UNIVERSITÄT BONN

BLUB
Belle Labs
University of Bonn

Beauty out of Bounds

a brief experimental overview on the *B* anomalies

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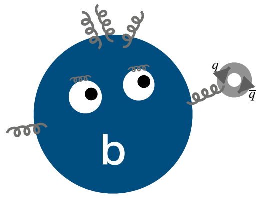
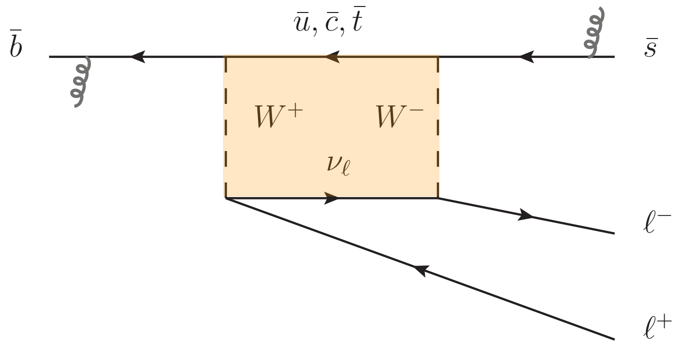
Florian Bernlochner | IRN Terascale Meeting 2022

Belle II



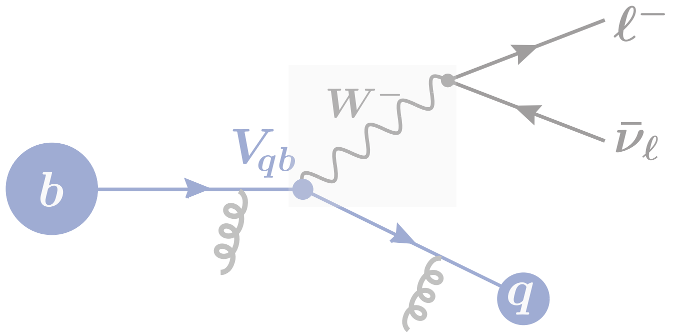
Meet the b Anomalies

Flavor Changing Neutral Currents



- **Rare decays** with decay rate $\sim 10^{-6}$
  - **Forbidden** at **tree-level,** involve **loops**
  - Heavy NP could be same order as SM
- **Experimentally very accessible**
  - **No neutrinos** in final state
  - **Several complementary final states** and observables

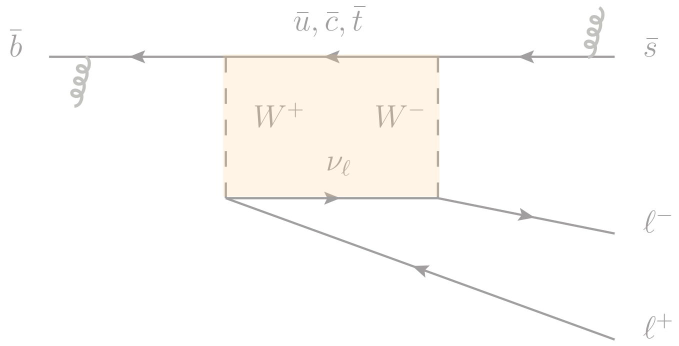
Flavor Changing Charged Currents



- **Not a rare decay** with decay rate $\sim 10^{-2}$
  - **Tree-level** transition
  - Heavy NP smaller than SM amplitude
- **Experimentally challenging**
  - At least **two neutrinos** in final state when studying τ**-leptons**

Meet the b Anomalies

Flavor Changing Neutral Currents



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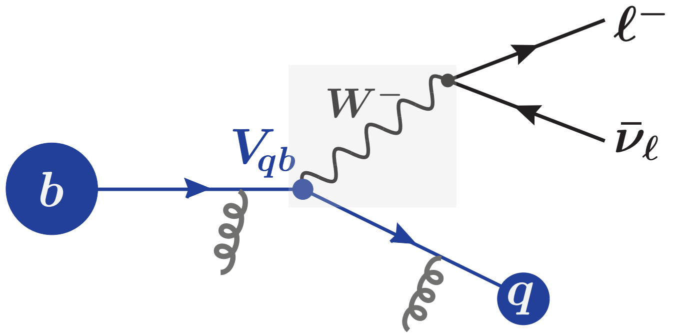
Experimentally very accessible

No neutrinos in final state

Several complementary final states and observables

Flavor Changing Charged Currents



Not a rare decay with decay rate $\sim 10^{-2}$

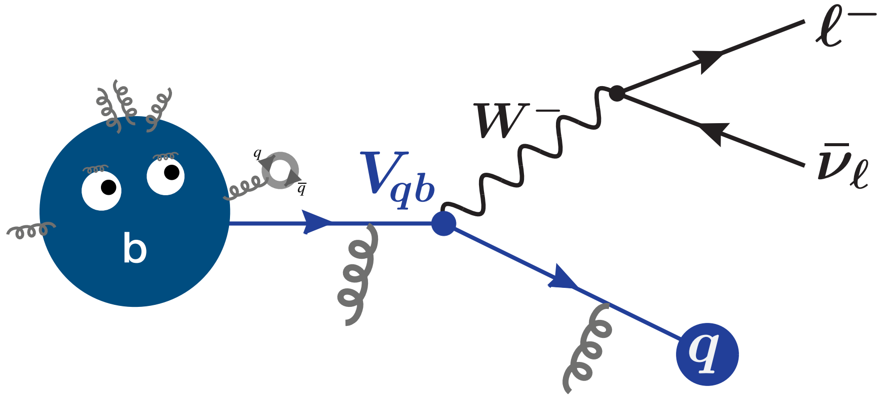
Tree-level transition

Heavy NP smaller than SM amplitude

Experimentally challenging

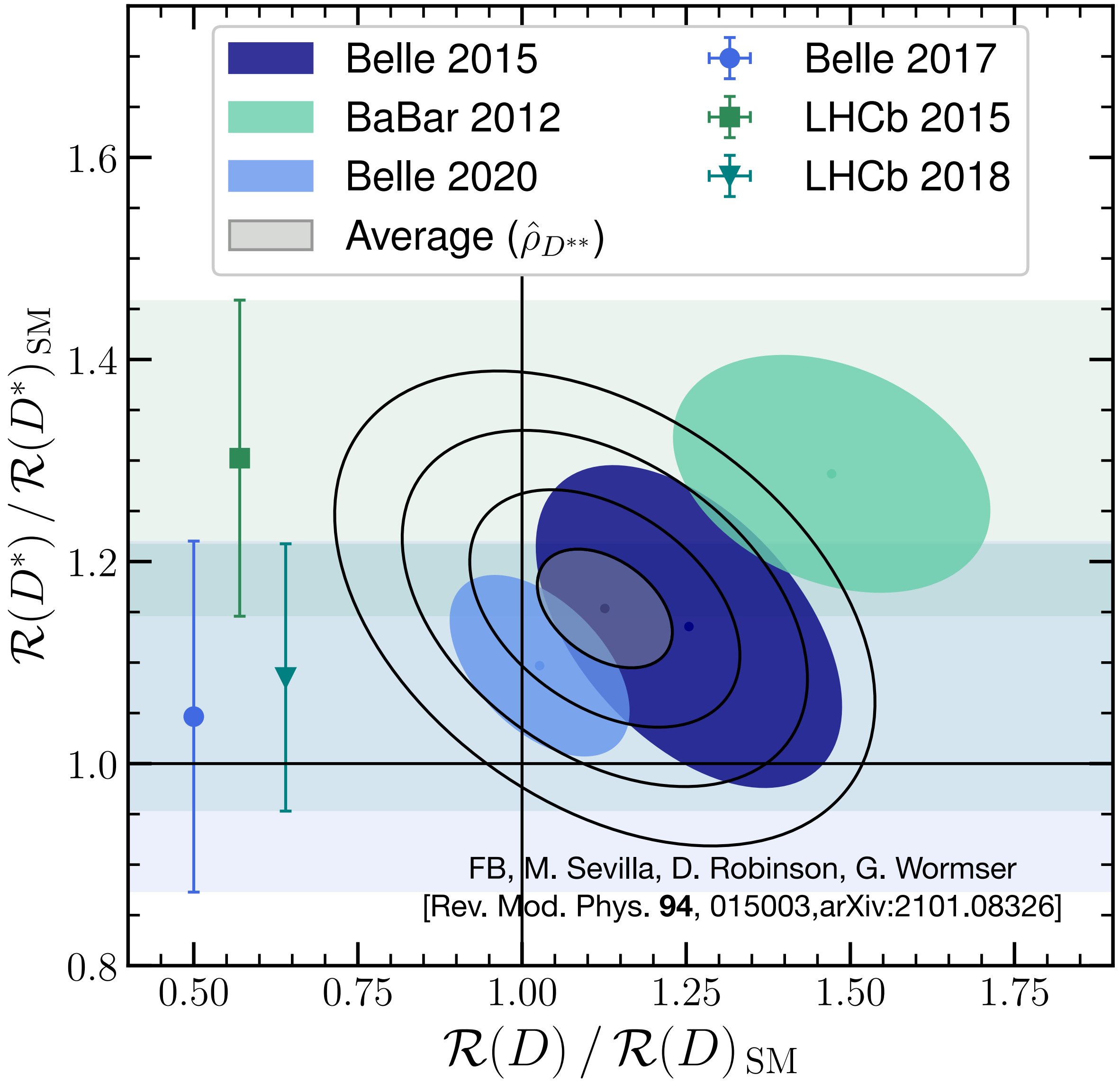
At least **two neutrinos** in final state when studying **τ-leptons**

FCCC: $b \to c\tau\bar{\nu}_\ell$ and friends



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

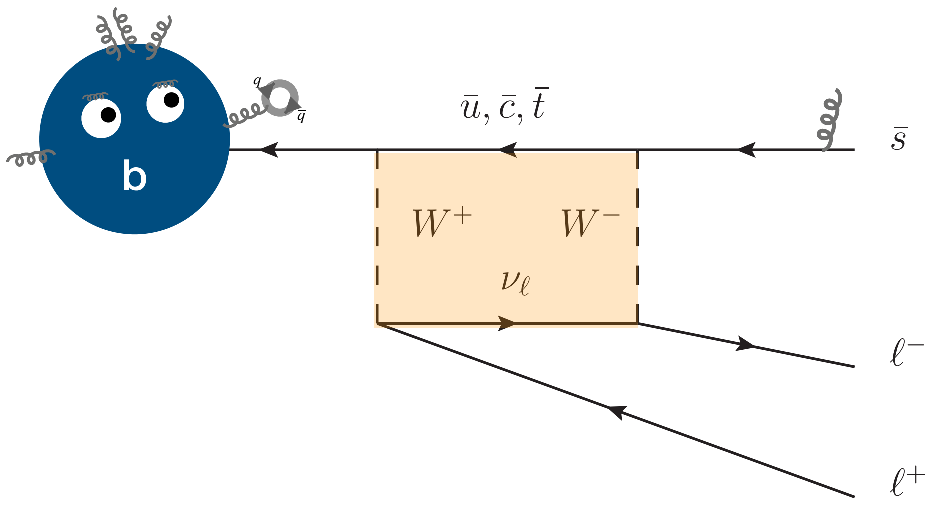
$\ell = e, \mu$



FB, M. Sevilla, D. Robinson, G. Wormser
[Rev. Mod. Phys. **94**, 015003,arXiv:2101.08326]

Obs.	Current World Av./Data	Current SM Prediction	Significance	
$\mathcal{R}(D)$	0.340 ± 0.030	0.299 ± 0.003	1.2σ	3.1σ
$\mathcal{R}(D^*)$	0.295 ± 0.014	0.258 ± 0.005	2.5σ	
$P_\tau(D^*)$	$-0.38 \pm 0.51^{+0.21}_{-0.16}$	-0.501 ± 0.011	0.2σ	
$F_{L,\tau}(D^*)$	$0.60 \pm 0.08 \pm 0.04$	0.455 ± 0.006	1.6σ	
$\mathcal{R}(J/\psi)$	$0.71 \pm 0.17 \pm 0.18$	0.2582 ± 0.0038	1.8σ	
$\mathcal{R}(\pi)$	1.05 ± 0.51	0.641 ± 0.016	0.8σ	
$\mathcal{R}(D)$	$\mathbf{0.337 \pm 0.030}$	0.299 ± 0.003	1.3σ	$\mathbf{3.6\sigma}$
$\mathcal{R}(D^*)$	$\mathbf{0.298 \pm 0.014}$	0.258 ± 0.005	2.5σ	

FCNC: $b \to s\ell\ell$ and friends



Observables of choice:

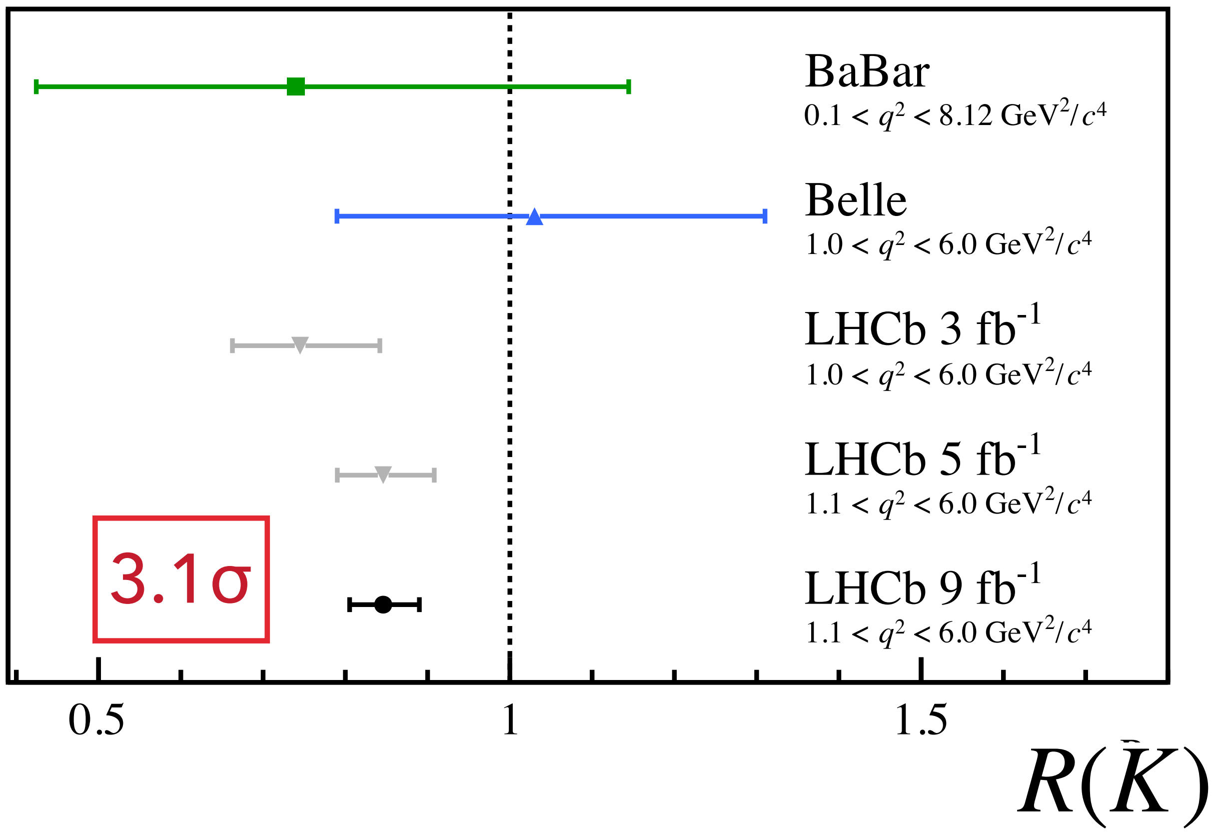
$$\mathcal{R}(K) = \frac{\mathcal{B}(B^+ \to K^+\, \mu\, \mu)}{\mathcal{B}(B^+ \to K^+\, e\, e)}$$

$$\mathcal{R}(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0}\, \mu\, \mu)}{\mathcal{B}(B^0 \to K^{*0}\, e\, e)}$$

In SM $= 1 \pm \text{small corrections}$

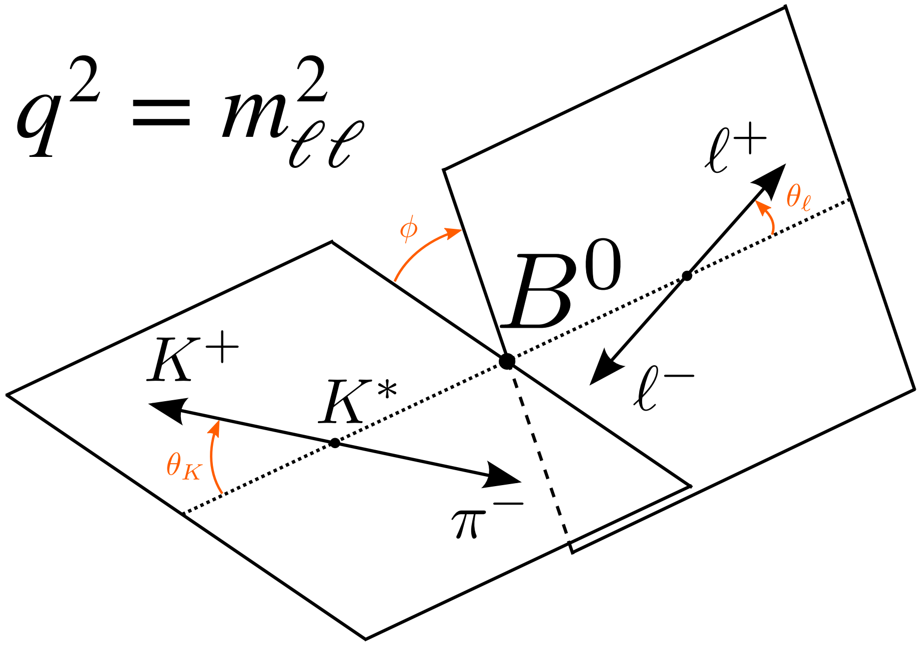
[arXiv:2103.11769]

$B^+ \to K^+\ell\ell$

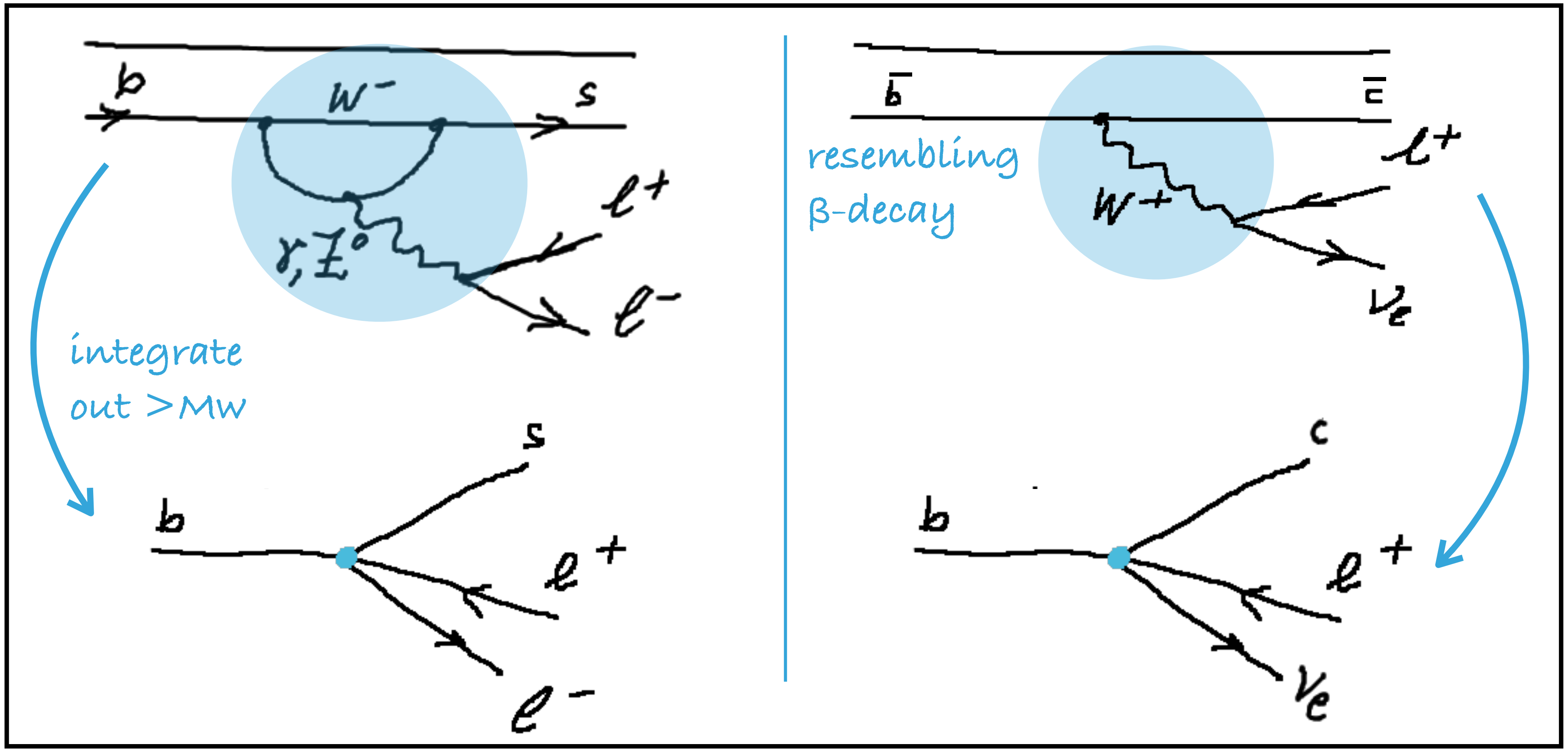


Angular relations and kinematic dependence:

$$q^2 = m^2_{\ell\ell}$$



Time to get effective



Nice Illustration from L. Grillo

$$\mathscr{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \mathscr{O}_i$$

$$\boxed{C_i = C_{\text{SM}} + C_{\text{NP}}}$$

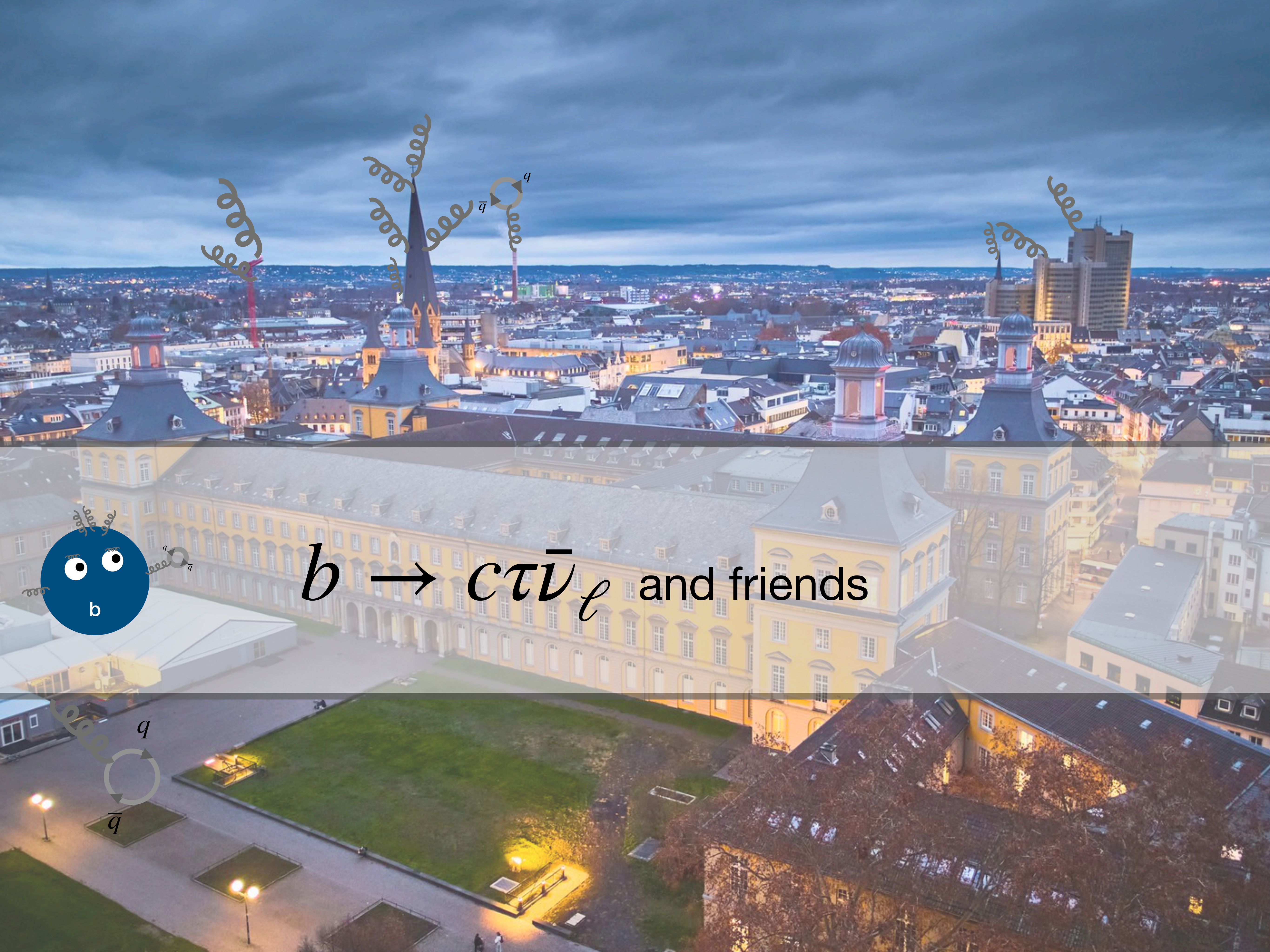
$$\mathscr{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \sum_i C_i \mathscr{O}_i$$

$$\boxed{C_i = C_{\text{SM}} + C_{\text{NP}}}$$

SM: **Vector** (C_9) and **Axial-Vector** (C_{10}) leptonic currents

Further contributions from $b \to s\gamma^*$ operator (C_7)

SM: **Vector - Axial-Vector** current



$b \to c\tau\bar{\nu}_\ell$ and friends

Measurement Strategies

Signal

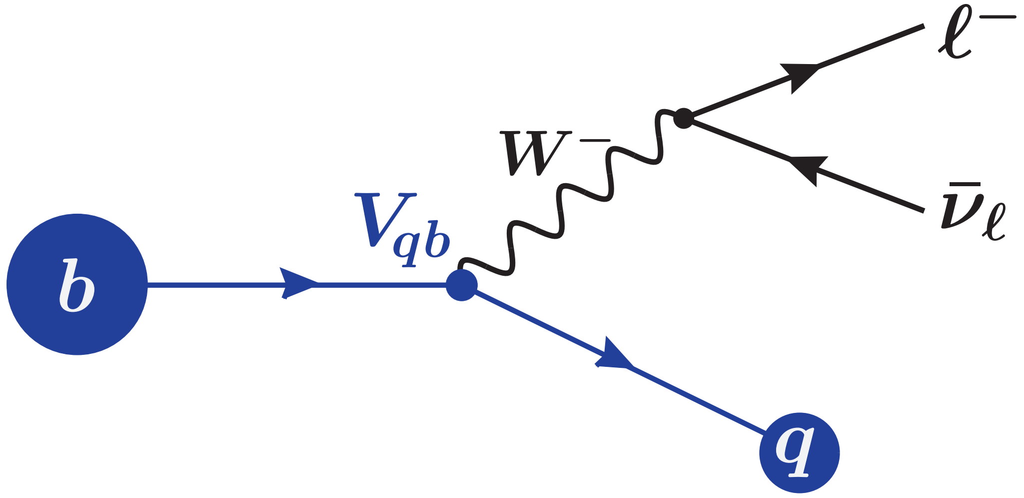
$$R = \frac{b \to q\,\tau\bar{\nu}_\tau}{b \to q\,\ell\bar{\nu}_\ell}$$

Normalization

$\ell = e, \mu$

1. **Leptonic or Hadronic τ decays?**

Some properties (e.g. τ **polarization**) readily **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**

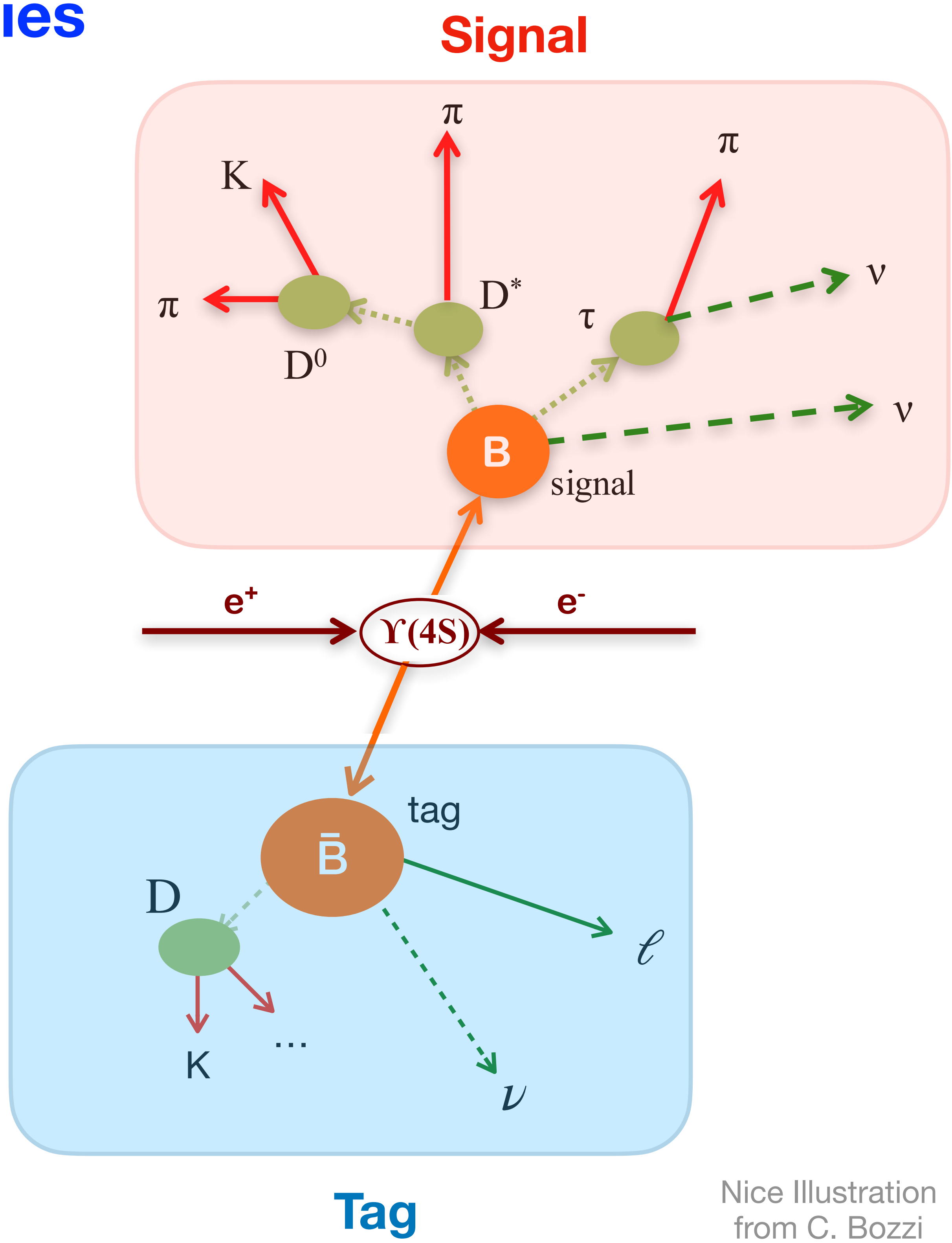
Measurement Strategies

3. Semileptonic decays at B-Factories

- e+/e- collision produces ***Y(4S)*** → ***B$\overline{B}$***
- Fully reconstruct one of the two B-mesons ('tag') → **possible** to **assign all particles** to either signal or tag B
- **Missing four-momentum (neutrinos)** can be reconstructed with high precision

$$p_{\mathrm{miss}} = (p_{\mathrm{beam}} - p_{B\mathrm{tag}} - p_{D^{(*)}} - p_{\ell})$$

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



Nice Illustration from C. Bozzi

Measurement Strategies

4. Semileptonic decays at LHCb

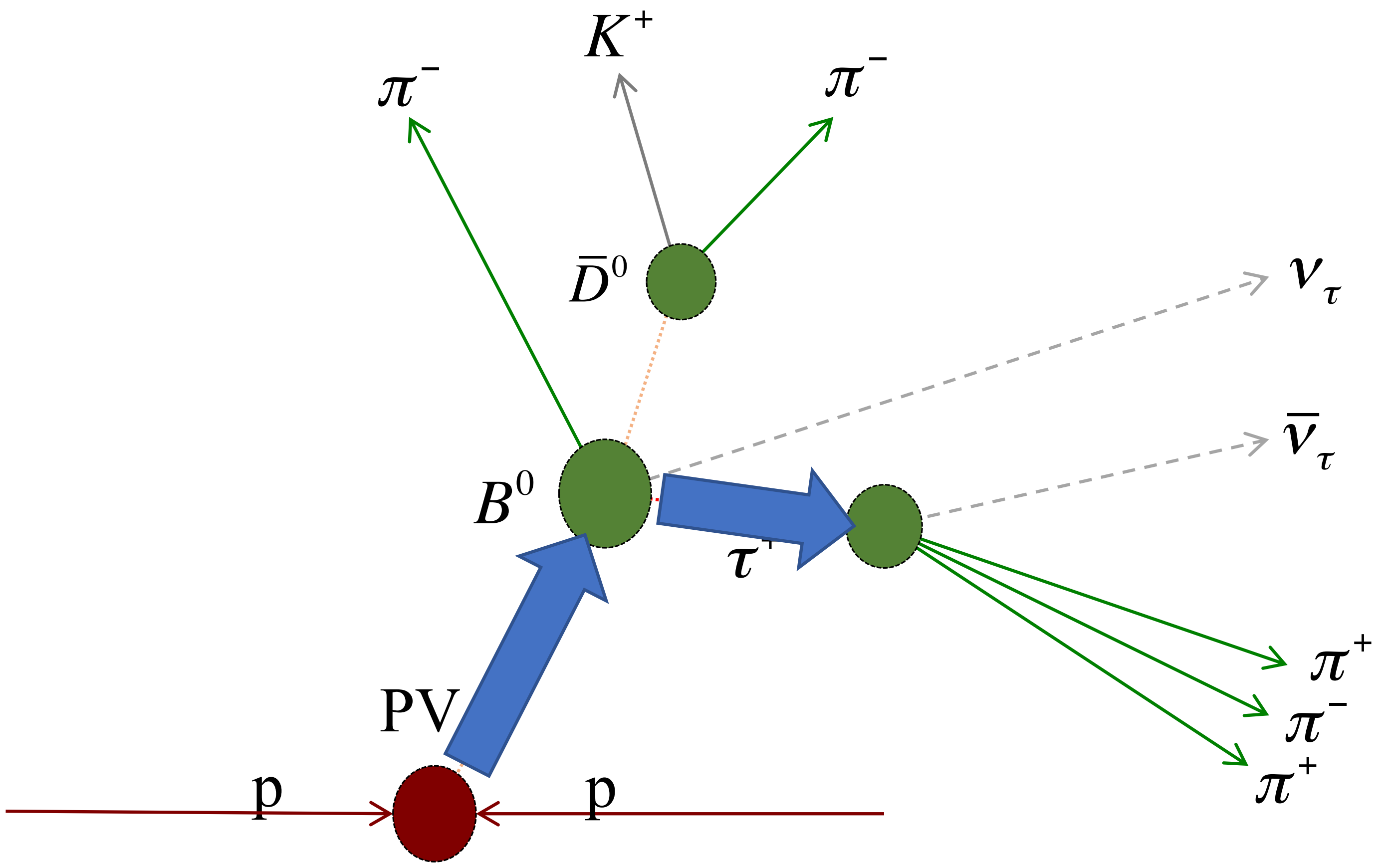
- No constraint from beam energy at a hadron machine, **but..**
- **Large Lorentz boost** with decay lengths in the range of **mm**

✓ **Well-separated decay vertices**

✓ **Momentum direction of decaying particle is well known**

- With known masses and other decay products can even **reconstruct four-momentum transfer squared q² up** to a two-fold ambiguity

$$q^2 = \left(p_{X_b} - p_{X_q}\right)^2$$



Nice Illustration from C. Bozzi

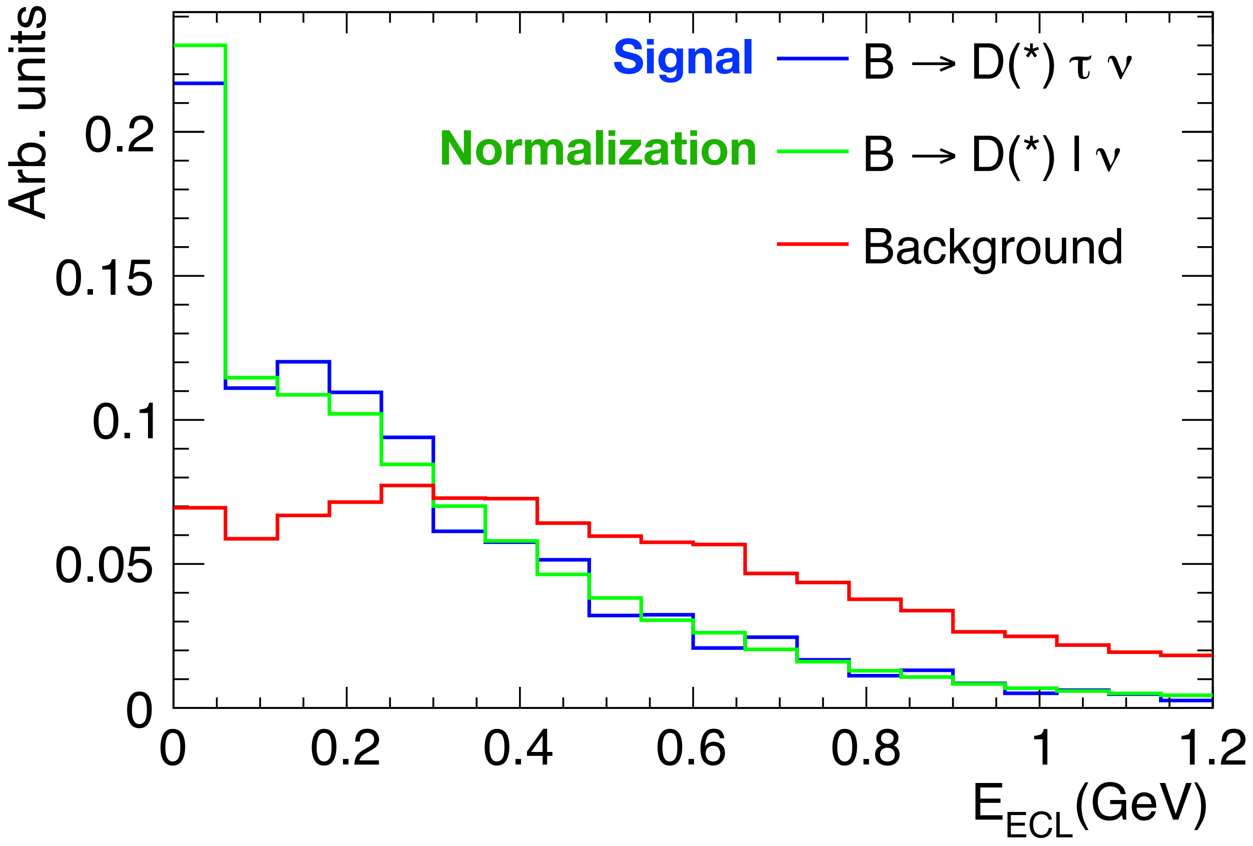
Even bit more complicated for leptonic tau decays

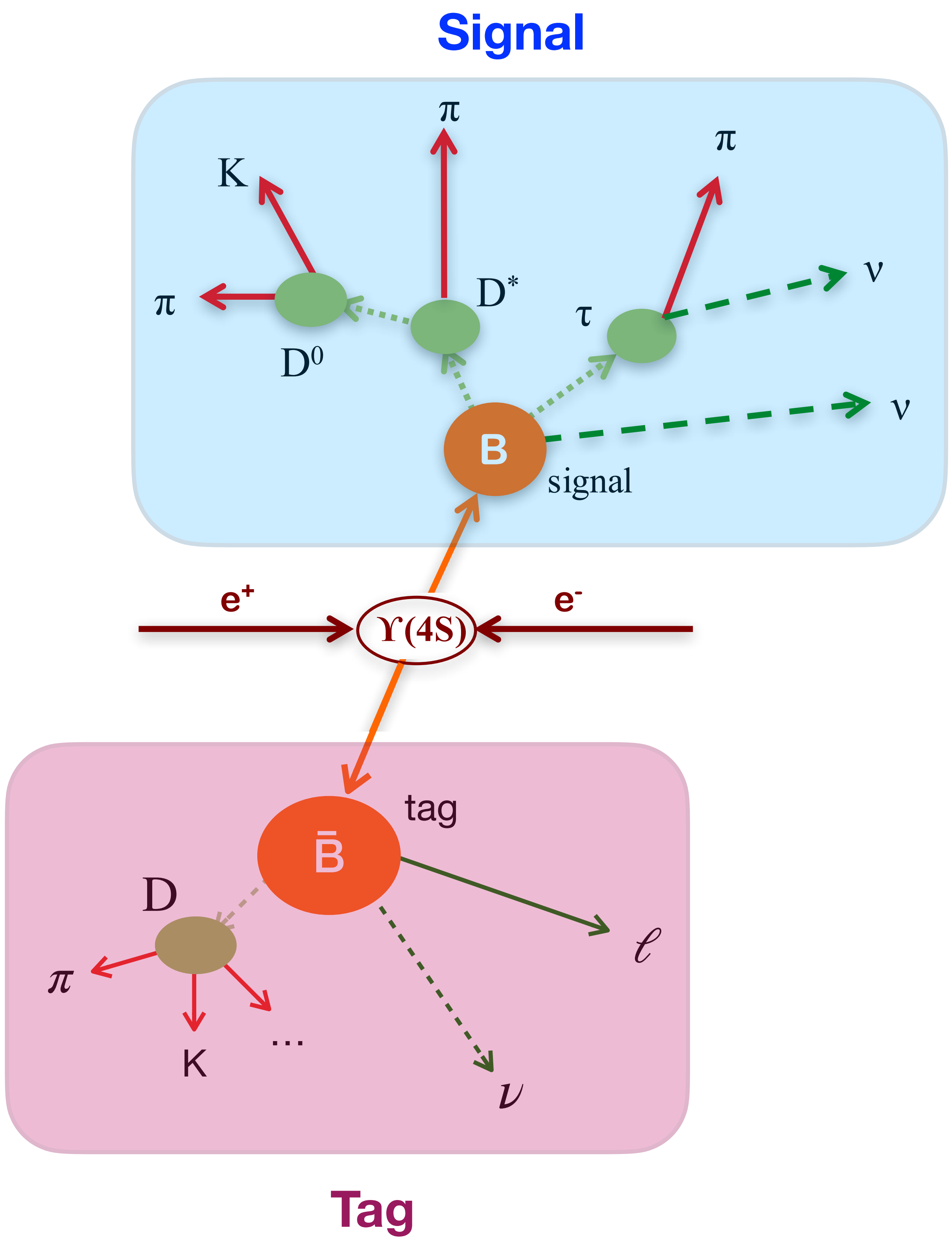
Latest $R(D^{(*)})$ from **Belle**

G. Caria et al (Belle),
Phys. Rev. Lett. 124, 161803, April 2020
[arXiv:1904.08794]

- Reconstruct one of the two B-mesons (‘tag’) in **semileptonic modes → possible to assign all particles in detector** to tag- & signal-side
- Demand Matching topology + **unassigned** energy in the calorimeter E_{ECL} to discriminate background from signal

$$E_{\text{extra}} = E_{\text{ECL}} = \sum_i E_i^{\gamma}$$

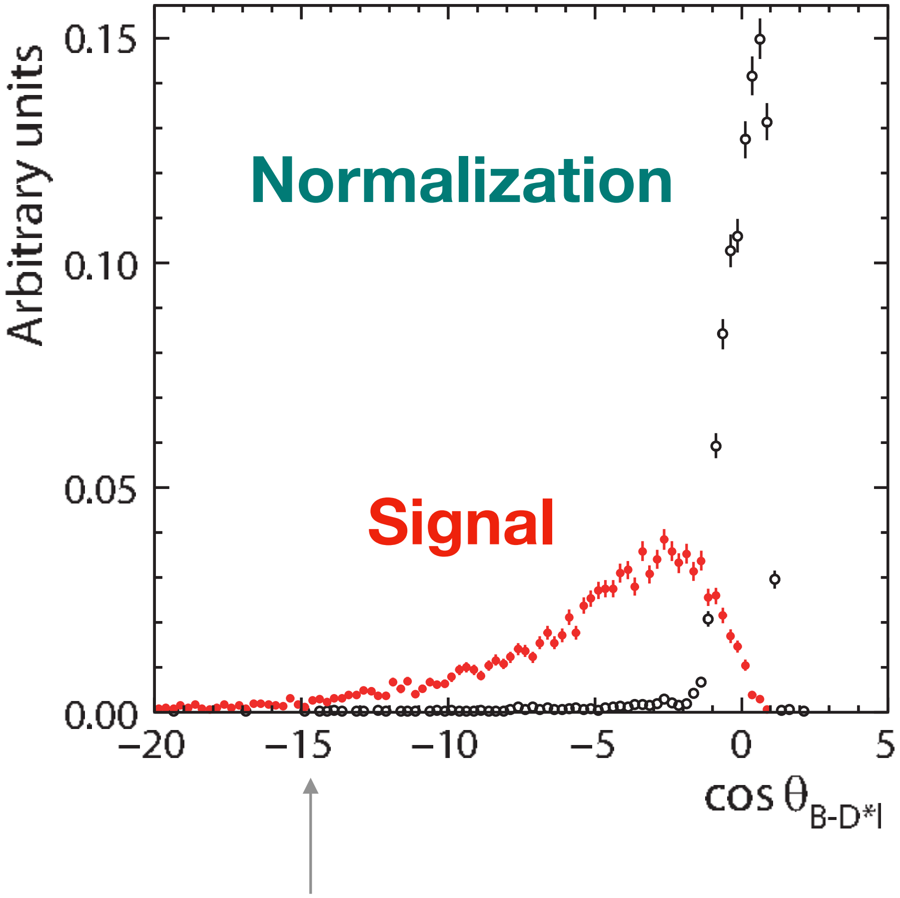


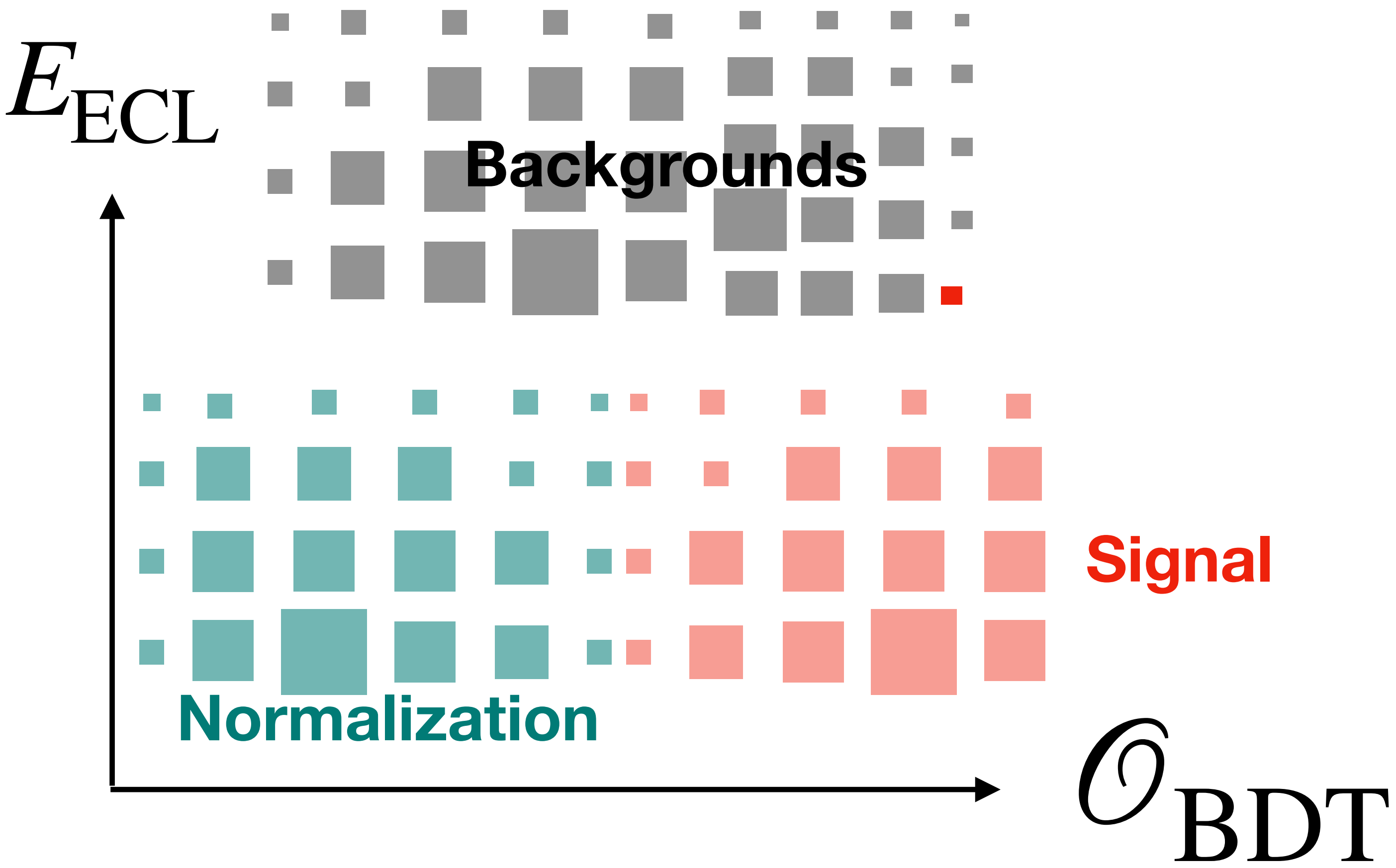


Separation of signal & normalization

- Use kinematic properties to separate $B \to D^{(*)}\tau\nu$ signal from $B \to D^{(*)}\ell\nu$ normalization

- Construct BDT with 3 variables: $\cos\theta_{B-D^{(*)}\ell}$, E_{vis}, $m^2_{\text{miss}} = p^2_{\text{miss}}$





In case you are wondering how a cosine can be outside [-1,1]: it's because the reconstruction uses measured energies and the definition assumes only a single missing neutrino

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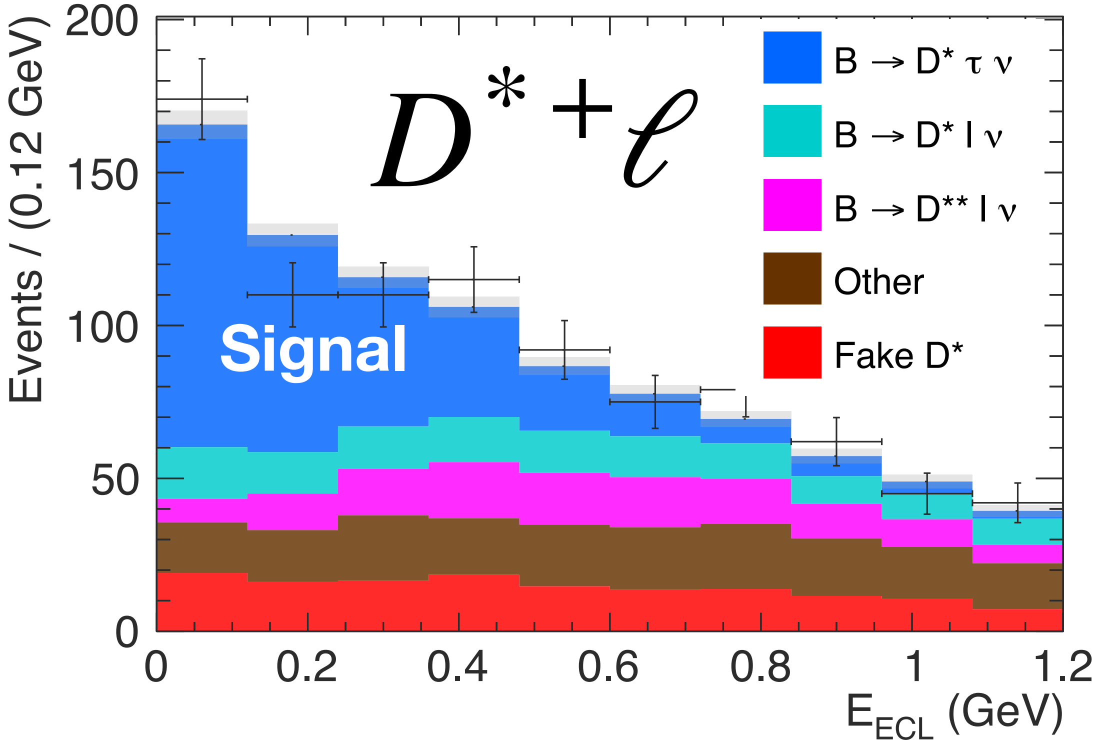
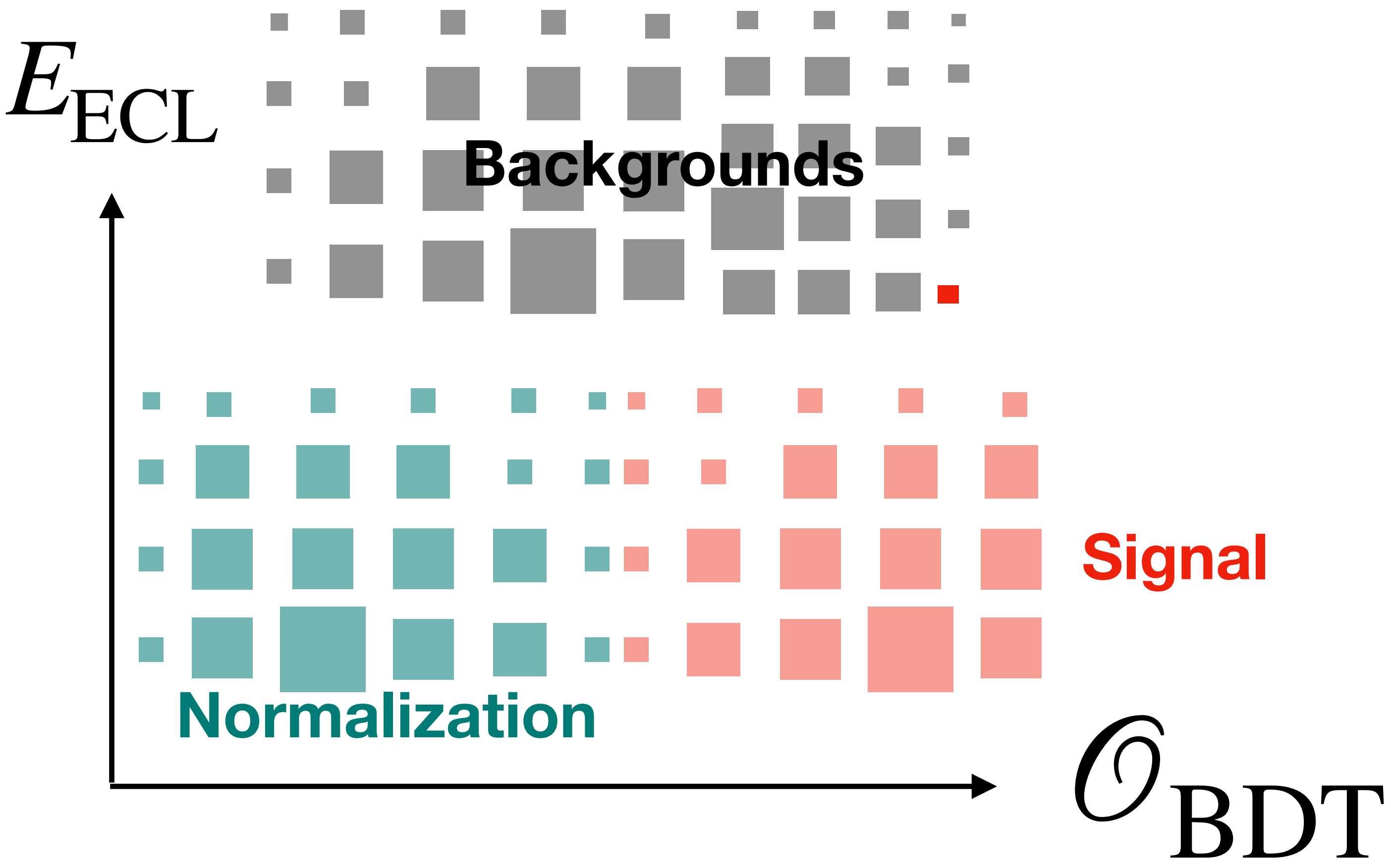


Signal-enriched selection with cut on $\mathcal{O}_{\text{BDT}}$



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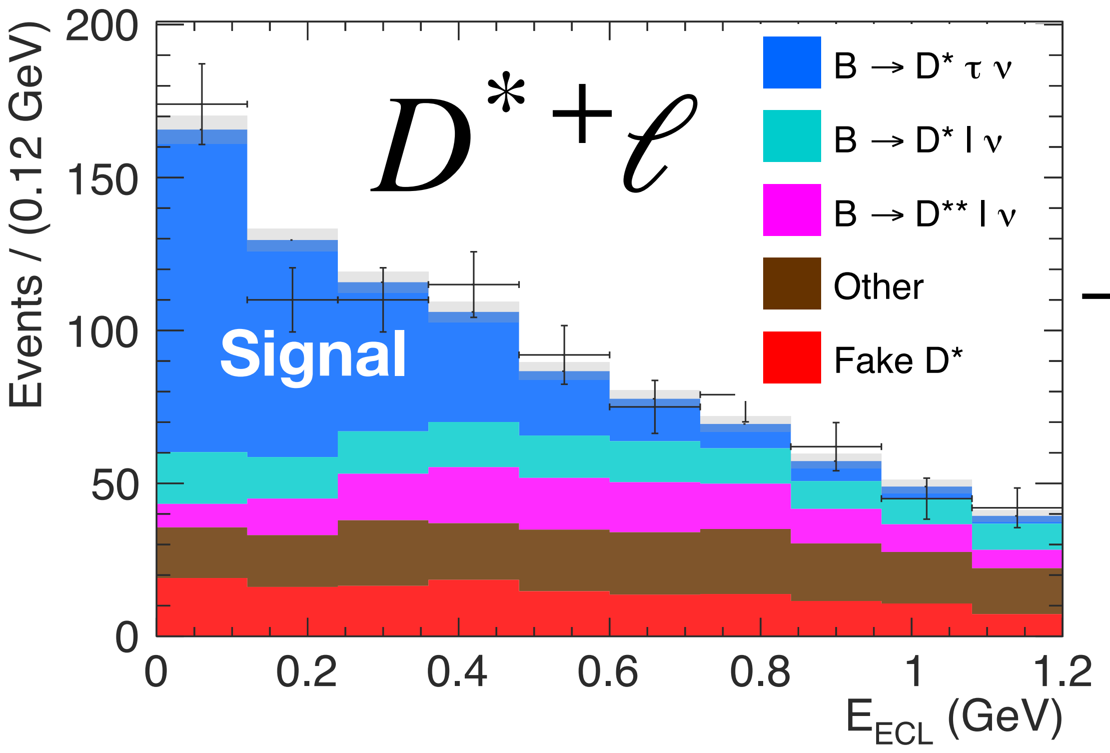


Signal enriched selection with cut on $\mathcal{O}_{\text{BDT}}$

$$\boxed{\begin{aligned} \mathcal{R}(D) &= 0.307 \pm 0.037 \pm 0.016 \\ \mathcal{R}(D^*) &= 0.283 \pm 0.018 \pm 0.014 \end{aligned}}$$

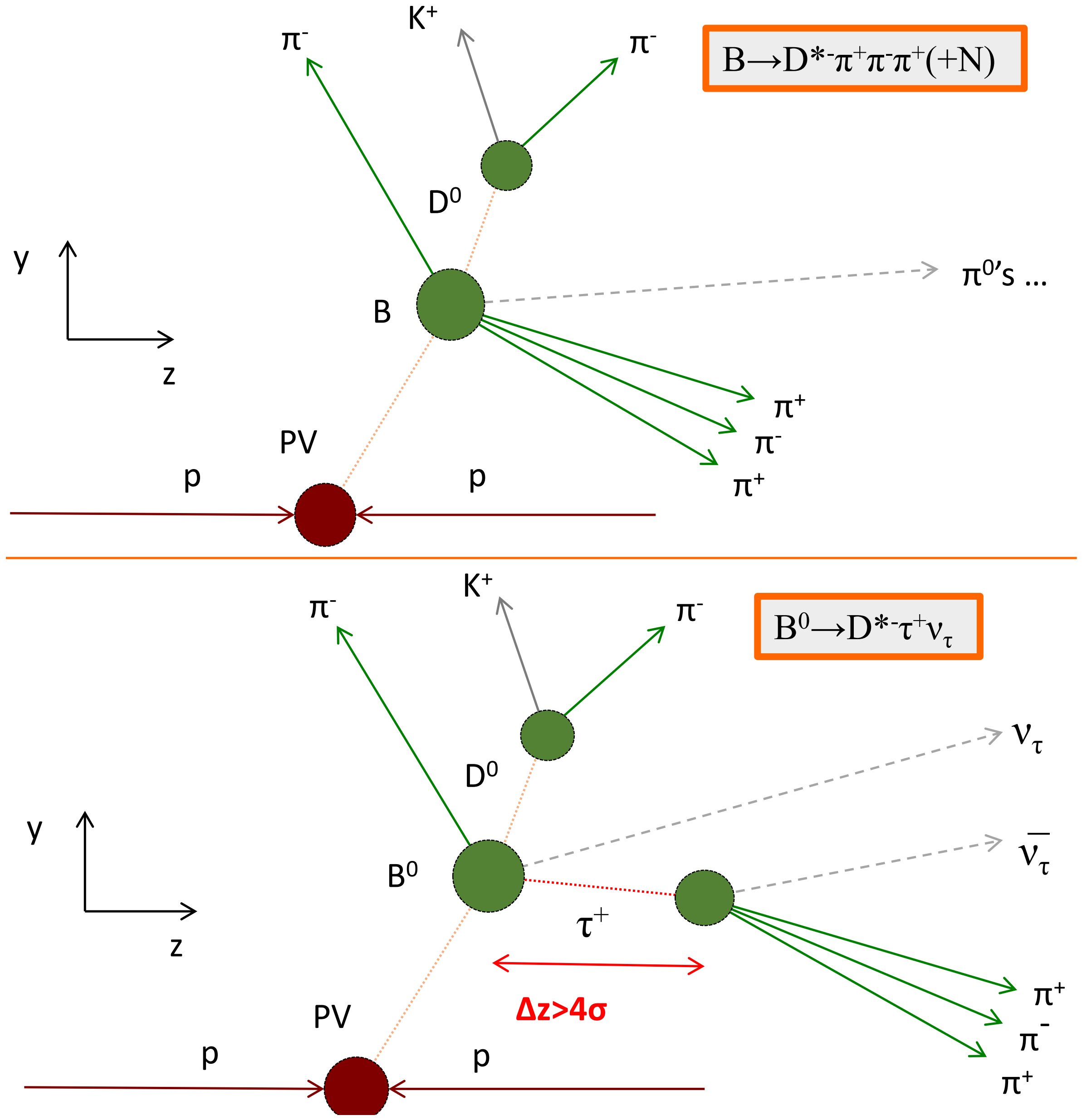
Most precise measurement to date

LHCb Measurement of $R(D^*)$

R. Aaij et al (LHCb),
Phys.Rev.Lett.120,171802 (2018) [arXiv:1708.08856]
Phys.Rev.D 97, 072013 (2018) [arXiv:1709.02505]

- Tau reconstructed via $\tau \to \pi^+\pi^+\pi^-(\pi^0)\nu$, only two neutrinos missing

Although a semileptonic decay is studied, nearly no background from $B \to D^* X \mu \nu$



- Main background: prompt **$X_b \to D^*\pi\pi\pi$ + neutrals**

  BF ~ 100 times larger than signal, all pions are promptly produced

- Suppressed by requiring minimum distance between ***X_b & τ vertices (> 4 $\sigma_{\Delta z}$)***

  $\sigma_{\Delta z}$: resolution of vertices separation

- Reduces this background by three orders of magnitude

LHCb Measurement of $R(D^*)$

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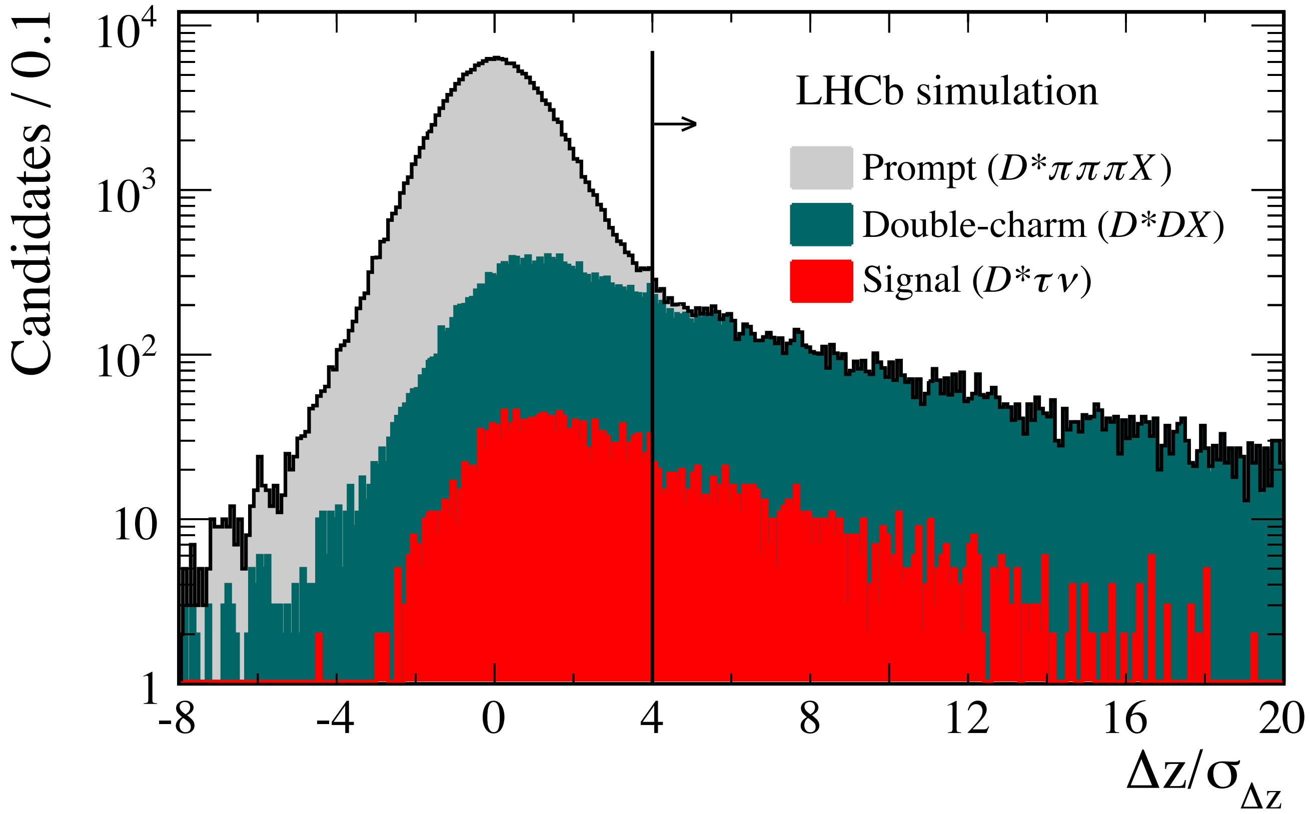

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$\sigma_{\Delta z}$: resolution of vertices separation

- Reduces this background by three orders of magnitude

- Remaining double charm bkgs:

$X_b \to D^{*-}D_s^+X$ ~ 10 x Signal
$X_b \to D^{*-}D^+X$ ~ 1 x Signal
$X_b \to D^{*-}D_{s0}^+X$~ 0.2 x Signal

LHCb Measurement of $R(D^*)$

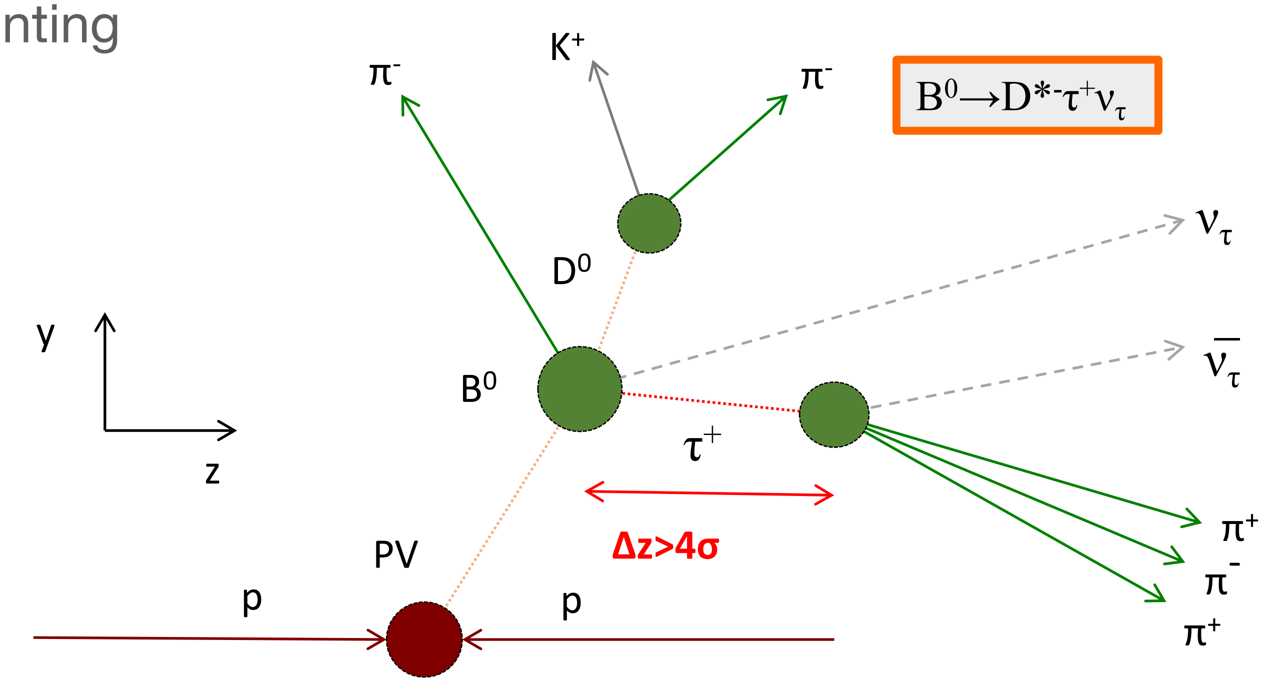
- Remaining backgrounds reduced via isolation & MVA

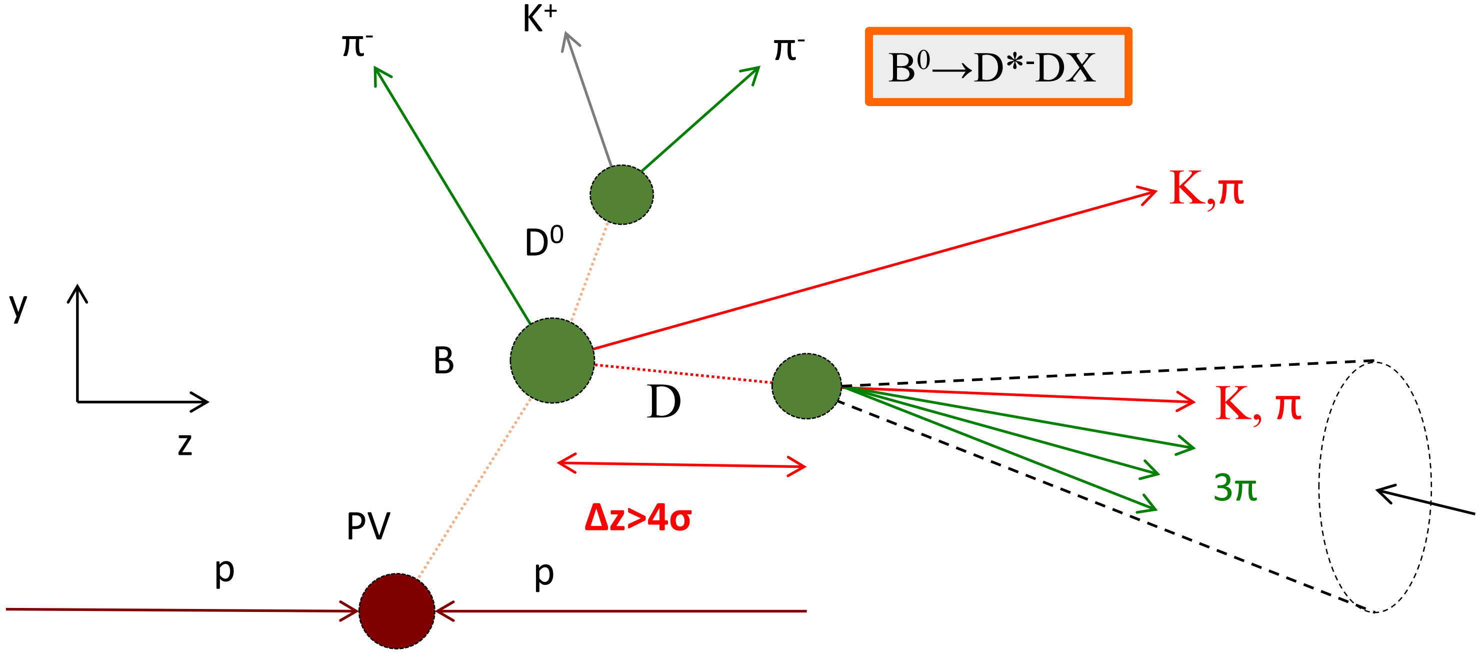
Require signal candidates to be well isolated

i.e. reject events with extra charged particles pointing to the B and/or τ

Events with additional neutral energy are suppressed with a MVA

More information about that in backup





Missing (neutral) energy in a cone around the 3π direction

LHCb Measurement of $R(D^*)$

- Extraction in **3D fit** to

MVA : q^2 : τ decay time

Invariant masses of 3π system
Invariant mass of $D^*3\pi$ system
Neutral isolation variables

q^2 reconstructed with some tricks (more in backup)

4 Bins 8 Bins 8 Bins

- Components:

1 Signal component for $\tau \rightarrow \pi^+\pi^+\pi^-(\pi^0)\nu$

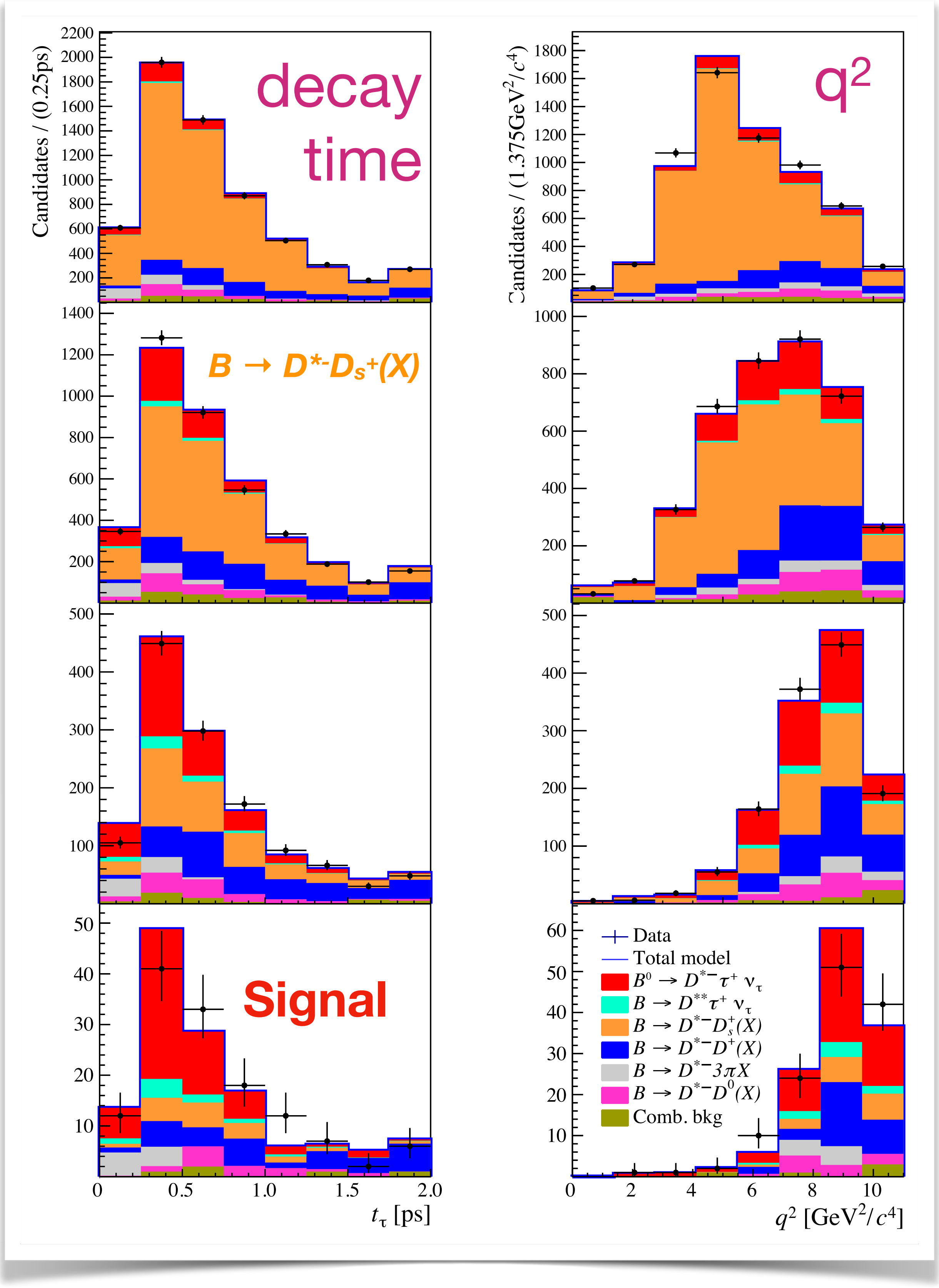
11 Background components

- ~ 1296 ± 86 Signal events
- Using normalisation mode and light lepton BFs:

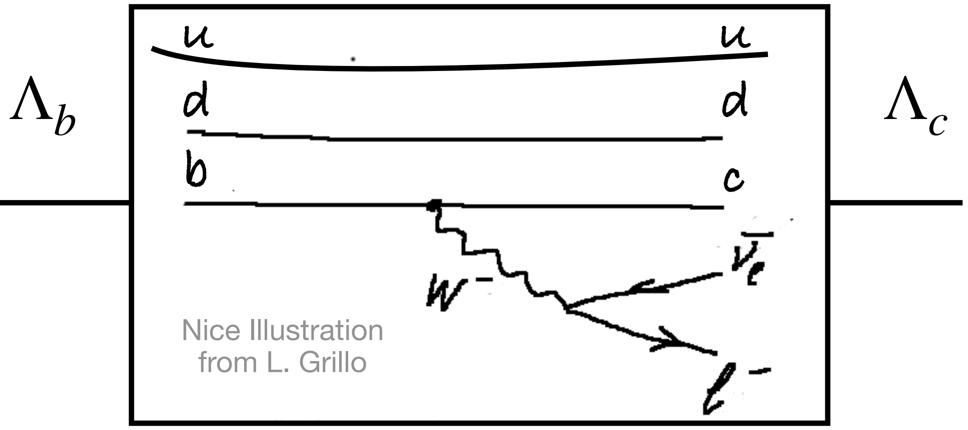
More information about normalization in backup

$R(D^*) = 0.286 \pm 0.019$ (stat) ± 0.025 (syst) ± 0.021 (norm)

Purer MVA Selection

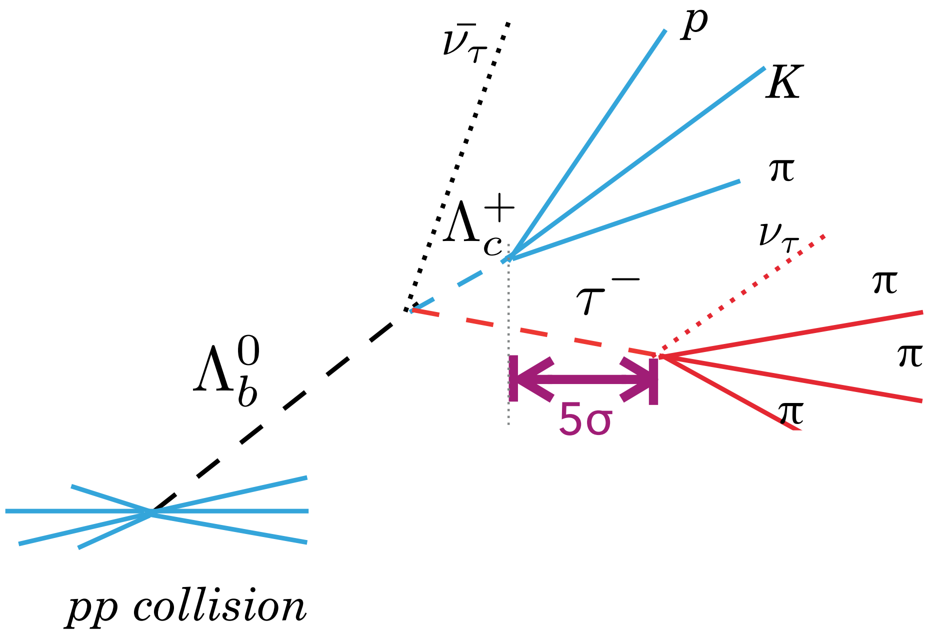


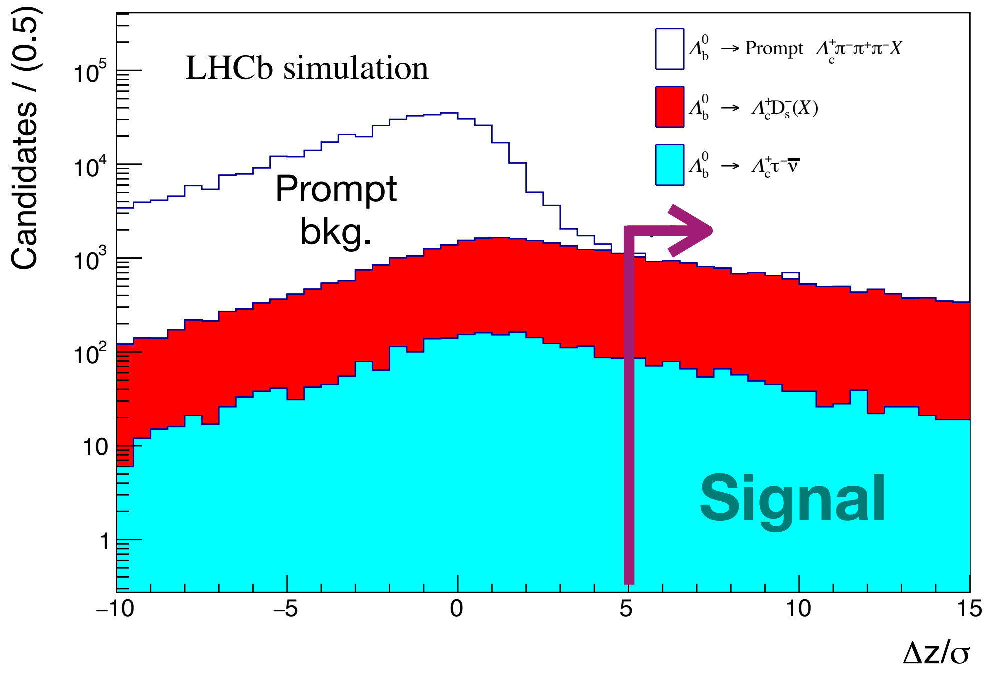
LHCb $R(\Lambda_c)$ Measurement



Nice Illustration from L. Grillo

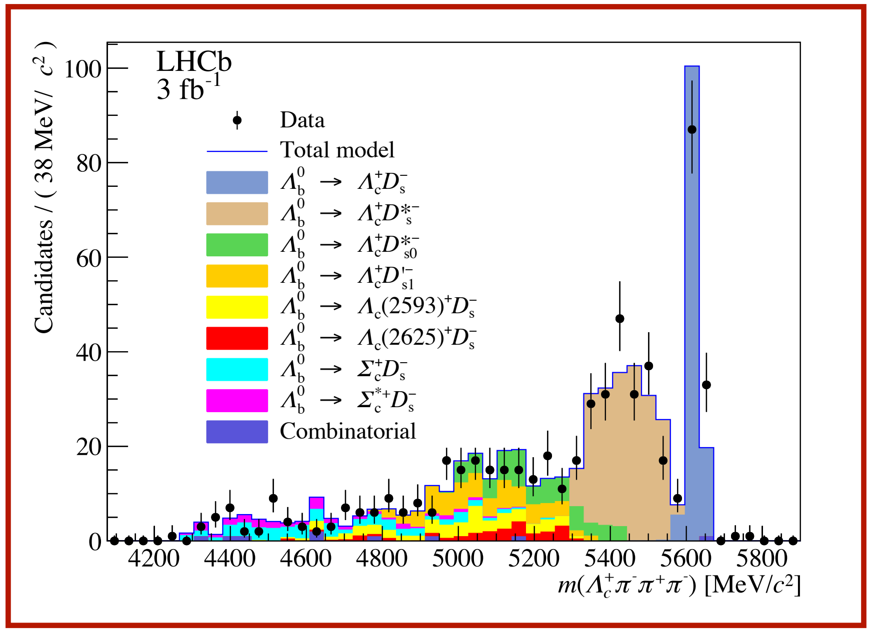
Same experimental Method: exploit vertex **separation**





Long-lived bkg. (D_s)

$m_{3\pi} \in [m_{D_s} - 45\,\mathrm{MeV}, m_{D_s} + 45\,\mathrm{MeV}]$



Bkg. composition constrained by fit to $m_{3\pi}$

Target **ratio**:

$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}$$
$$= \frac{N_{sig}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}} \times \frac{1}{\mathcal{B}(\tau^- \to 3\pi(\pi^0)\nu_\tau)}$$

- Extraction in **3D fit** to
  MVA : q^2 : τ decay time

Kinematic and angular information of 3π system, neutral energy in cone around 3π direction

$$\boxed{\begin{array}{c} N(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau) = 349 \pm 40 \\ N(\Lambda_b^0 \to \Lambda_c^+ D_s^-(X)) = 2757 \pm 80 \end{array}}$$

External input:

$$\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi) = (6.14 \pm 0.94) \times 10^{-3}$$

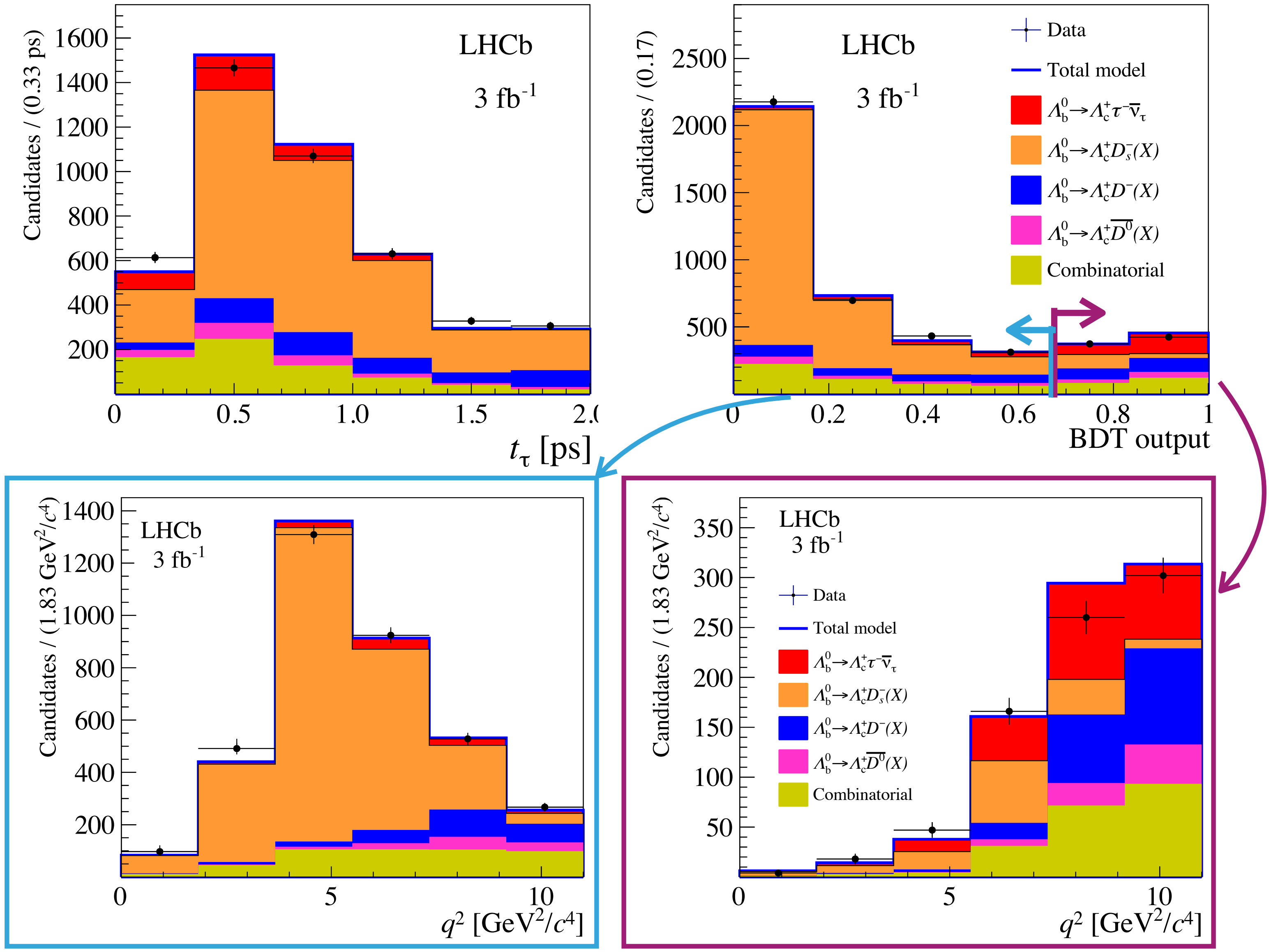
$$\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ \tau \bar{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\,\%$$

First observation with 6.1 σ !

More external input:

$$\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ \mu \bar{\nu}_\mu) = (6.2 \pm 1.4)\,\%$$

$$R(\Lambda_c^+) = 0.242 \pm 0.026_{\text{stat}} \pm 0.040_{\text{syst}} \pm 0.059_{\text{ext}}$$



Compatible with SM

$$R(\Lambda_c^+)_{\text{SM}} = 0.340 \pm 0.004$$

F. Bernlochner, Zoltan Ligeti, Dean J. Robinson, William L. Sutcliffe, [arXiv:1808.09464, [arXiv:1812.07593]

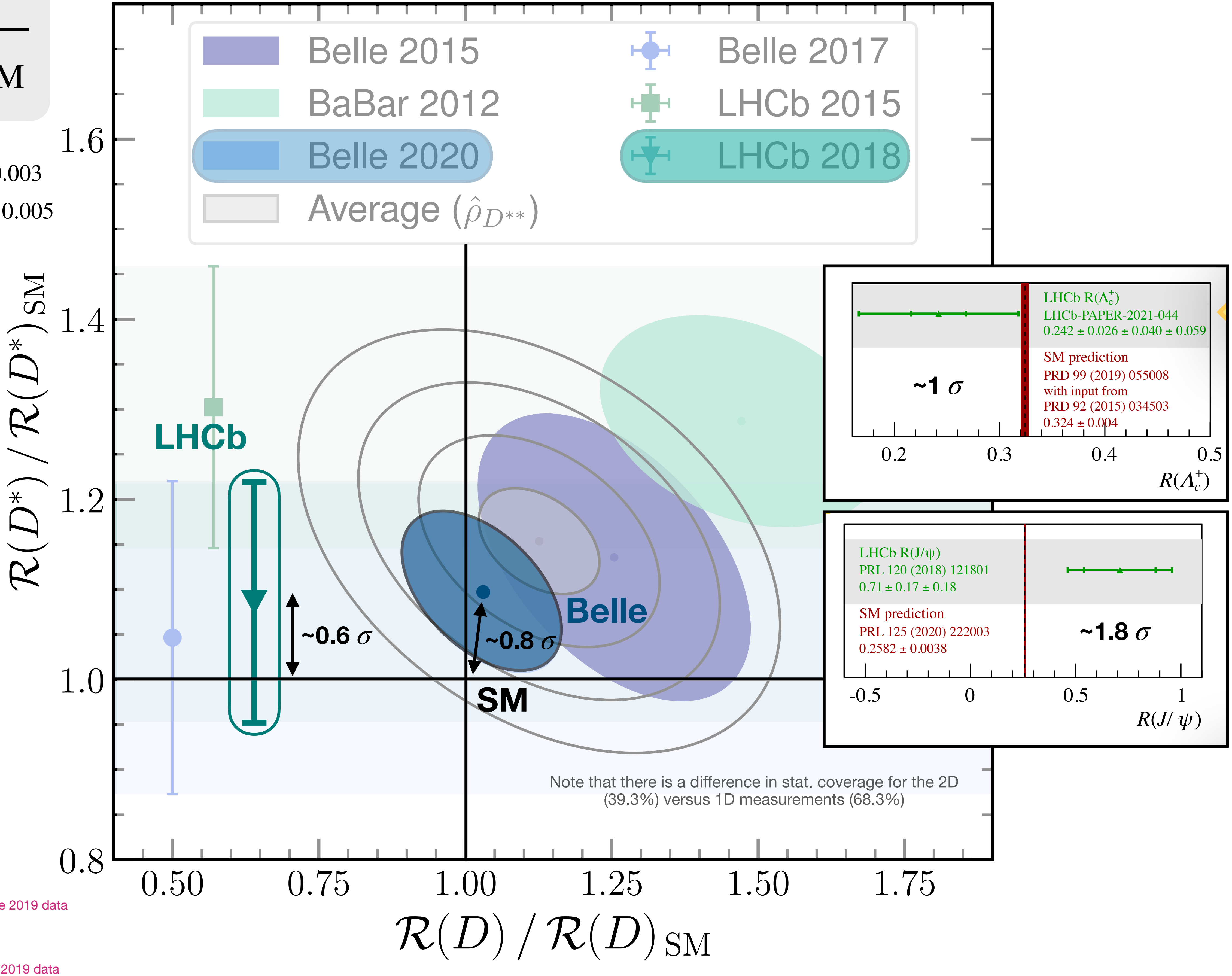
FB, M. Sevilla, D. Robinson, G. Wormser
[Rev. Mod. Phys. **94**, 015003,arXiv:2101.08326]

$$\frac{\mathscr{R}(D^{(*)})}{\mathscr{R}(D^{(*)})_{\mathrm{SM}}}$$

$\mathscr{R}(D)_{\mathrm{SM}} = 0.299 \pm 0.003$

$\mathscr{R}(D^{*})_{\mathrm{SM}} = 0.258 \pm 0.005$

HFLAV arithmetic average
of SM Calculations



Note that there is a difference in stat. coverage for the 2D
(39.3%) versus 1D measurements (68.3%)

More Recent SM Calculations:

BaBar B->D*
https://arxiv.org/abs/1903.10002
- R(D*)=0.253+-0.005

Gambino, Jung, Schacht using Belle 2019 data
https://arxiv.org/abs/1905.08209
- R(D*)=0.254 +0.007 -0.006

Bordone, Jung, van Dyk using Belle 2019 data
https://arxiv.org/abs/1908.09398
- RD=297+-0.003, RD*=0.250+-0.003

See also: https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html

$b \to s\ell\ell$ and friends

Lepton Universality Tests

Lepton Universal transitions in the SM

- **Very precise** SM **predictions**

  QCD uncertainties cancel, uncertainties $\sim 10^{-4}$

  But $\sim 1\,\%$ QED correction

  [Bordone et al., EPJC 76 (2016) 8:440]

Observables of choice:

$$\mathcal{R}(K) = \frac{\mathcal{B}(B^+ \to K^+ \mu\,\mu)}{\mathcal{B}(B^+ \to K^+ e\,e)}$$

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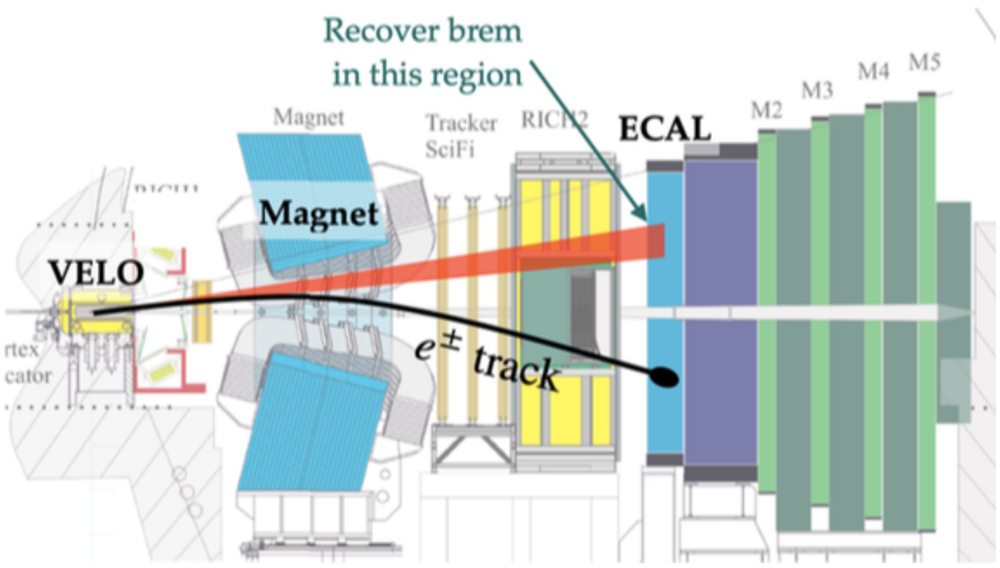
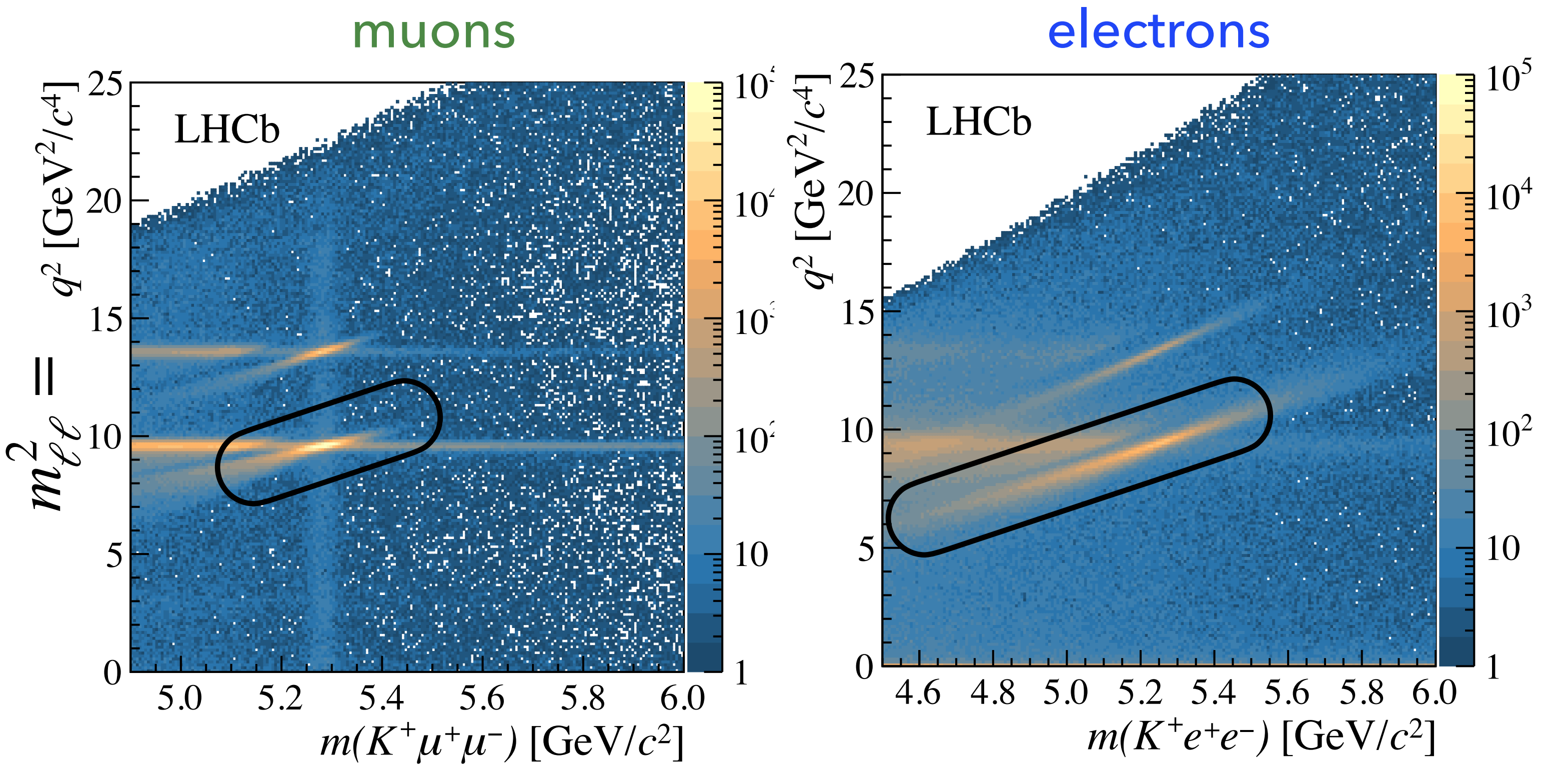
In SM $= 1 \pm \text{small corrections}$

- **LHCb Challenge: Identifying electrons**

  Results in less electrons (lower trigger rate) with worse resolution (Bremsstrahlung)





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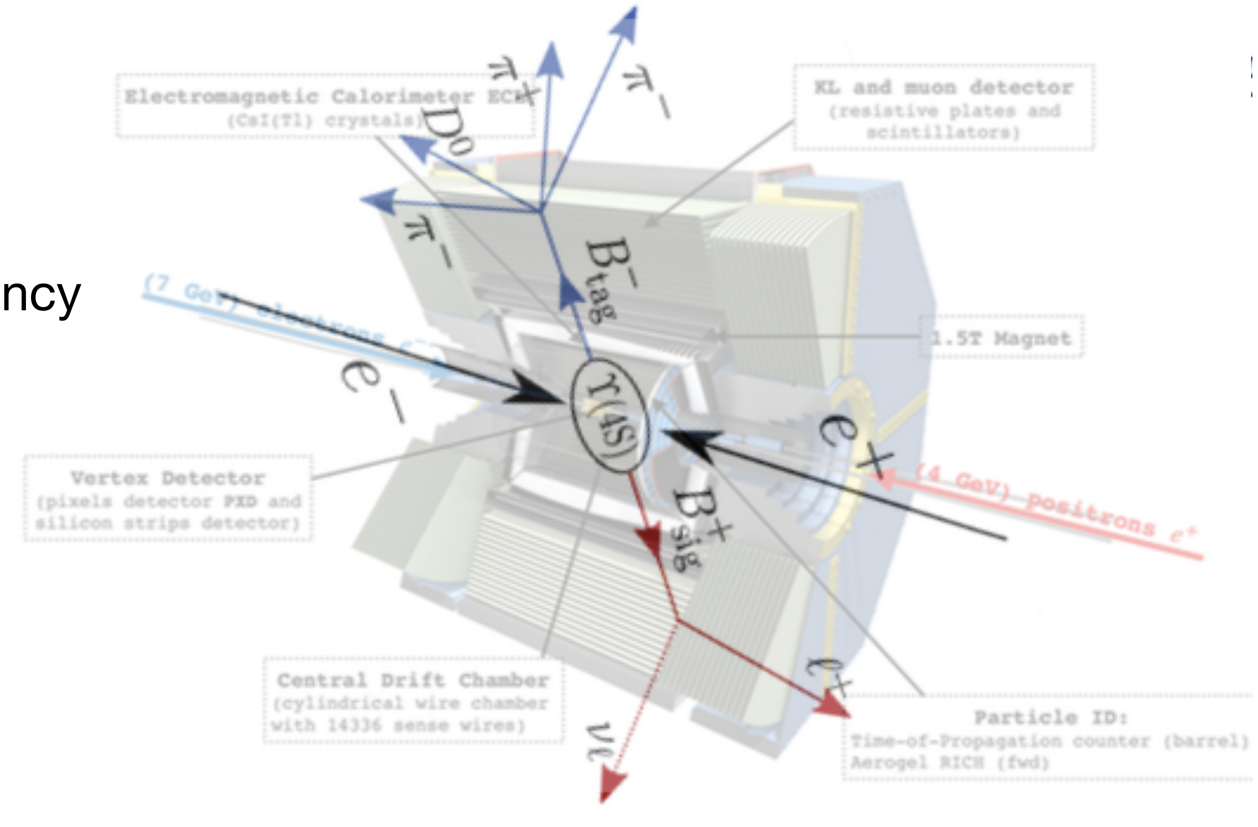
In SM $= 1 \pm \text{small corrections}$

Belle (II) Challenge: Very rare decay

Hermetic Detector

Excellent electron (& muon) reconstruction efficiency

Known initial state, tagging for missing energy information



LFU @ Belle

[arXiv:1908.01848]
[arXiv:1904.02440]

- Full Belle data set (**0.71/ab**)

$$B^+ \to K^{*+}(K^+\pi^0, K_S^0\pi^+)\,\ell\ell$$

$$B^0 \to K^{*0}(K^+\pi^-, K_S^0\pi^0)\,\ell\ell$$

- Fit to beam-constrained mass, energy difference used in multivariate bkg suppression

$$M_{bc} = \sqrt{E_{\text{beam}}^2 - |\mathbf{p_B}|^2} \sim m_B$$

$$\Delta E = E_B - E_{\text{beam}} \sim 0$$

- **Multivariate background** suppression

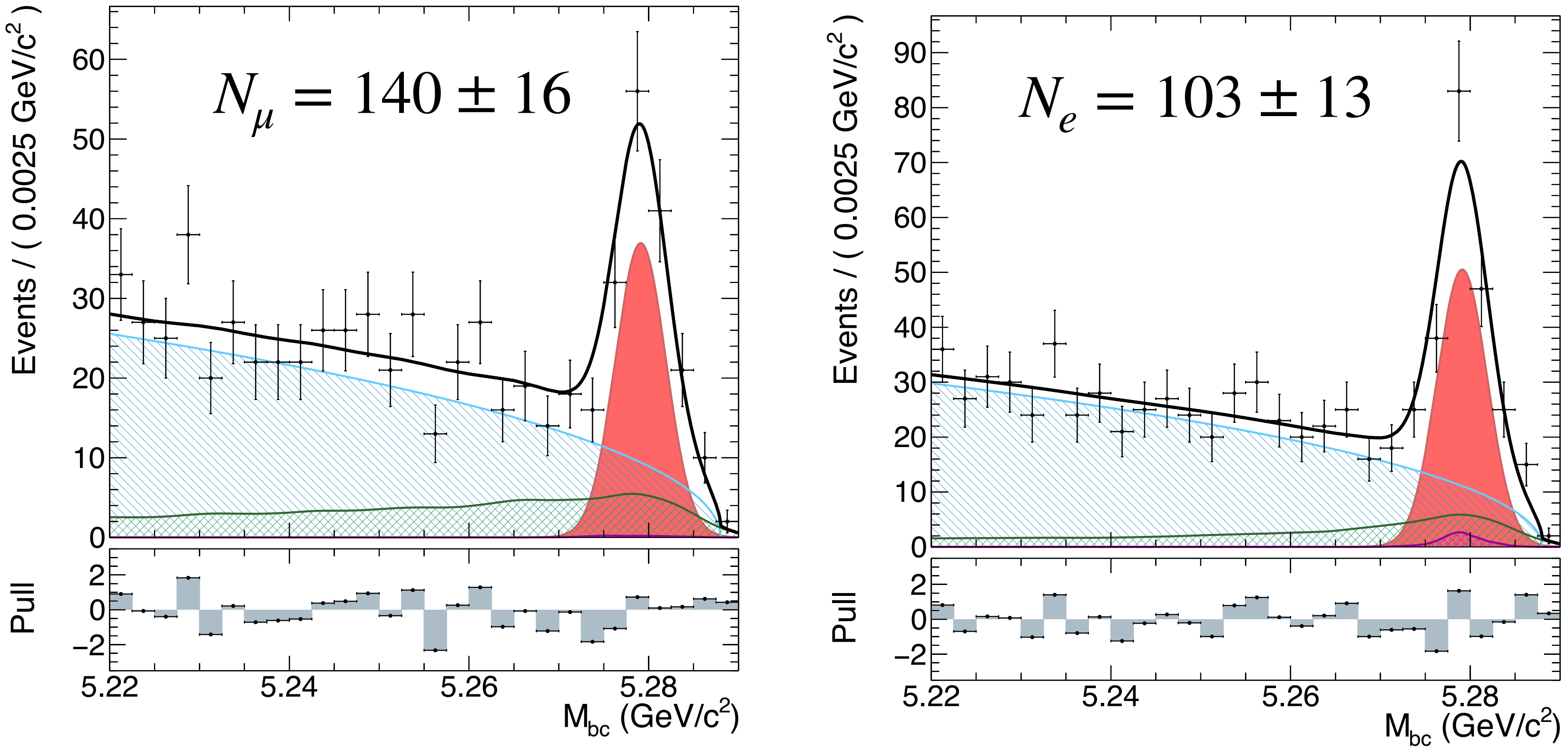
Consistent with **SM expectation,**
statistically limited

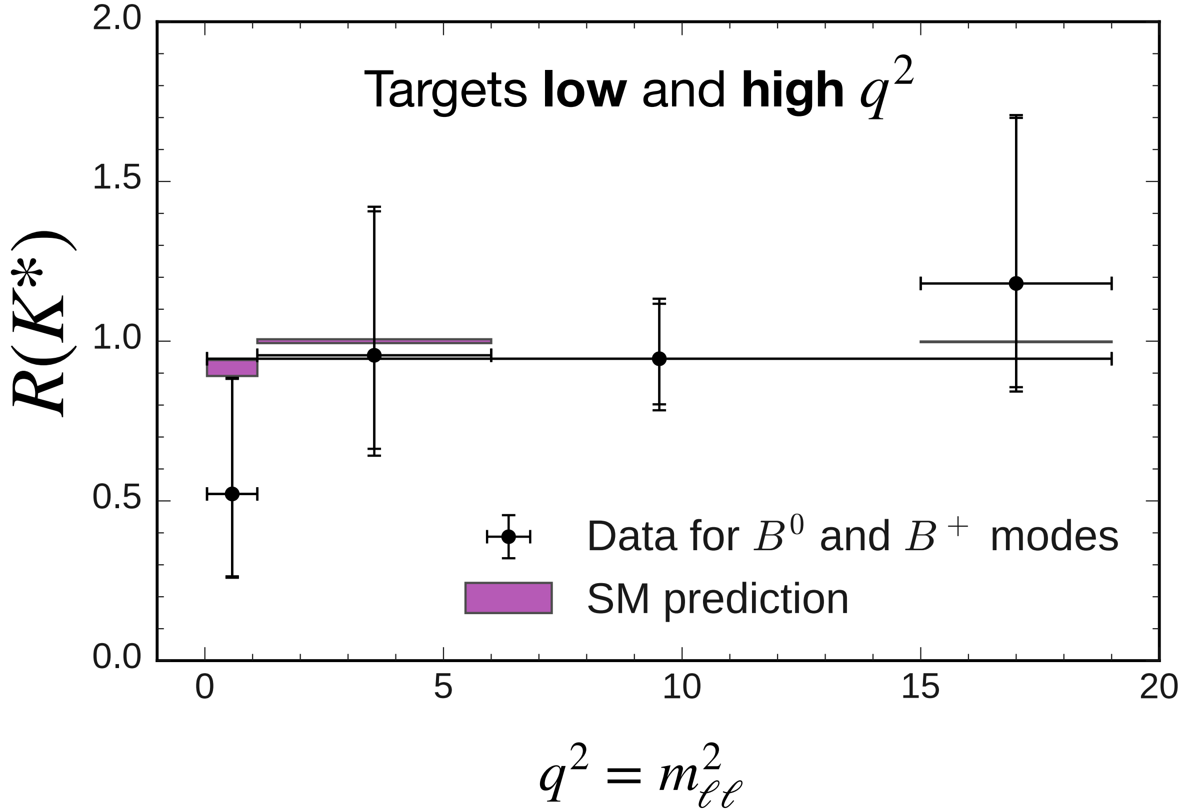
Belle also measured LFU ratios of

$$B^+ \to K^+\,\ell\ell$$

$$B^0 \to K_S^0\,\ell\ell$$

(also consistent with SM)





LFU @ Belle II

[arXiv:1908.01848]
[arXiv:1904.02440]

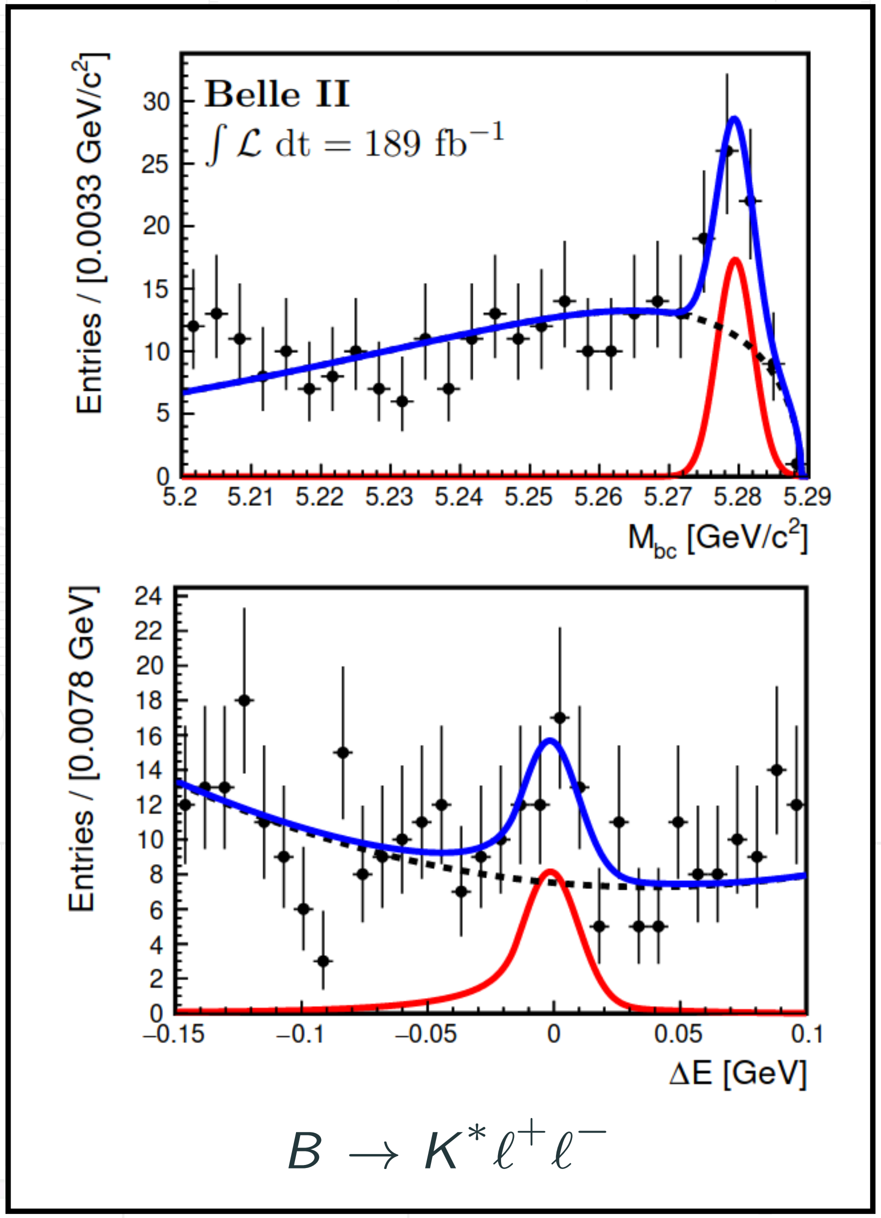
Belle II is starting to pick up steam:

First results presented at **Moriond EW** this year

$\mathcal{B}(B \to K^{*}\mu^{+}\mu^{-}) = (1.28 \pm 0.29^{+0.08}_{-0.07}) \times 10^{-6}$ (PDG: $(1.06 \pm 0.09) \times 10^{-6}$)

$\mathcal{B}(B \to K^{*}e^{+}e^{-}) = (1.04 \pm 0.48^{+0.09}_{-0.09}) \times 10^{-6}$ (PDG: $(1.19 \pm 0.20) \times 10^{-6}$)

$\mathcal{B}(B \to K^{*}\ell^{+}\ell^{-}) = (1.22 \pm 0.28^{+0.08}_{-0.07}) \times 10^{-6}$ (PDG: $(1.06 \pm 0.10) \times 10^{-6}$)



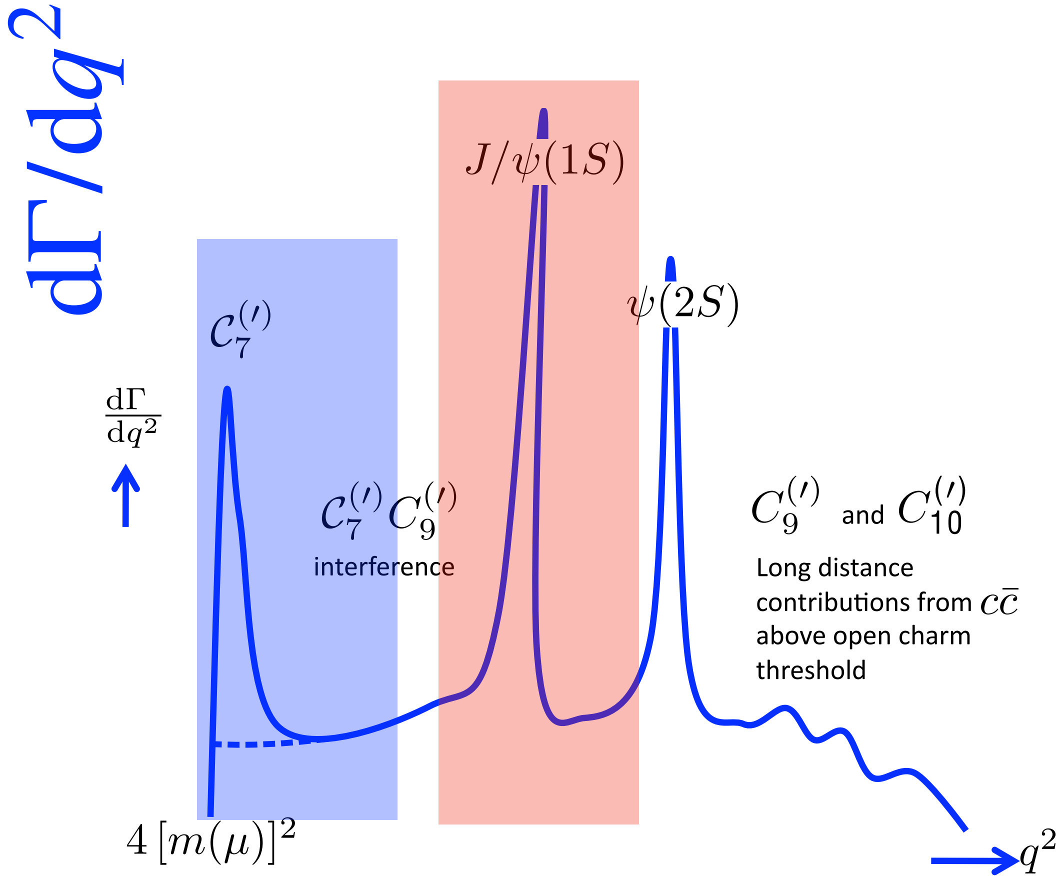
$B \to K^{*}\ell^{+}\ell^{-}$

LFU @ LHCb: Strategy

Experimentally even better: measure double ratios

$$R(K^{(*)}) = \frac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to J/\psi(\to \mu^+\mu^-)K^{(*)})} \Big/ \frac{\mathscr{B}(B \to K^{(*)}e^+e^-)}{\mathscr{B}(B \to J/\psi(\to e^+e^-)K^{(*)})}$$

Lepton-flavour universal!



$$q^2 = m_{\ell\ell}^2$$

Cross check with $\psi(2S)$:

$$R_K^{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.986 \pm 0.013$$

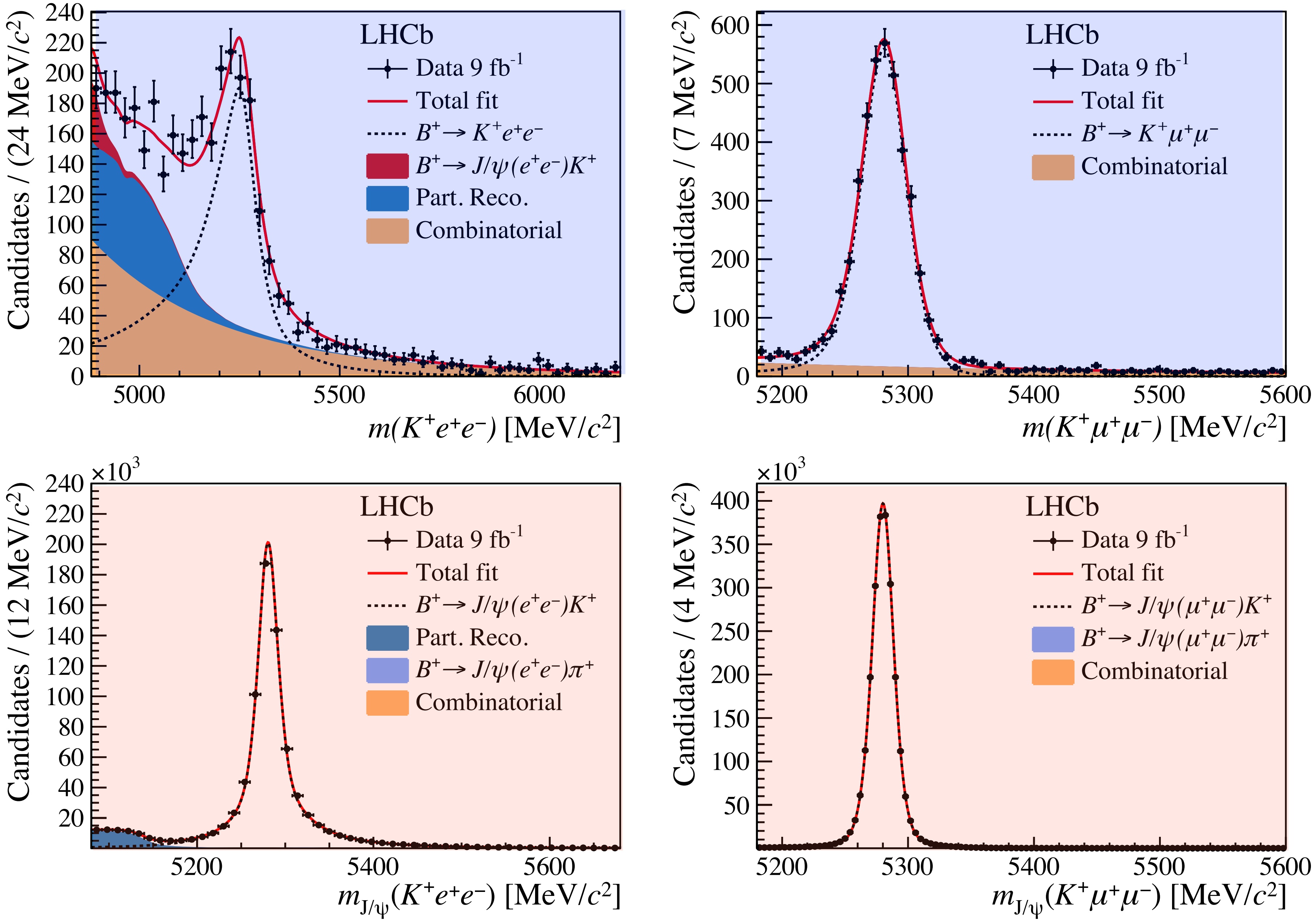
$$R(K^+) = \frac{\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{\mathscr{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathscr{B}(B^+ \to K^+e^+e^-)}{\mathscr{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

Electrons

Muons

$q^2 = m_{\ell\ell}^2 \in [1.1,6)\,\mathrm{GeV}^2$

$q^2 = m_{\ell\ell}^2 \in [1.1,6)\,\mathrm{GeV}^2$



$q^2 = m_{\ell\ell}^2 \in [6,12.96)\,\mathrm{GeV}^2$

$q^2 = m_{\ell\ell}^2 \in [8.68,10.09)\,\mathrm{GeV}^2$

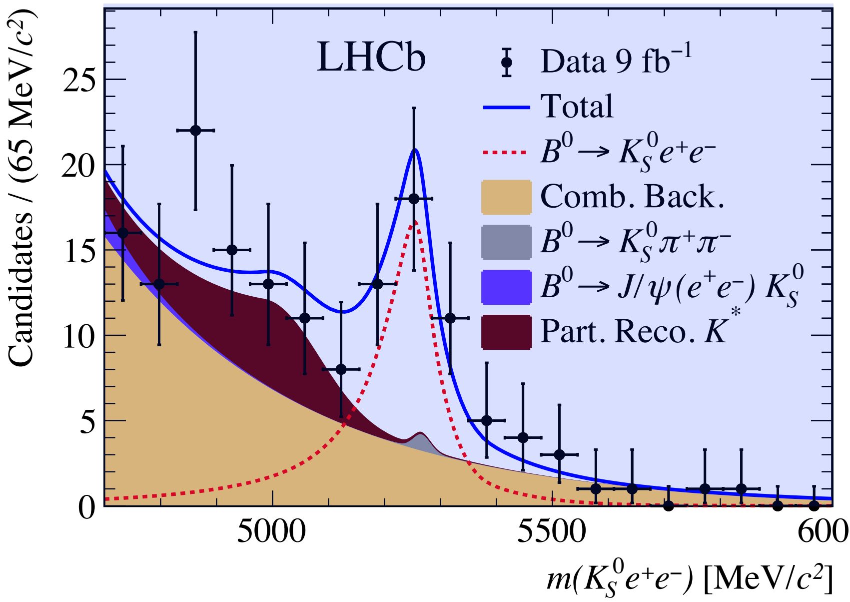
$$R(K_S^0) = \frac{\mathcal{B}(B^0 \to K_S^0 \mu^+\mu^-)}{\mathcal{B}(B^0 \to J/\psi(\to \mu^+\mu^-)K_S^0)} \Big/ \frac{\mathcal{B}(B^0 \to K_S^0 e^+e^-)}{\mathcal{B}(B^0 \to J/\psi(\to e^+e^-)K_S^0)}$$

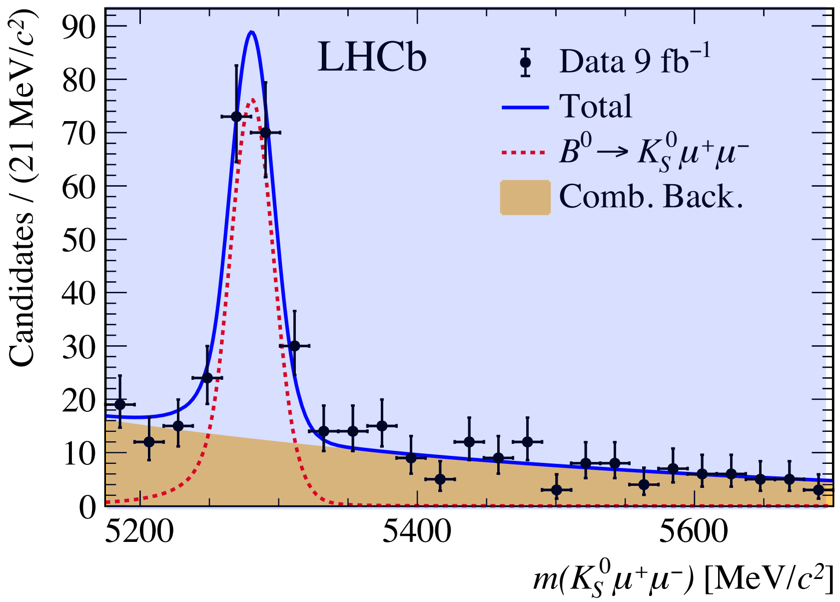
Electrons

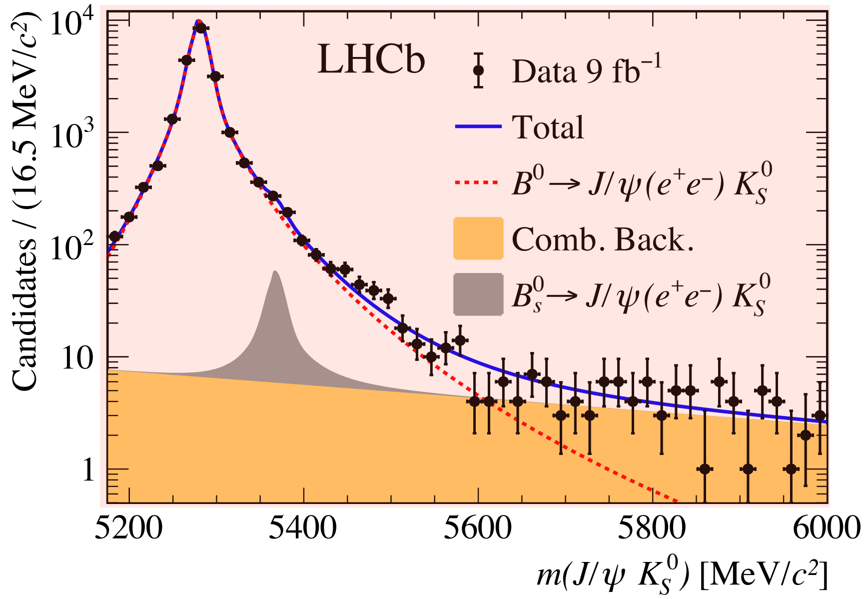
Muons

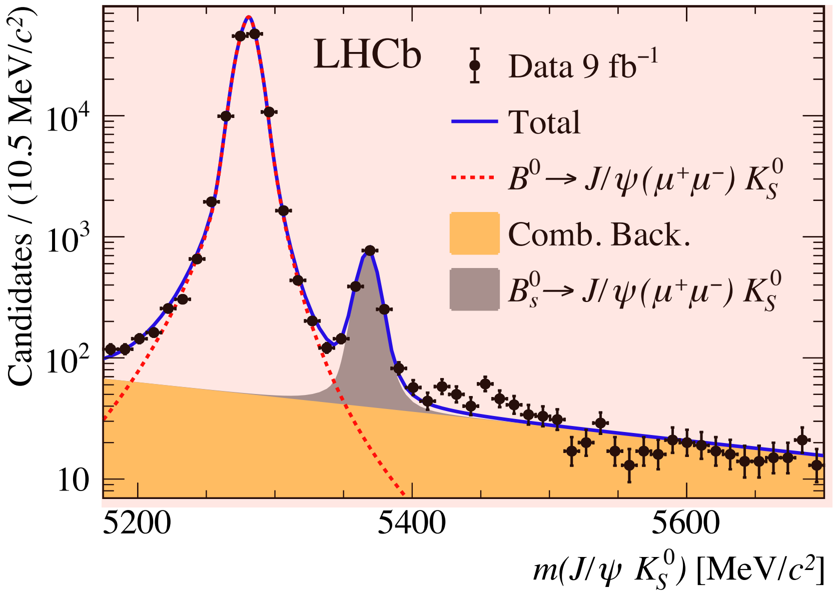
$q^2 = m_{\ell\ell}^2 \in [1.1,6)\,\mathrm{GeV}^2$

$q^2 = m_{\ell\ell}^2 \in [1.1,6)\,\mathrm{GeV}^2$







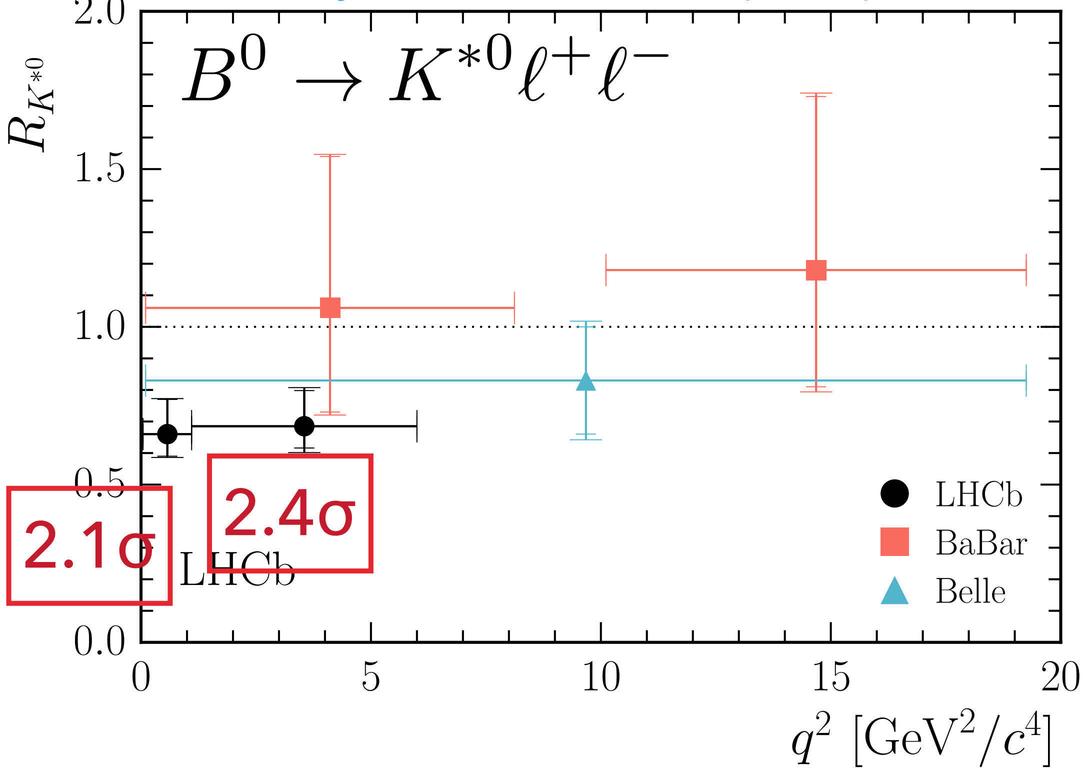


$q^2 = m_{\ell\ell}^2 \in [6,11)\,\mathrm{GeV}^2$

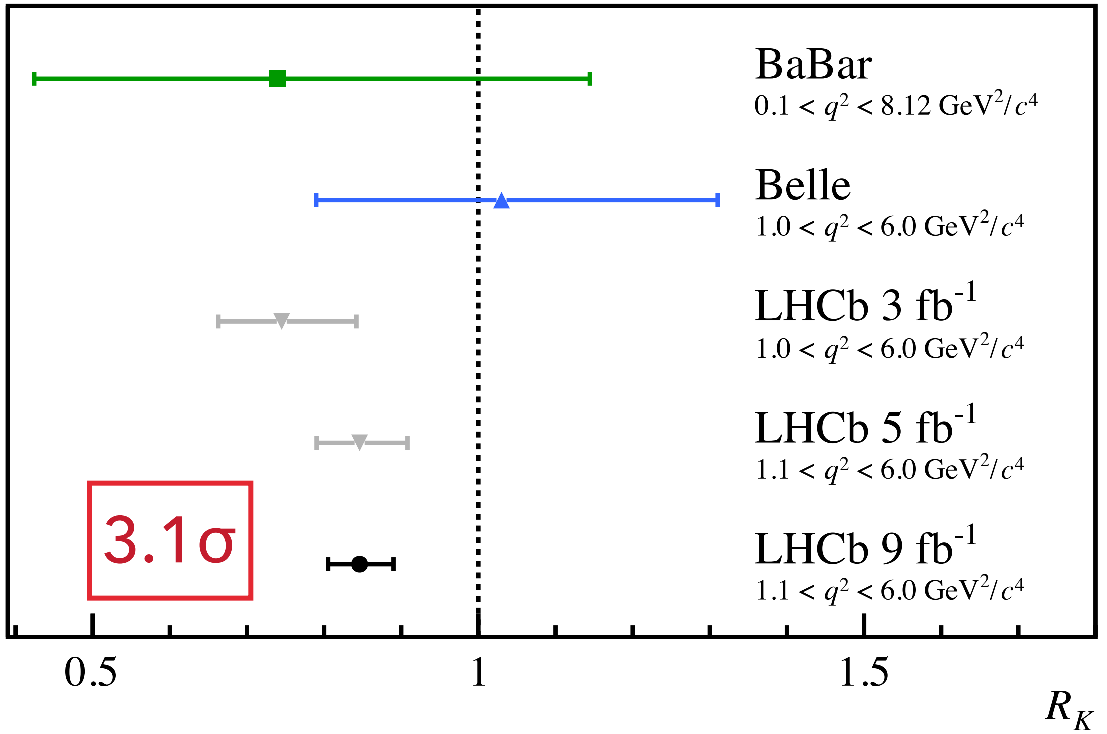
$q^2 = m_{\ell\ell}^2 \in [8.98,10.21)\,\mathrm{GeV}^2$

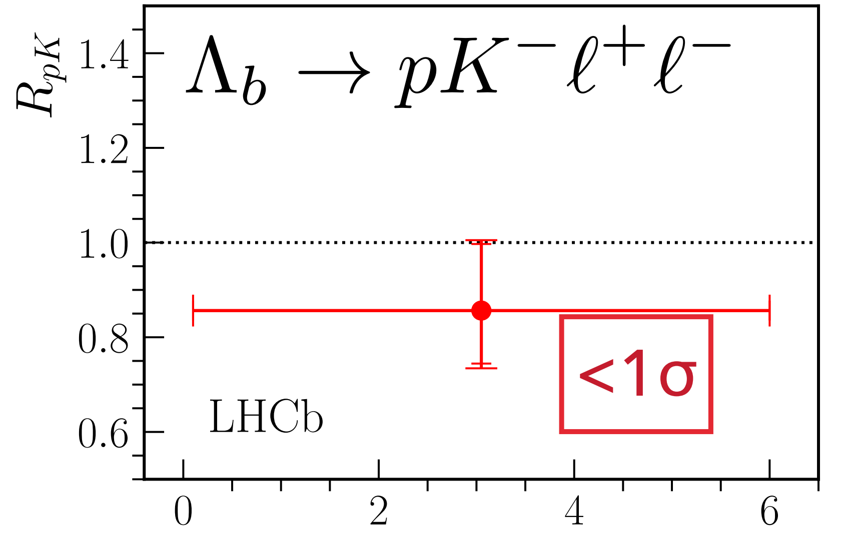
Summary LFU Tests

Phys. Rev. Lett. 125 (2020) 011802

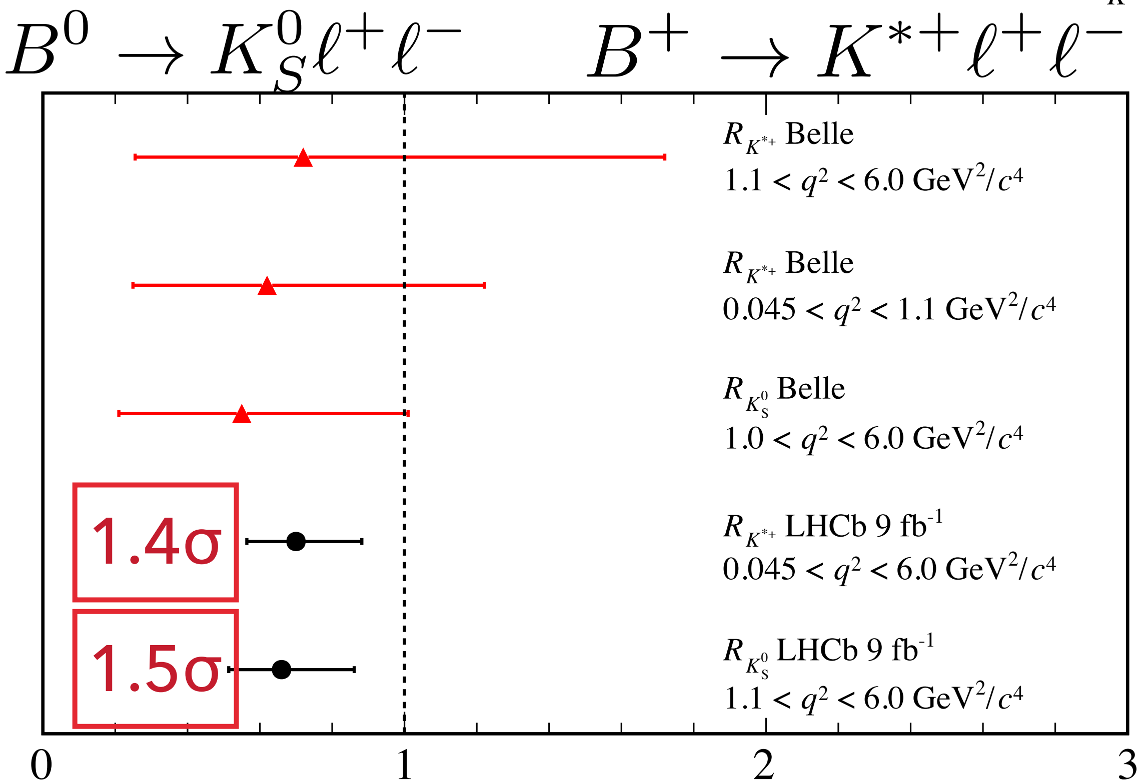


$B^+ \to K^+\ell^+\ell^-$ arXiv:2103.11769





JHEP 05 (2020) 040



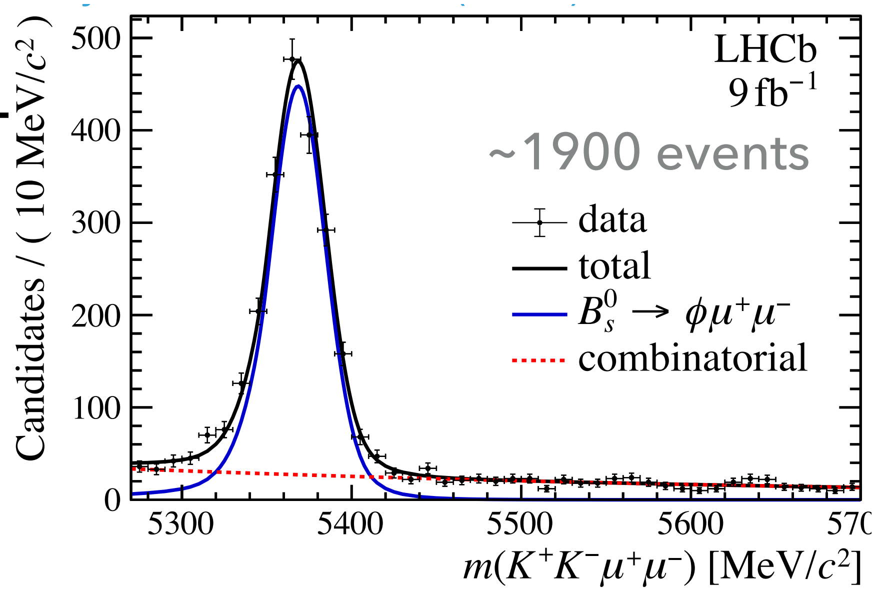
arXiv:2110.09501

Angular Analyses @ LHCb

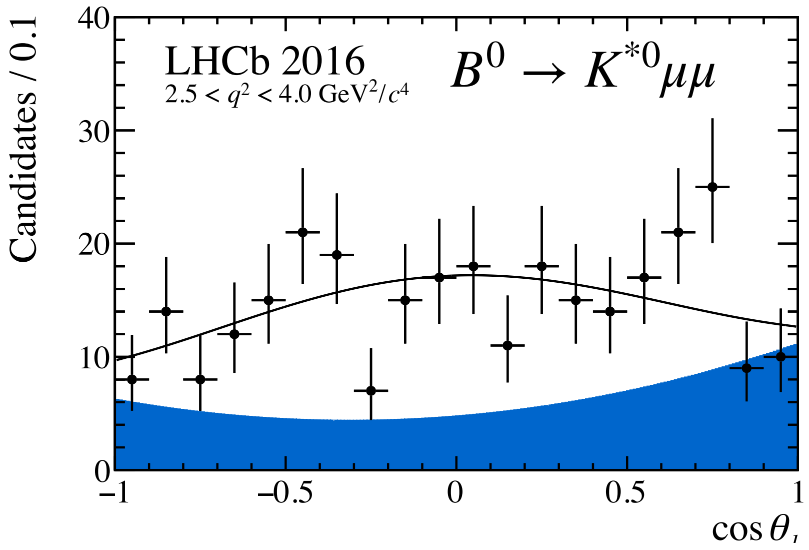
$B \to K^* \mu\mu$ and $B_s \to \phi\mu\mu$ decays fully described by 4D decay rate:

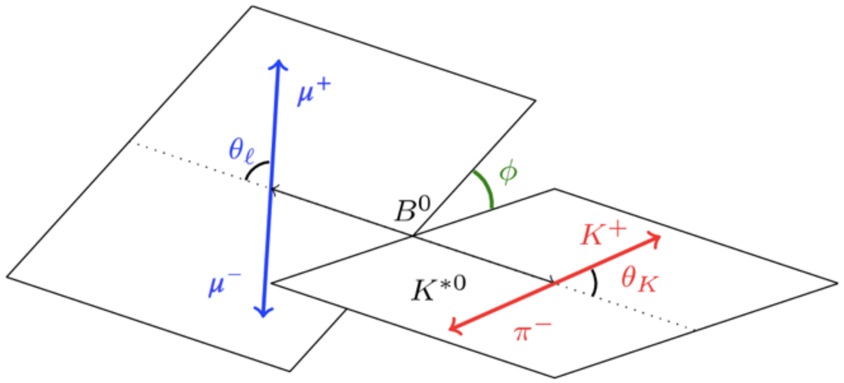
$$\frac{d^4\Gamma(B \to V\mu^+\mu^-)}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \sum_i I_i(q^2) f_i(\vec{\Omega})$$

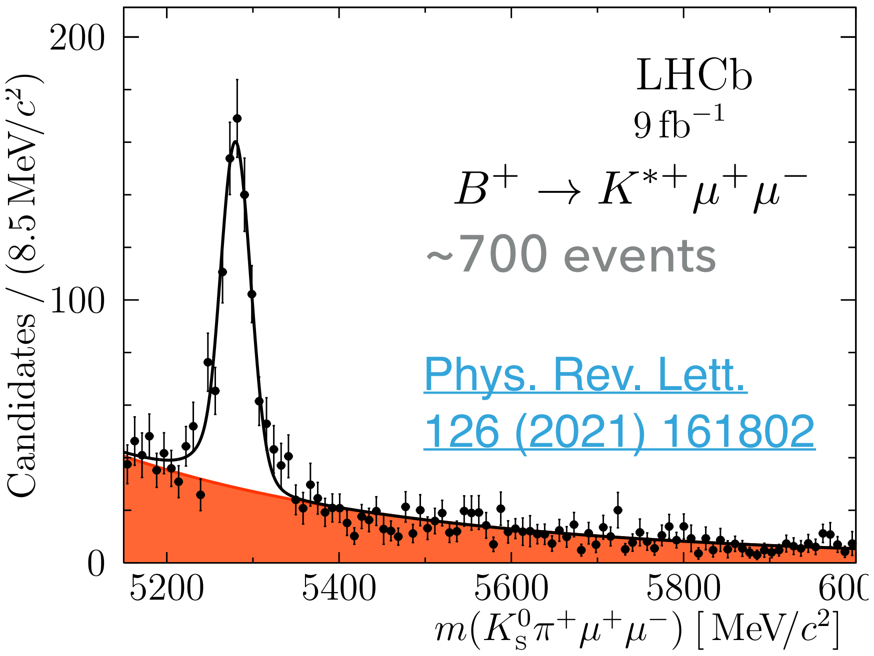
Measure angular observables as a function of q^2



~1900 events

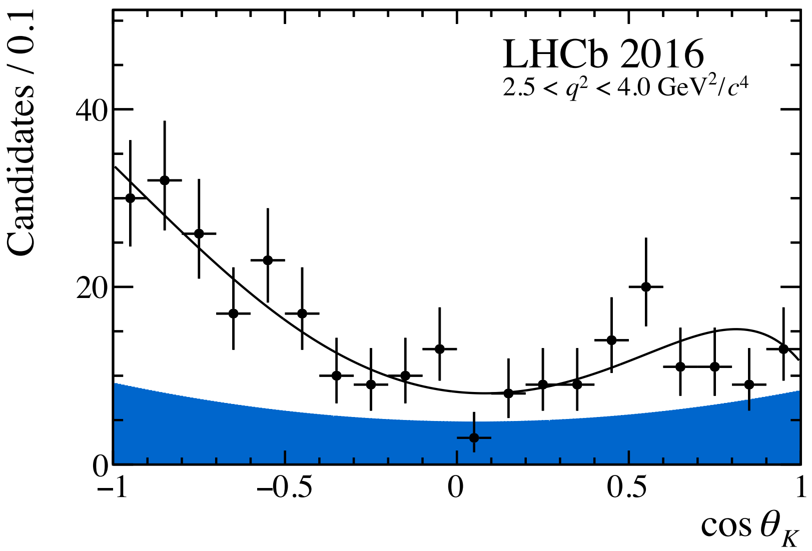


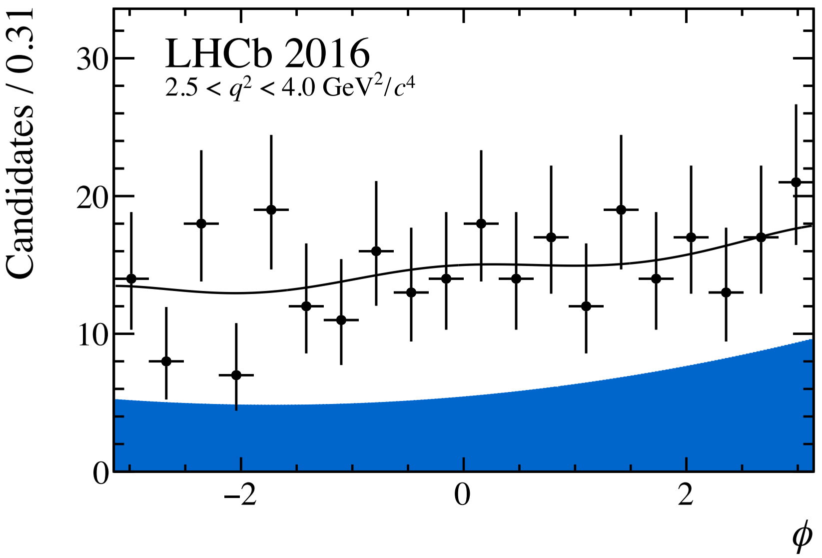


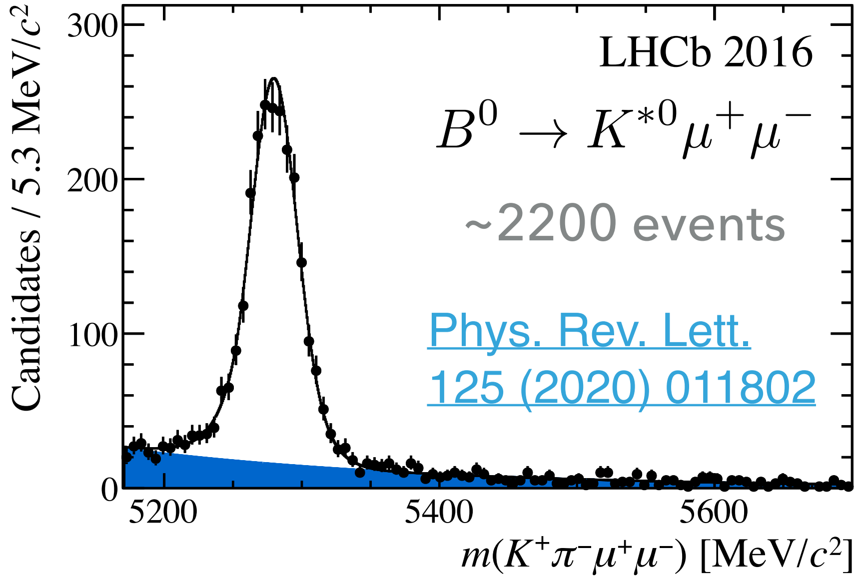


~700 events

Phys. Rev. Lett. 126 (2021) 161802



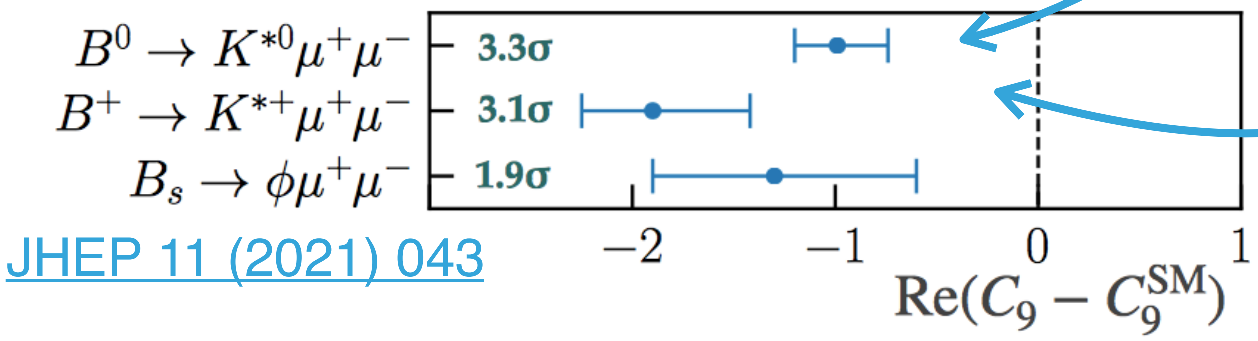




~2200 events

Phys. Rev. Lett. 125 (2020) 011802

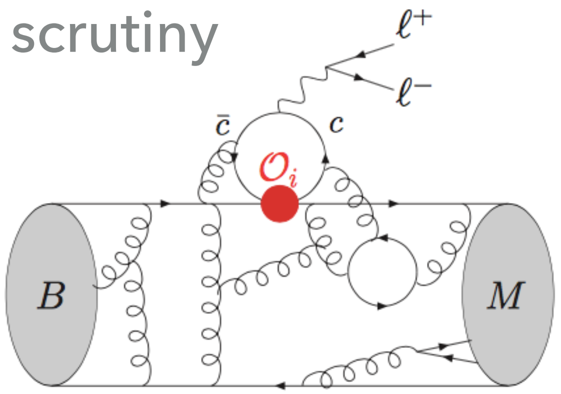
- SM prediction challenging, but uncertainties smaller than for BFs
- Optimised observables where hadronic uncertainties cancel out at 1st order (e.g. P5′)
- A growing number of global fits to $b \to s\ell\ell$ results (and others)
  - Algueró et al: arXiv:2104.08921
  - Altmannshofer et al: arXiv:2103.13370
  - Ciucchini et al: arXiv:1903.09632
  - Geng et al arXiv:2103.12738
  - Hurth et al: arXiv:2104.10058
  - Kowalska et al: arXiv:1903.10932
  - …
- Global tension with SM:

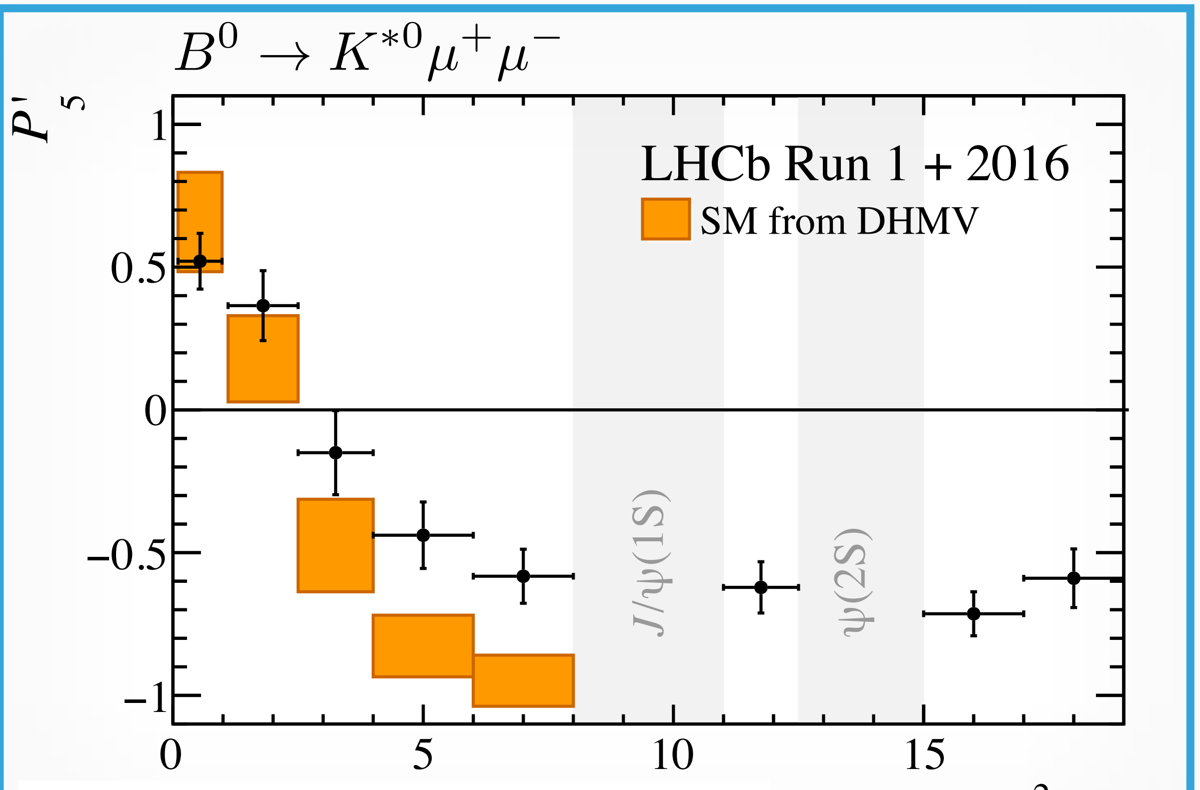


JHEP 11 (2021) 043

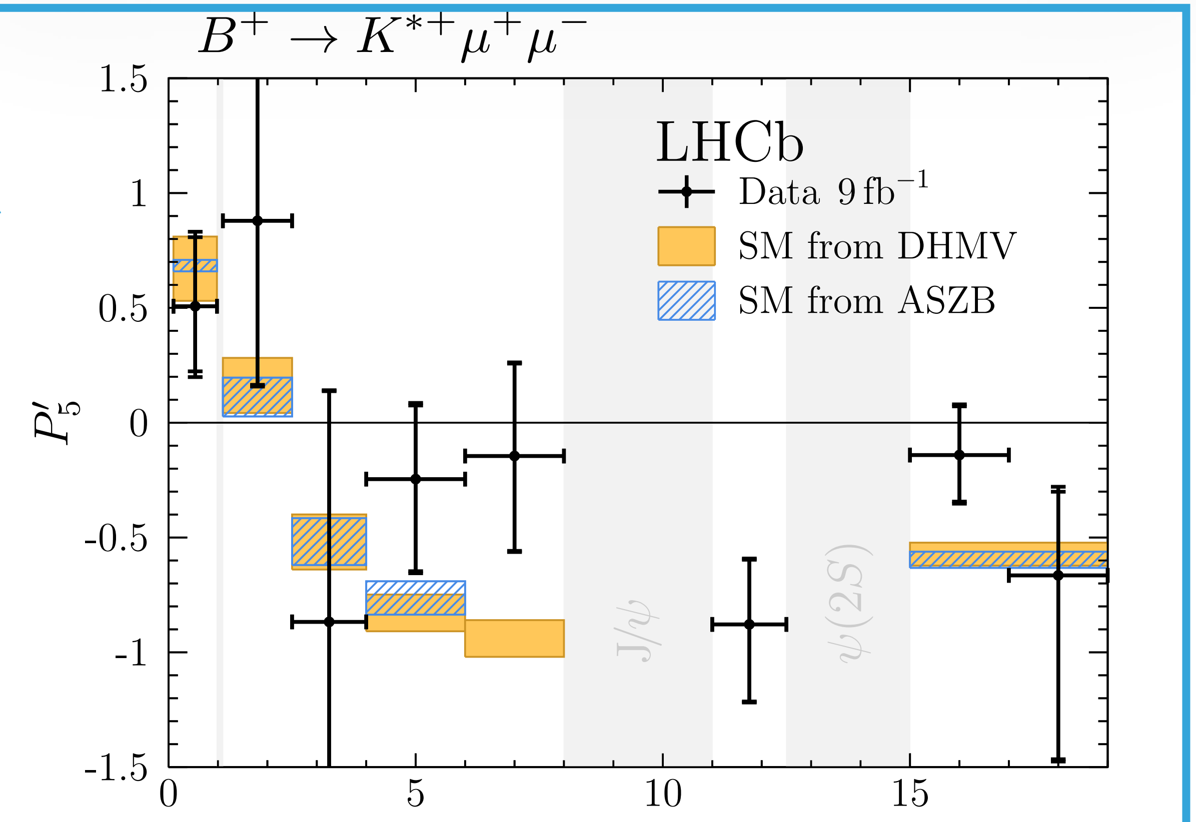
- Theory uncertainty under scrutiny

Charm resonances could have an **undesired impact** on measurements and precision of SM predictions





Phys. Rev. Lett. 125 (2020) 011802



Phys. Rev. Lett.126 (2021) 161802

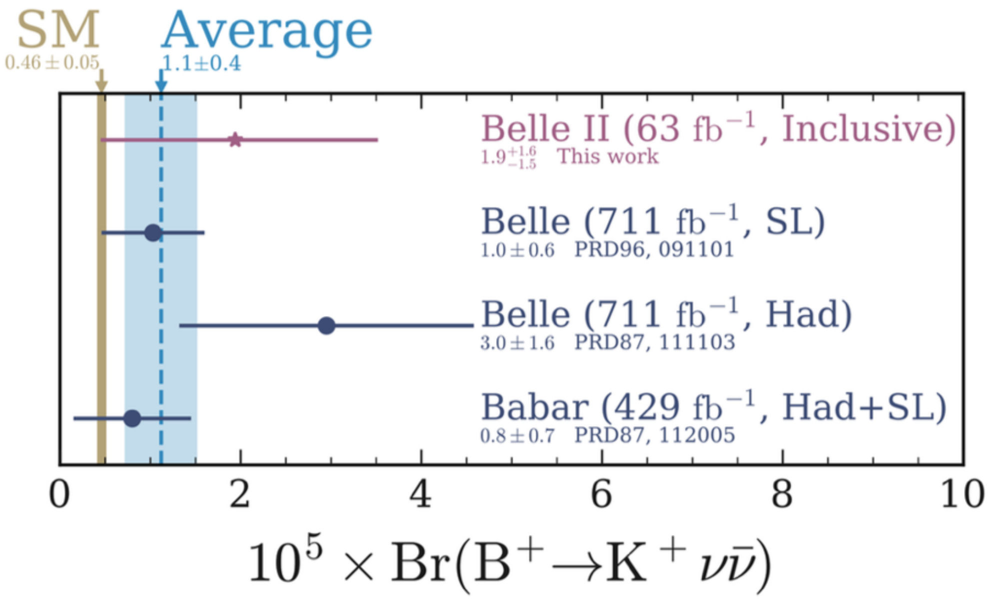
$B^+ \to K^+\nu\bar{\nu}$ @ Belle II

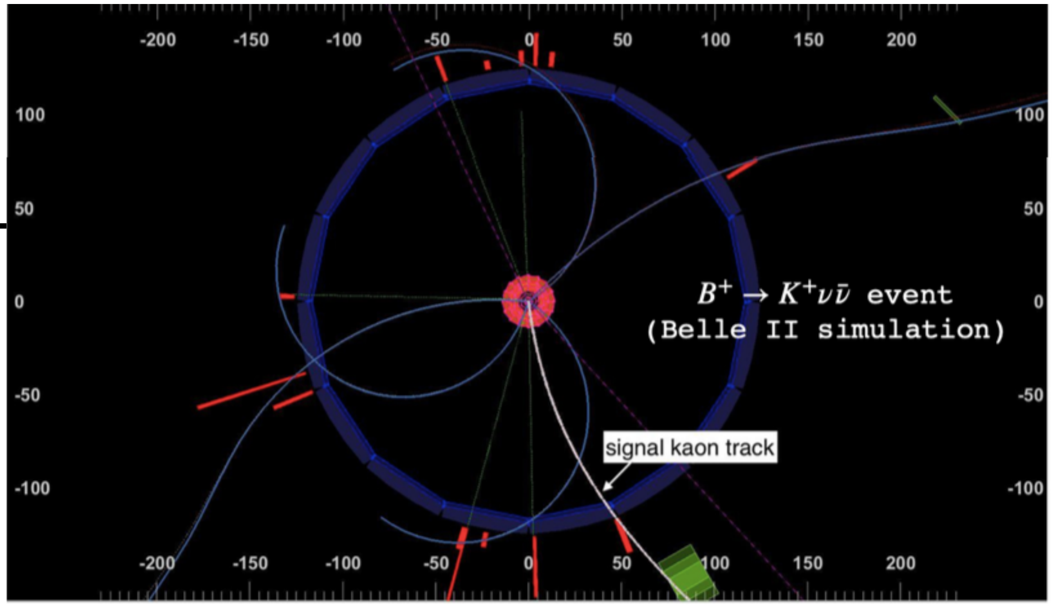
- $b \to s\nu\bar{\nu}$ complementary probe, **free** of charm resonances

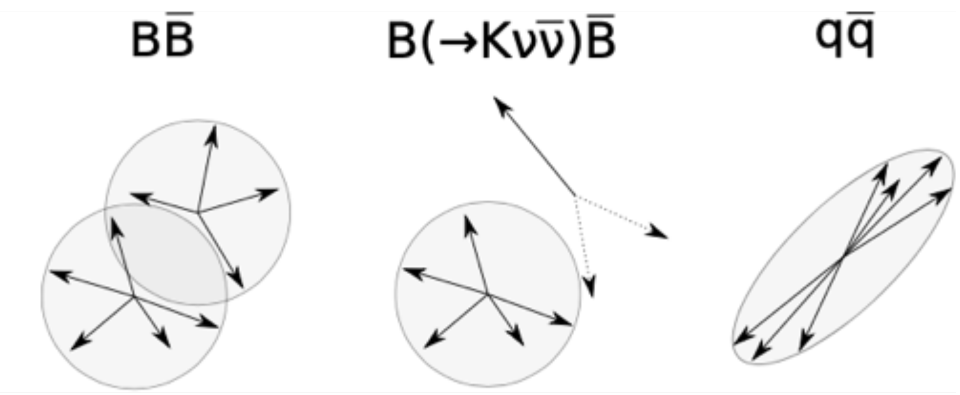
- Implausible measurement for LHCb: e.g. single charged Kaon in final state, nothing else

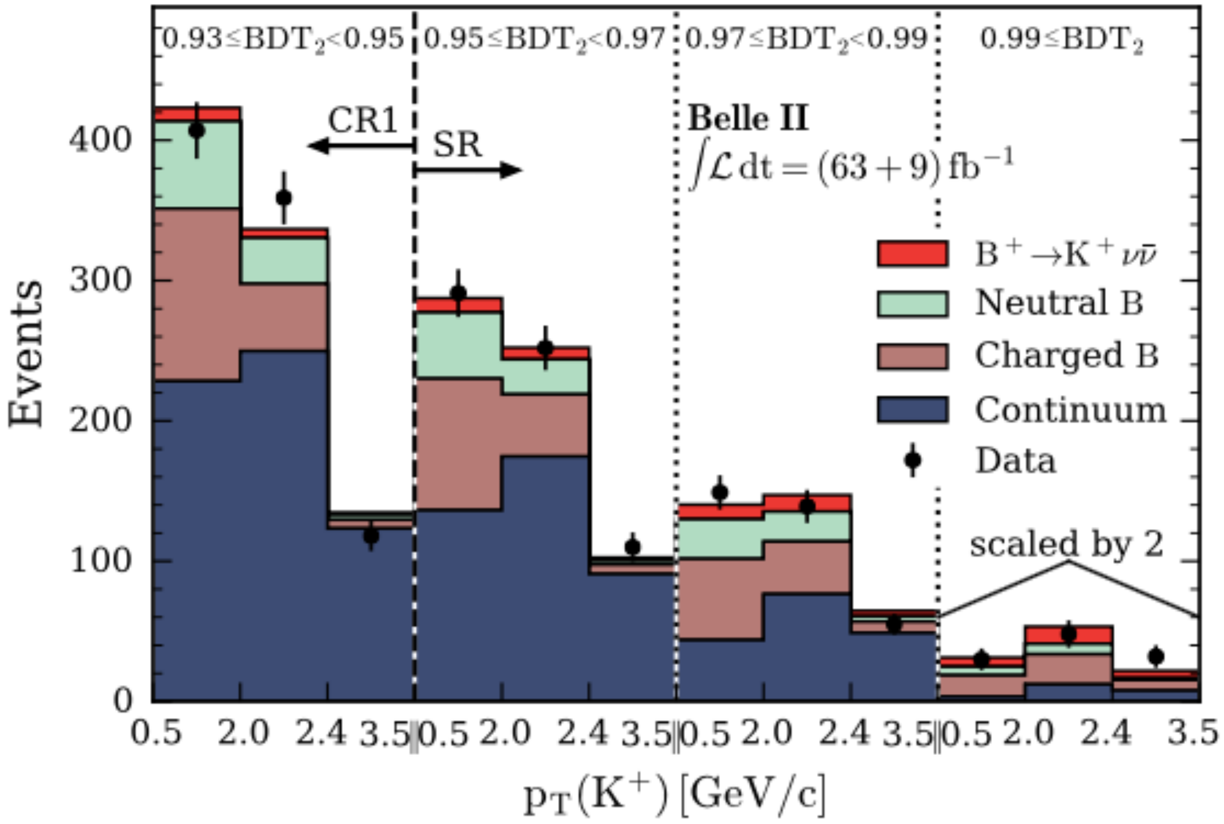
  Feasible with **Belle II,** arXiv:2104.12624 building on **inclusive** tagging technique

- **Multivariate background** subtraction essential, already competitive with **63/fb**





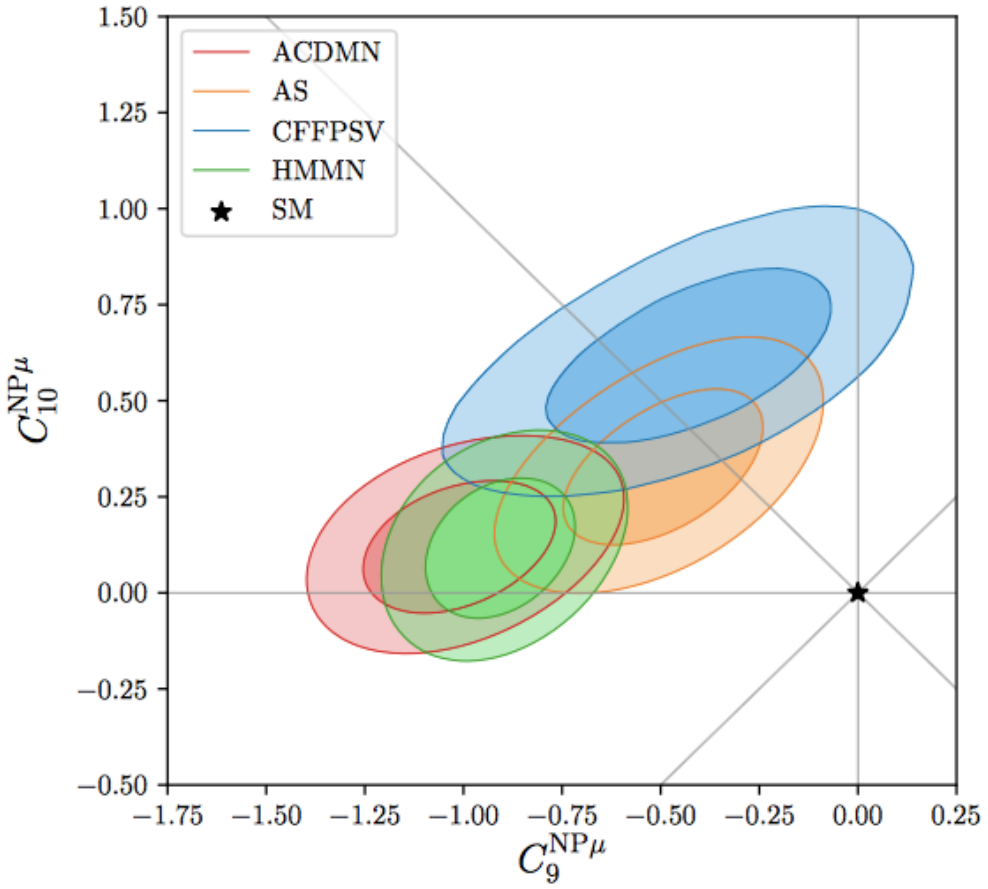




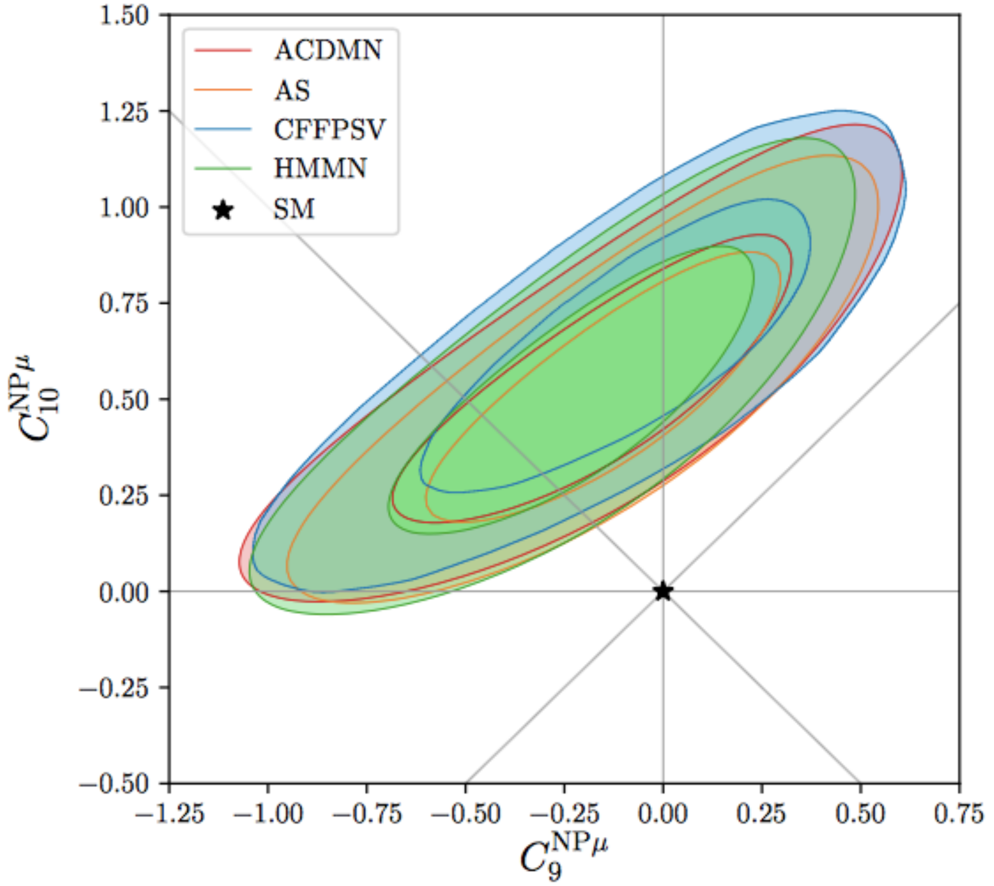
Global New Physics Fits

with measurements
from ATLAS & CMS(!)

- Combine the information from so many observables and channels fitting the EFT coefficients [B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl, Flavour Anomany Workshop '21]



Global fit



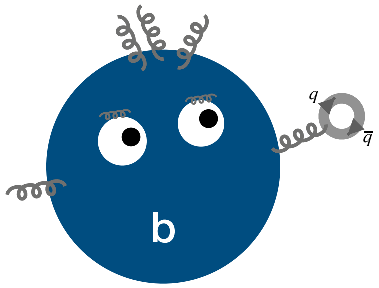
LFU ratios & $B_s \to \mu\mu$ only

- Attempt to have a best estimate of combined global significance to SM fitting all WC together: 4.3 σ tension with SM [arXiv:2104.05631] with only clean observables

Summary & Outlook

Summary & Conclusions

Semileptonic and **rare decays** offer excellent probes to search for new physics



Measurements of **semileptonic** decays with τ make use of **SM nature** of **process** in extraction $(q^2, m^2_{\text{miss}}, p_\ell)$, i.e. not straightforward to make interpretations of enhancements

Measurements of **rare decays** have no missing particles, clean extraction possible. Experimental challenges are **identification** (LHCb) and **small BF** $\sim 10^{-6}$ (Belle II)

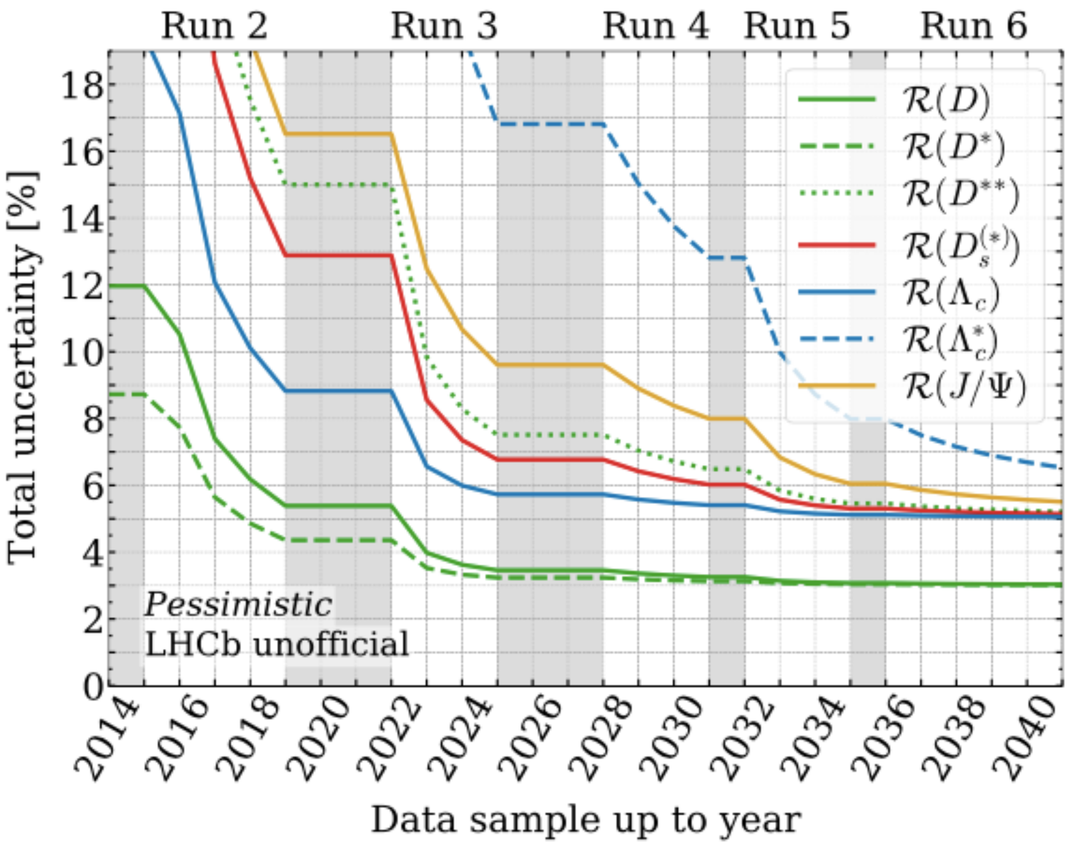
Hint of **Lepton Flavor Universality violation** in combinations $\sim \mathbf{3 - 4}\sigma$

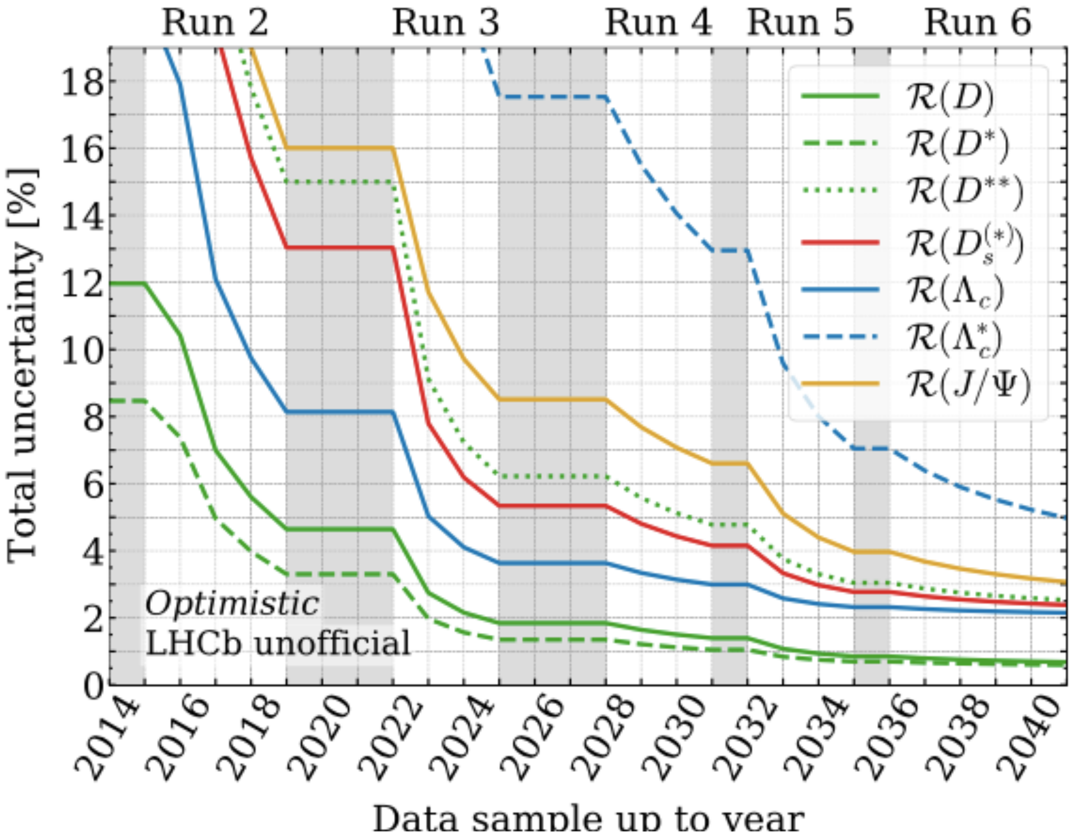
Looking forward to **new experimental** measurements:

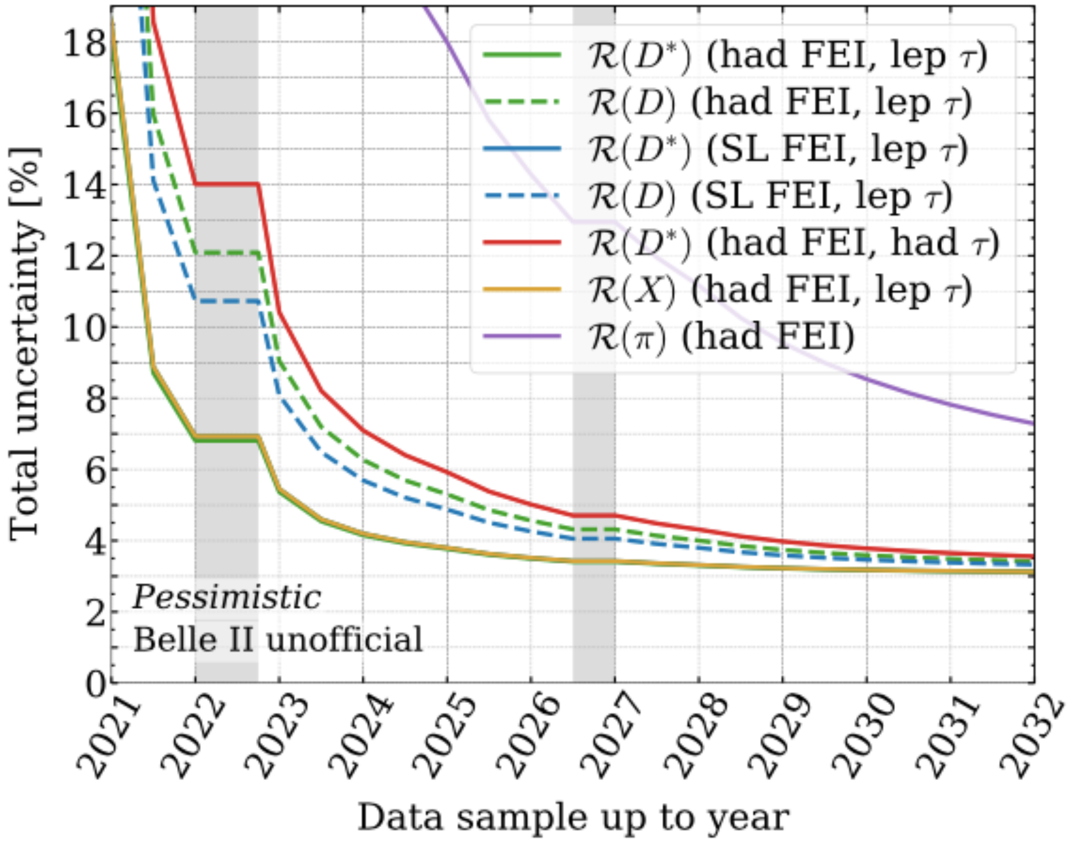
LHCb will record **unprecedented** n**umber of B mesons in Run 3, Belle II** is **ramping** up and both have a very complementary physics program and both **will shed light on this.**

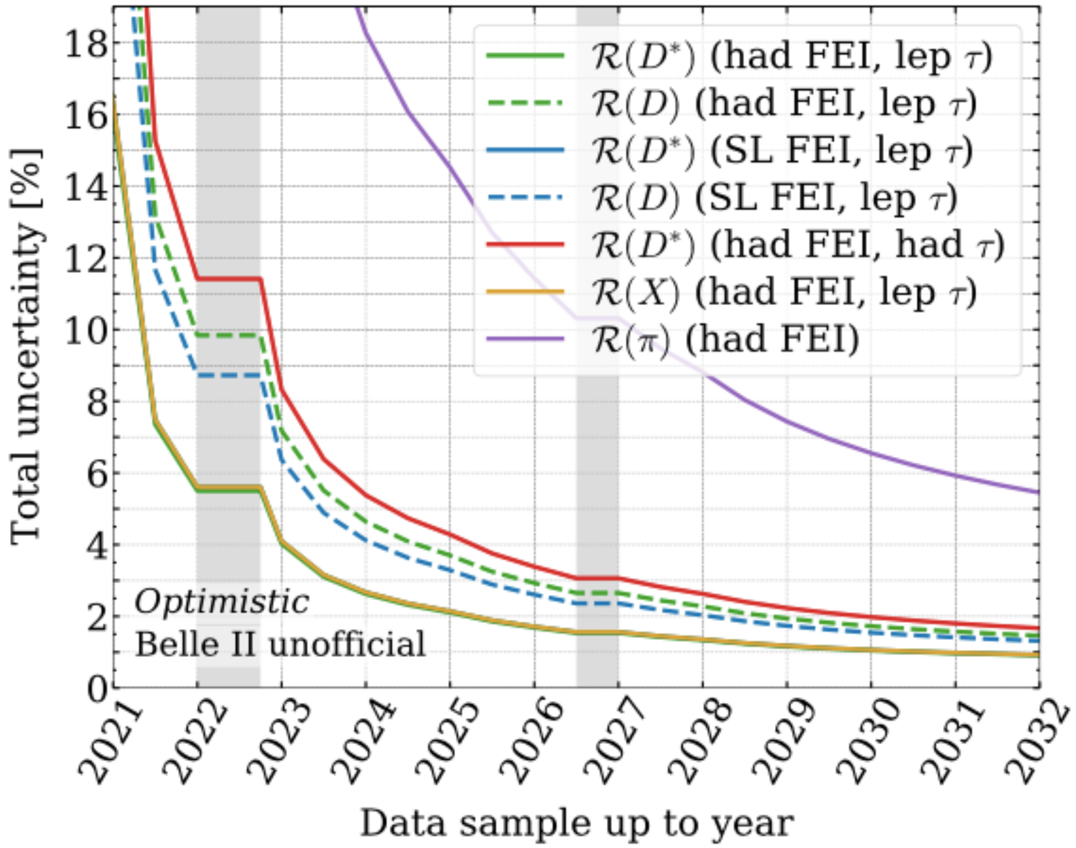
Backup

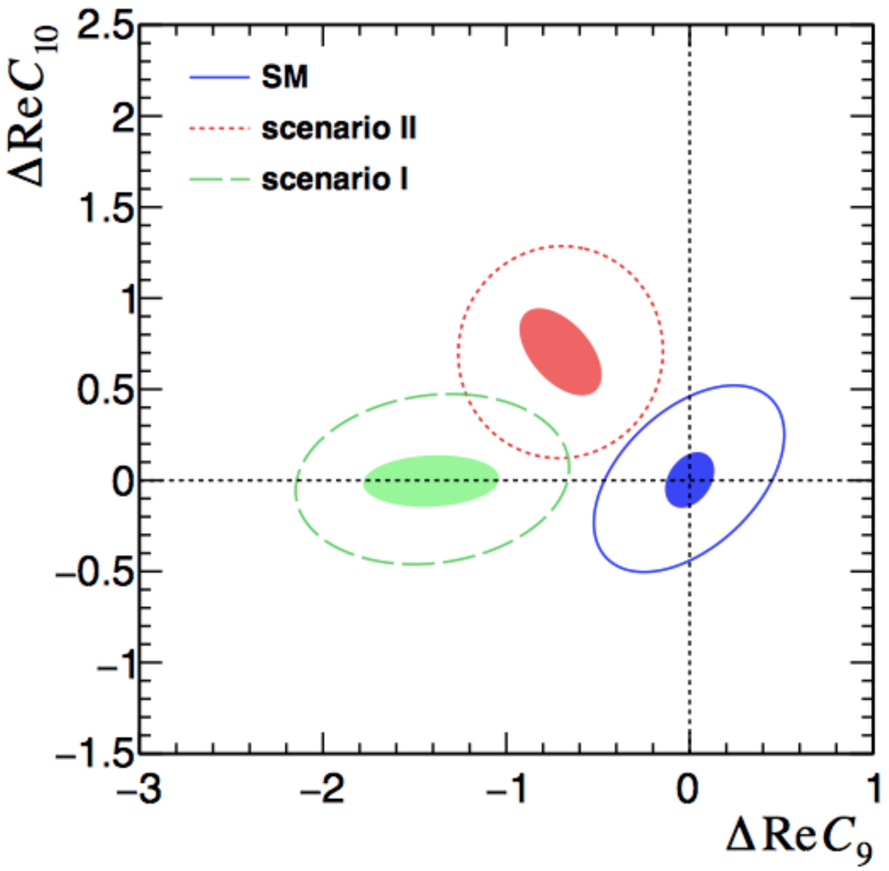
FB, M. Sevilla, D. Robinson, G. Wormser
[Rev. Mod. Phys. **94**, 015003,arXiv:2101.08326]



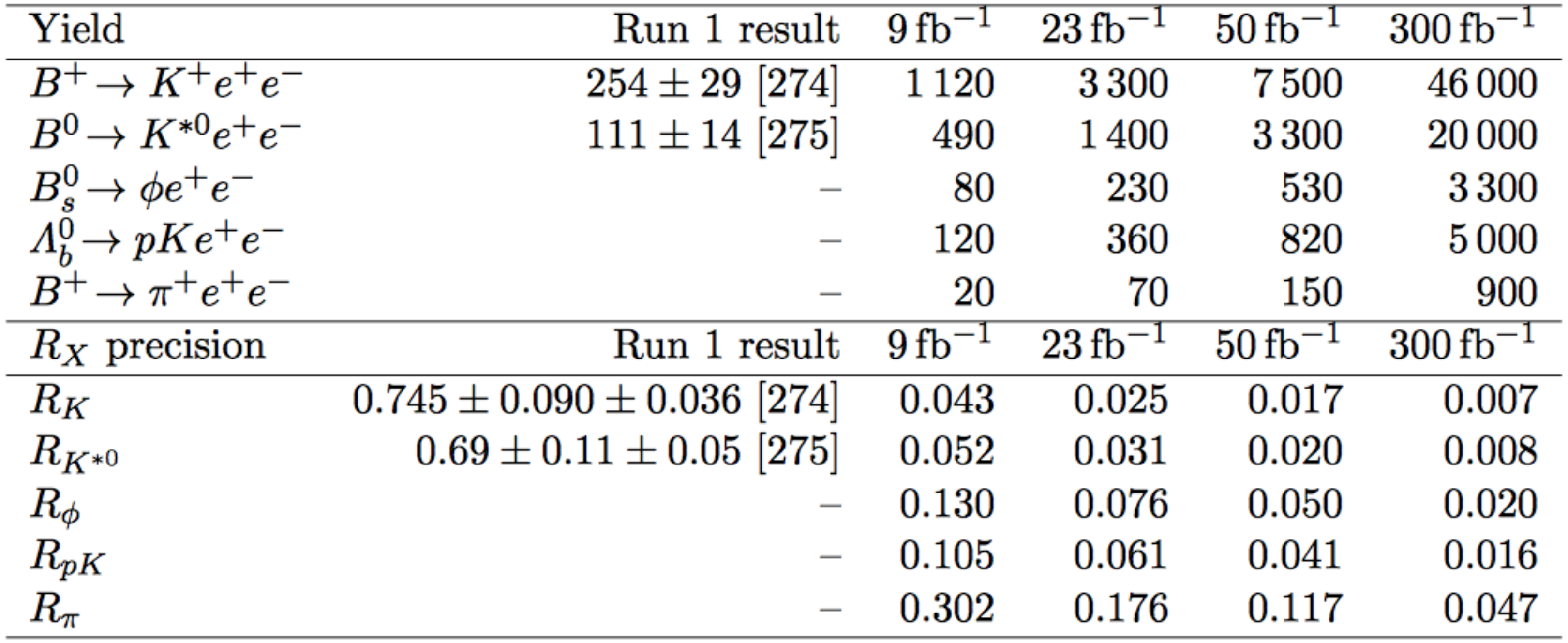




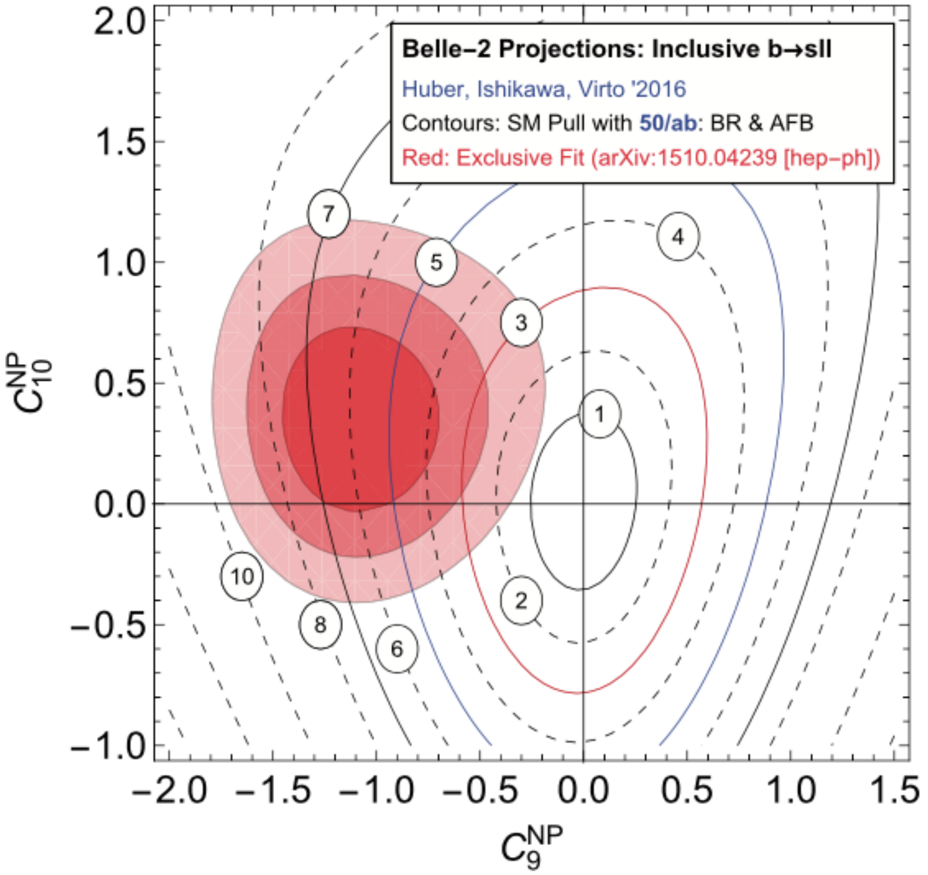




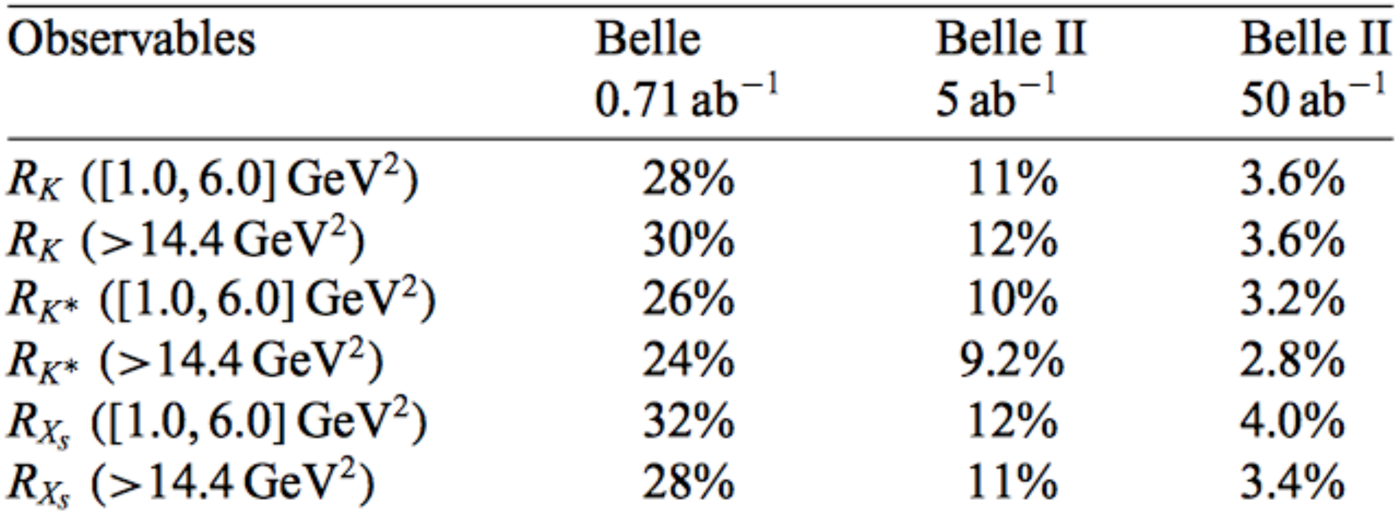
Physics case for an LHCb Upgrade II



Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+ e^+ e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0} e^+ e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+ e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pK e^+ e^-$	–	120	360	820	5 000
$B^+ \to \pi^+ e^+ e^-$	–	20	70	150	900
R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	0.745 ± 0.090 ± 0.036 [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.69 ± 0.11 ± 0.05 [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047



The Belle II physics book

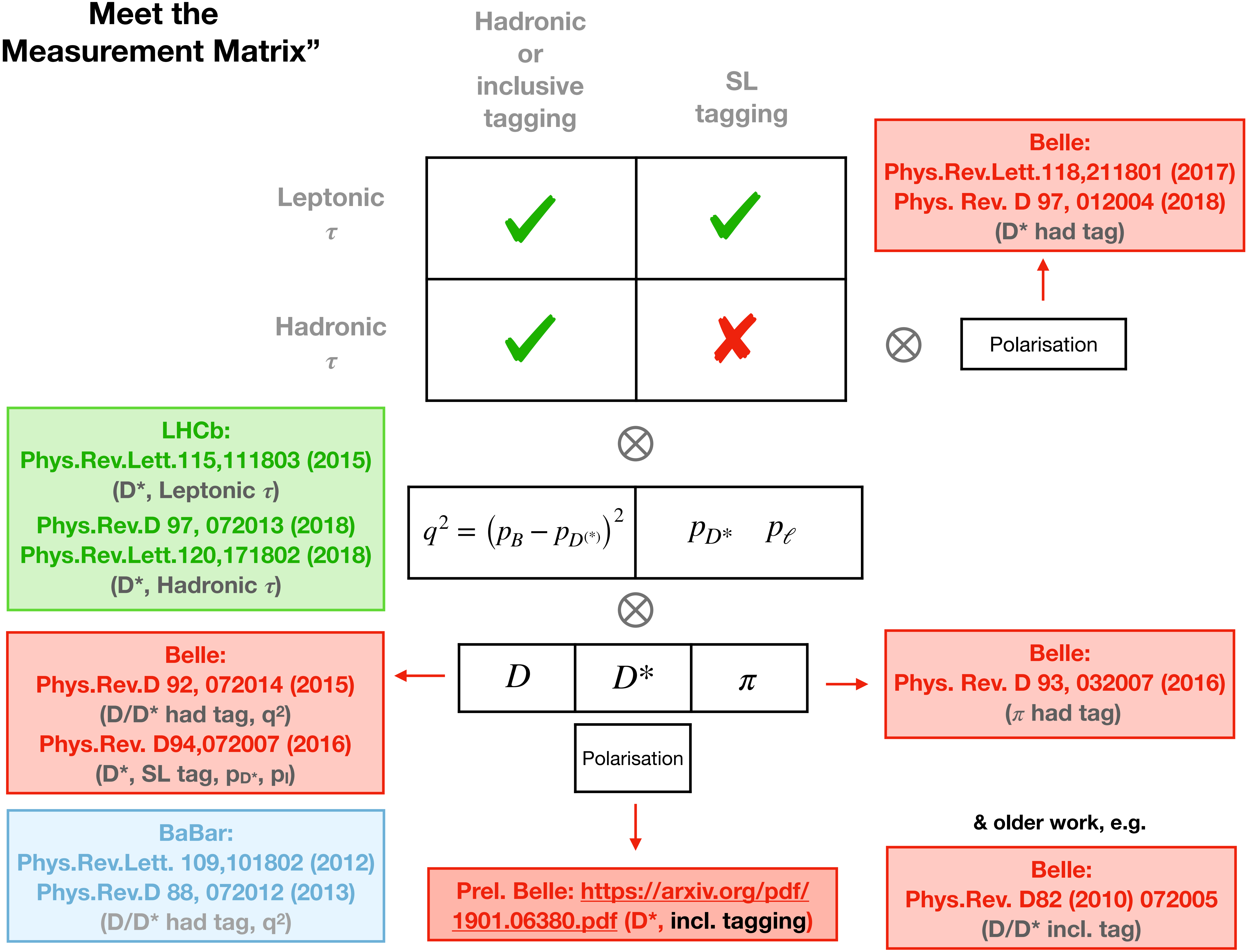


Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (>14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (>14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (>14.4 GeV^2)	28%	11%	3.4%

Table 5: Expected errors on several selected observables in radiative and electroweak penguin B decays. Note that 50 ab^{-1} projections for B_s decays are not provided as we do not expect to collect such a large $\Upsilon(5S)$ data set.

Observables	Belle	Belle II	
	(2017)	5 ab^{-1}	50 ab^{-1}
$\mathcal{B}(B \to K^{*+} \nu\overline{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^{+} \nu\overline{\nu})$	$< 19 \times 10^{-6}$	30%	11%

Meet the “Measurement Matrix”



	Hadronic or inclusive tagging	SL tagging
Leptonic τ	✓	✓
Hadronic τ	✓	✗

$\otimes$ Polarisation

$\otimes$

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

$\otimes$

D	D^*	π

Polarisation

Belle:
Phys.Rev.Lett.118,211801 (2017)
Phys. Rev. D 97, 012004 (2018)
(D* had tag)

LHCb:
Phys.Rev.Lett.115,111803 (2015)
(D*, Leptonic τ)
Phys.Rev.D 97, 072013 (2018)
Phys.Rev.Lett.120,171802 (2018)
(D*, Hadronic τ)

Belle:
Phys.Rev.D 92, 072014 (2015)
(D/D* had tag, q^2)
Phys.Rev. D94,072007 (2016)
(D*, SL tag, p_{D^*}, p_l)

Belle:
Phys. Rev. D 93, 032007 (2016)
(π had tag)

BaBar:
Phys.Rev.Lett. 109,101802 (2012)
Phys.Rev.D 88, 072012 (2013)
(D/D* had tag, q^2)

Prel. Belle: https://arxiv.org/pdf/1901.06380.pdf (D*, incl. tagging)

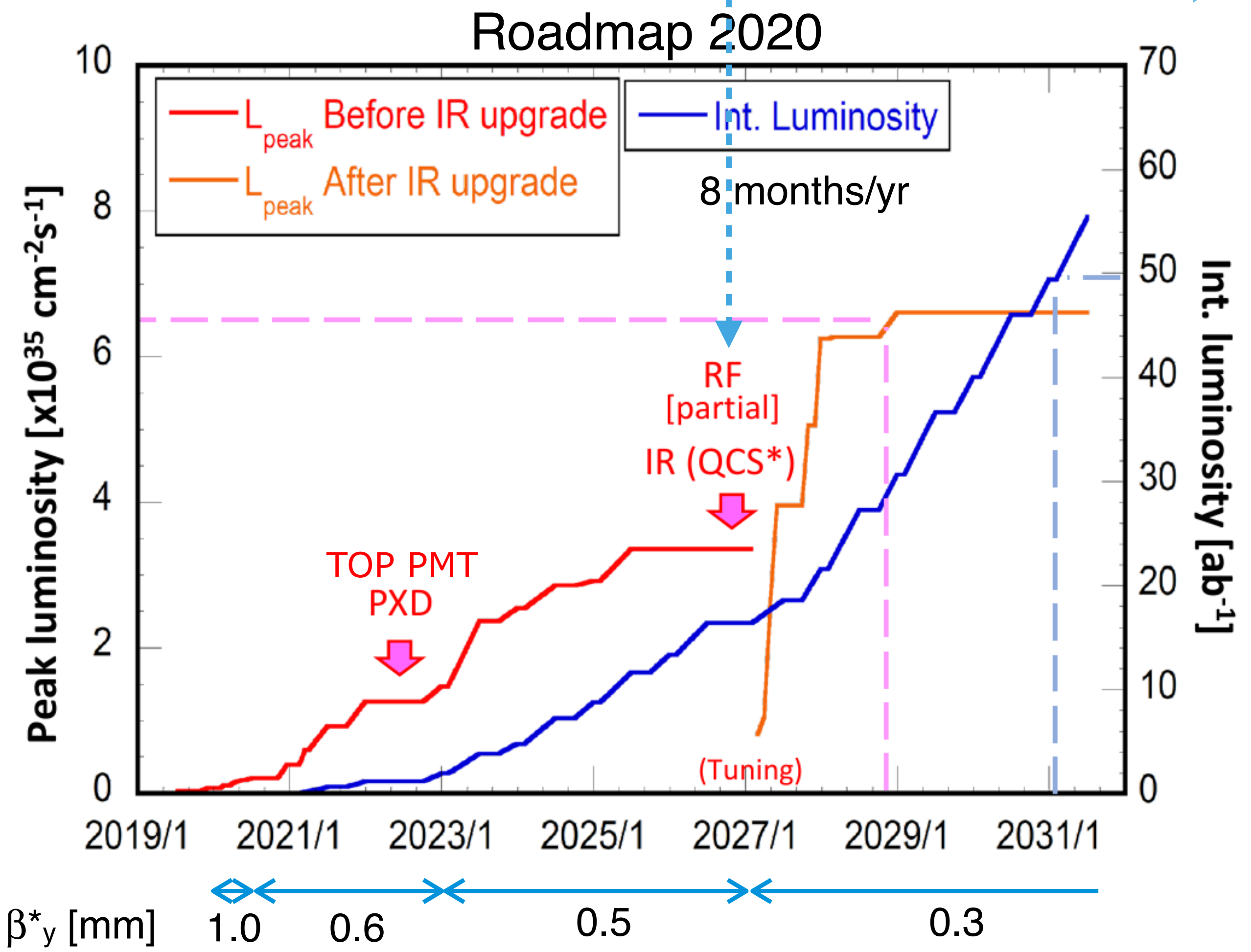
& older work, e.g.

Belle:
Phys.Rev. D82 (2010) 072005
(D/D* incl. tag)

Opportunity for detector upgrade in 2026
- increase resilience against background
- improve performance

Goal: prepare LoI's by end of 2020

Polarization and/or luminosity upgrades?



Run 1		**LS1**		Run 2				**LS2**			Run 3			**LS3**			Run 4			**LS4**	Run 5			**LS5**	Run 6		
2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	
1.1	**2.0**	-	-	**0.3**	**1.7**	**1.7**	**2.2**	-	-	-	**8.3**	**8.3**	**8.3**	-	-	-	**8.3**	**8.3**	**8.3**	-	**50**	**50**	**50**	-	**50**	**50**	**fb^{-1}**

Limiting Systematics

				Systematic uncertainty [%]					**Total uncert. [%]**		
Result	Experiment	τ decay	Tag	MC stats	$D^{(*)}l\nu$	$D^{**}l\nu$	Other bkg.	Other sources	**Syst.**	**Stat.**	**Total**
$\mathcal{R}(D)$	*BABAR* [a]	$\ell\nu\nu$	Had.	5.7	2.5	5.8	3.9	0.9	**9.6**	**13.1**	**16.2**
	Belle[b]	$\ell\nu\nu$	Semil.	4.4	0.7	0.8	1.7	3.4	**5.2**	**12.1**	**13.1**
	Belle[c]	$\ell\nu\nu$	Had.	4.4	3.3	4.4	0.7	0.5	**7.1**	**17.1**	**18.5**
$\mathcal{R}(D^*)$	*BABAR* [a]	$\ell\nu\nu$	Had.	2.8	1.0	3.7	2.3	0.9	**5.6**	**7.1**	**9.0**
	Belle[b]	$\ell\nu\nu$	Semil.	2.3	0.3	1.4	0.5	4.7	**4.9**	**6.4**	**8.1**
	Belle[c]	$\ell\nu\nu$	Had.	3.6	1.3	3.4	0.7	0.5	**5.2**	**13.0**	**14.0**
	Belle[d]	$\pi\nu$, $\rho\nu$	Had.	3.5	2.3	2.4	8.1	2.9	**9.9**	**13.0**	**16.3**
	LHCb[e]	$\pi\pi\pi(\pi^0)\nu$	—	4.9	4.0	2.7	5.4	4.8	**10.2**	**6.5**	**12.0**
	LHCb[f]	$\mu\nu\nu$	—	6.3	2.2	2.1	5.1	2.0	**8.9**	**8.0**	**12.0**

Latest $R(D^{(*)})$ from Belle: *Systematics*

Result	Contribution	Uncertainty [%]	
		Sys.	Stat.
$\mathcal{R}(D)$	$B \to D^{**}\ell\bar{\nu}_\ell$	0.8	
	PDF modeling	4.4	
	Other bkg.	2.0	
	$\epsilon_{\text{sig}}/\epsilon_{\text{norm}}$	1.9	
	Total systematic	**5.2**	
	Total statistical		**12.1**
	Total	**13.1**	
$\mathcal{R}(D^*)$	$B \to D^{**}\ell\bar{\nu}_\ell$	1.4	
	PDF modeling	2.3	
	Other bkg.	1.4	
	$\epsilon_{\text{sig}}/\epsilon_{\text{norm}}$	4.1	
	Total systematic	**4.9**	
	Total statistical		**6.4**
	Total	**8.1**	

LHCb Measurement of $R(D^*)$: *Systematics*

Contribution	Uncertainty [%]		
	Sys.	Ext.	Stat.
Double-charm bkg.	5.4		
Simulated sample size	4.9		
Corrections to simulation	3.0		
$B \to D^{**} l\nu$ bkg.	2.7		
Normalization yield	2.2		
Trigger	1.6		
PID	1.3		
Signal FFs	1.2		
Combinatorial bkg.	0.7		
Modeling of τ decay	0.4		
Total systematic	**9.1**		
$\mathcal{B}(B \to D^* \pi\pi\pi)$		3.9	
$\mathcal{B}(B \to D^* \ell\nu)$		2.3	
$\mathcal{B}(\tau^+ \to 3\pi\nu)/\mathcal{B}(\tau^+ \to 3\pi\pi^0\nu)$		0.7	
Total external		**4.6**	
Total statistical			**6.5**
Total		**12.0**	

LHCb Measurement of $R(D^*)$

- Actually measure BF relative to **$B^0 \to D^*\pi^+\pi^+\pi^-$**

$$\boxed{K_{had}(D^*) = \frac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}} = \frac{N(B^0 \to D^{*-}\tau^+\nu_\tau)}{N(B^0 \to D^{*+}\pi^-\pi^+\pi^-)} \times \frac{1}{BR(\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau)} \times \frac{\varepsilon(B^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\varepsilon(B^0 \to D^{*-}\tau^+\nu_\tau)}$$

- Measured to about 4% precision

most precise measurement from BaBar: Phys. Rev. D94 (2016) 091101)

- Dedicated control samples for remaining backgrounds

$X_b \to D^{*-}D_s^+X$ ⟶ Use **$D_s^+ \to 3\pi$** and fit **$m(D^*D_s)$ to constrain individual contributions**

$X_b \to D^{*-}D^+X$ ⟶ Use **$D^+ \to K3\pi$** to correct q^2, but float in fit

- Extraction in **3D maximum likelihood fit** to MVA : q^2 : τ decay time

↑

Invariant masses of 3π system

Invariant mass of $D^*3\pi$ system

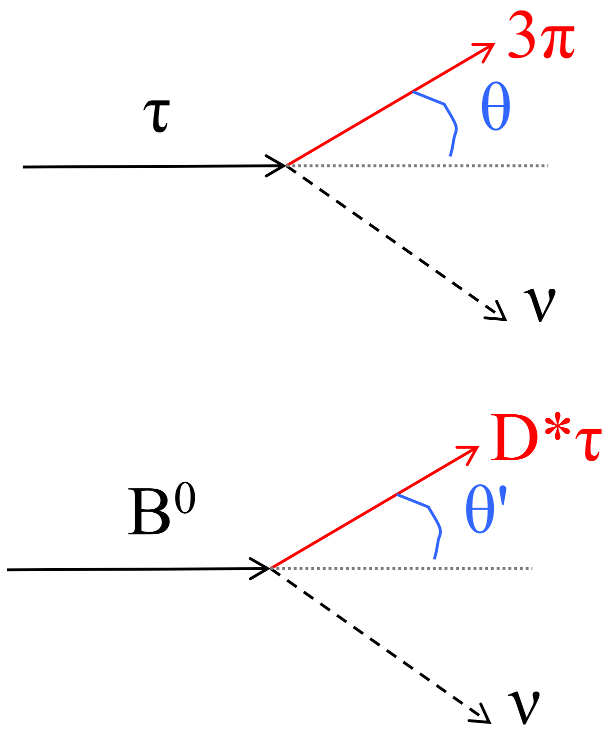
Neutral isolation variables

LHCb Measurement of $R(D^*)$: q^2

4-fold ambiguity:

$$|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\vec{p}_{3\pi}|\cos\theta \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2\sin^2\theta}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2\cos^2\theta)}$$

$$|\vec{p}_{B^0}| = \frac{(m_{D*\tau}^2 + m_{B^0}^2)|\vec{p}_{D*\tau}|\cos\theta' \pm E_{D*\tau}\sqrt{(m_{B^0}^2 - m_{D*\tau}^2)^2 - 4m_{B^0}^2|\vec{p}_{D*\tau}|^2\sin^2\theta'}}{2(E_{D*\tau}^2 - |\vec{p}_{D*\tau}|^2\cos^2\theta')}$$



Laboratory frame

Can be approximated by doing:

$$\theta_{max} = \arcsin\left(\frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau|\vec{p}_{3\pi}|}\right) \qquad \theta'_{max} = \arcsin\left(\frac{m_{B^0}^2 - m_{D*\tau}^2}{2m_{B^0}|\vec{p}_{D*\tau}|}\right)$$

Possible to reconstruct rest frame variables such as tau decay time and q^2.
These variables have **negligible biases**, and **sufficient resolution** to preserve good discrimination between signal and background.

Slide from C. Bozzi

LHCb Measurement of $R(D^*)$: *Control samples*

Use **exclusive $D_s \to 3\pi$** decays to select a $X_b \to D^{*-} D_s^+ X$ control sample

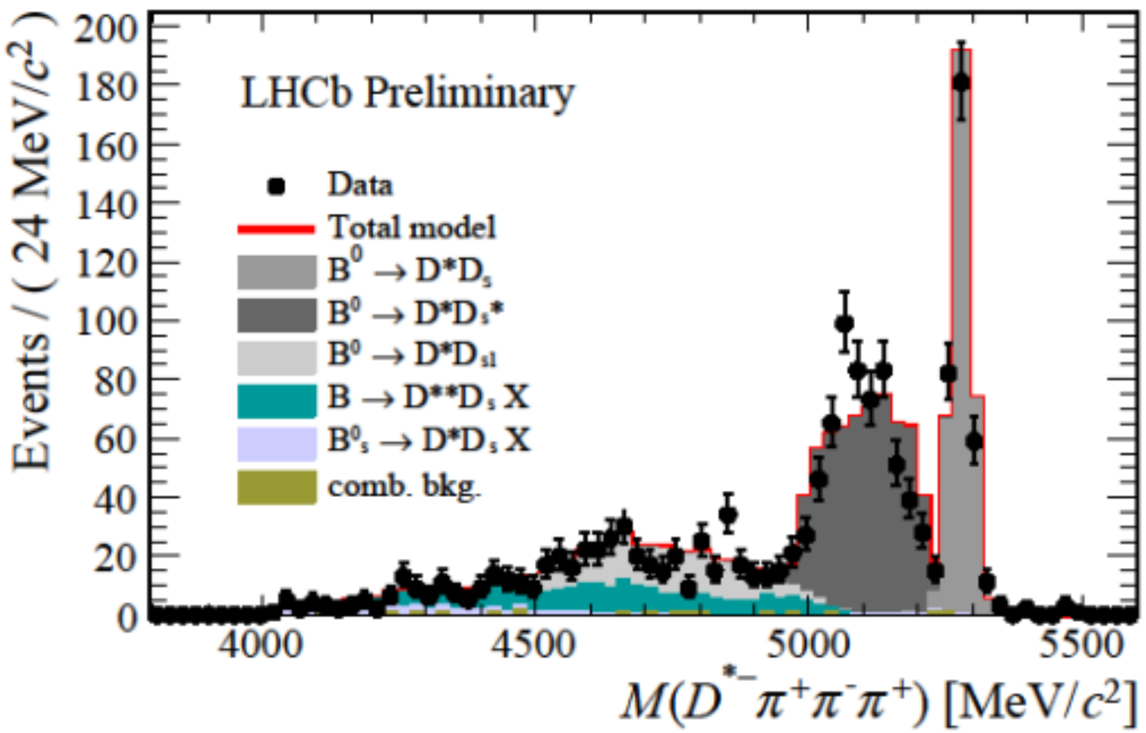
Determine the different $X_b \to D^{*-} D_s^+ X$ contributions from a fit to m(D*Ds):

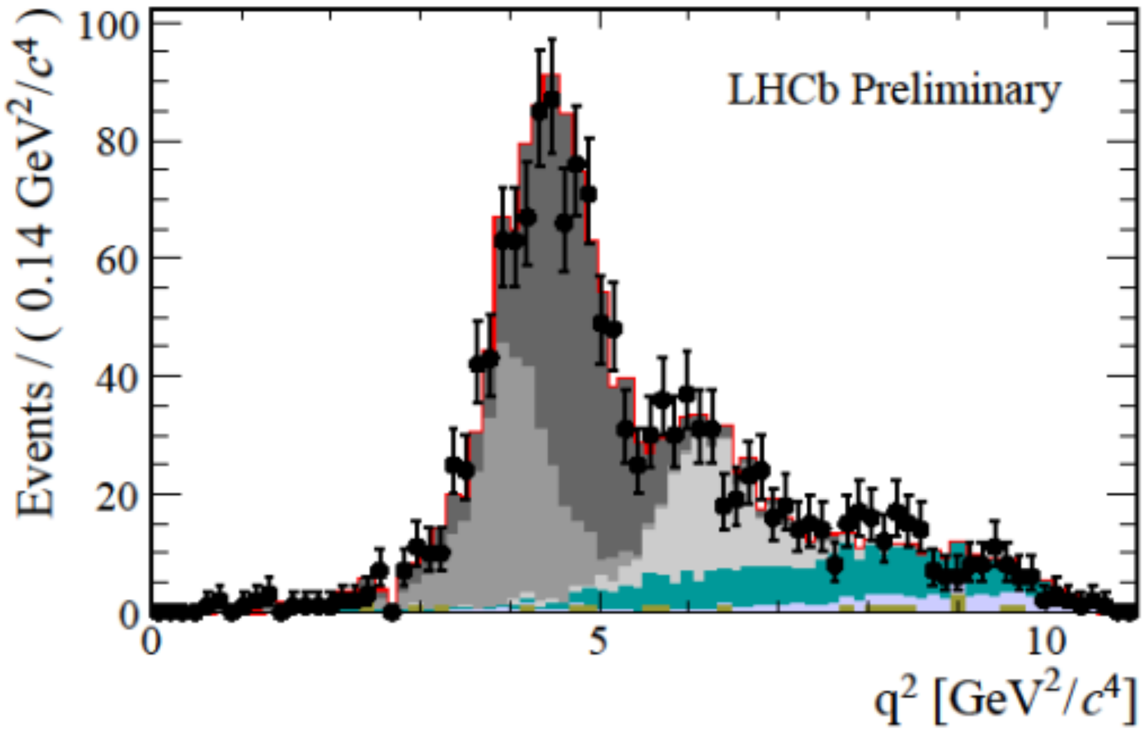
- $B^0 \to D^* D_s$, $B^0 \to D^* D_s^*$, $B^0 \to D^* D_{s0}^*$, $B^0 \to D^* D_{s1}'$, $B_s \to D^* D_s X$, $B \to D^{**} D_s X$

only 20% of D_s originates directly from B, 40% originates from Ds*, 40% from Ds**

- Uncertainties in the fit parameters propagated to final analysis.

LHCb-PAPER-2017-017





Slide from C. Bozzi

LHCb Measurement of $R(D^*)$: *Control samples*

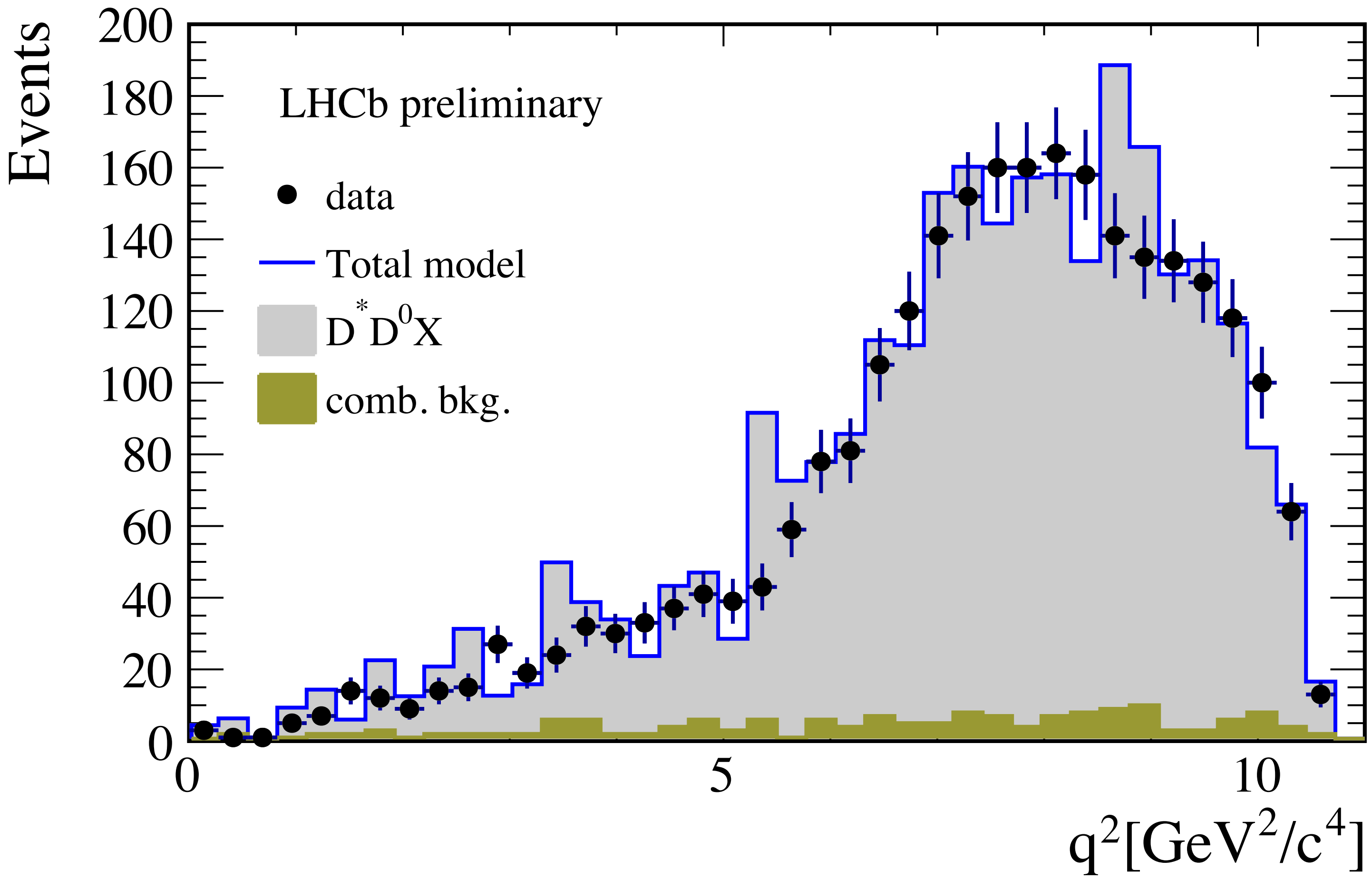
$X_b \rightarrow D^{*-} D^0 X$ decays can be isolated by selecting exclusive **$D^0 \rightarrow K^- 3\pi$** decays (kaon recovered using isolation tools).

A correction to the q^2 distributions is applied to the Monte Carlo to match data.

In contrast to the D_s^+ case, most 3π final states in D^+ and D° decays originate from $D^{+,0} \rightarrow K^{0,+} 3\pi$

For the D°, the inclusive 4 prongs BR constrains strongly the rate of 3π events

LHCb-PAPER-2017-017



Unfortunately, this constraint does not exist for the D^+ mesons, $K3\pi\pi°$ is poorly known, the inclusive BR is not measured

We let the D^+ component float in the fit

Slide from C. Bozzi

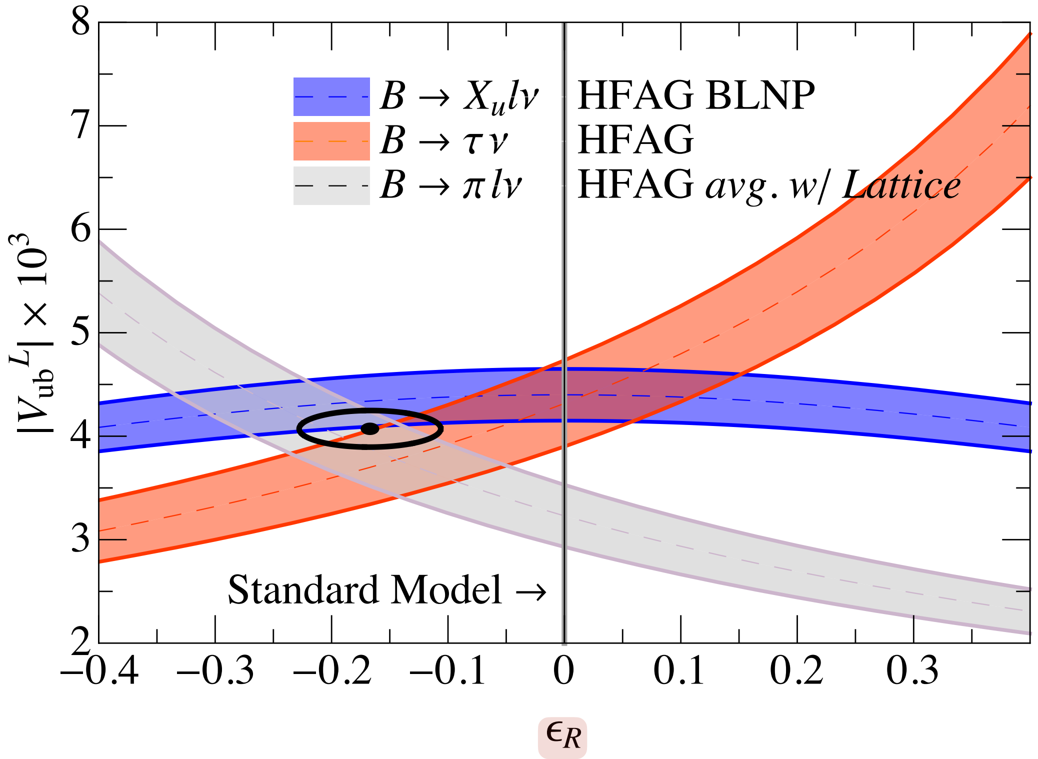
The two categories of measurements

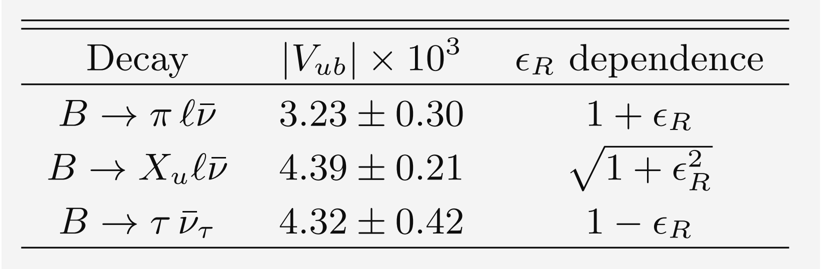
1st Category

Measurements that have **no** or **trivial** or **negligible** dependence on parameter of interest

Example: **Right-handed currents** & $|V_{ub}|$

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L \big(\bar{u} \gamma_\mu P_L b + \epsilon_R \, \bar{u} \gamma_\mu P_R b \big) \big(\bar{\nu} \gamma^\mu P_L \ell \big) + \text{h.c.},$$





Decay	$\lvert V_{ub}\rvert \times 10^3$	ϵ_R dependence
$B \to \pi\, \ell \bar{\nu}$	3.23 ± 0.30	$1 + \epsilon_R$
$B \to X_u \ell \bar{\nu}$	4.39 ± 0.21	$\sqrt{1+\epsilon_R^2}$
$B \to \tau\, \bar{\nu}_\tau$	4.32 ± 0.42	$1 - \epsilon_R$

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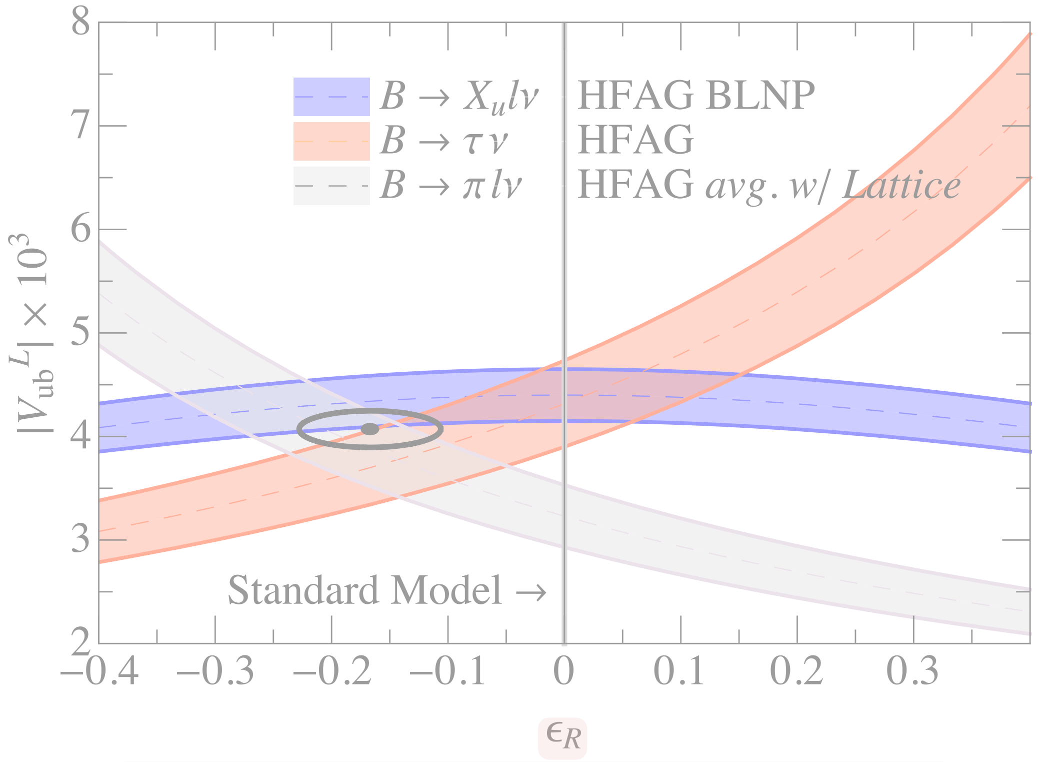

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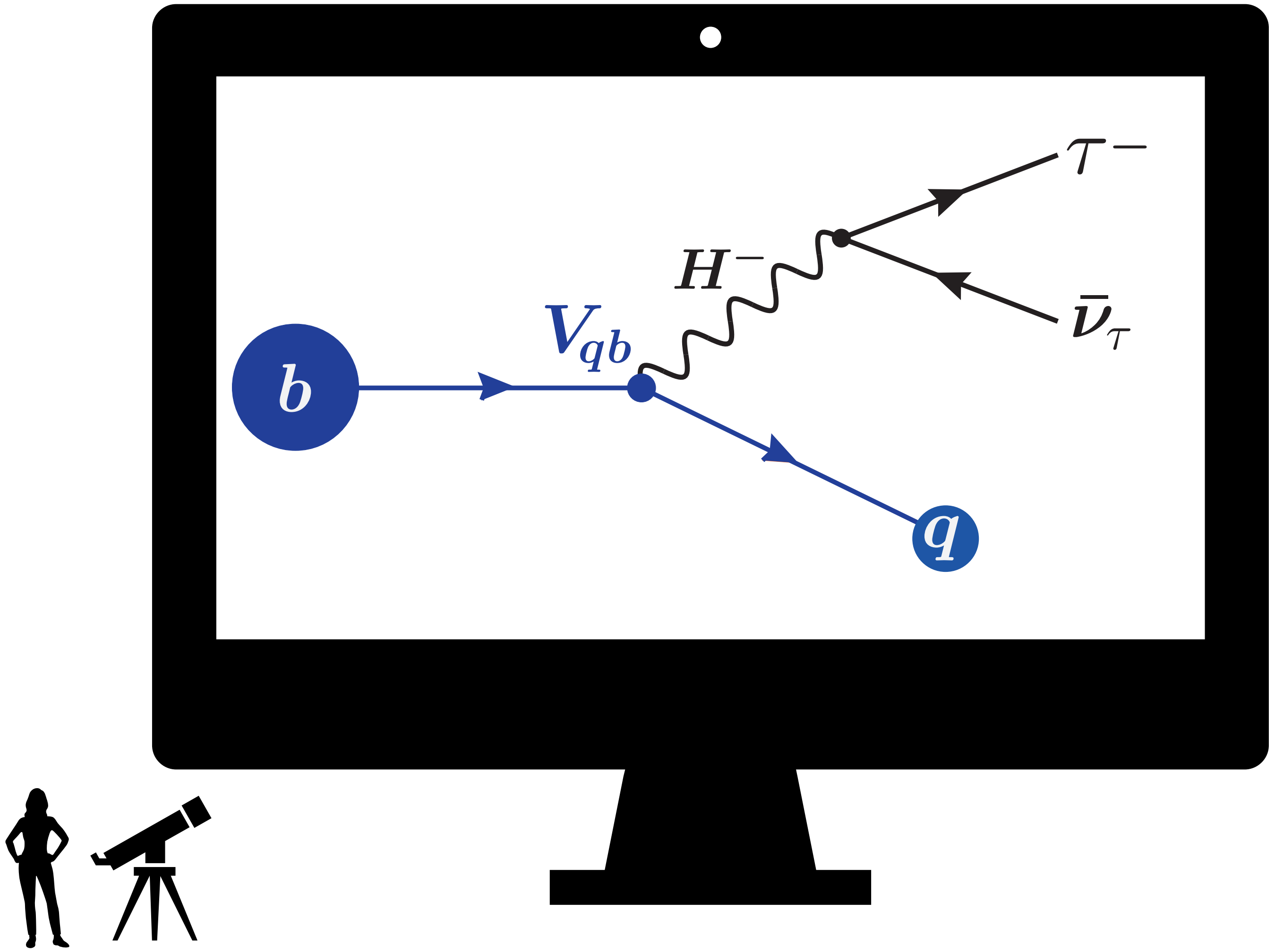
2nd Category

Measurements that have **non-trivial** dependence on parameter of interest / other params.



- Let's say you want to use the **measured** $R(D^{(*)})$ **ratios** to learn something about the anomaly and **your favorite model** that could explain it!

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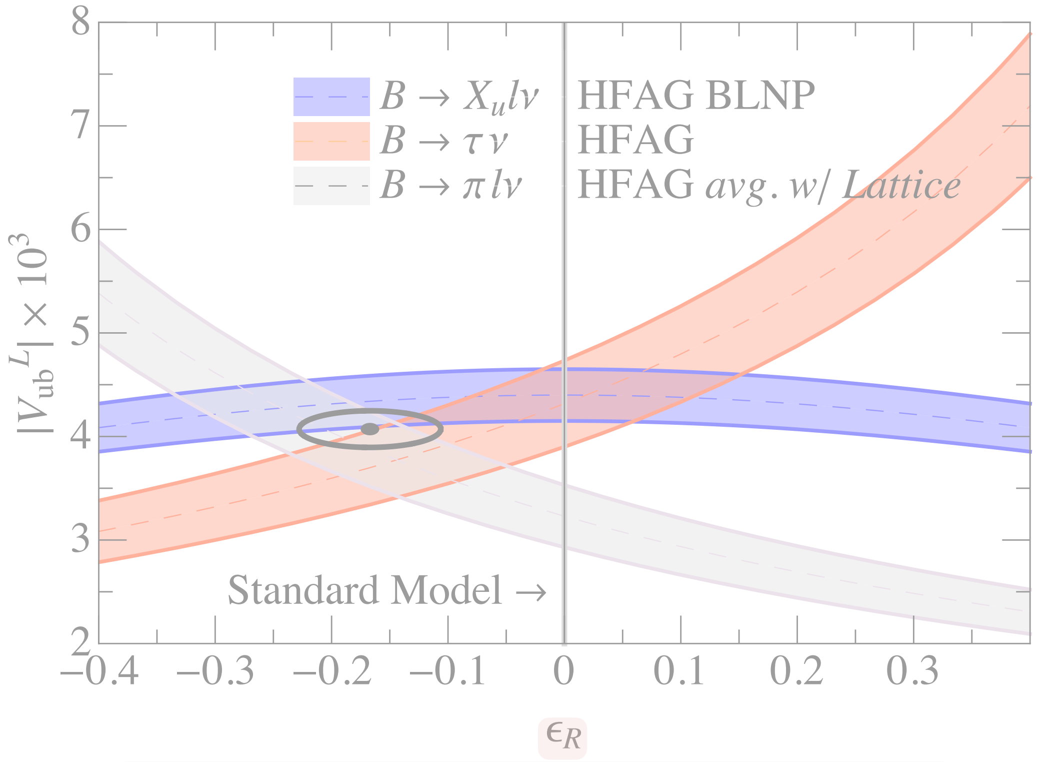

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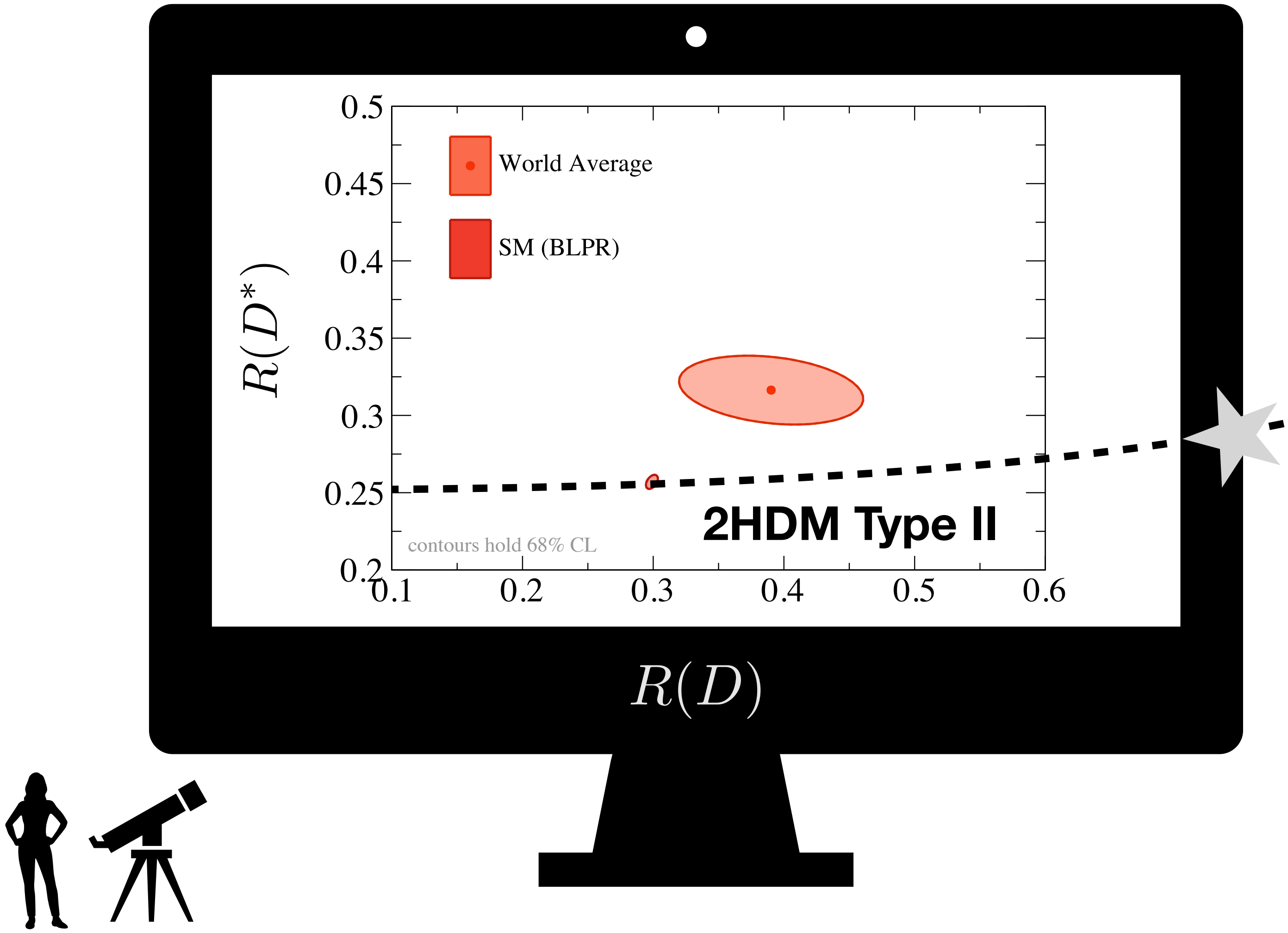

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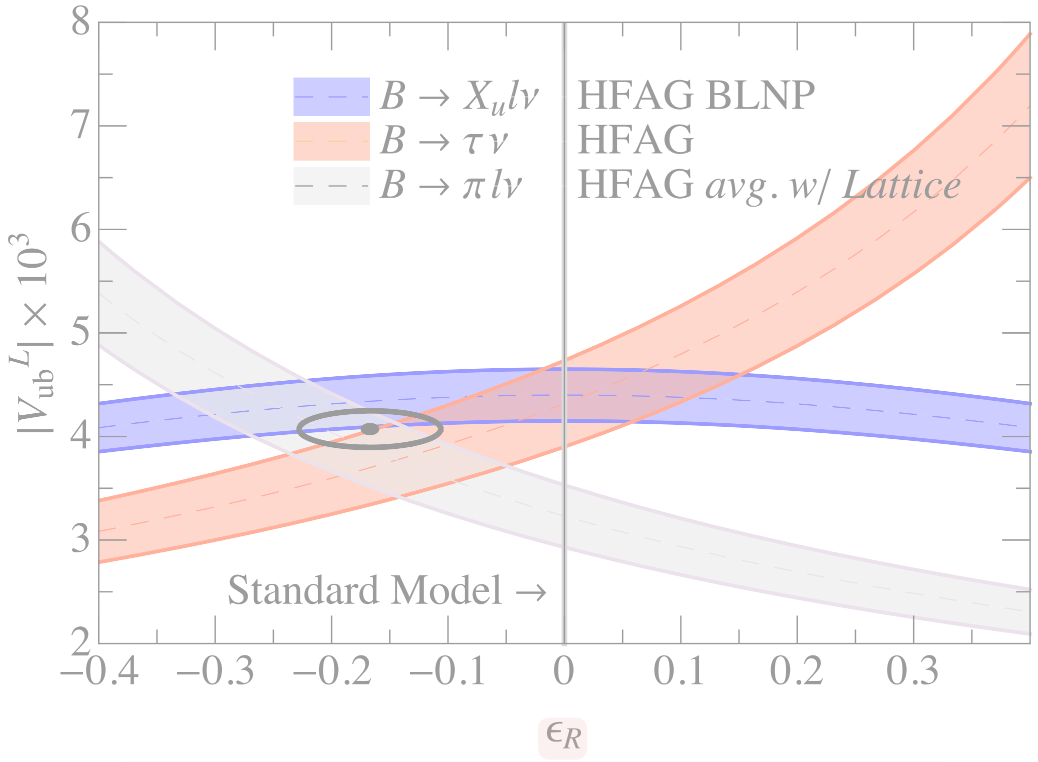

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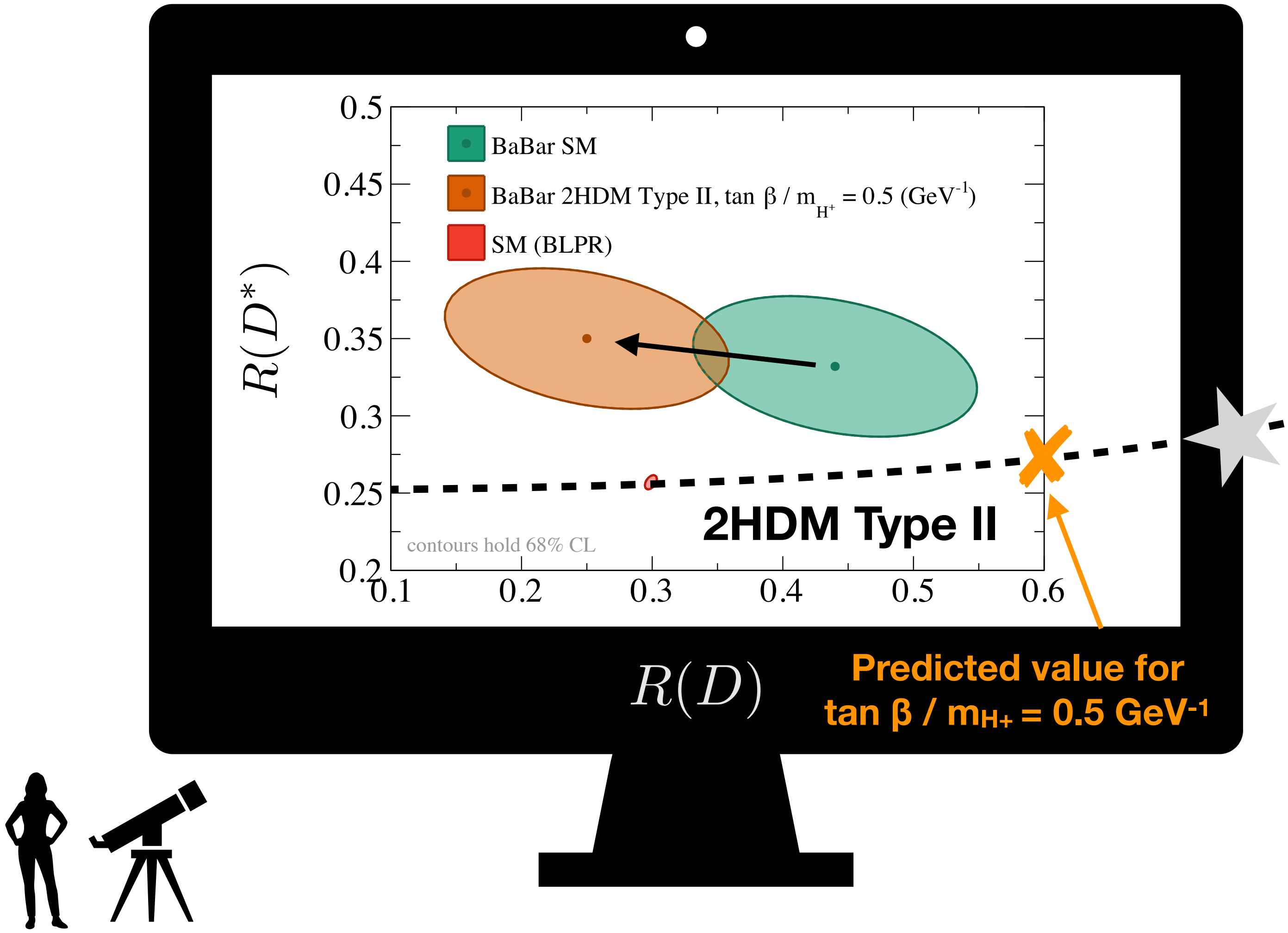


Predicted value for tan β / m_{H+} = 0.5 GeV^{-1}

- As it turns out, **not that easy** — the **measured points** themselves are **extracted assuming** the **SM** and kinematic distributions sensitive to the PoI are altering the measurement

NP Interpretation Strategies for $H_b \to H_c \tau \bar{\nu}$

What you can do today

#1

Just fit ratios, hope that **bias** is small with respect to the current precision

Frankly a perfectly sane strategy; after all the experiments do not provide any other information one could use and not all measurements might have such a strong dependence as e.g. BaBar

……

What we should allow you to do

#2

Fold your model into the MC simulation, directly confront the data

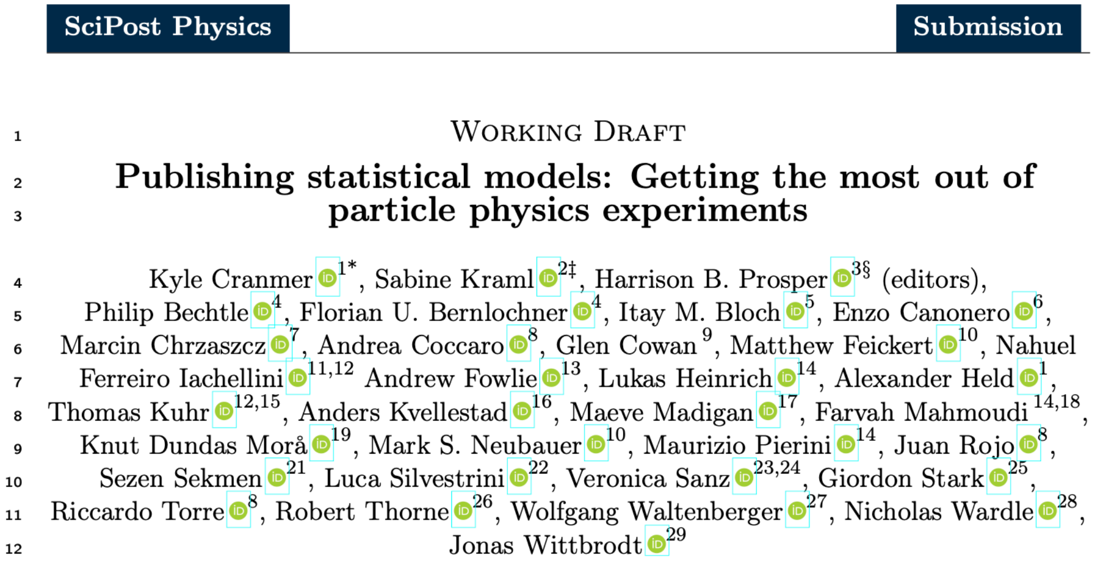
#3

Provide theorists with direct measurements of Wilson coefficients; these can be used to confront your favorite model

↓

<u>Benefit:</u> no biases, more sensitivity as shape of <u>**all**</u> kinematic distributions help distinguish between models

a fairly prominent problem



SciPost Physics **Submission**

WORKING DRAFT

Publishing statistical models: Getting the most out of particle physics experiments

Kyle Cranmer[1*], Sabine Kraml[2‡], Harrison B. Prosper[3§] (editors), Philip Bechtle[4], Florian U. Bernlochner[4], Itay M. Bloch[5], Enzo Canonero[6], Marcin Chrzaszcz[7], Andrea Coccaro[8], Glen Cowan[9], Matthew Feickert[10], Nahuel Ferreiro Iachellini[11,12] Andrew Fowlie[13], Lukas Heinrich[14], Alexander Held[1], Thomas Kuhr[12,15], Anders Kvellestad[16], Maeve Madigan[17], Farvah Mahmoudi[14,18], Knut Dundas Morå[19], Mark S. Neubauer[10], Maurizio Pierini[14], Juan Rojo[8], Sezen Sekmen[21], Luca Silvestrini[22], Veronica Sanz[23,24], Giordon Stark[25], Riccardo Torre[8], Robert Thorne[26], Wolfgang Waltenberger[27], Nicholas Wardle[28], Jonas Wittbrodt[29]

[to appear soon]

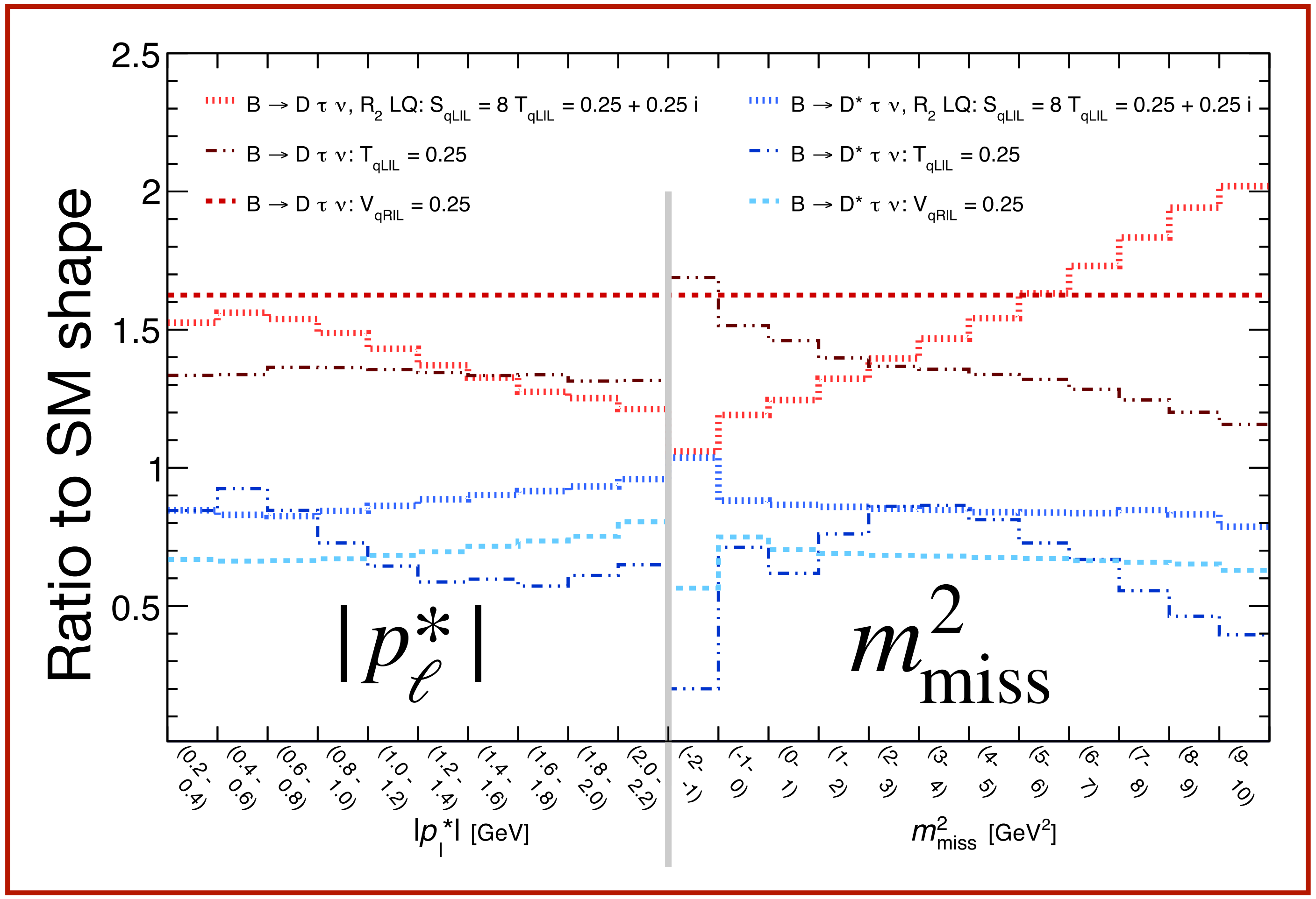
$b \to c\tau\bar{\nu}_\tau$

$\tau \to \ell\bar{\nu}_\ell\nu_\tau$

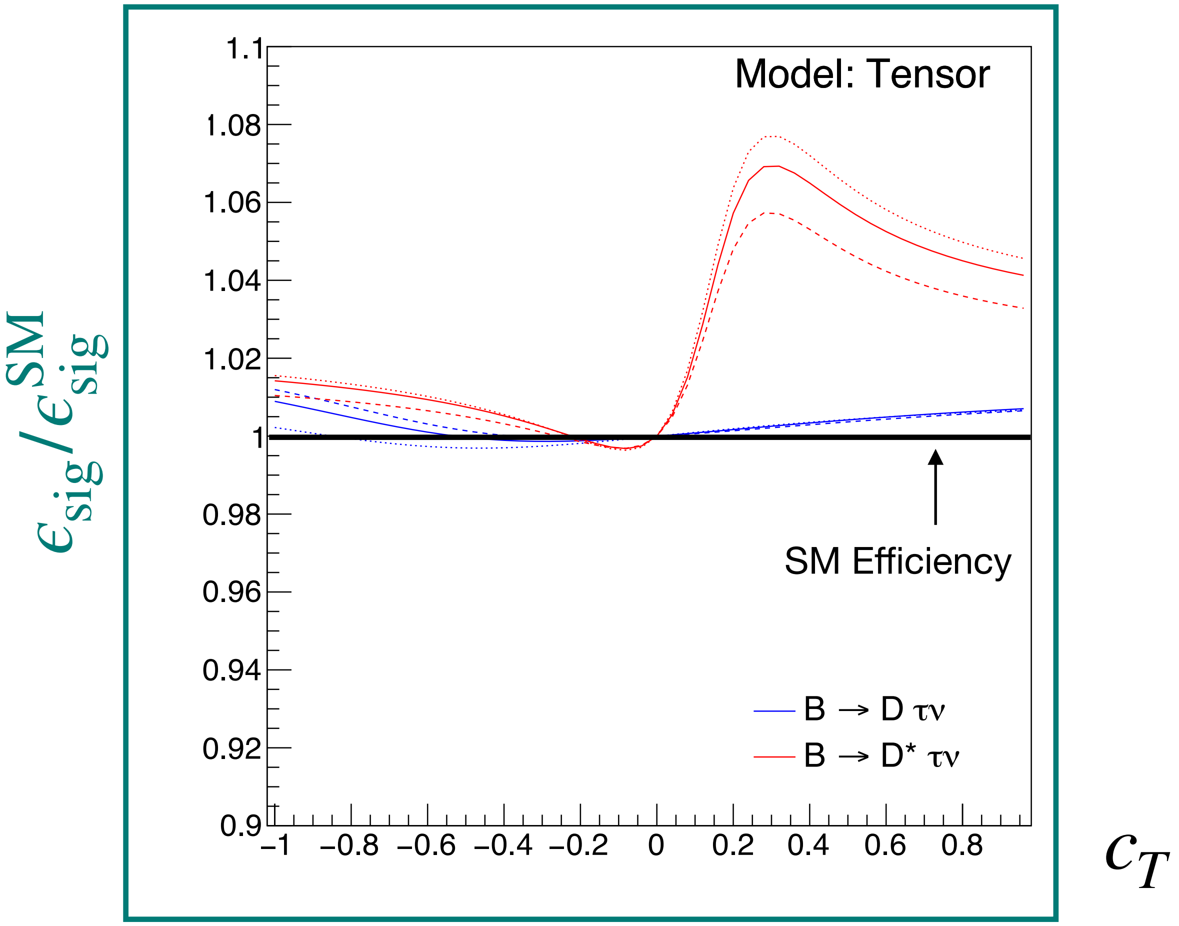
Use **kinematic** quantities (e.g. $|p_\ell^*|, m_{\text{miss}}^2, q^2$)

to **subtract background**

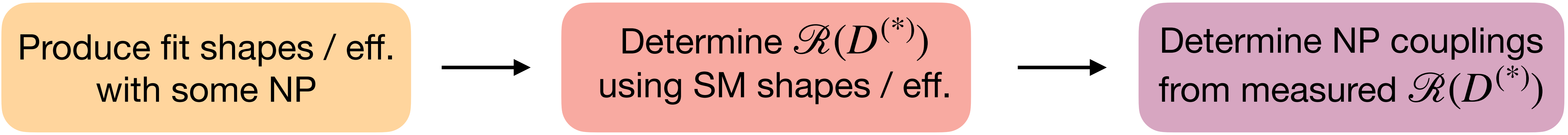
$$\mathcal{R}(D^{(*)}) = \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}}$$



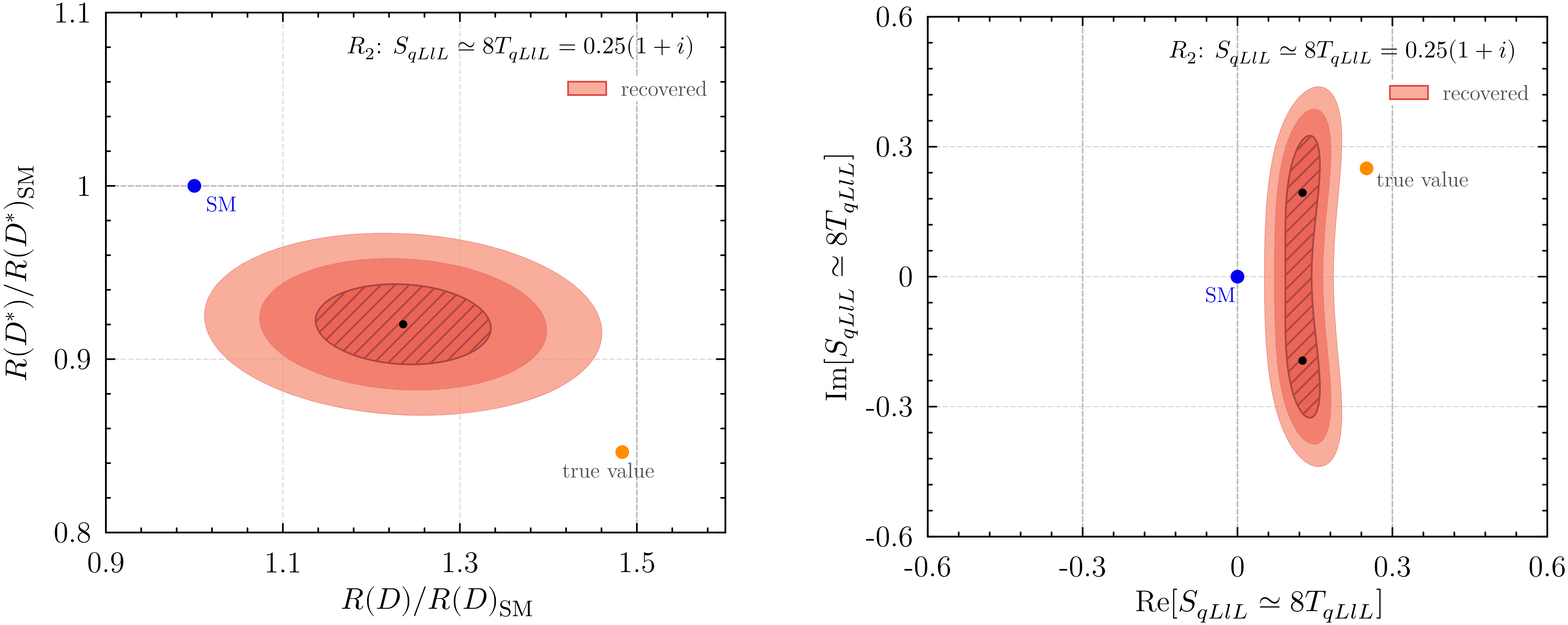
Assume **SM** acceptance x efficiency



Slightly dramatic example of what could happen



Produce fit shapes / eff. with some NP → Determine $\mathscr{R}(D^{(*)})$ using SM shapes / eff. → Determine NP couplings from measured $\mathscr{R}(D^{(*)})$



Note: the values were chosen intentionally not to reproduce the measured values to avoid the temptation to correct measured values..

HAMMER — a tool to correct $H_b \to H_c \tau \bar{\nu}$ to arbitrary NP

Challenge: Produce MC for each NP working point

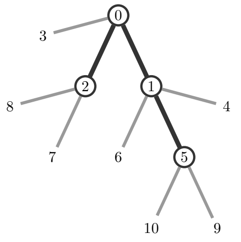
- **Need** a **MC generator** that incorporates **all NP effects** and **modern form factors** (e.g. EvtGen does not)
- **Very expensive**; MC statistics is already one of the largest systematic uncertainties on these measurements

HAMMER offers a solution to these problems

SM or Phase-space MC can be corrected to NP or FFs via ratio of event weights

$$r_I = \frac{d\Gamma_I^{\text{new}}/d\mathcal{PS}}{d\Gamma_I^{\text{old}}/d\mathcal{PS}},$$

Helicity Amplitude Module
for Matrix Element Reweighting



To correct angular distributions one needs to do this for all D* and τ decay products

encode hadronic form factors

tensor that encodes amplitudes of given process

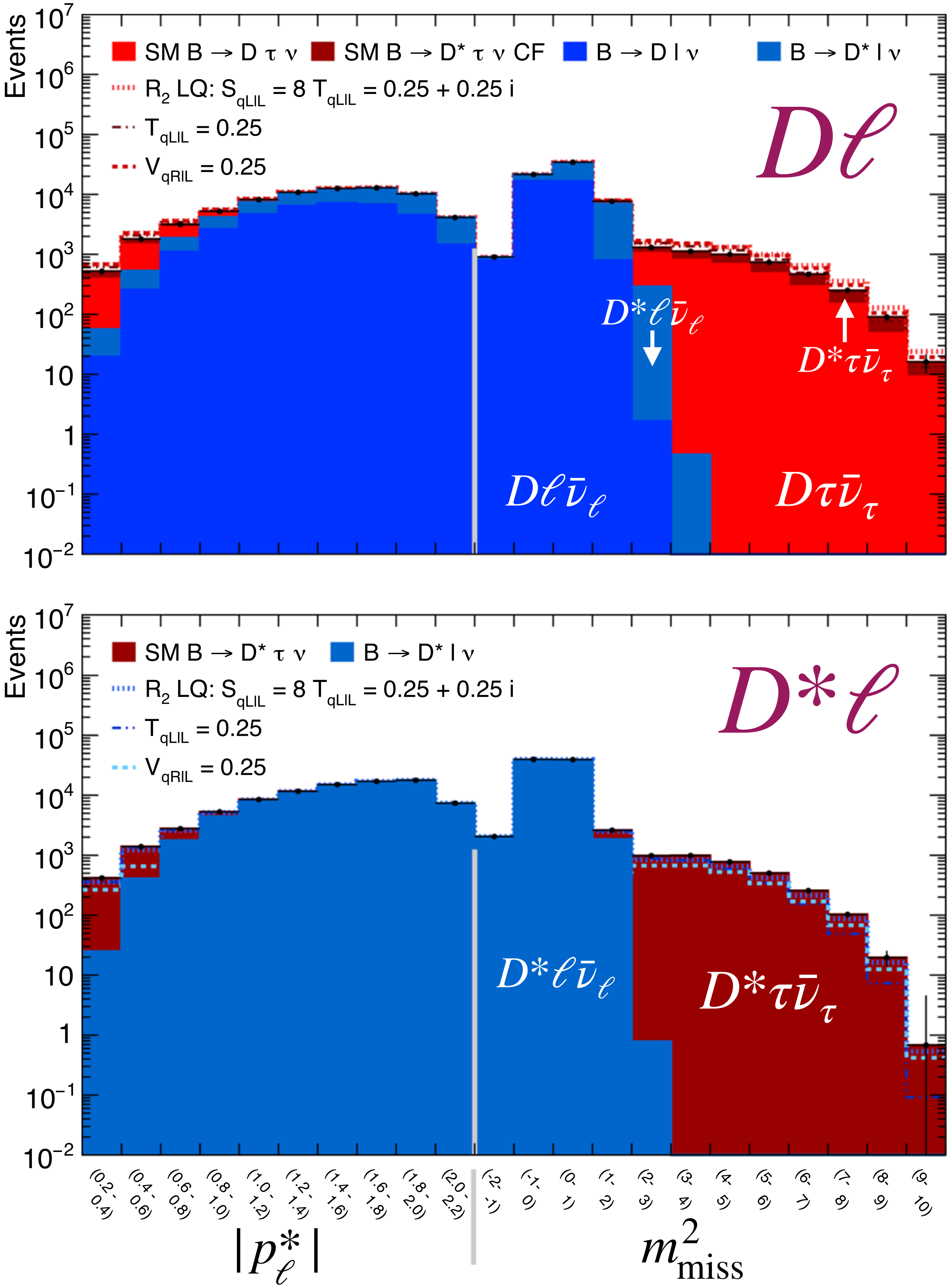
$$\sum_{\alpha,i,\beta,j} c_\alpha c_\beta^\dagger F_i F_j^\dagger W_{\alpha i \beta j},$$

sum independent of Wilson coefficients c_α
→ can exploit this to create **fast predictions**

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

An illustrative Toy Example

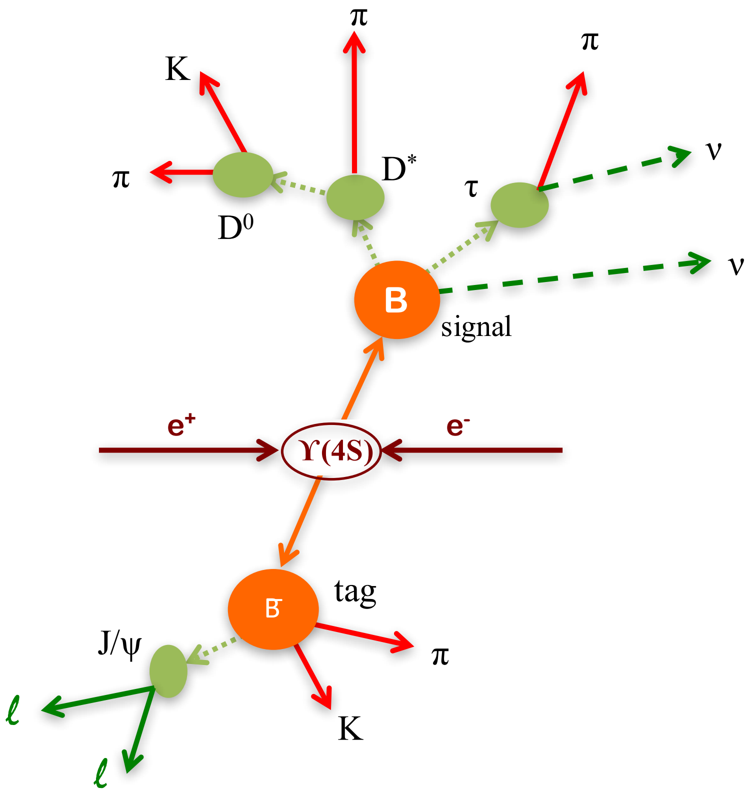
FB, S. Duell, Z. Ligeti, M. Papucci, D. Robinson
Eur. Phys. J. C (2020) **80**: 883 [arXiv:2002:00020]



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

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

Corresponds to a guestimate of how an analysis with 5/ab of Belle II data could look like in a single channel



A toy example