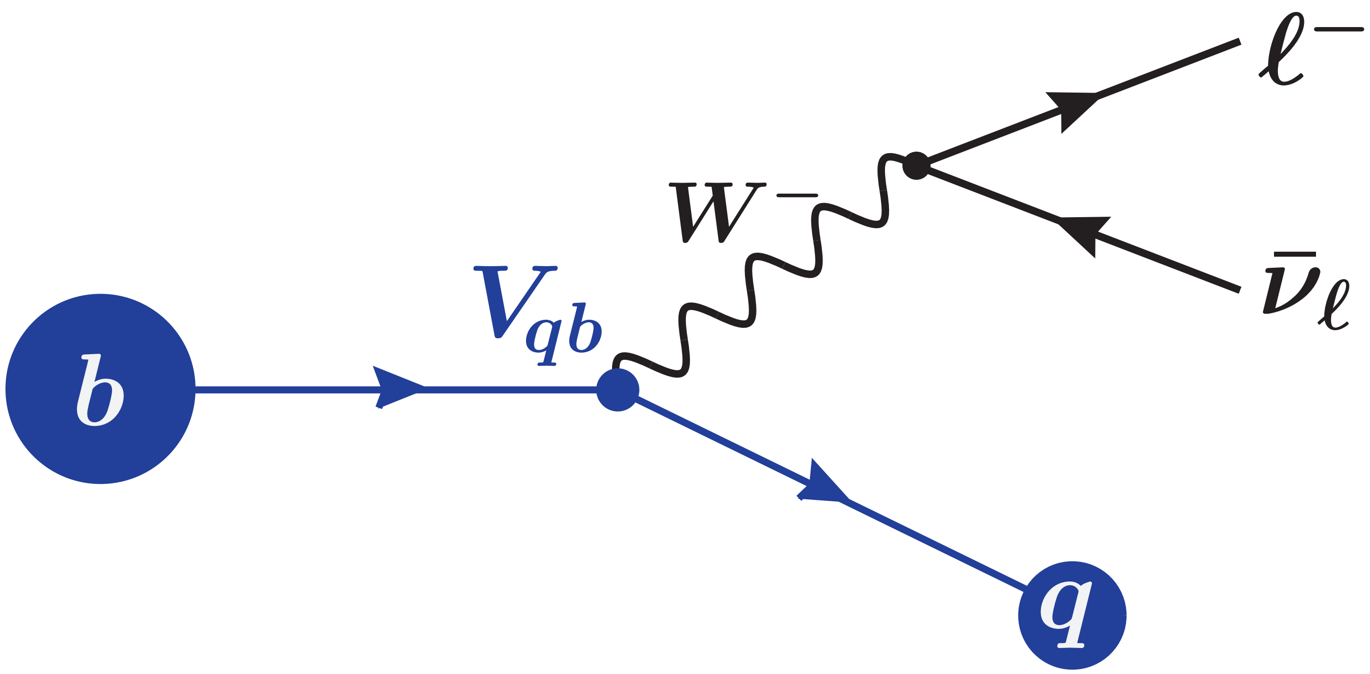

APS April Meeting 2021, **April 17 - 20**

Review on latest results on $R(D^{(*)})$ & Outlook

Minisymposium on *Precision Measurements with Leptons*

Belle Belle II LHCb

Florian Bernlochner
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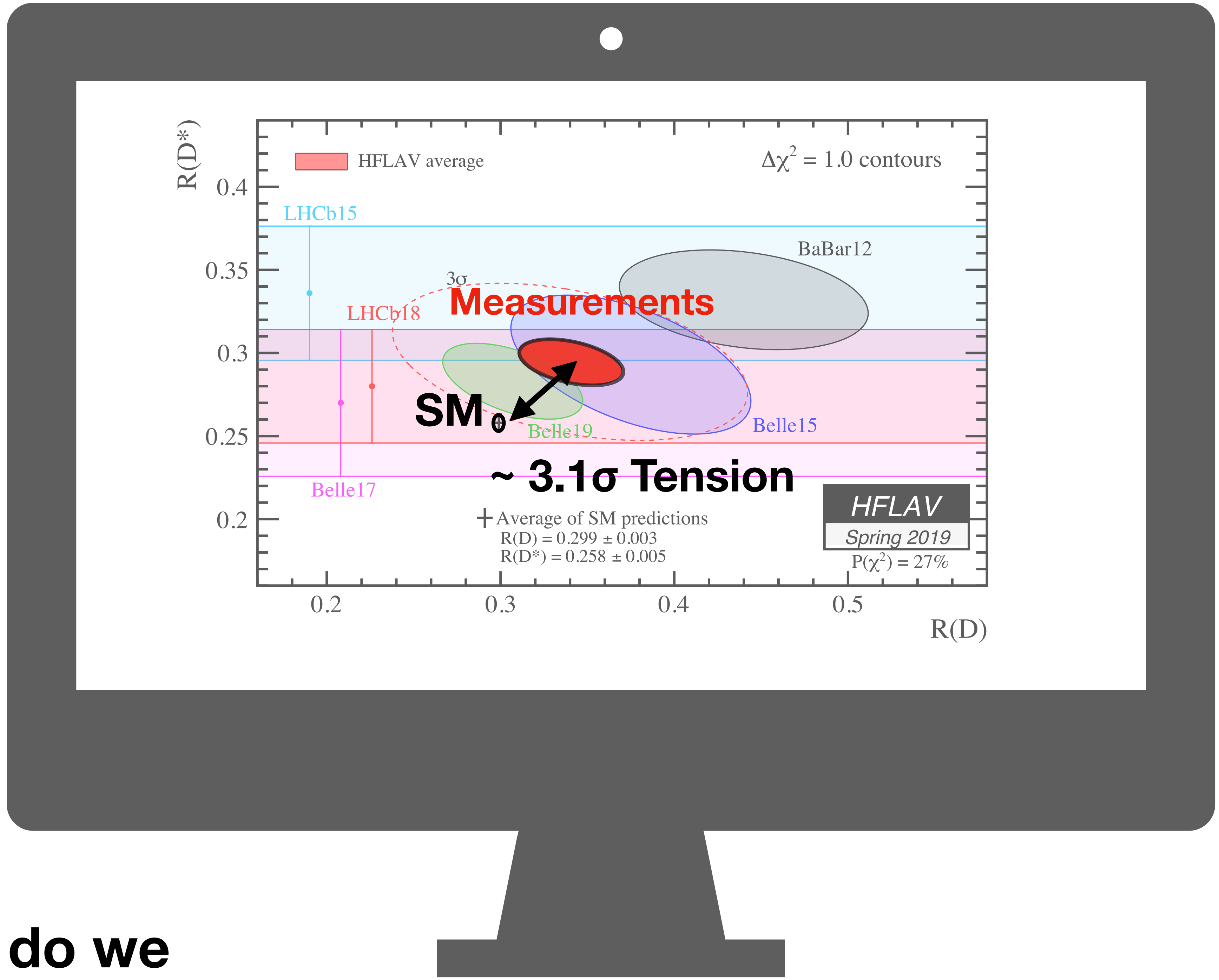
UNIVERSITÄT BONN

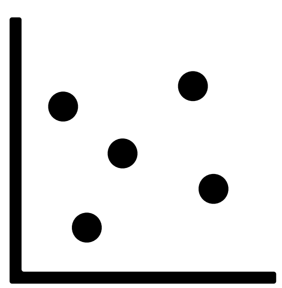
$$R = \frac{b \to q\, \tau \bar{\nu}_\tau}{b \to q\, \ell \bar{\nu}_\ell}$$

$\ell = e, \mu$

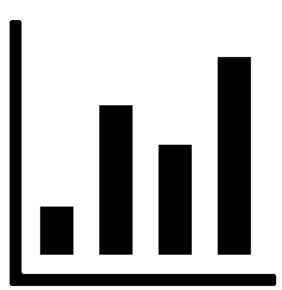
↓

$$R(D^{(*)}, \pi, J/\psi)$$

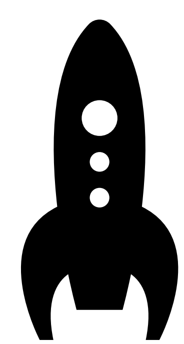




1. How do we measure?



2. Latest measurements
from Belle & LHCb



3. Outlook
for Belle II & LHCb

Measurement Strategies

Signal

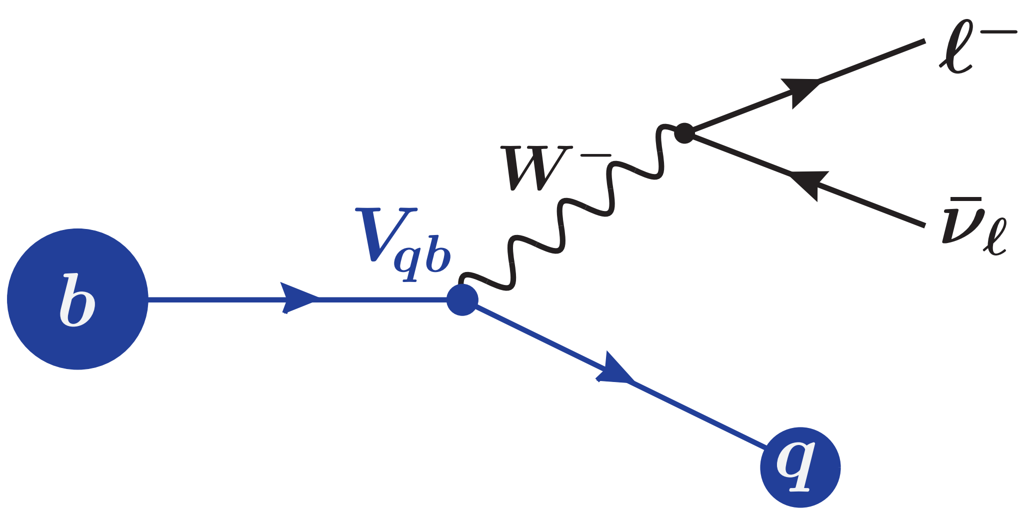
$$R = \frac{b \to q\,\tau\bar{\nu}_\tau}{b \to q\,\ell\bar{\nu}_\ell}$$

Normalization

$\ell = e, \mu$

1. Leptonic or Hadronic τ decays?

Some properties (e.g. τ **polarisation**) 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**

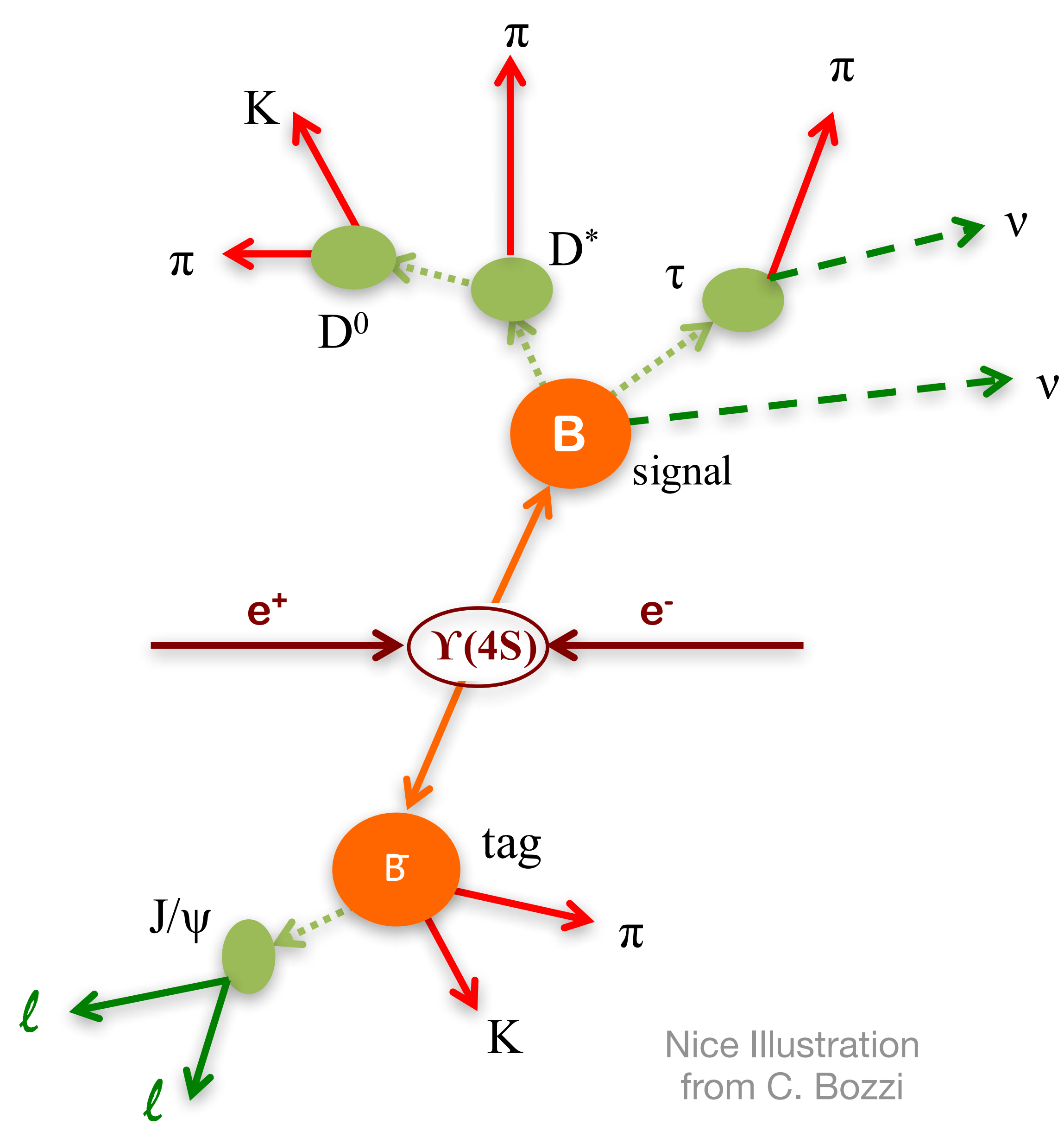
Measurement Strategies

3. Semileptonic decays at B-Factories

- e+/e- collision produces ***Y(4S)* → *BB̄***
- 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

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

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



Nice Illustration from C. Bozzi

Measurement Strategies

4. Semileptonic decays at LHCb

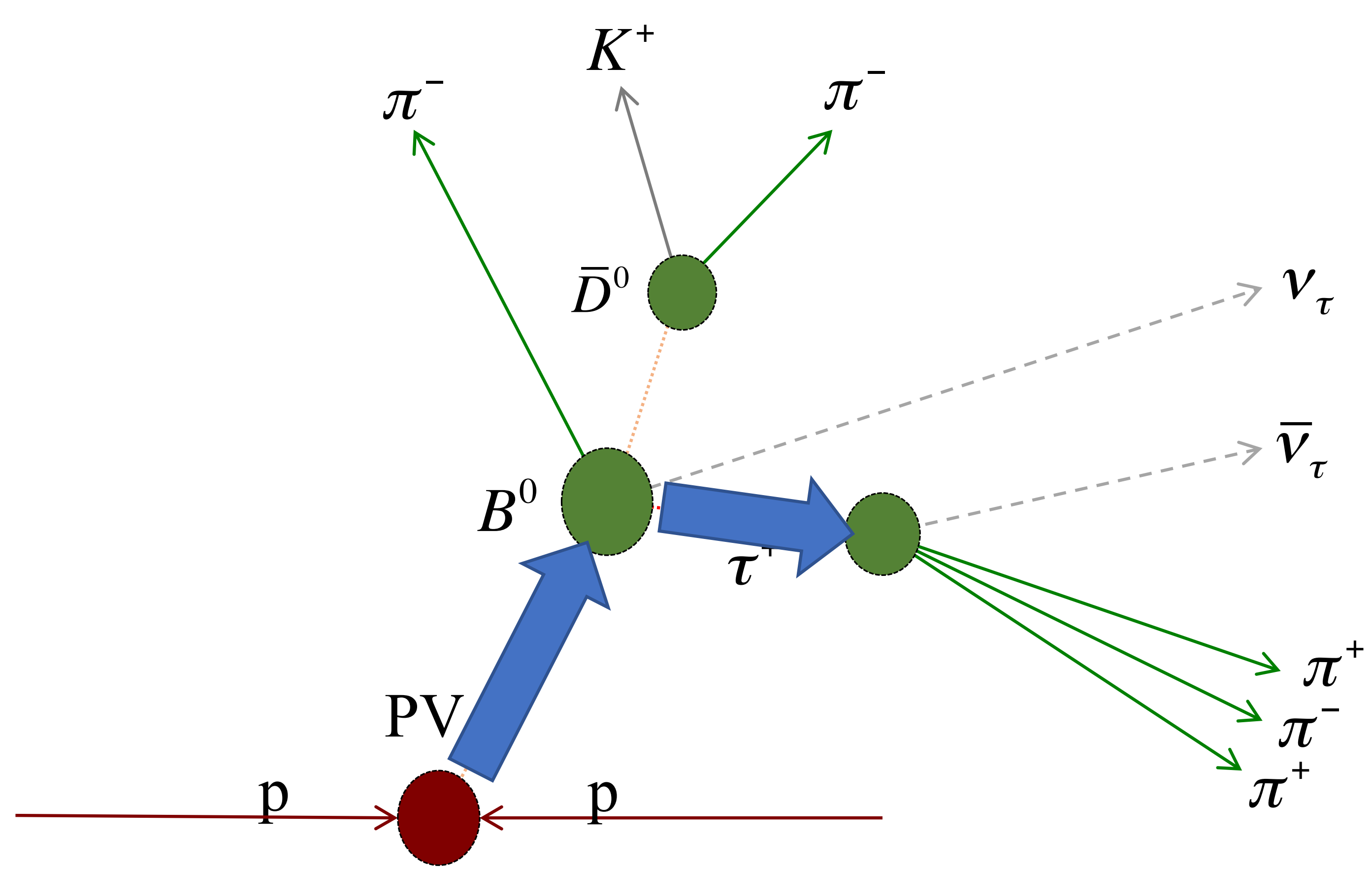
- No constraint from beam energy at a hadron machine, **but..**
- **Large Lorentz boost** with decay lengths in the range of **mm**

  ✓ **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

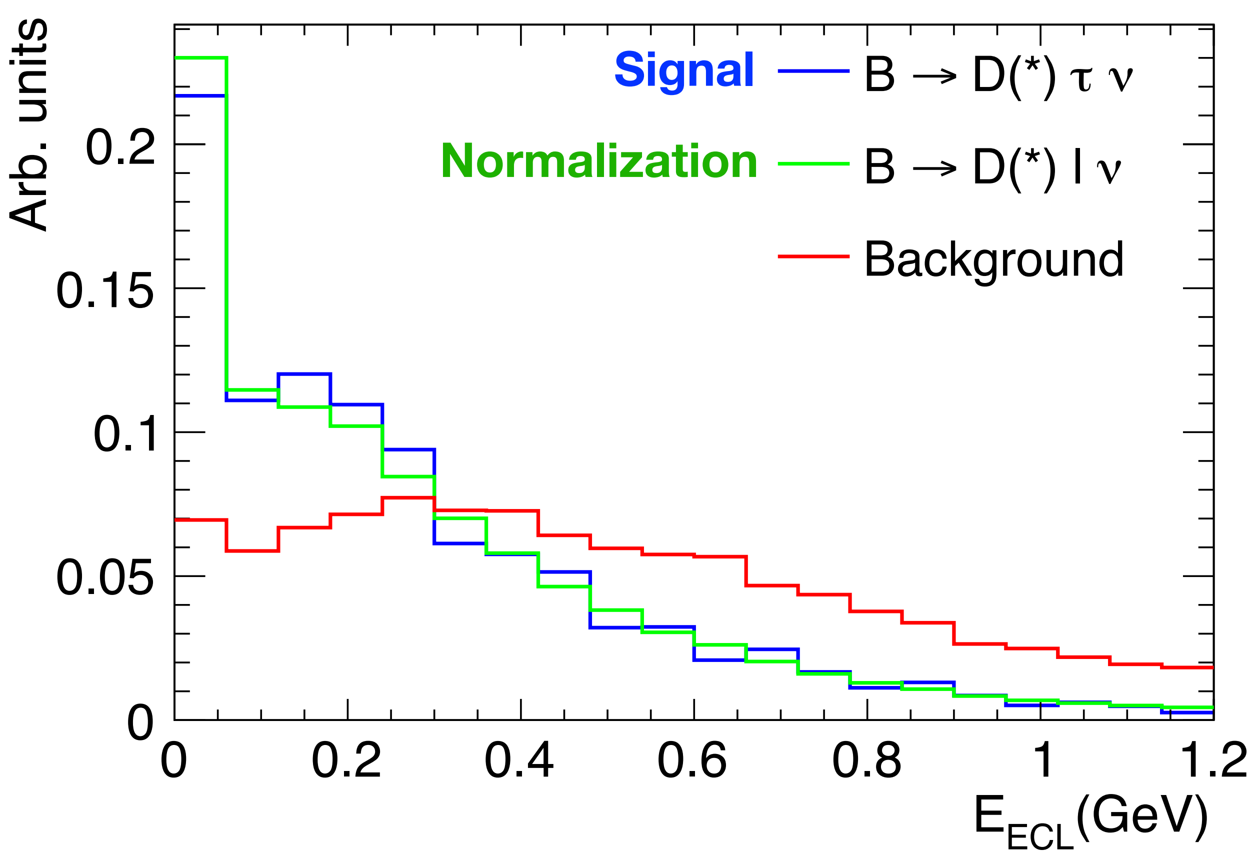
Even bit more complicated for leptonic tau decays

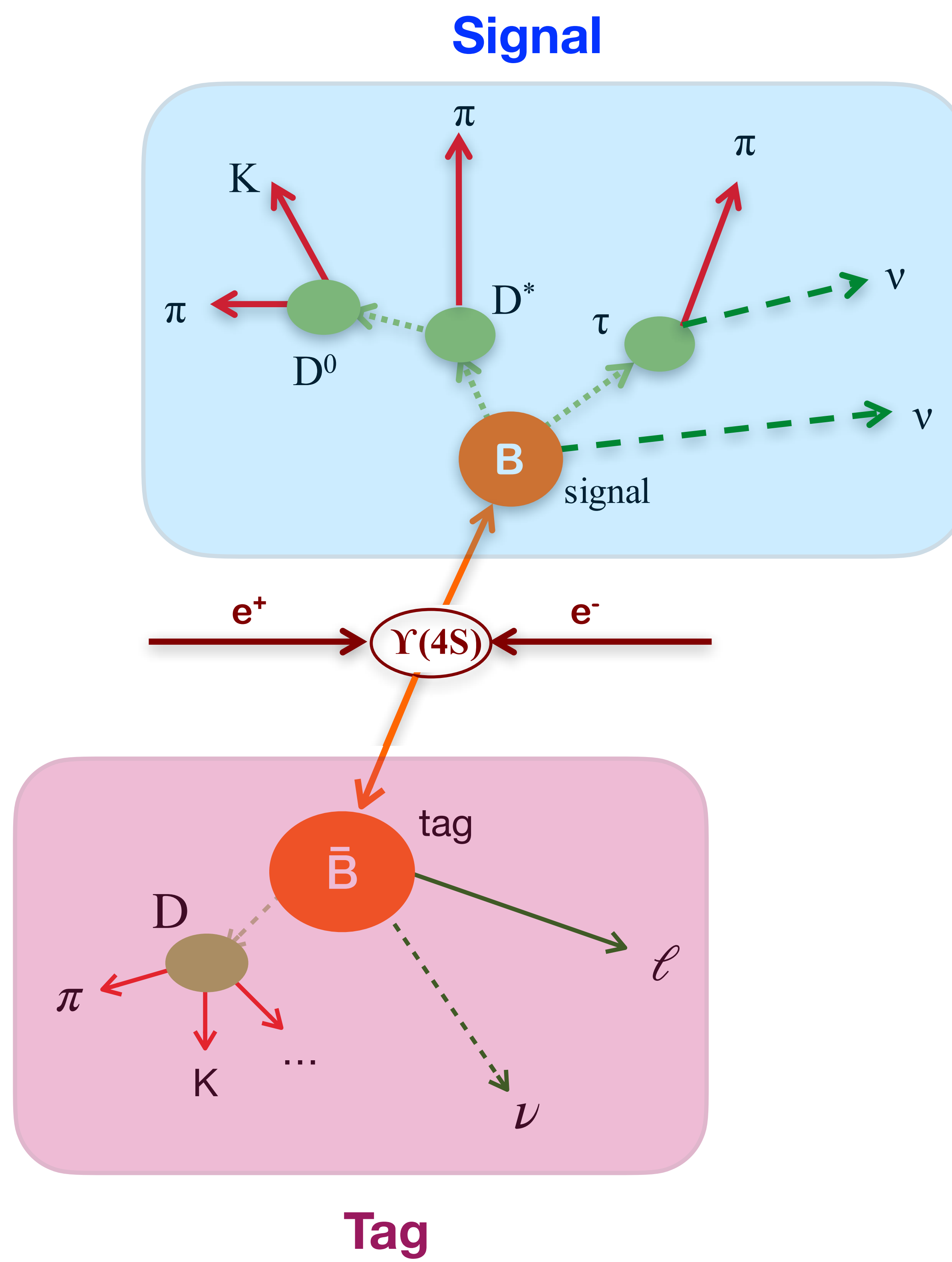
Latest $R(D^{(*)})$ from Belle

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

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

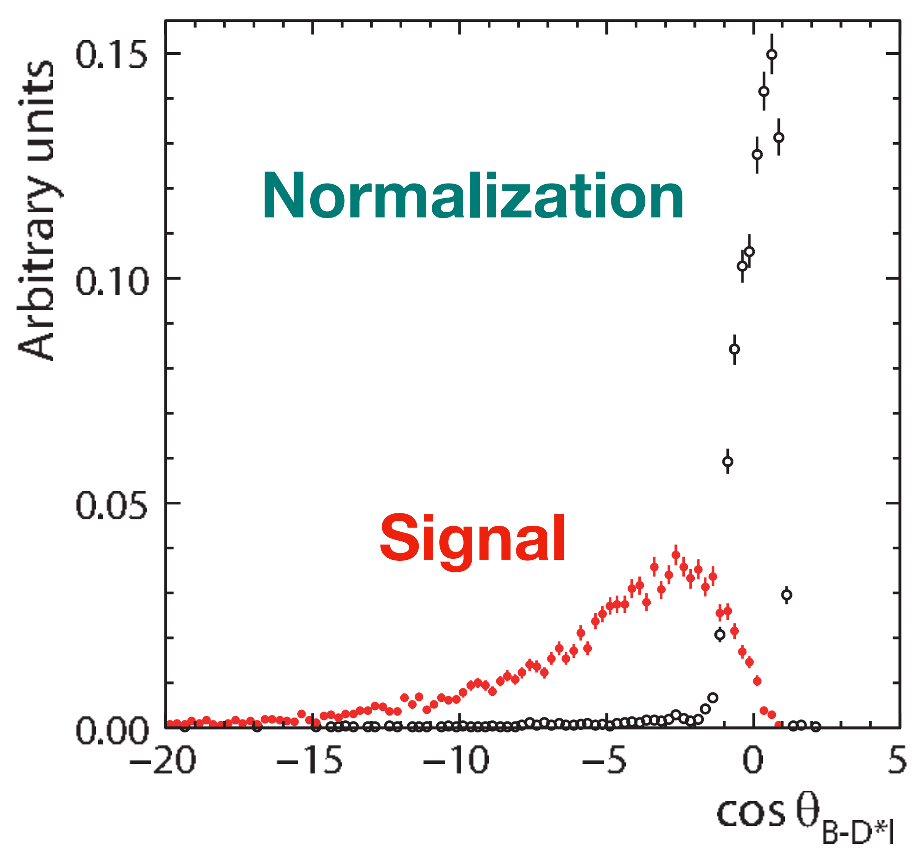


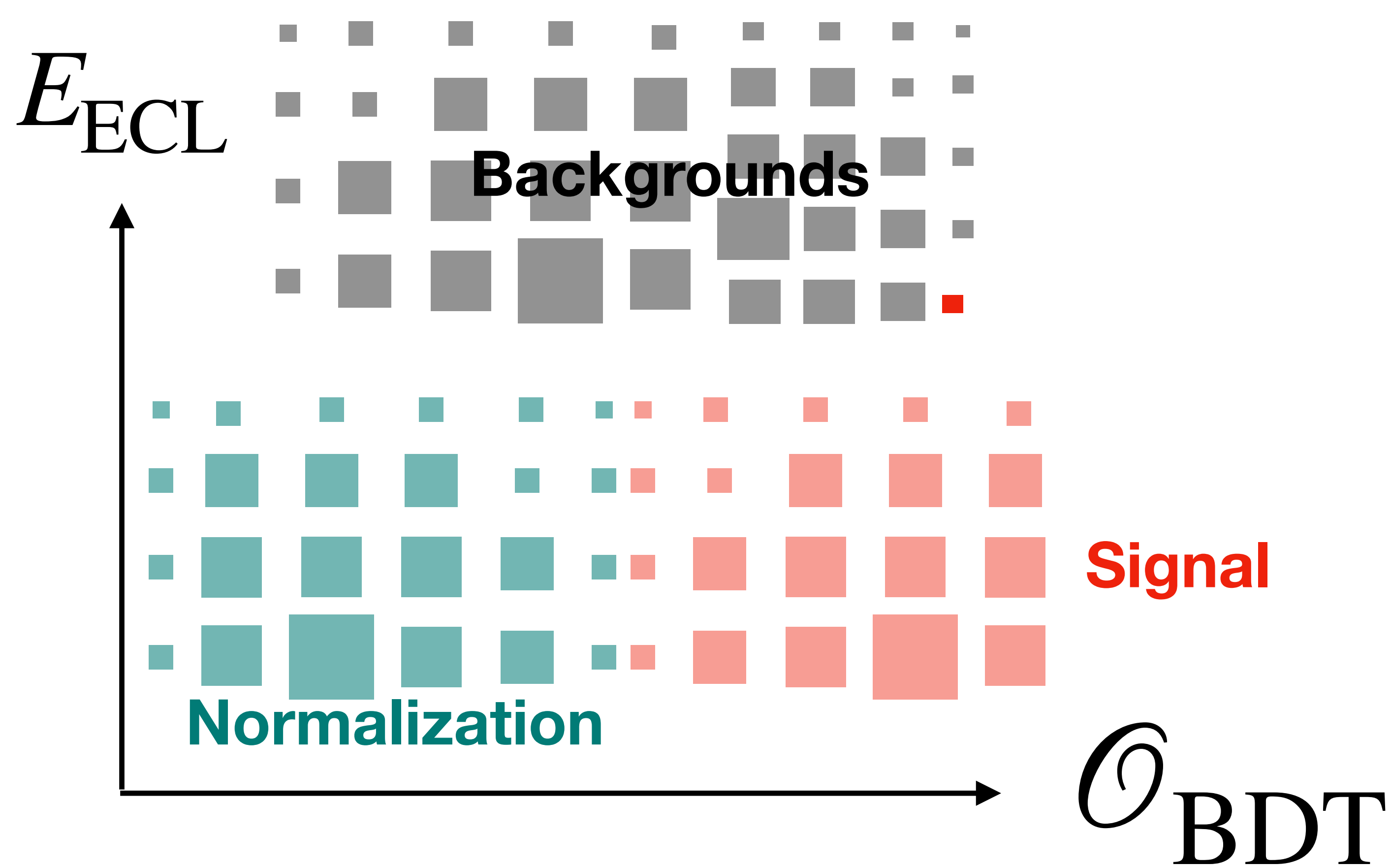


Separation of signal & normalization

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

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





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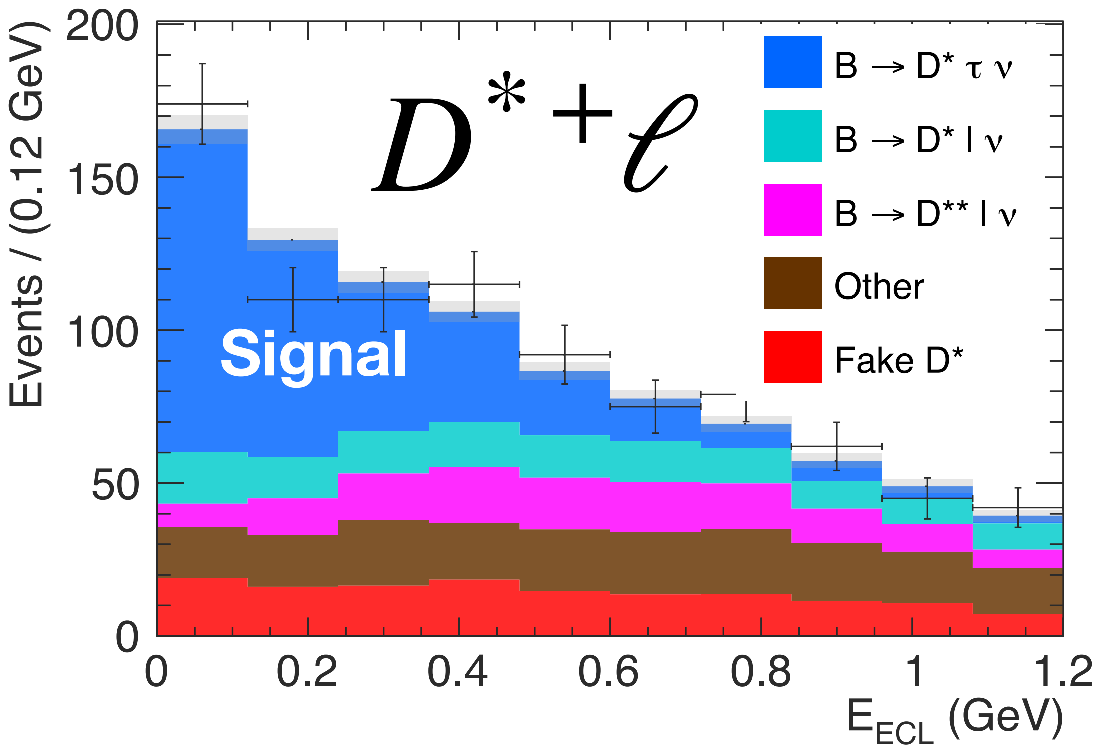
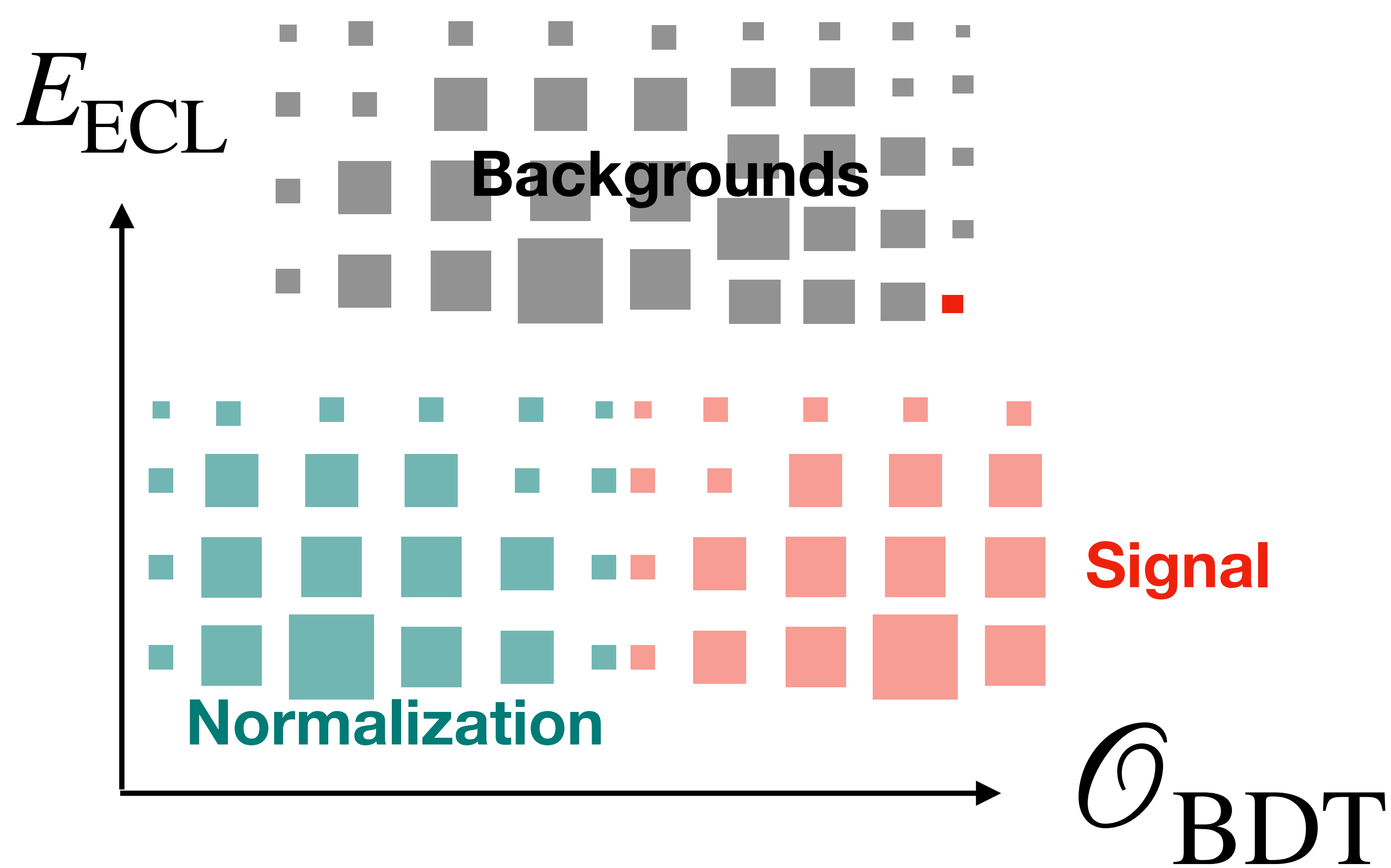


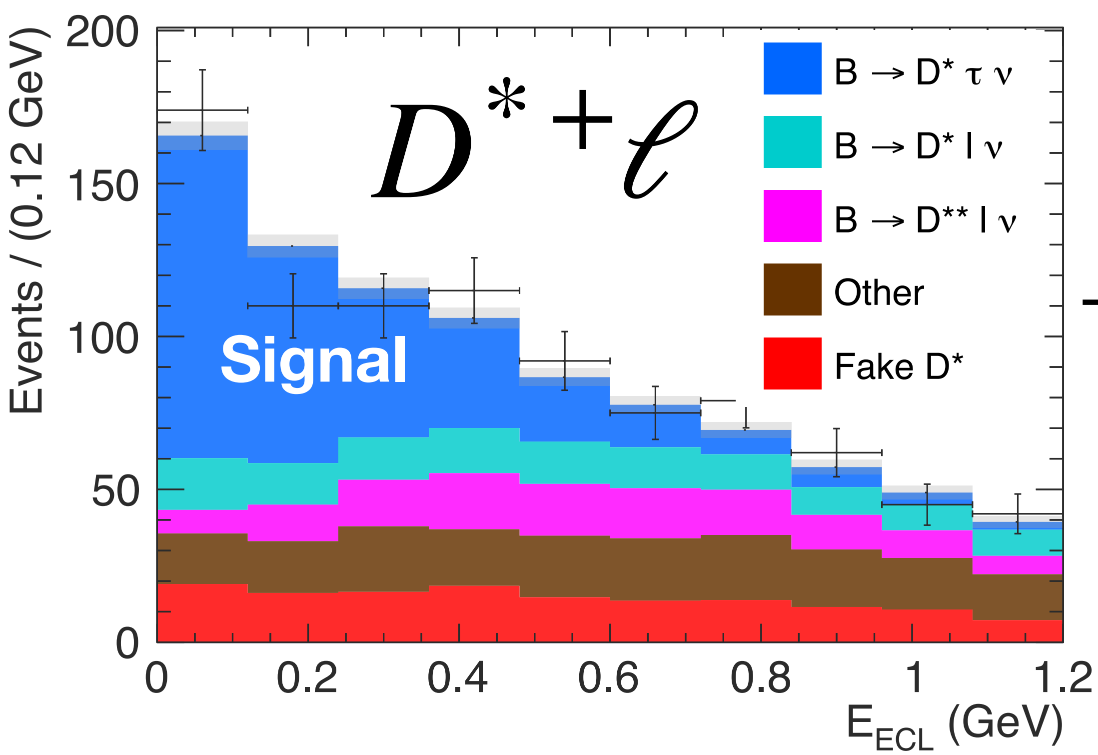
Signal-enriched selection with cut on $\mathcal{O}_{\mathrm{BDT}}$



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}, $m^2_{\text{miss}} = p^2_{\text{miss}}$



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

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$

$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

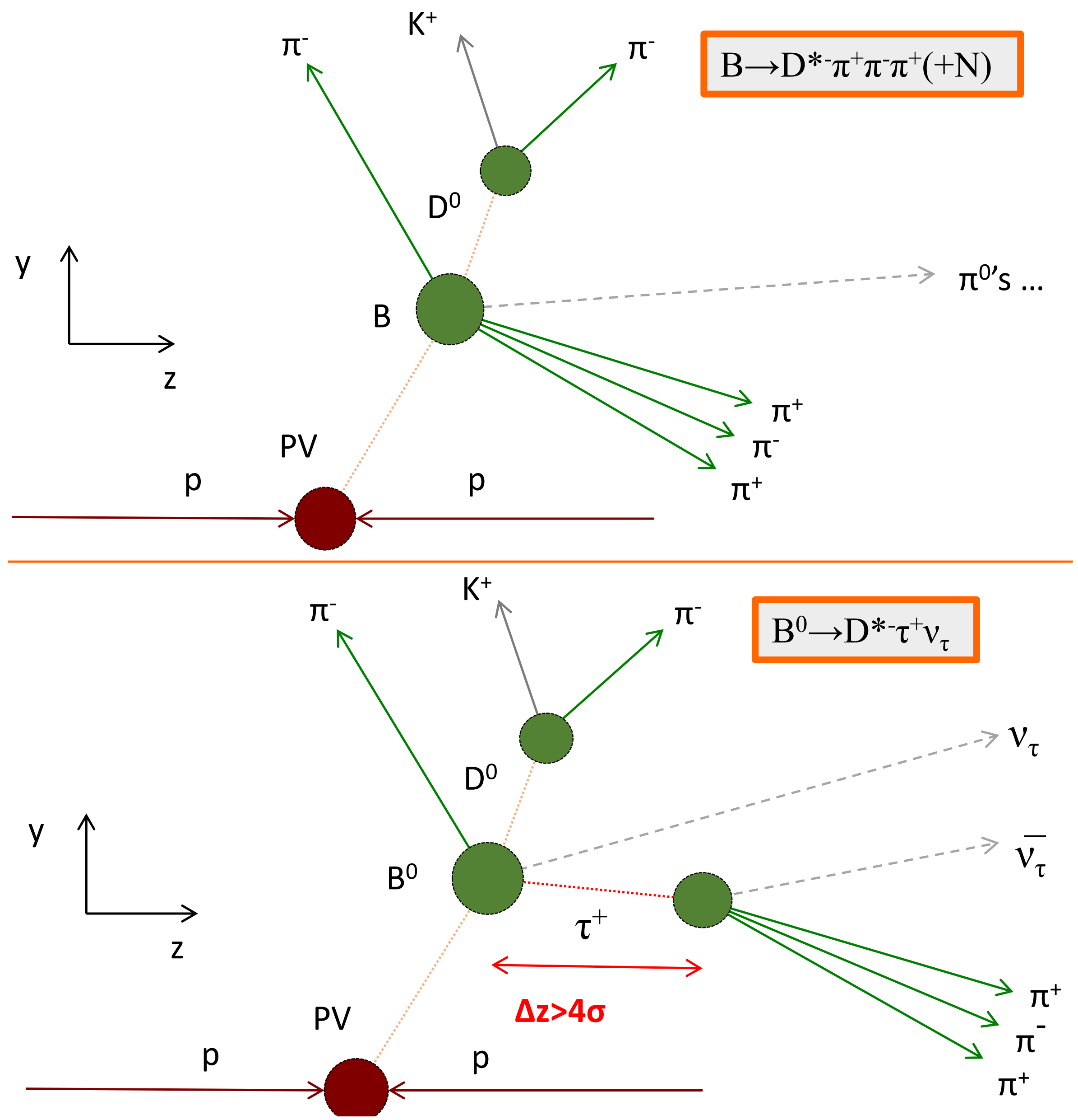
Most precise measurement to date

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 $\sigma_{\Delta z}$)***

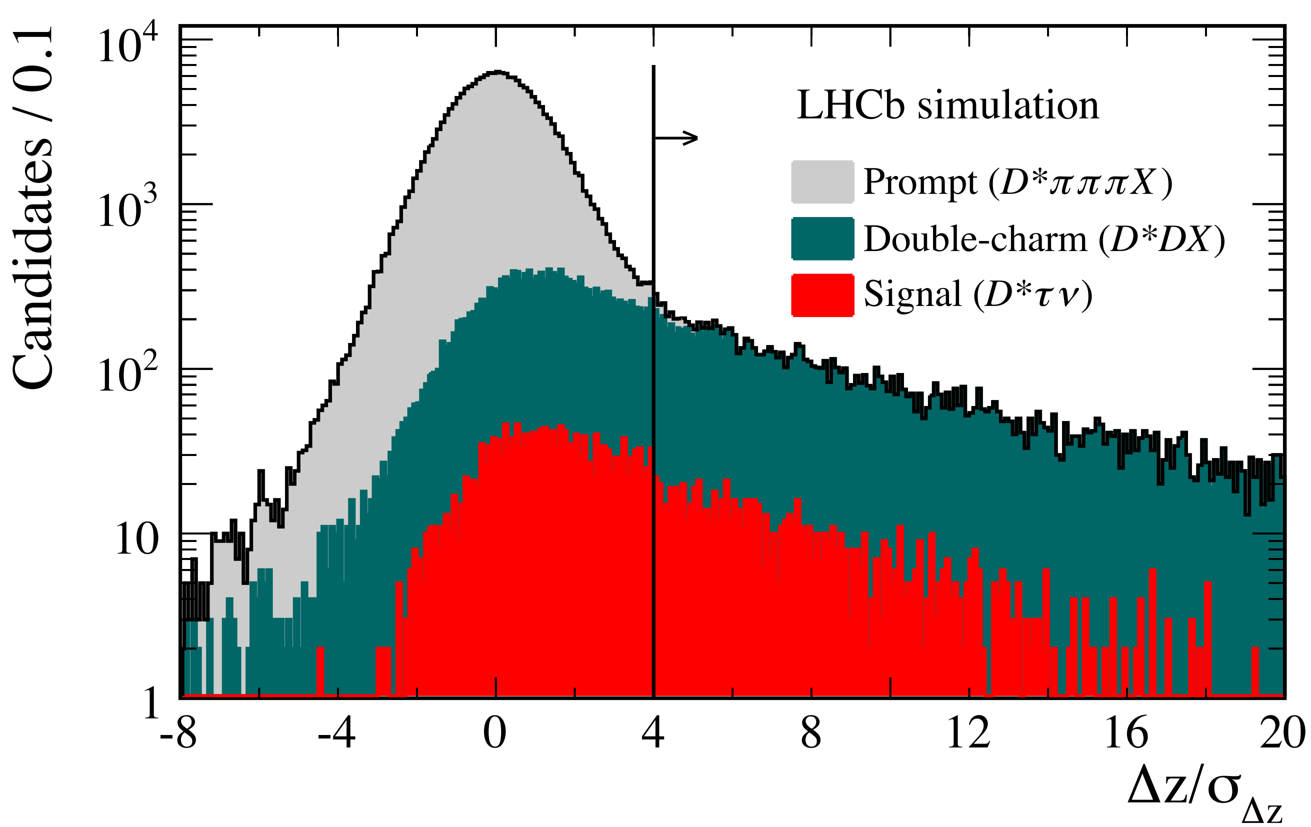
$\sigma_{\Delta z}$: resolution of vertices separation

- Reduces this background by three orders of magnitude

LHCb Measurement of $R(D^*)$

- 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 $B \to D^* X\mu\nu$



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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

- 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 $R(D^*)$

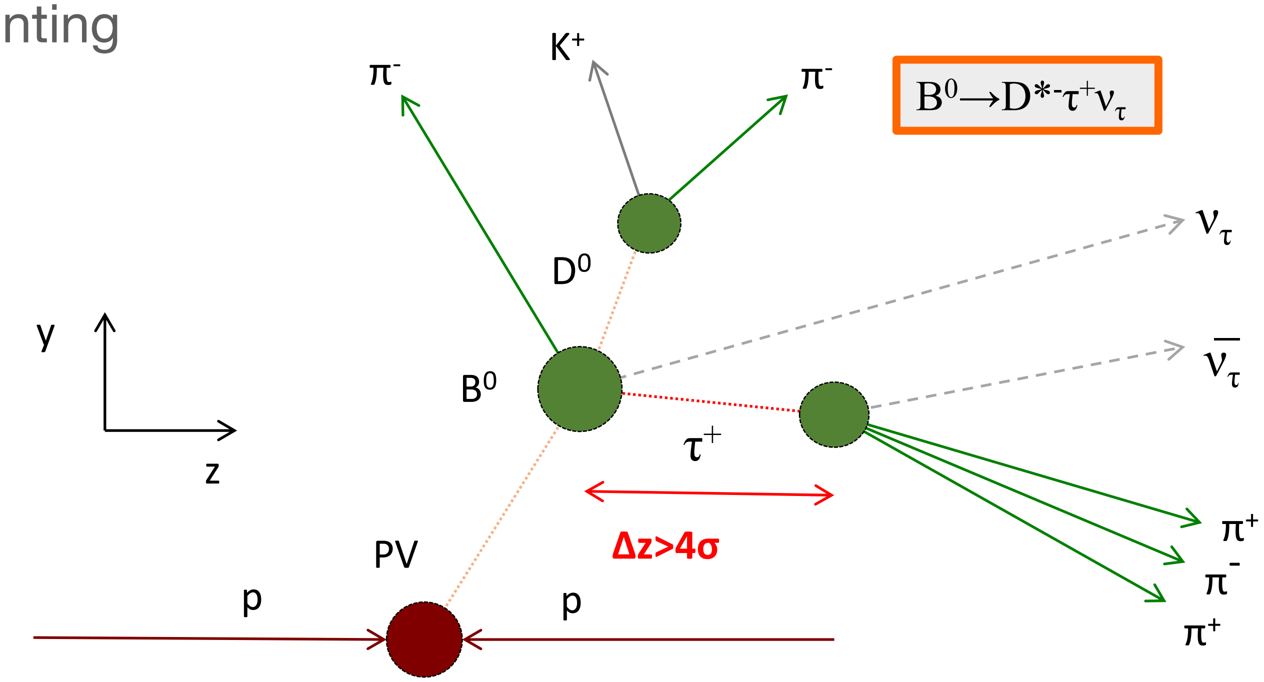
- Remaining backgrounds reduced via isolation & MVA

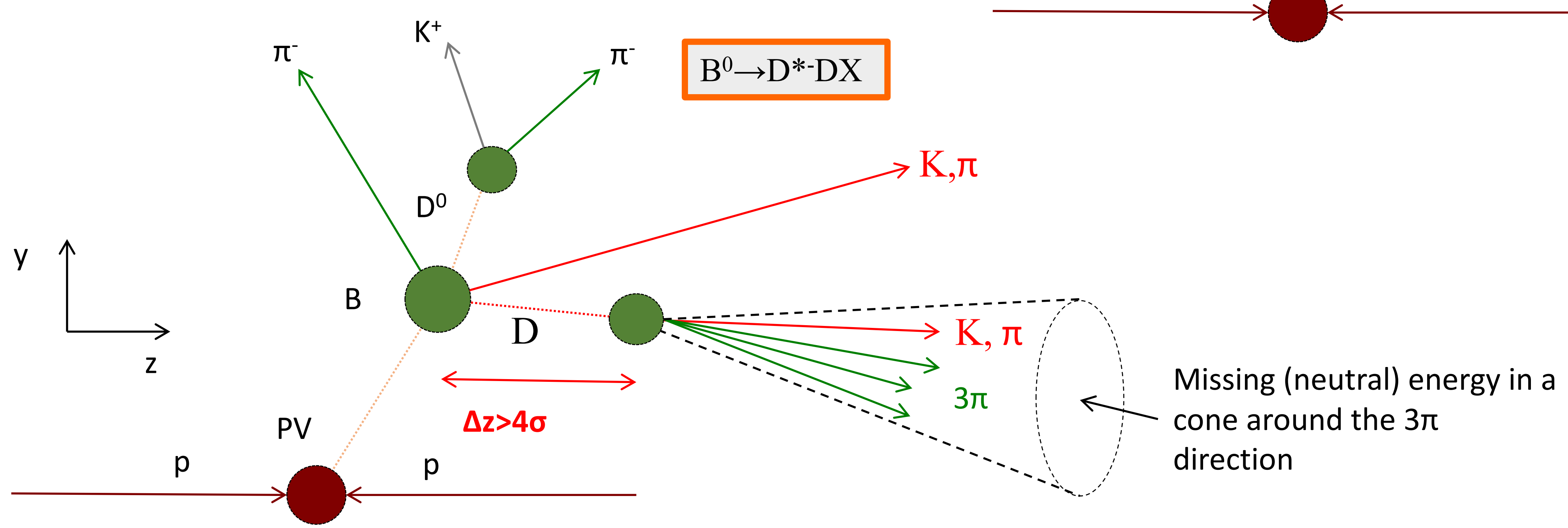
Require signal candidates to be well isolated

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





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

  Both reconstructed with some tricks (more in backup)

  4 Bins   8 Bins   8 Bins

- Components:

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

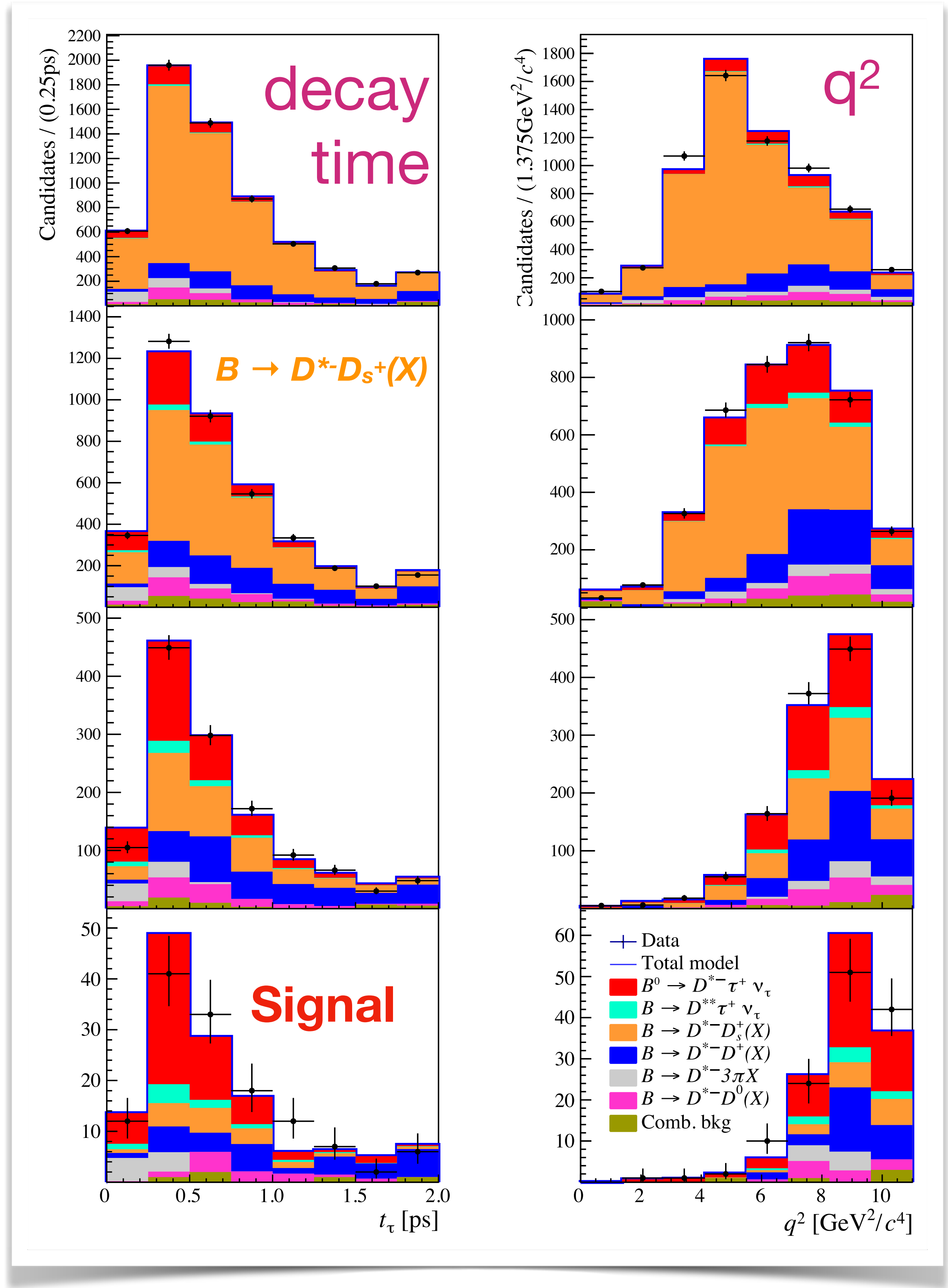
11 Background components

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

More information about normalization in backup

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

Purer MVA Selection



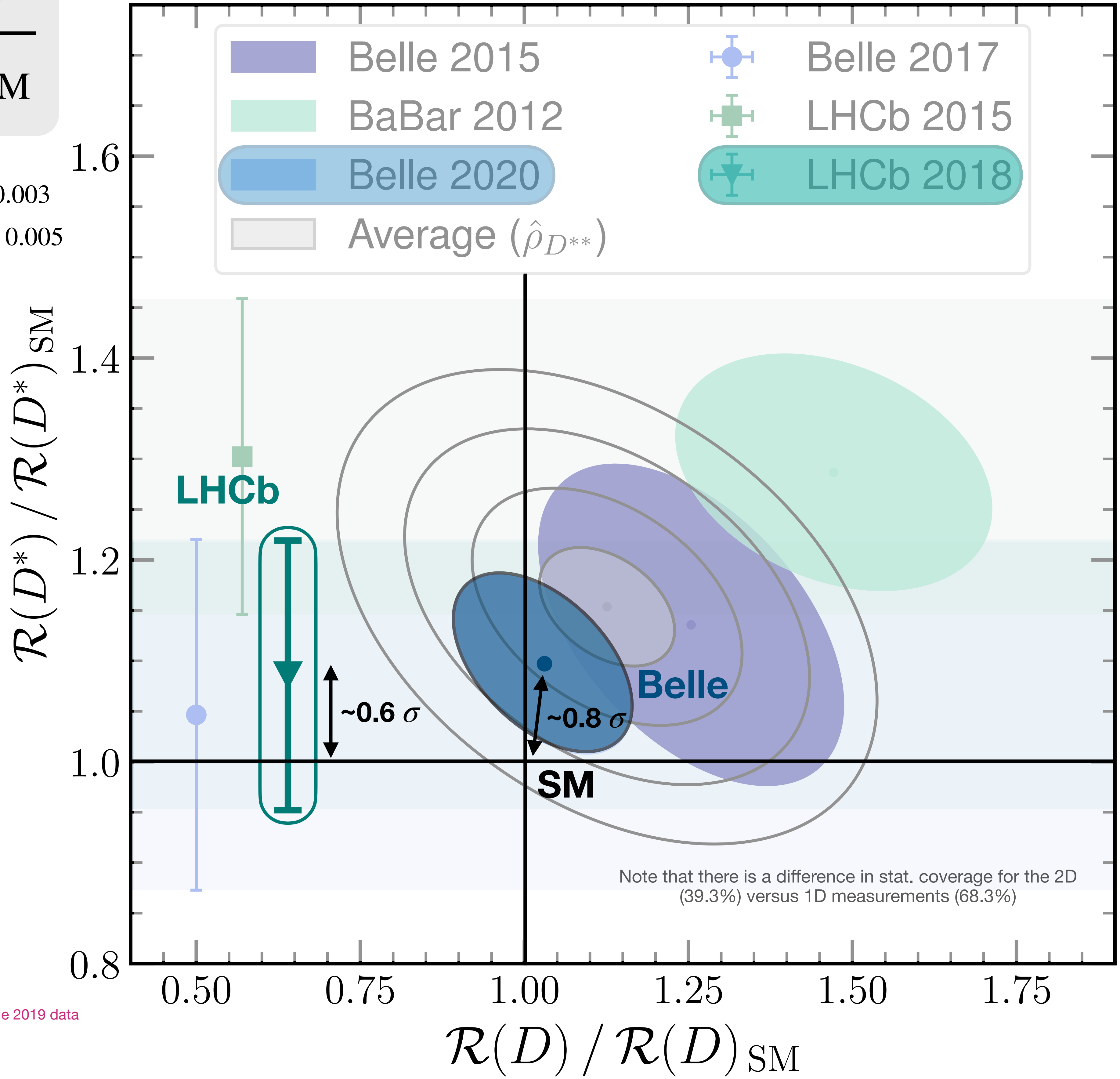
$$\frac{\mathscr{R}(D^{(*)})}{\mathscr{R}(D^{(*)})_{\mathrm{SM}}}$$

FB, M. Franco Sevilla, D. Robinson, G. Wormser
[arXiv:2101.08326], submitted to Review of Modern Physics

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

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

HFLAV arithmetic average of SM Calculations



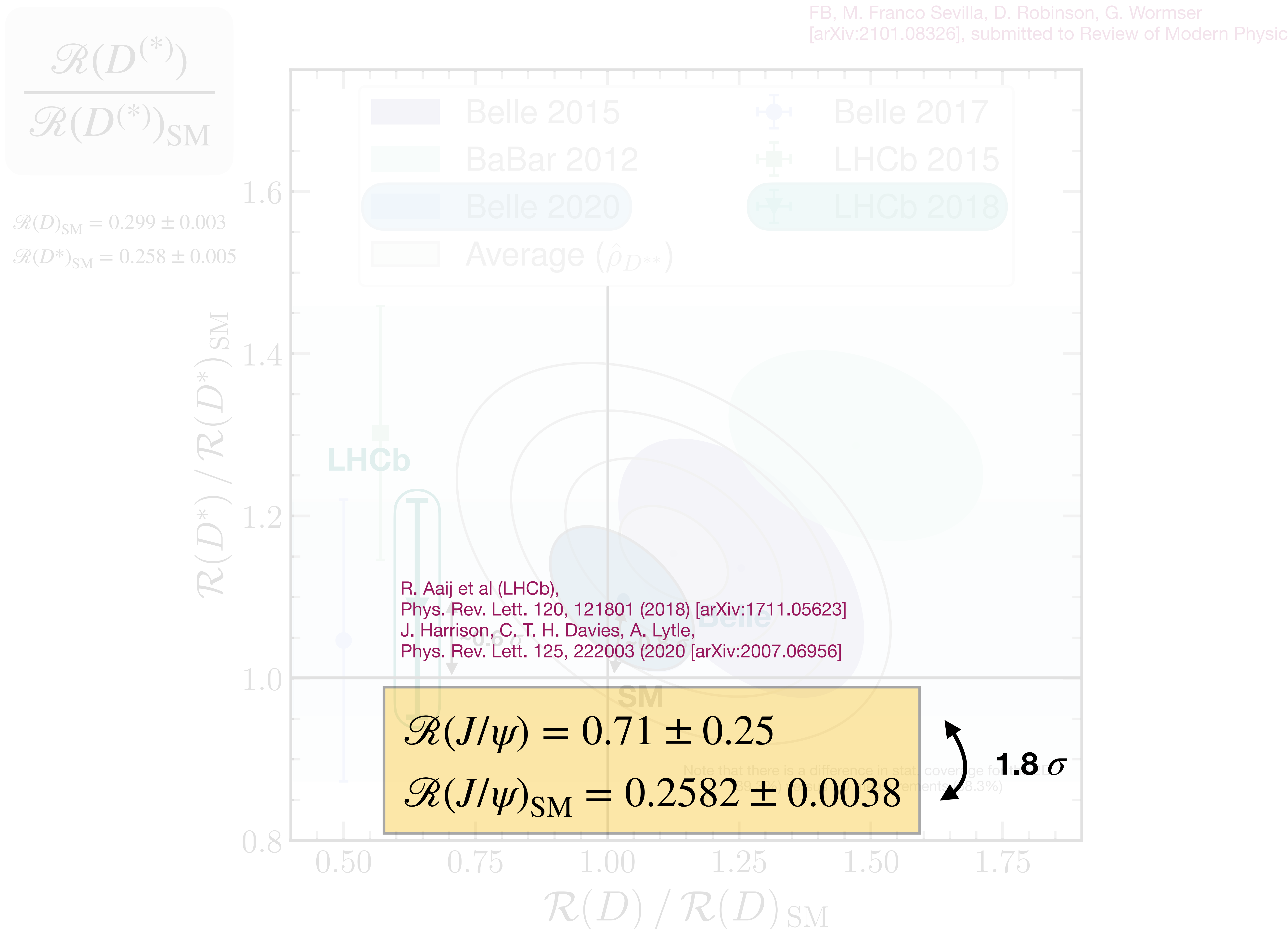
More Recent SM Calculations:

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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$\frac{\mathcal{R}(D^{(*)})}{\mathcal{R}(D^{(*)})_{SM}}$
$\mathcal{R}(D)_{SM} = 0.299 \pm 0.003$
$\mathcal{R}(D^*)_{SM} = 0.258 \pm 0.005$
Belle 2015
BaBar 2012
Belle 2020
Average ($\hat{\rho}_{D^{**}}$)
Belle 2017
LHCb 2015
LHCb 2018
LHCb
SM
$\mathcal{R}(D^*) / \mathcal{R}(D^*)_{SM}$
$\mathcal{R}(D) / \mathcal{R}(D)_{SM}$
R. Aaij et al (LHCb),
Phys. Rev. Lett. 120, 121801 (2018) [arXiv:1711.05623]
J. Harrison, C. T. H. Davies, A. Lytle,
Phys. Rev. Lett. 125, 222003 (2020 [arXiv:2007.06956]
$\mathcal{R}(J/\psi) = 0.71 \pm 0.25$
$\mathcal{R}(J/\psi)_{SM} = 0.2582 \pm 0.0038$
1.8 σ

Outlook

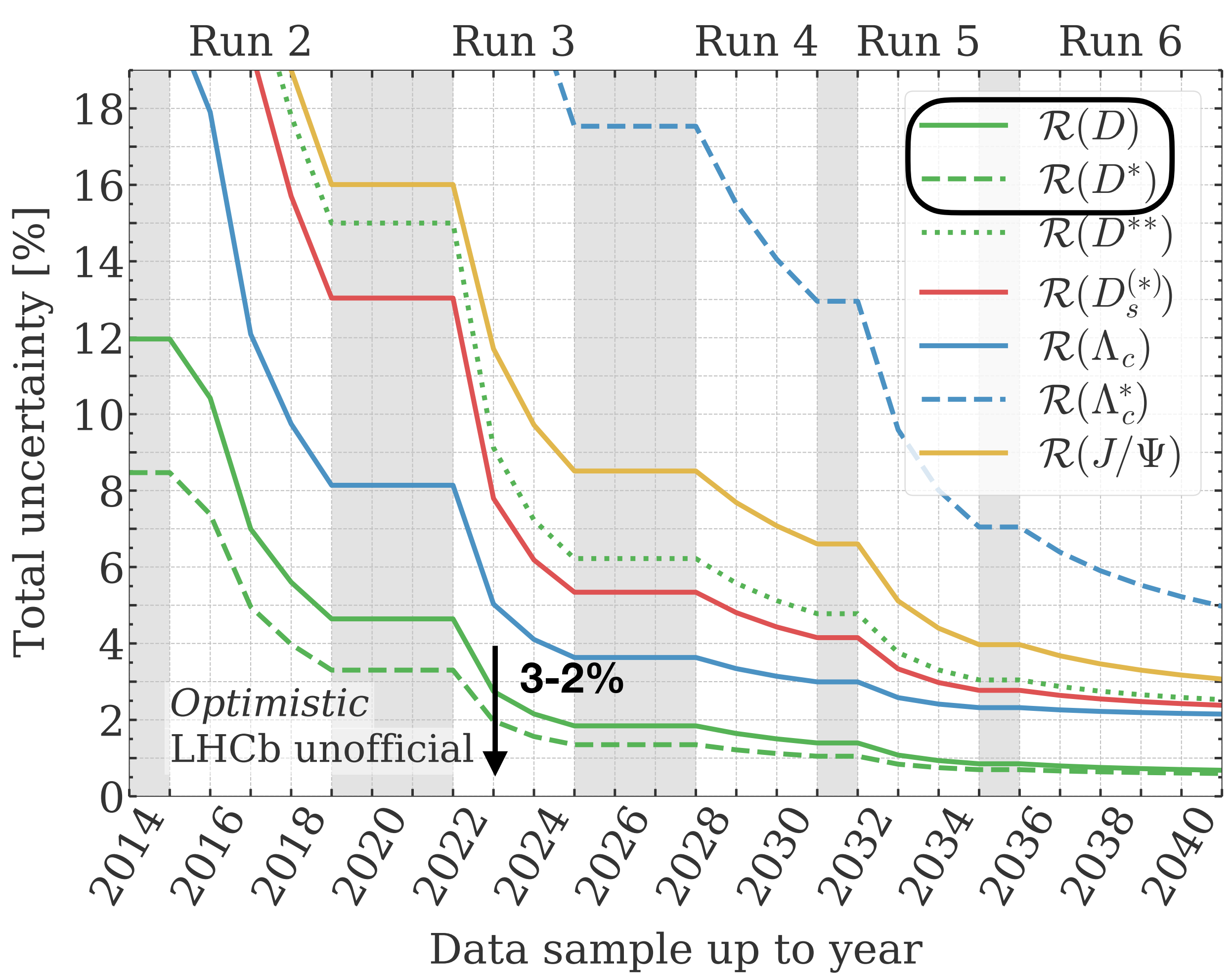
FB, M. Franco Sevilla, D. Robinson, G. Wormser
[arXiv:2101.08326], submitted to Review of Modern Physics

Much larger LHCb & Belle II data sets are **coming soon**

Will **push precision** of measured ratios considerably

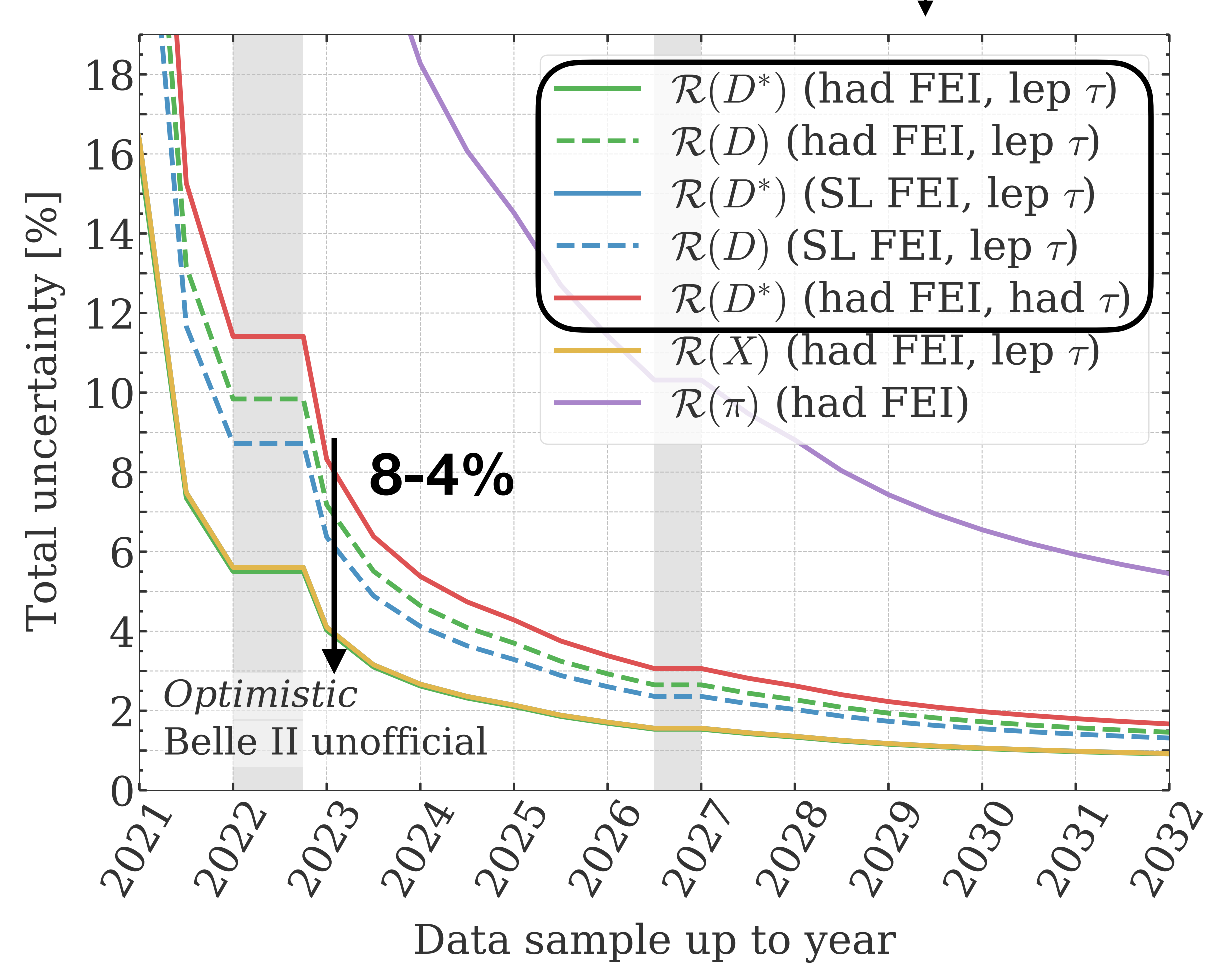
→ several ab^{-1} & several 10 x fb^{-1}

LHCb

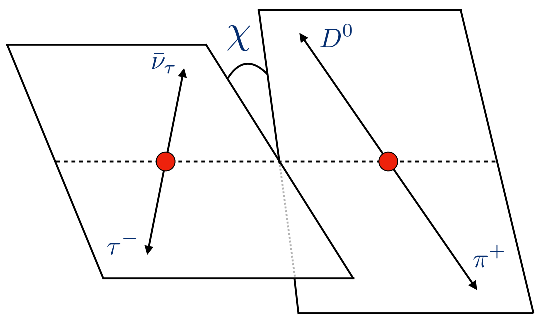


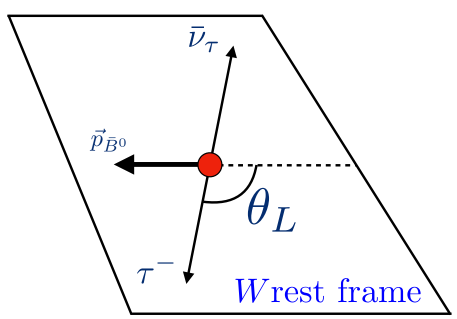
Belle II

orthogonal tagging selections



Outlook

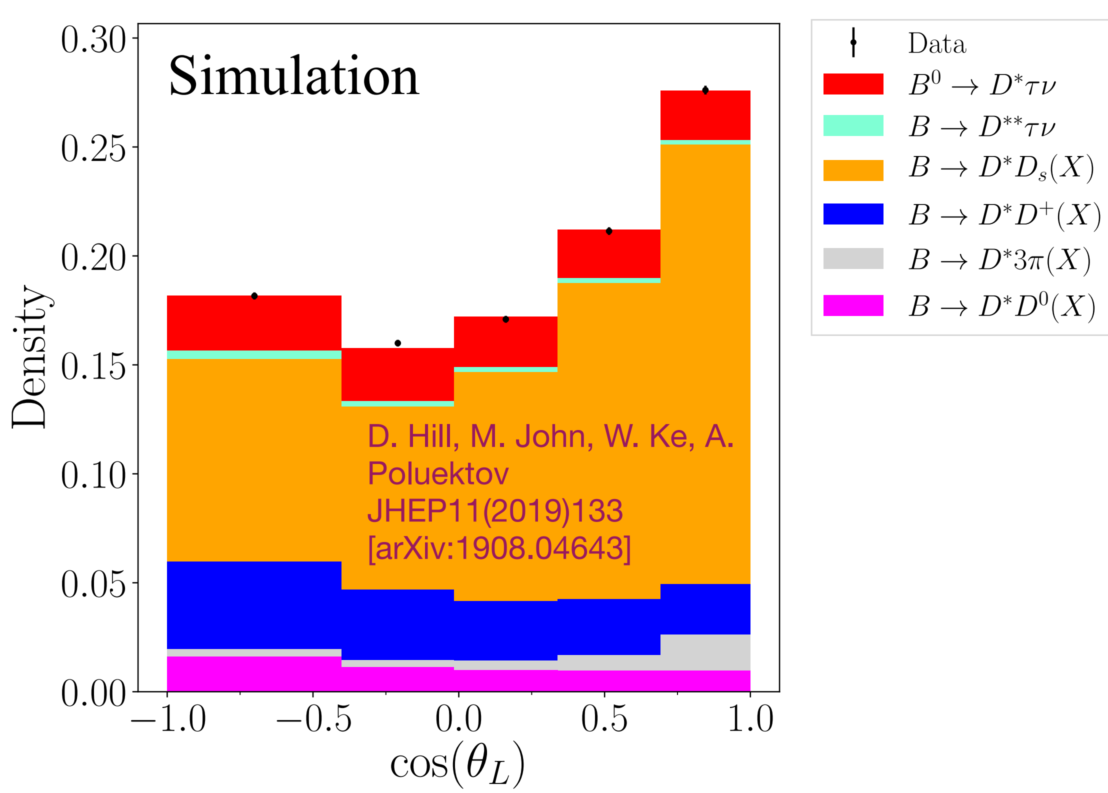




Novel ideas are emerging how to make best use of the available data

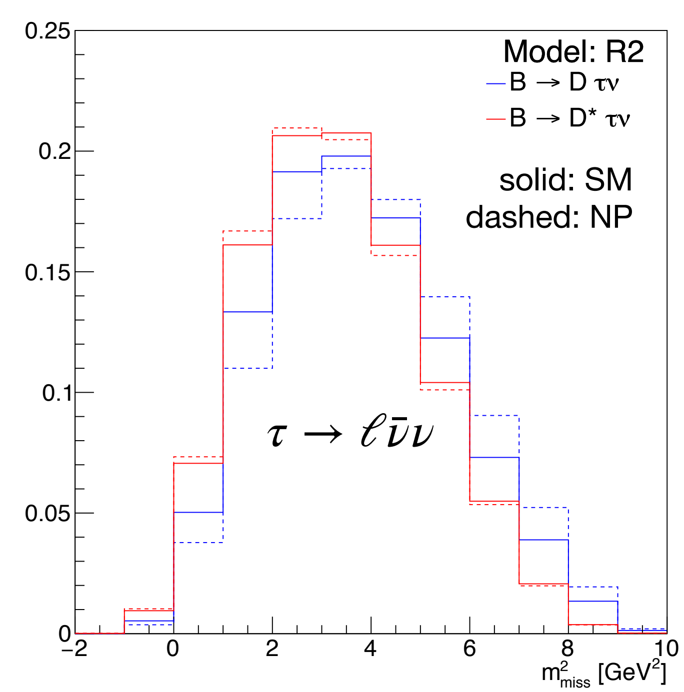
Model-independent interpretations via **angular analyses** or **direct determinations** of **NP couplings**

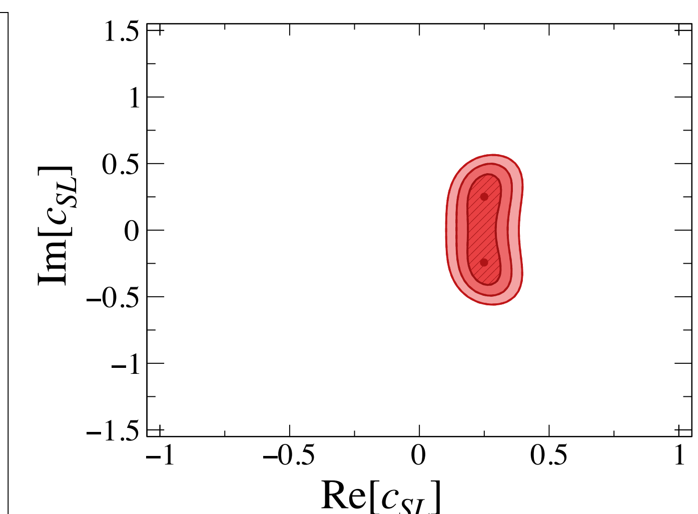
LHCb



Belle II

FB, M. Franco Sevilla, D. Robinson, G. Wormser [arXiv:2101.08326], submitted to Review of Modern Physics





Directly constrained NP coupling from kinematic shape

More Slides

Meet the “Measurement Matrix”

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

$\otimes$ Polarisation → **Belle:** Phys.Rev.Lett.118,211801 (2017) Phys. Rev. D 97, 012004 (2018) (D* had tag)

$\otimes$

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

$\otimes$

D	D^*	π

Polarisation

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, q²)
Phys.Rev. D94,072007 (2016)
(D*, SL tag, p_{D^*}, p_l)

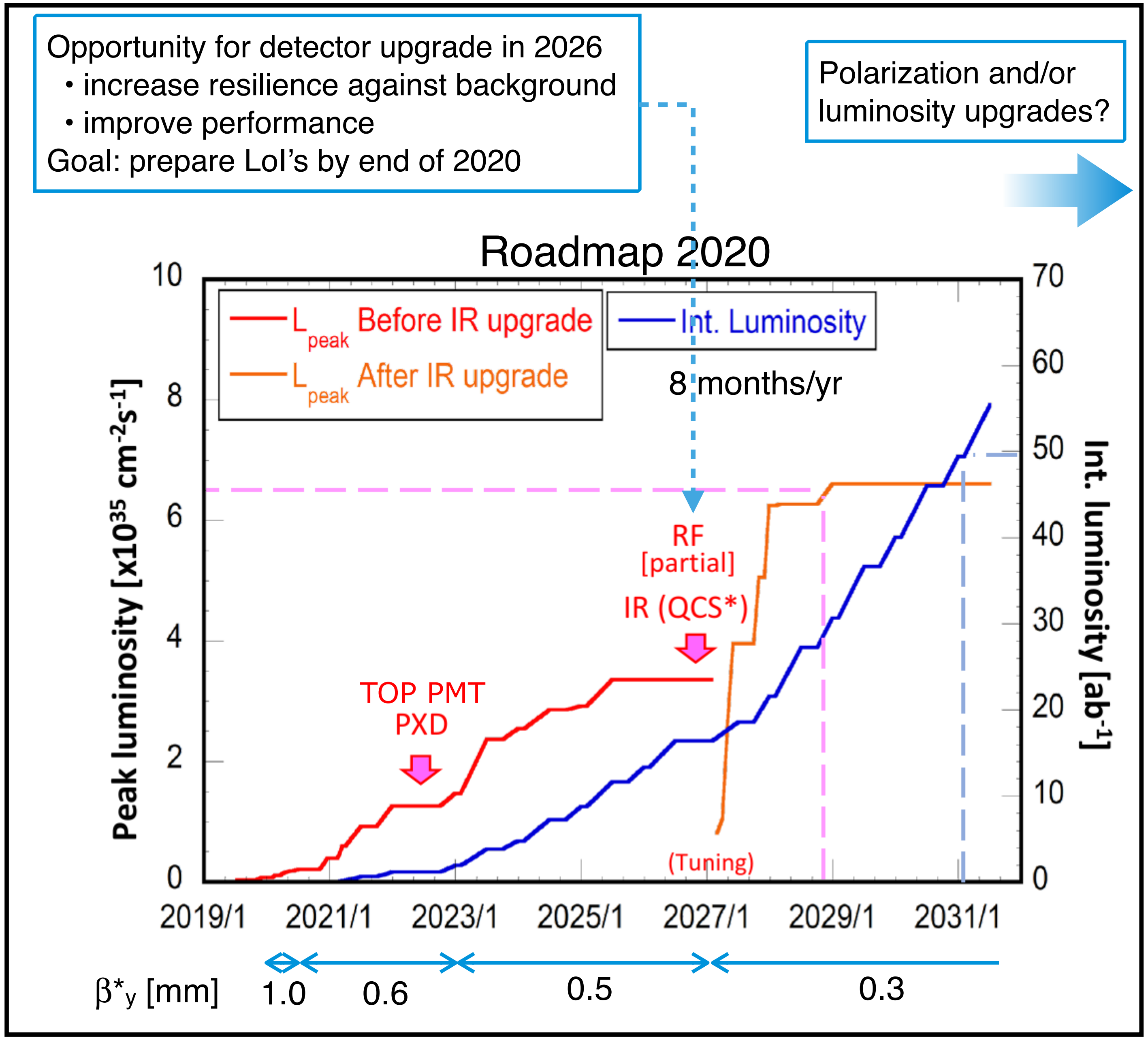
Belle:
Phys. Rev. D 93, 032007 (2016)
(π had tag)

BaBar:
Phys.Rev.Lett. 109,101802 (2012)
Phys.Rev.D 88, 072012 (2013)
(D/D* had tag, q²)

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)



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	
	$\epsilon_{\rm sig}/\epsilon_{\rm norm}$	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	
	$\epsilon_{\rm sig}/\epsilon_{\rm norm}$	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 **$B^0 \to D^*\pi^+\pi^+\pi^-$**

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

- 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

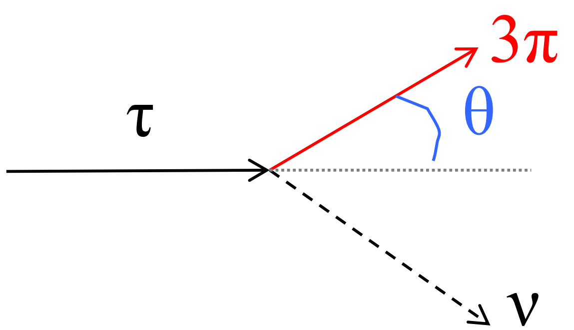
Invariant mass of $D^*3\pi$ system

Neutral isolation variables

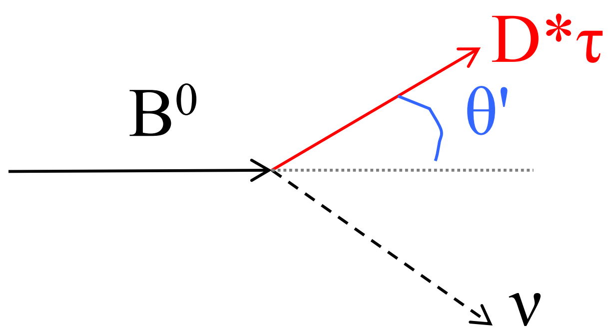
LHCb Measurement of $R(D^*)$: q^2 & τ decay time

4-fold ambiguity:

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



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



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.

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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.

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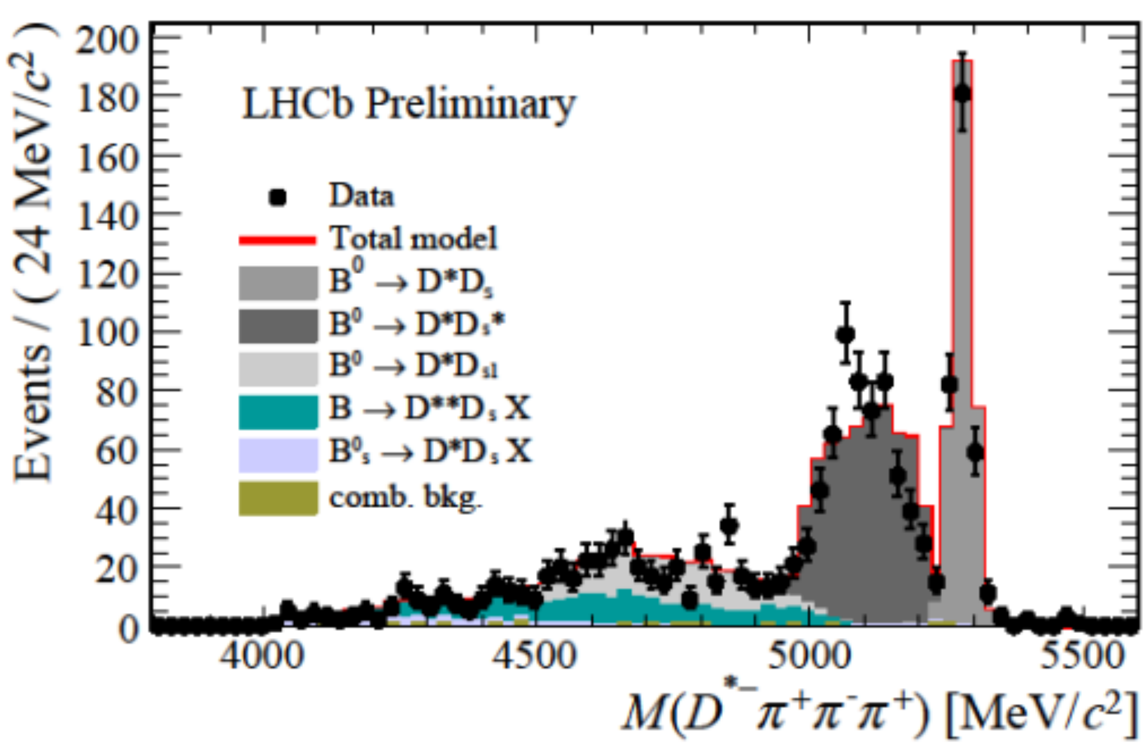

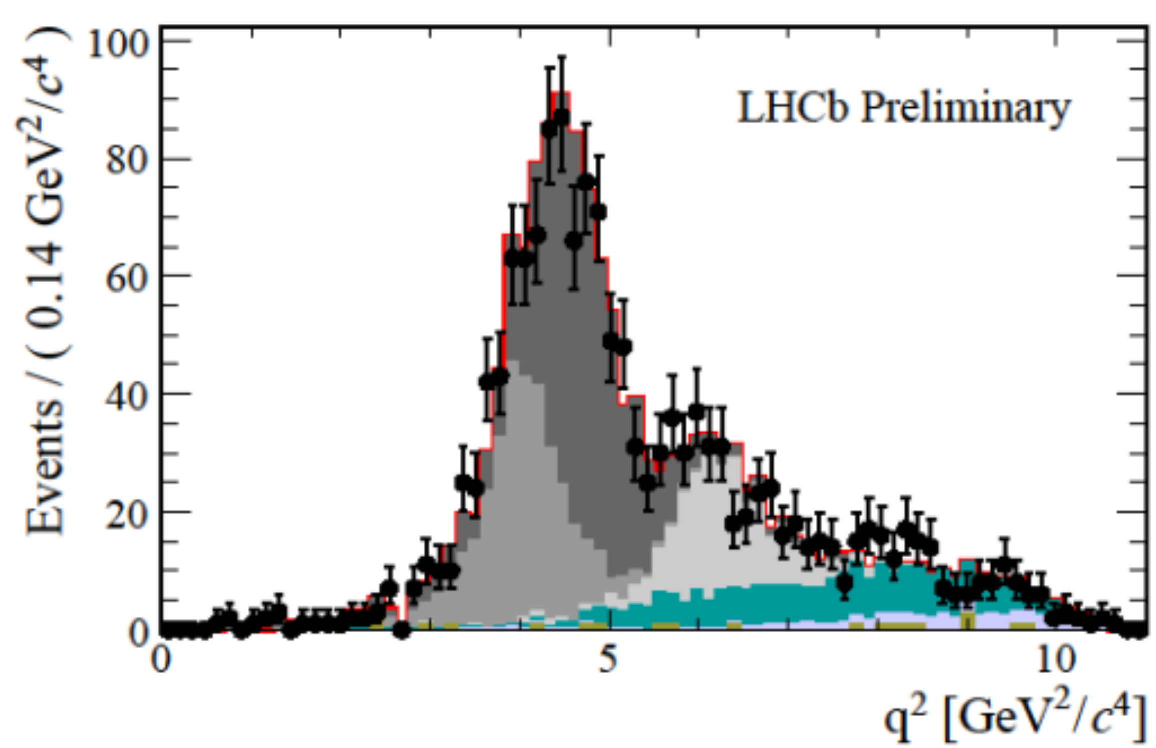

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LHCb Measurement of $R(D^*)$: *Control samples*

$X_b \rightarrow D^{*-} D^0 X$ decays can be isolated by selecting exclusive $\mathbf{D^0 \rightarrow K^- 3\pi}$ 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 $D^{+,0} \rightarrow K^{0,+} 3\pi$

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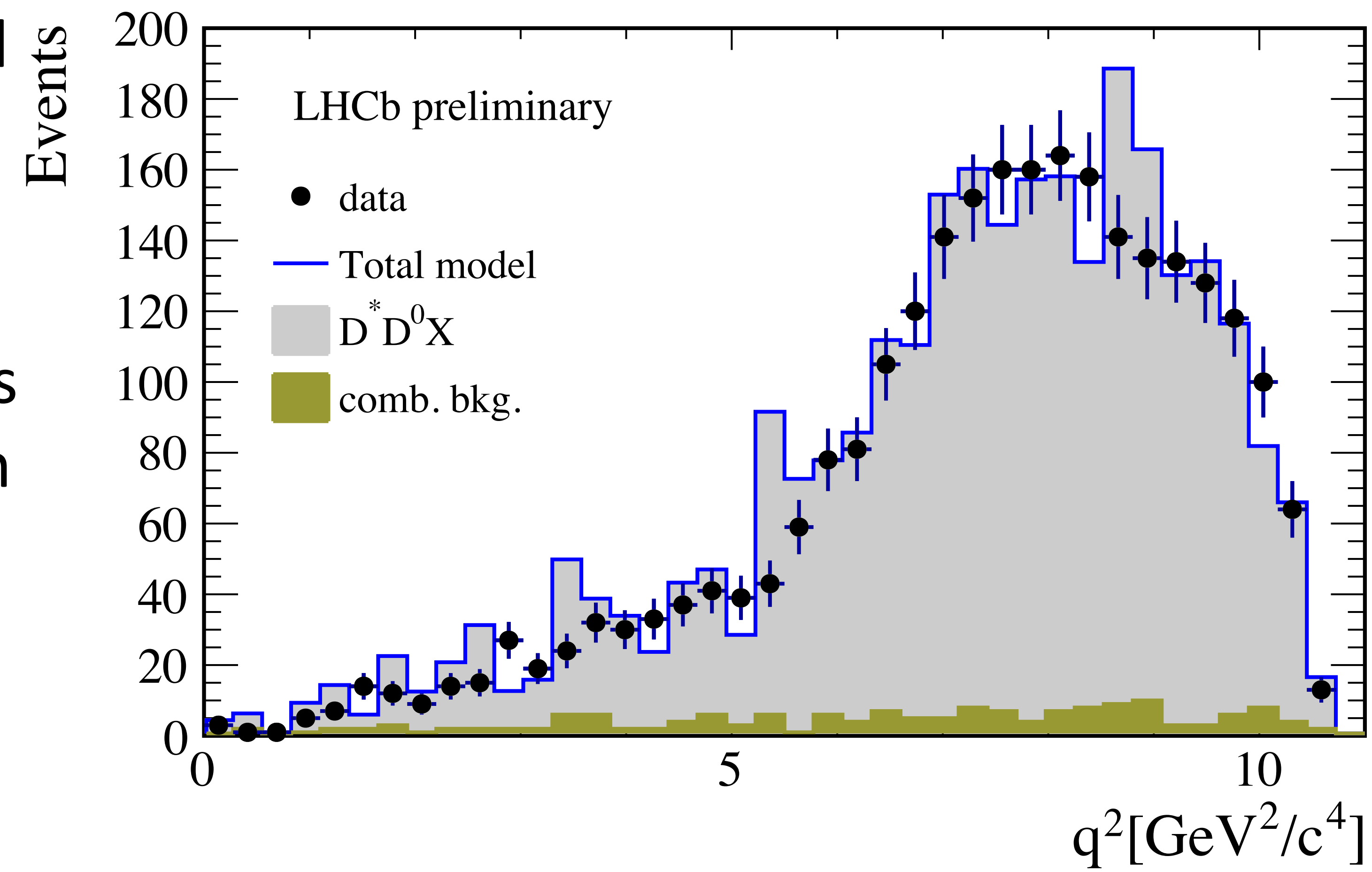

For the D°, the inclusive 4 prongs BR constrains strongly the rate of 3π events

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

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