KIT
Karlsruher Institut für Technologie

Bundesministerium für Bildung und Forschung

Measurements of R(D$^{(*)}$) and similar ratios

from Belle, BaBar and an outlook for Belle II

XXIV Cracow EPIPHANY Conference on Advances in Heavy Flavour Physics

Emmy Noether-Programm
DFG

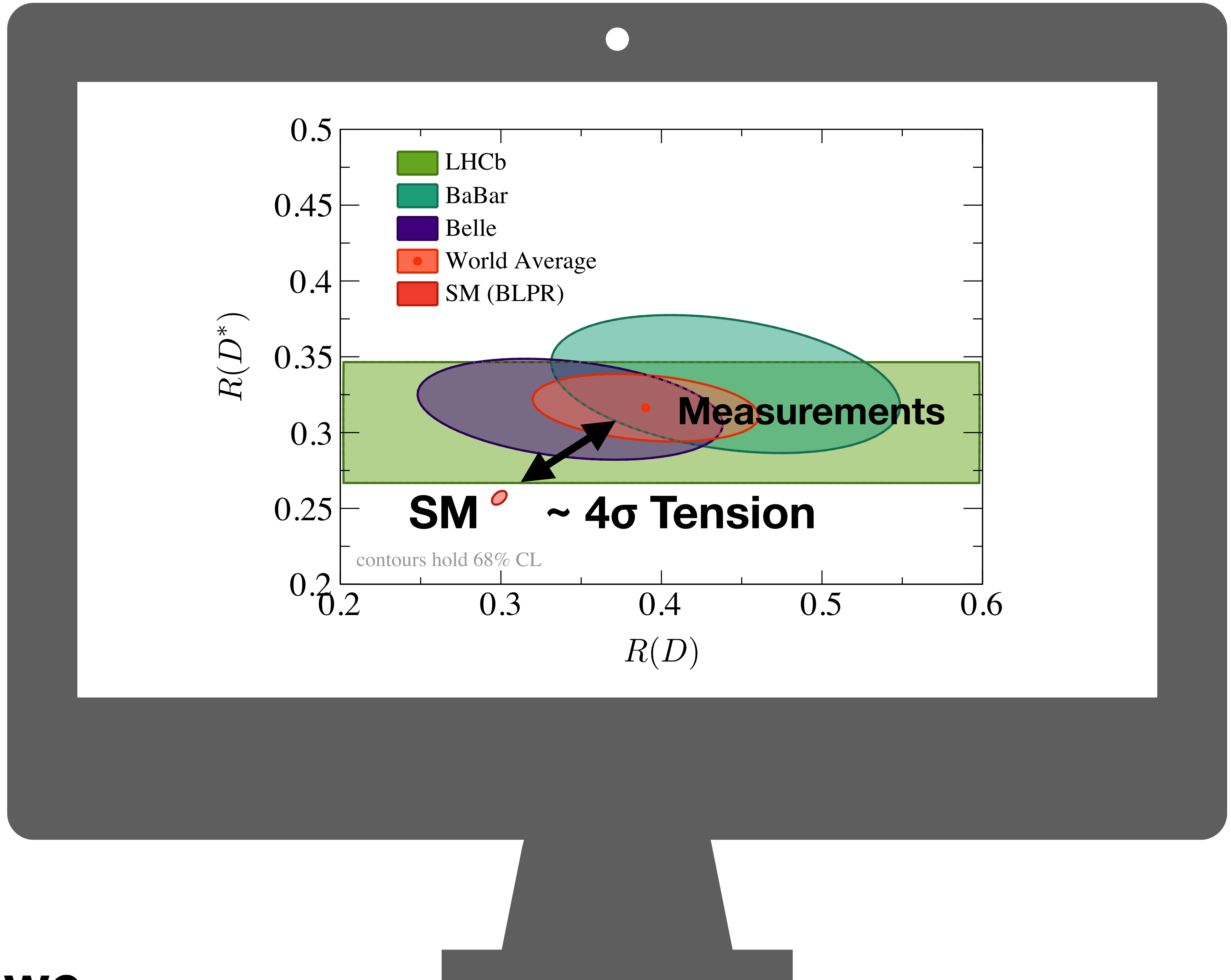
Florian Bernlochner | florian.bernlochner@kit.edu

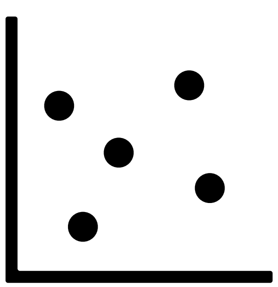
$$R = \frac{b \to q\,\tau\bar{\nu}_\tau}{b \to q\,\ell\bar{\nu}_\ell}$$

$\ell = e, \mu$

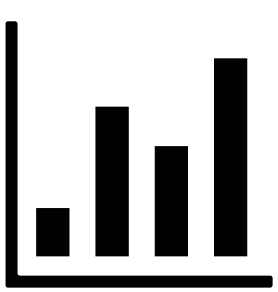
$\downarrow$

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

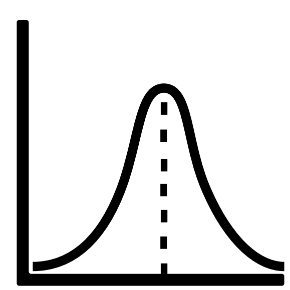




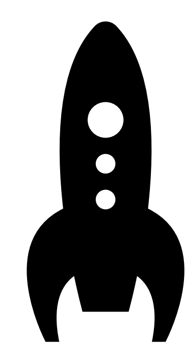
1. How do we measure?



2. How do we predict?



3. Is it really 4σ?



4. The future

1. How do we measure?

and why do we think we got it (mostly) right!

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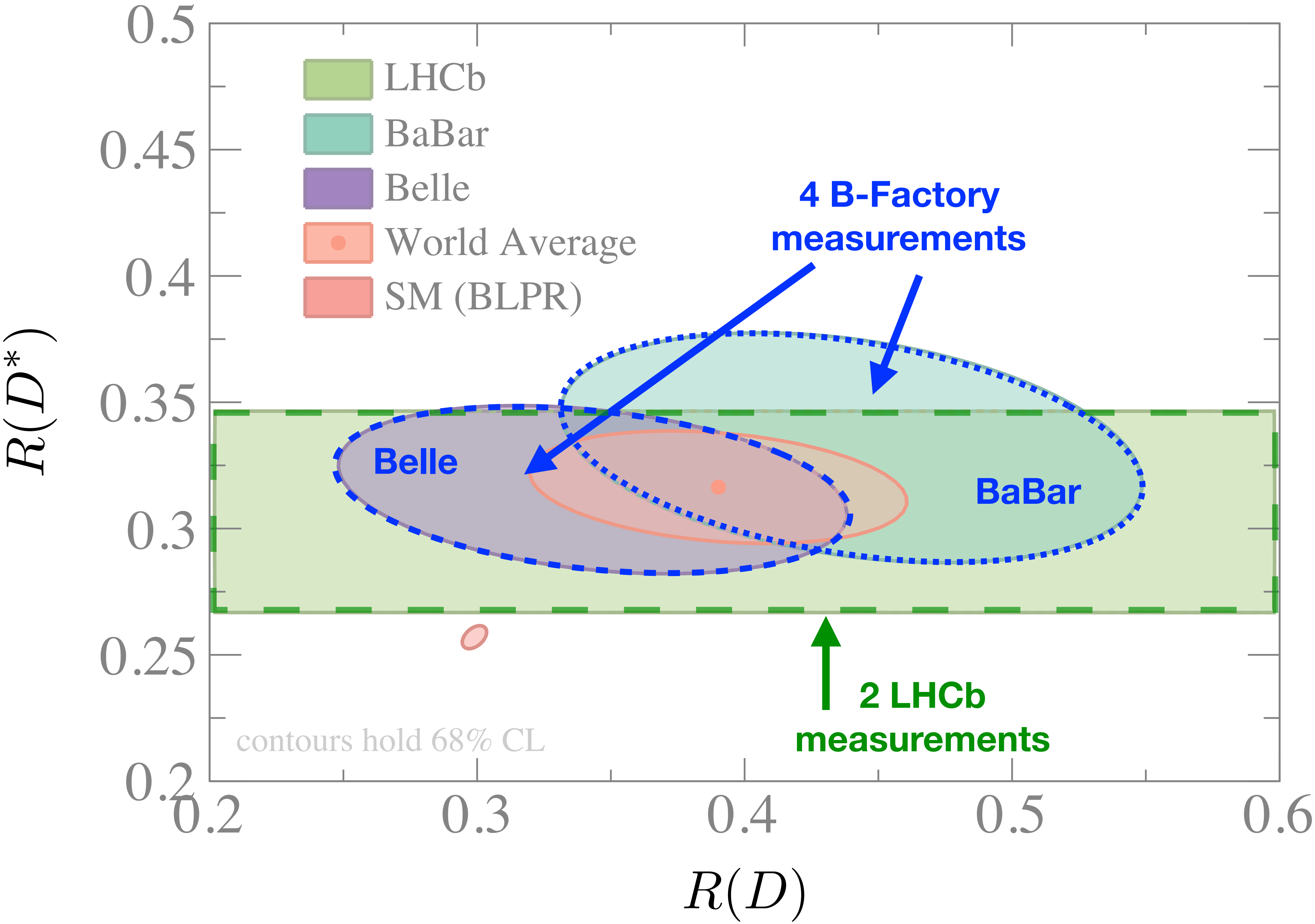


+ 1 B-Factory measurement of $R(\pi)$

1 LHCb measurement of $R(J/\psi)$

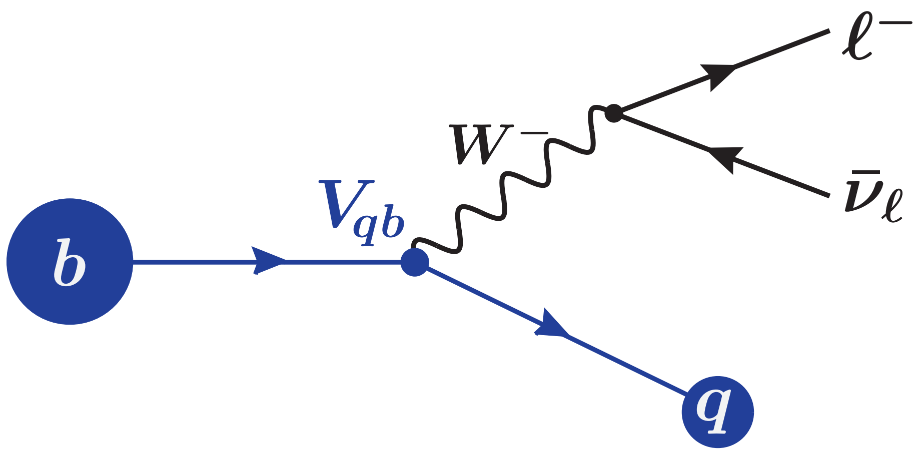
Overview

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

$\ell = e, \mu$

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**

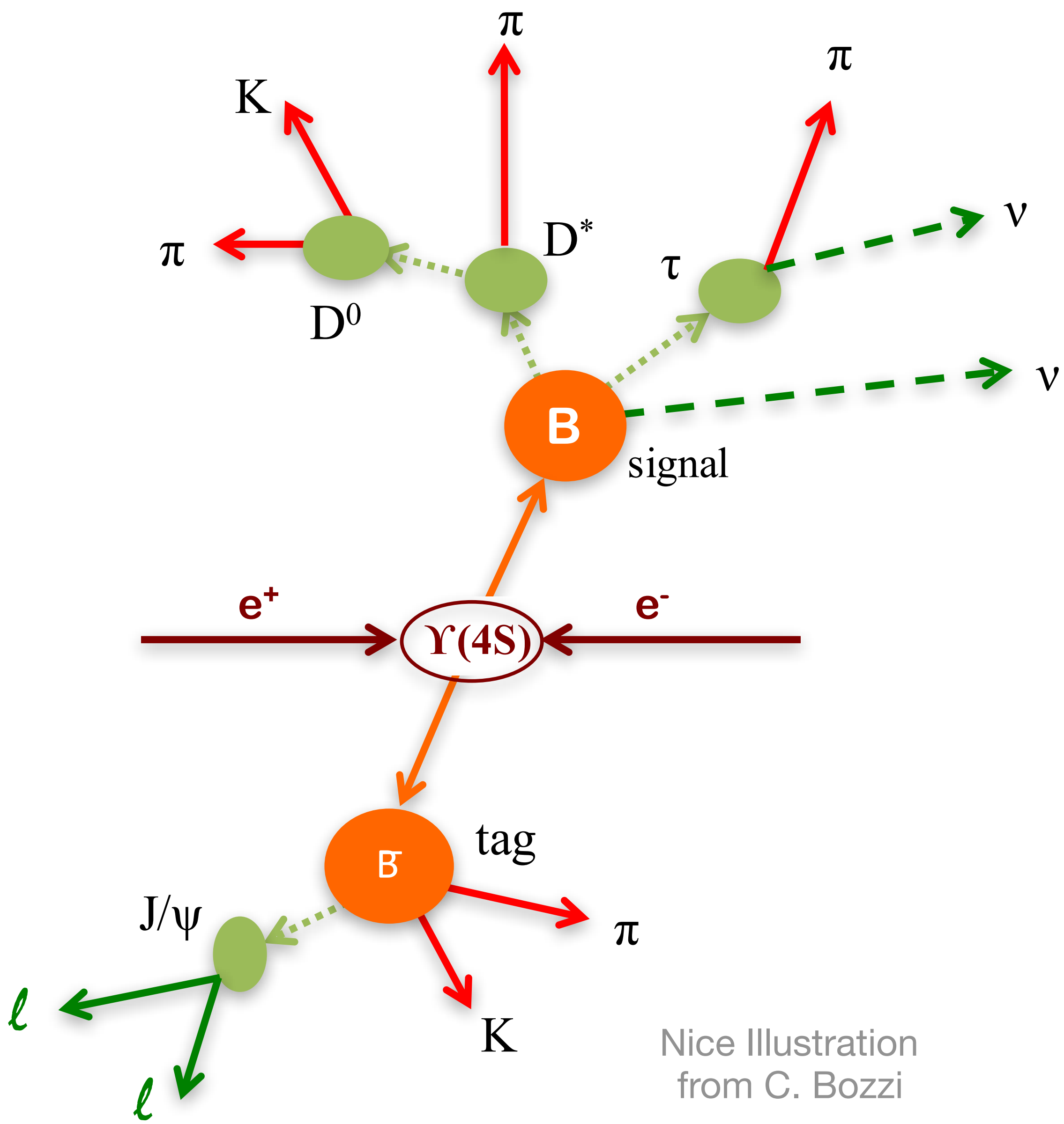
Overview

3. Semileptonic decays at B-Factories

- e+/e- collision produces ***Y(4S) → BB̄***
- Fully reconstruct one of the two B-mesons ('tag') → **possible** to measure **momentum** of signal B
- **Missing four-momentum** (**neutrinos**) can be reconstructed with high precision

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

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

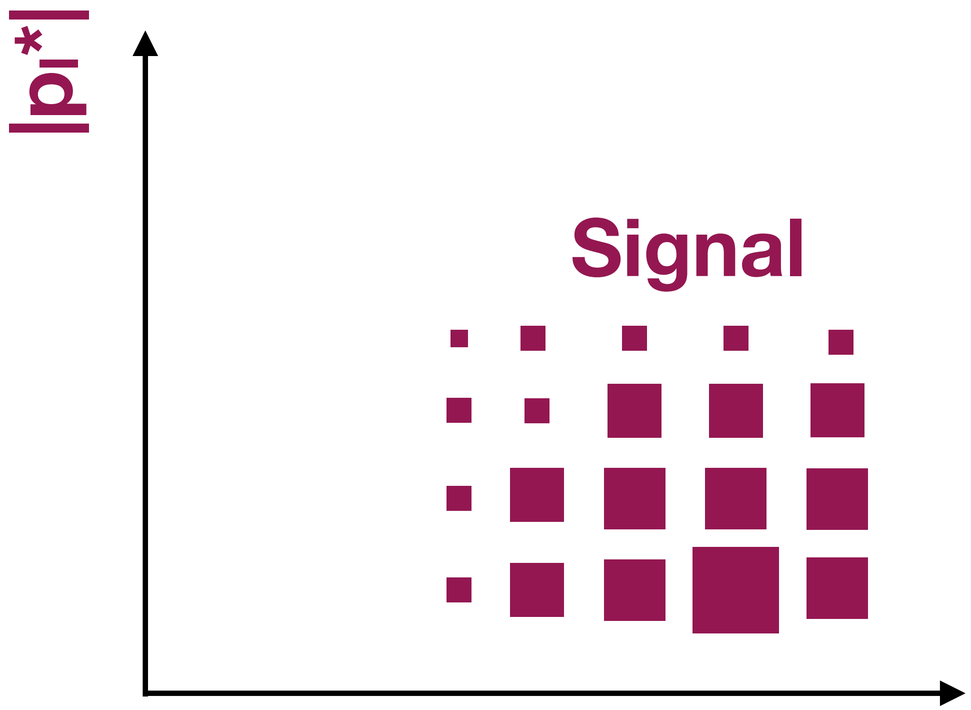


Nice Illustration from C. Bozzi

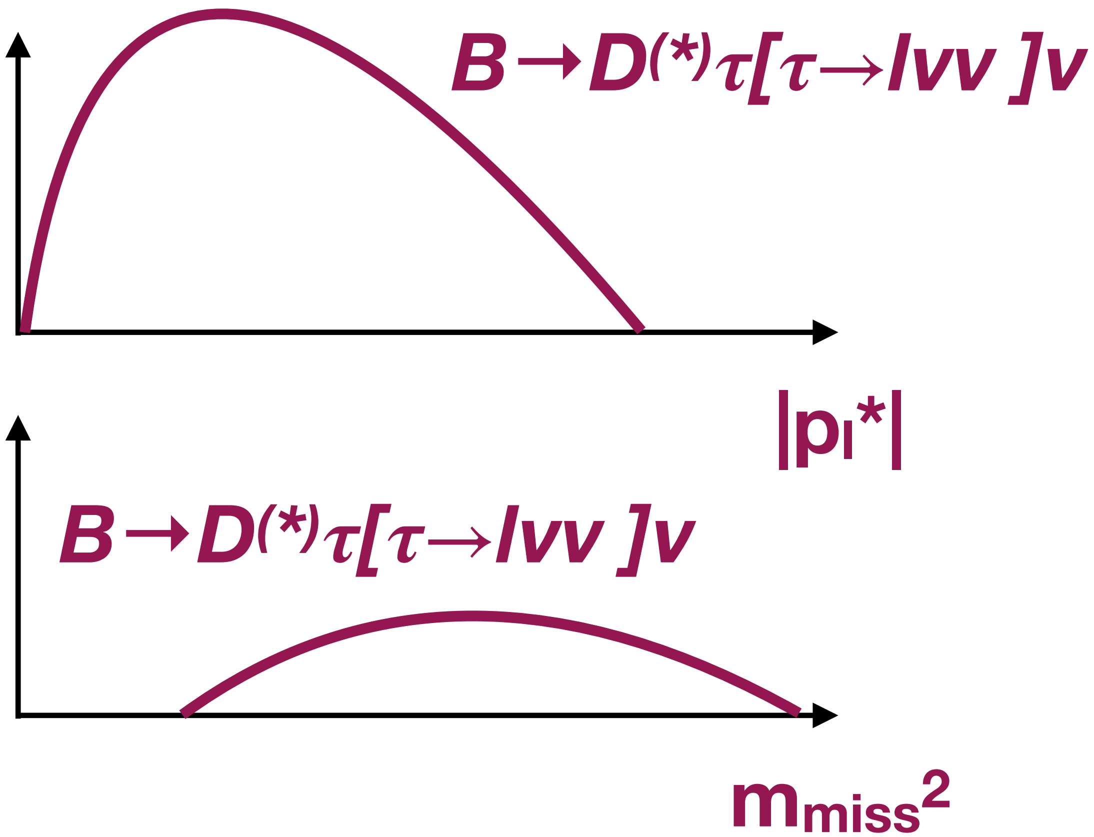
BaBar Measurement of $R(D^{(*)})$

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

- Use of $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$ to reconstruct **τ-lepton**
- Simultaneous analysis of *R(D)* vs. *R(D*)* using $B^0 \to D^{*-}\tau\nu$, $B^- \to D^{*0}\tau\nu$, $B^0 \to D^-\tau\nu$, $B^- \to D^0\tau\nu$
- Unbinned maximum likelihood fit in 2D to m_{miss}^2 and $|p_l^*|$



$$(p_{\text{beam}} - p_{B\text{tag}} - p_{D^{(*)}} - p_\ell)^2 = m_{miss}^2$$



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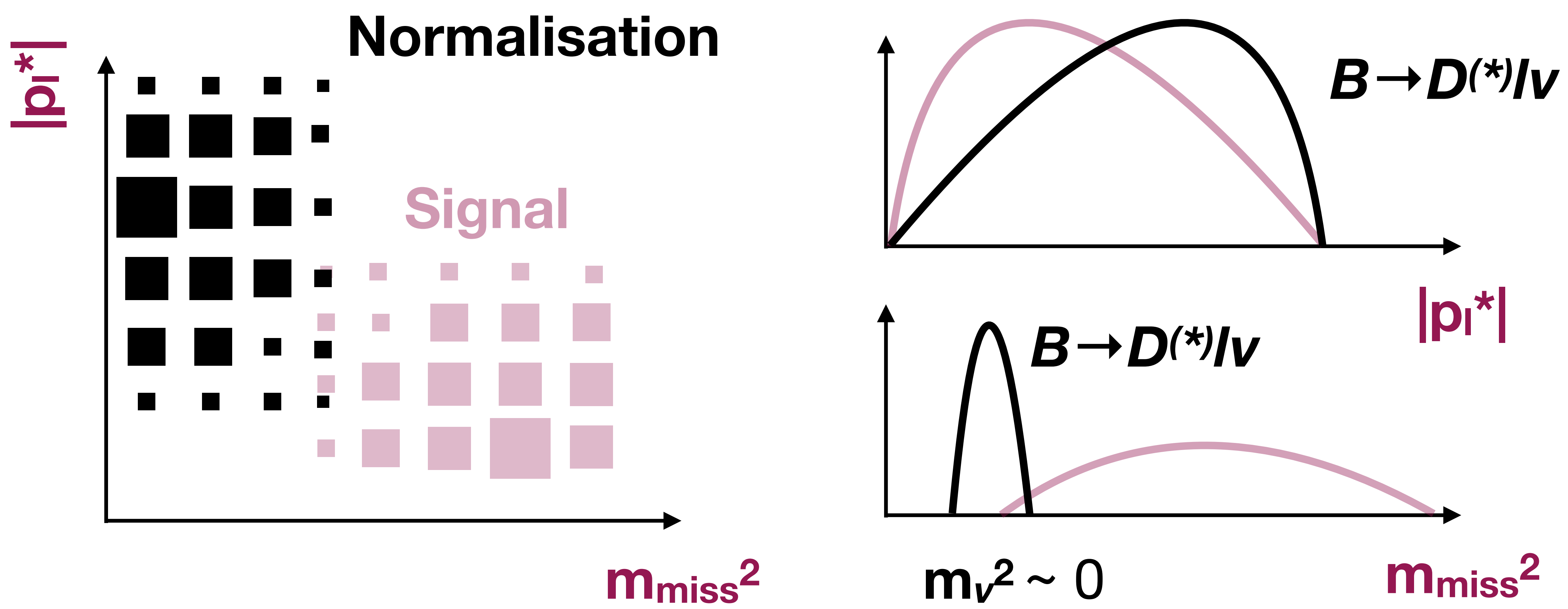

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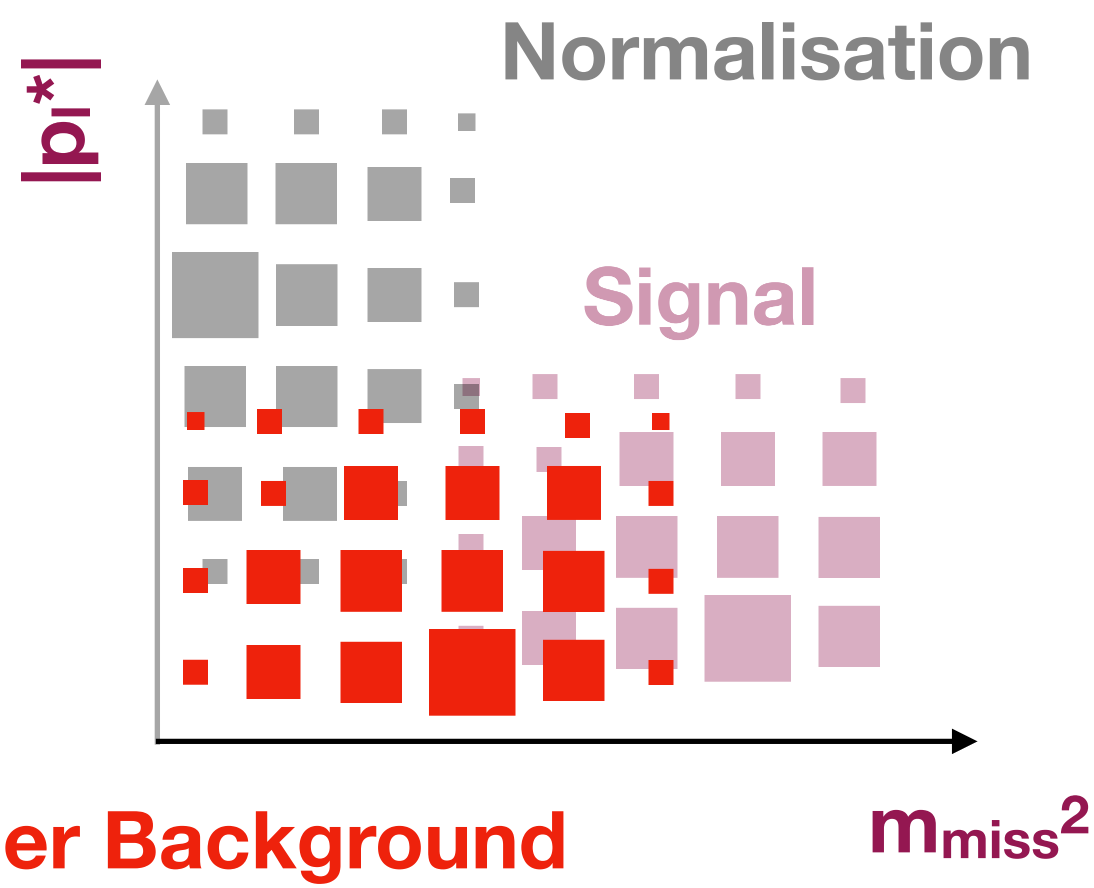

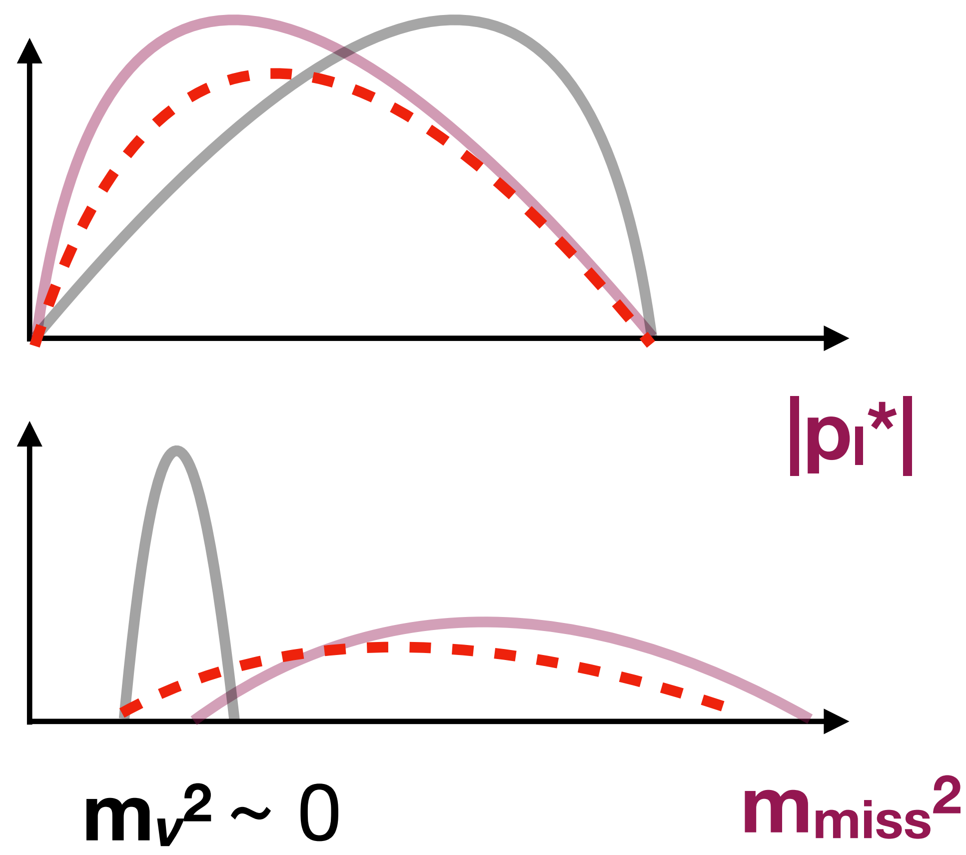

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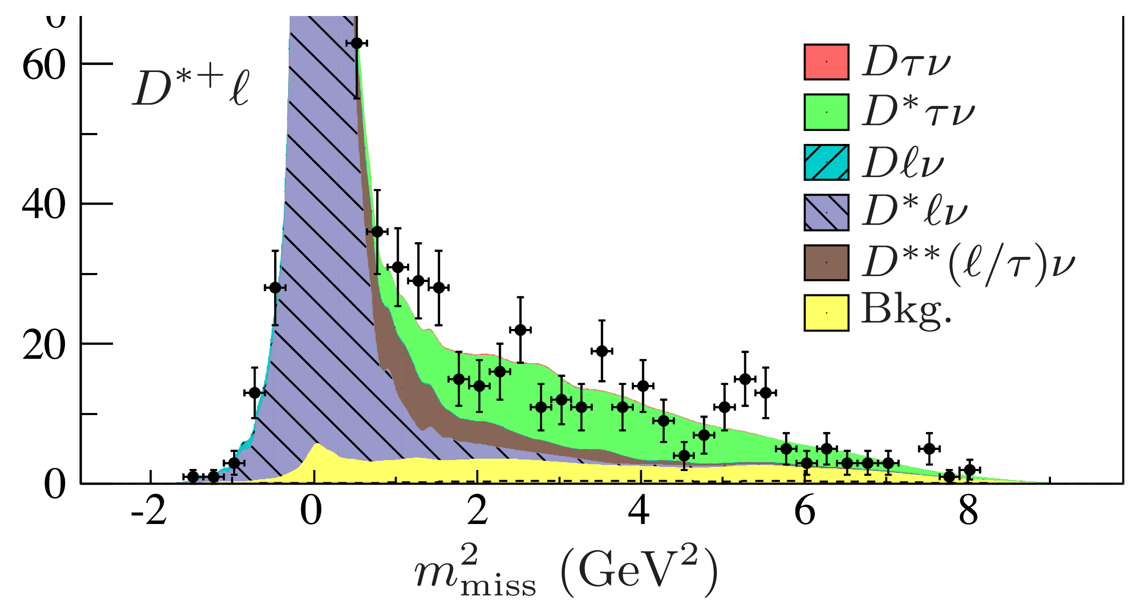

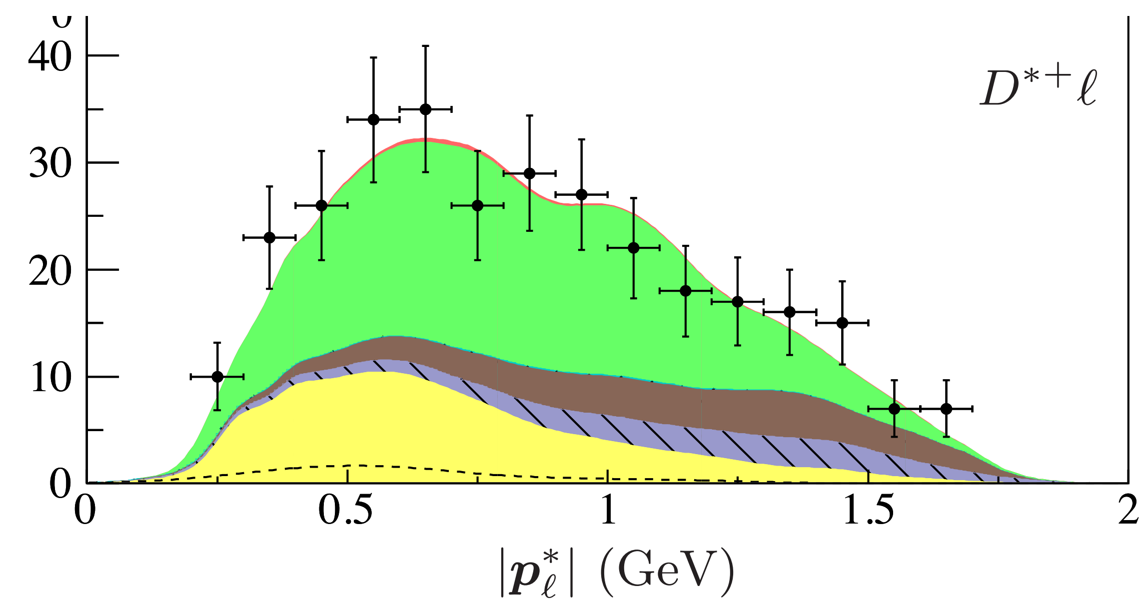

$$\mathcal{R}(D^{(*)}) = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}},$$

$R(D) = 0.440 \pm 0.058$ (stat) ± 0.042 (syst) (2σ from SM)
$R(D^*) = 0.332 \pm 0.024$ (stat) ± 0.018 (syst) (2.7σ from SM)

✓ **Combination is 3.4σ from SM**

Belle Measurements of $R(D^{(*)})$

Phys.Rev.D 92, 072014 (2015)
Phys.Rev. D94,072007 (2016)
Phys.Rev.Lett.118,211801 (2017)

Several results using different techniques:

- $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$, *hadronic tag*

$R(D) = 0.375 \pm 0.064$ (stat) ± 0.026 (syst)
$R(D^*) = 0.293 \pm 0.038$ (stat) ± 0.015 (syst)

Analysis very similar to BaBar

- $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$, *semileptonic tag*

$R(D^*) = 0.302 \pm 0.030$ (stat) ± 0.011 (syst)

- $\tau \to \pi\nu$ and $\tau \to \rho\nu$, *hadronic tag*

$R(D^*) = 0.270 \pm 0.035$ (stat) ± 0.027 (syst)
$P_\tau(D^*) = -0.38 \pm 0.51$ (stat) ± 0.18 (syst)

First measurement of polarisation

Phys. Rev. D 95, 115008 (2017)

✓ **All $R(D^{(*)})$ measurements consistent but above SM**

$R(D)_{SM} = 0.299 \pm 0.003$
$R(D^*)_{SM} = 0.257 \pm 0.003$

Belle Measurements of $R(D^{(*)})$

Phys.Rev.D 92, 072014 (2015)

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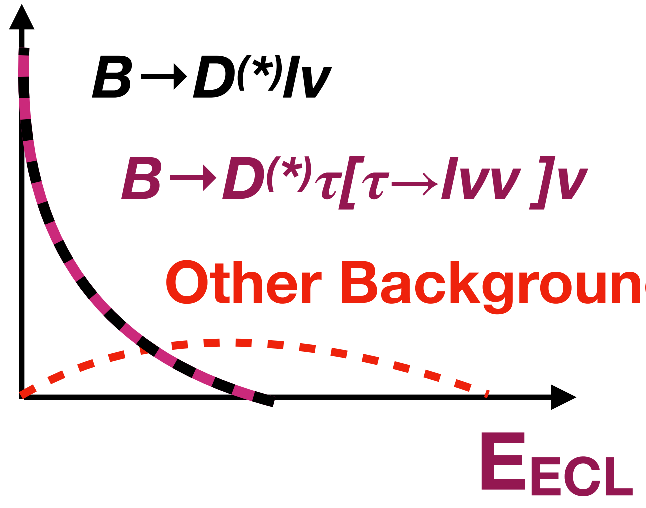
- Multivariate hadronic tagging algorithm with **Neural Network**
- Use binned likelihood fit in 2D to **m_{miss}^2** and signal **Neural Network**

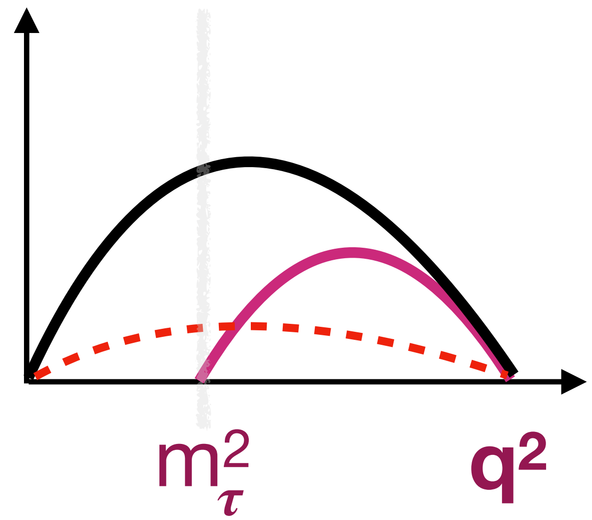
- **E_{ECL}** (unassigned energy in the calorimeter)
- **q^2** (four-momentum transfer)

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

- **$|p_l^*|$ + more variables**

Most discriminating variable: E_{ECL}





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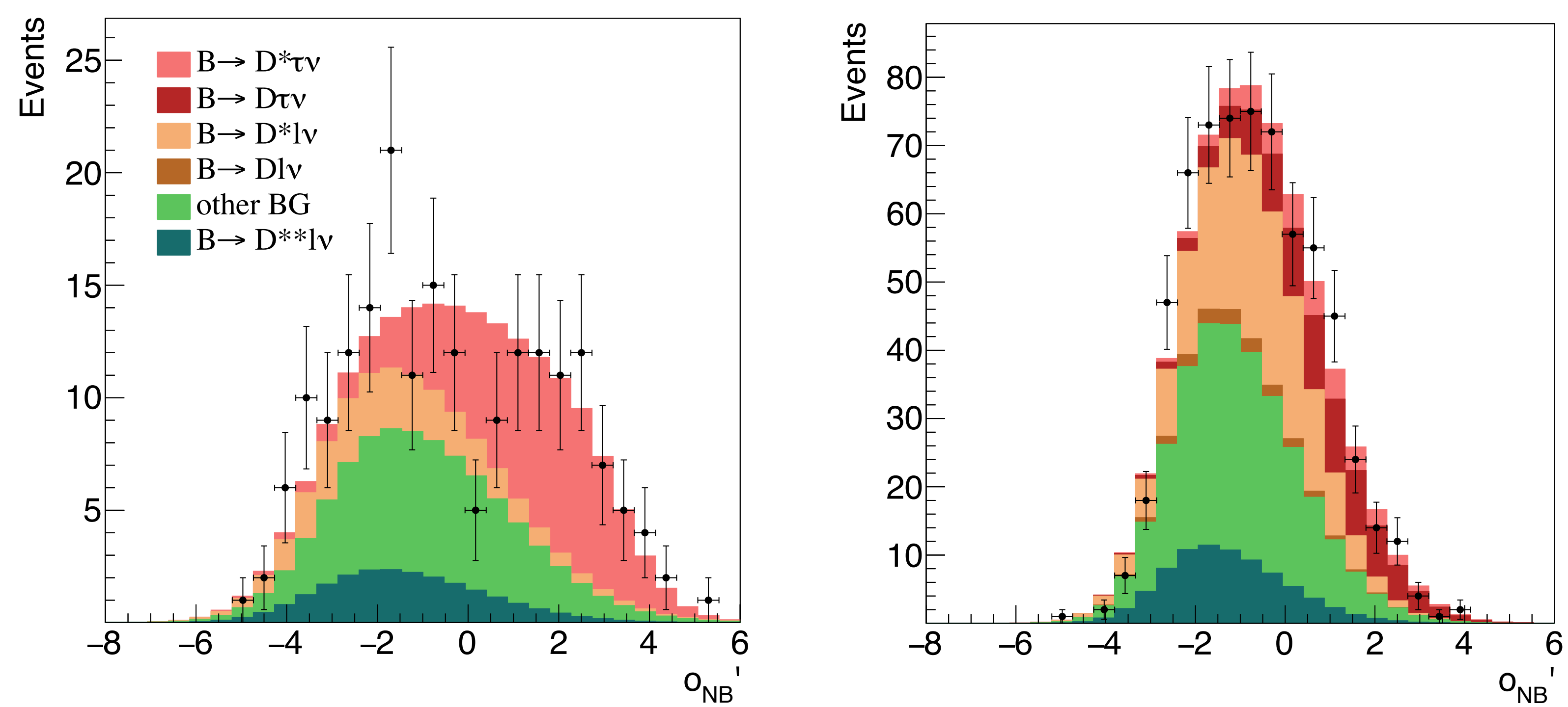
Classifier Distributions after m_{miss}^2 cut to enhance signal

$$\mathcal{R}(D^{(*)}) = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}},$$



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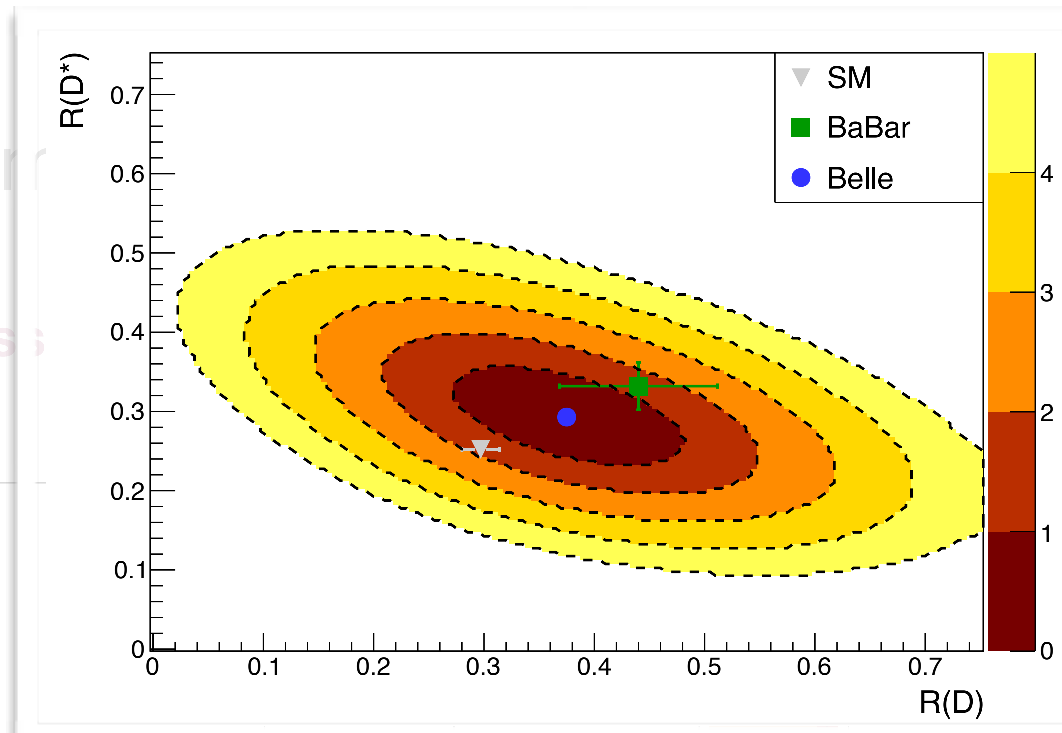

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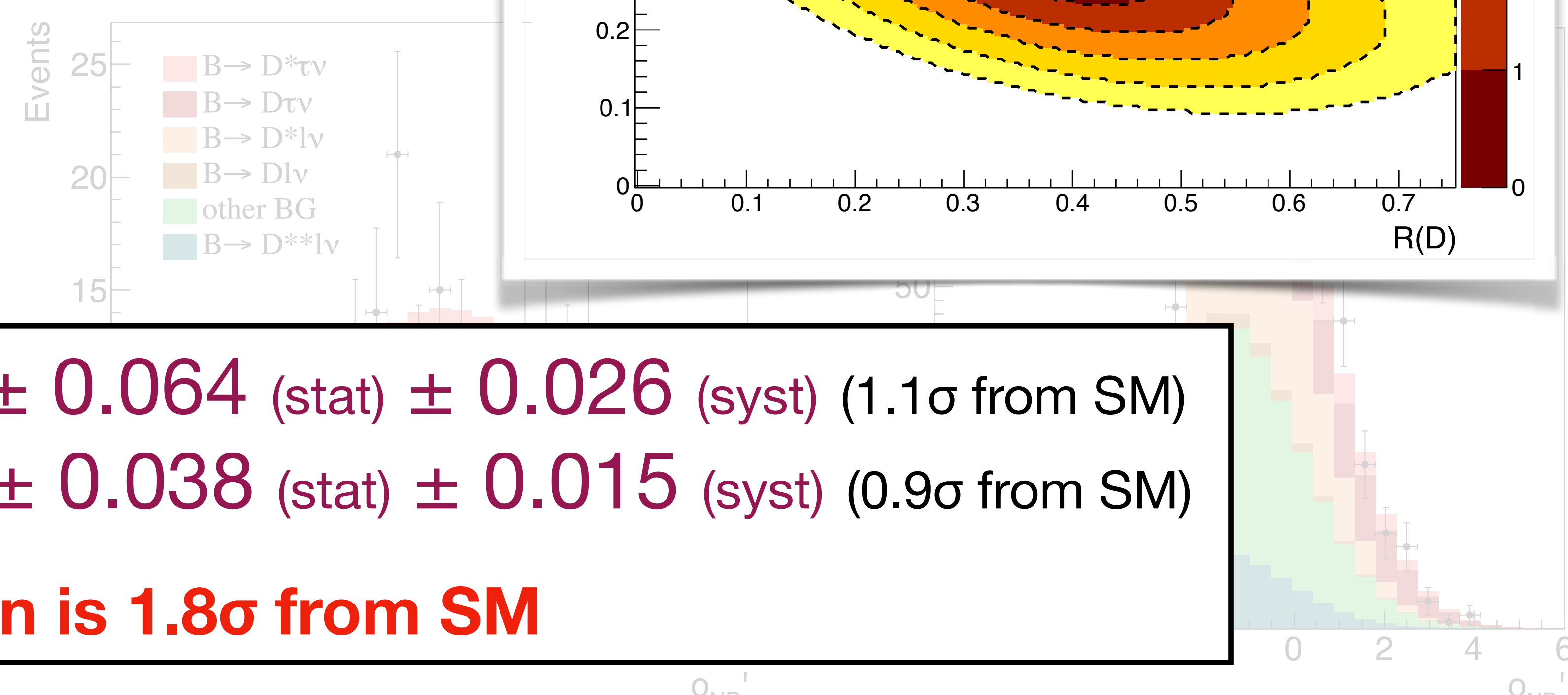


$\mathcal{R}(D^{(*)})$

R(D) = 0.375 ± 0.064 (stat) ± 0.026 (syst) (1.1σ from SM)
R(D*) = 0.293 ± 0.038 (stat) ± 0.015 (syst) (0.9σ from SM)

✓ **Combination is 1.8σ from SM**

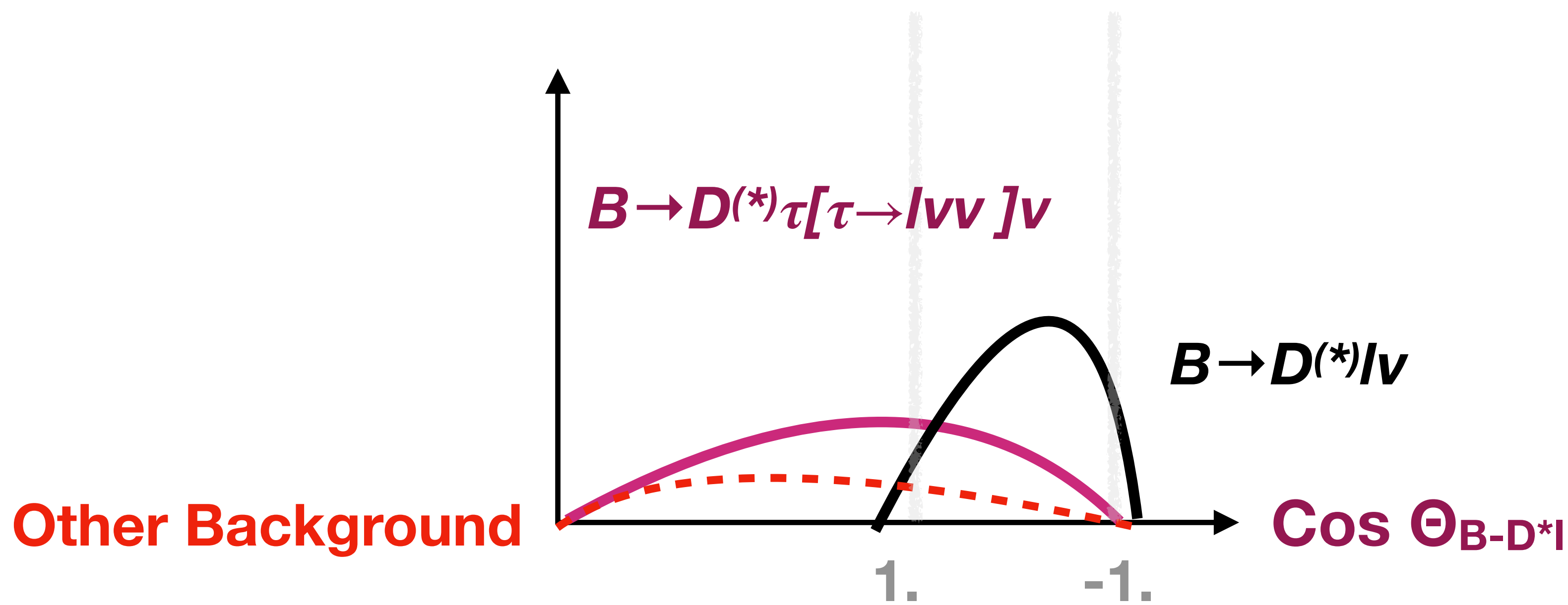
Belle Measurements of $R(D^*)$

Phys.Rev. D94,072007 (2016)

- Use of $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$ to reconstruct **τ-lepton**
- Instead of **hadronic** use prompt **semileptonic** for tag-side reconstruction; *only measures R(D*) due to large backgrounds*
  - Larger BF, but less information due to tag-side neutrino

Discriminating variable m_{miss}^2 less powerful due to second neutrino, but can use angle between *B* and *D*l*

$$\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\text{beam}}E_{D^*\ell} - m_B^2c^4 - M_{D^*\ell}^2c^4}{2|\vec{p}_B|\cdot|\vec{p}_{D^*\ell}|c^2},$$



Belle Measurements of *R(D*)*

Phys.Rev. D94,072007 (2016)

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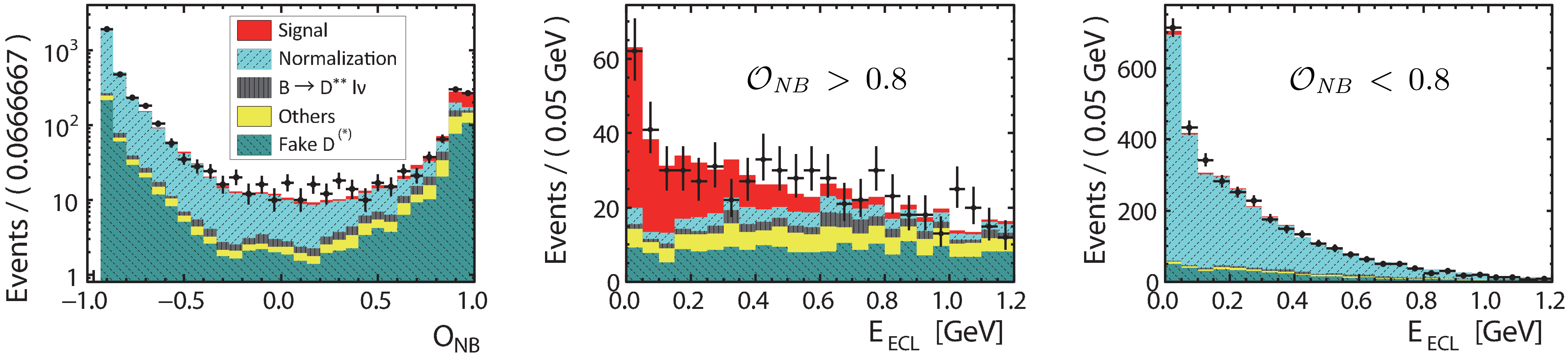
  - Neural Network with Cos Θ_{B-D^*l},, m_{miss}^2, visible energy
- Use binned likelihood fit in 2D to **E_{ECL}** and **Neural Network**
  - Post-fit projections:



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R(D*) = 0.302 ± 0.030 (stat) ± 0.011 (syst) (1.4σ from SM)

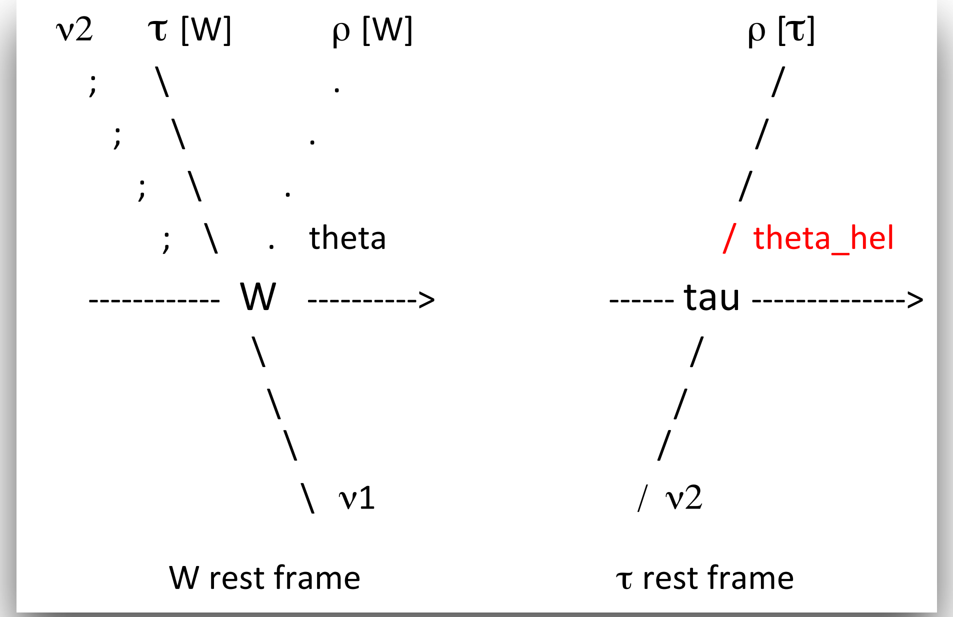
Belle Measurements of *R(D*)*

Phys.Rev.Lett.118,211801 (2017)
+ [arXiv:1709.00129]

- Decay angles of $\tau \to \pi \nu$ and $\tau \to \rho \nu$ encode ***τ-polarisation***, sensitive to NP!

  ✓ **Need to reconstruct helicity angle, but a-priorio τ-restframe not accessible**

  ✓ **Luckily there is a relation between *<(τh) in τν-frame and this angle***



Nice Illustration
from V. Luth

- **Hadronic** tagging essential to reconstruct this frame

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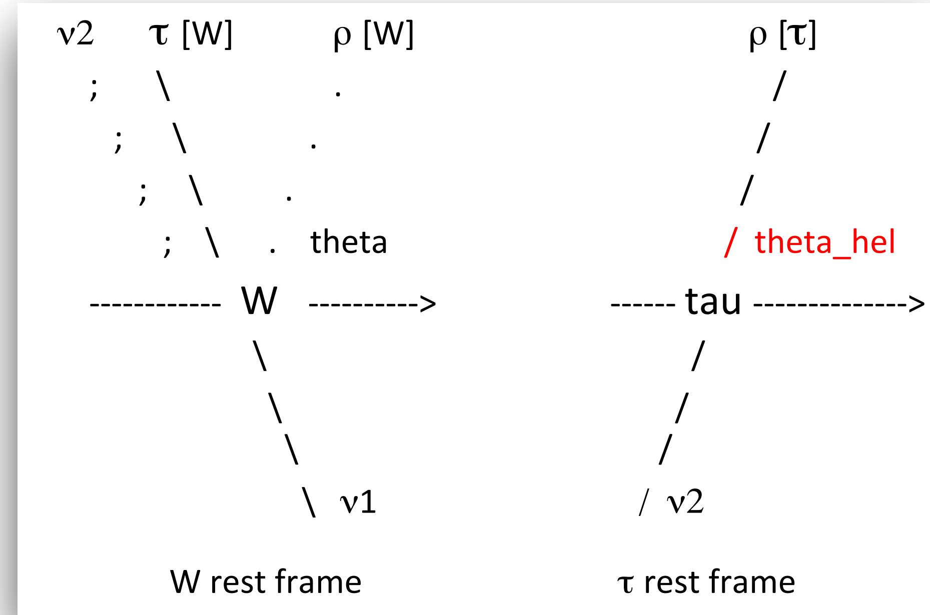

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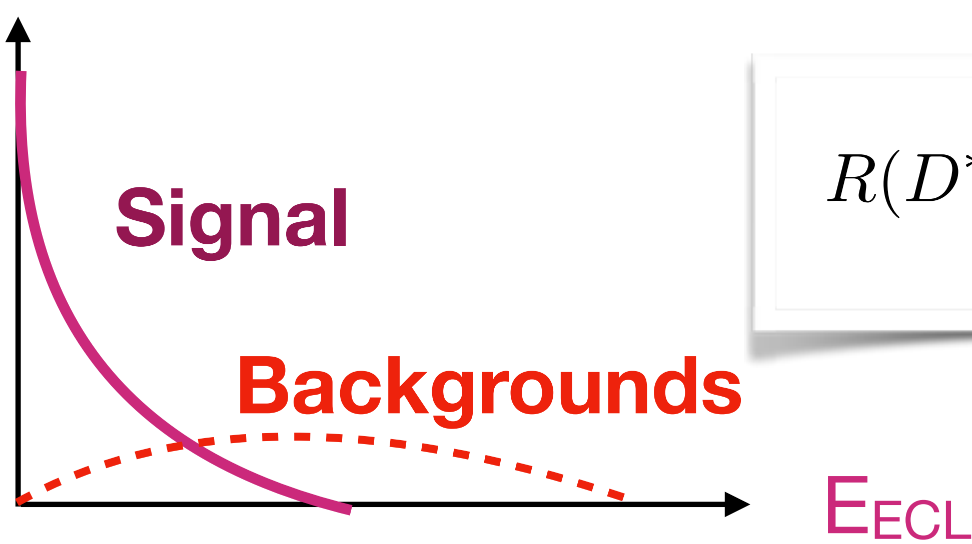
- Signal extraction via E_{ECL} **(unassigned energy in the calorimeter)** and in two bins of helicity angle $\cos\Theta_{hel}$ with binned likelihood fit



$$R(D^*) = \frac{\epsilon^j_{\rm norm} N^{ij}_{\rm sig}}{\mathcal{B}^i_\tau \epsilon^{ij}_{\rm sig} N^j_{\rm norm}},$$

$$P_\tau(D^*) = \frac{2}{\alpha_i} \frac{N^{Fij}_{\rm sig} - N^{Bij}_{\rm sig}}{N^{Fij}_{\rm sig} + N^{Bij}_{\rm sig}},$$

Normalisation: $B \to D^* \ell \nu$

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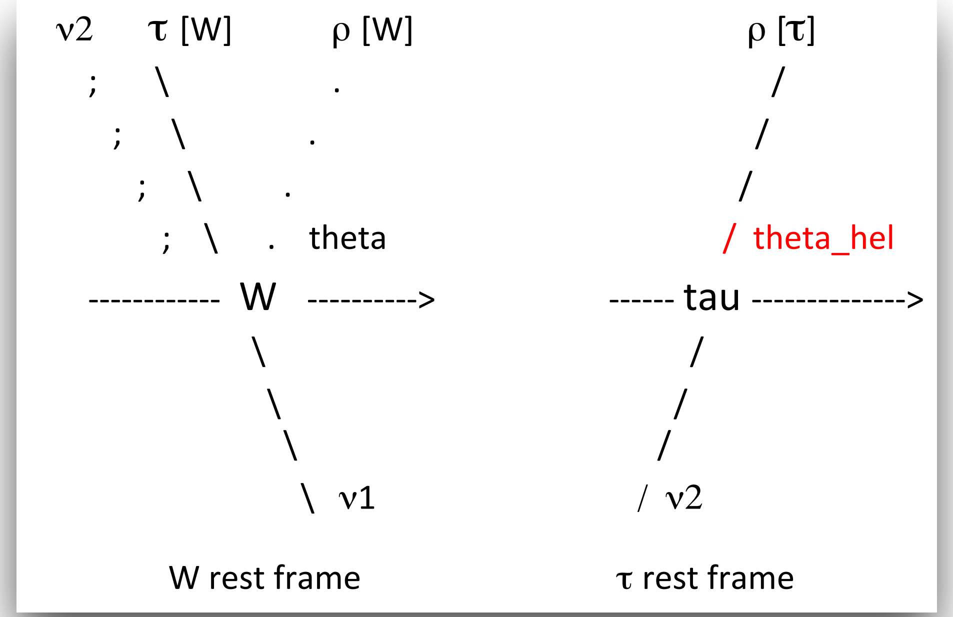

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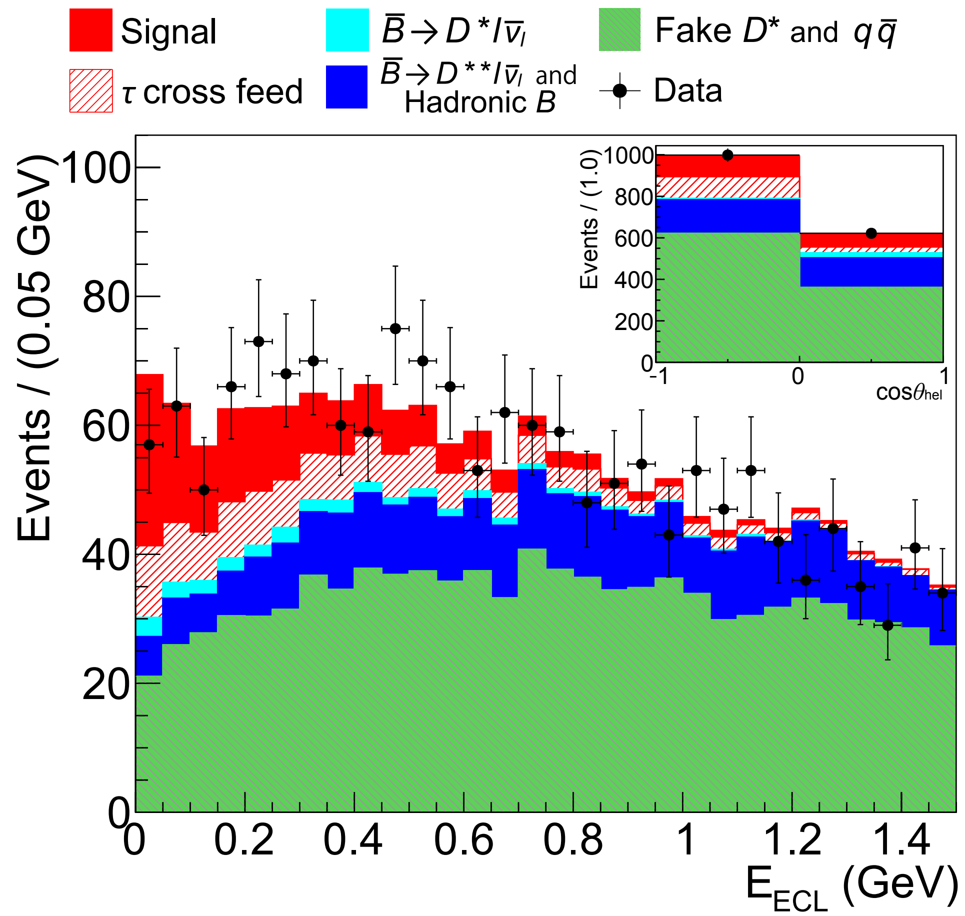
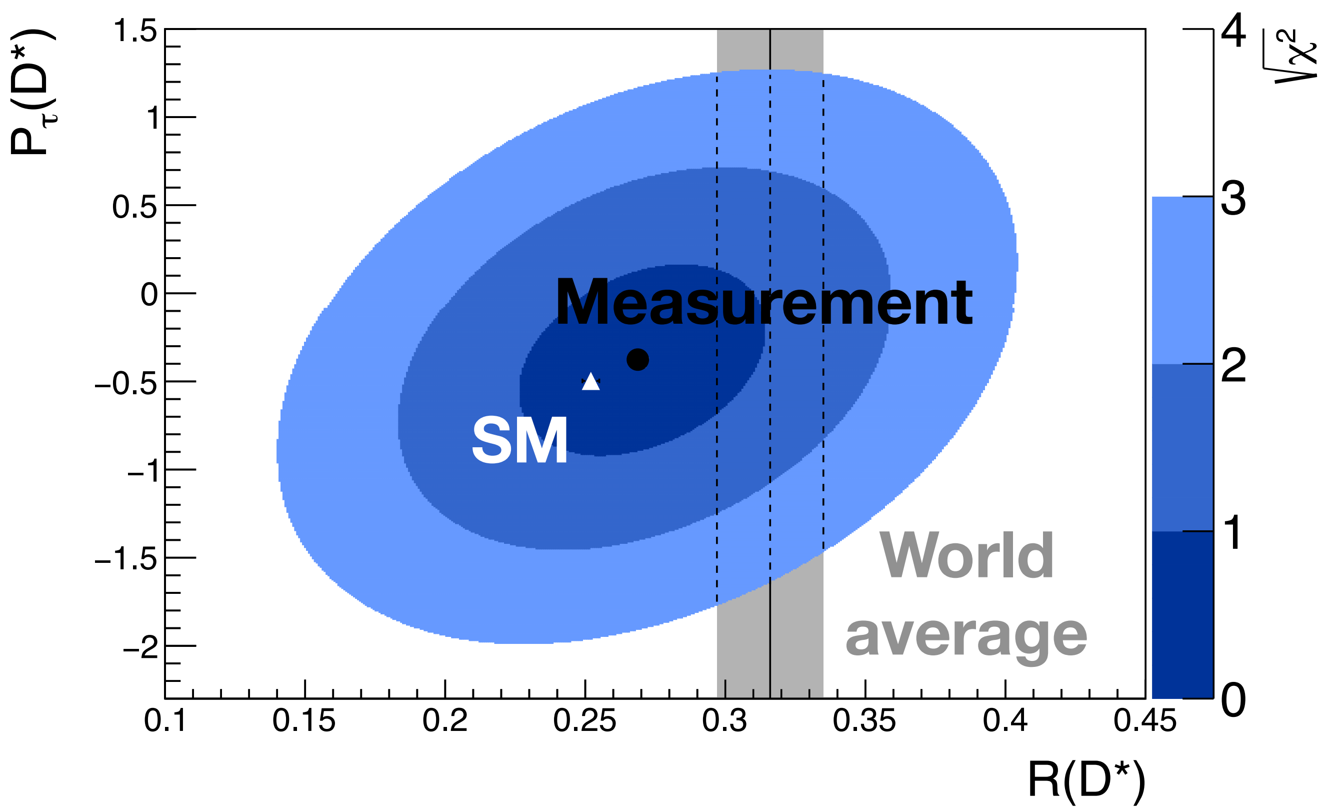




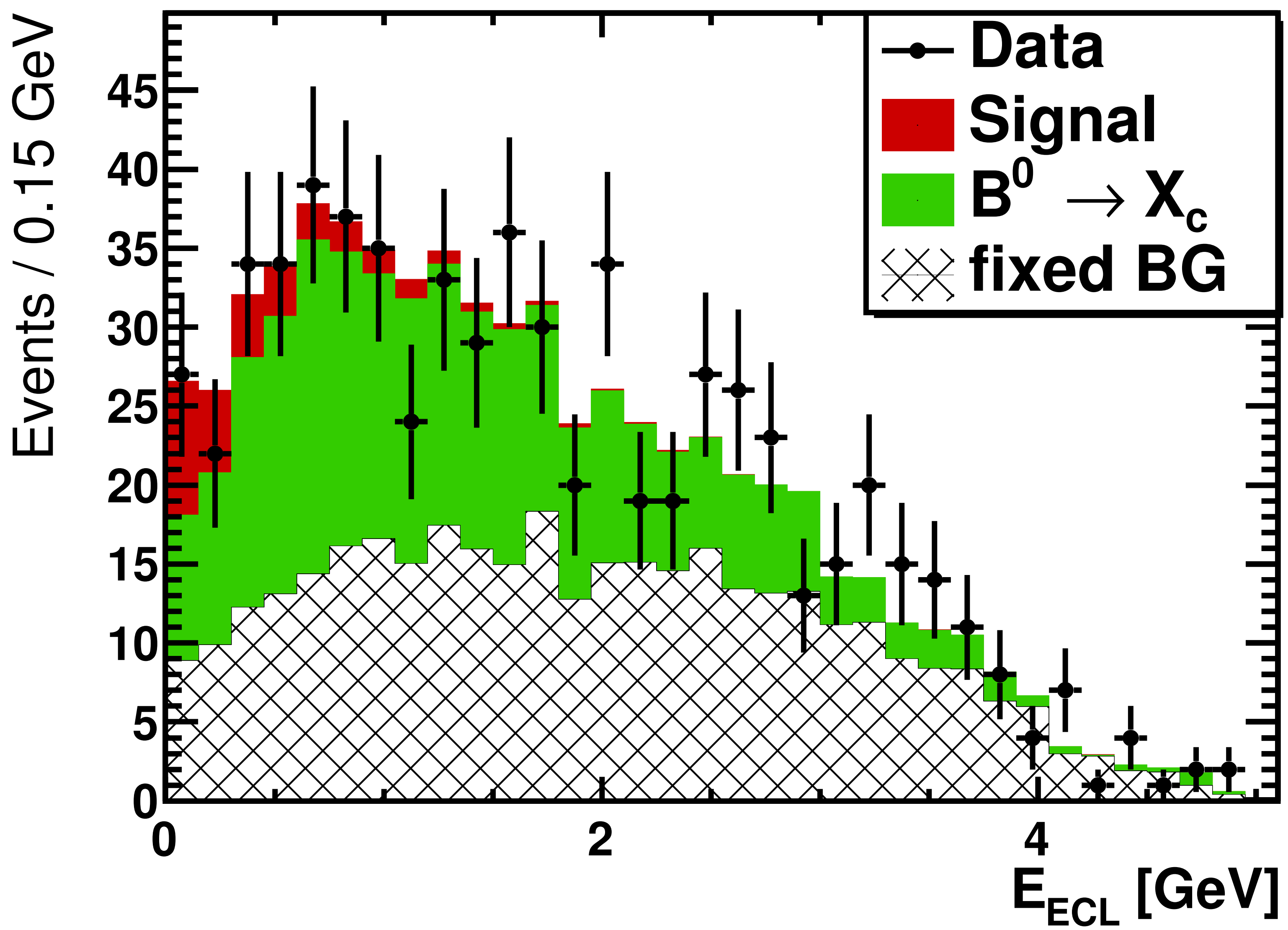
One more interesting ratio from Belle

Phys. Rev. D 93, 032007 (2016)

$$R(\pi) = \frac{\mathcal{B}(B \to \pi\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to \pi\ell\bar{\nu}_\ell)}$$

- Use **Hadronic** tagging and reconstruct

$\tau\to\ell\nu\nu$, $\tau\to\pi\nu\nu$, $\tau\to\rho\nu\nu$, $\tau\to a_1\nu\nu$



1D Likelihood fit in E_{ECL}

$R(\pi)$ = 1.05 ± 0.51

$R(\pi)_{SM}$ = 0.641 ± 0.016

2. How do we predict?

with a focus on $R(D/D^*/\pi)$, similar things do apply though to $R(J/\psi)$

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Form Factor **Bootcamp** with $B \to D\ell\nu$ as an example

$$f_+(q^2)$$

$$f_-(q^2)$$

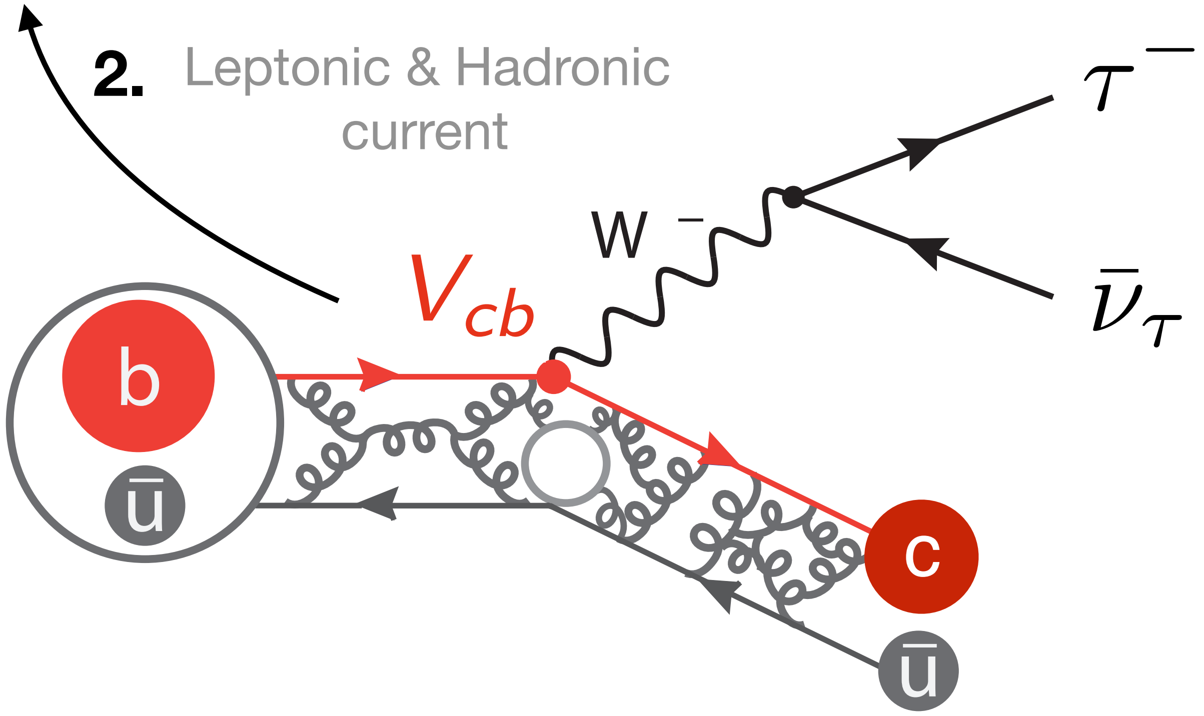
Four-momentum transfer squared encodes QCD dynamics

$$\sim v(p_\ell)\,(\not{m}_\ell + \not{m}_\nu)\,\bar{u}(p_\nu)$$

$$H^\mu L_\mu = \langle B(p)|V^\mu - A^\mu|D(p')\rangle L_\mu = \left[f_+(q^2)\,(p+p')^\mu + f_-(q^2)\,(p-p')^\mu\right] L_\mu$$

2. Leptonic & Hadronic current

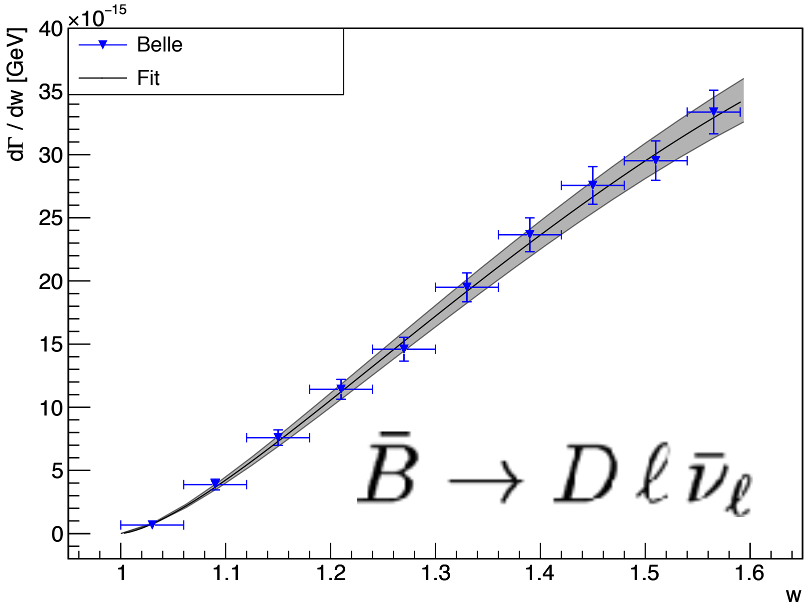
1.



Form Factor Bootcamp with $B \to D\ell\nu$ as an example

$$f_+(q^2)$$

Can be **studied** with **light lepton modes**, but also in **lattice (high q²)** or **sum rules**



$$f_-(q^2)$$

$$\sim v(p_\ell)\,(\not{m}_\ell + \not{m}_\nu)\,\bar{u}(p_\nu)$$

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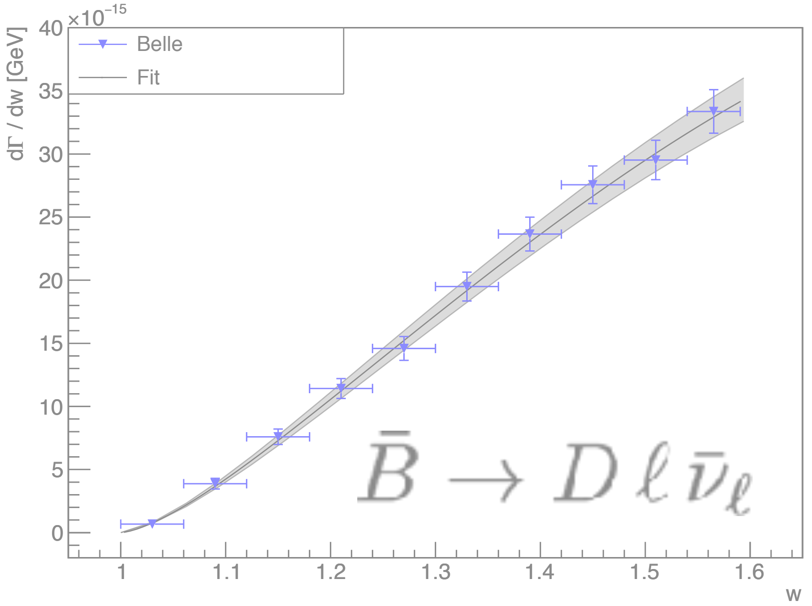


$$f_-(q^2)$$

$$\sim v(p_\ell)\,(\not{m}_\ell + \not{m}_\nu)\,\bar{u}(p_\nu)$$

Proportional to **basically ~ 0** in **light lepton modes**, cannot be constrained experimentally in this way

But important for heavy leptons, **need input** from **lattice** or **HQET relations**

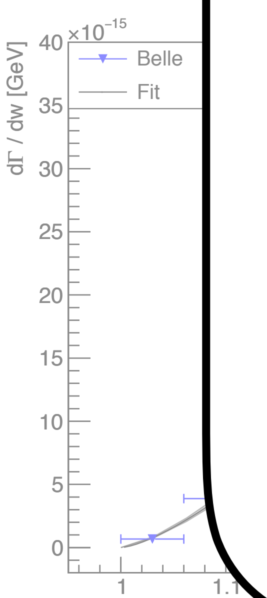
Form Factor **Bootcamp** with $B \to D \ell \nu$ as an example

$$f_+(q^2)$$

$$f_-(q^2)$$

$$\sim v(p_\ell)\,(\not{m}_\ell + \not{m}_\nu)\,\bar{u}(p_\nu)$$

Can be
modes



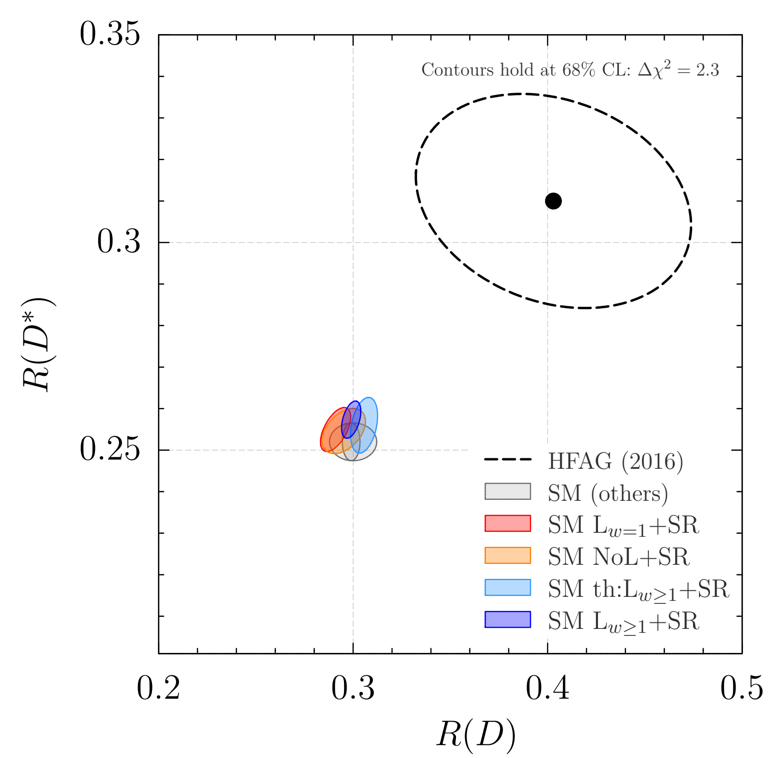
ly ~ 0 in
nnot be
lly in this

y leptons,
e or **HQET**
relations

State of the art predictions combine light lepton measurements and lattice + QCD sum rules for

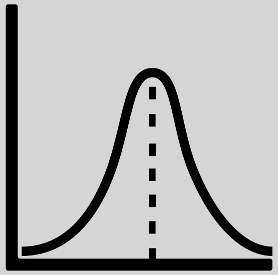
Different inputs leave a fairly consistent picture

arXiv: 1606.08030
arXiv: 1703.05330
arXiv: 1707.09509
…



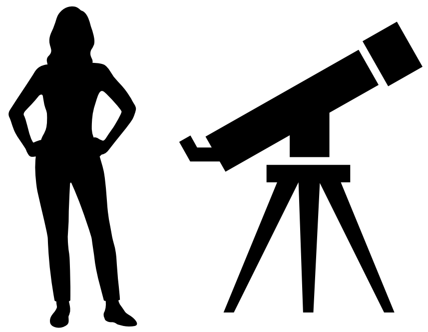
3. Is it really 4σ?

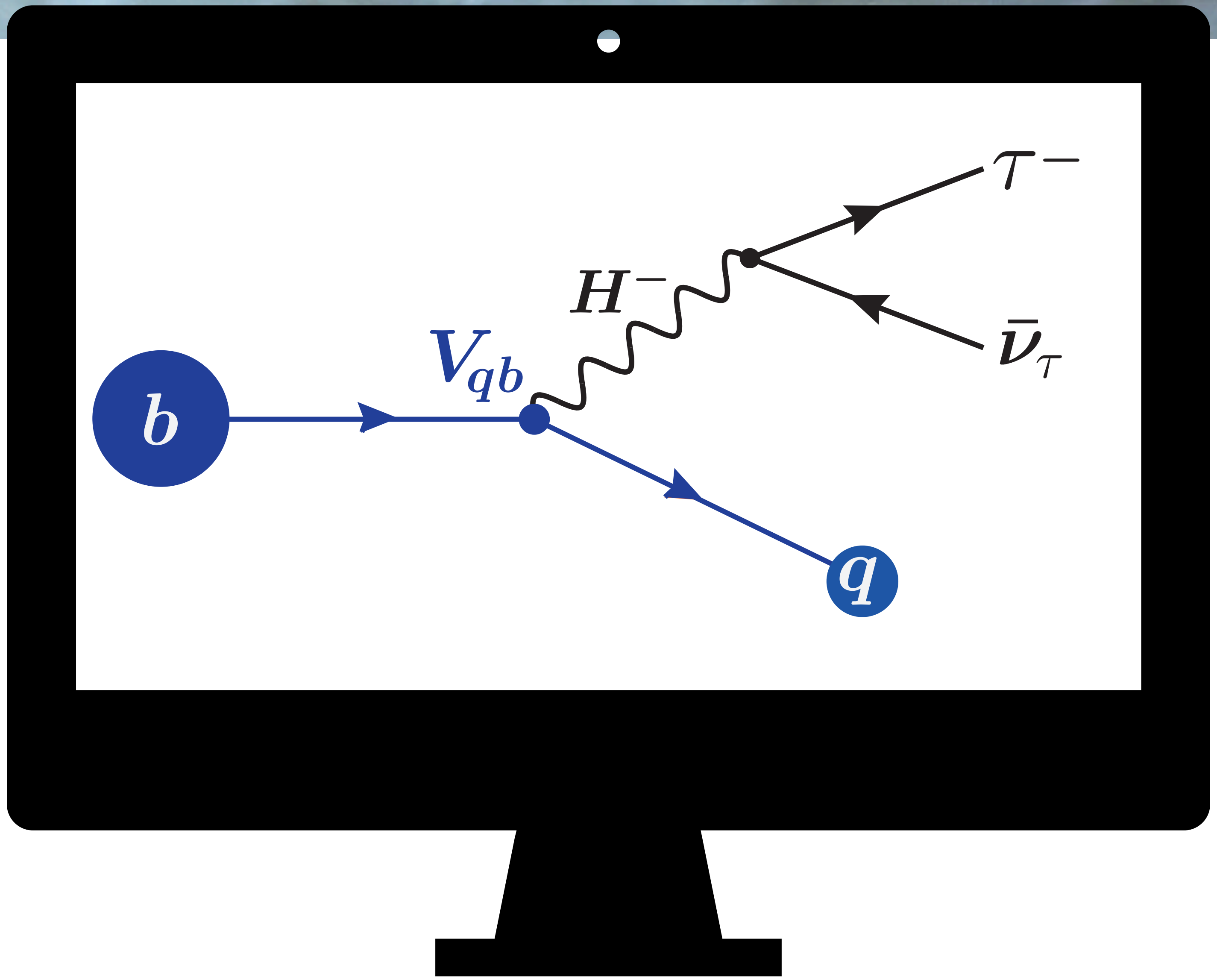
well, depends what you want to conclude!



Florian Bernlochner | florian.bernlochner@kit.edu

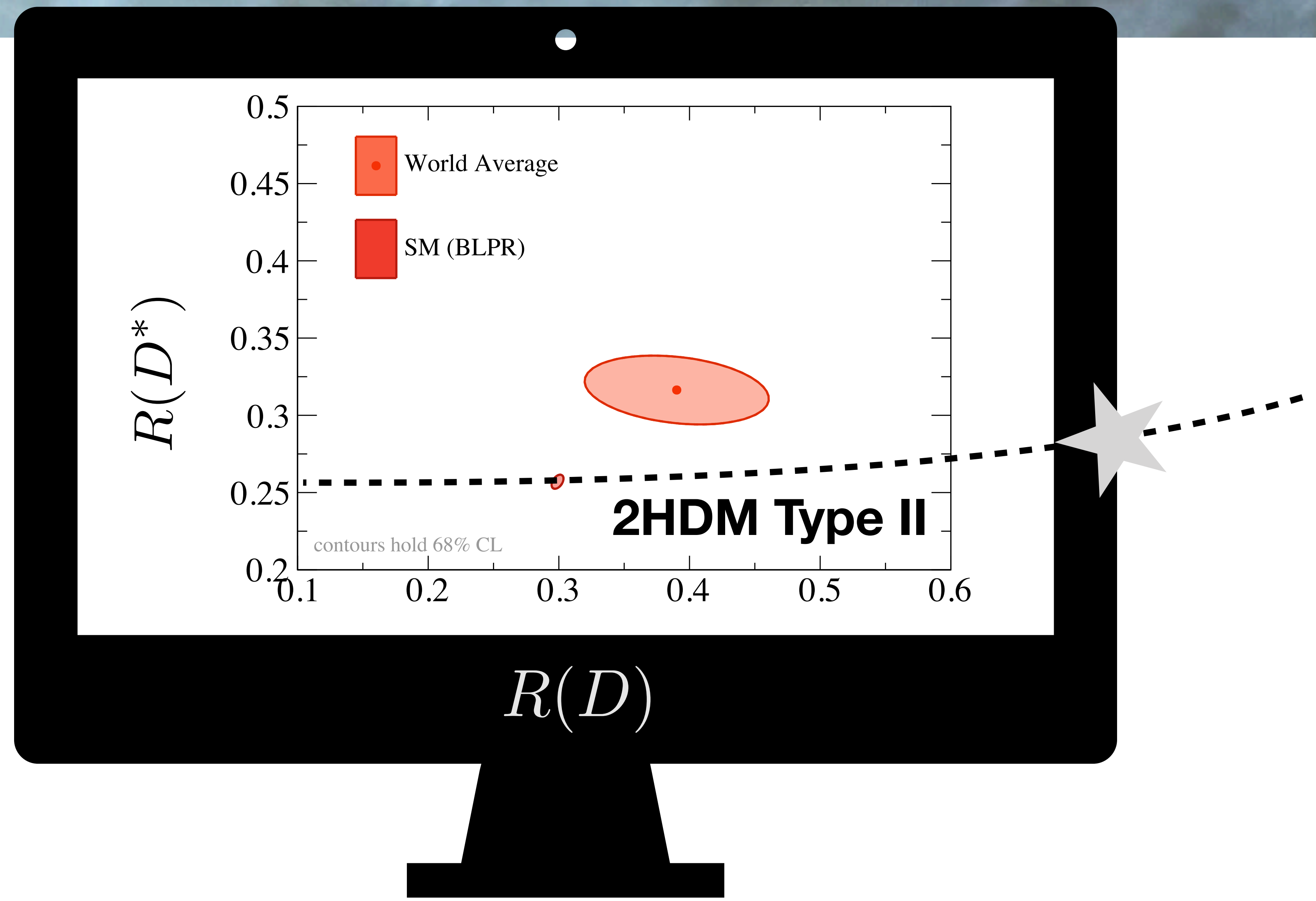
Let me explain what I mean:

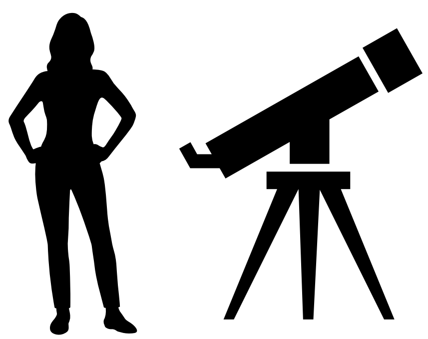




- Let's say you want to use the **measured ratios** to learn something about the anomaly and **your favourite model** that could explain it!

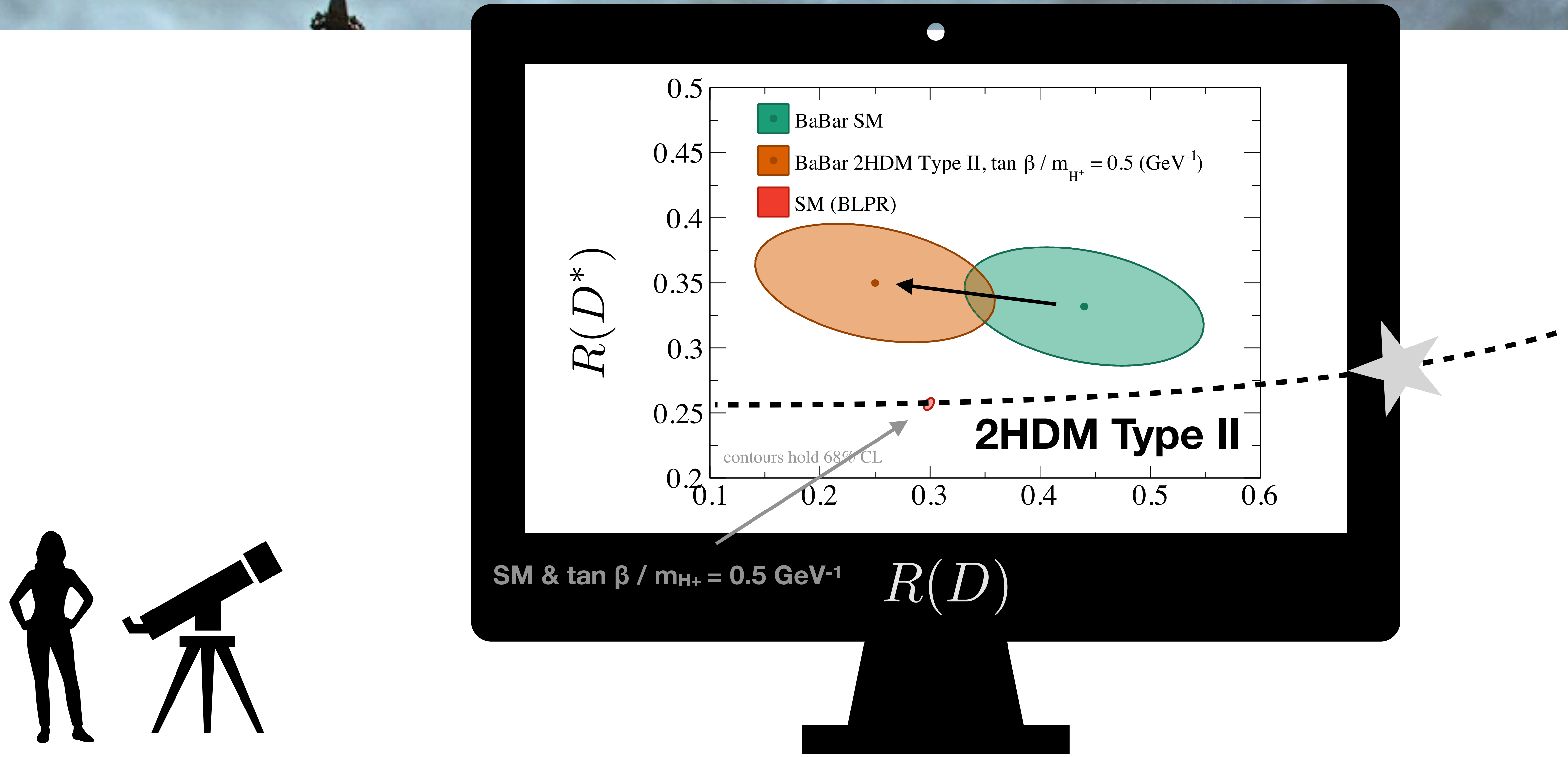
Let me explain what I mean:





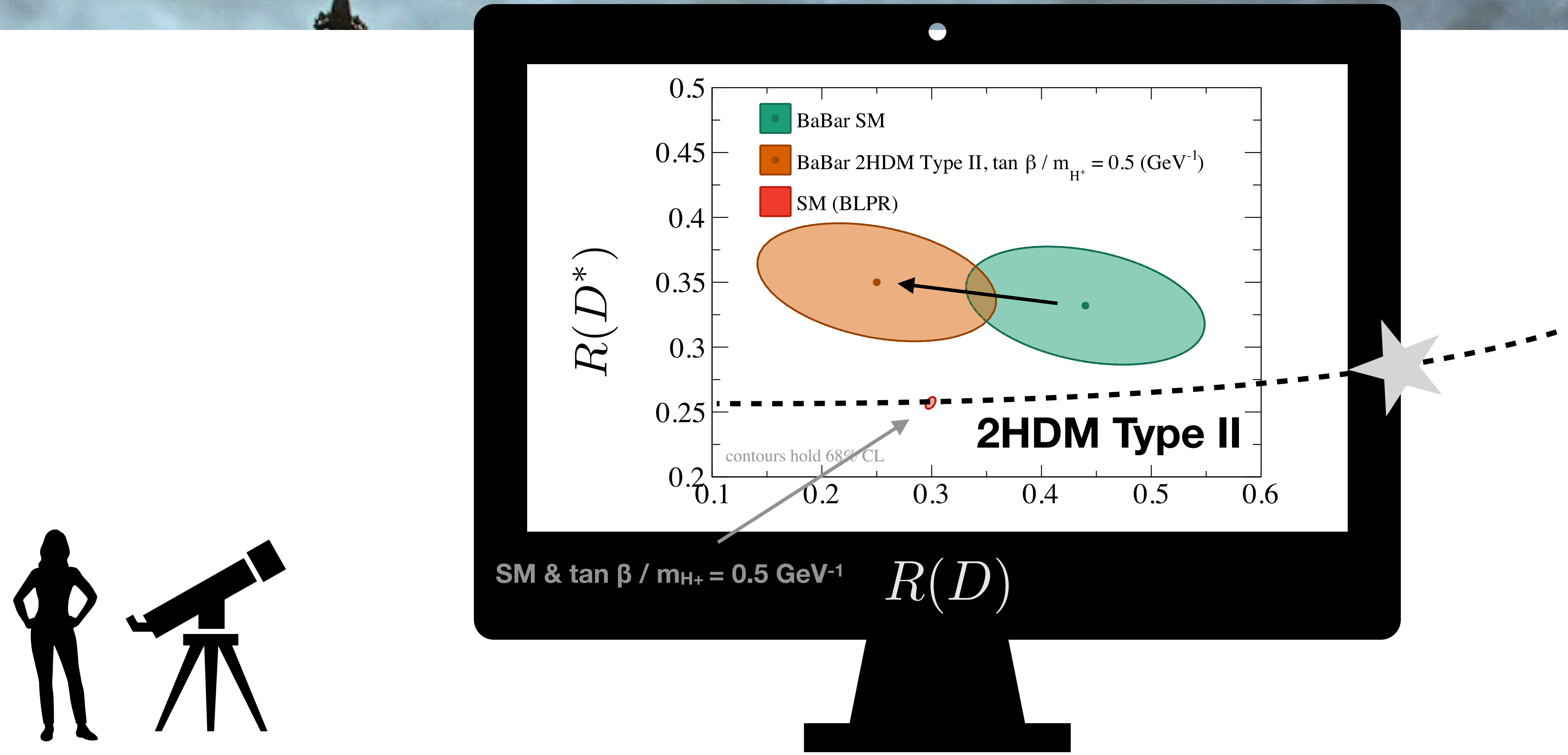
- Let's say you want to use the **measured ratios** to learn something about the anomaly and **your favourite model** that could explain it!

Let me explain what I mean:



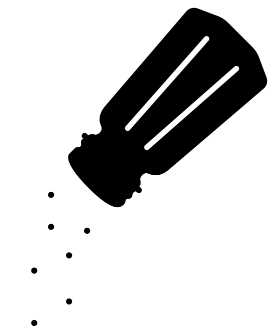
- As it turns out, **not that easy** — the **measured points** themselves are **extracted assuming** the **SM**.

Let me explain what I mean:



- **Why is this happening exactly?**
  - **Change in kinematics** of final state particles (**q^2!**)
  - Dominant effect here: **τ-polarisation**
    (full explanation in backup)

Thus..

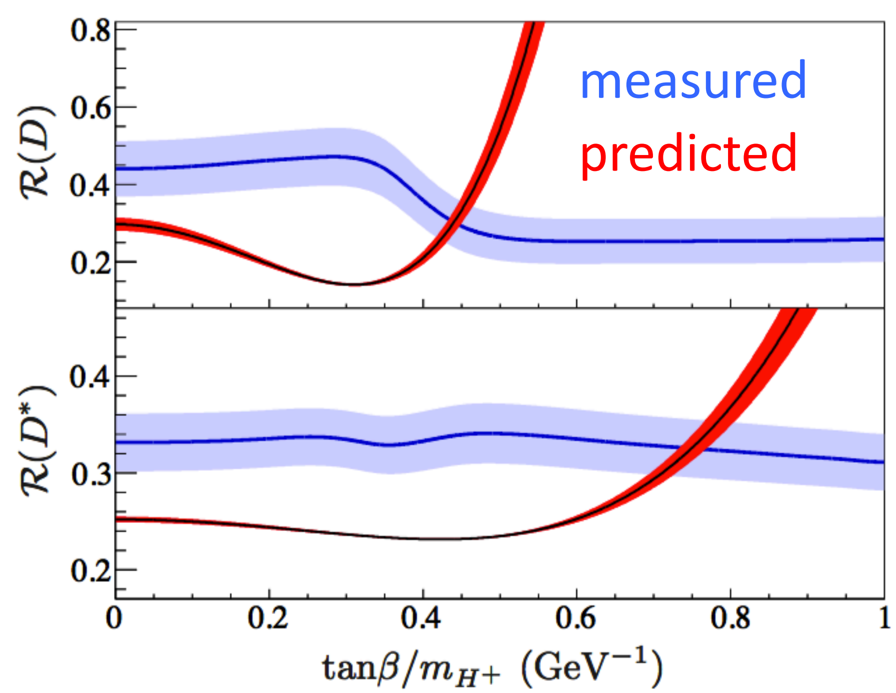


- You can **test models** against the measured ratios, but **keep in mind** that these **results** should be **taken with a grain of salt**

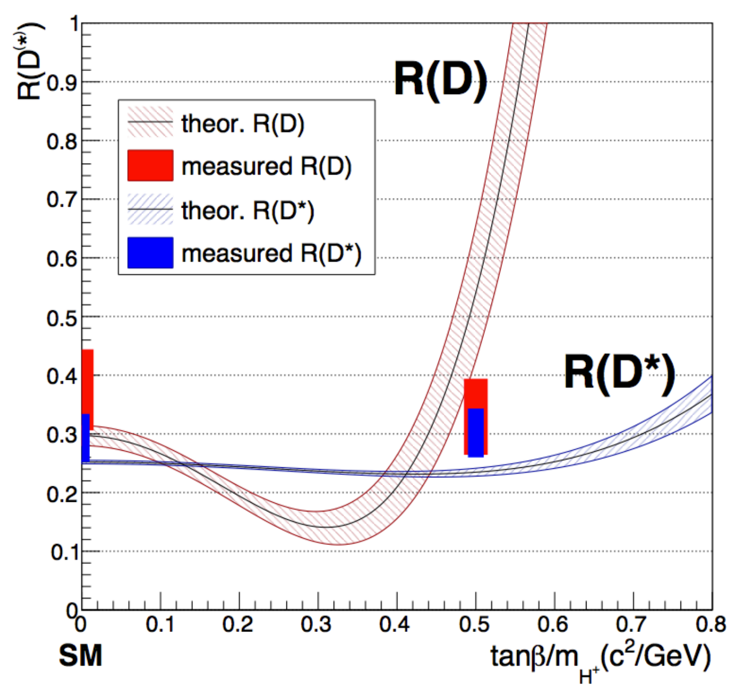
- Fully **consistent tests** right now **only possible within experiments**

Examples:

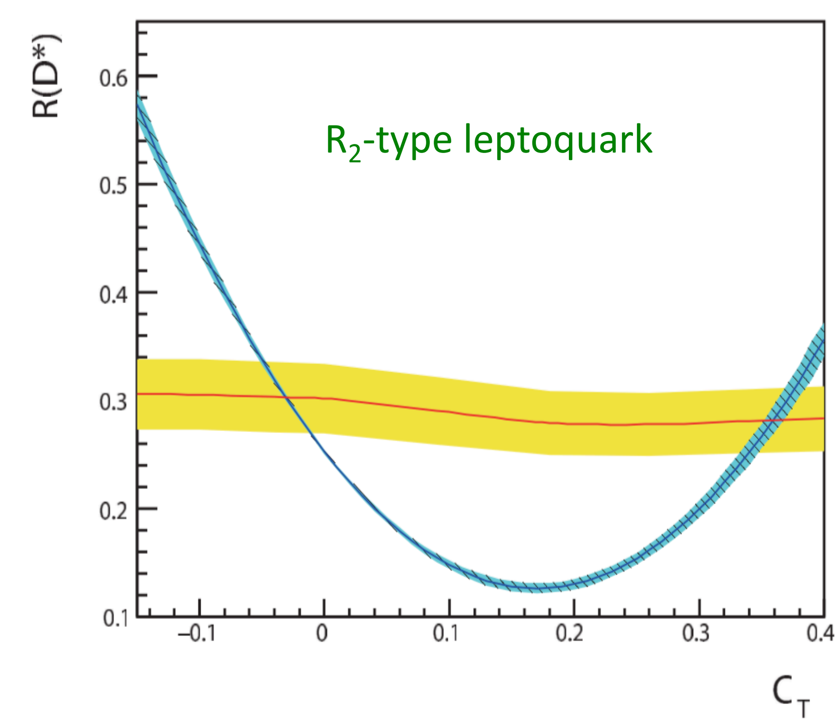
BaBar disfavours 2HDM type II



Belle more compatible



Belle studied two 2 types of leptoquark models. Results allow additional contributions from scalar and vector operators

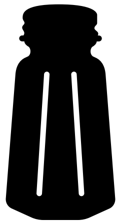


Thus..

- You can **test models** against the measured ratios, but **keep in mind** that these **results** should be **taken with a grain of salt**

- Fully **consistent tests** right now **only possible within experiments**

- **Better:** Experiments should extract limits on **Wilson coefficients** directly, that **allow meaningful reinterpretation**



✓ **Need help from theorists**

Helicity Amplitude Module
for Matrix Element Reweighting

180x.xxxxx FB, S. Duell, M. Papucci, Z. Ligeti, D. Robinson

4. Looking ahead

$$\frac{\text{BaBar data set}}{\text{CLEO data set}} \sim \frac{\text{Belle II data set}}{\text{Belle data set}} \sim 50:1 \sim \frac{\text{LHCb Upgrade}}{\text{LHCb 1/fb}}$$

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Belle II: a next generation B-Factory experiment

Electromagnetic Calorimeter:

Thallium activated Caesium Iodide scintillation crystals

KL and Muon detection system

RPC based

Particle identification

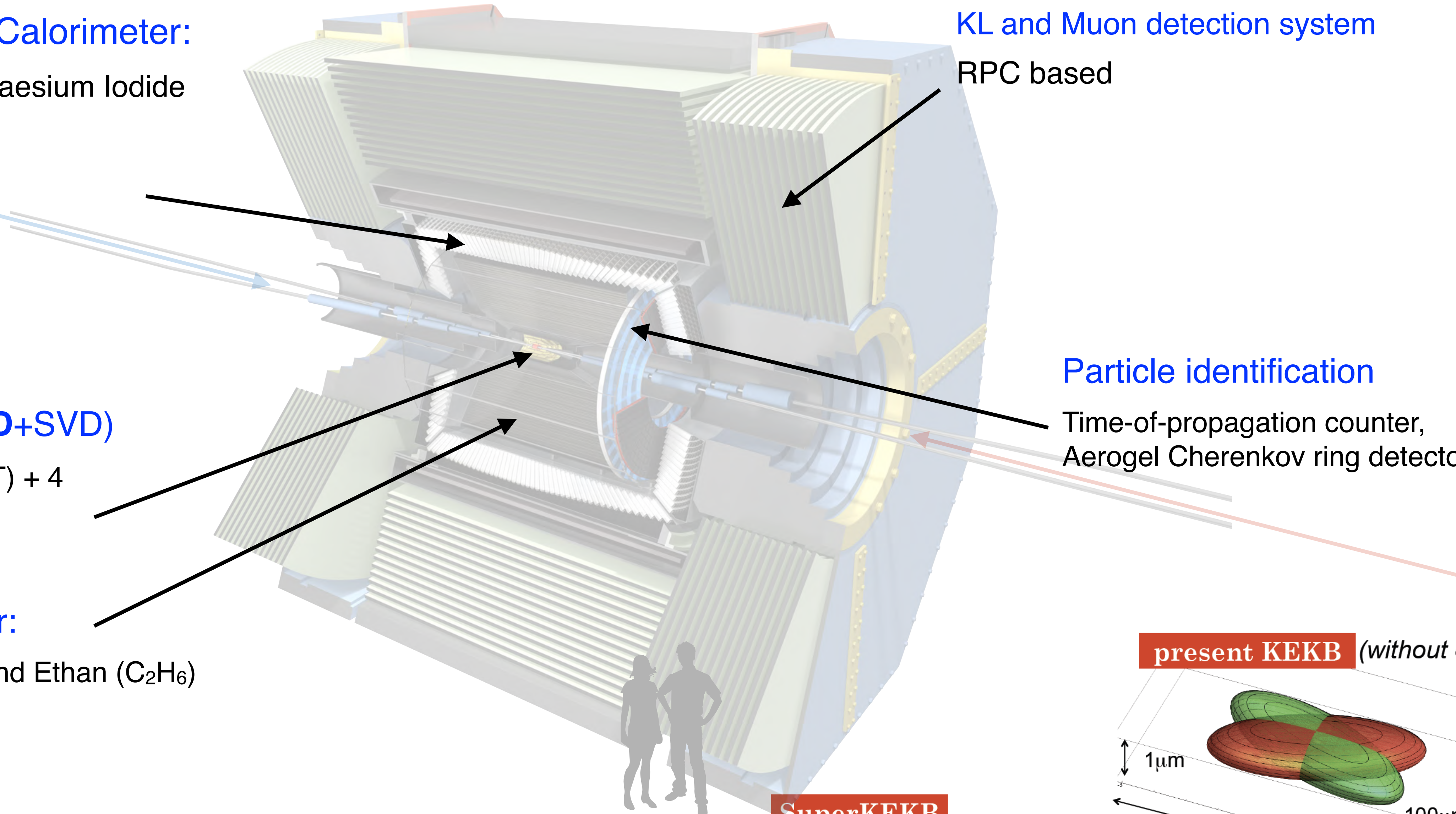
Time-of-propagation counter, Aerogel Cherenkov ring detector

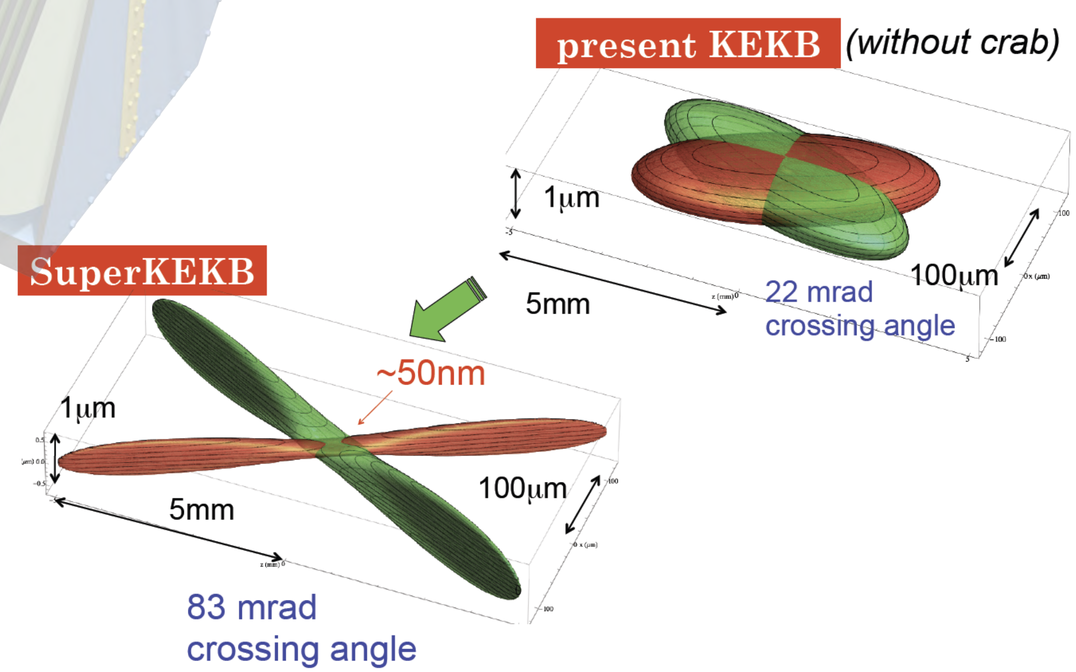
Vertex detectors (PXD+SVD)

2 layers of Pixel (DEPFET) + 4 layers of strips (DSSD)

Central drift chamber:

Gas mixture of Helium and Ethan (C_2H_6)

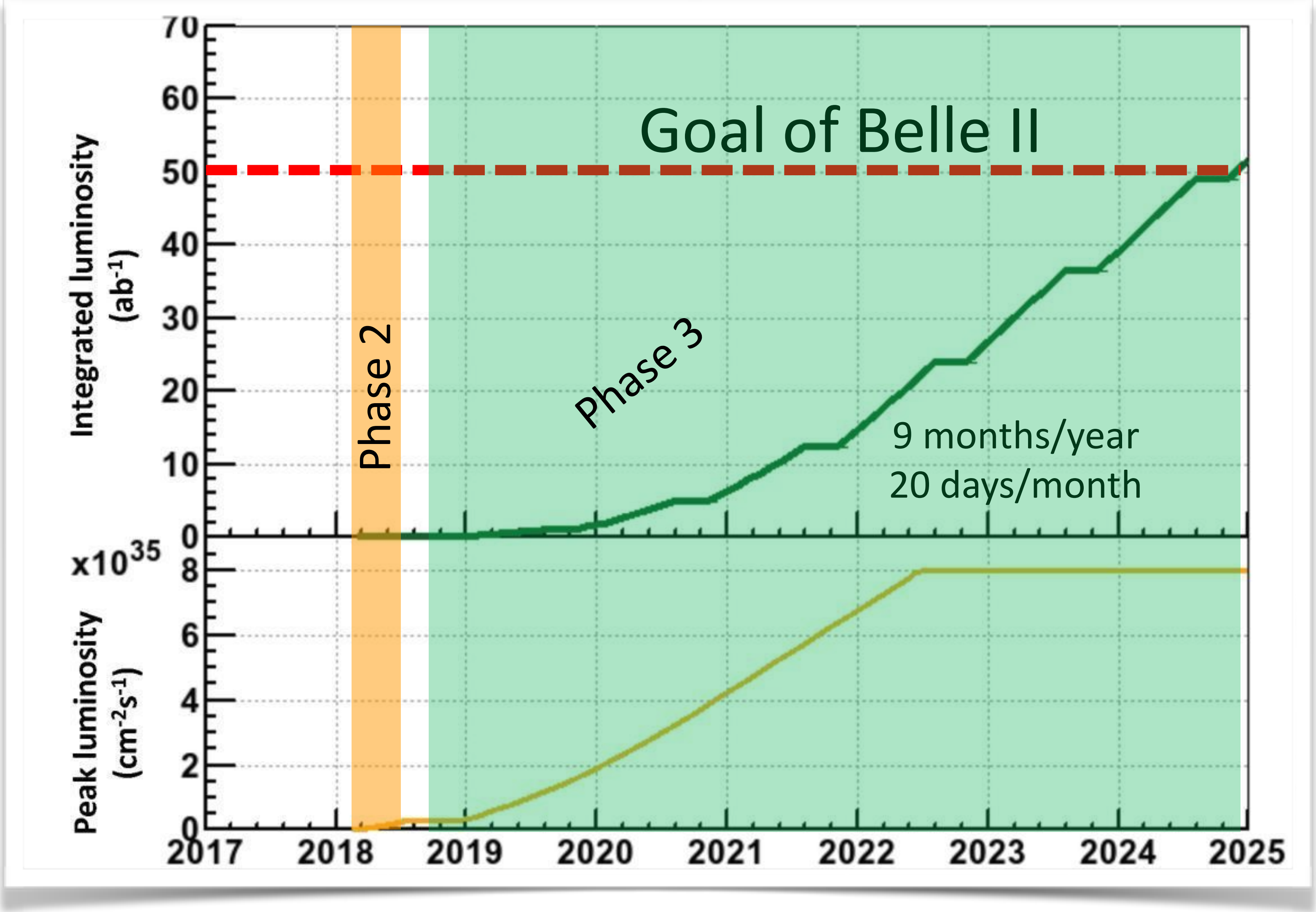




LER / HER	KEKB	SuperKEKB
Energy [GeV]	3.5 / 8	4.0 / 7.0
Luminosity [10^{34} cm^{-2} s^{-1}]	2,1	**80**

Belle II ramp up Phases

- Ramp up in **three** phases
  - **Phase I 2016:** No detector over interaction region, study of beam properties
  - **Phase II 2018:** First collisions, but no **PXD. Instead BEAST II (radiation monitoring system)**
  - **Phase III 2019:** First Physics with full detector



$\sqrt{s} = 10.58\,\mathrm{GeV}$

$e^{+} \longrightarrow \Upsilon(4S) \longleftarrow e^{-}$

$\langle b\bar{b}\rangle$

Average separation

$\Upsilon(4S) \to B^0 \, \overline{B}^0$

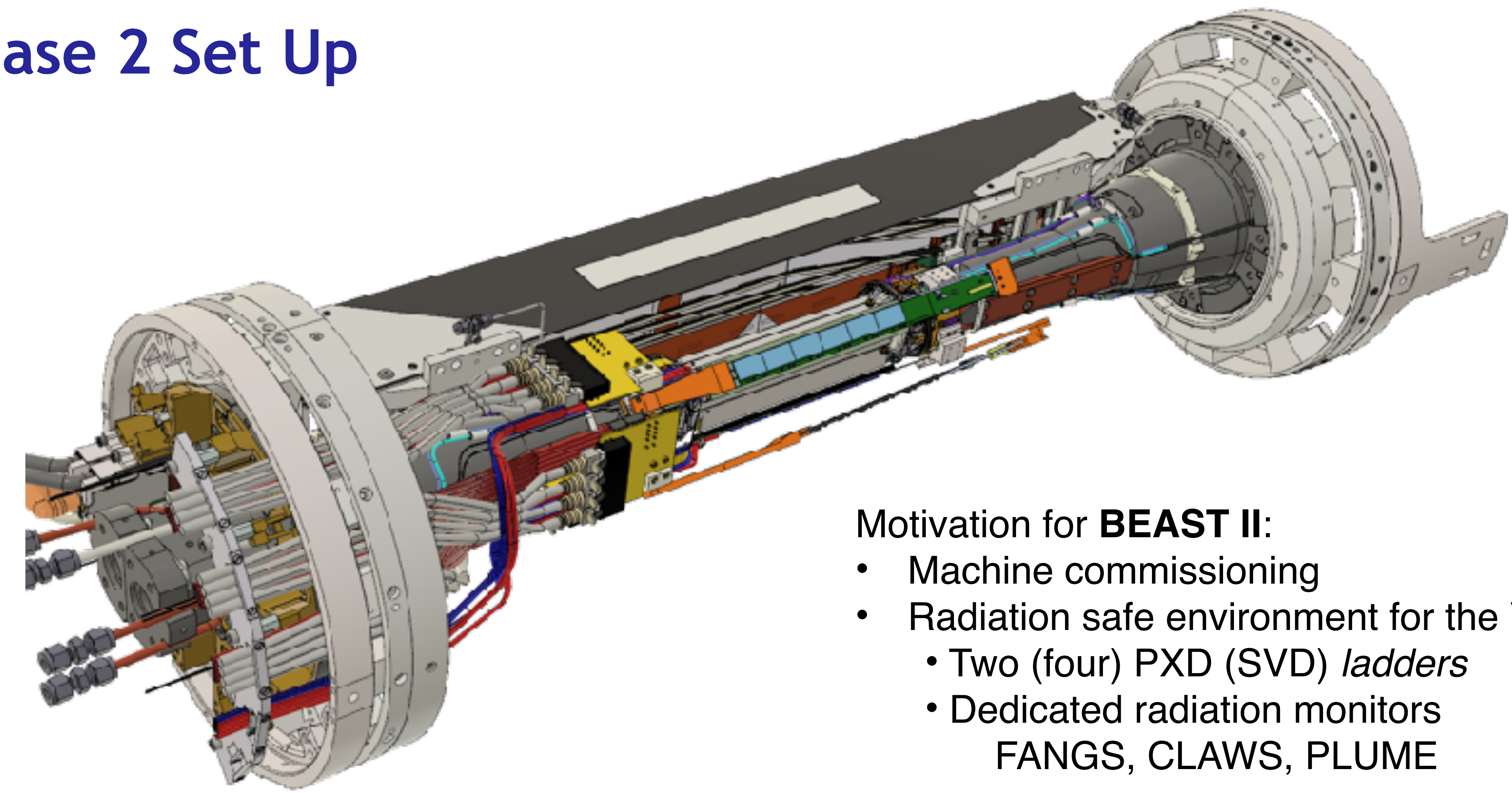
$\langle b\bar{b}\rangle \longrightarrow \langle \bar{b}d\rangle\, \langle b\bar{d}\rangle$

$\Delta z \approx c\,\beta\,\gamma\,\tau_B \approx\ 130\,\mu\mathrm{m}$

B-meson lifetime

About a factor of two smaller than BaBar!

Phase 2 Set Up



Motivation for **BEAST II**:

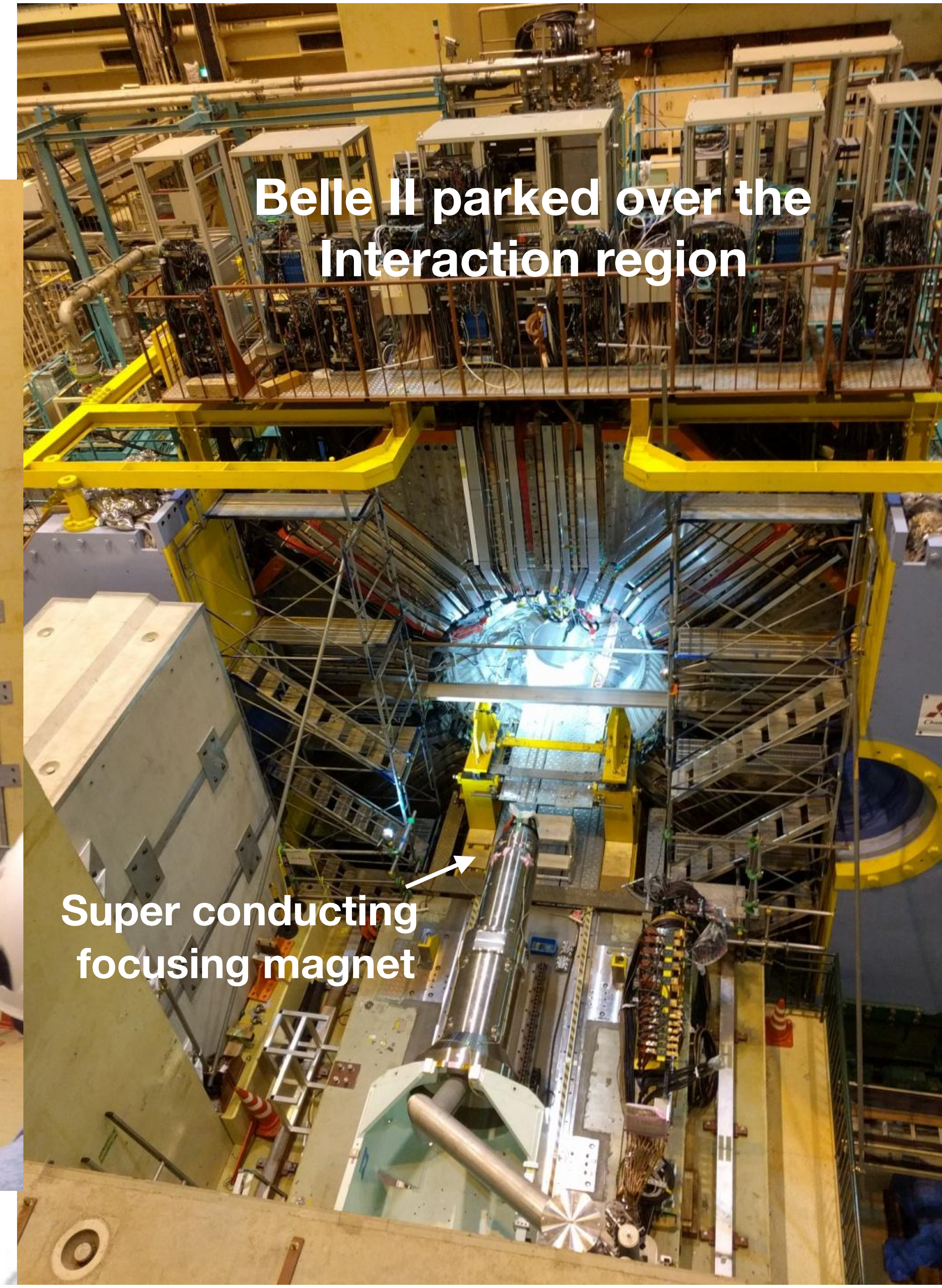
- Machine commissioning
- Radiation safe environment for the VXD:
  - Two (four) PXD (SVD) *ladders*
  - Dedicated radiation monitors FANGS, CLAWS, PLUME

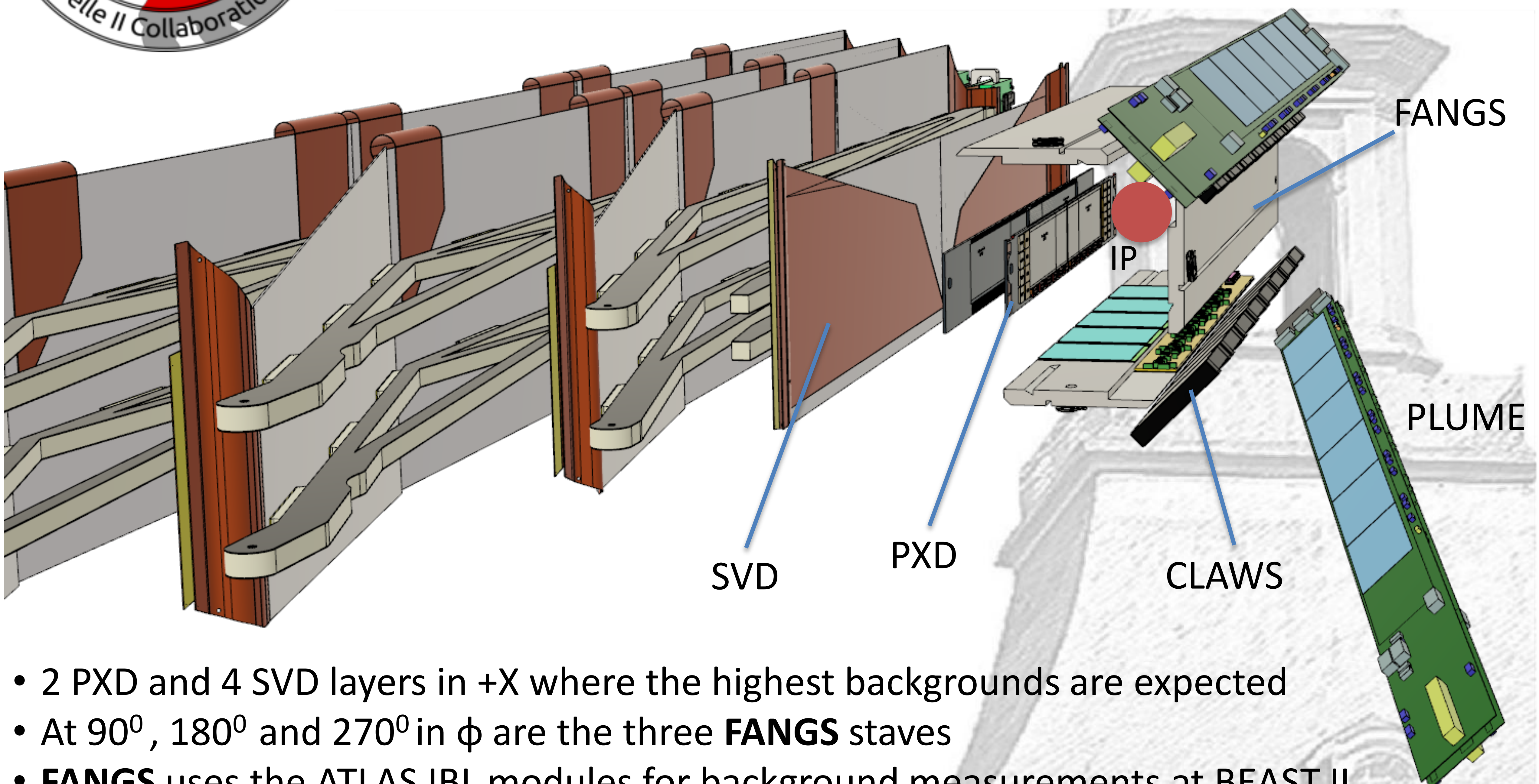
Many thanks to Carlos Marinas, Patrick Ahlburg and Botho Paschen
For the nice illustrations and pictures!


Tsukuba Hall (2016)


Belle II Control Room

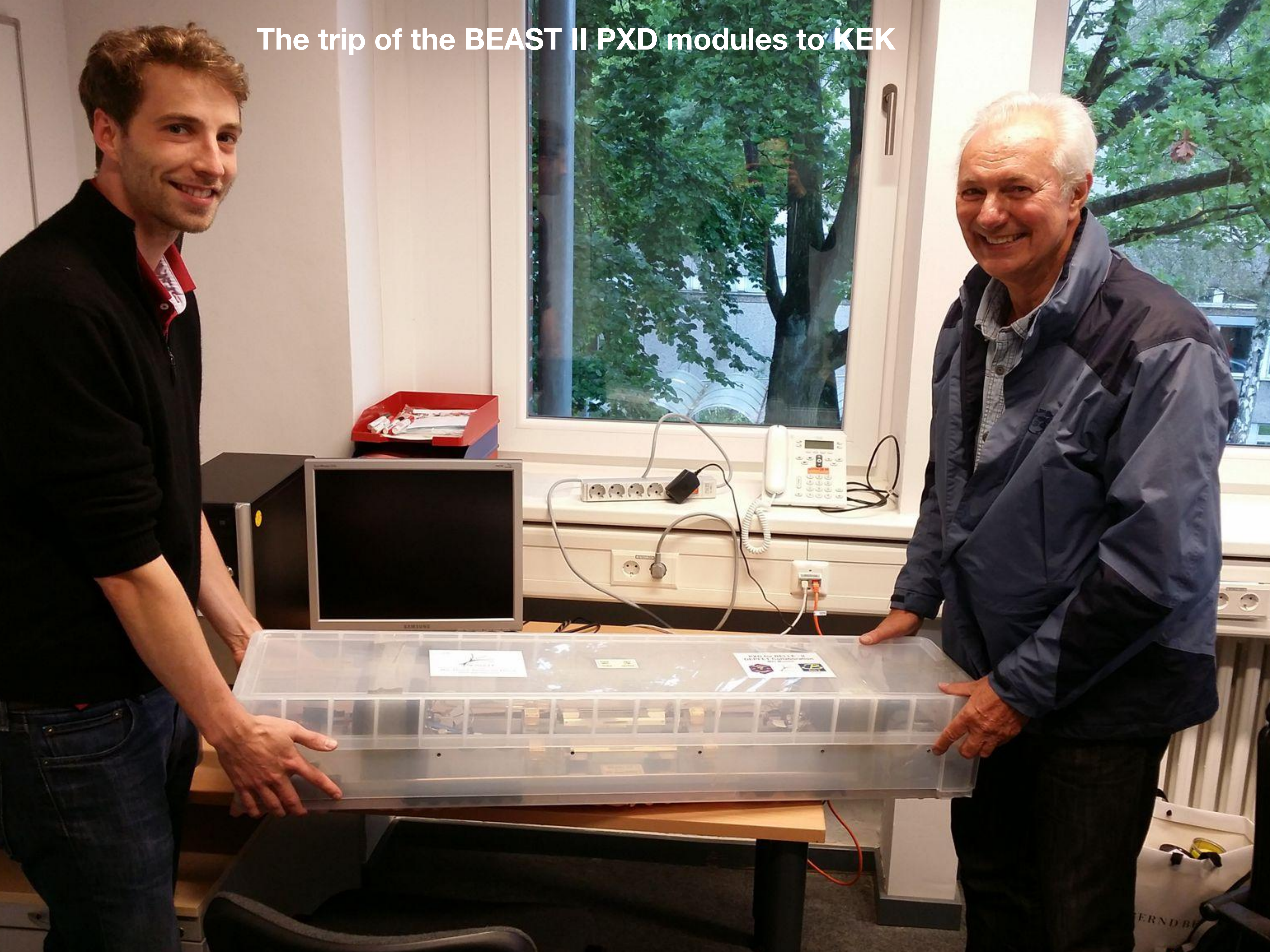

Tsukuba Hall (End of 2017)


Belle II parked over the Interaction region
Super conducting focusing magnet



- 2 PXD and 4 SVD layers in +X where the highest backgrounds are expected
- At 90^0, 180^0 and 270^0 in ϕ are the three **FANGS** staves
- **FANGS** uses the ATLAS IBL modules for background measurements at BEAST II

The trip of the BEAST II PXD modules to KEK

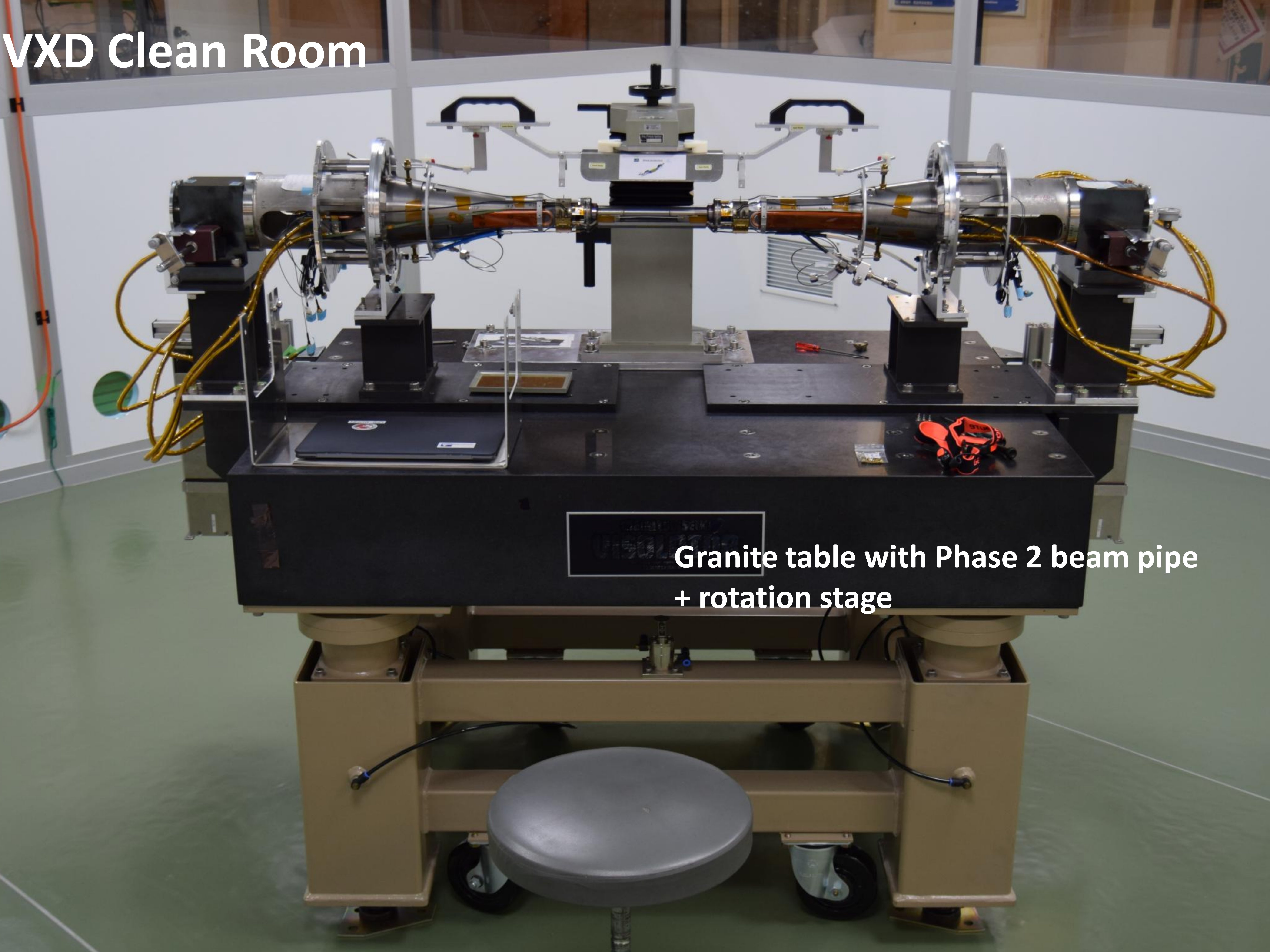


Airplane business class with extra pillows – 4000 Eur

Bus to Tsukuba station 1.5 hr - 10 Eur

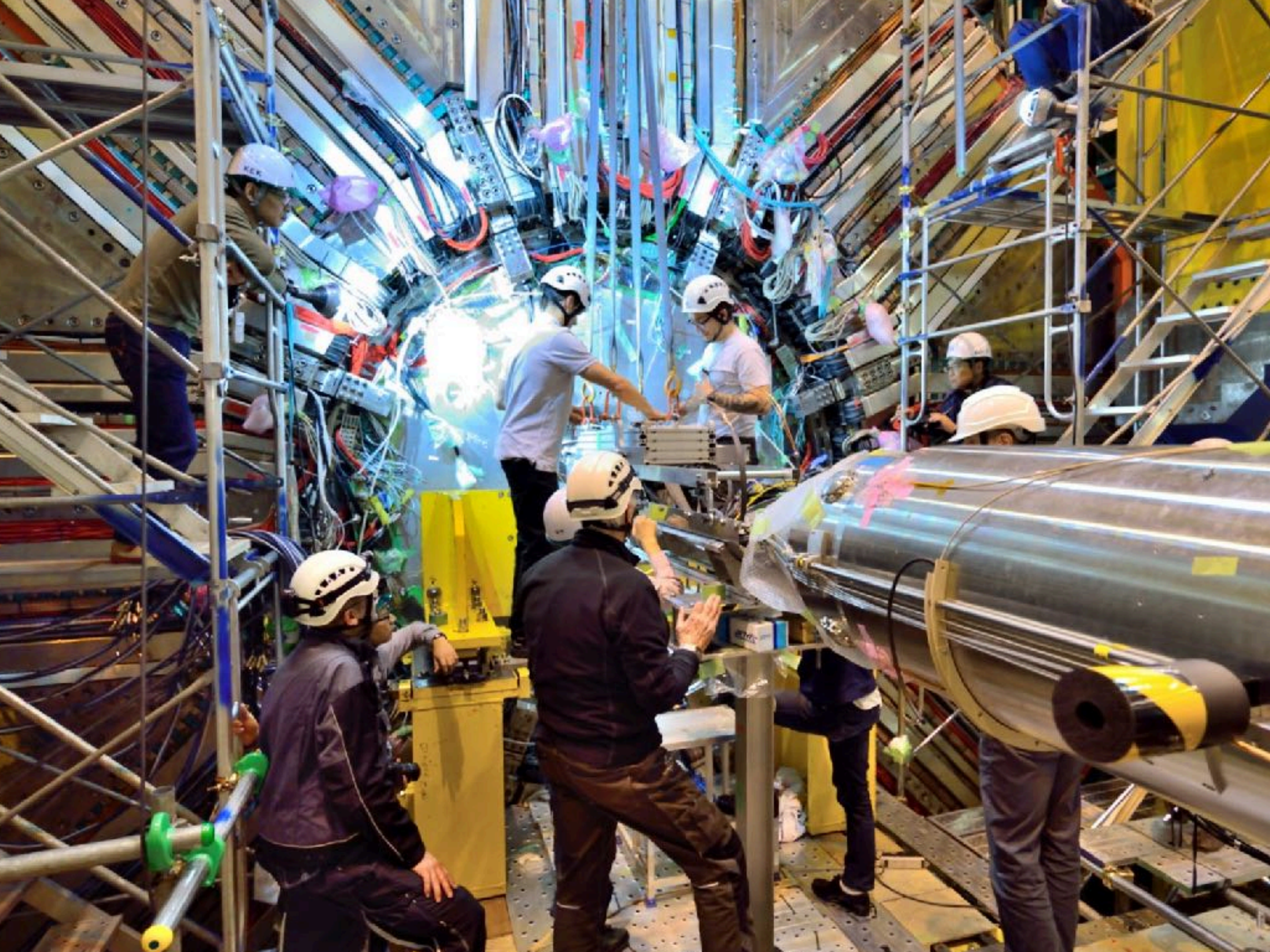

BEAST PXD in the Belle clean room - priceless

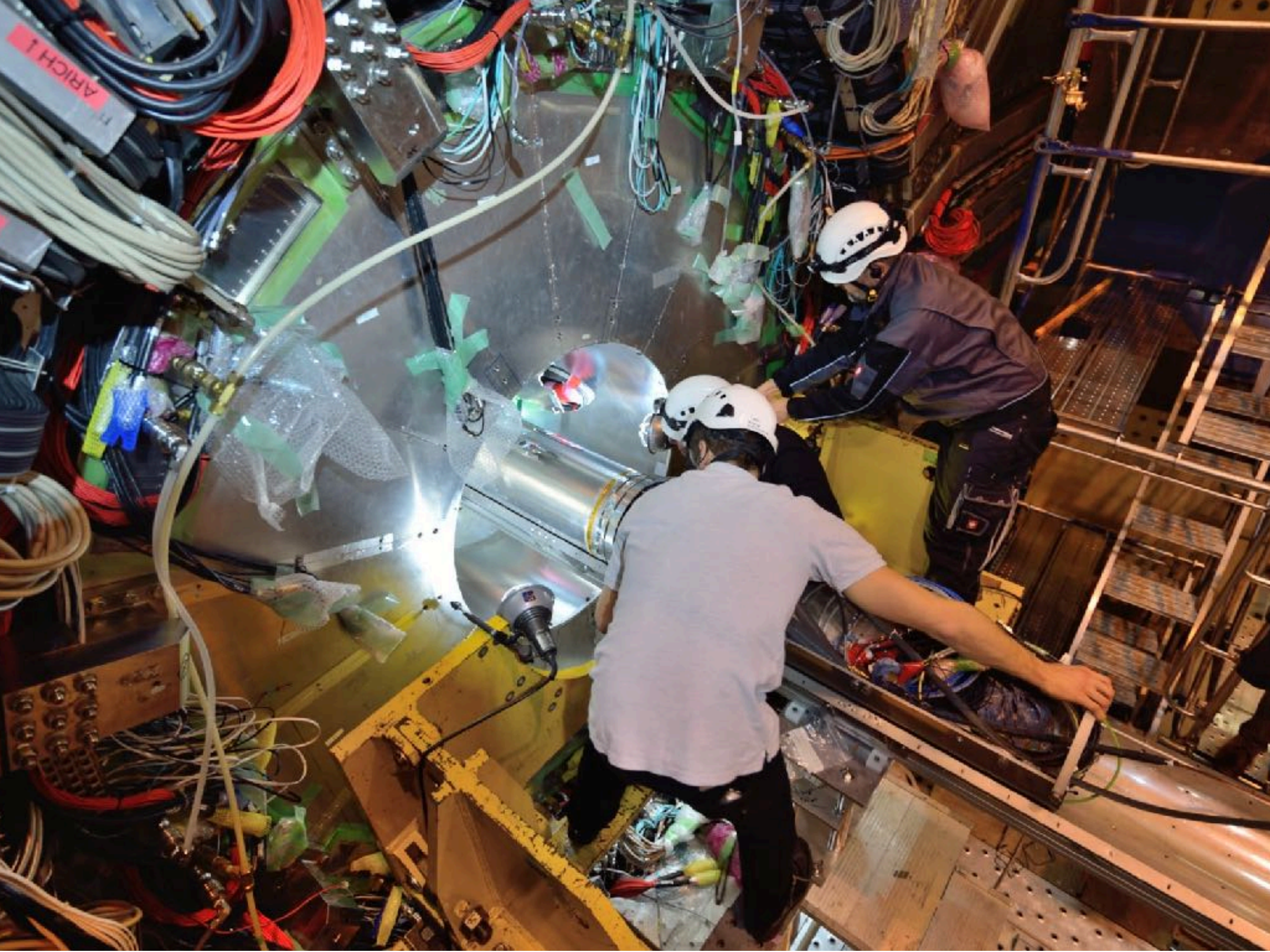
VXD Clean Room

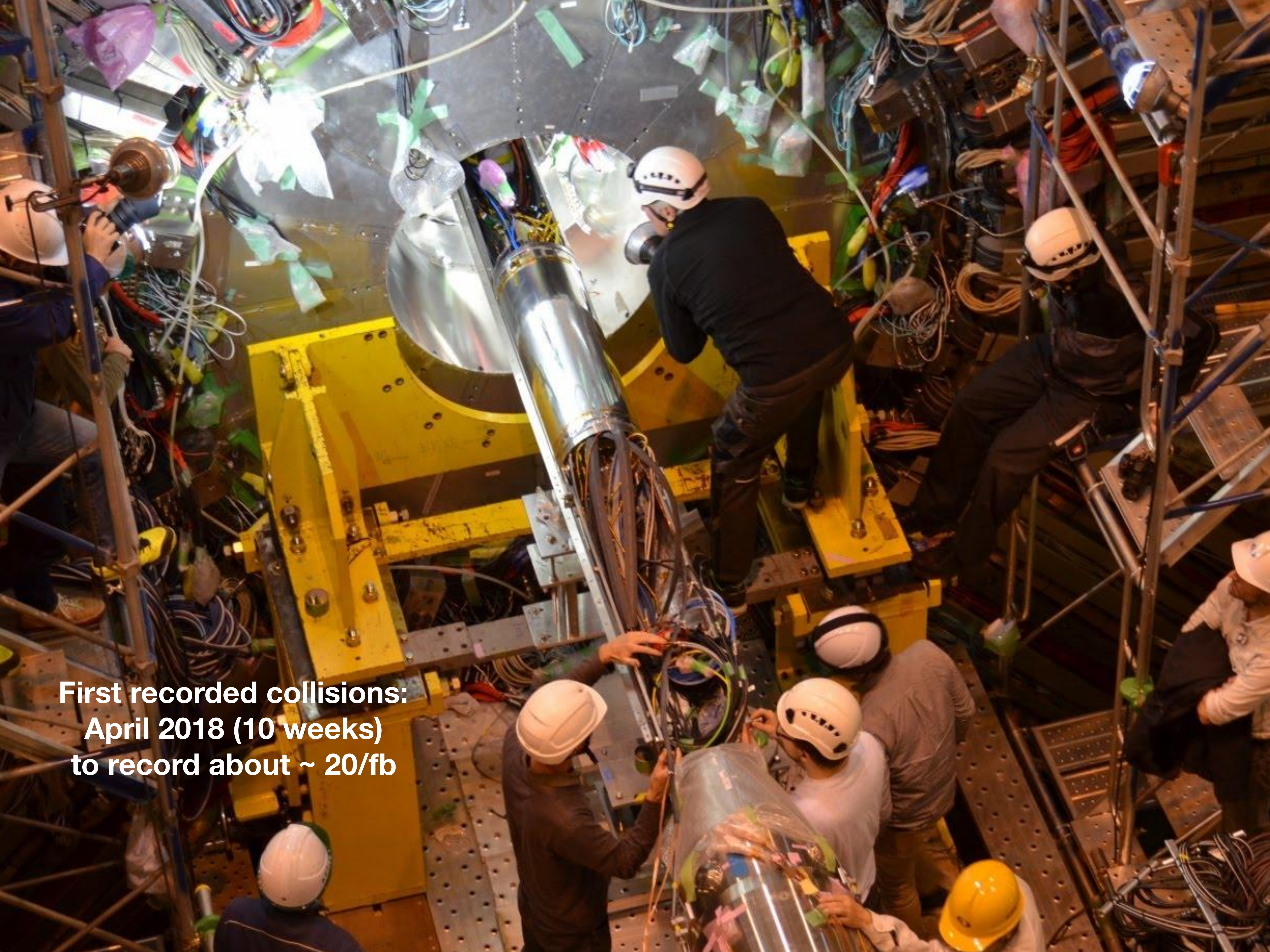



Warm-up phase..


KEK
DESY

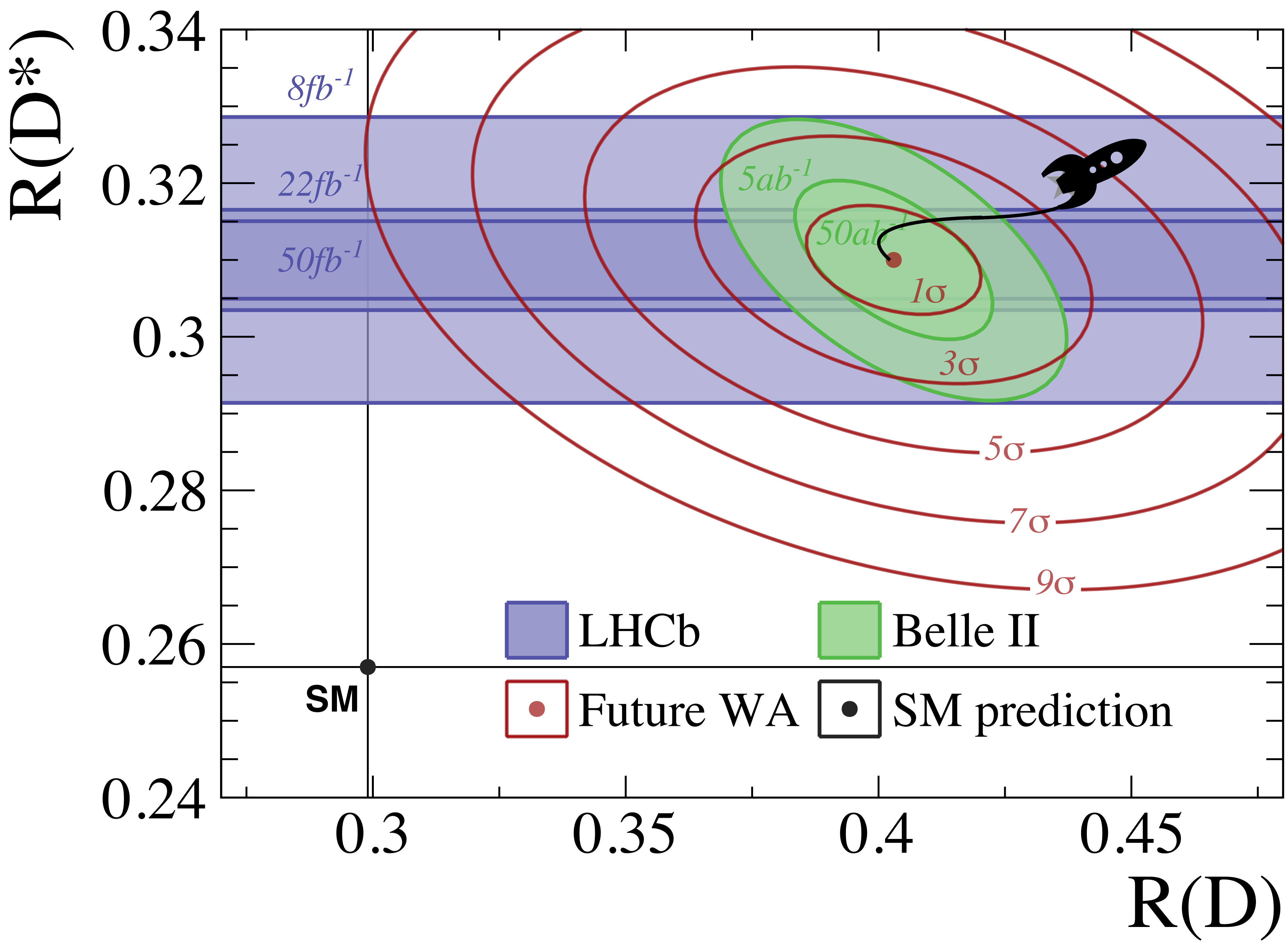




ARICH


First recorded collisions:
April 2018 (10 weeks)
to record about ~ 20/fb

Looking ahead...

J. Albrecht, FB, S. Reicher, M. Kenzie, D. Straub, A. Tully
arXiv:1709.10308

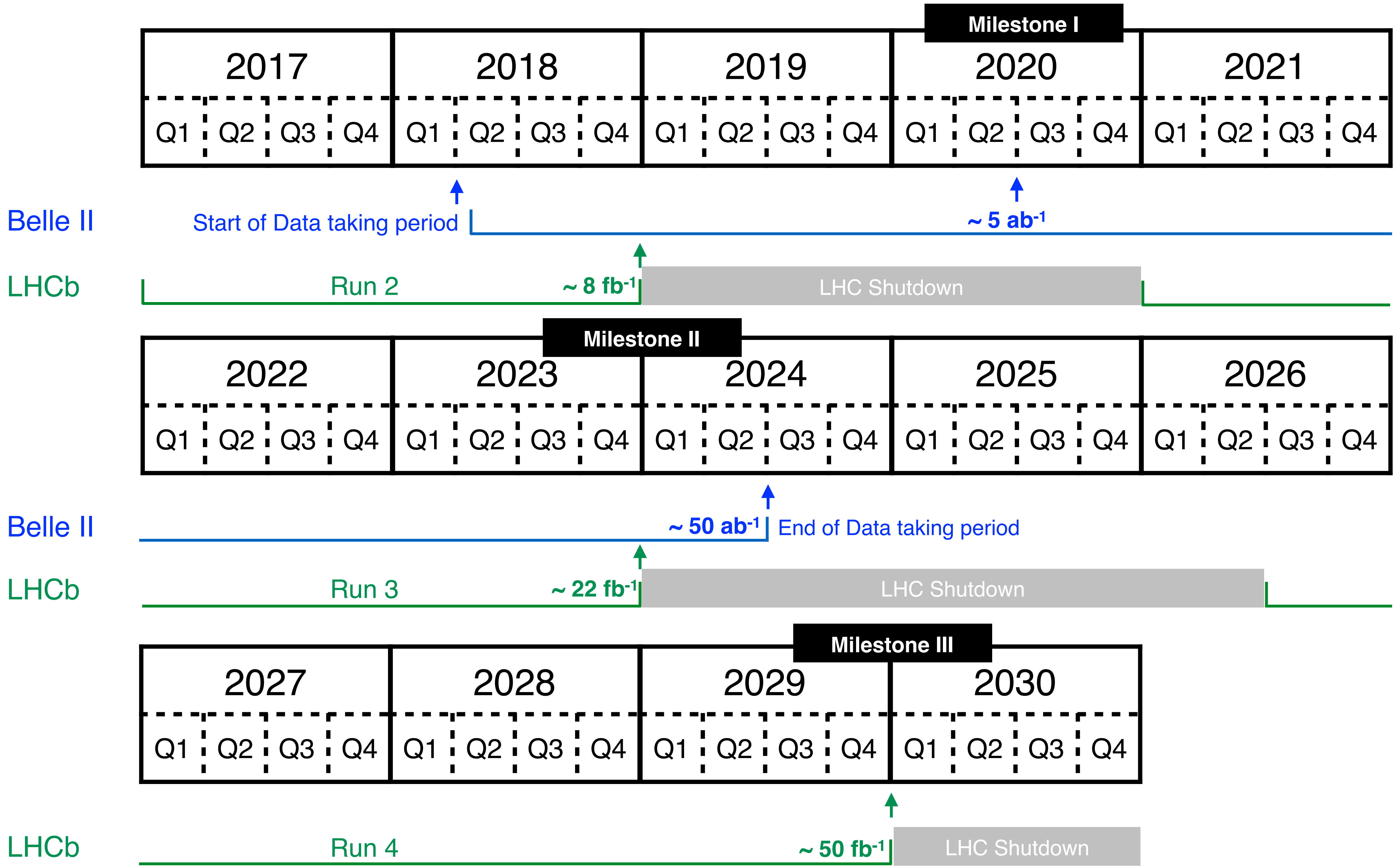


LHCb
10/fb & 22/fb
4% & 2%

Belle II
5/ab & 50/ab
R(D): 5.6% & 3.2%
R(D*): 3.9% & 2.2%

More slides

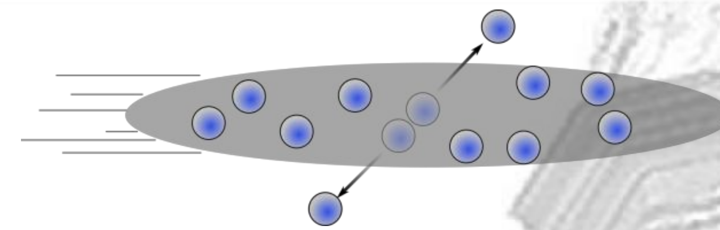
B-Factory & LHCb future timelines

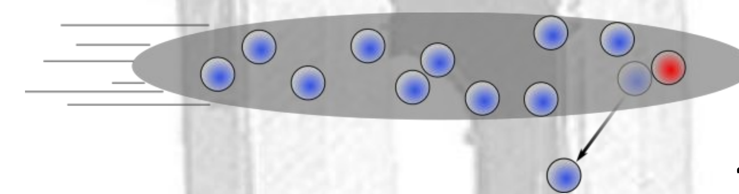


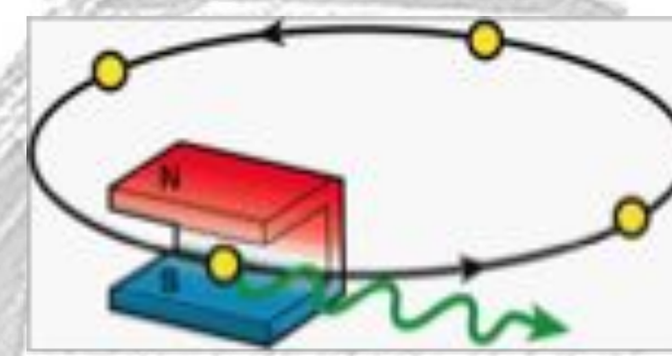
All the stuff we dont want

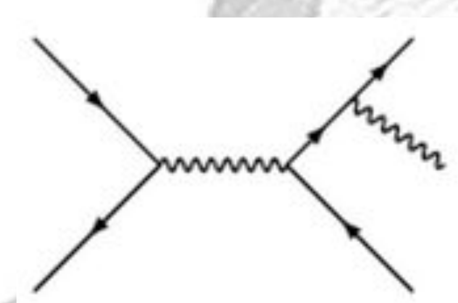
- From the beams:
  - **Touschek scattering (1):** Coulomb scattering between two particles in the same bunch
  - **Beam-gas (2):** scattering off residual gas atoms in the beam pipe
  - **Synchrotron radiation (3):** photons emitted when electrons are bent by magnetic fields

- From collisions:
  - **Radiative Bhabha (4)**


1


2


3


4

BaBar Measurement of $R(D^{(*)})$

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

Source of uncertainty	Fractional uncertainty (%) $\mathcal{R}(D^0)$	$\mathcal{R}(D^{*0})$	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	Correlation 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

Belle Measurements of $R(D^{(*)})$

Phys.Rev.Lett.118,211801 (2017)
+ [arXiv:1709.00129]

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	$^{+10.4\%}_{-9.4\%}$	$^{+0.21}_{-0.16}$

LHCb Measurements of *R(D*)*

Phys.Rev.Lett.115,111803 (2015)

Table 1: Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Overview

4. Semileptonic decays at LHCb

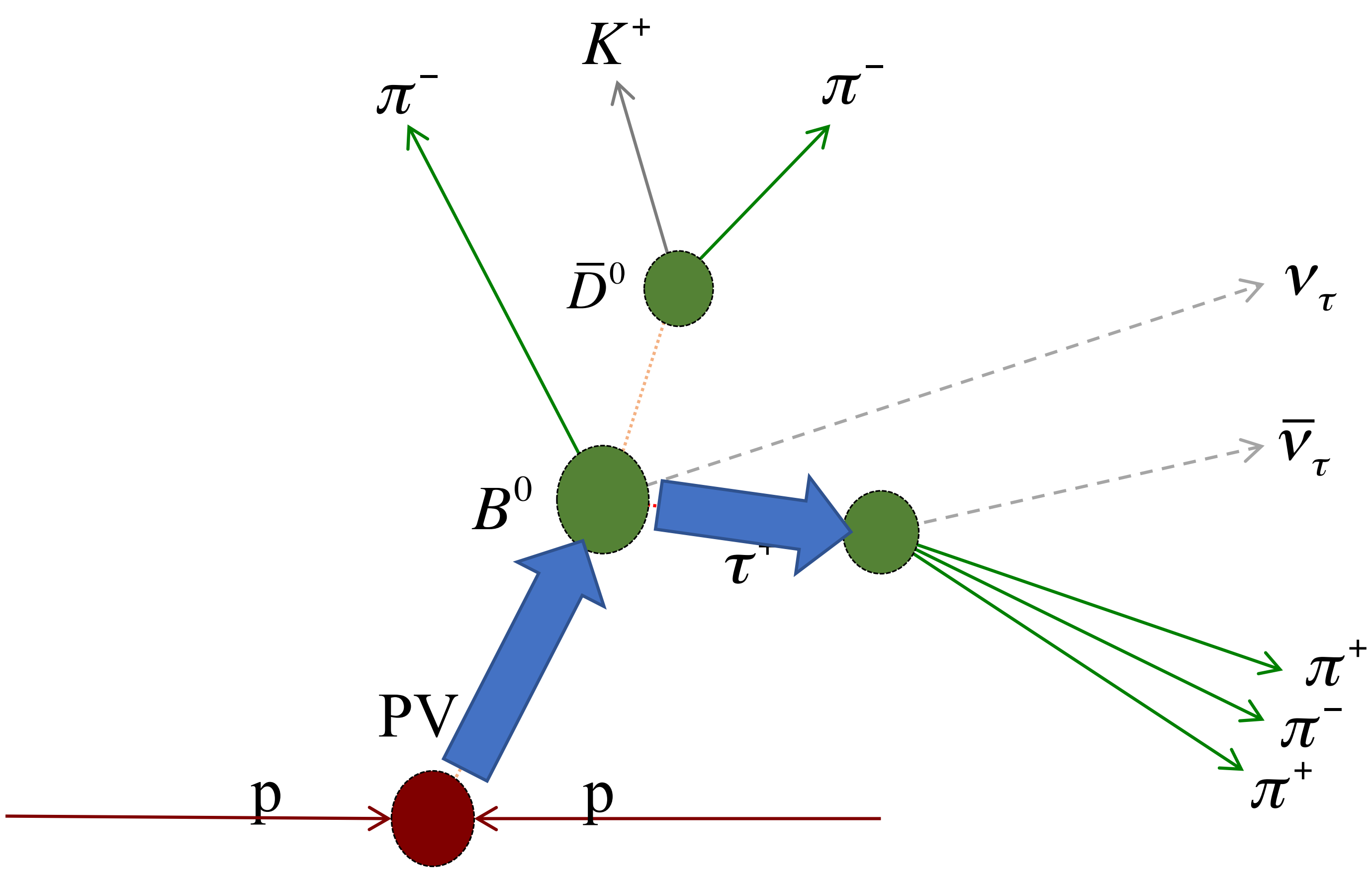
- No constraint from beam energy at a hadron machine, **but..**
- **Large Lorentz boost** with decay lengths in the range of **mm**

  ✓ **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

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



Nice Illustration from C. Bozzi

LHCb Measurements of *R(D*)*

Phys.Rev.Lett.115,111803 (2015)
arXiv:1711.02505

Two measurements using different final states:

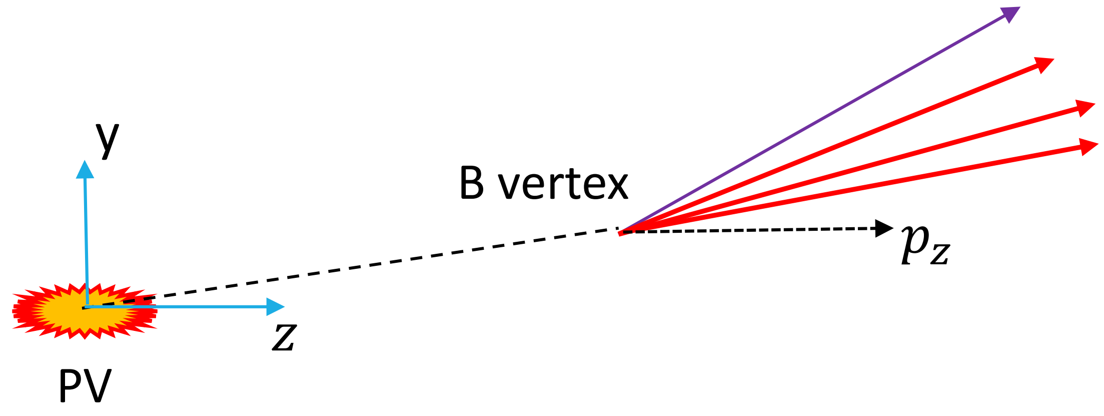
- $\tau \to \mu\nu\nu$ using $B^0 \to D^{*-}\tau\nu$
- $\tau \to \pi\pi\pi(\pi^0)\nu$ using $B^0 \to D^{*-}\tau\nu$ New!

✓ **All R(D*) measurements consistent but above SM**

LHCb Measurements of *R(D*)*

Phys.Rev.Lett.115,111803 (2015)
arXiv:1711.02505

- First measurement at a hadron collider!
- Tau reconstructed with $\tau \rightarrow \mu \nu \nu$
- The B momentum is approximated by:



$$(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu} \quad \Longrightarrow \quad (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

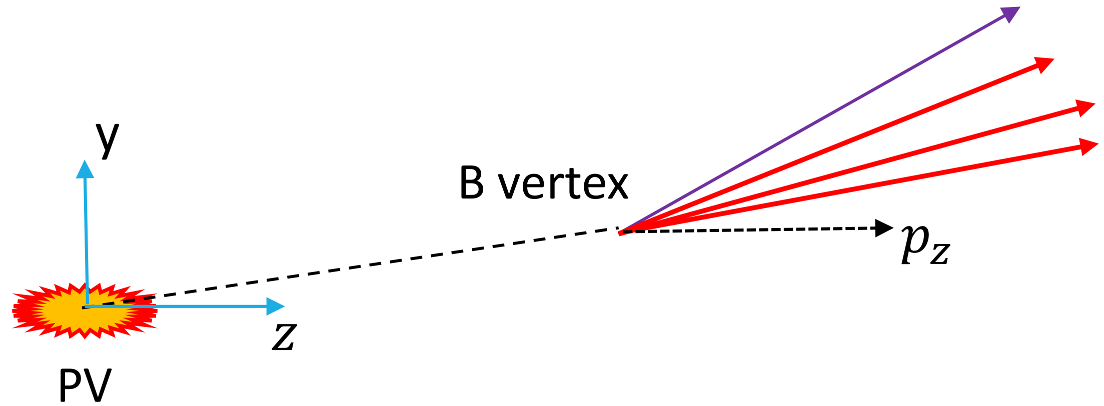
B boost along z axis much larger than boost of decay products in B rest frame, results in a resolution of about 18% on p_B

- Can be used to calculate m_{miss}^2 and $q^2 = (p_B - p_{D^*})^2$ and boost muon in B-rest frame

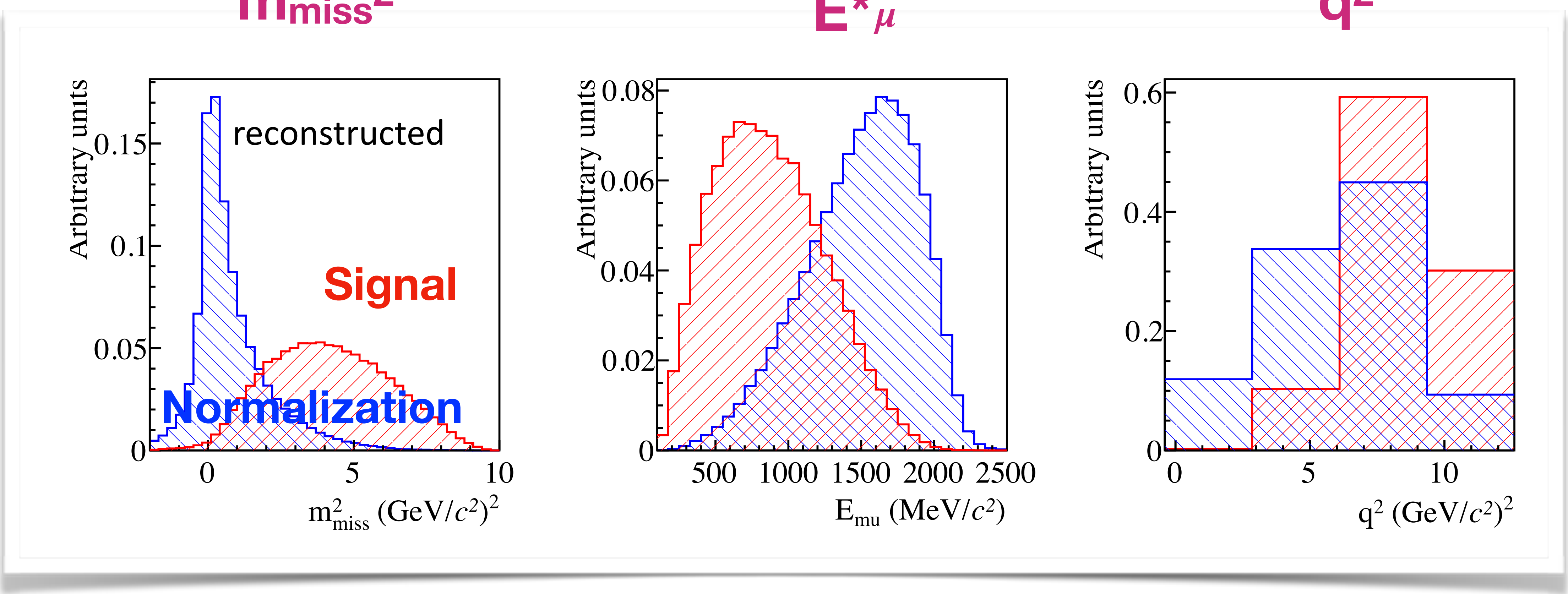
LHCb Measurements of *R(D*)*

Phys.Rev.Lett.115,111803 (2015)

- First measurement at a hadron collider!
- Tau reconstructed with $\tau \to \mu \nu \nu$
- The B momentum is approximated by:



m_{miss}^2 E^*_μ q^2



LHCb Measurements of *R(D*)*

Phys.Rev.Lett.115,111803 (2015)

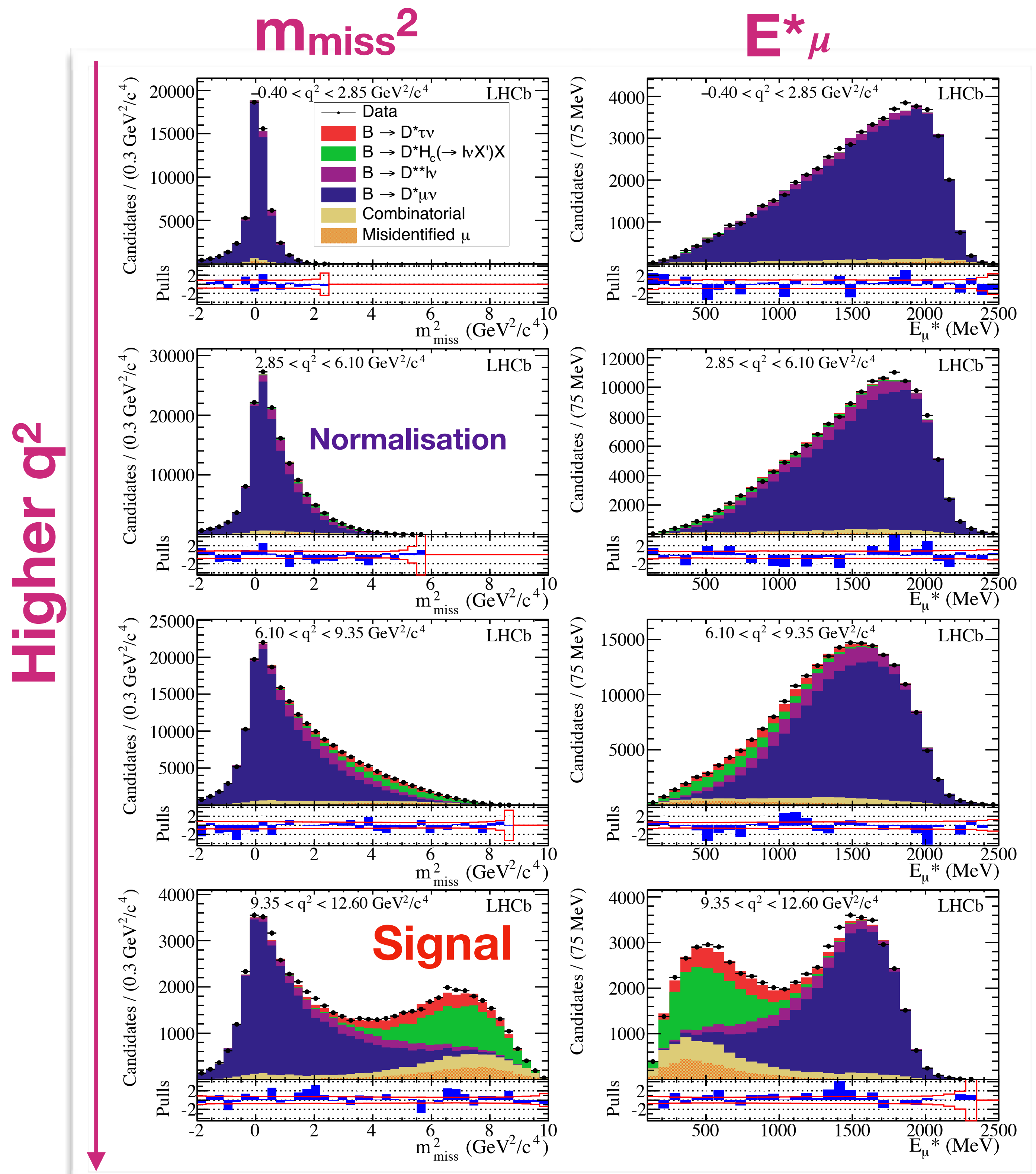
- No additional particles via MVA isolation
- Extract signal in binned **3D** fit to **m_{miss}^2, E^*_μ and 4 bins of q^2**

  Simultaneously fit 3 control regions defined by isolation criteria
- Signal yield: ~**16500 Events**

  B-Factories: O(1000 Events)

R(D*) = 0.336 ± 0.027 (stat) ± 0.030 (syst)

Compatible with BaBar and Belle, but 2.1σ from SM

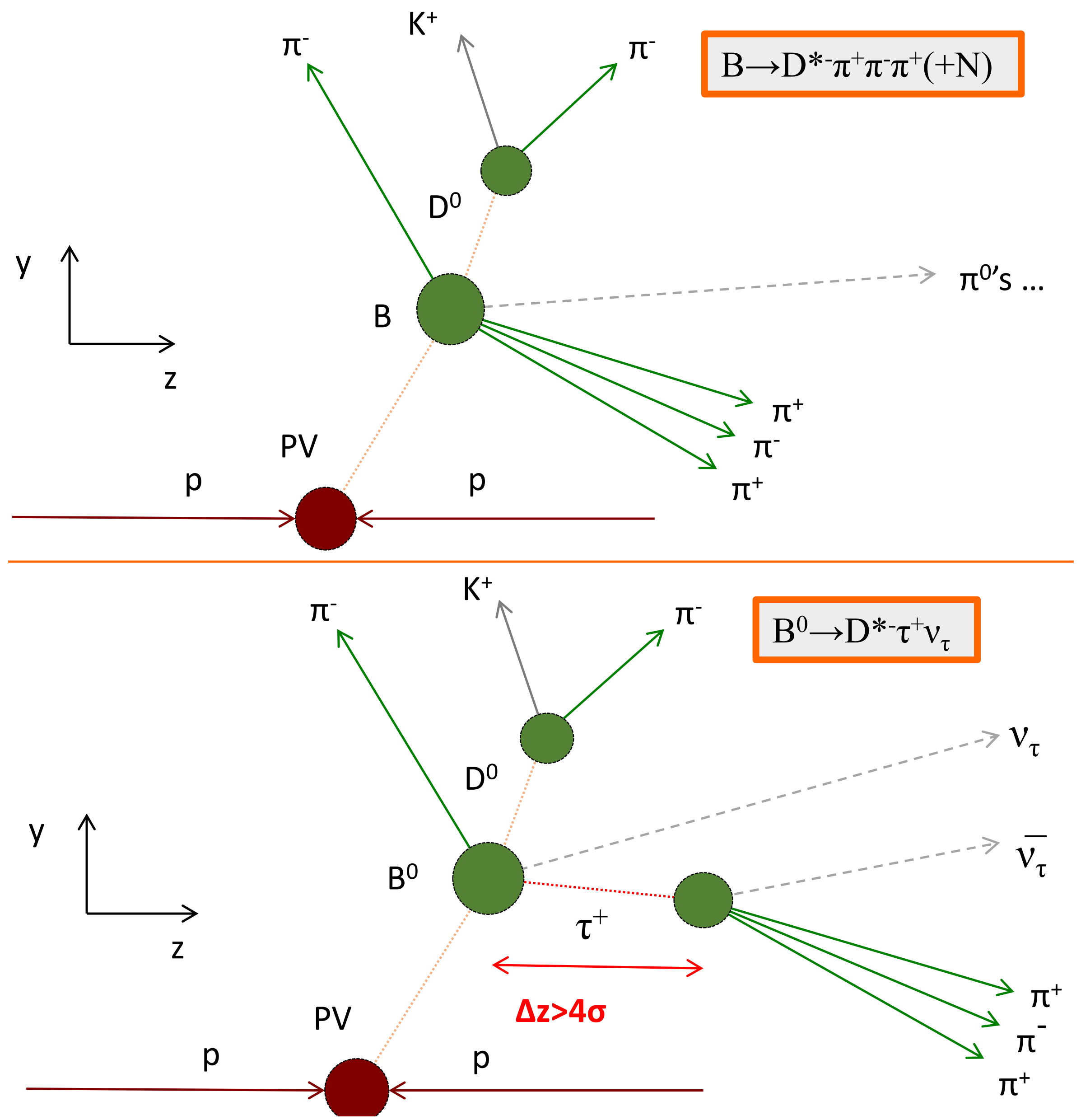


New LHCb Measurement of *R(D*)*

arXiv:1711.02505

- 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

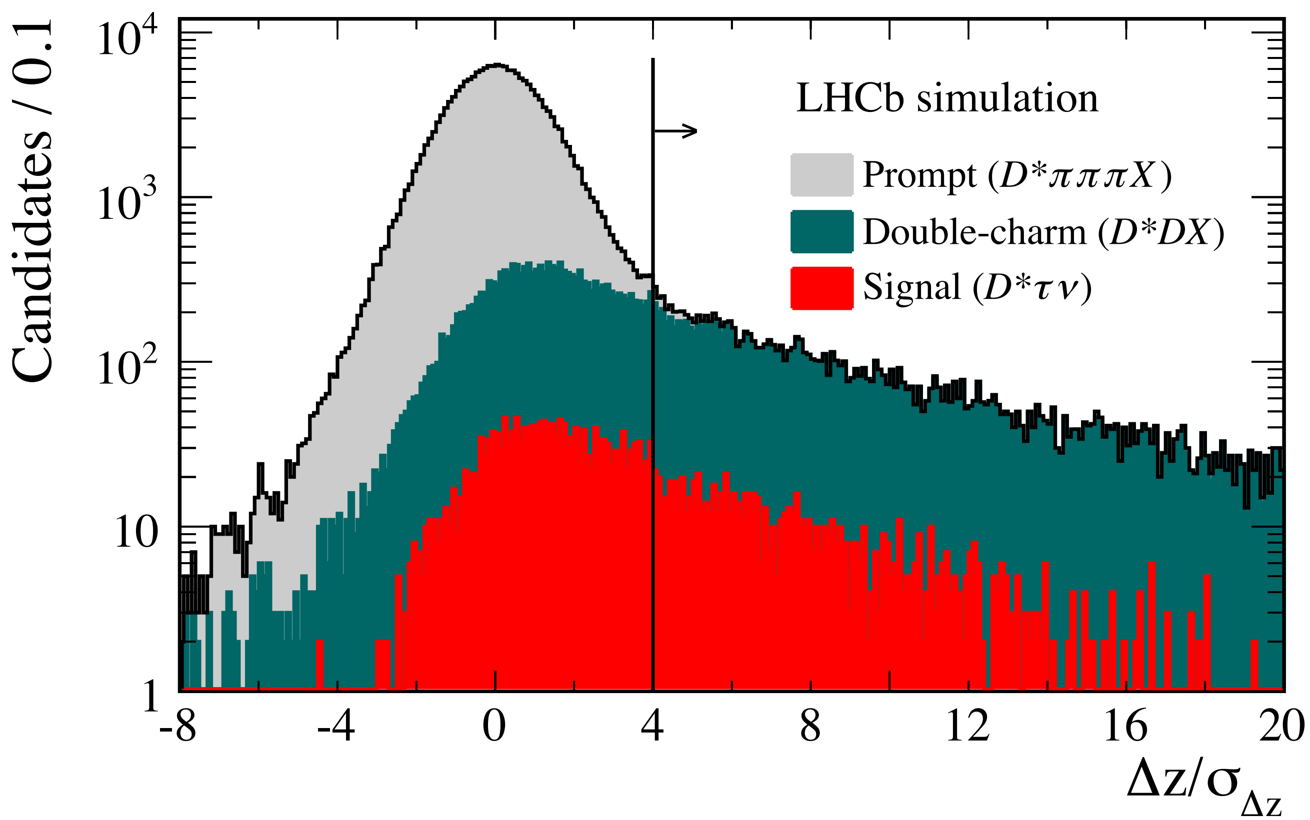
- Reduces this background by three orders of magnitudes

New LHCb Measurement of $R(D^*)$

arXiv:1711.02505

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

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



- Remaining double charm bkgs:

  $X_b \rightarrow D^{*-}D_s^+X$ ~ 10 x Signal

  $X_b \rightarrow D^{*-}D^+X$ ~ 1 x Signal

  $X_b \rightarrow D^{*-}D_{s0}^+X$ ~ 0.2 x Signal

- Main background: prompt **$X_b \rightarrow D^*\pi\pi\pi$ + 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 magnitudes

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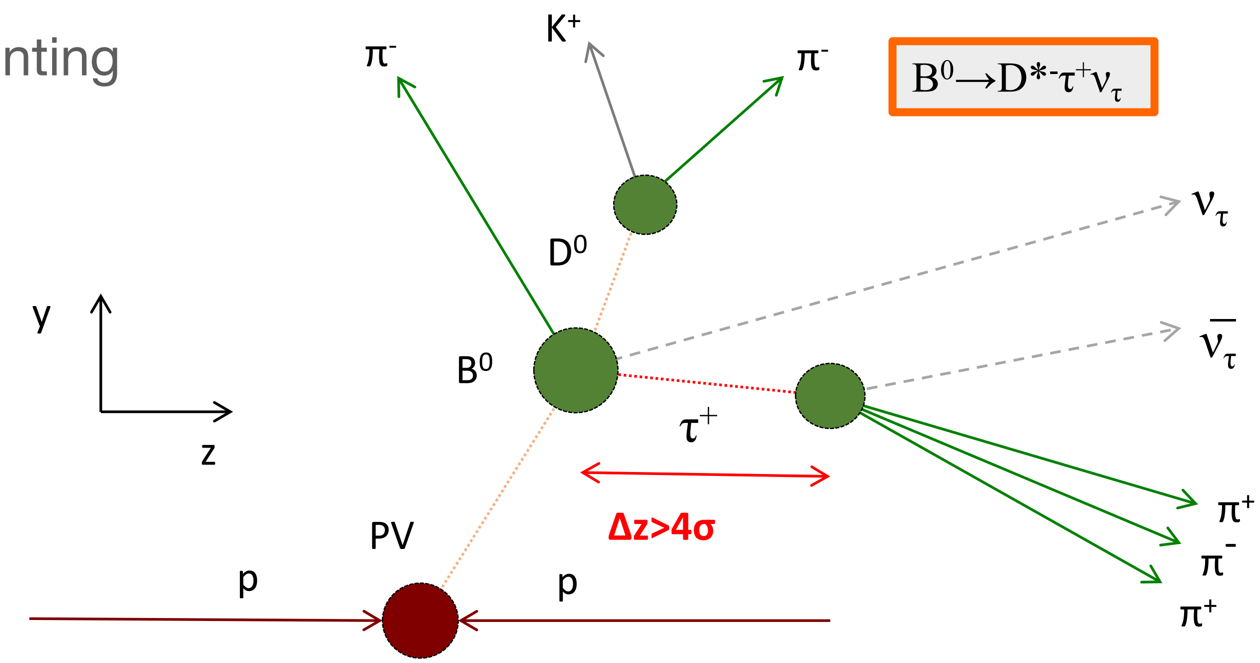
- Remaining backgrounds reduced via isolation & MVA

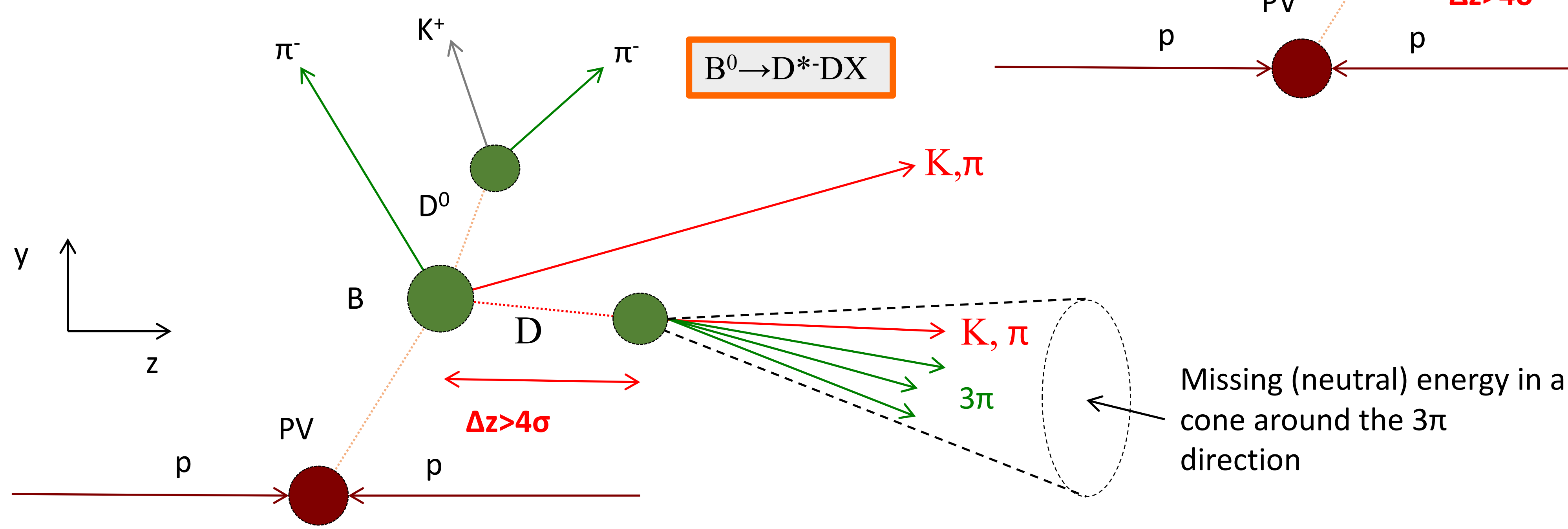
  Require signal candidates to be well isolated

  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





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- 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

- ~ 1273 ± 85 Signal events

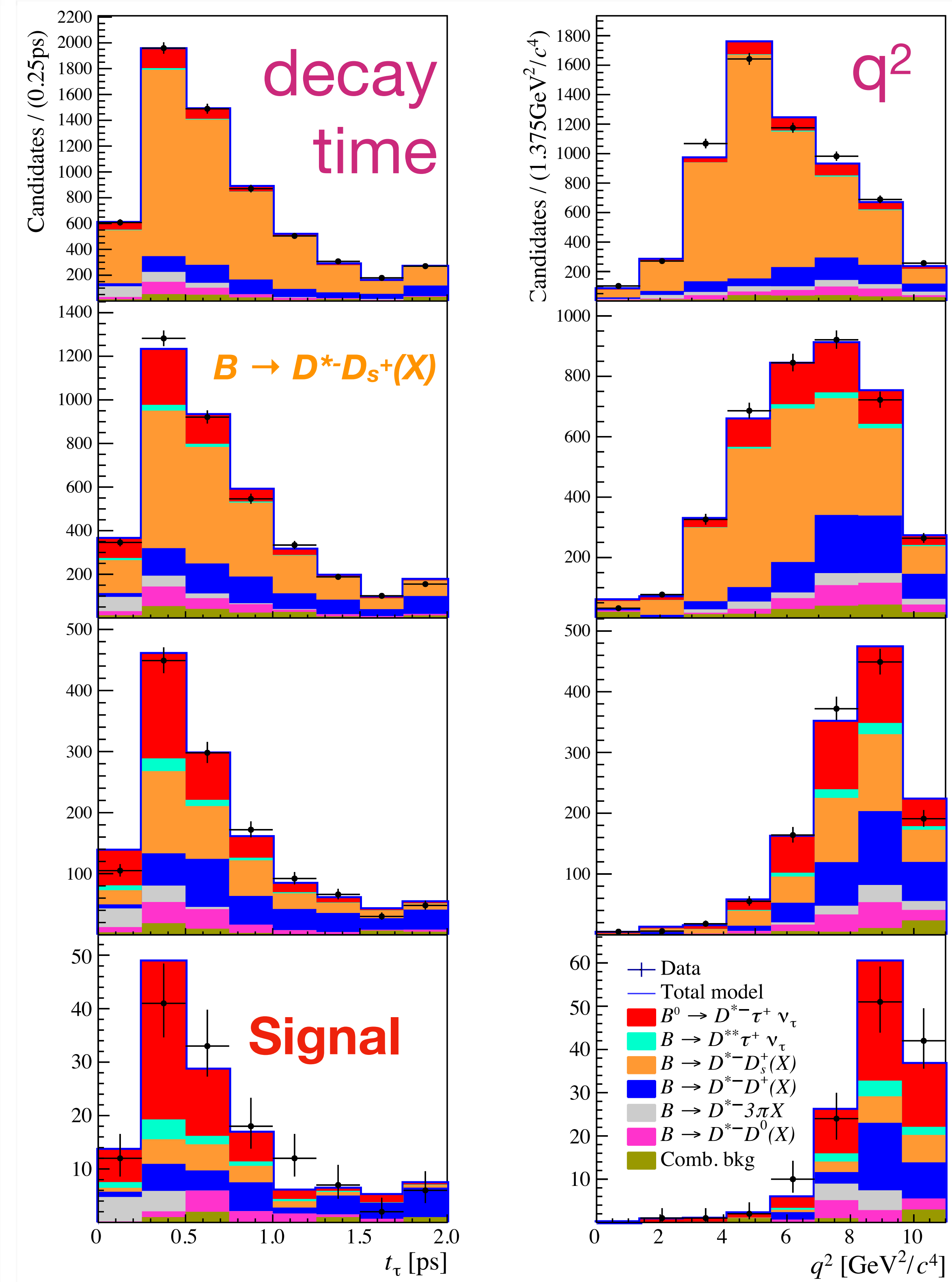
- Using normalisation mode and light lepton BFs:

More information about normalisation in backup

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

0.9σ higher than SM

Purer MVA Selection

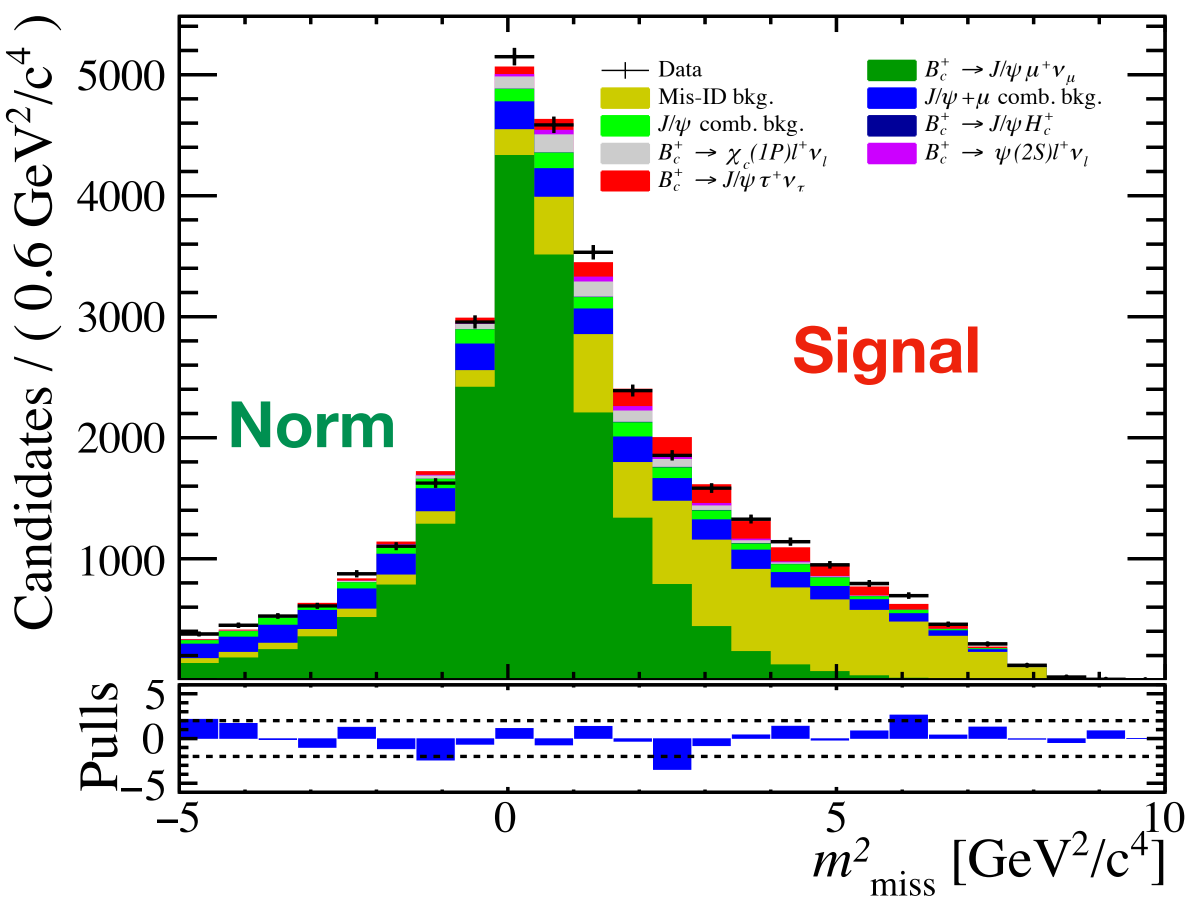


More interesting ratios from LHCb and Belle!

arXiv:1711.05623 | Phys. Rev. D 93, 032007 (2016)

$\tau \to \mu\nu\nu$

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)},$$

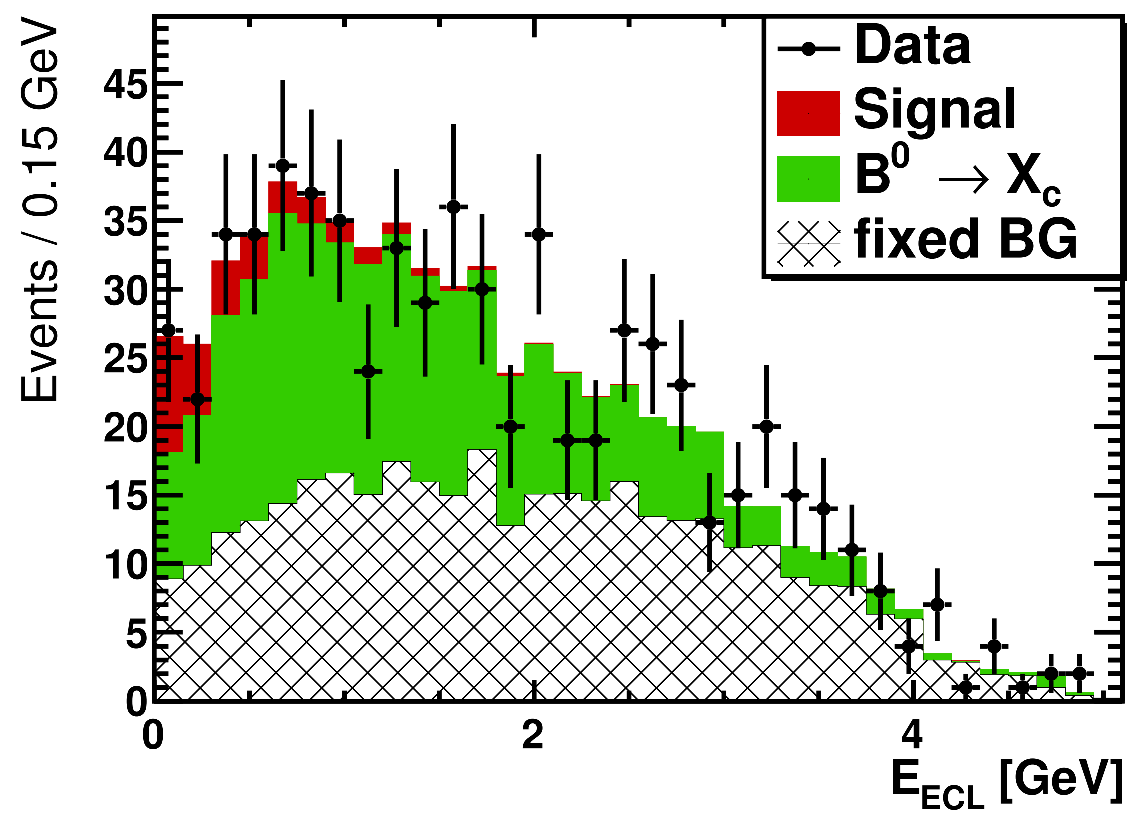


3D fit (q^2, m_{miss}^2, Z) determines

R(J/ψ) = 0.71 ± 0.17 ± 0.18 $R(J/\psi)_{SM} \sim 0.28$

$\tau \to \ell\nu\nu$, $\tau \to \pi\nu\nu$, $\tau \to \rho\nu\nu$, $\tau \to a_1\nu\nu$

$$R(\pi) = \frac{\mathcal{B}(B \to \pi\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to \pi\ell\bar{\nu}_\ell)}$$



1D fit in E_{ECL} determines

R(π) = 1.05 ± 0.51 $R(\pi)_{SM} = 0.641 \pm 0.016$

New LHCb Measurement of *R(D*)*

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- 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

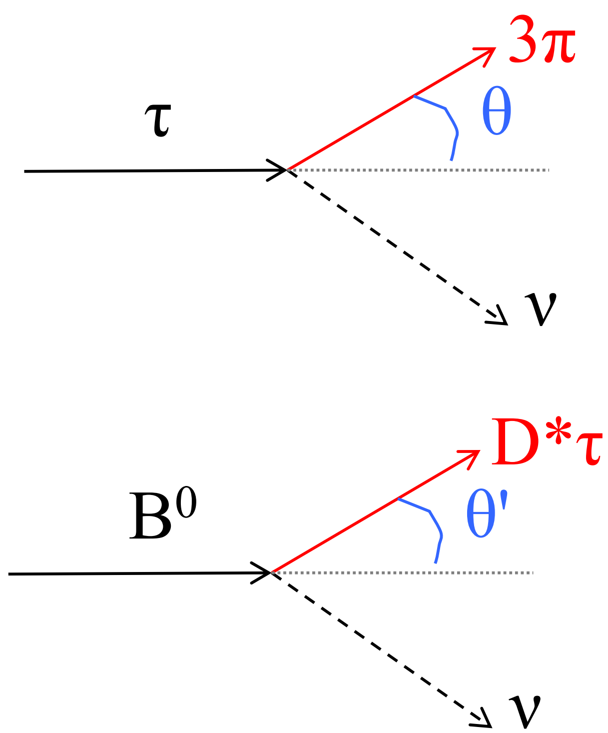
Both reconstructed with some tricks (more in backup)

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

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

New LHCb Measurement of *R(D*): Control samples*

arXiv:1711.02505

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

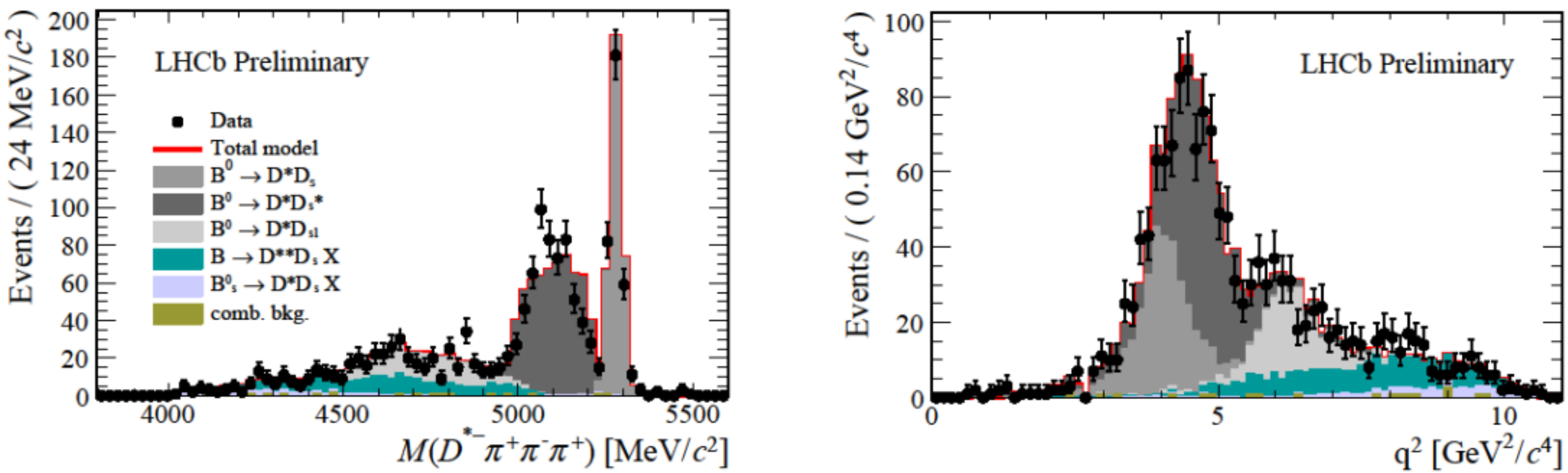
Determine the different $X_b \to D^{*-} D_s^+ X$ contributions from a fit to m(D*Ds):

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

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

New LHCb Measurement of *R(D*): Control samples*

arXiv:1711.02505

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

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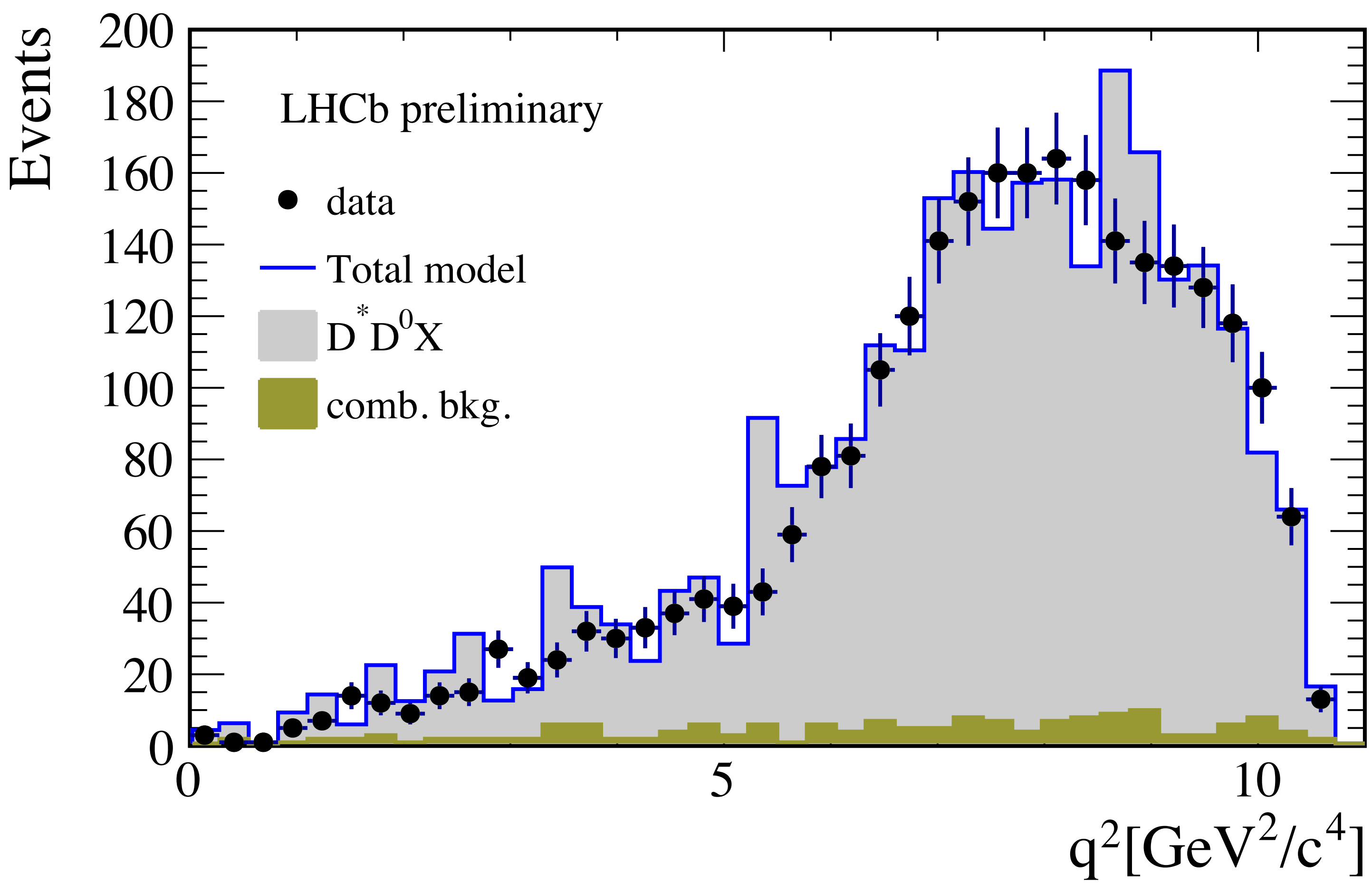

For the D°, the inclusive 4 prongs BR constrains strongly the rate of 3π events

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

We let the D^+ component float in the fit

Slide from C. Bozzi

New LHCb Measurement of *R(D*)*: Systematics

arXiv:1711.02505

Source	$\delta R(D^{*-})/R(D^{*-})[\%]$
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Total uncertainty	8.9

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