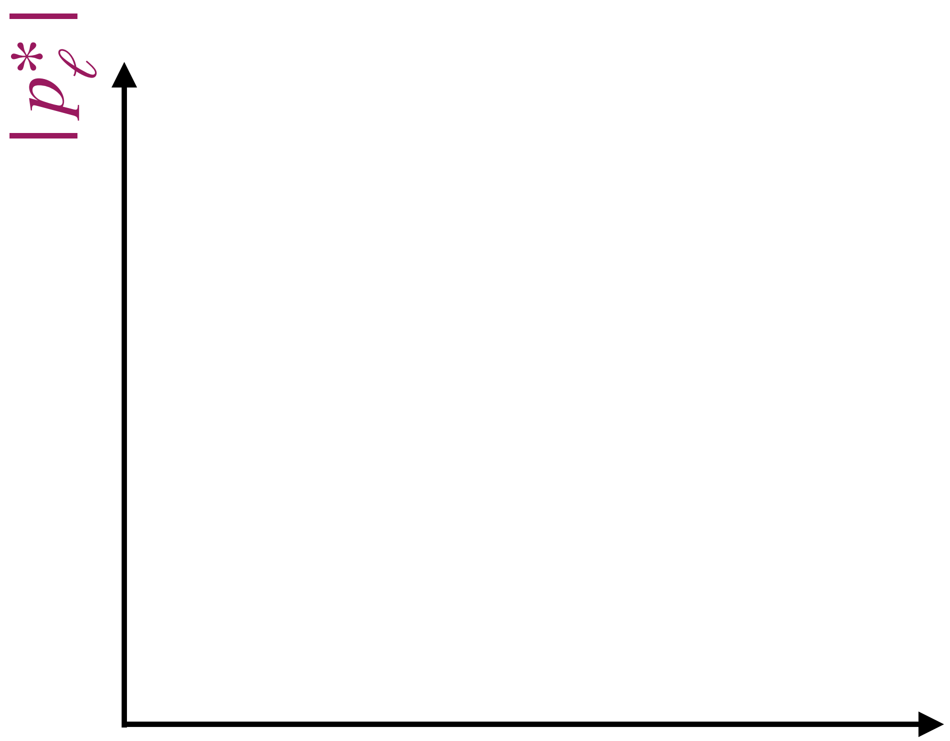
$$N^{exp}_{trk} = N^{obs}_{trk}$$



$E_{extra/ECL}$ = **unassigned** neutral energy depositions

Example: *Hadronic Tag* Measurement:

- Use $\tau \to e\,\bar{\nu}_e\,\nu_\tau$ and $\tau \to \mu\,\bar{\nu}_\mu\,\nu_\tau$ to reconstruct **τ-lepton**
- Simultaneous analysis of $\mathscr{R}(D)$ & $\mathscr{R}(D^*)$ using $B^0 \to D^{(*)-}\tau\bar{\nu}_\tau$ & $B^- \to D^{(*)0}\tau\bar{\nu}_\tau$
- Fit in 2D to m^2_{miss} and $|p^*_\ell|$



$$\left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_\ell - p_{D^{(*)}}\right)^2 = m^2_{\text{miss}}$$

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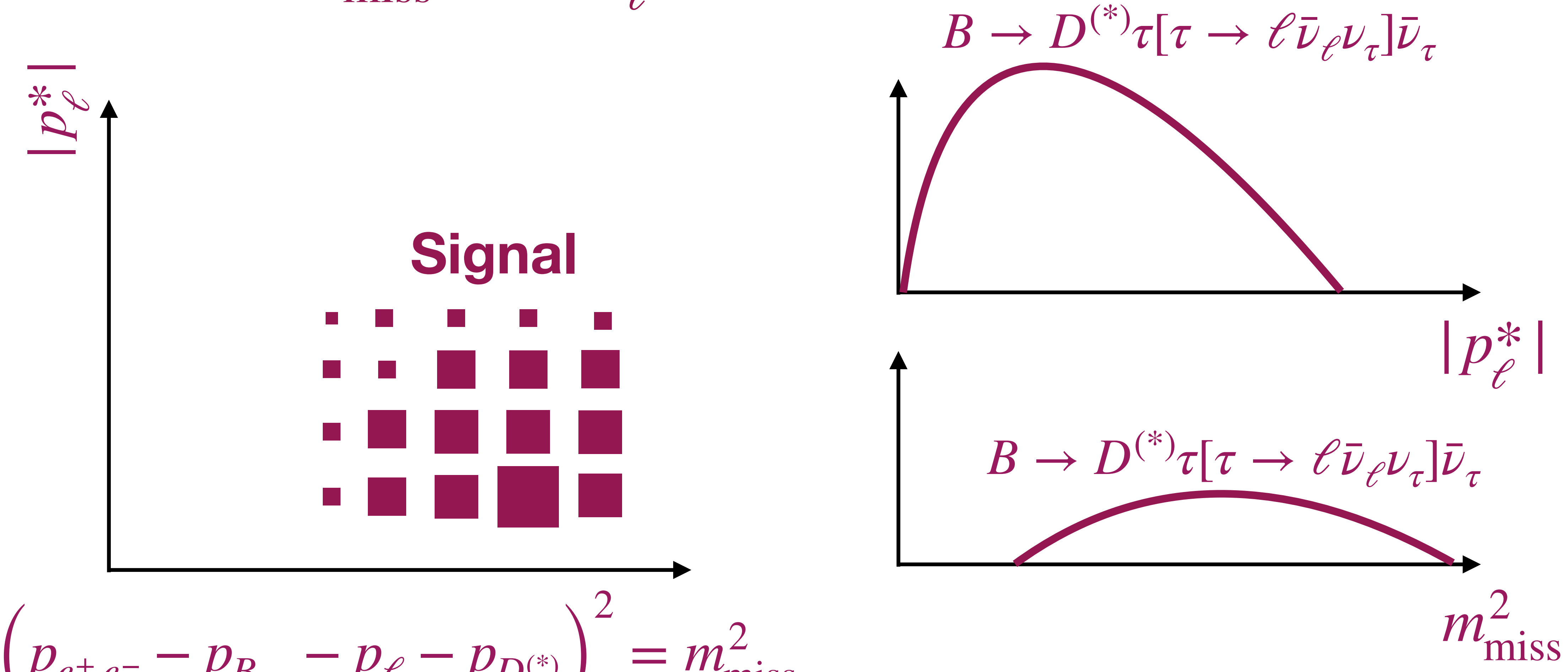

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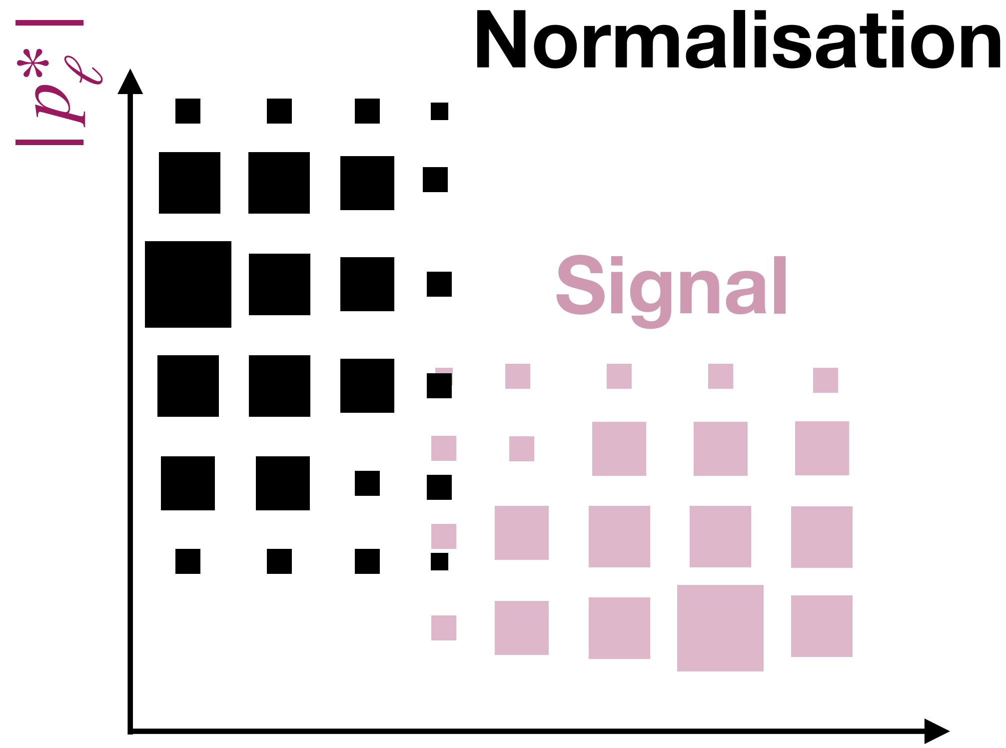

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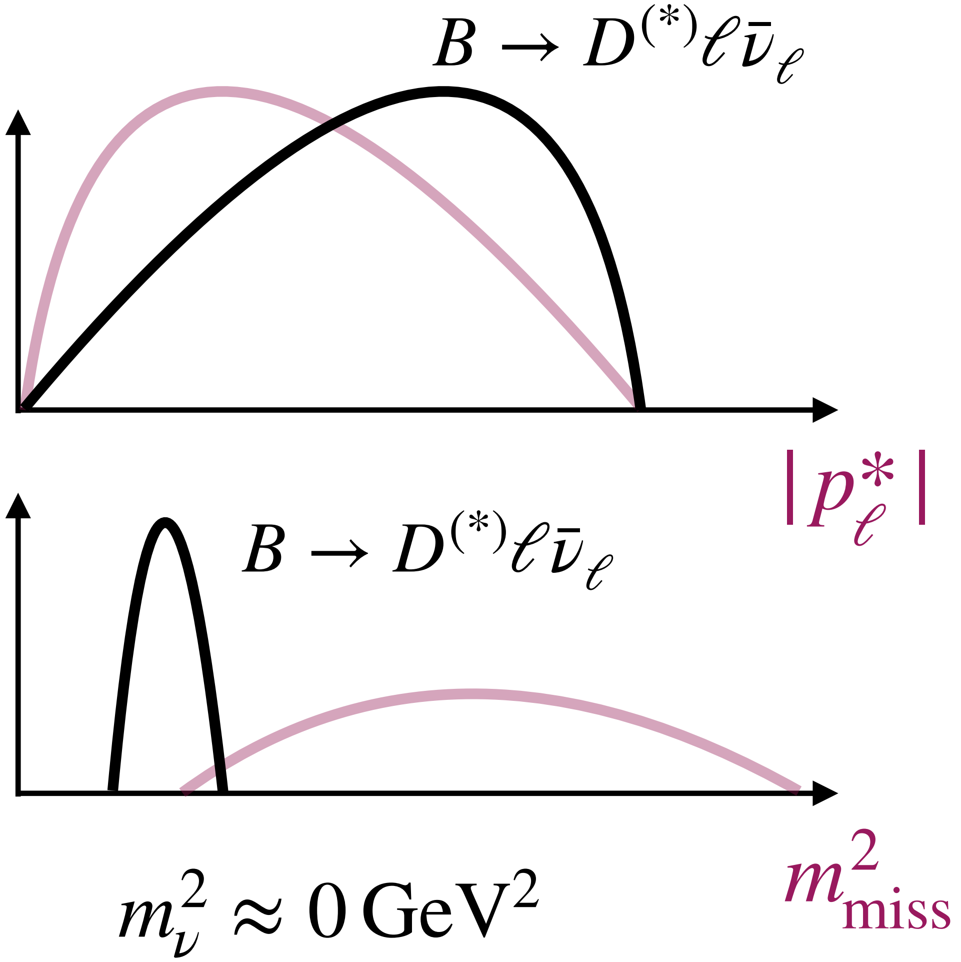

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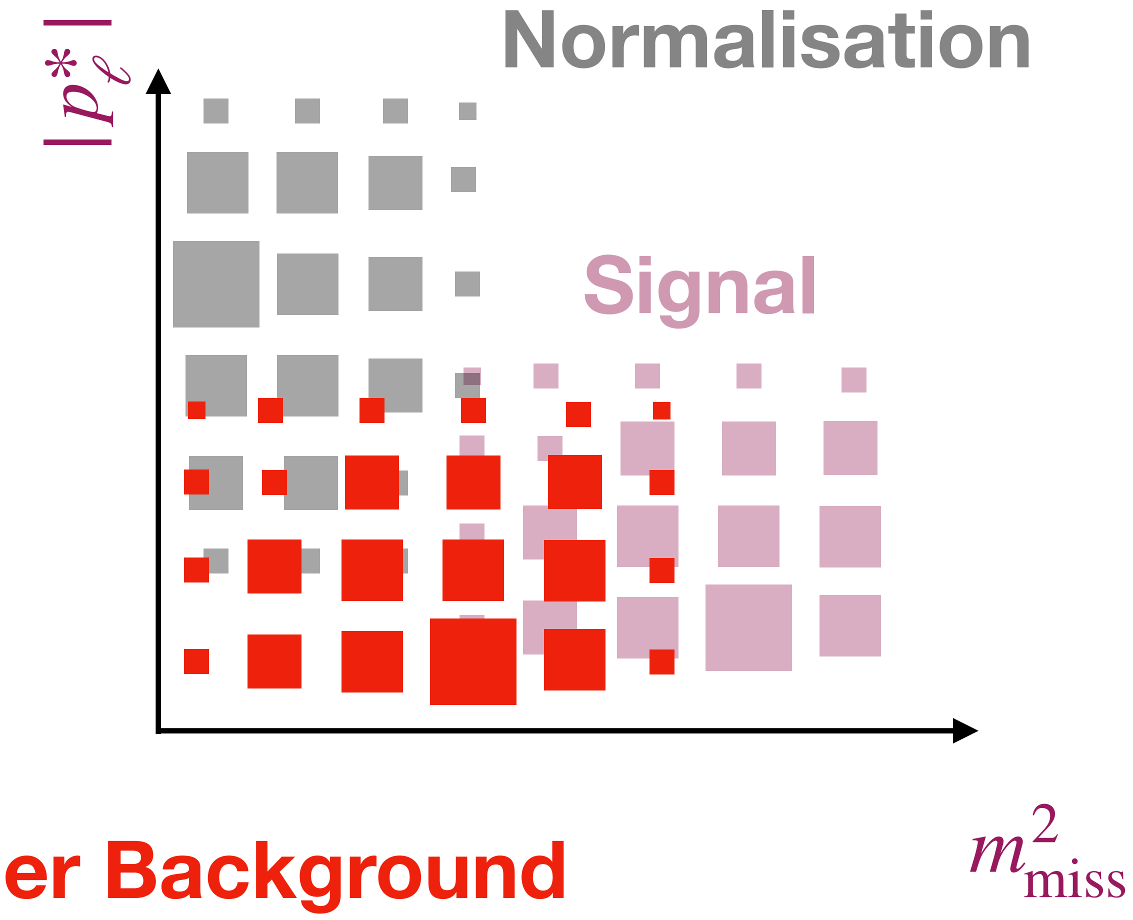
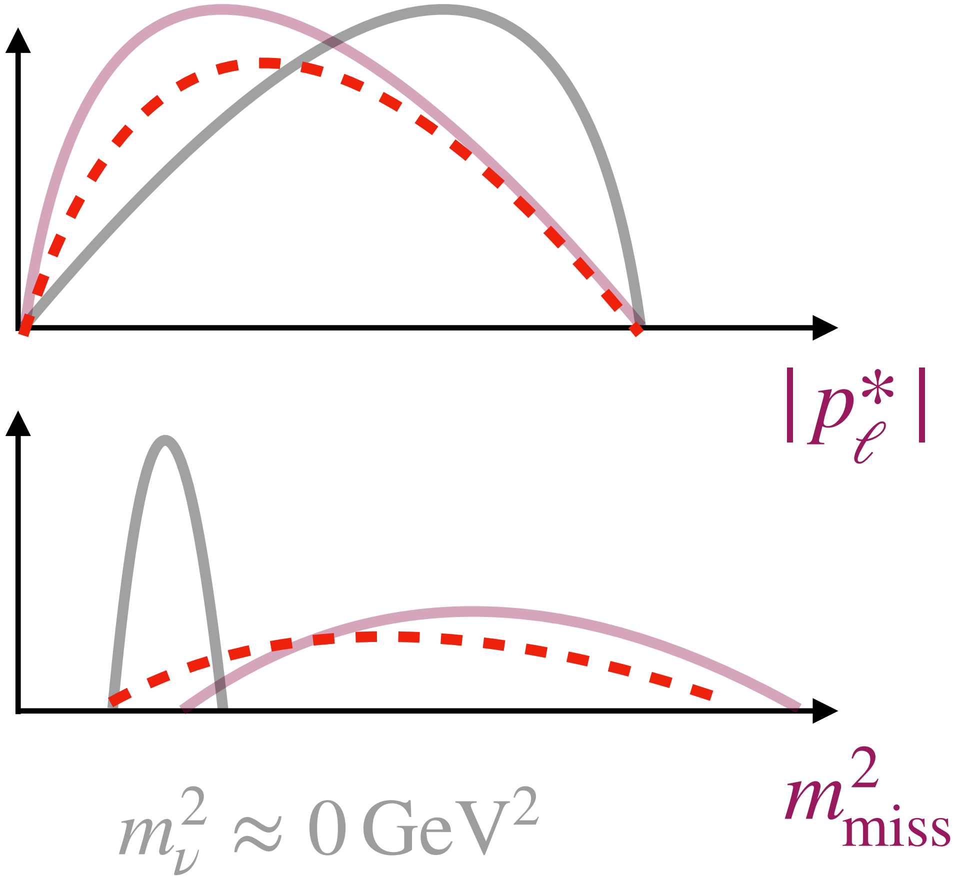
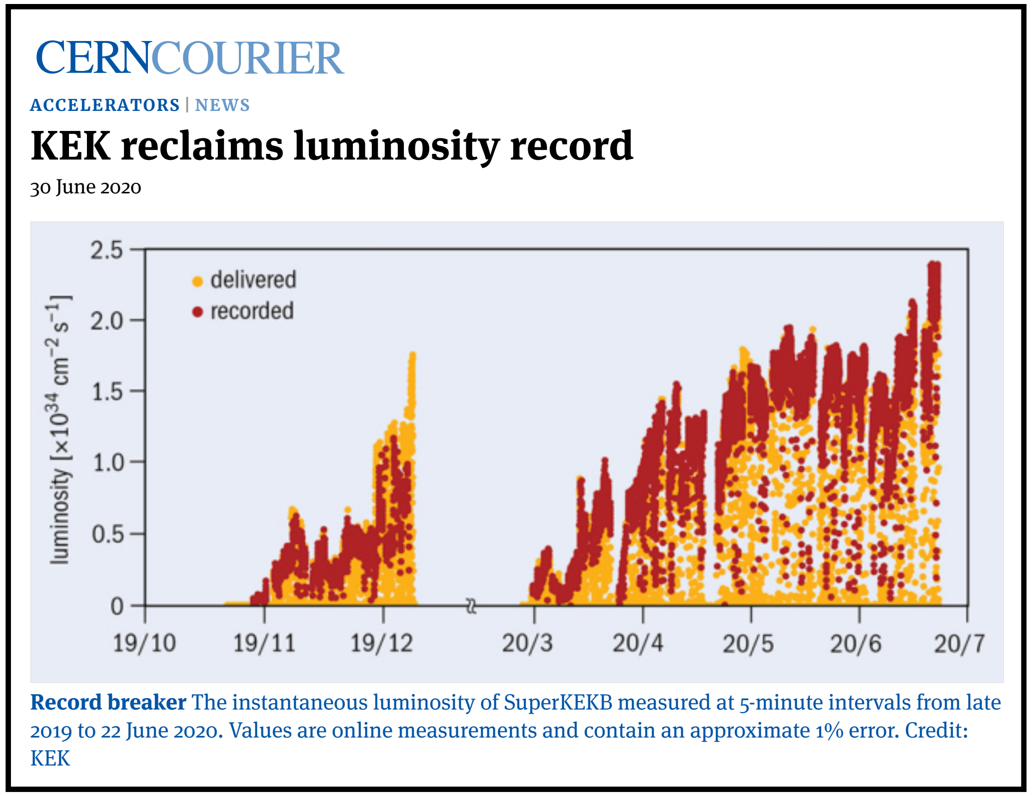




Extrapolating to Belle II

Florian Bernlochner | Snowmass 2021

Belle II Status



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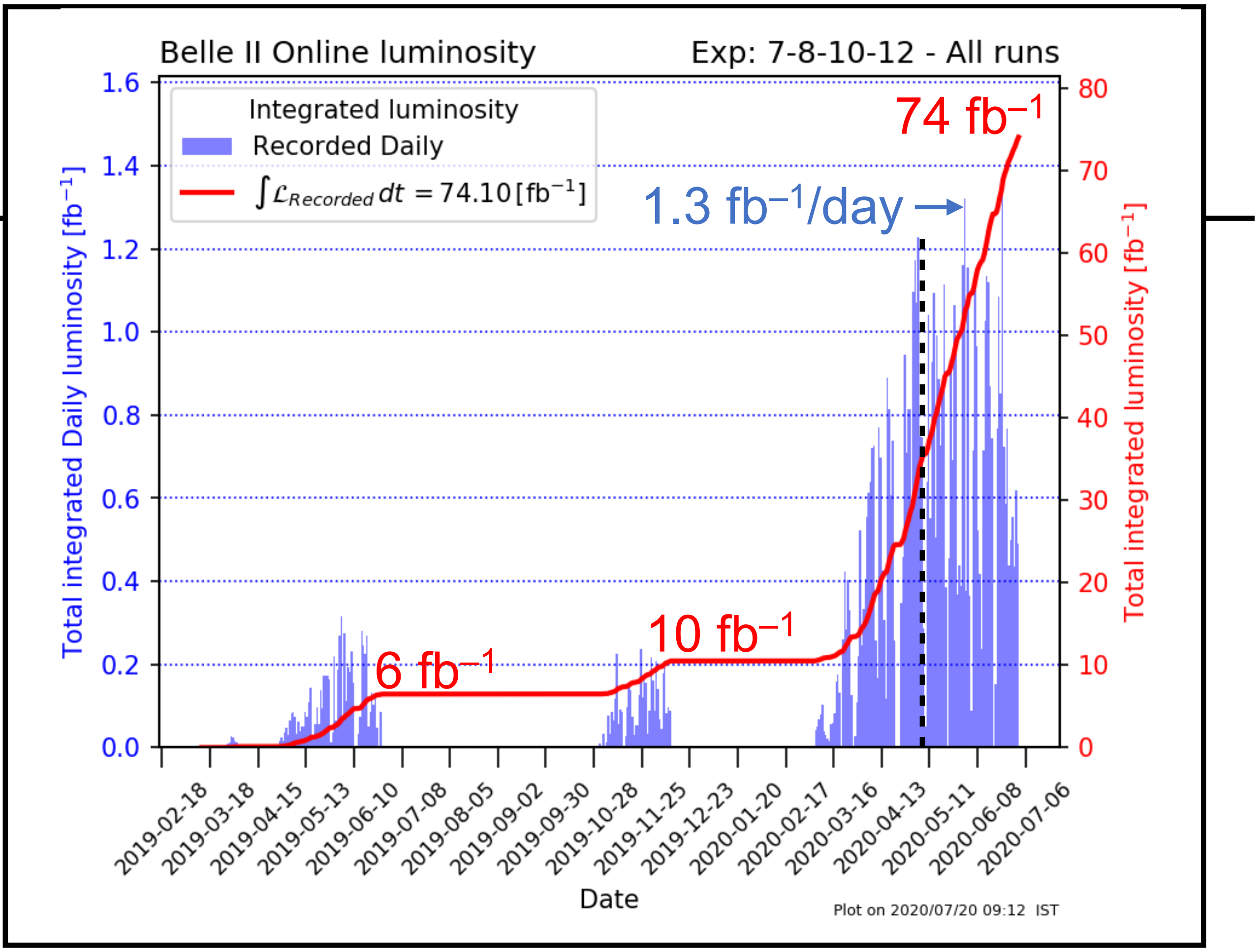
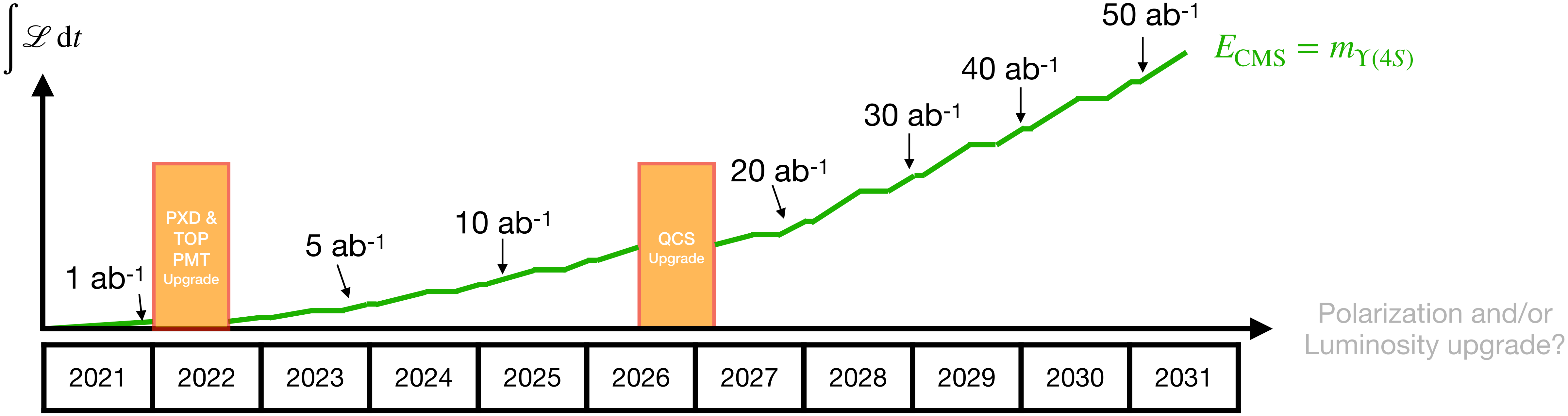
ACCELERATORS | NEWS

KEK reclaims luminosity record

30 June 2020

Record breaker The instantaneous luminosity of SuperKEKB measured at 5-minute intervals from late 2019 to 22 June 2020. Values are online measurements and contain an approximate 1% error. Credit: KEK





Estimated Uncertainties on $\mathscr{R}(D^{(*)})$ and $P_\tau(D^*)$

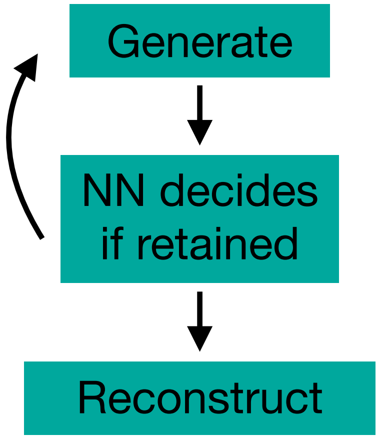
Belle II Physics Book, Prog Theor Exp Phys (2019), [arXiv:1808.10567]

	Belle (Had, ℓ^-)	Belle (Had, ℓ^-)	Belle (SL, ℓ^-)	Belle (Had, h^-)
Source	R_D	R_{D^*}	R_{D^*}	R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}\%$
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}\%$	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}\%$
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}\%$	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}\%$	$^{+10.0}_{-9.0}\%$

	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

MC statistics → Maybe can use ML to identify which decays make it pass our hadronic tagging?

$B \to D^{**}\ell\bar{\nu}_\ell$ → More data and dedicated measurements will help reducing this



Generate

NN decides if retained

Reconstruct

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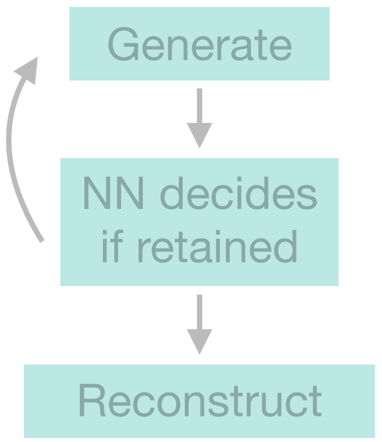

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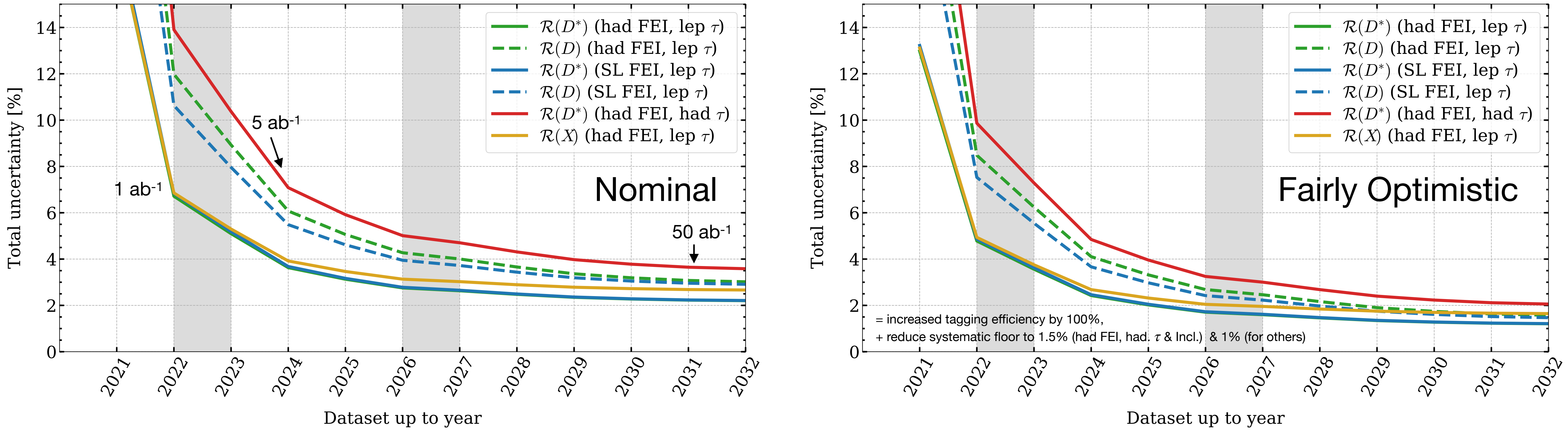
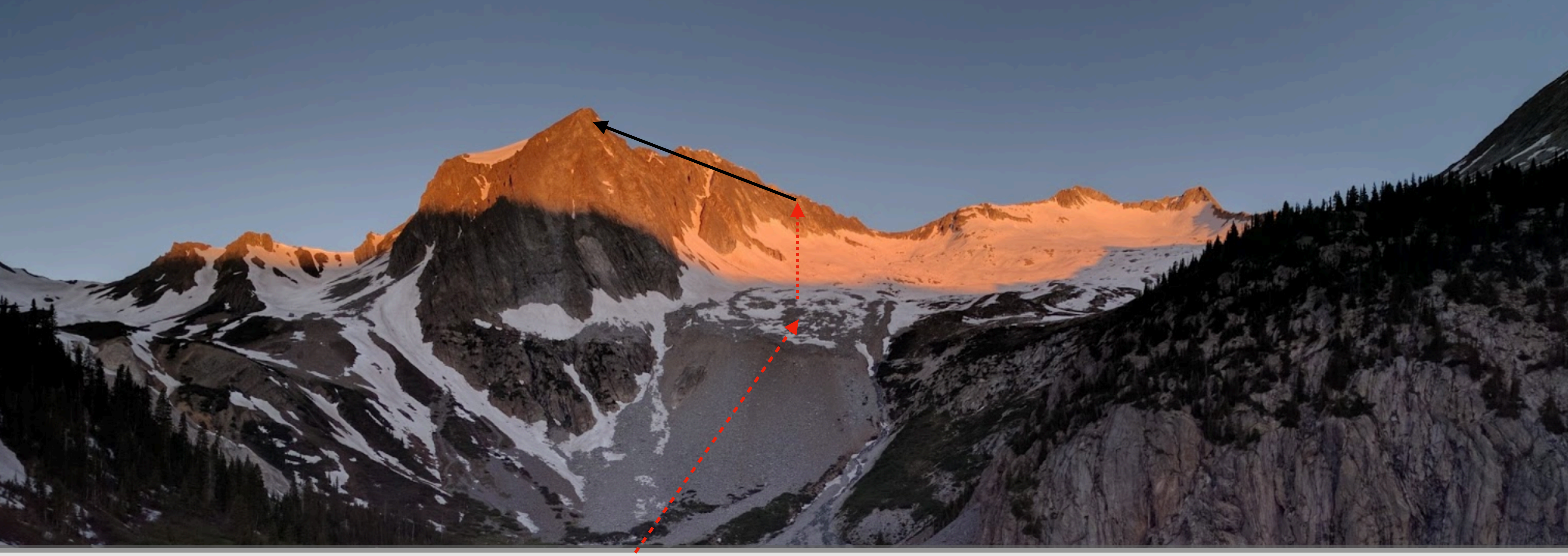
(My extrapolation folded with the above table and the luminosity profile)



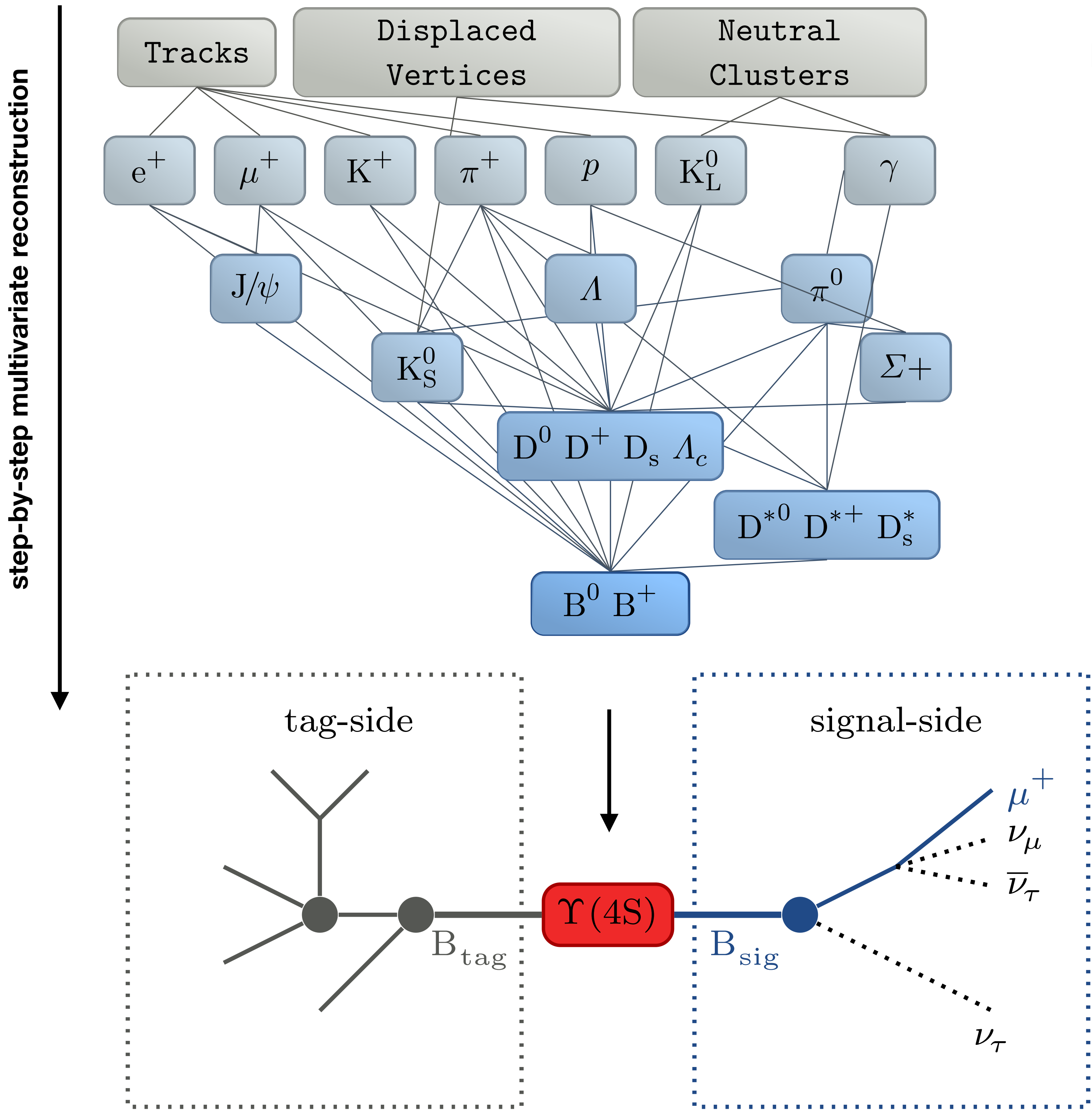
= increased tagging efficiency by 100%,
+ reduce systematic floor to 1.5% (had FEI, had. τ & Incl.) & 1% (for others)

Many thanks to Ana and Manuel!



Novel Ideas

The Full Event Interpretation



Low-level detector information

Detector “stable” particles

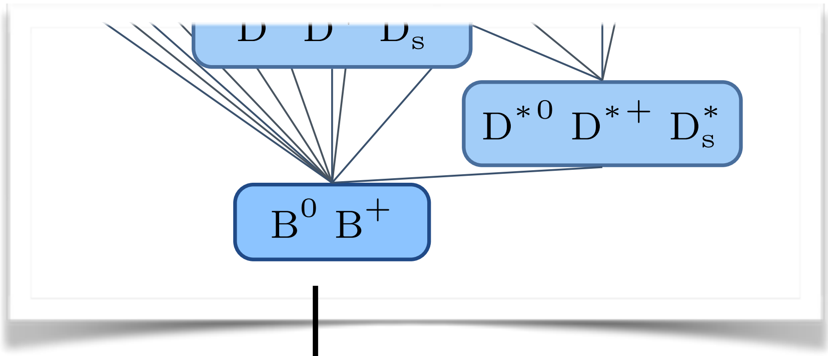
Detector “unstable” particles

~ 200 BDTs
reconstruct
entire decay cascade

T. Keck et al, Computing and Software for Big Science volume 3, Article number: 6 (2019) [arXiv:1807.08680]

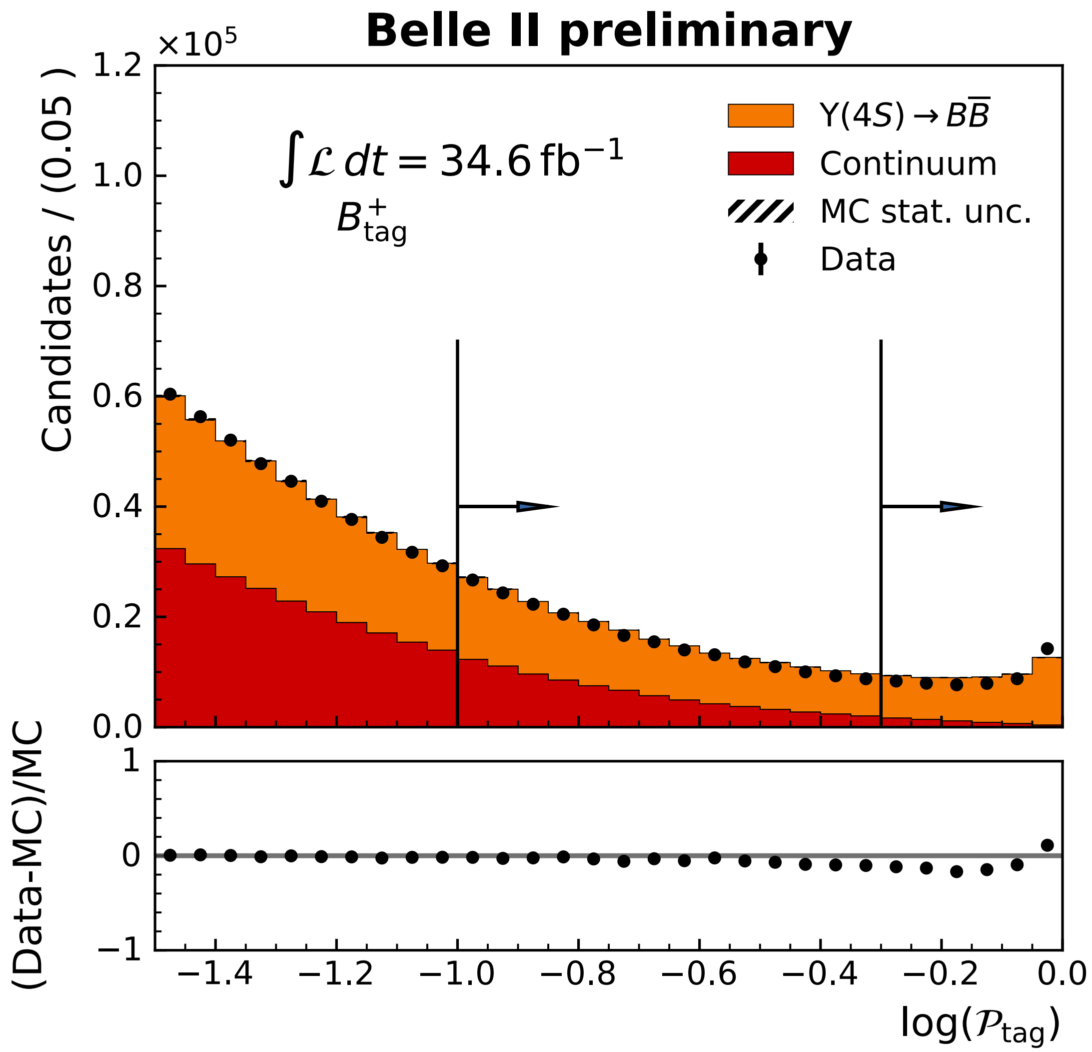
The Full Event Interpretation applied to Belle II Data

Belle II Collaboration, BELLE2-CONF-PH-2020-005, [arXiv:2008.06096]



$\mathscr{P}_{\text{tag}}$ =

Output classifier = Measure of how well we reconstructed the B-Meson decay



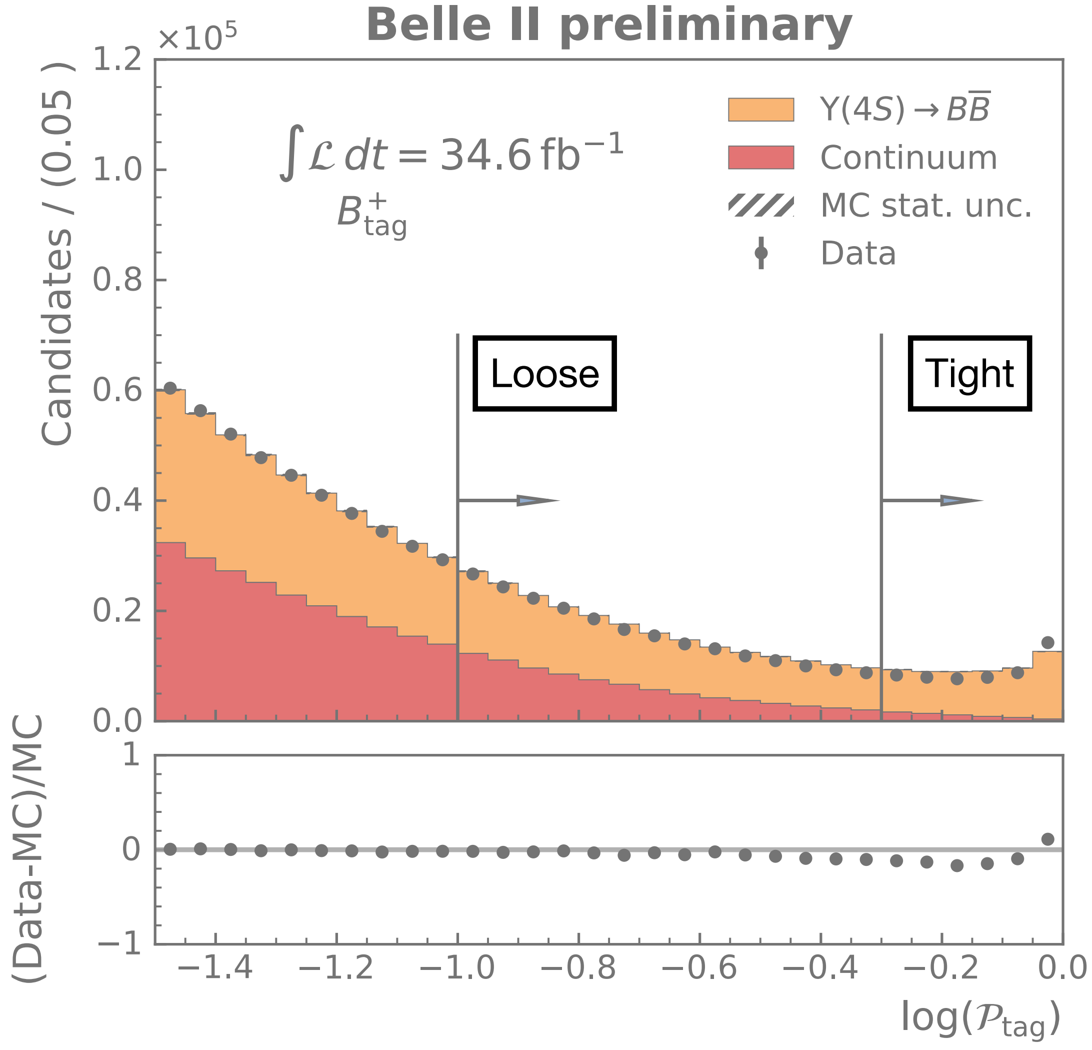
The Full Event Interpretation applied to Belle II Data

beam constrained mass

Belle II Collaboration, BELLE2-CONF-PH-2020-005, [arXiv:2008.06096]

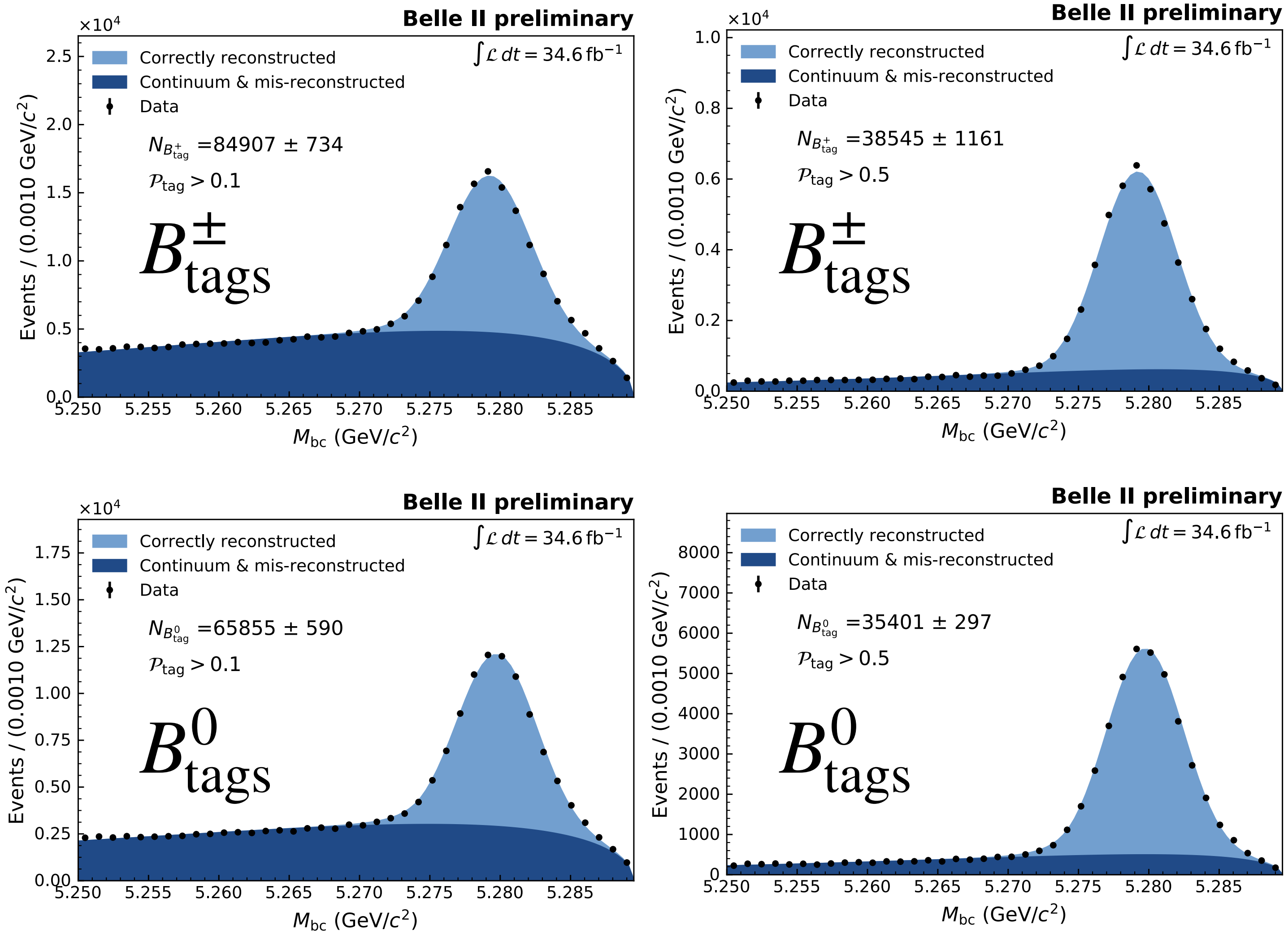
ca. 5.279 GeV

$$m_{bc} = \sqrt{E_{\mathrm{beam}}^2/4 - |\vec{p}_{B_{\mathrm{tag}}}|^2} \simeq m_B$$

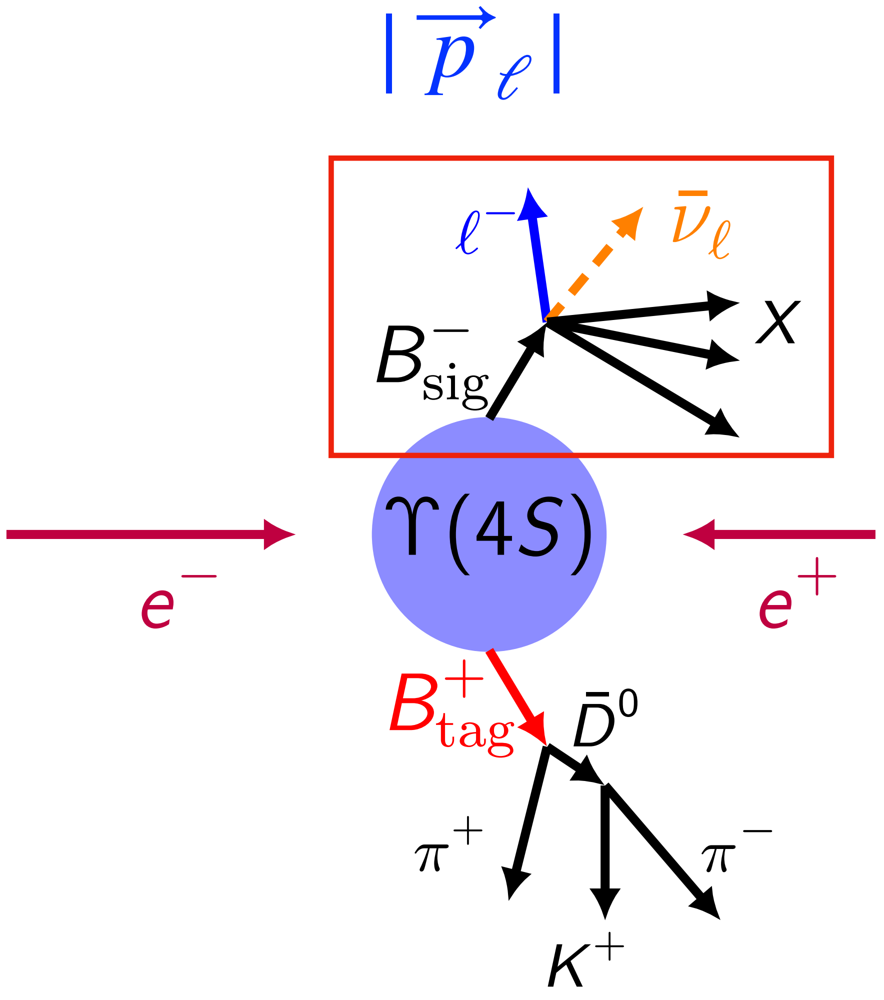


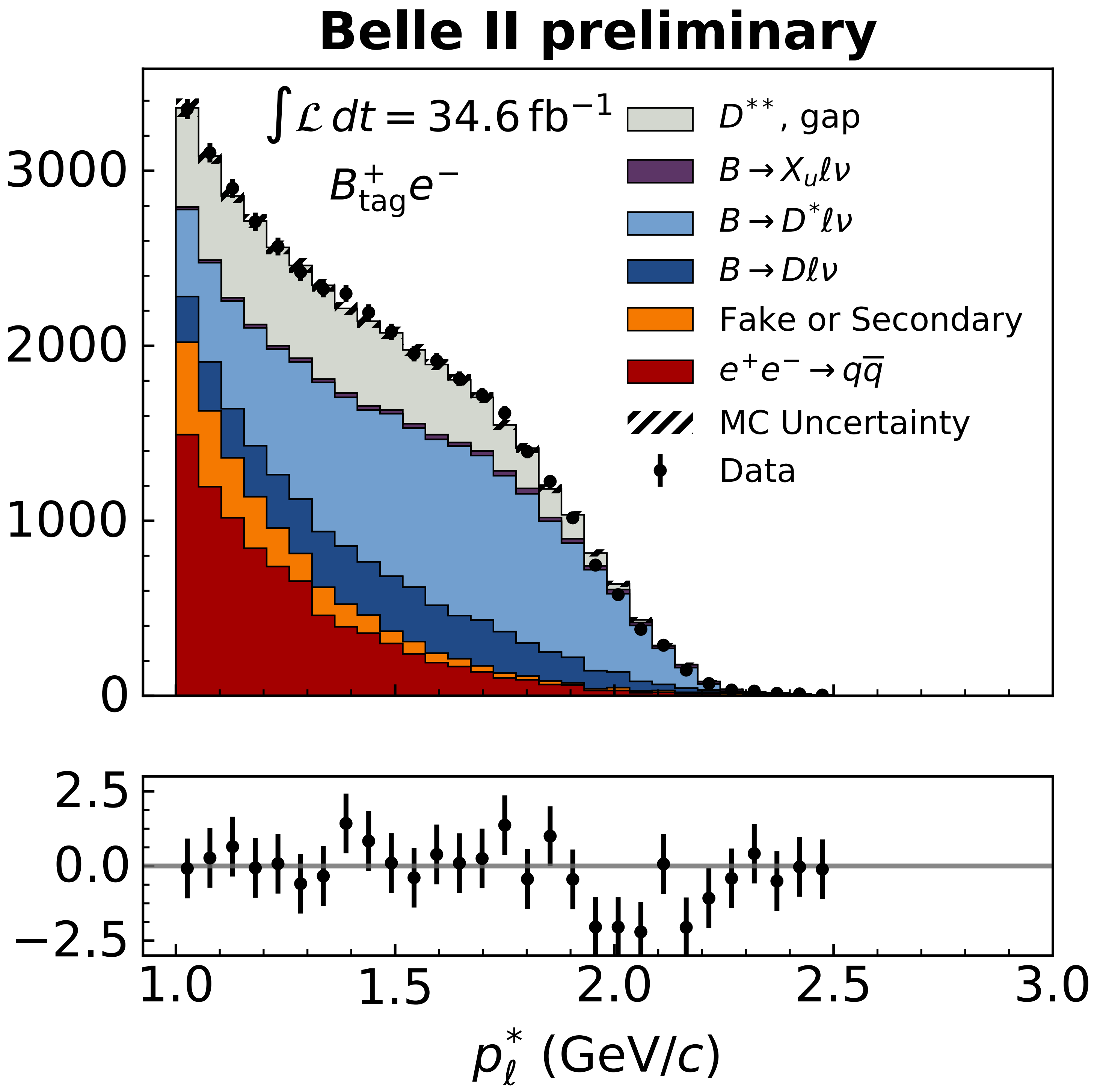
Loose Selection

Tight Selection



Belle II Collaboration, BELLE2-CONF-PH-2020-005, [arXiv:2008.06096]

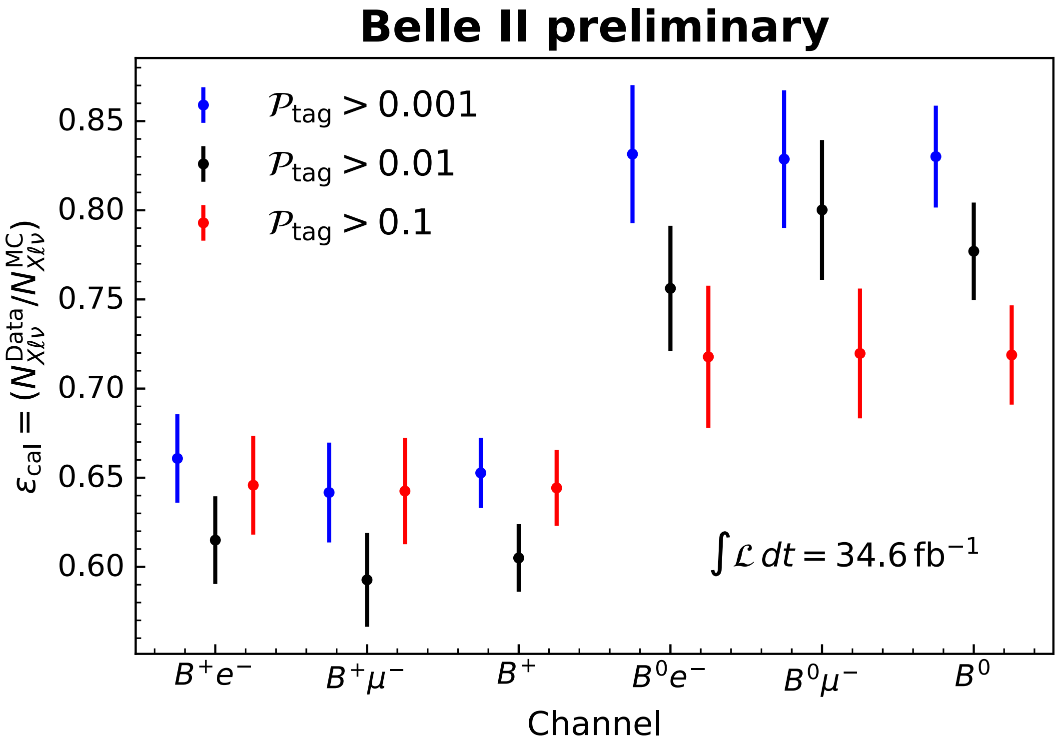




Belle II Collaboration, BELLE2-CONF-PH-2020-005, [arXiv:2008.06096]

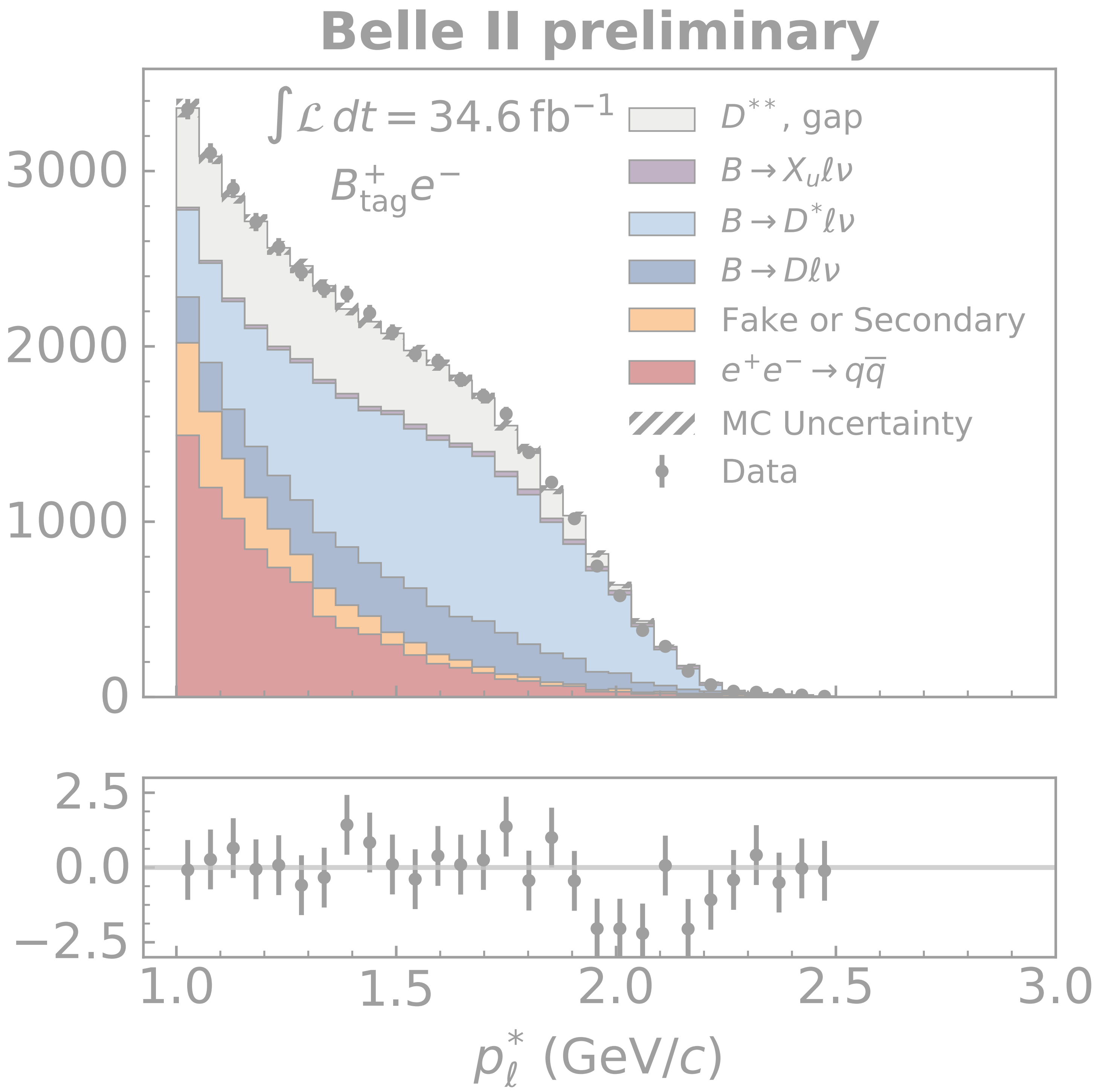
Efficiency Calibration

$$\epsilon_{\mathrm{cal}} = \frac{N^{\mathrm{Data}}_{X\ell\bar{\nu}_\ell}}{N^{\mathrm{MC}}_{X\ell\bar{\nu}_\ell}}$$

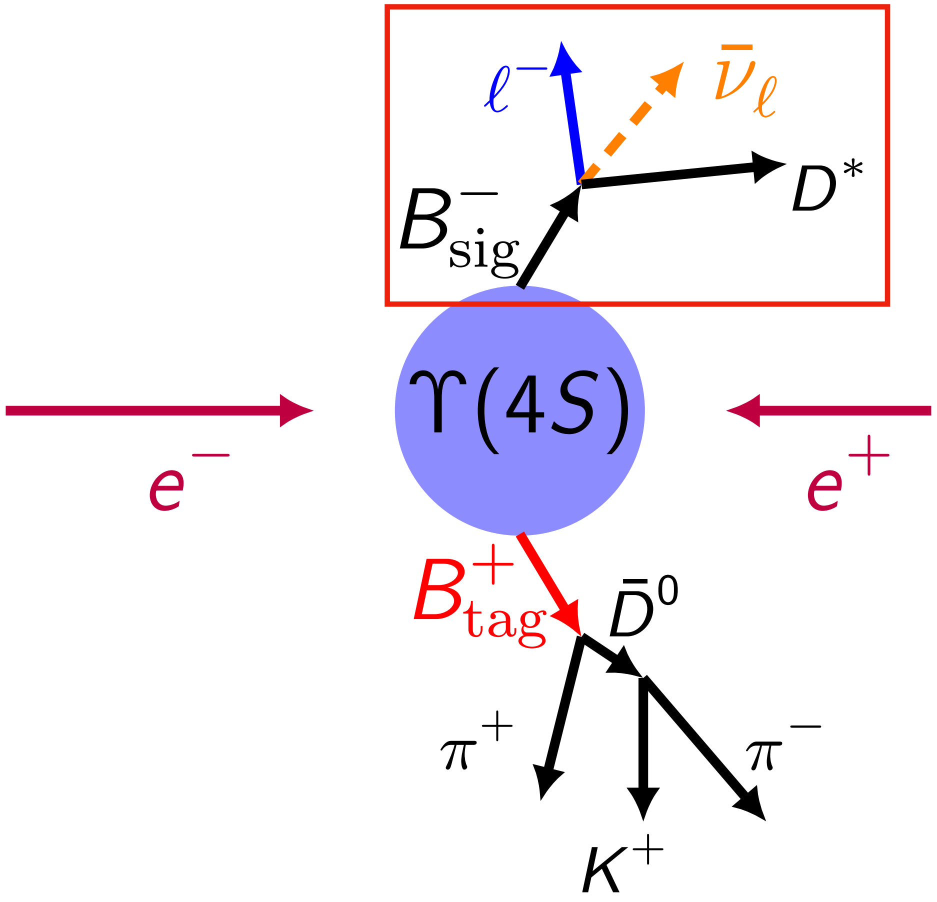


B^+		
$\mathcal{P}_{\mathrm{tag}} >$	ϵ	uncertainty [%]
0.001	0.65 ± 0.02	3.0
0.01	0.61 ± 0.02	3.1
0.1	0.64 ± 0.02	3.3

B^0		
$\mathcal{P}_{\mathrm{tag}} >$	ϵ	uncertainty [%]
0.001	0.83 ± 0.03	3.4
0.01	0.78 ± 0.03	3.5
0.1	0.72 ± 0.03	3.9



$$m_\nu^2 = \left(p_\nu\right)^2 \simeq m_{\text{miss}}^2 = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_\ell - p_{D^*}\right)^2 \sim 0\,\text{GeV}^2$$



Belle II Collaboration, BELLE2-CONF-PH-2020-009, [arXiv:2008.10299]

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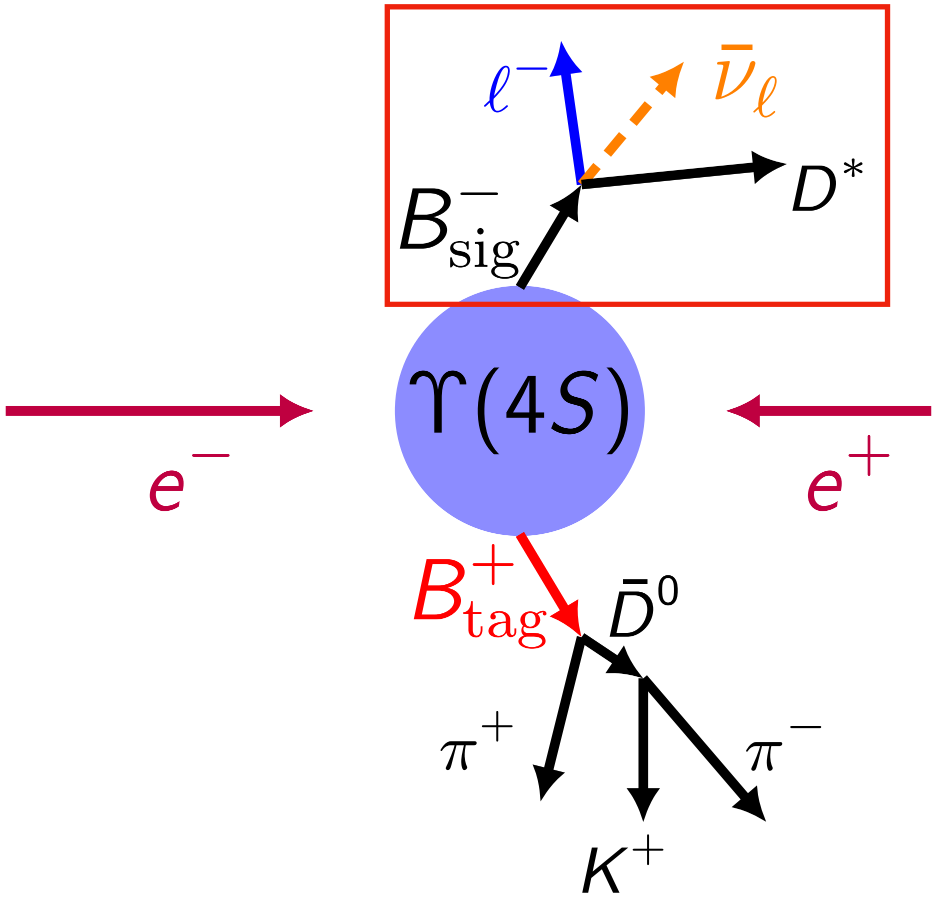
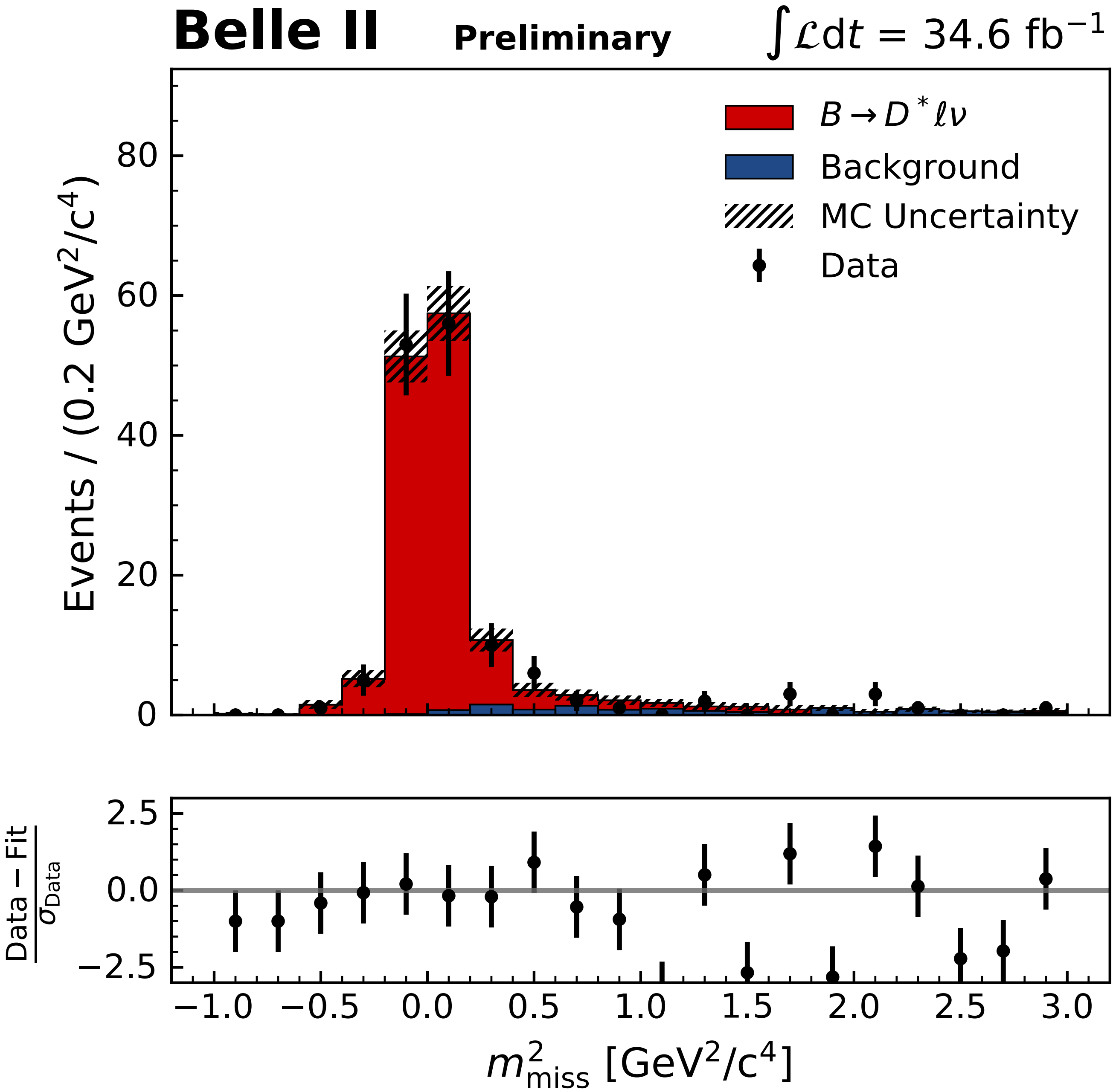
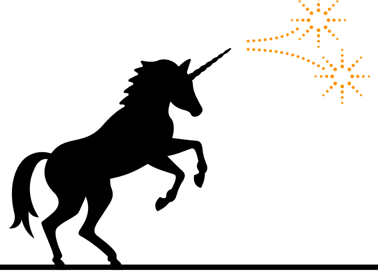




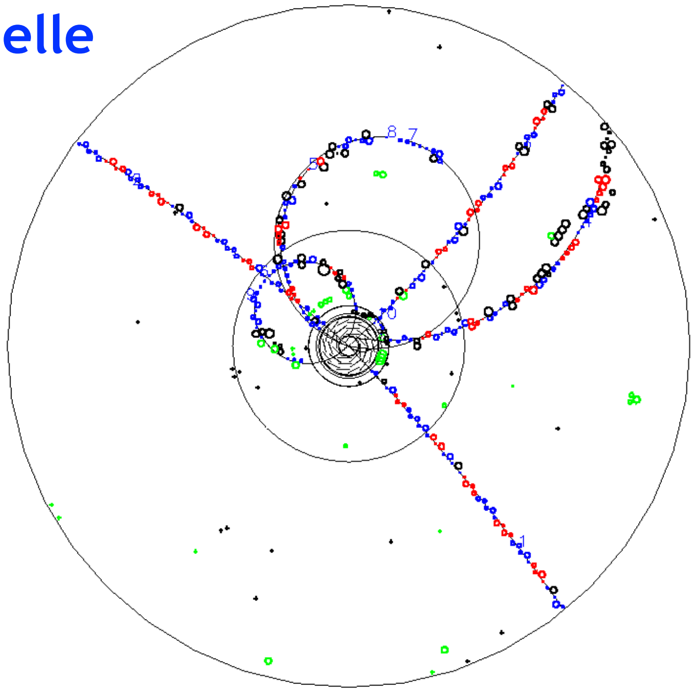
$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = \left(4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_s}\right)\%\,,$$

World Average: $\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = (5.05 \pm 0.14)\%$

Beam background — be gone!

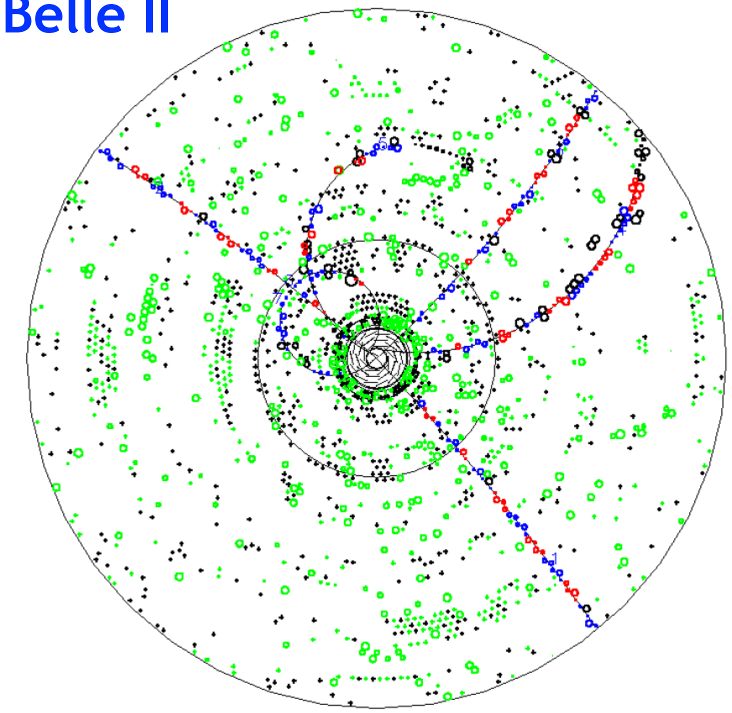


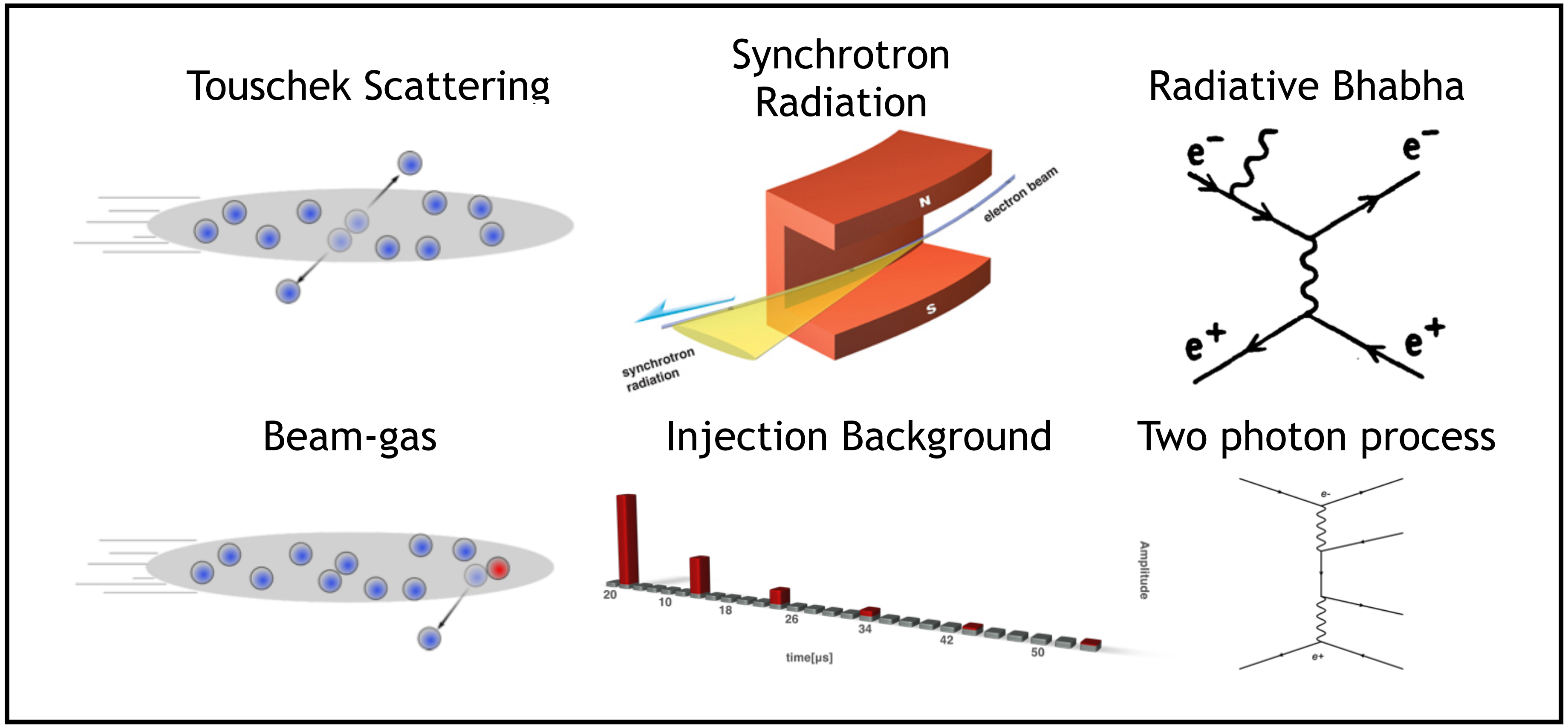
Belle



Background x 20

Belle II





Touschek Scattering

Synchrotron Radiation

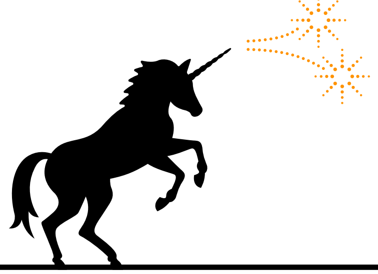
Radiative Bhabha

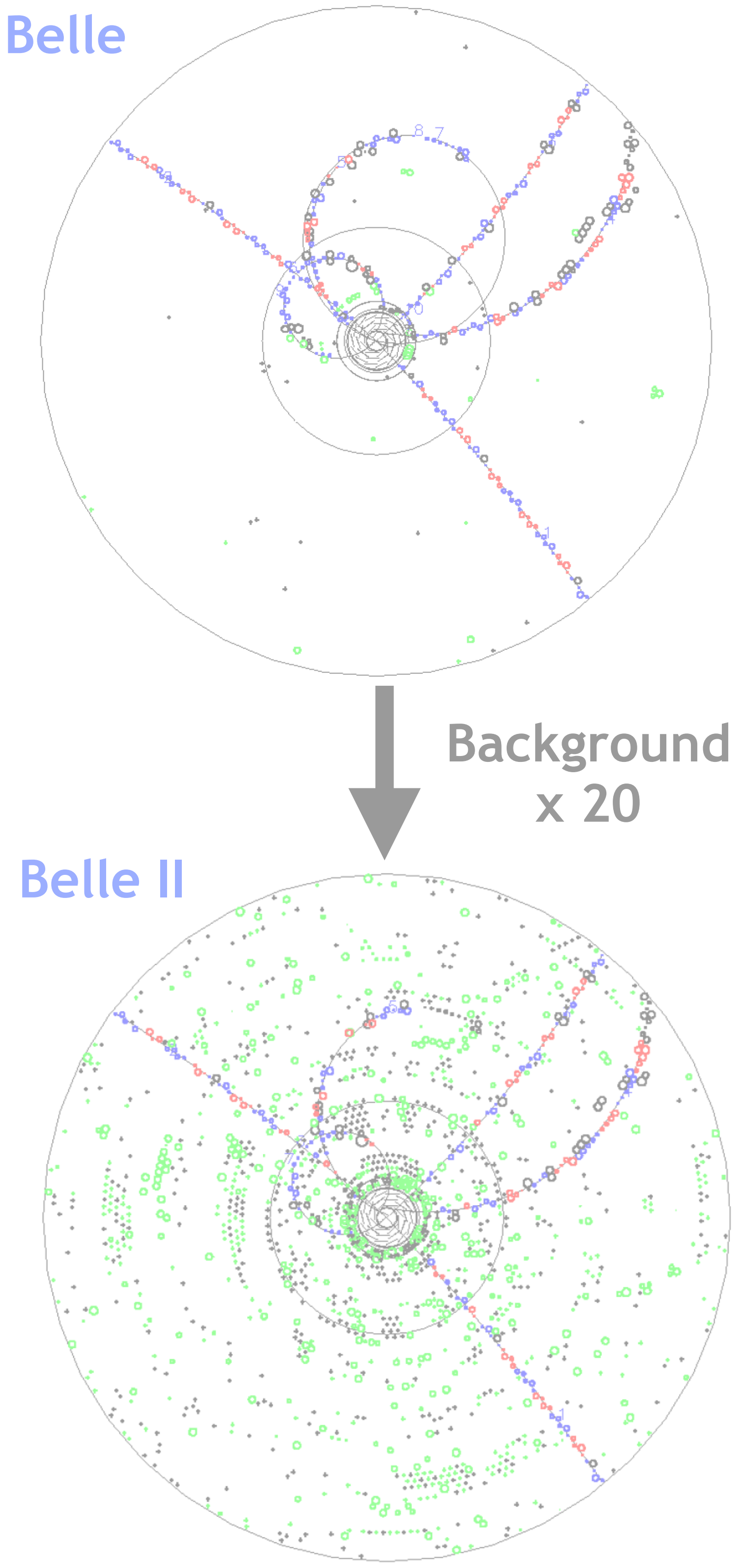
Beam-gas

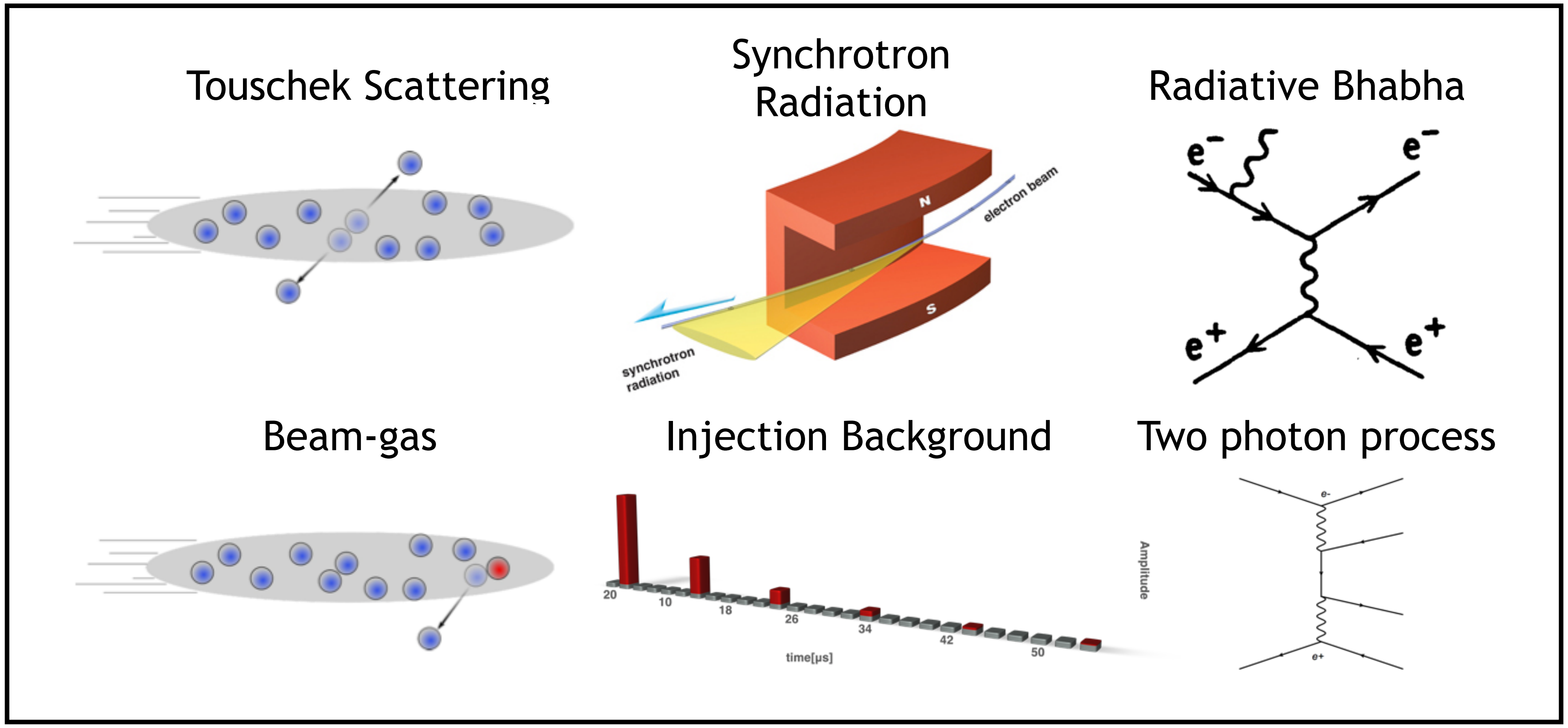
Injection Background

Two photon process

Beam background — be gone!



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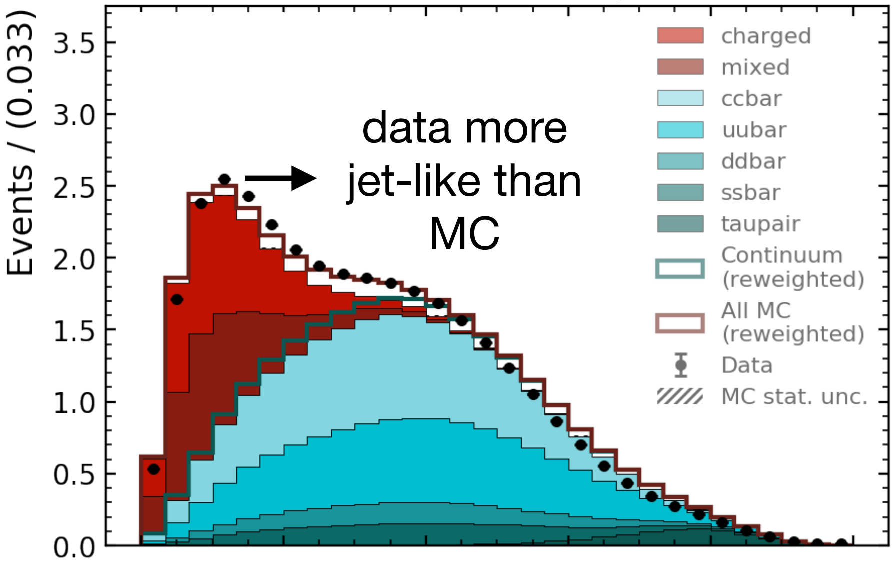
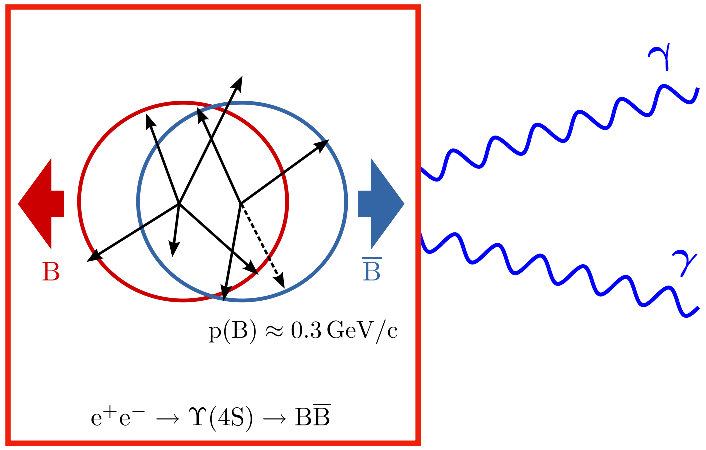


$$\mathscr{R}_2 = \mathscr{H}_2/\mathscr{H}_0$$



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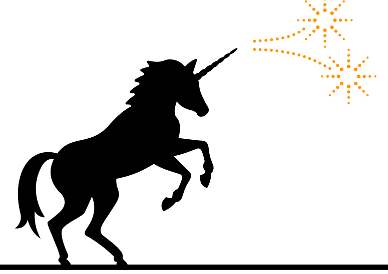
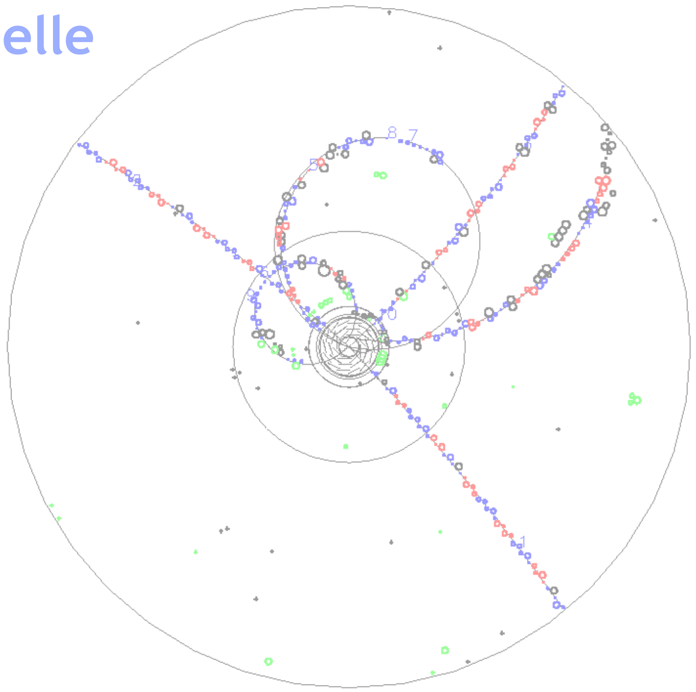
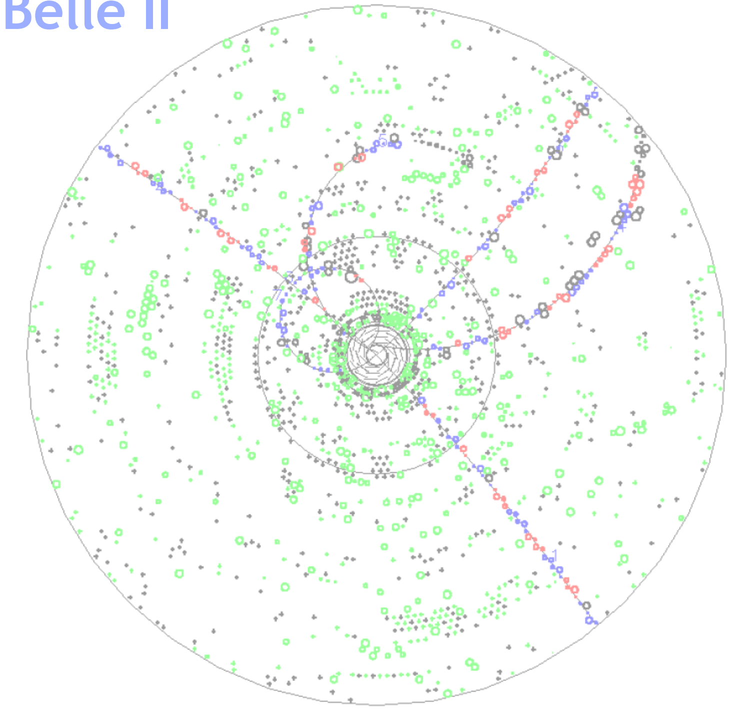


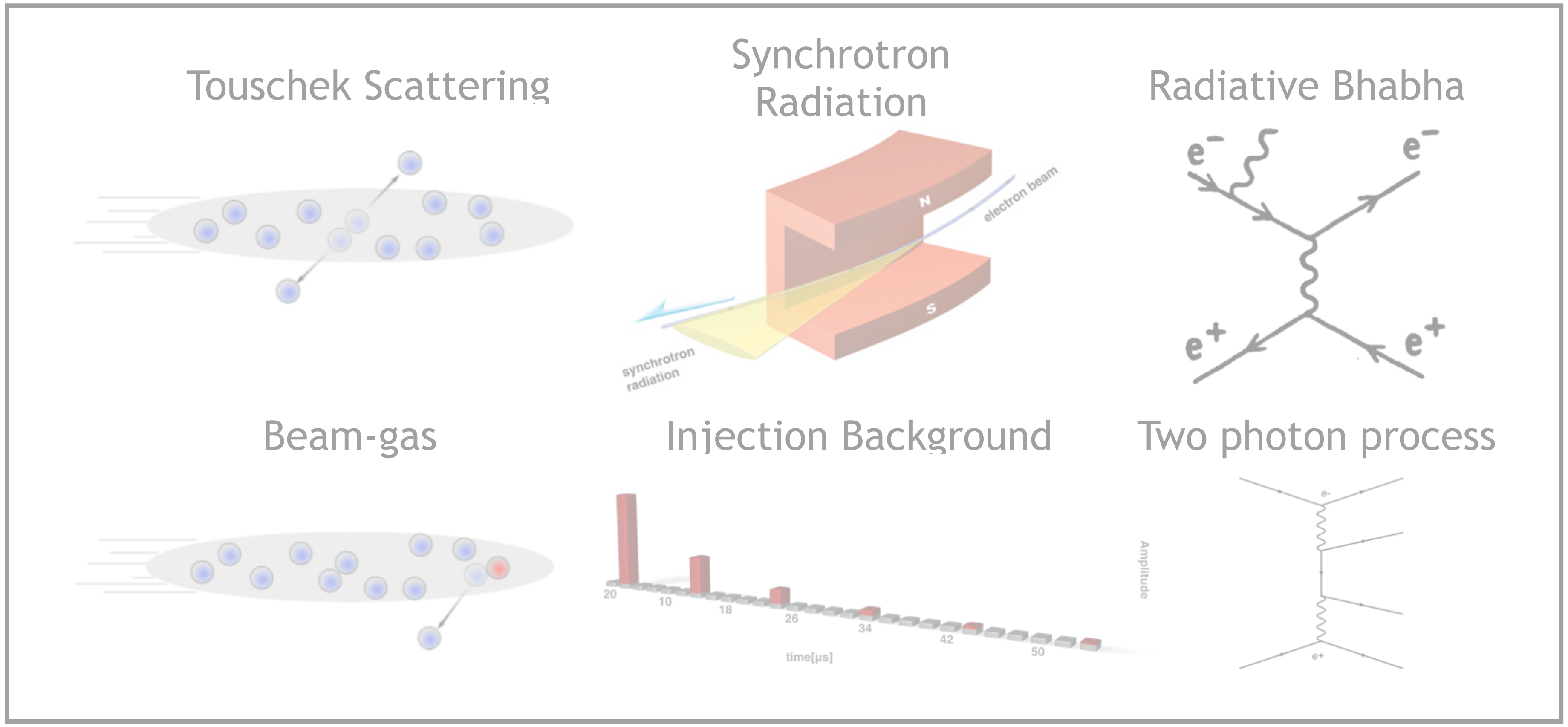
Belle



Background
x 20

Belle II





Touschek Scattering

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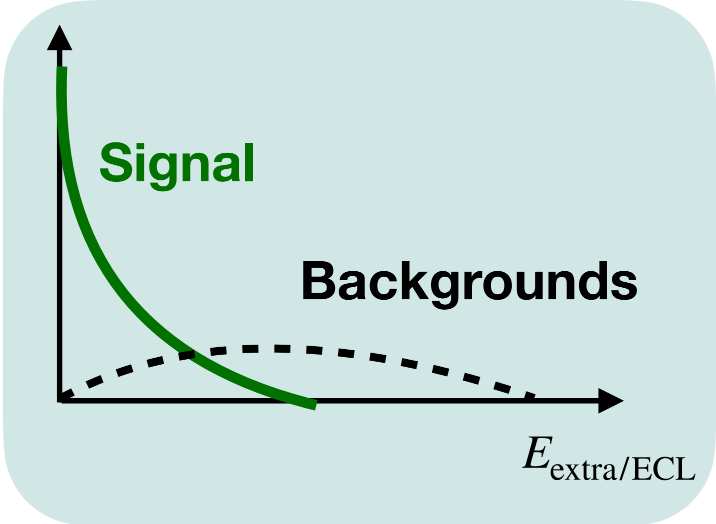
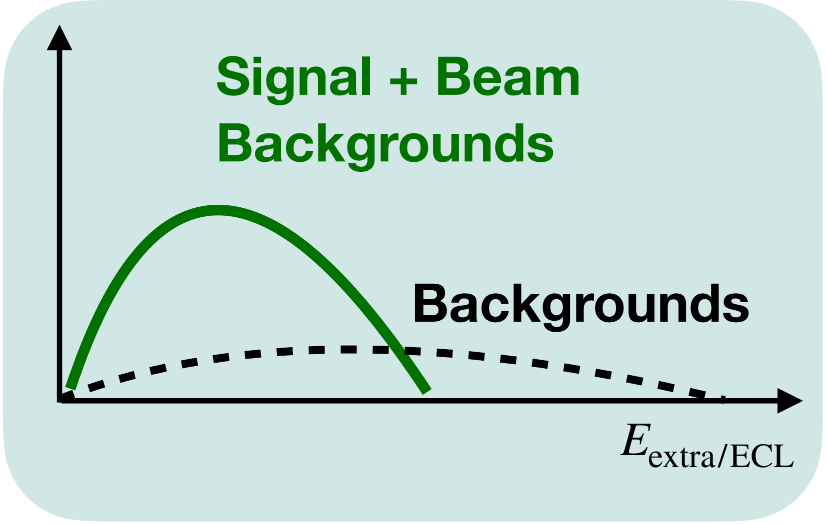
Two photon process

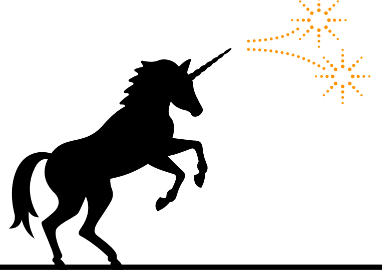
Ideal best case



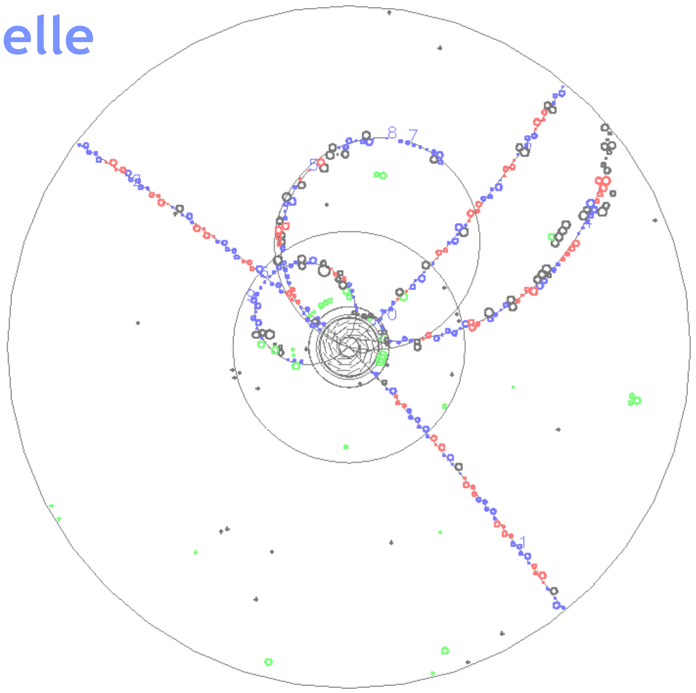
More realistic case



Beam background — be gone!

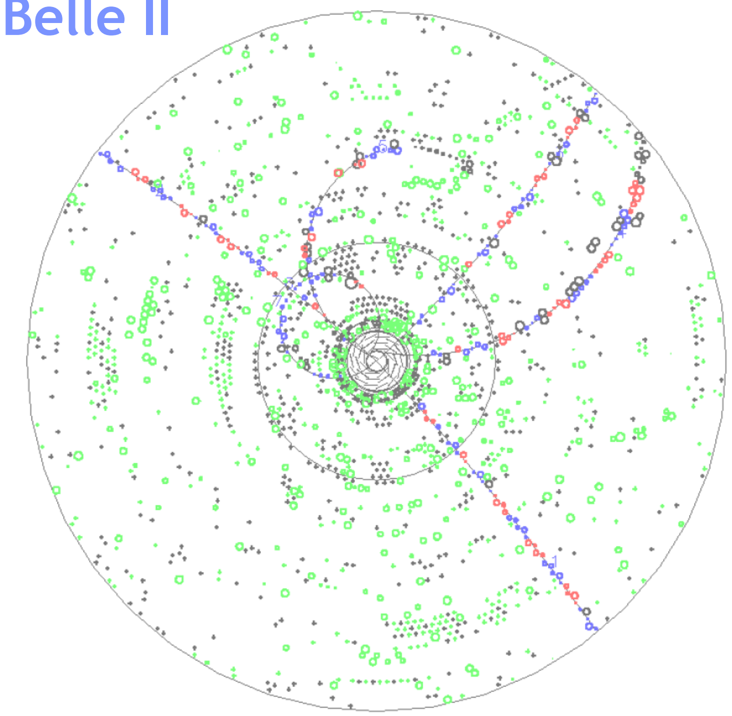


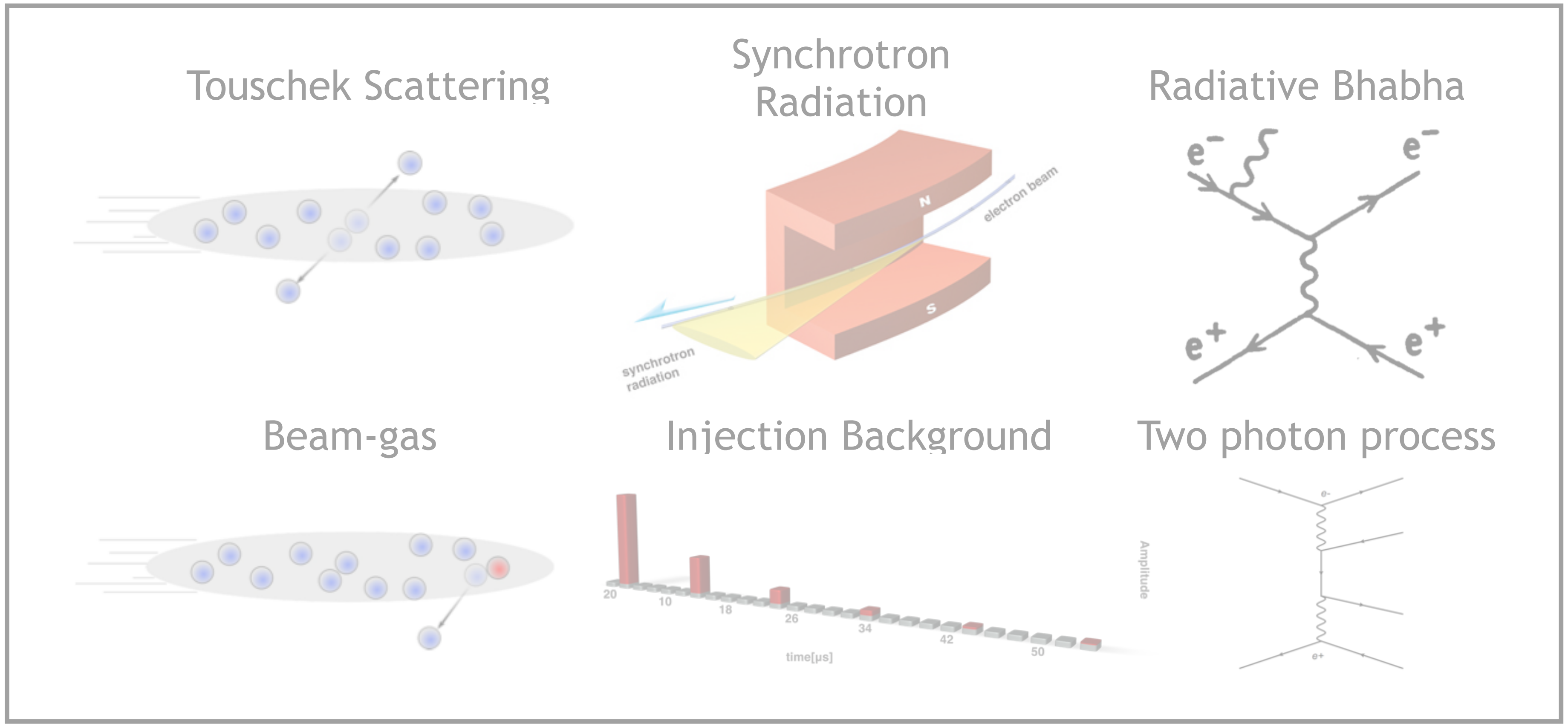
Belle



Background x 20

Belle II

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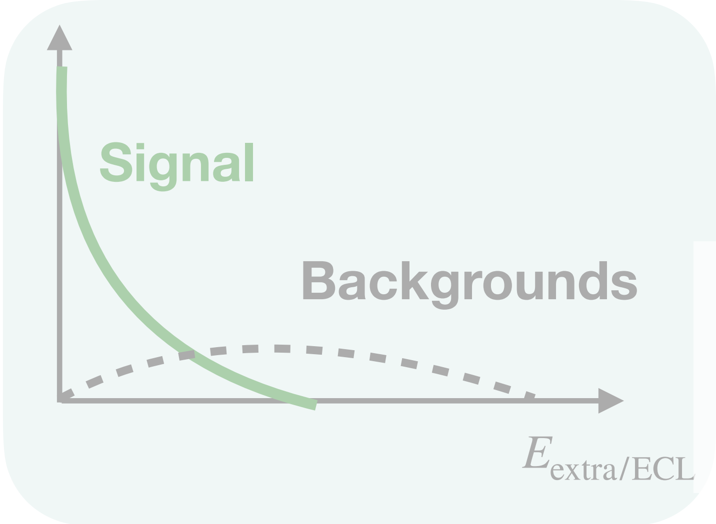
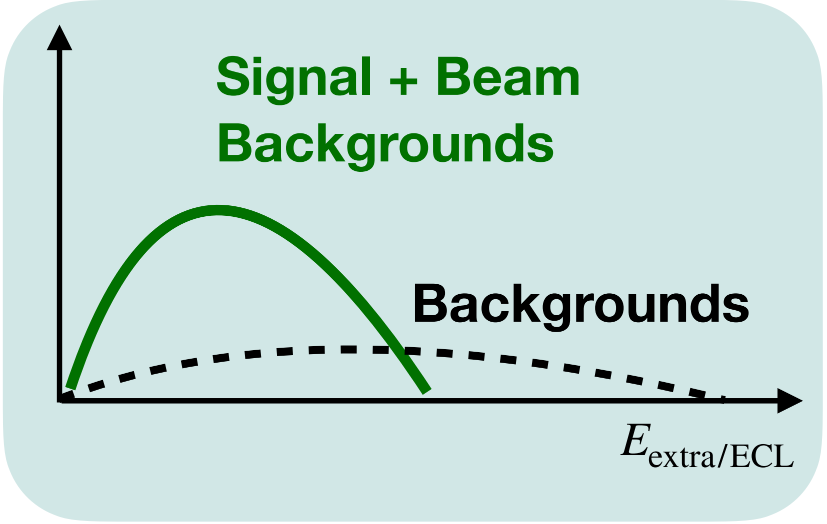


Is there a way back?

?

More realistic case



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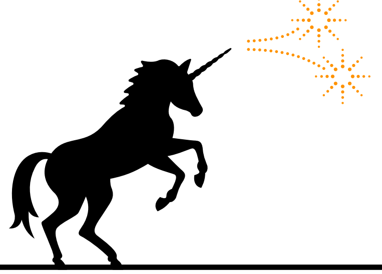
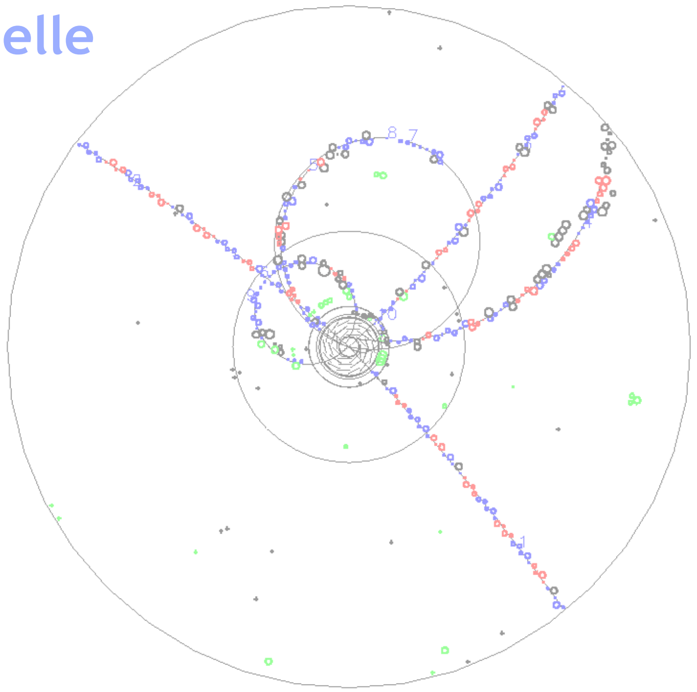


Belle



Background
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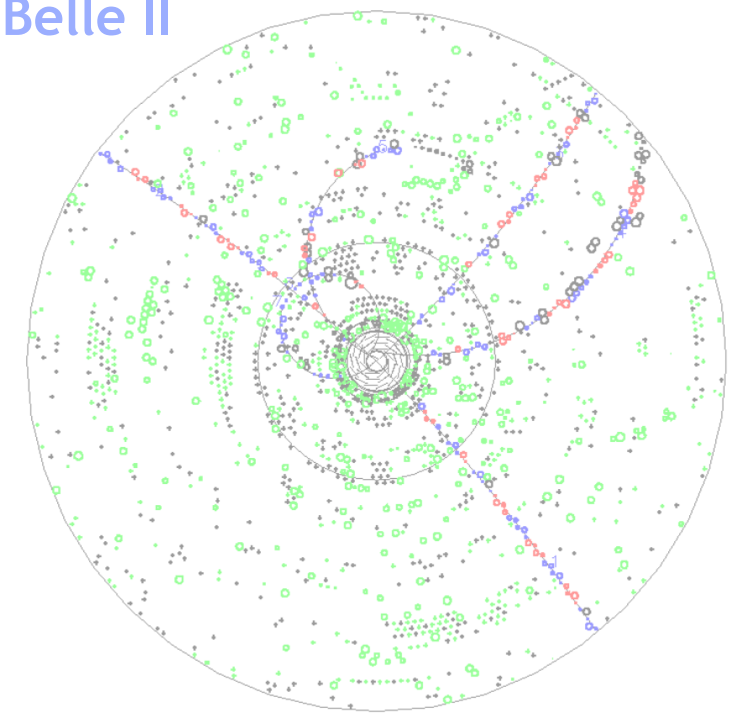
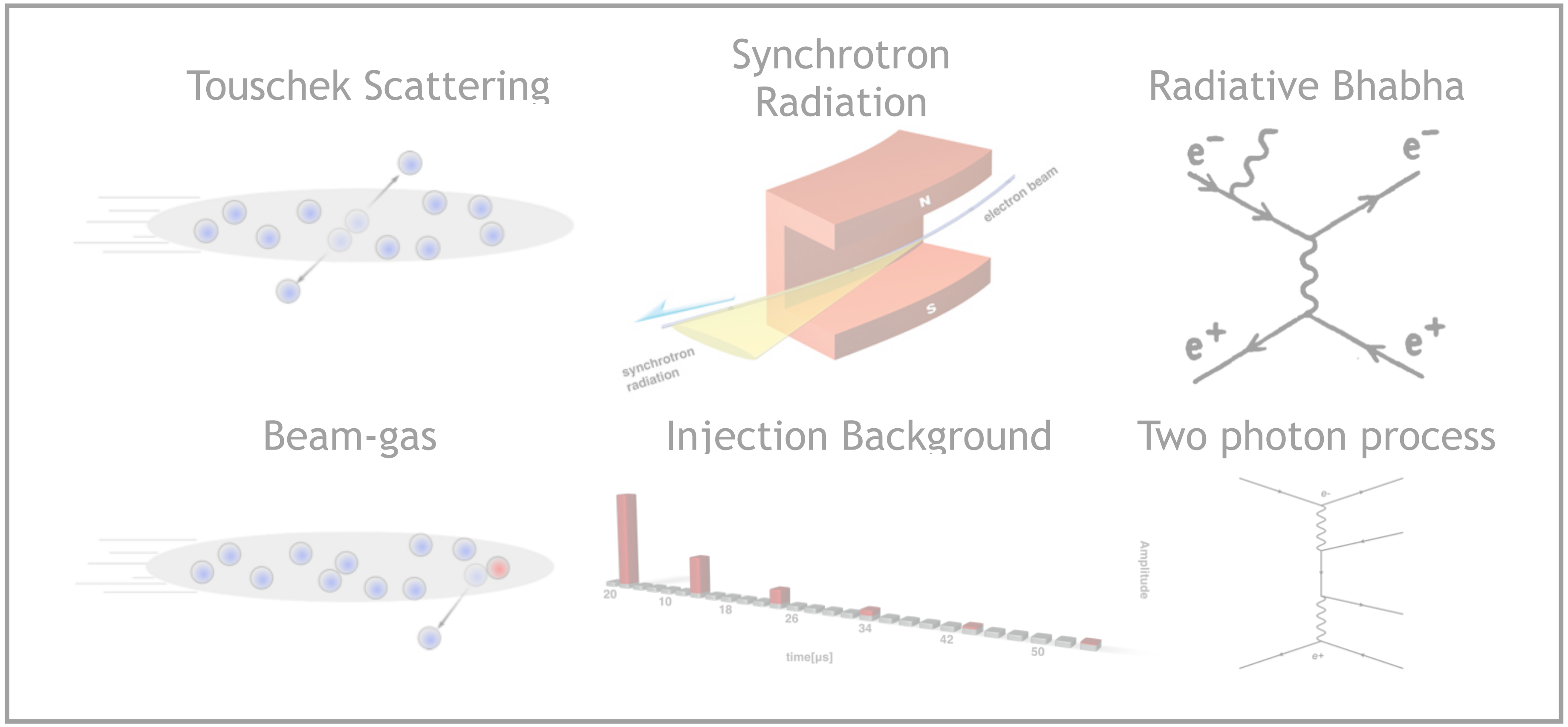
Belle II



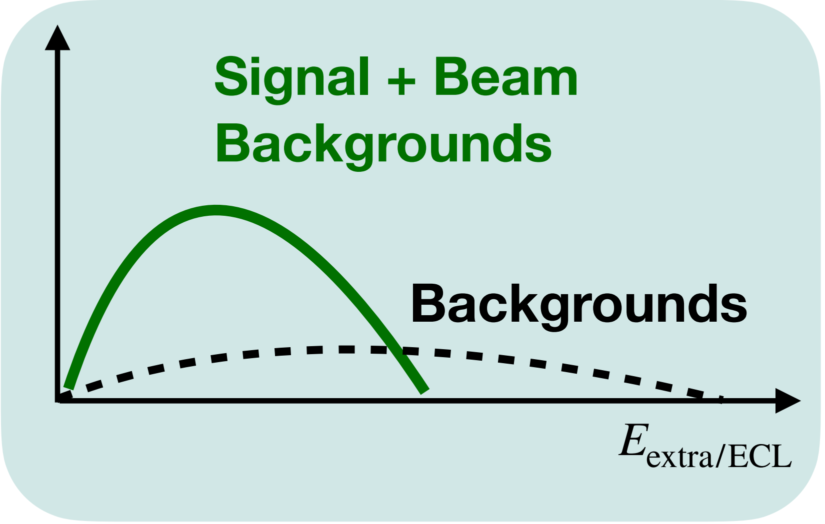


let's ask our future overlords

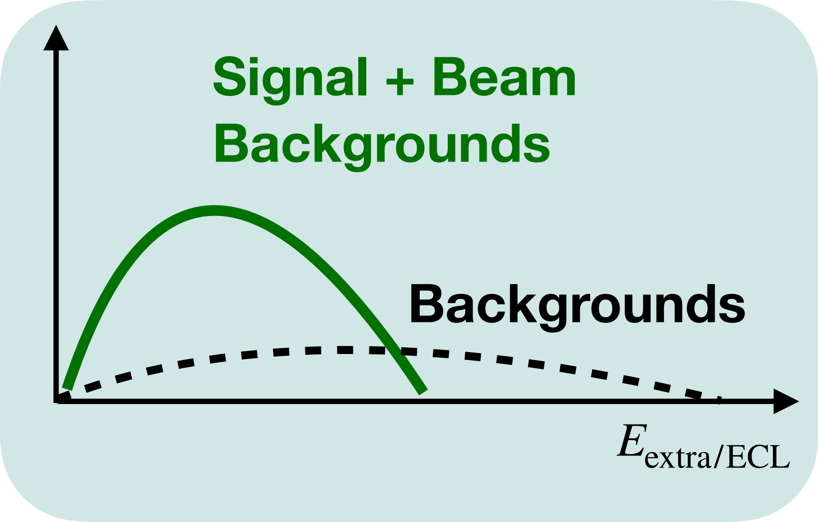
Is there a way back?

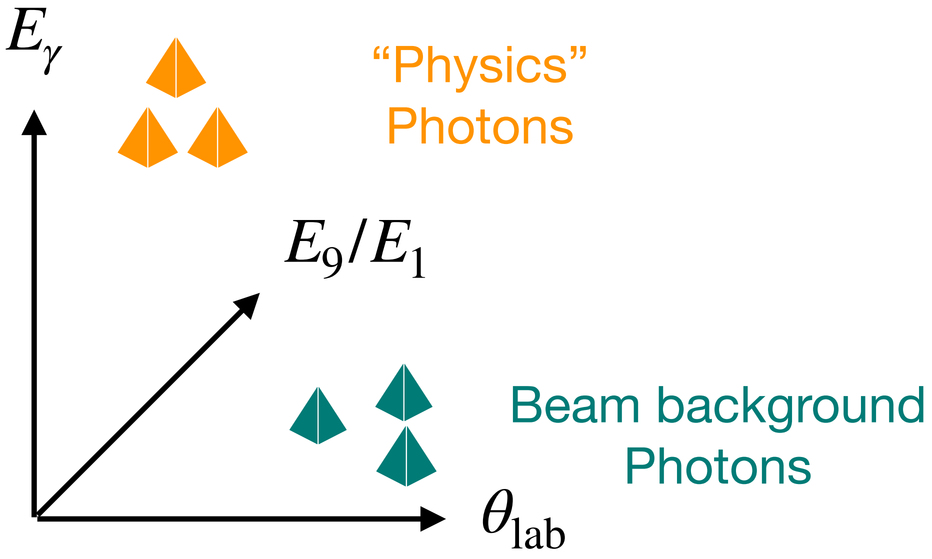
?

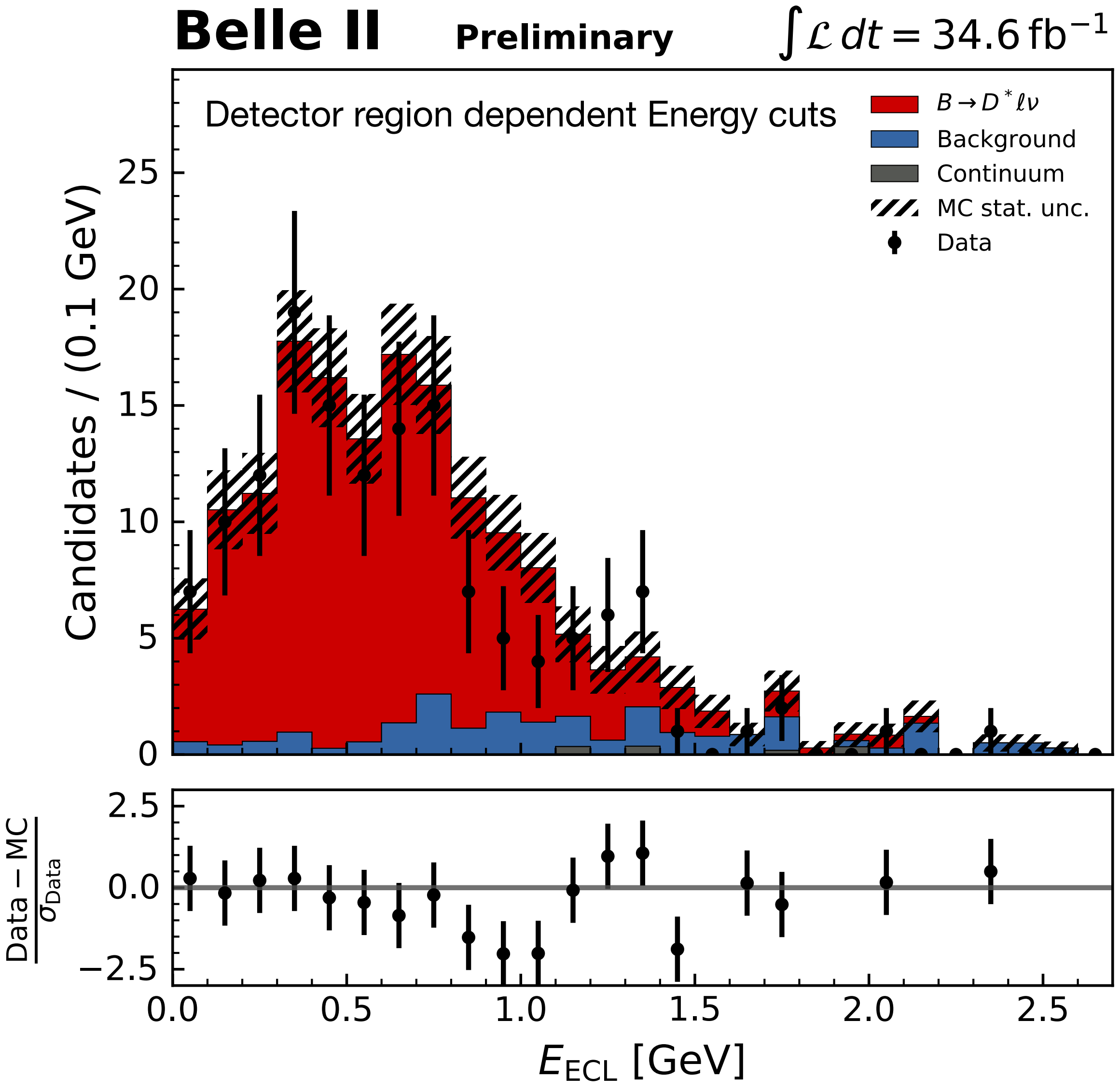
More realistic case



Belle II Collaboration, BELLE2-CONF-PH-2020-009, [arXiv:2008.10299]





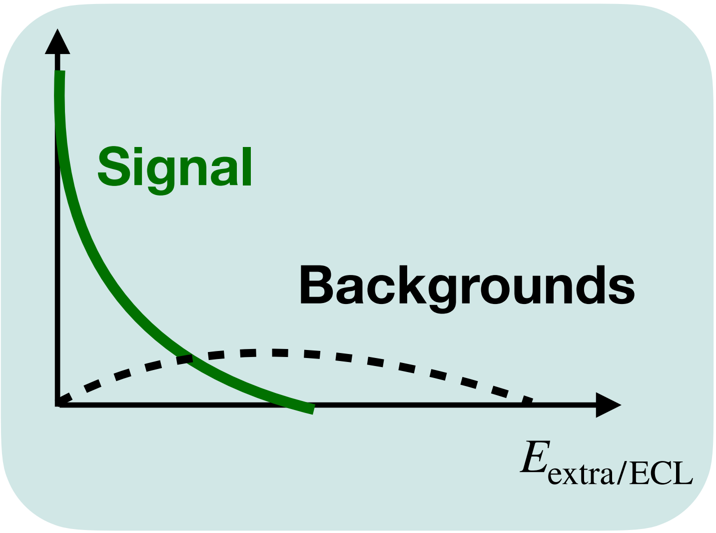


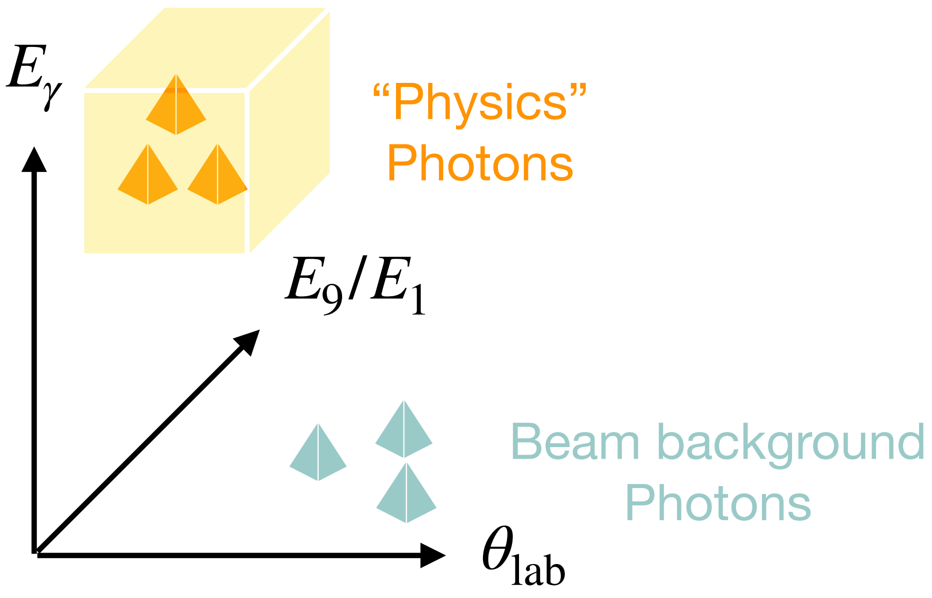
+ lateral Energy distribution, second moment of cluster energy distribution, azimuthal angle, Zernike moments of cluster shower

Train BDT to recognize beam background photons from $e^+e^- \to \mu^+\mu^-$ tagged events;

Only include photons that are not identified as such

Belle II Collaboration, BELLE2-CONF-PH-2020-009, [arXiv:2008.10299]





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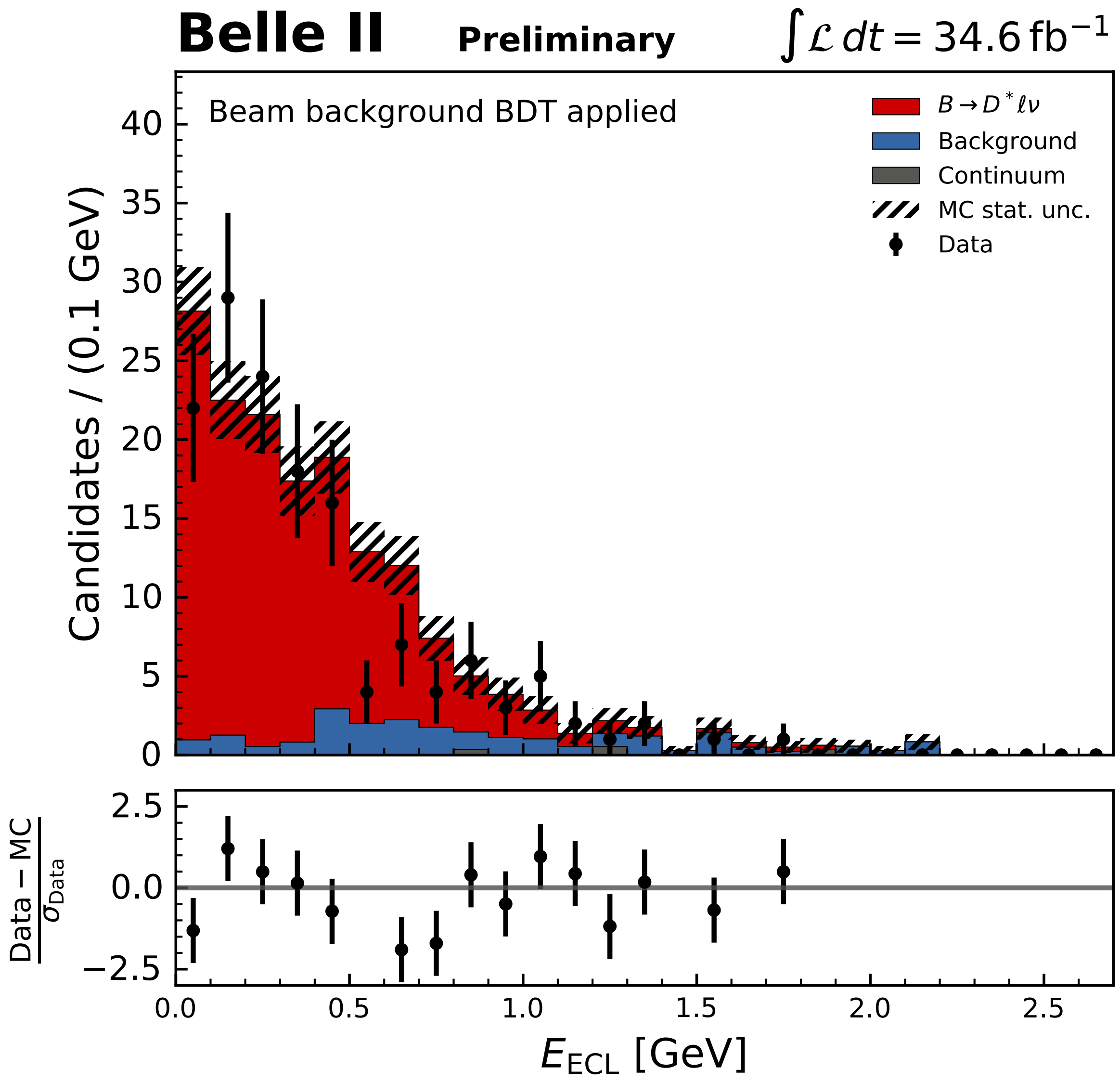


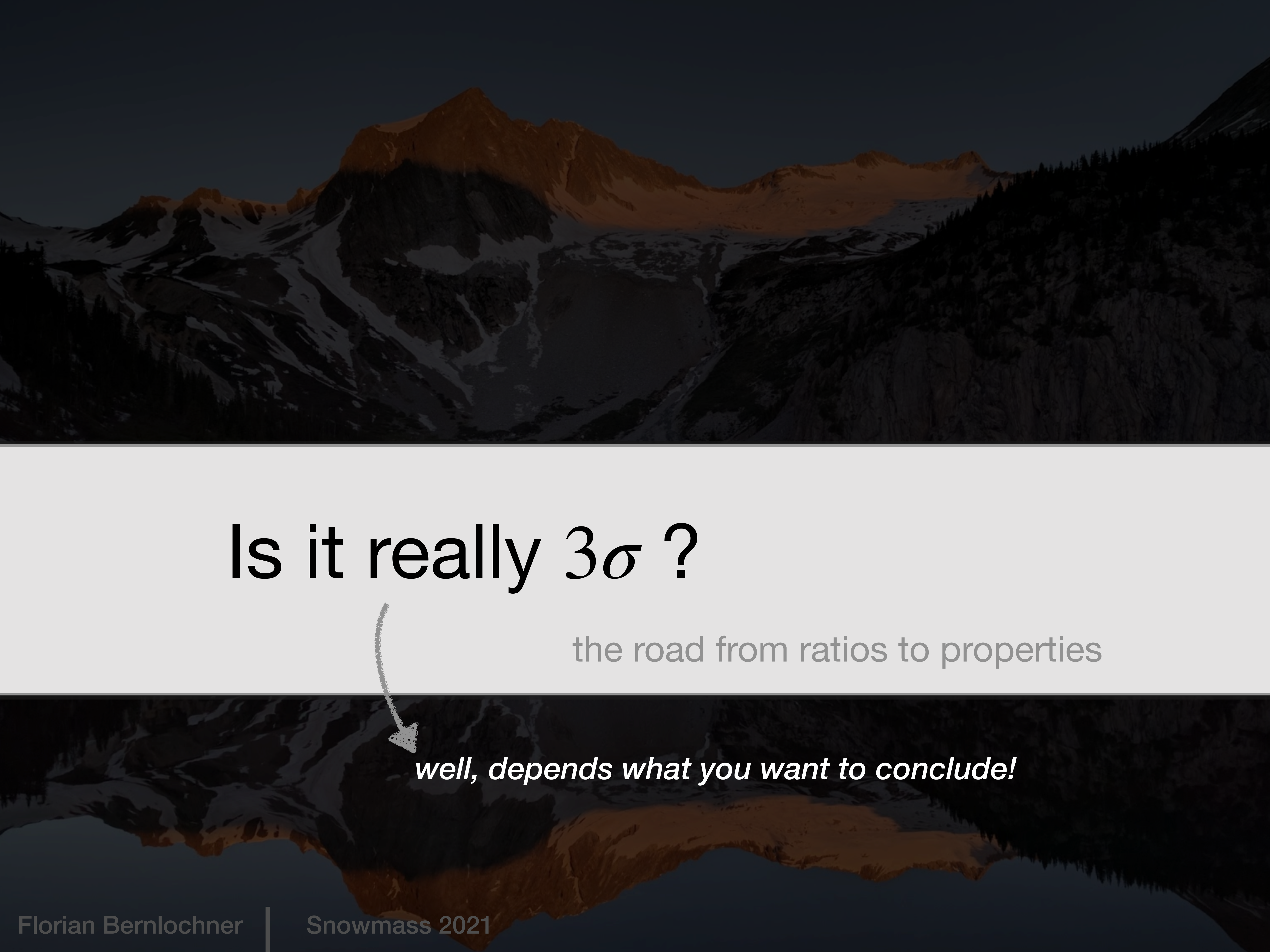
Train BDT to recognize beam background photons from $e^+e^- \to \mu^+\mu^-$ tagged events;

Only include photons that are not identified as such

Going beyond the state-of-the-Art

the road from ratios to properties

Florian Bernlochner | Snowmass 2021

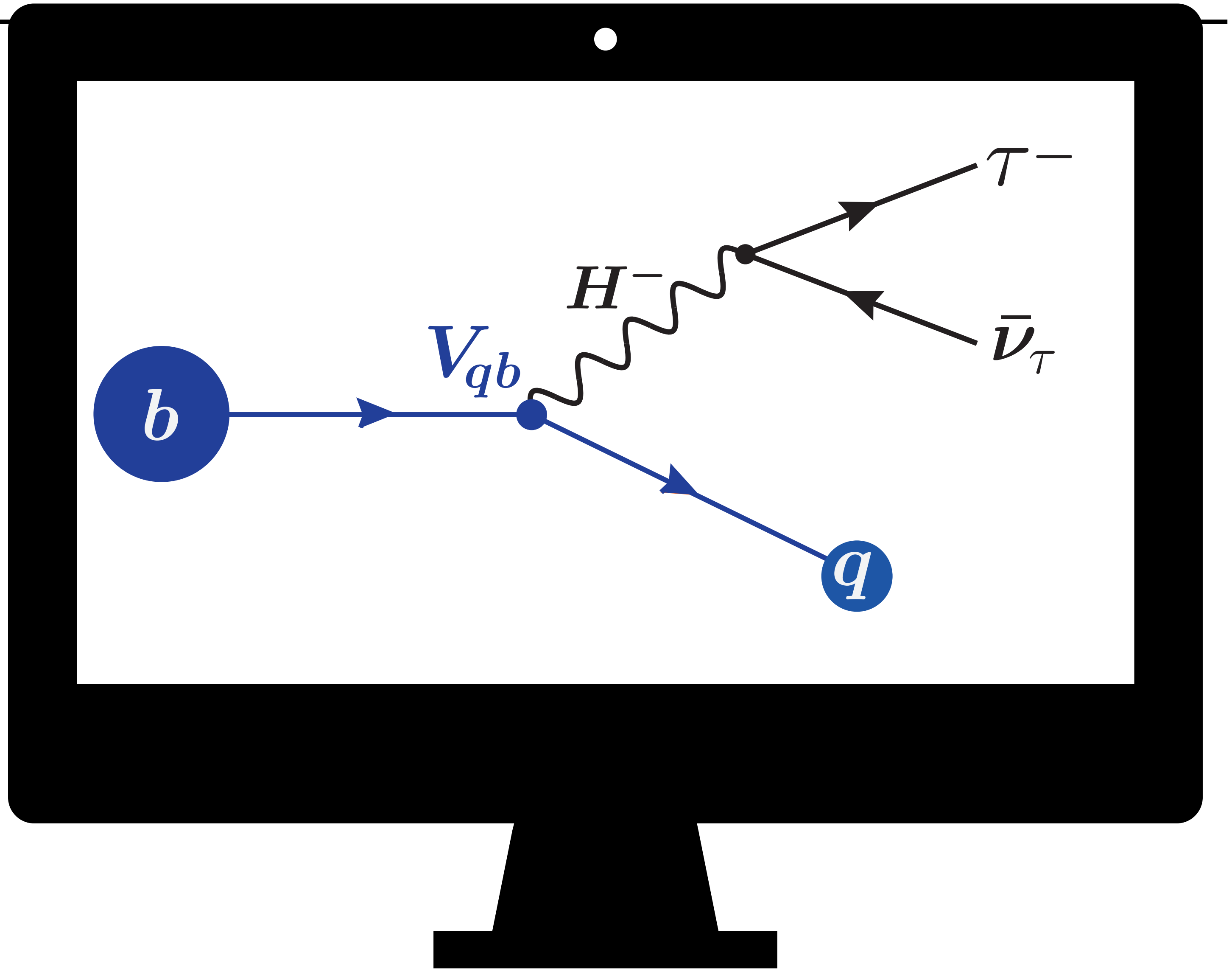


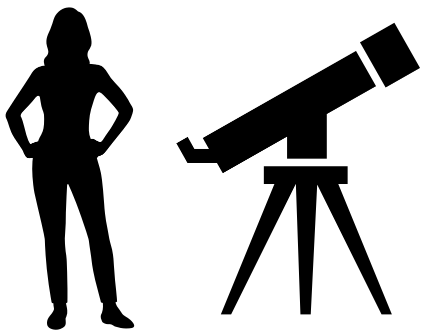
Is it really 3σ ?

the road from ratios to properties

well, depends what you want to conclude!

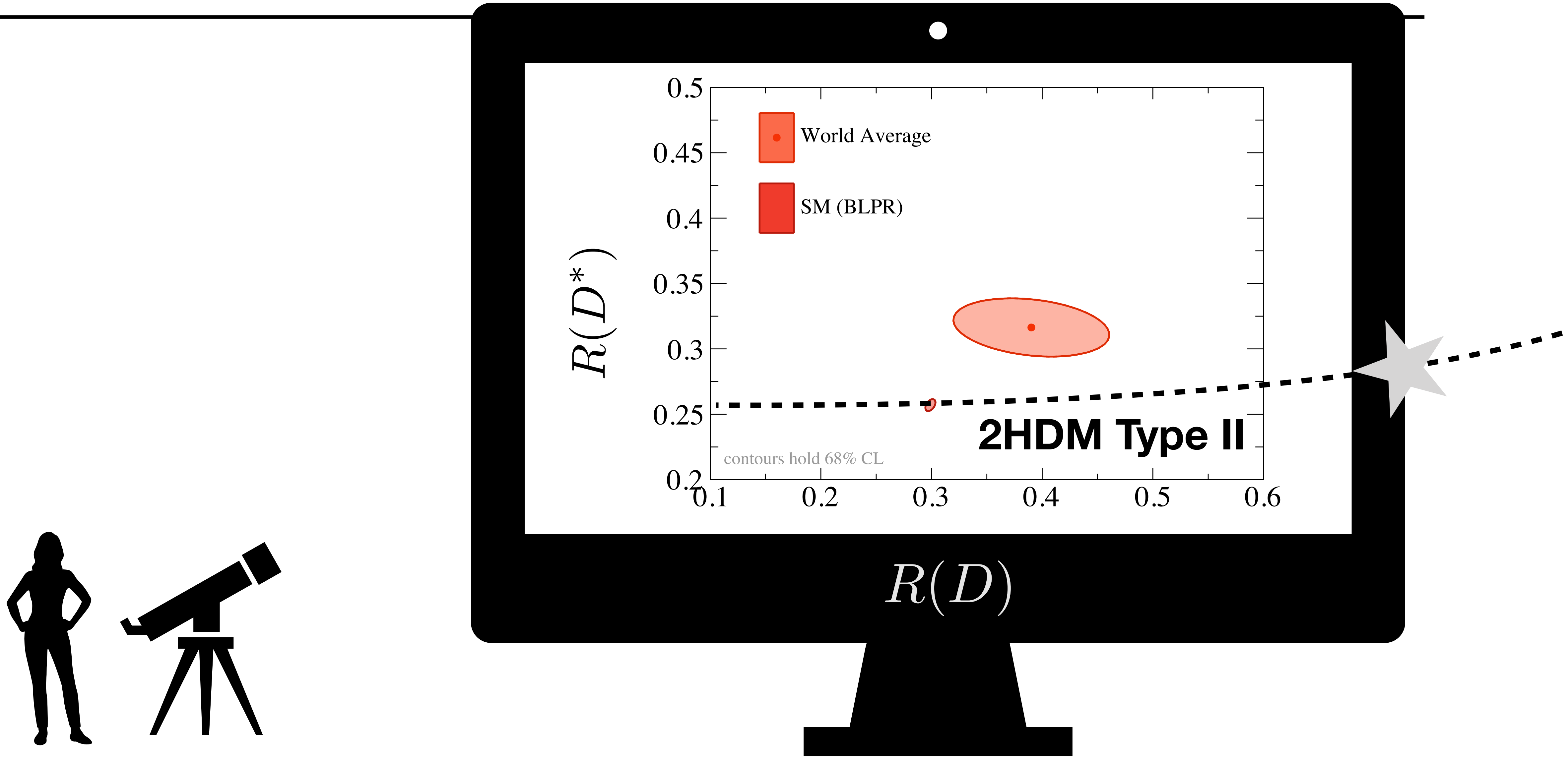
Let me explain what I mean:





- Let’s say you want to use the **measured ratios** to learn something about the anomaly and **your favourite model** that could explain it!

Let me explain what I mean:



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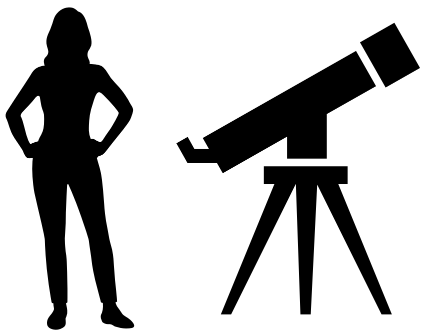
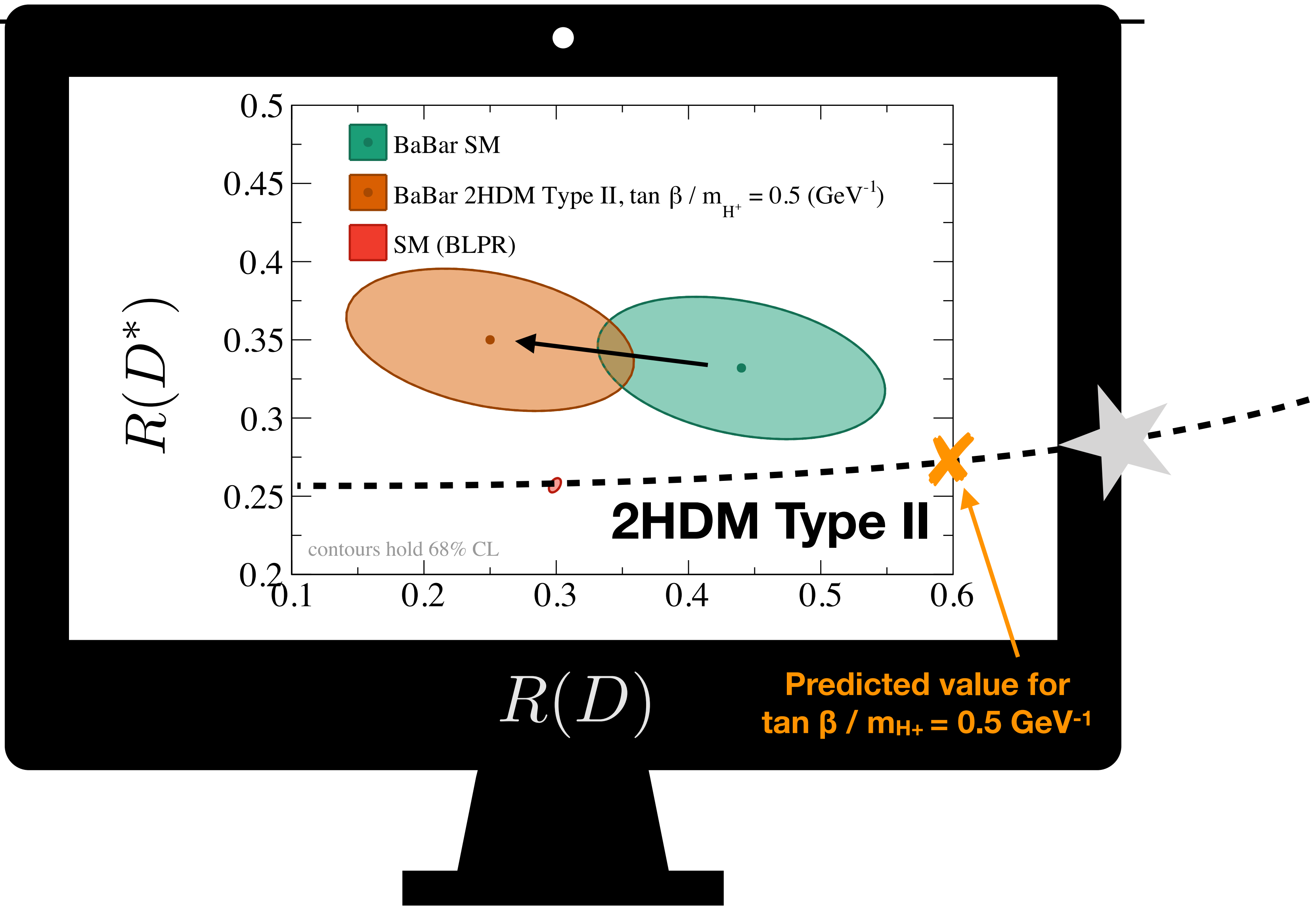


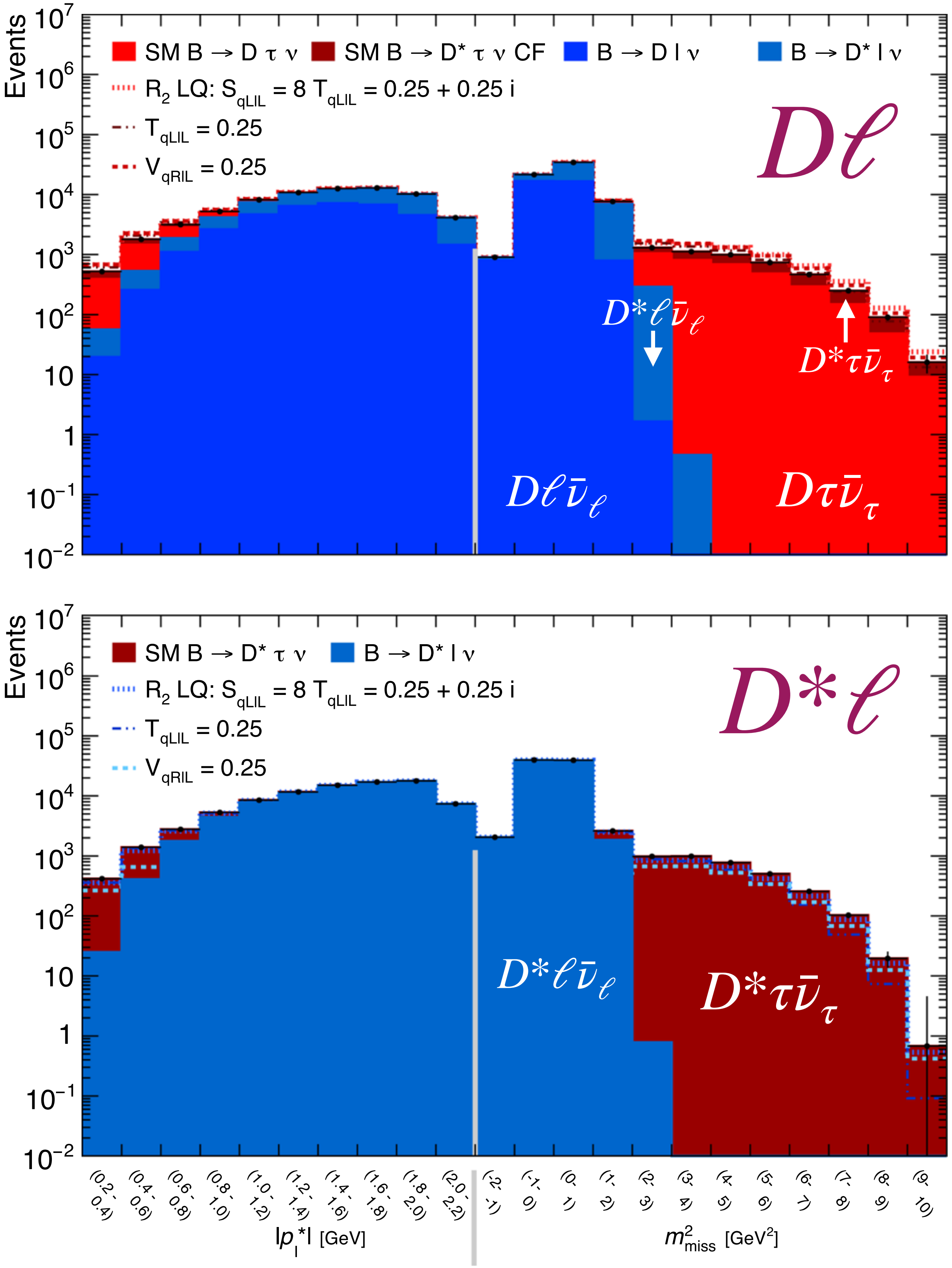


Predicted value for tan β / m_{H+} = 0.5 GeV^{-1}

- As it turns out, **not that easy** — the **measured points** themselves are **extracted assuming** the **SM**.

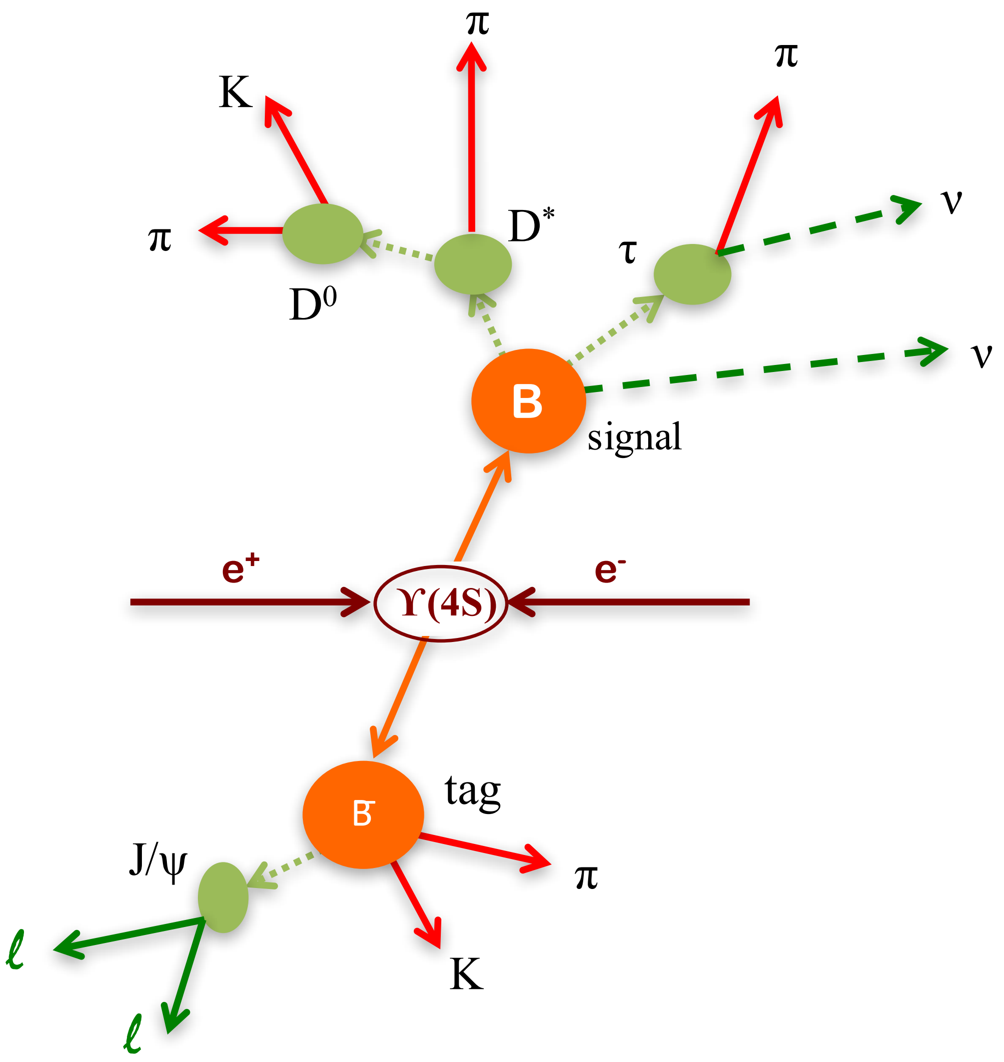
An illustrative Toy Example

FB, S. Duell, Z. Ligeti, M. Papucci, D. Robinson
Eur. Phys. J. C (2020) **80**: 883 [arXiv:2002:00020]



2 Categories: $D\ell, D^*\ell$

Joint 2D fit in $m^2_{\rm miss} : |p^*_\ell|$



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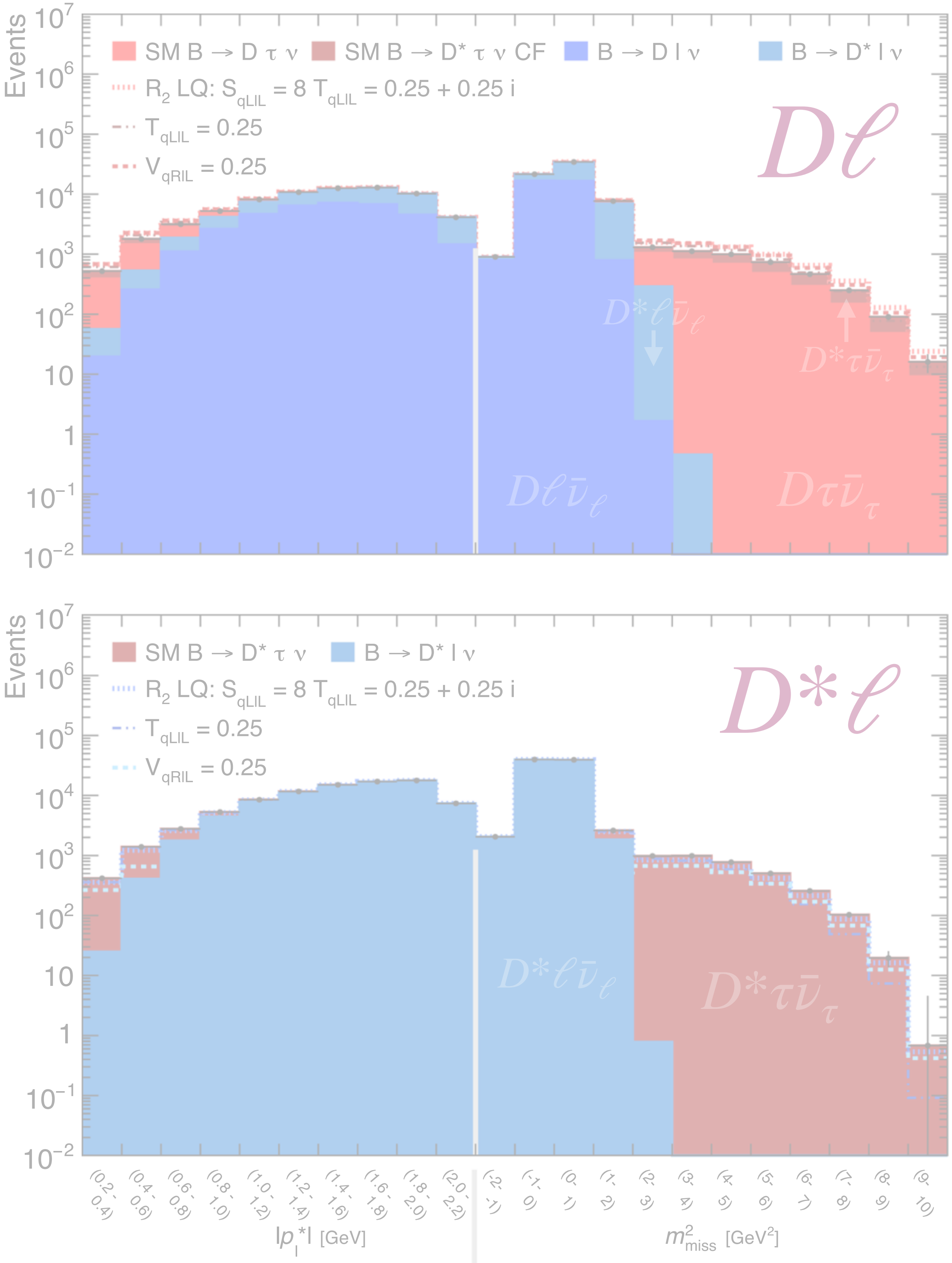
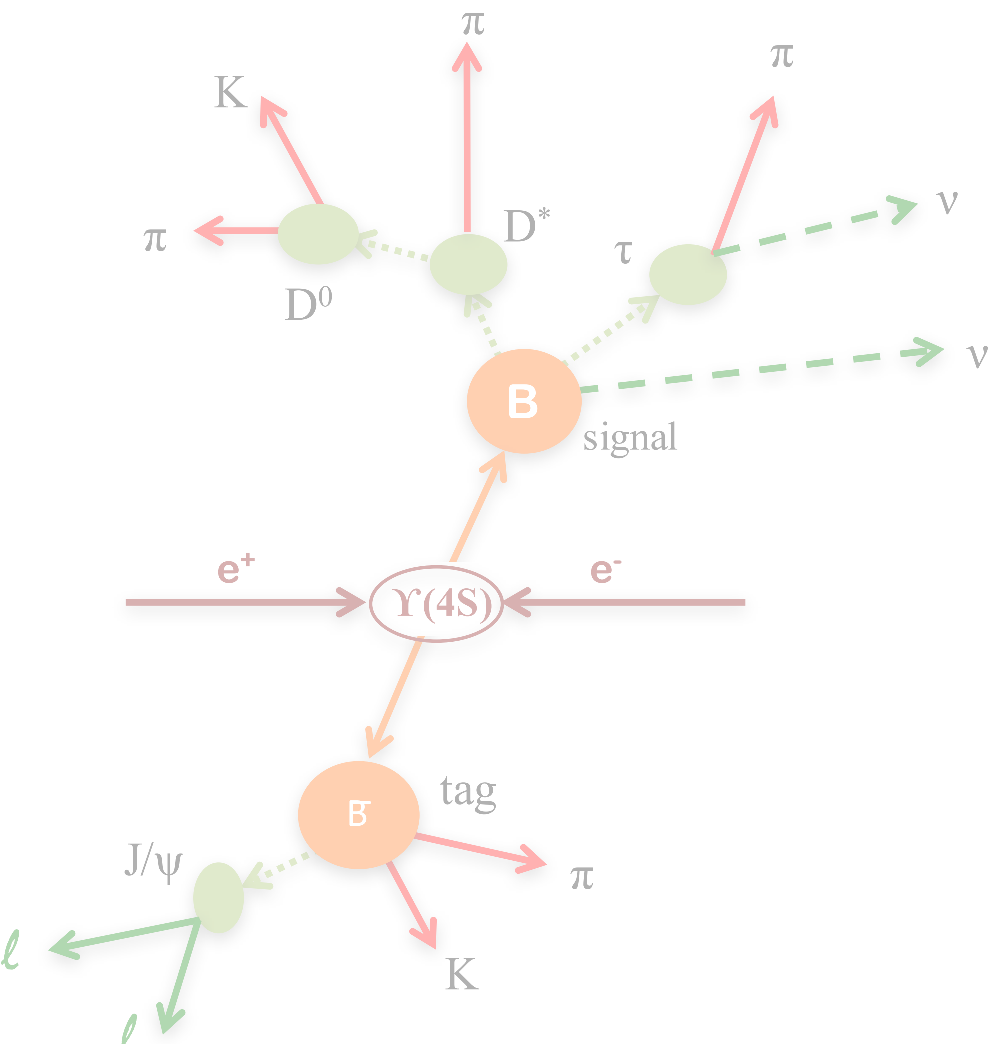


$$\mathscr{R}(D^{(*)}) = \frac{N_{\rm sig}}{N_{\rm norm}} \times \frac{\epsilon_{\rm norm}}{\epsilon_{\rm sig}}$$

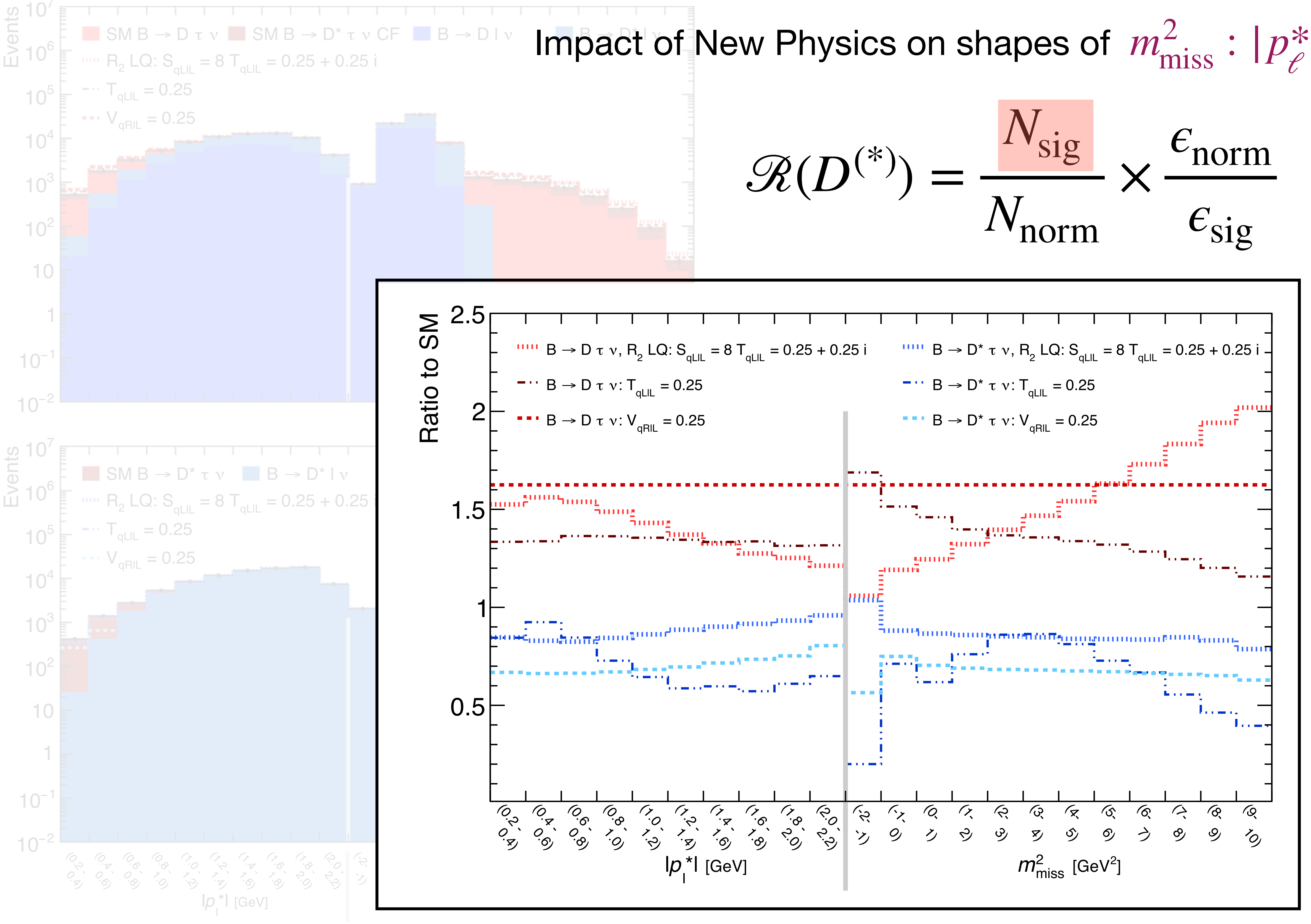


An illustrative Toy Example

FB, S. Duell, Z. Ligeti, M. Papucci, D. Robinson
Eur. Phys. J. C (2020) **80**: 883 [arXiv:2002:00020]

Impact of New Physics on shapes of $m^2_{\text{miss}} : |p^*_\ell|$

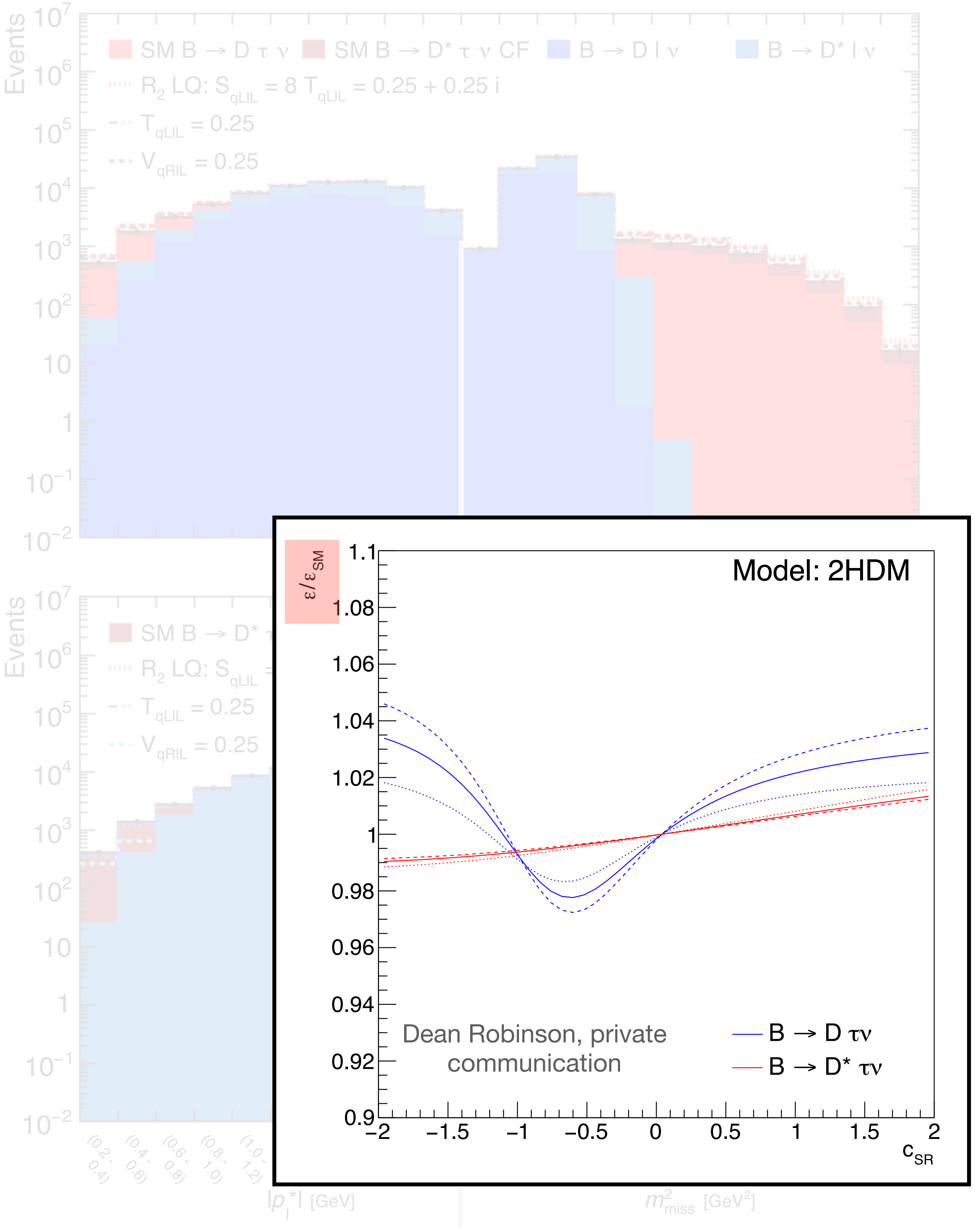
$$\mathscr{R}(D^{(*)}) = \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}}$$

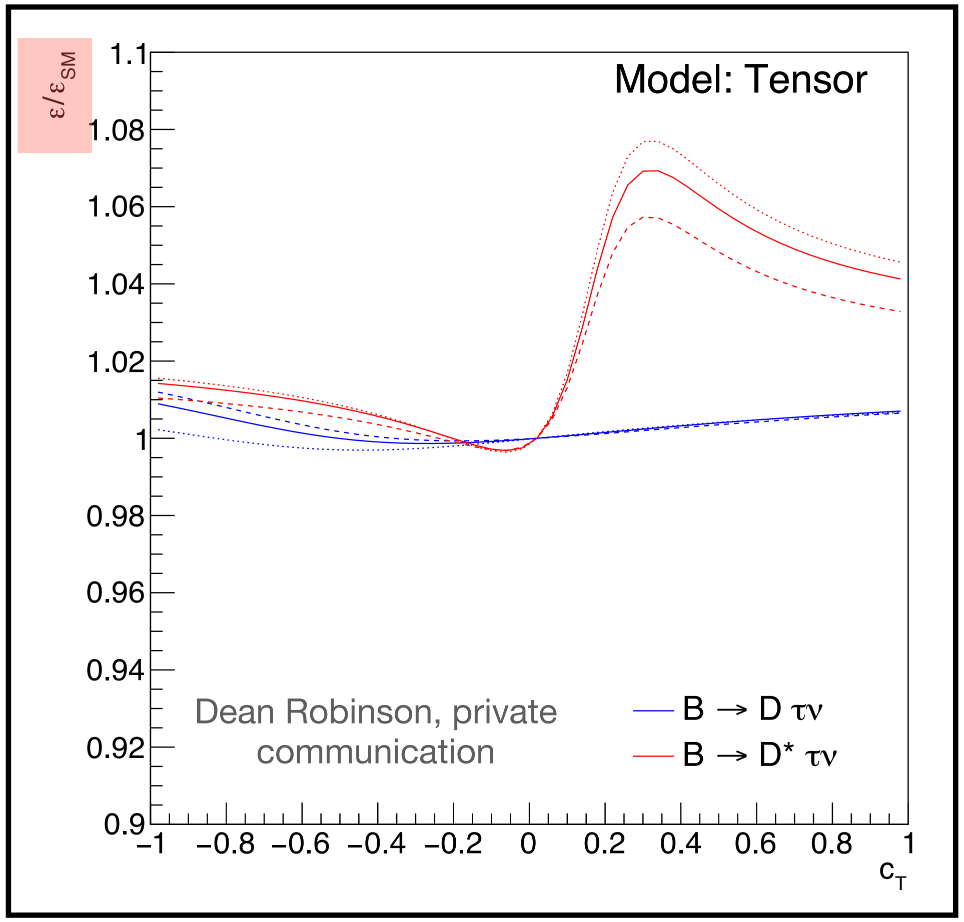


An illustrative Toy Example

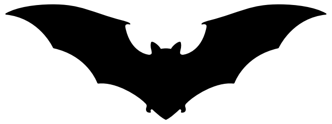
Impact of New Physics on efficiencies

$$\mathscr{R}(D^{(*)}) = \frac{N_{\mathrm{sig}}}{N_{\mathrm{norm}}} \times \frac{\epsilon_{\mathrm{norm}}}{\boxed{\epsilon_{\mathrm{sig}}}}$$



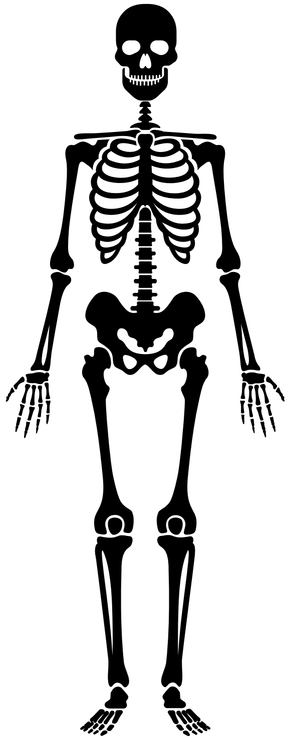


The Little Shop of Horrors:



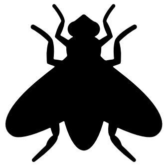
Step #1: Inject New Physics

Step #2: Extract $\mathscr{R}(D/D^*)$ with SM templates



Step #3: Make an interpretation of that value to determine the New Physics coupling

How well will it match?



All of course inside the world of our toy example

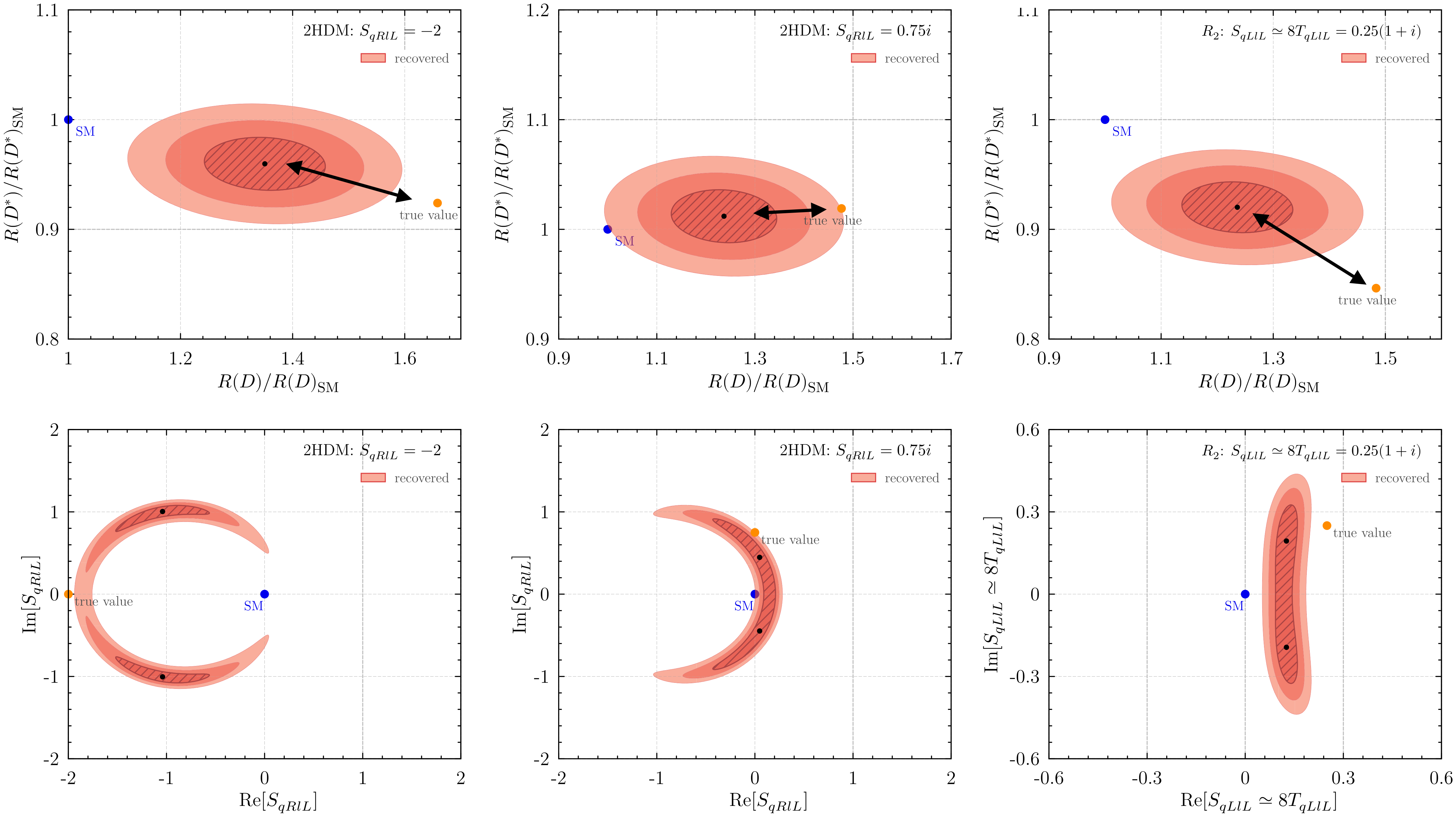
Disclaimer

These scenarios were not picked to impress anybody; they are just an **illustration** of what **can happen** and why we need to move on from pure rate measurements.

Beware of the Bias

$$
\begin{aligned}
\text{2HDM } (-2):\ & \hat{R}(D)_{\rm rec} = 1.35(7)\,, && \hat{R}(D)_{\rm th} = 1.66 \\
& \hat{R}(D^*)_{\rm rec} = 0.96(2)\,, && \hat{R}(D^*)_{\rm th} = 0.92 \\
\text{2HDM } (0.75i):\ & \hat{R}(D)_{\rm rec} = 1.24(7)\,, && \hat{R}(D)_{\rm th} = 1.48 \\
& \hat{R}(D^*)_{\rm rec} = 1.01(2)\,, && \hat{R}(D^*)_{\rm th} = 1.02 \\
R_2:\ & \hat{R}(D)_{\rm rec} = 1.24(7)\,, && \hat{R}(D)_{\rm th} = 1.48 \\
& \hat{R}(D^*)_{\rm rec} = 0.92(2)\,, && \hat{R}(D^*)_{\rm th} = 0.85\,.
\end{aligned}
$$

FB, S. Duell, Z. Ligeti, M. Papucci, D. Robinson
Eur. Phys. J. C (2020) **80**: 883 [arXiv:2002:00020]



Take home message: the actual true value of the NP coupling could be ruled out by your interpretation of $\mathscr{R}(D/D^*)$

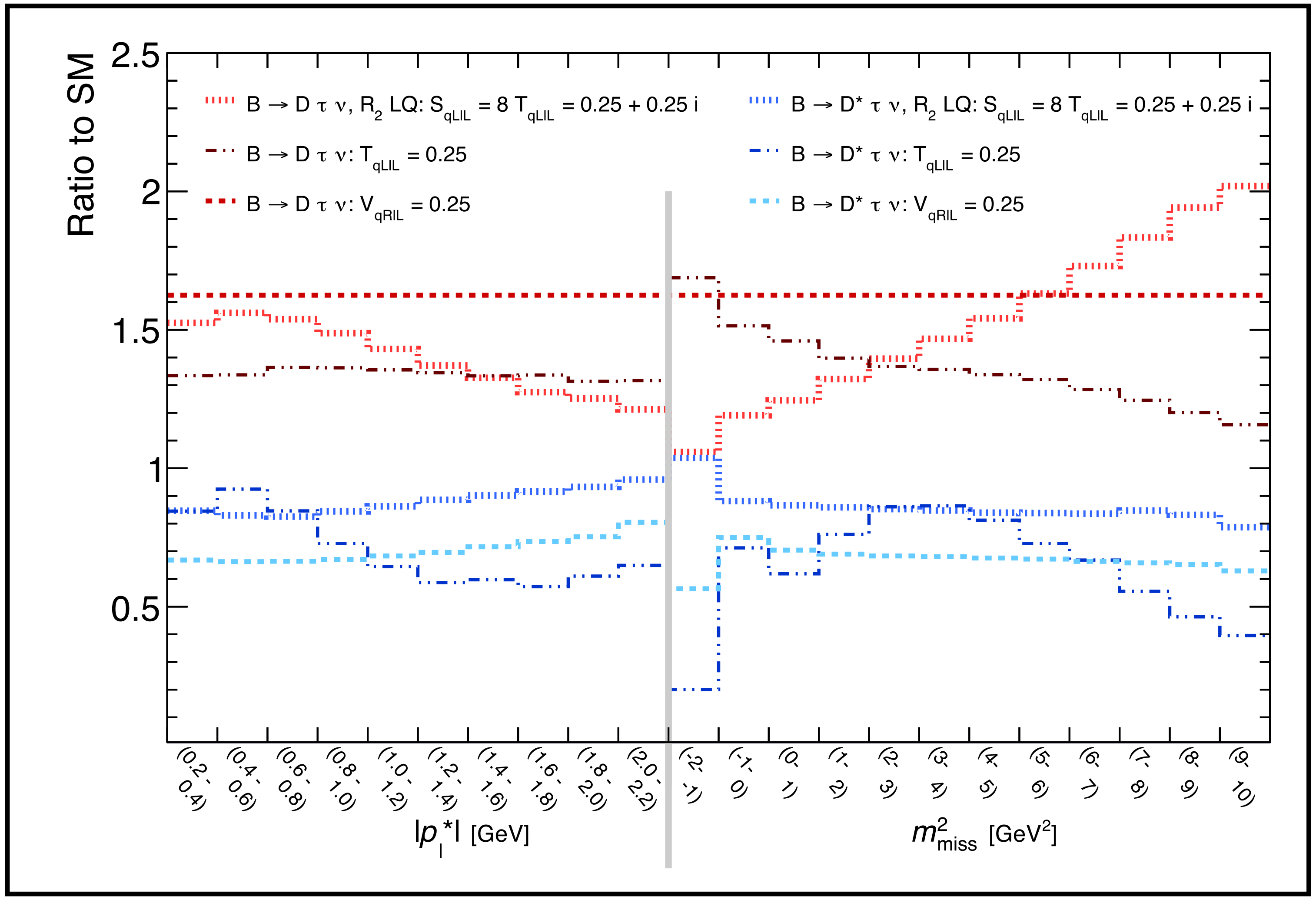
Looking Ahead

the road is wide

Going Wilson

Let’s start with some good news:

Whenever your measurement is
prone to a bias it likely has sensitivity to
constrain it too
(otherwise you would likely not be sensitive to it!)



We can use the
the shape and
complementary information in
$B \to D\tau\bar{\nu}_\tau$ and $B \to D^*\tau\bar{\nu}_\tau$
(and other channels!)
to **disentangle** the **type**
and **strength** of **new physics**

Going Wilson

FB, S. Duell, Z. Ligeti, M. Papucci, D. Robinson
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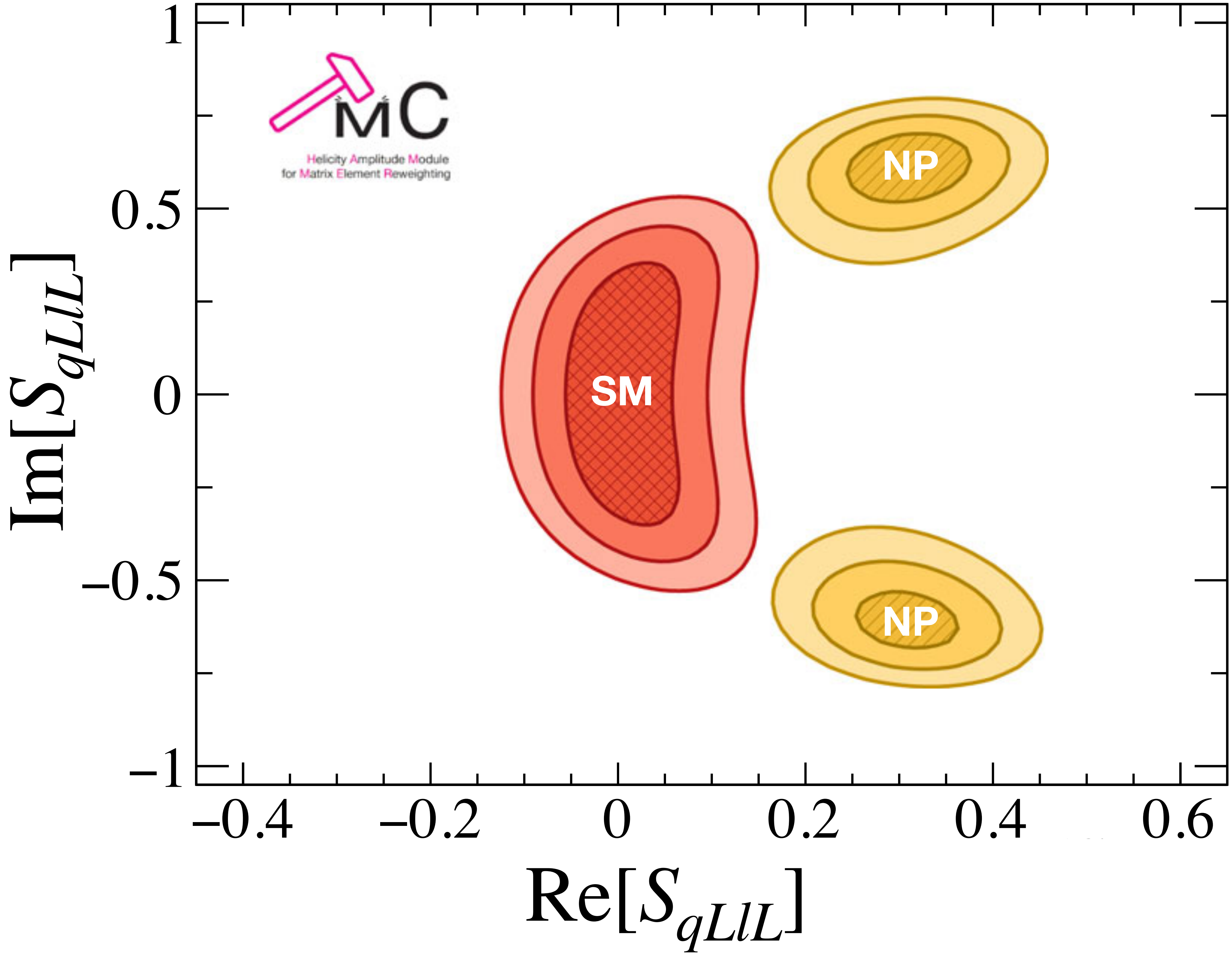

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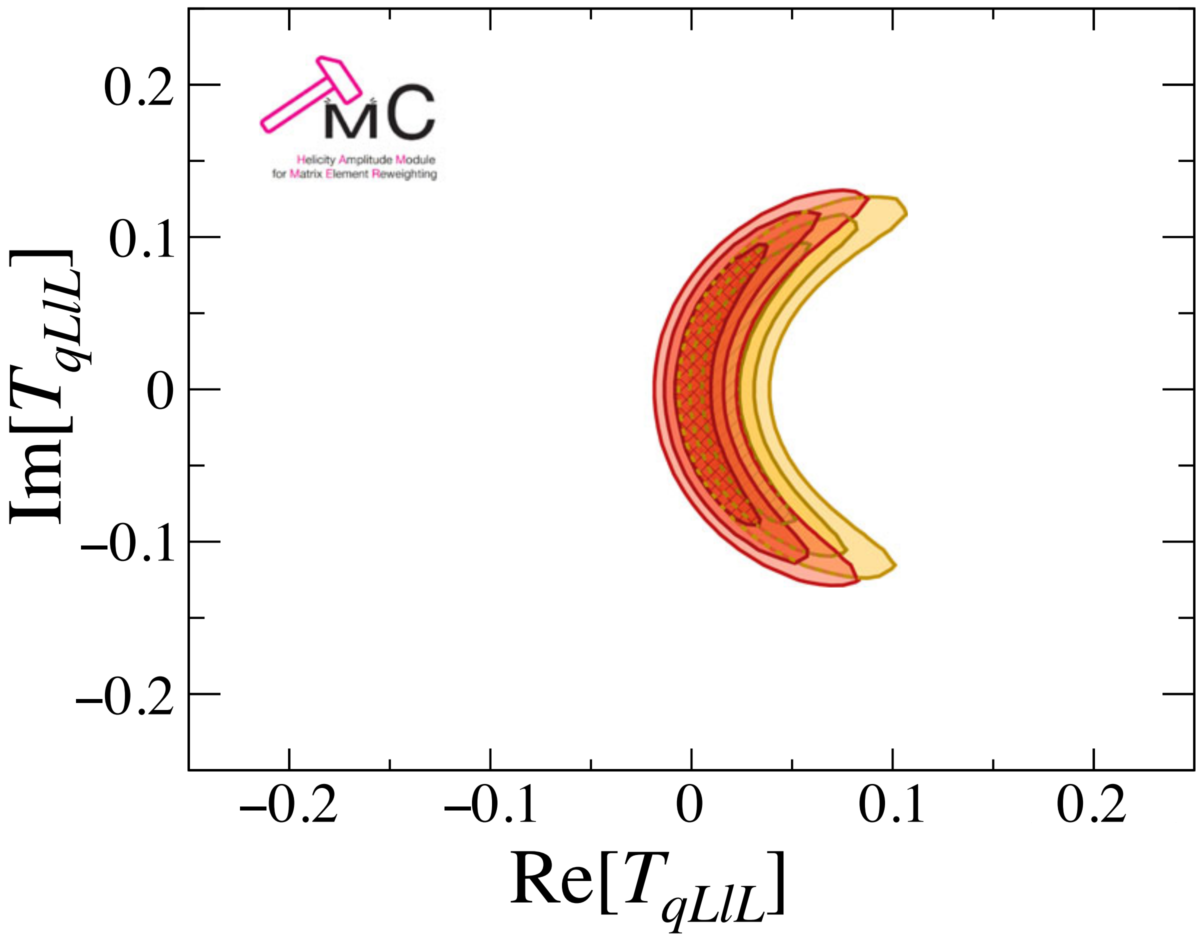
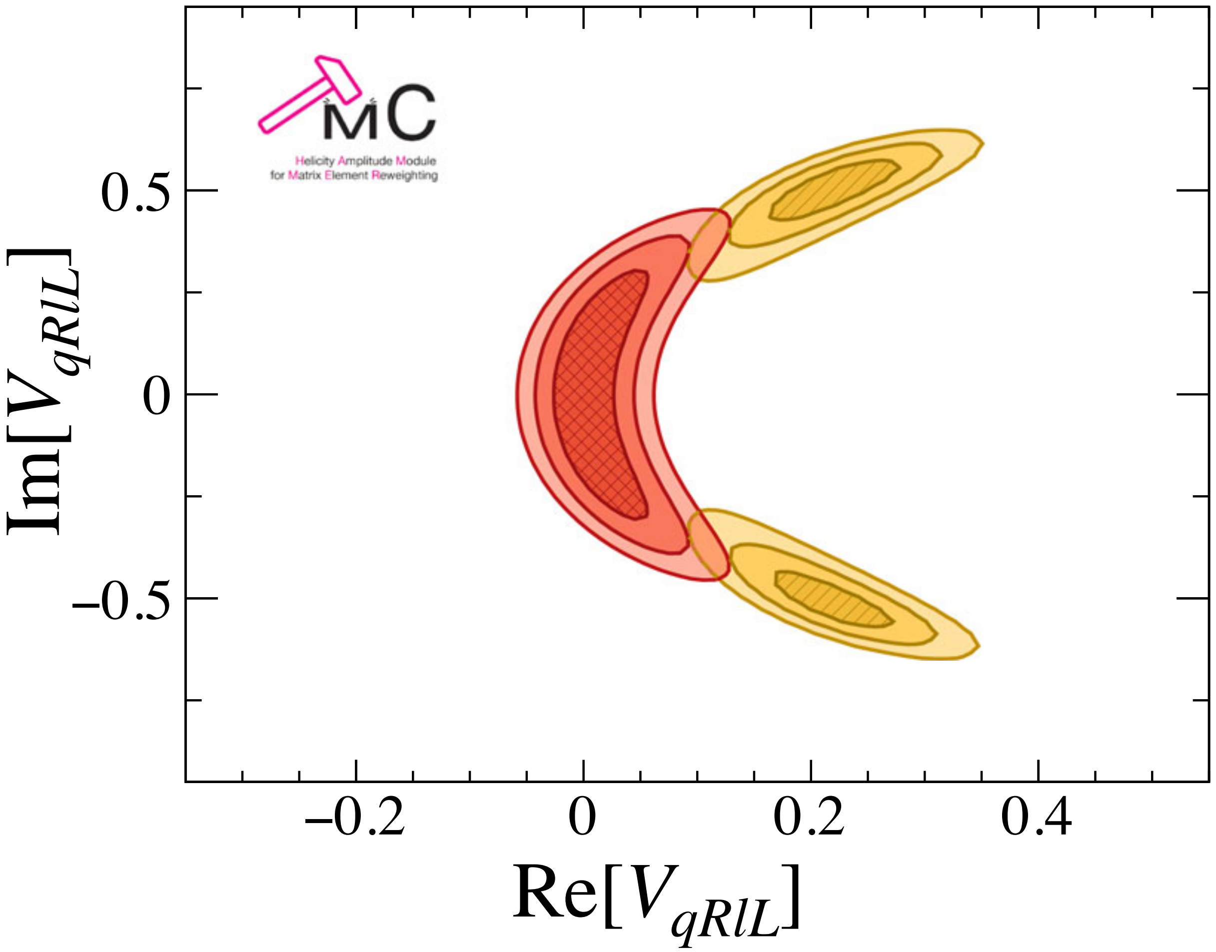
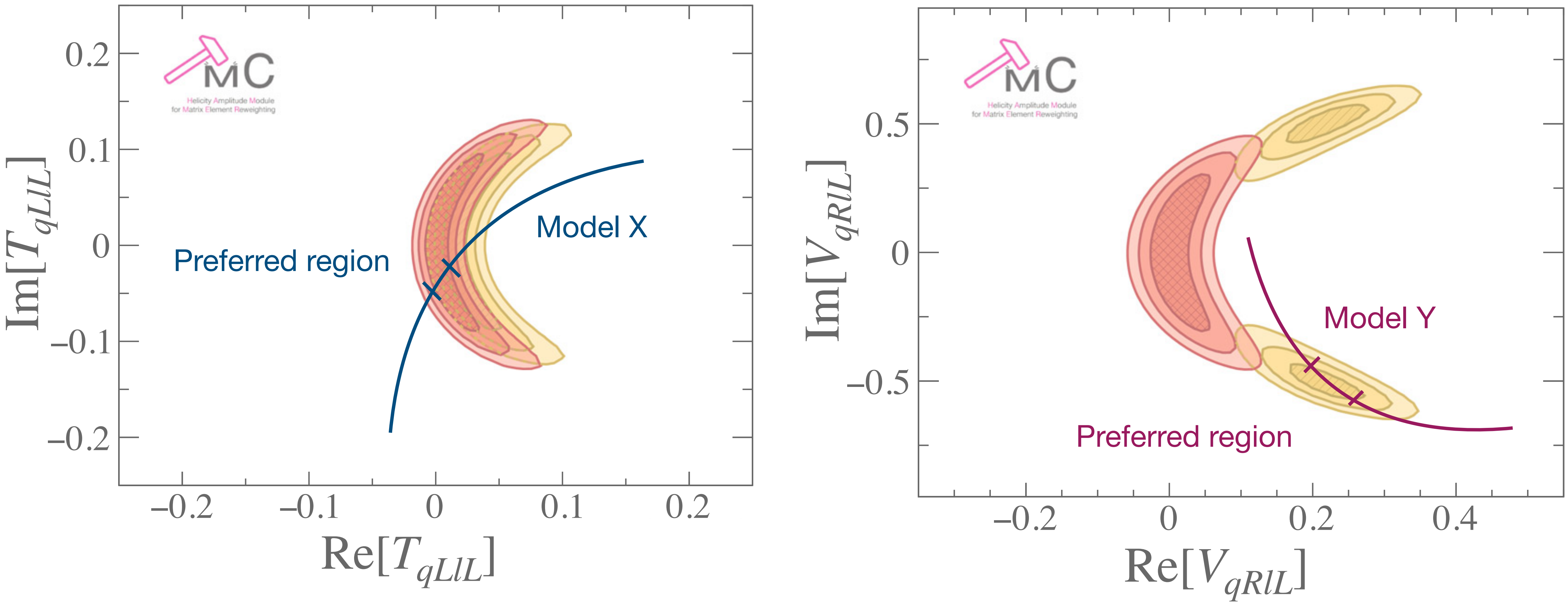




Going Wilson



Model builders can make direct interpretations of the bounds
w/o introducing any biases

—> Can finally do consistent $b \to s\ell\ell$ and $b \to c\tau\bar{\nu}_\tau$ fits

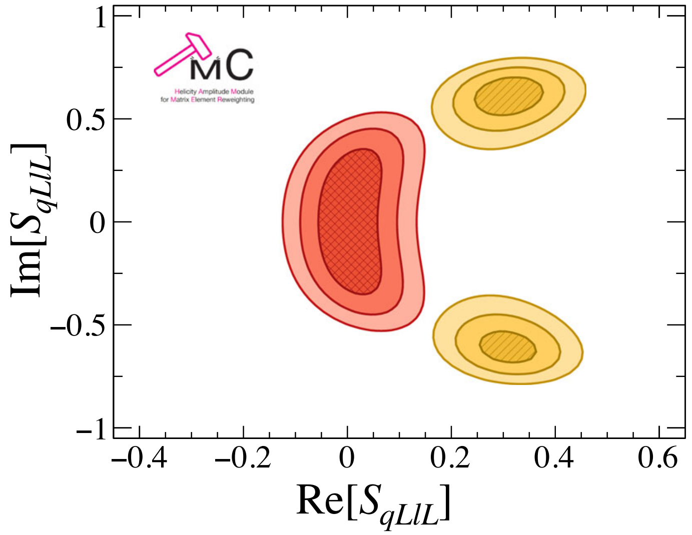
—> Also can readily combine $B \to D^{(*)}\tau\bar{\nu}_\tau$, $B_s \to D_s^{(*)}\tau\bar{\nu}_\tau$, $\Lambda_b \to \Lambda_c\tau\bar{\nu}_\tau$, $B_c \to J/\Psi\tau\bar{\nu}_\tau$ information

We come in peace — let's join our efforts

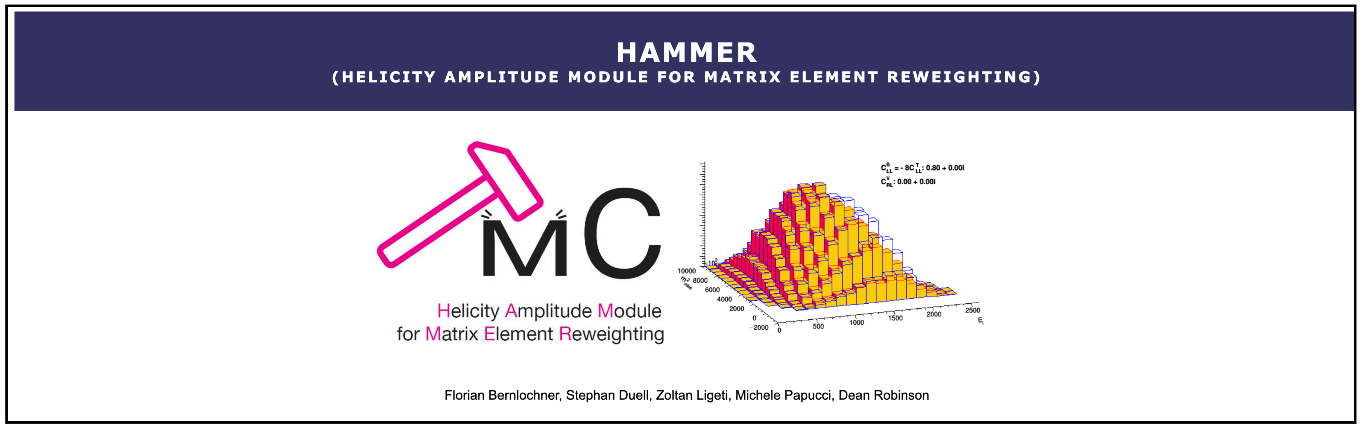
—> Also can readily combine $B \to D^{(*)}\tau\bar{\nu}_\tau$, $B_s \to D_s^{(*)}\tau\bar{\nu}_\tau$, $\Lambda_b \to \Lambda_c\tau\bar{\nu}_\tau$, $B_c \to J/\Psi\tau\bar{\nu}_\tau$ information

Can we fit all **20 couplings together**?

Belle II + LHCb =



+ additional properties (D^* and τ polarizations, q^2, …)



HAMMER

(HELICITY AMPLITUDE MODULE FOR MATRIX ELEMENT REWEIGHTING)

Helicity Amplitude Module
for Matrix Element Reweighting

Florian Bernlochner, Stephan Duell, Zoltan Ligeti, Michele Papucci, Dean Robinson

https://hammer.physics.lbl.gov/

Outlook

Let's talk about things I have not talked about:

$\mathscr{R}(D_s^{(*)})$

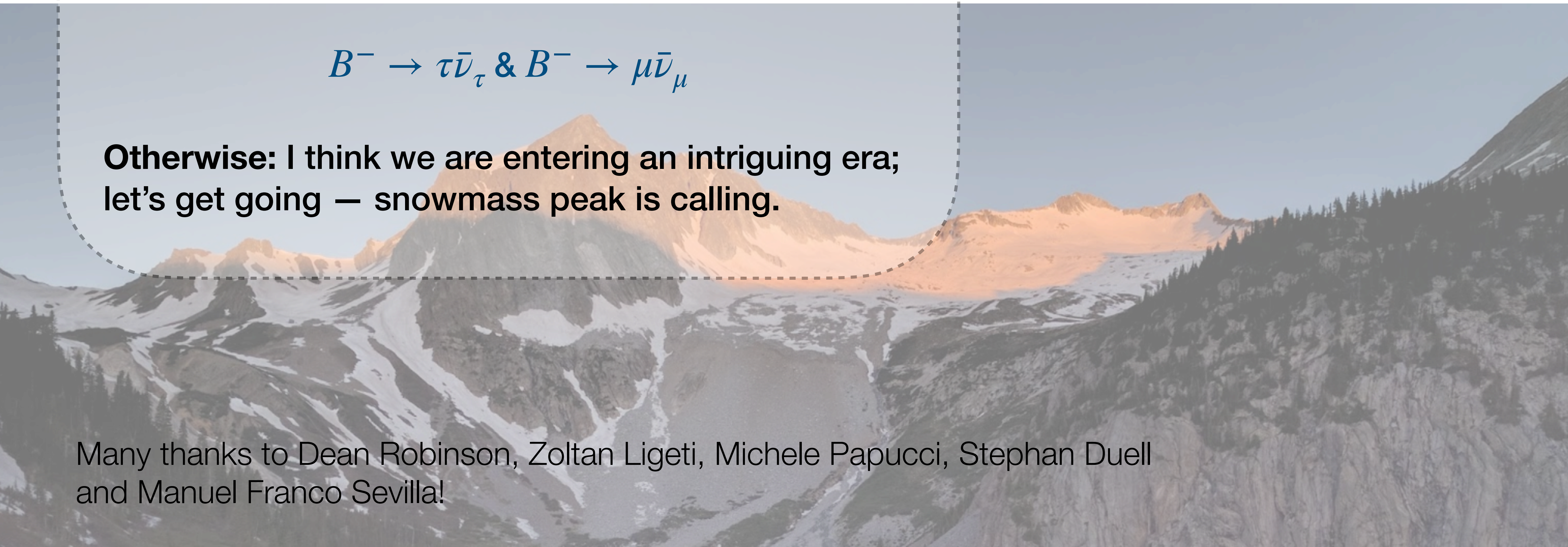
$\mathscr{R}(D^{**}_{\text{narrow}})$

$\mathscr{R}(DX)$ as a proxy for $\mathscr{R}(X_c)$

$\mathscr{R}(\pi, \rho, \omega)$

$B^- \to \tau\bar{\nu}_\tau$ & $B^- \to \mu\bar{\nu}_\mu$

Otherwise: I think we are entering an intriguing era; let's get going — snowmass peak is calling.



Many thanks to Dean Robinson, Zoltan Ligeti, Michele Papucci, Stephan Duell and Manuel Franco Sevilla!

More Information

Belle II Luminosity Status

beam current **x2**

beam-beam param. **x1**

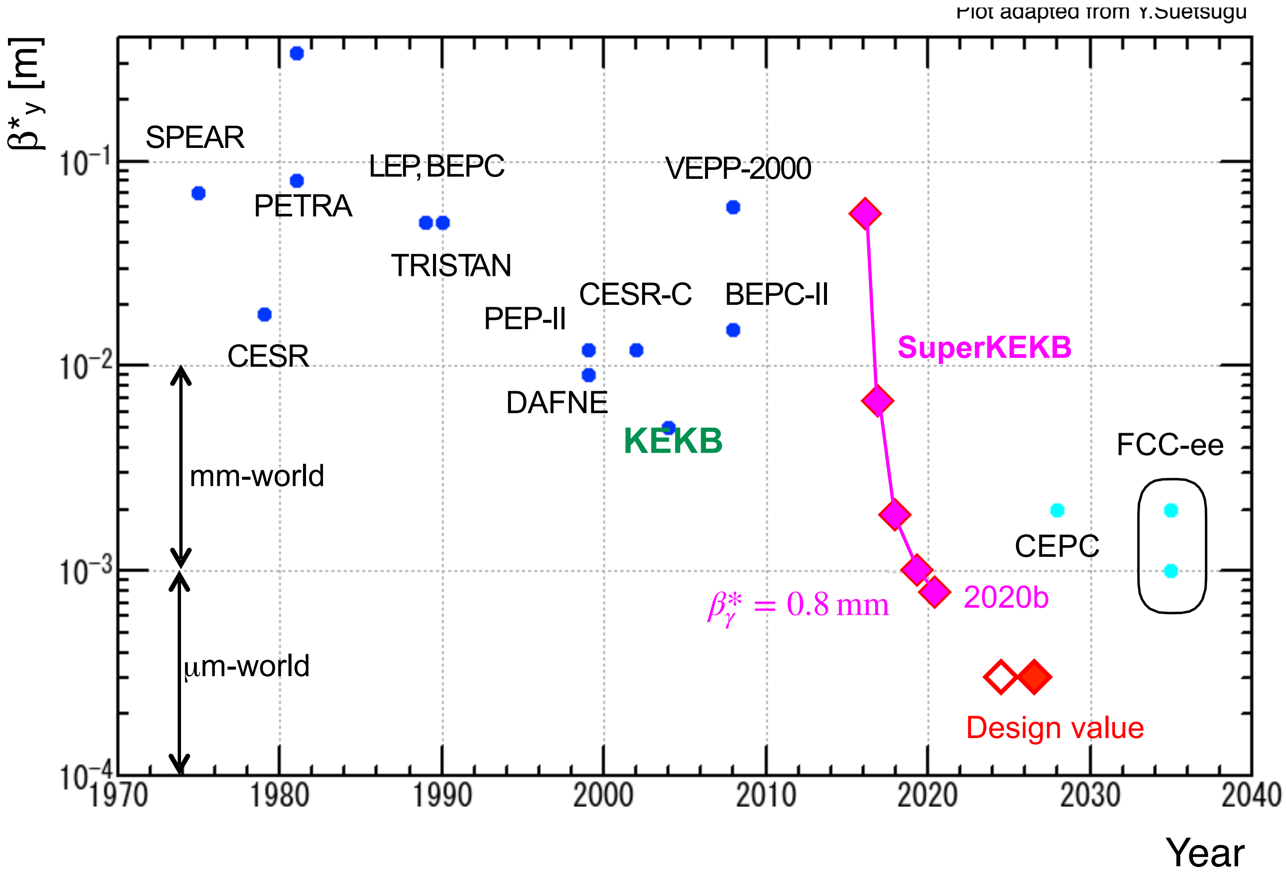
$$L = \frac{\gamma_\pm}{2er_r}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{R_L}{R_\xi}\frac{I_\pm\xi_{y\pm}}{\beta_{y\pm}^*}$$

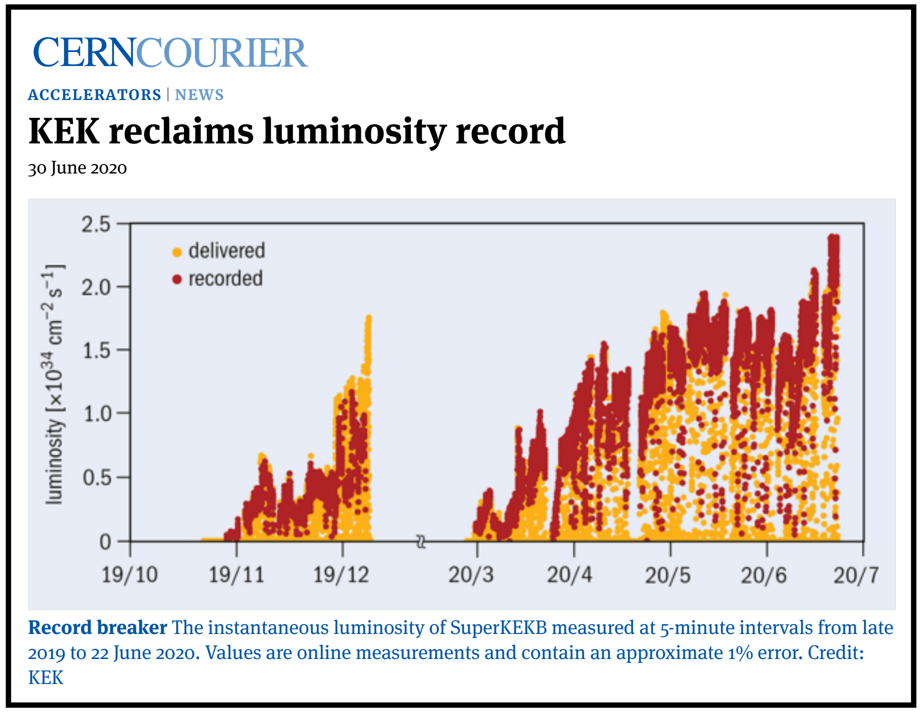
vertical beta function **x 1/20**

LER / HER	KEKB	SuperKEKB	L-Factor
Energy [GeV]	3.5 / 8	4.0 / 7.0	
Crossing angle $2\phi_x$ [mrad]	22	**83**	
β_y^* [mm]	5.9 / 5.9	**0.27 / 0.30**	**x 20**
β_x^* [mm]	1200	**32 / 25**	
$I_\pm$ [A]	1.64 / 1.19	**2.8 / 2.0**	**x 1.5**
$\varepsilon_x = \sigma_x \times \sigma_{x'}$ [nm]	18 / 24	**3.2 / 4.6**	
$\varepsilon_y = \sigma_y \times \sigma_{y'}$ [pm]	140 / 140	13 / 16	
$\xi_{y\pm} \sim (\beta_y^*/\varepsilon_y)^{1/2} / \sigma_x^*$	0.129 / 0.09	**0.09 / 0.09**	**x 1**
# of bunches	1584	1800	
Luminosity [10^{34} cm^{-2} s^{-1}]	2.1	**60**	**x 30**

Roadmap2020

Plot adapted from Y.Suetsugu





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ACCELERATORS | NEWS

KEK reclaims luminosity record

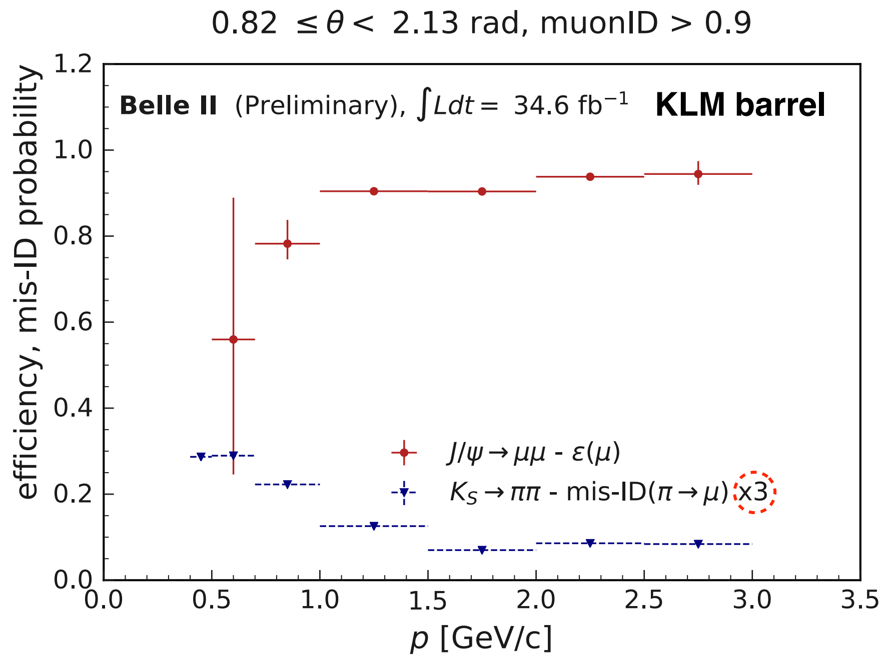
30 June 2020

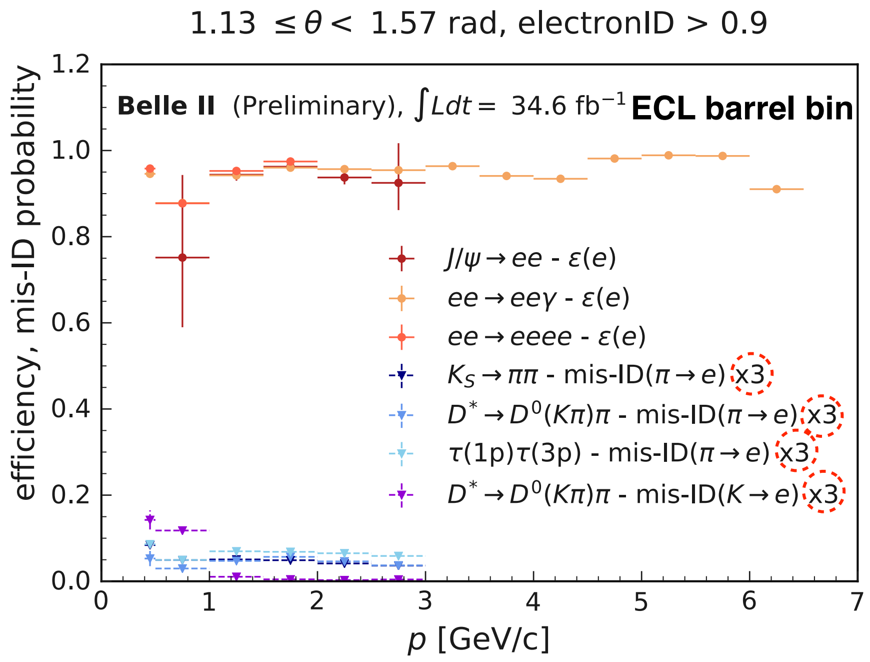
Record breaker The instantaneous luminosity of SuperKEKB measured at 5-minute intervals from late 2019 to 22 June 2020. Values are online measurements and contain an approximate 1% error. Credit: KEK

Lepton and Hadron ID Performance at Belle II

Lepton ID

$$\ell\text{ID} = \frac{\mathcal{L}_\ell}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}$$

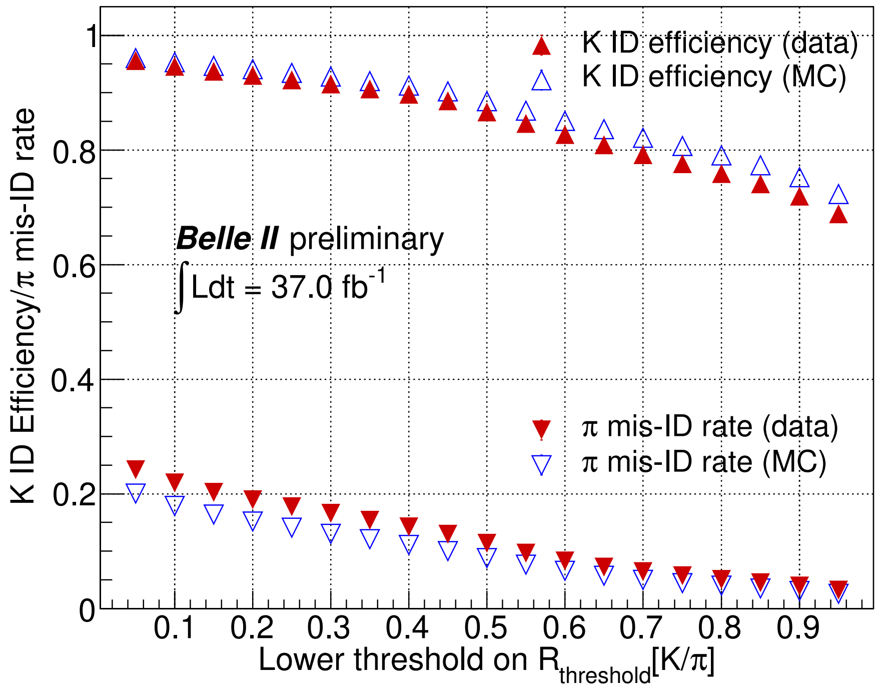

0.82 ≤ θ < 2.13 rad, muonID > 0.9

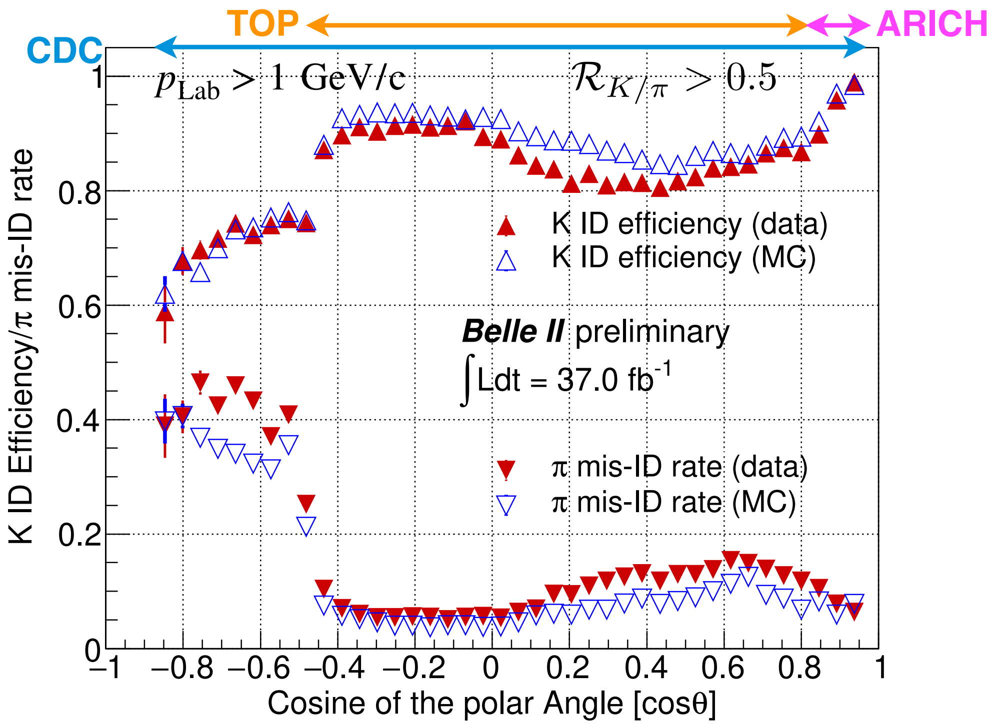

1.13 ≤ θ < 1.57 rad, electronID > 0.9

Hadron ID

$$D^{*+} \to D^0[K^-\pi^+]\pi^+$$

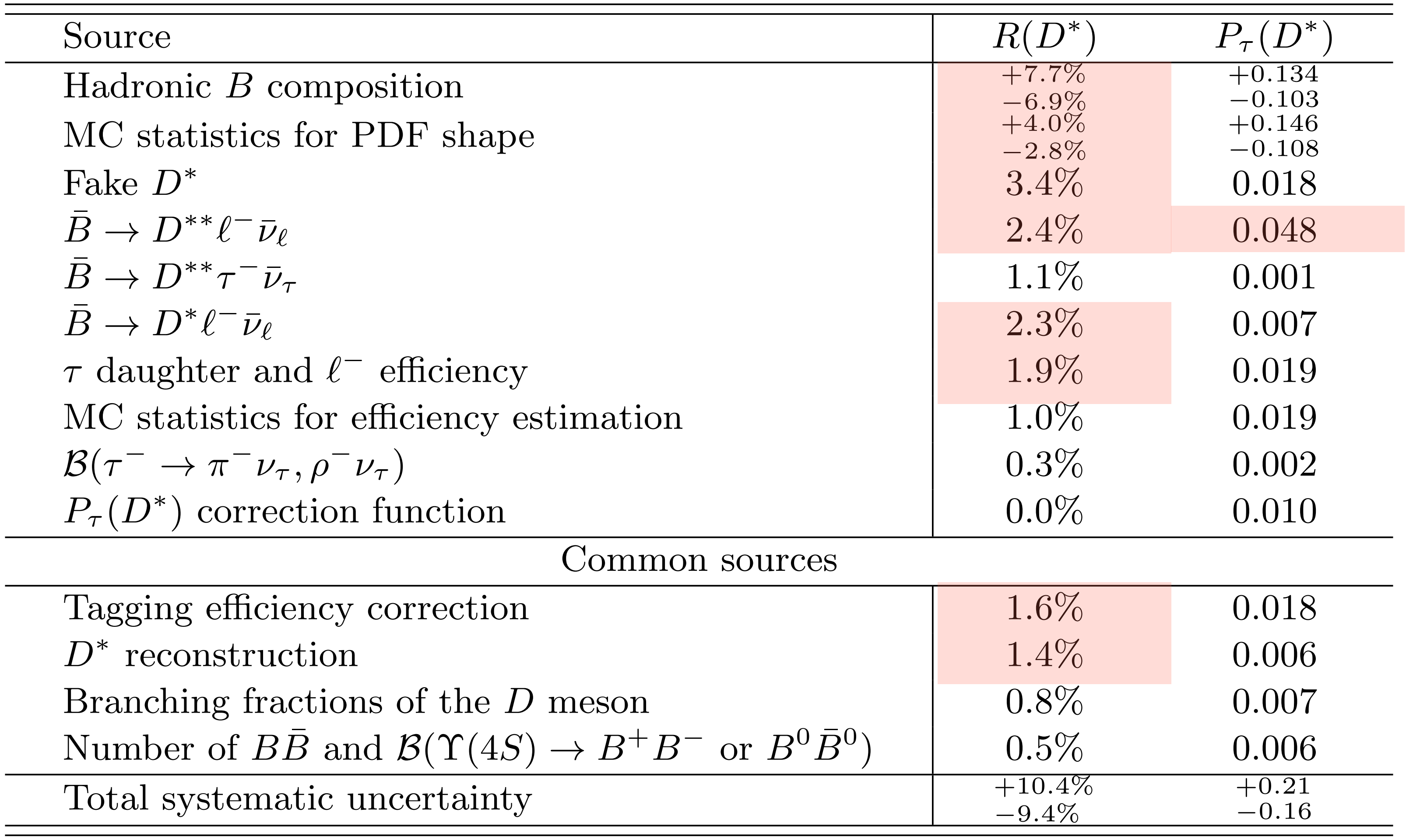
$$\mathcal{R}_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$





Systematics for Belle Hadronic tagged + had. τ

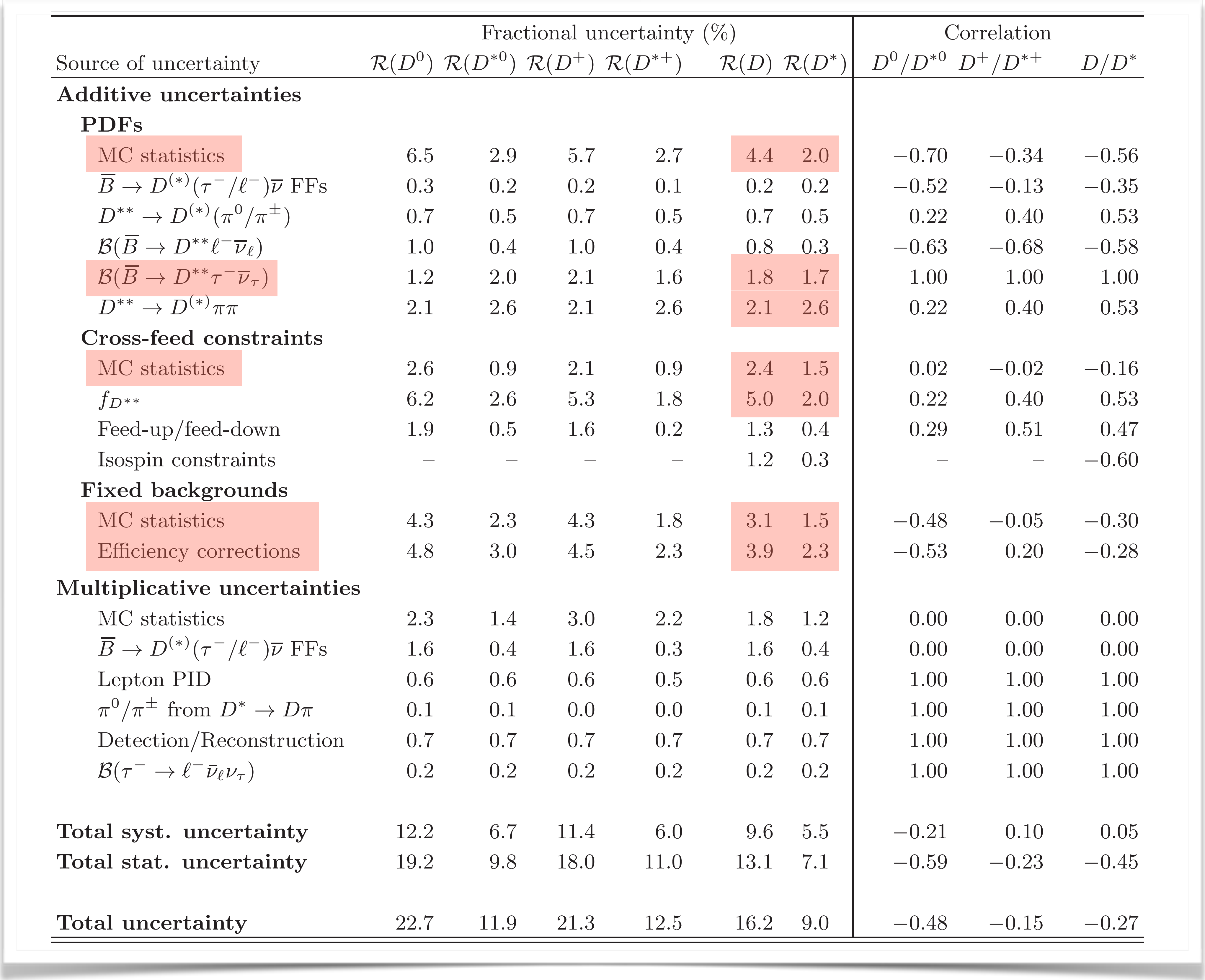
Phys.Rev.Lett.118,211801 (2017) arXiv:1612.00529 [hep-ex] ,
Phys.Rev.D 97, 012004 (2018) arXiv:1709.00129_[hep-ex]



Source	$R(D^*)$	$P_\tau(D^*)$
Hadronic B composition	$^{+7.7\%}_{-6.9\%}$	$^{+0.134}_{-0.103}$
MC statistics for PDF shape	$^{+4.0\%}_{-2.8\%}$	$^{+0.146}_{-0.108}$
Fake D^*	3.4%	0.018
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$	2.4%	0.048
$\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$	1.1%	0.001
$\bar{B} \to D^{*}\ell^-\bar{\nu}_\ell$	2.3%	0.007
τ daughter and ℓ^- efficiency	1.9%	0.019
MC statistics for efficiency estimation	1.0%	0.019
$\mathcal{B}(\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau)$	0.3%	0.002
$P_\tau(D^*)$ correction function	0.0%	0.010
Common sources		
Tagging efficiency correction	1.6%	0.018
D^* reconstruction	1.4%	0.006
Branching fractions of the D meson	0.8%	0.007
Number of $B\bar{B}$ and $\mathcal{B}(\Upsilon(4S) \to B^+B^-$ or $B^0\bar{B}^0)$	0.5%	0.006
Total systematic uncertainty	$^{+10.4\%}_{-9.4\%}$	$^{+0.21}_{-0.16}$

Systematics for BaBar Hadronic tagged + lep. τ

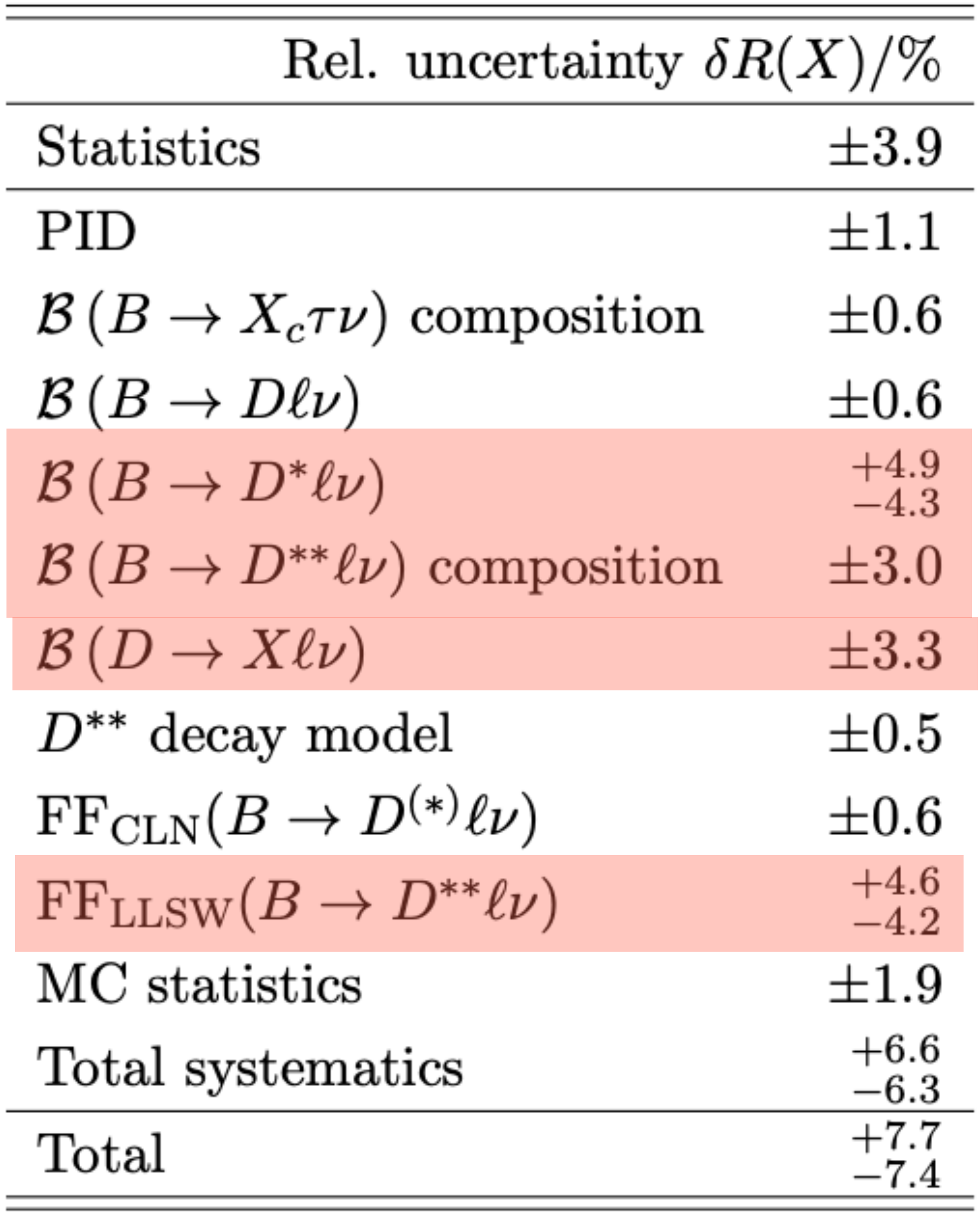
Phys.Rev.Lett. 109,101802 (2012)
Phys.Rev.D 88, 072012 (2013)



	Fractional uncertainty (%)						Correlation		
Source of uncertainty	$\mathcal{R}(D^0)$	$\mathcal{R}(D^{*0})$	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	D^0/D^{*0}	D^+/D^{*+}	D/D^*
Additive uncertainties									
PDFs									
MC statistics	6.5	2.9	5.7	2.7	4.4	2.0	−0.70	−0.34	−0.56
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	0.3	0.2	0.2	0.1	0.2	0.2	−0.52	−0.13	−0.35
$D^{**} \to D^{(*)}(\pi^0/\pi^\pm)$	0.7	0.5	0.7	0.5	0.7	0.5	0.22	0.40	0.53
$\mathcal{B}(\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell)$	1.0	0.4	1.0	0.4	0.8	0.3	−0.63	−0.68	−0.58
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	1.2	2.0	2.1	1.6	1.8	1.7	1.00	1.00	1.00
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6	2.1	2.6	2.1	2.6	0.22	0.40	0.53
Cross-feed constraints									
MC statistics	2.6	0.9	2.1	0.9	2.4	1.5	0.02	−0.02	−0.16
$f_{D^{**}}$	6.2	2.6	5.3	1.8	5.0	2.0	0.22	0.40	0.53
Feed-up/feed-down	1.9	0.5	1.6	0.2	1.3	0.4	0.29	0.51	0.47
Isospin constraints	–	–	–	–	1.2	0.3	–	–	−0.60
Fixed backgrounds									
MC statistics	4.3	2.3	4.3	1.8	3.1	1.5	−0.48	−0.05	−0.30
Efficiency corrections	4.8	3.0	4.5	2.3	3.9	2.3	−0.53	0.20	−0.28
Multiplicative uncertainties									
MC statistics	2.3	1.4	3.0	2.2	1.8	1.2	0.00	0.00	0.00
$\overline{B} \to D^{(*)}(\tau^-/\ell^-)\overline{\nu}$ FFs	1.6	0.4	1.6	0.3	1.6	0.4	0.00	0.00	0.00
Lepton PID	0.6	0.6	0.6	0.5	0.6	0.6	1.00	1.00	1.00
$\pi^0/\pi^\pm$ from $D^* \to D\pi$	0.1	0.1	0.0	0.0	0.1	0.1	1.00	1.00	1.00
Detection/Reconstruction	0.7	0.7	0.7	0.7	0.7	0.7	1.00	1.00	1.00
$\mathcal{B}(\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2	0.2	0.2	0.2	1.00	1.00	1.00
Total syst. uncertainty	12.2	6.7	11.4	6.0	9.6	5.5	−0.21	0.10	0.05
Total stat. uncertainty	19.2	9.8	18.0	11.0	13.1	7.1	−0.59	−0.23	−0.45
Total uncertainty	22.7	11.9	21.3	12.5	16.2	9.0	−0.48	−0.15	−0.27

Systematics for Incl. Hadronic tagged + lep. τ

Jan Hasenbusch, private communication



	Rel. uncertainty $\delta R(X)/\%$
Statistics	± 3.9
PID	± 1.1
$\mathcal{B}(B \to X_c \tau \nu)$ composition	± 0.6
$\mathcal{B}(B \to D \ell \nu)$	± 0.6
$\mathcal{B}(B \to D^* \ell \nu)$	$^{+4.9}_{-4.3}$
$\mathcal{B}(B \to D^{**} \ell \nu)$ composition	± 3.0
$\mathcal{B}(D \to X \ell \nu)$	± 3.3
D^{**} decay model	± 0.5
$\mathrm{FF}_{\mathrm{CLN}}(B \to D^{(*)} \ell \nu)$	± 0.6
$\mathrm{FF}_{\mathrm{LLSW}}(B \to D^{**} \ell \nu)$	$^{+4.6}_{-4.2}$
MC statistics	± 1.9
Total systematics	$^{+6.6}_{-6.3}$
Total	$^{+7.7}_{-7.4}$

$B^- \to \tau\bar{\nu}_\tau$

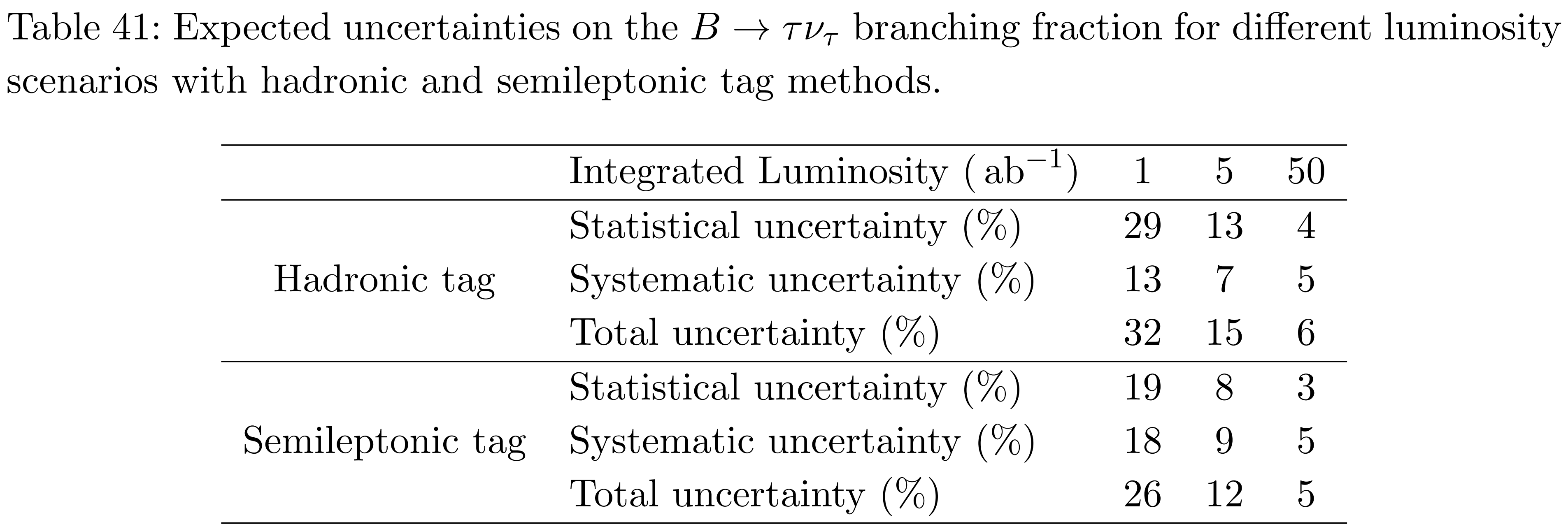


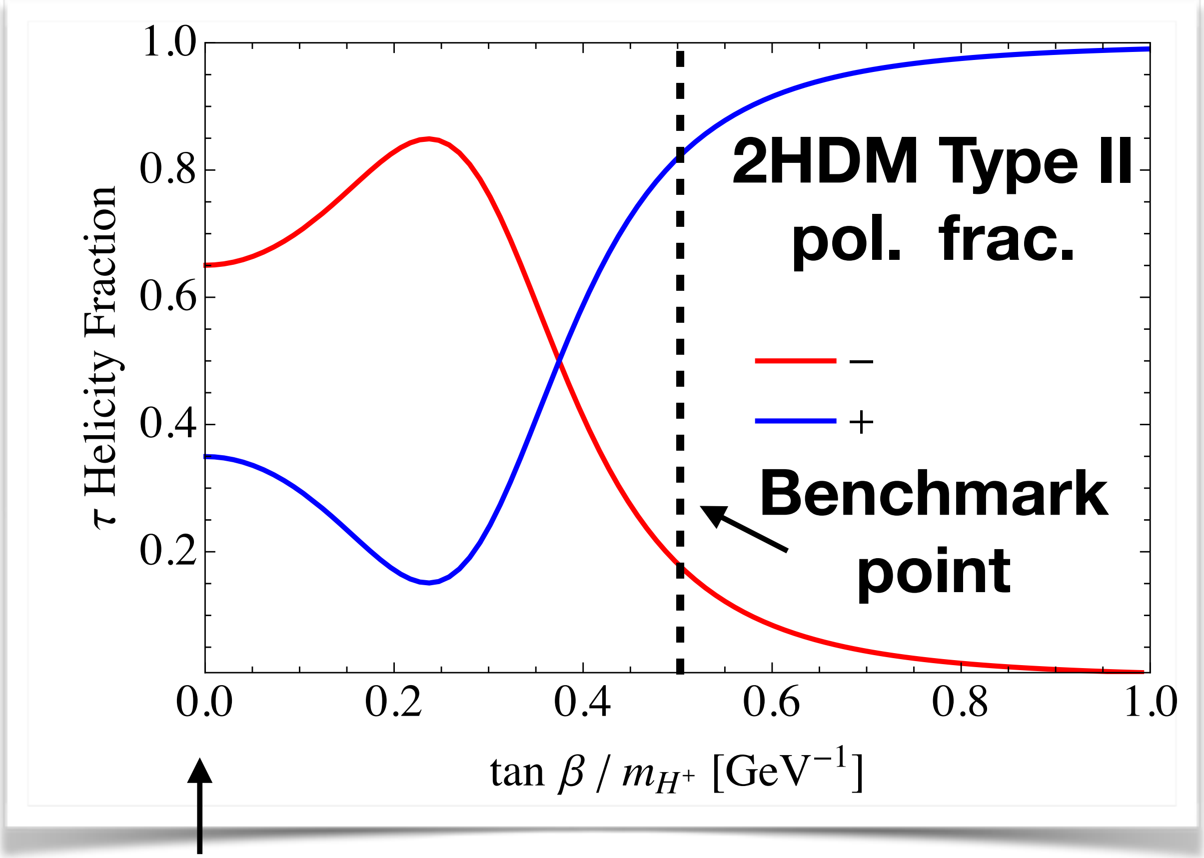
Table 41: Expected uncertainties on the $B \to \tau\nu_\tau$ branching fraction for different luminosity scenarios with hadronic and semileptonic tag methods.

	Integrated Luminosity (ab^{-1})	1	5	50
Hadronic tag	Statistical uncertainty (%)	29	13	4
	Systematic uncertainty (%)	13	7	5
	Total uncertainty (%)	32	15	6
Semileptonic tag	Statistical uncertainty (%)	19	8	3
	Systematic uncertainty (%)	18	9	5
	Total uncertainty (%)	26	12	5

Impact of **τ-polarisation in $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ decays :**

- **secondary lepton** emitted preferentially **in** the **direction** of the τ
  - **Carries more momentum of the τ-lepton**

\+ **secondary lepton** emitted preferentially **against** the **direction** of the τ
  - **Carries less momentum of the τ-lepton**



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