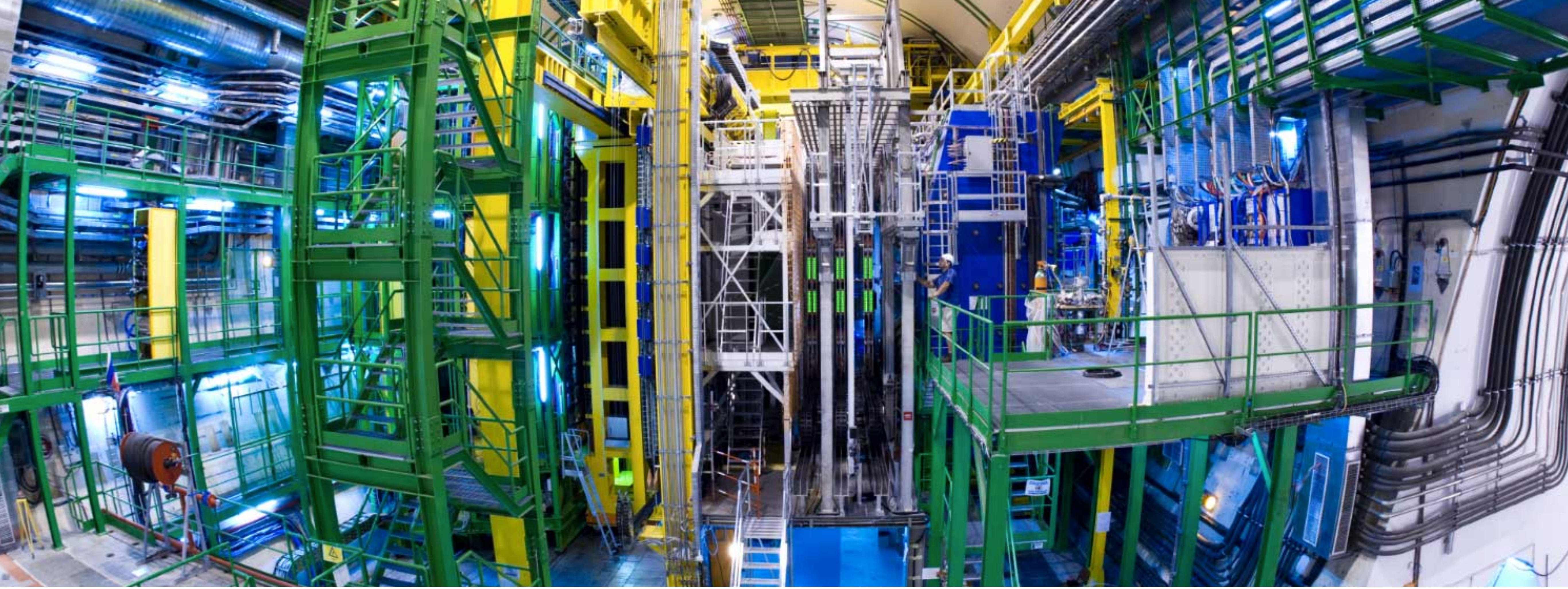


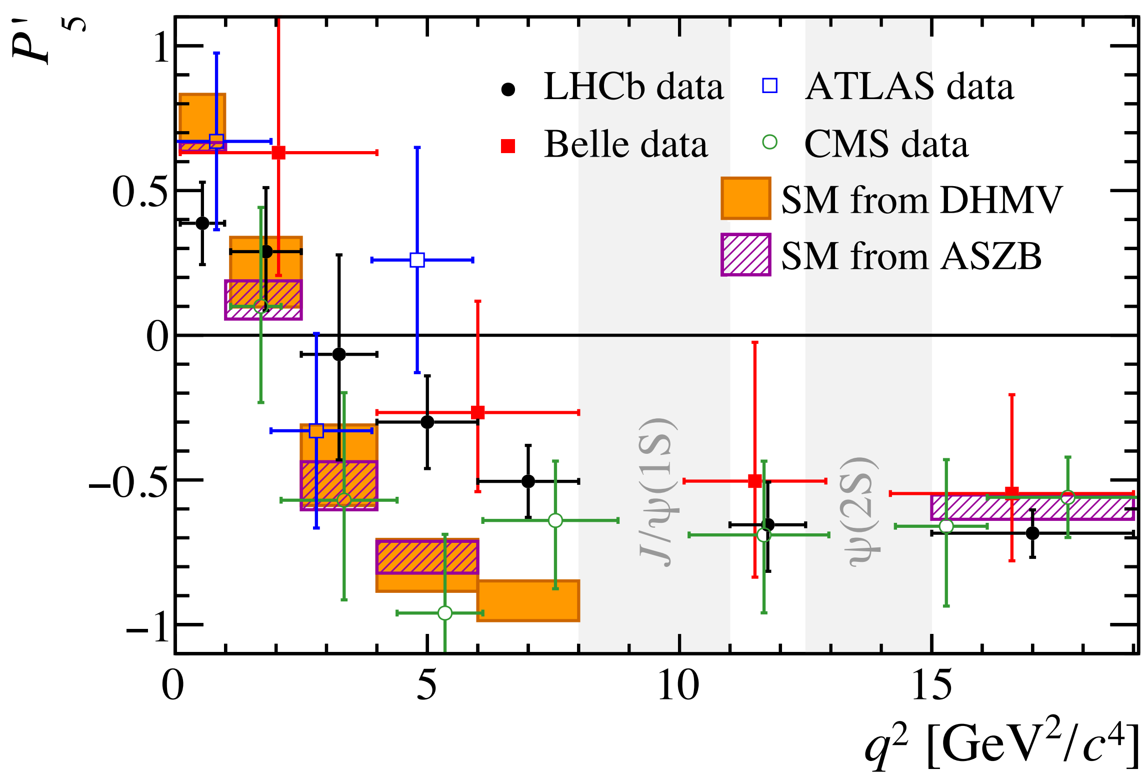
Lepton universality tests with tree-level semileptonic decays

Mika Vesterinen
University of Oxford

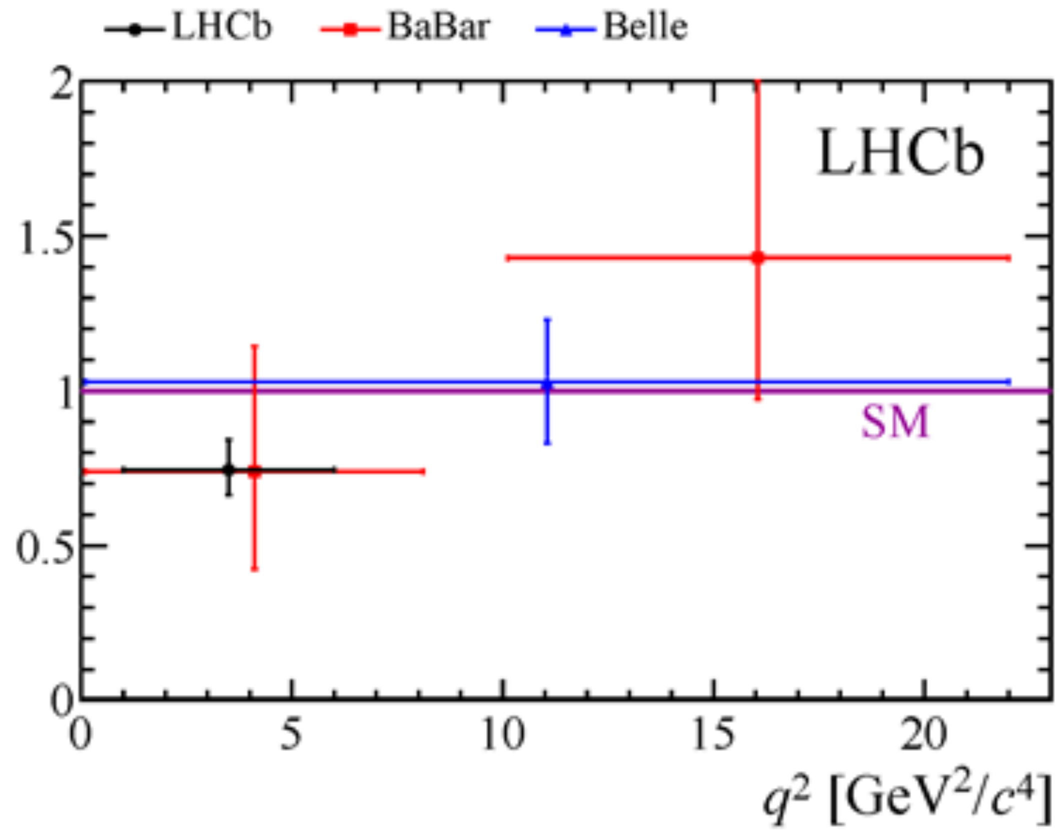
DESY colloquium

24-25 April 2018

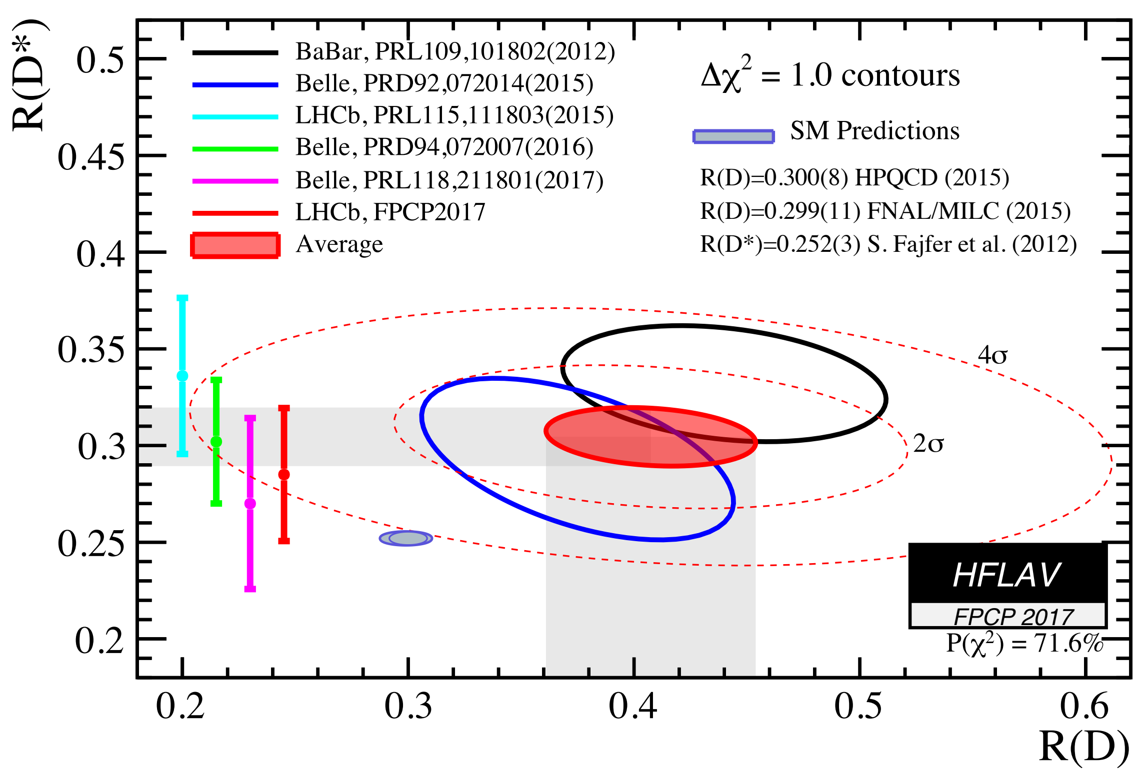
UNIVERSITY OF OXFORD



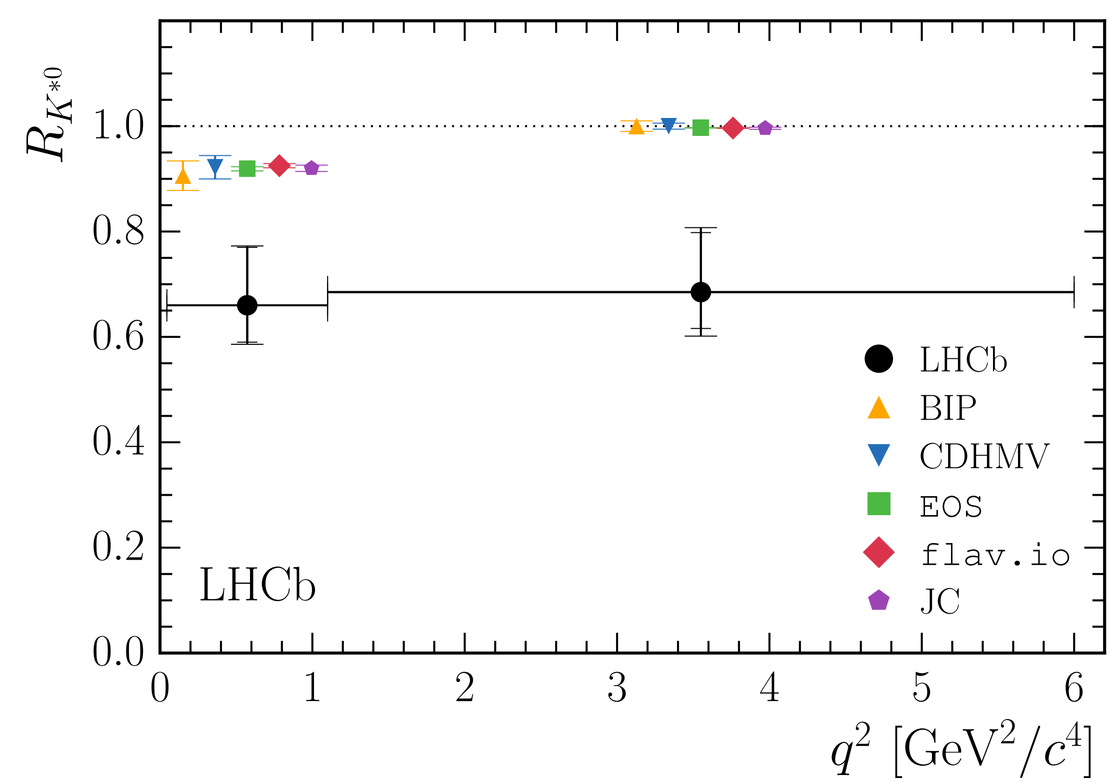
P'_5
LHCb data
ATLAS data
Belle data
CMS data
SM from DHMV
SM from ASZB
$J/\psi(1S)$
$\psi(2S)$
q^2 [GeV$^2/c^4$]



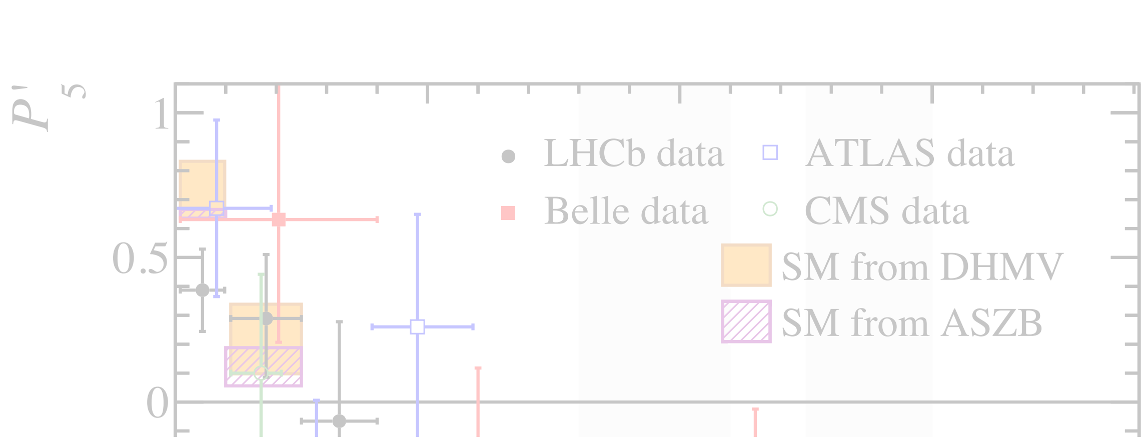
LHCb
BaBar
Belle
LHCb
SM
q^2 [GeV$^2/c^4$]

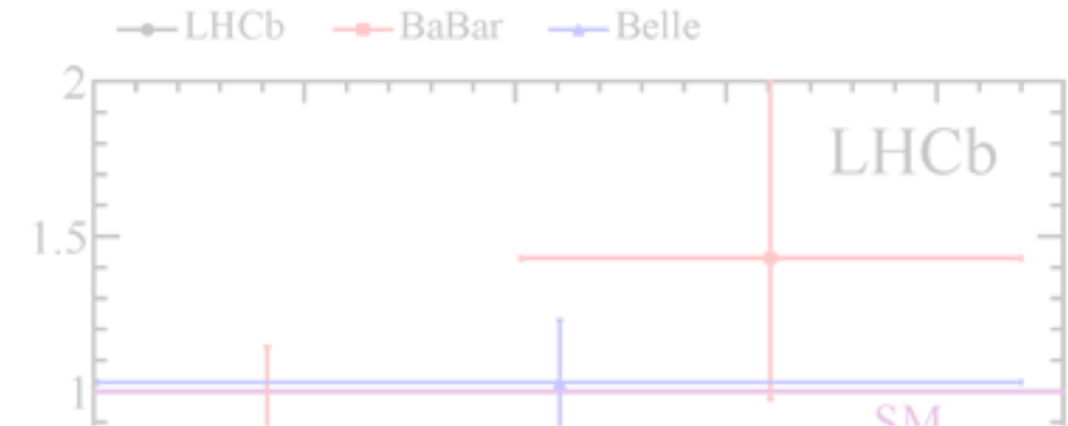


R(D*)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
$\Delta\chi^2$ = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
4σ
2σ
HFLAV
FPCP 2017
P(χ^2) = 71.6%
R(D)



$R_{K^{*0}}$
LHCb
BIP
CDHMV
EOS
flav.io
JC
LHCb
q^2 [GeV$^2/c^4$]

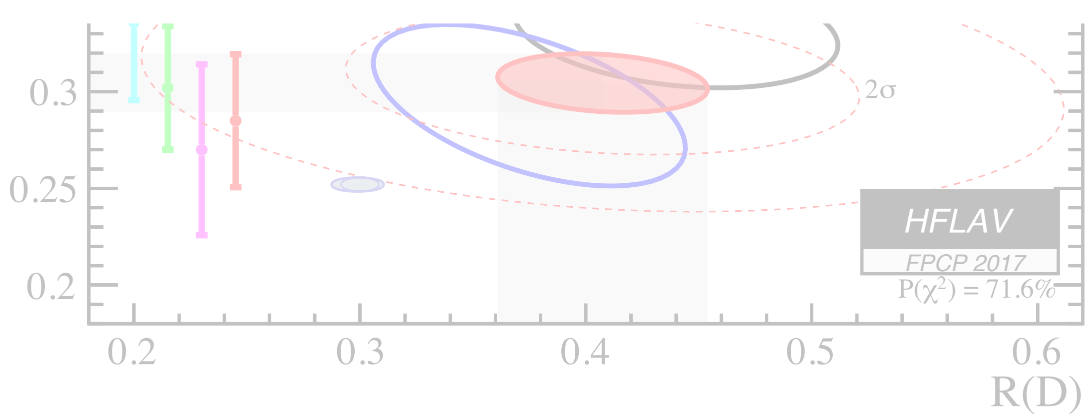




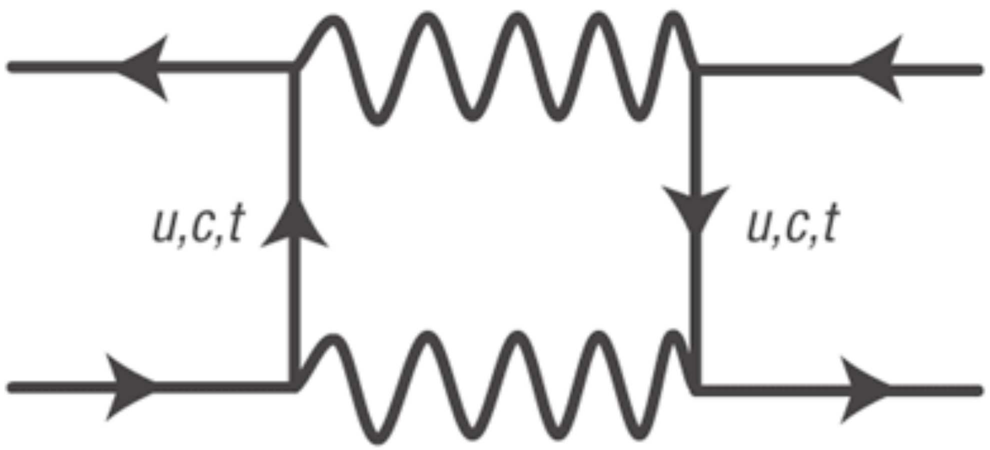
1. Introduction to B physics and LHCb

2. LHCb tests of Lepton Universality in tree decays

3. Future prospects



Searching for new physics beyond the SM

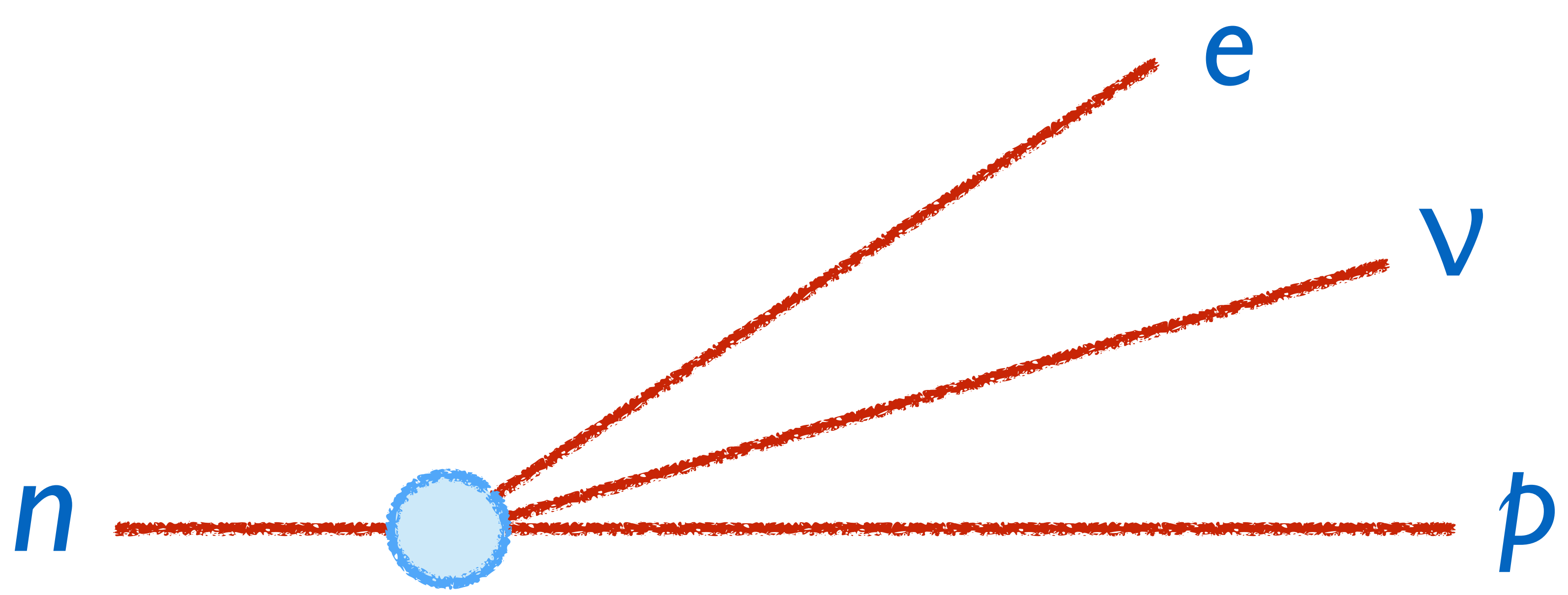


Direct: Sensitivity to heavier BSM scales requires higher **energy**

Indirect: Sensitivity to heavier BSM scales requires higher **precision**

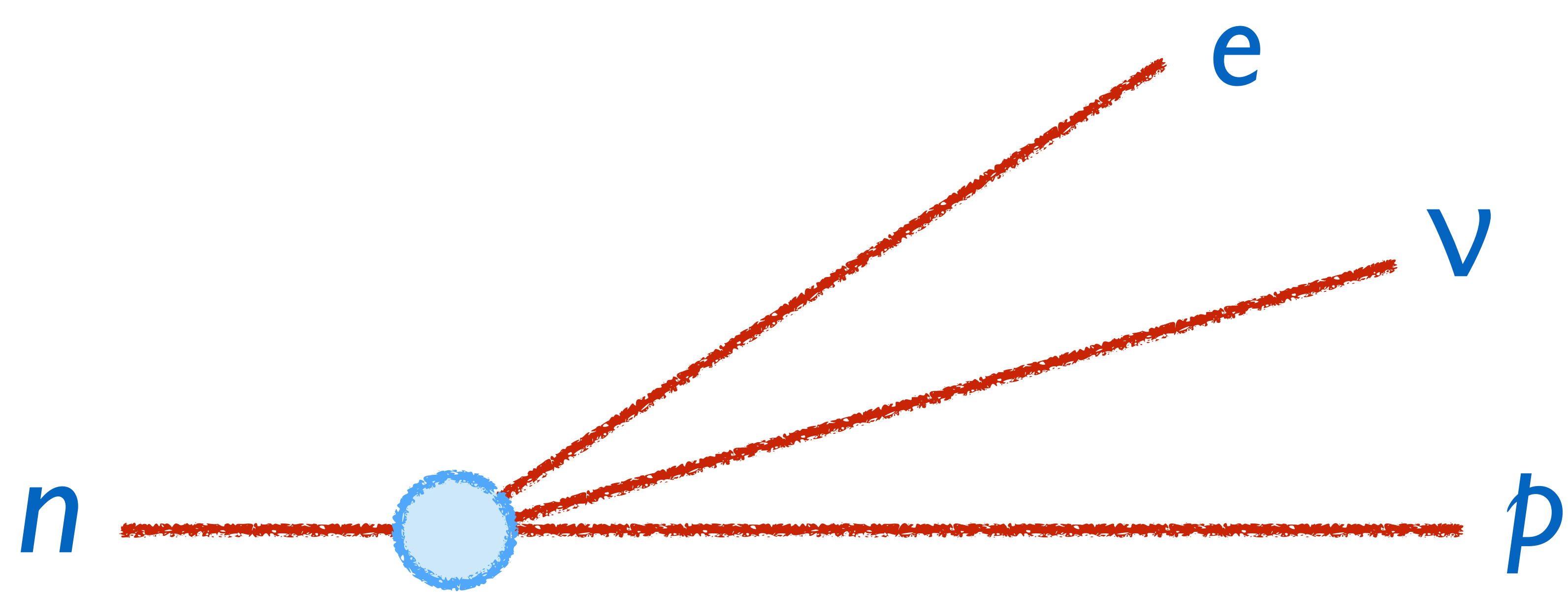
Indirect example

$m_n \sim 1$ GeV

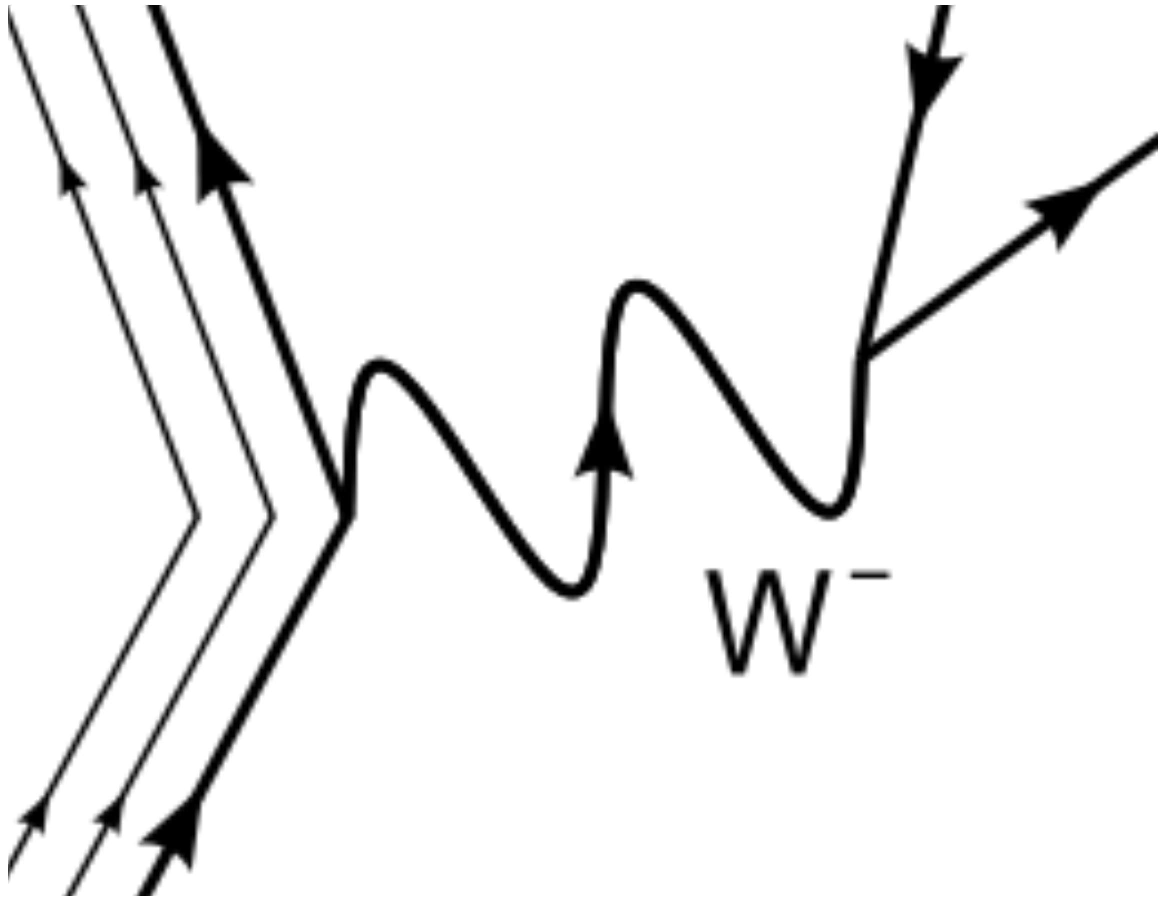


Indirect example

$m_n \sim 1$ GeV



$m_W \sim 100$ GeV



$$\text{Amplitude} \propto \frac{g^2}{m_W^2}$$

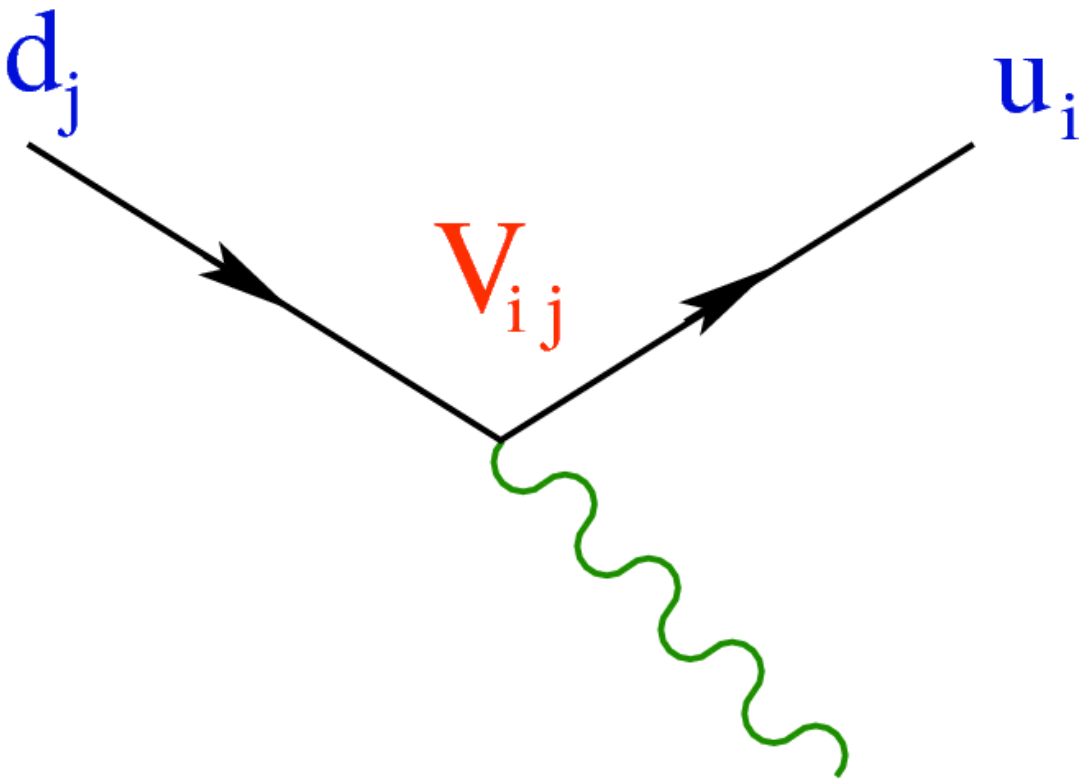
How to see…

…a measurable effect of a tiny BSM amplitude that is inversely proportional to the BSM mass scale?

Focus on processes/observables for which

- SM contribution is suppressed,
- and can be precisely computed.
- Experiments can reach high precision.

Quark flavour mixing



$$V_{CKM} \approx \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

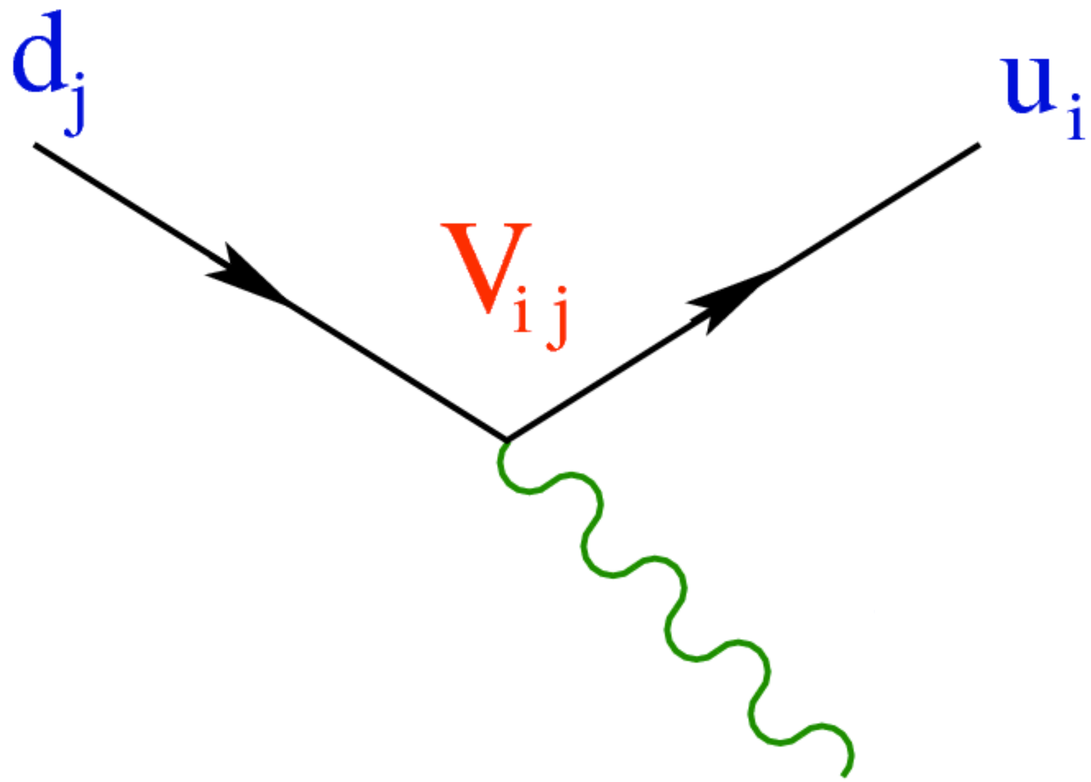
V_{CKM} is hierarchical => SM amplitudes suppressed.

(V_{CKM} is also the sole source of CPV in the SM*)

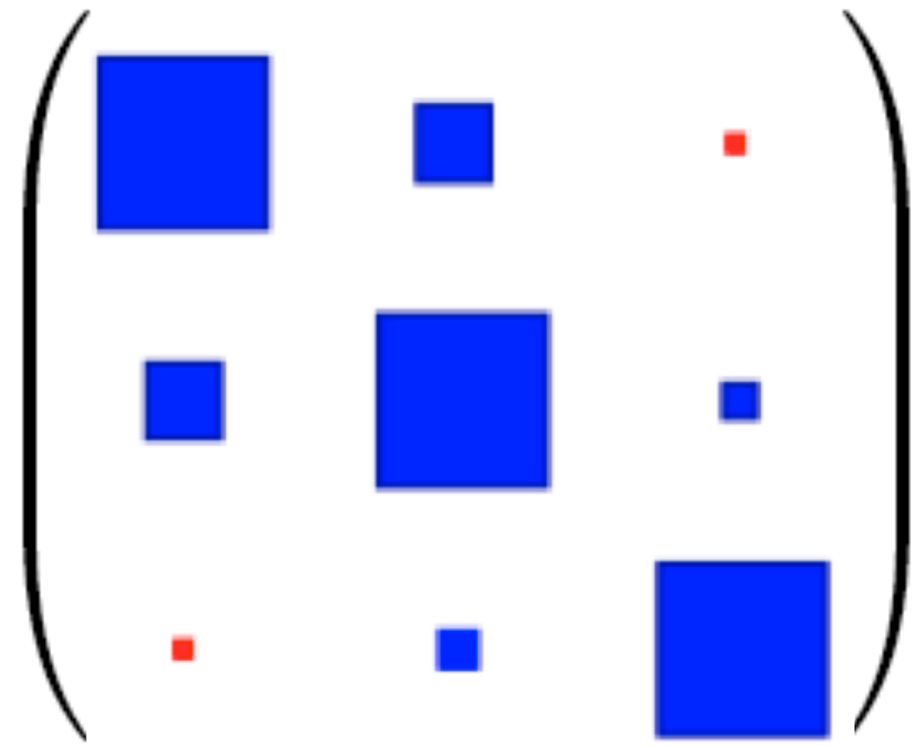
V_{CKM} must be unitary => testability.

*For SM with $\theta_{QCD} = m_{\nu} = 0$

Quark flavour mixing



$V_{CKM} \approx$



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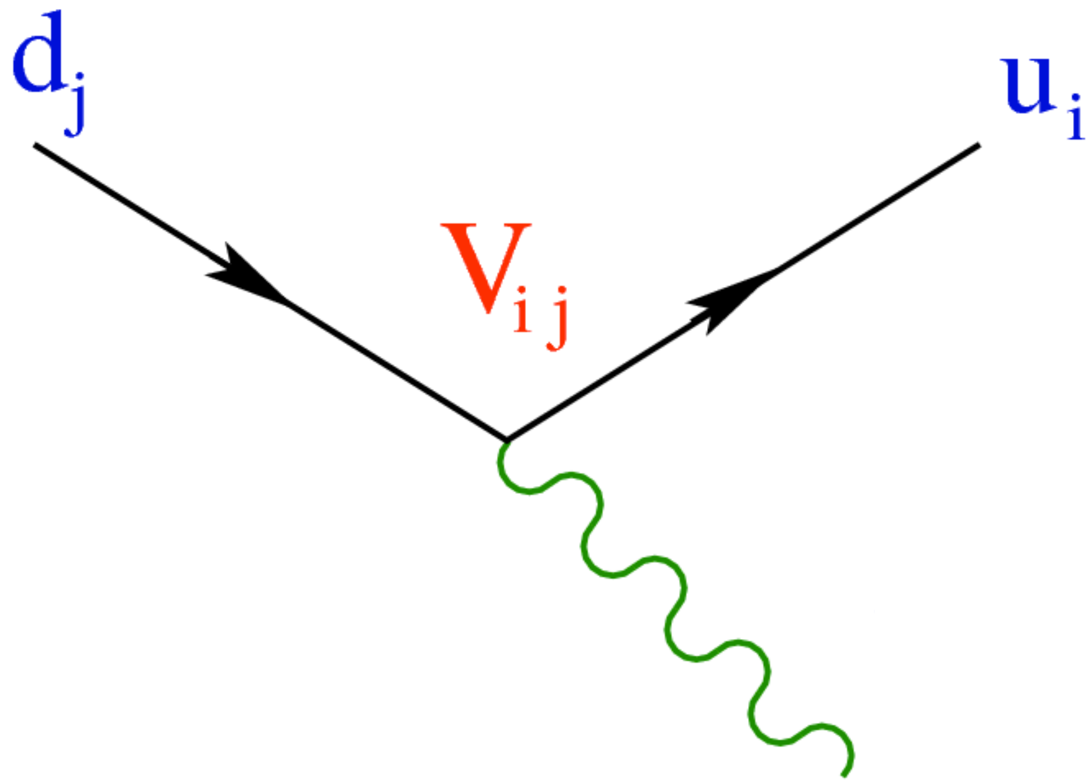
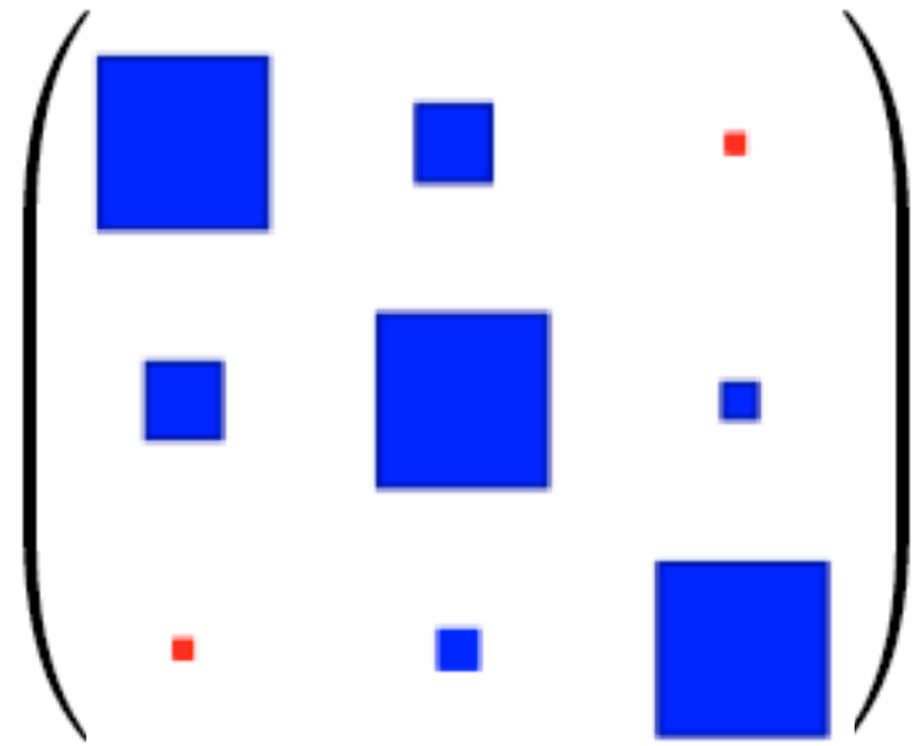
Quark flavour mixing



$V_{CKM} \approx$ 

V_{CKM} is hierarchical => SM amplitudes suppressed.

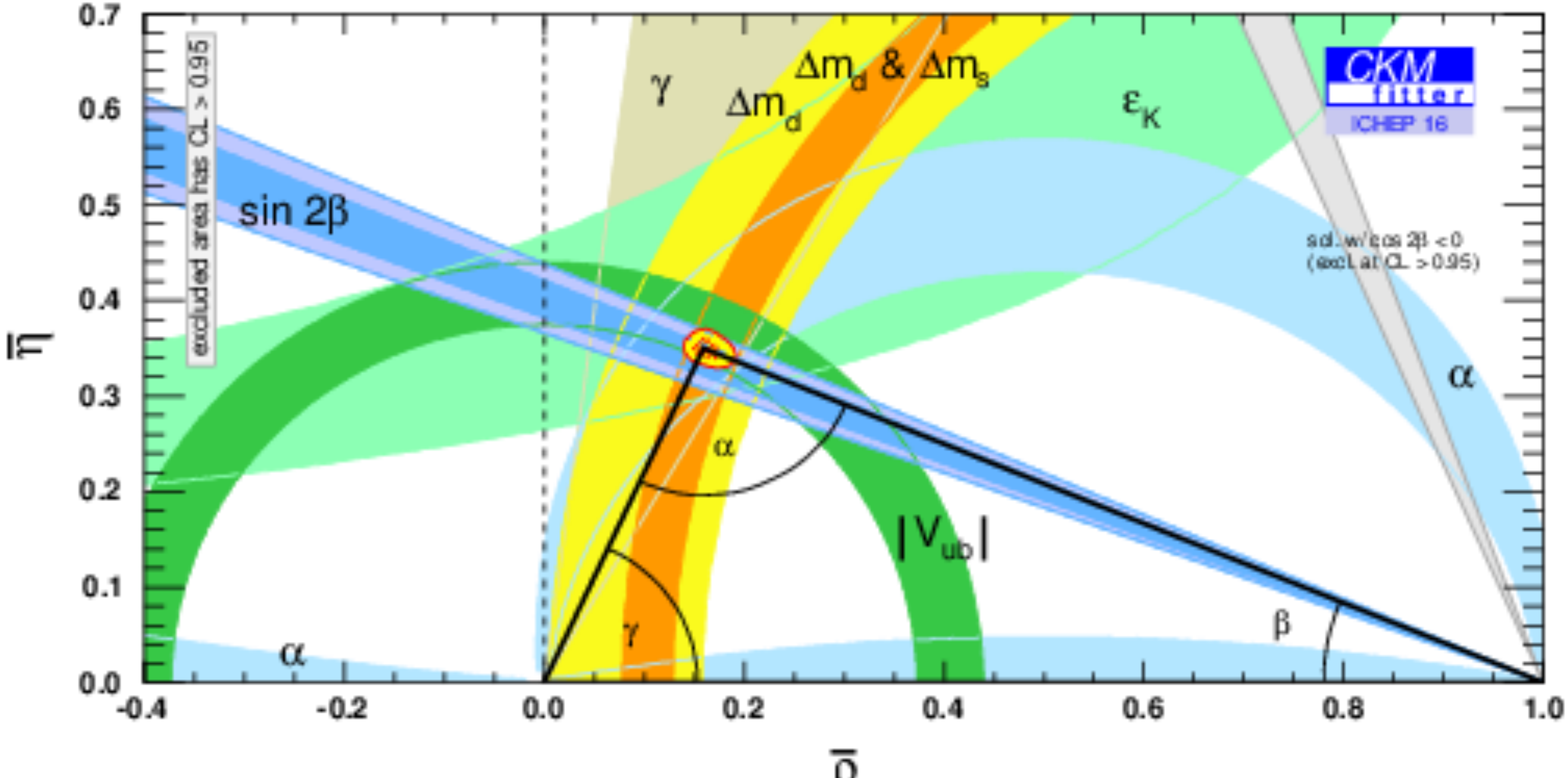
(V_{CKM} is also the sole source of CPV in the SM*)

V_{CKM} must be unitary => testability.

$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*} = 0$$

*For SM with $\theta_{QCD} = m_{V} = 0$

The Unitarity Triangle today

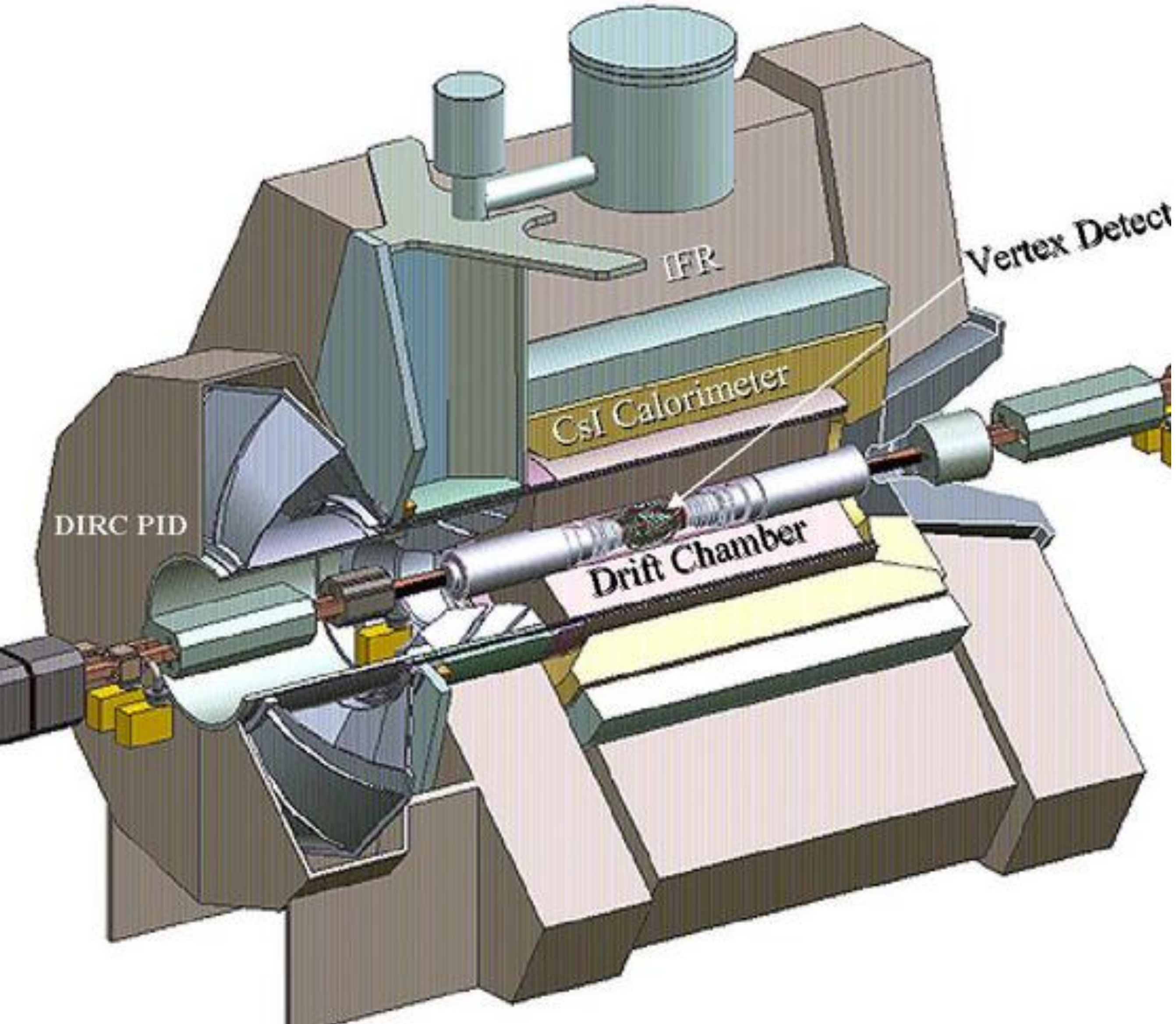


The SM CKM mechanism is the leading source of quark flavour mixing.

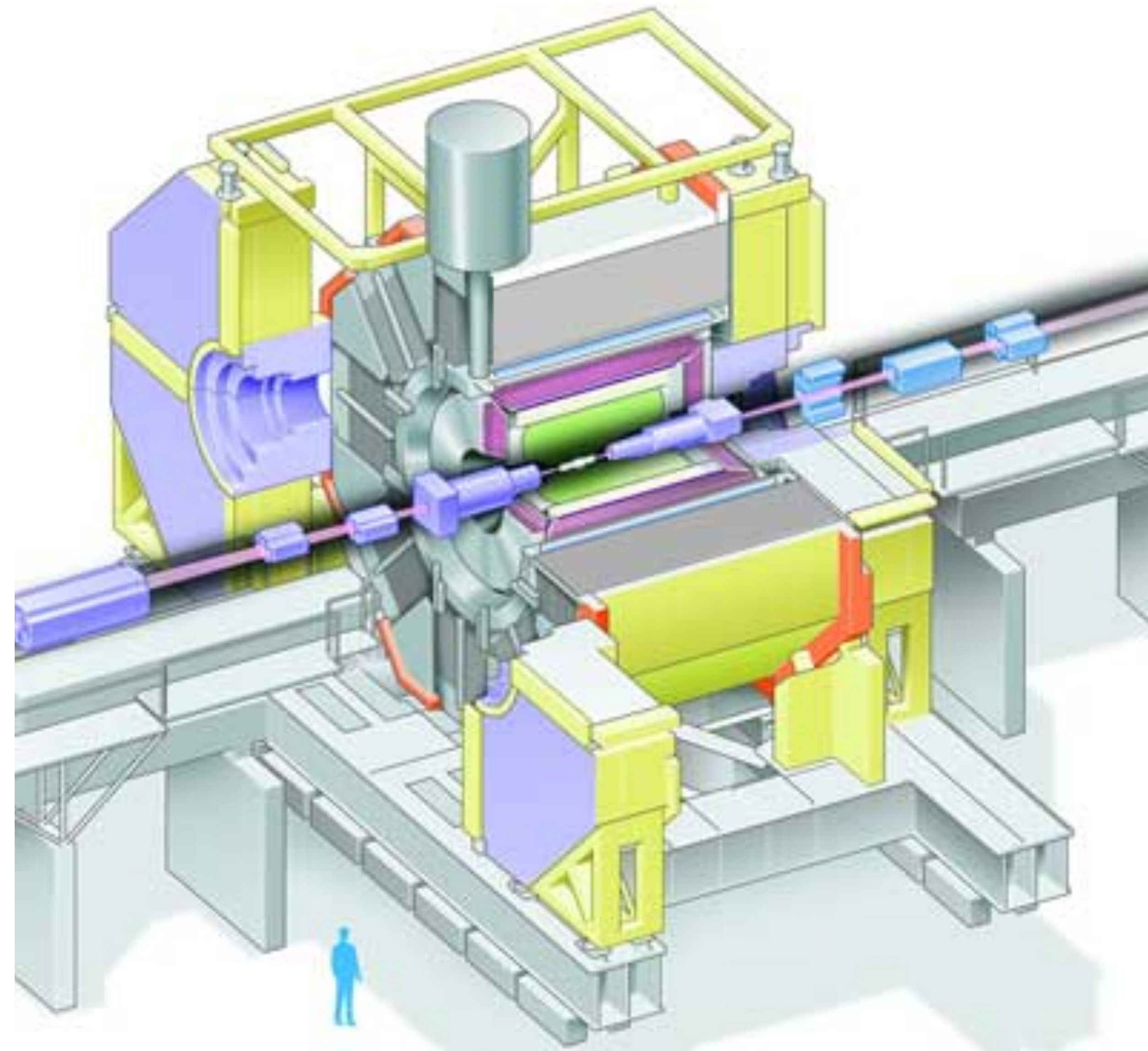
We are nowhere near exhausting the potential BSM sensitivity of quark flavour.

BaBar and Belle

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$$



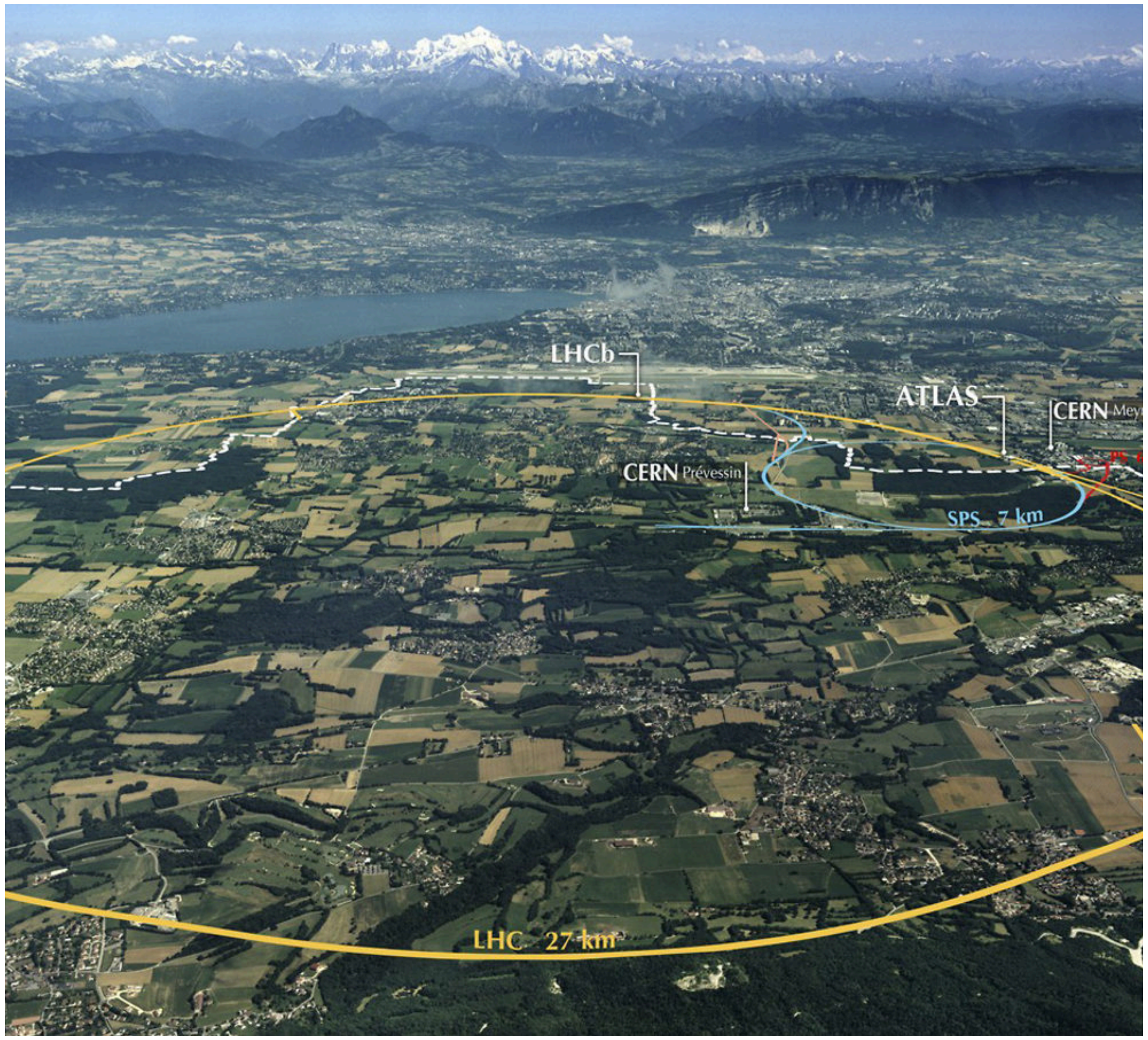
BaBar1999-2008
~500 million BB

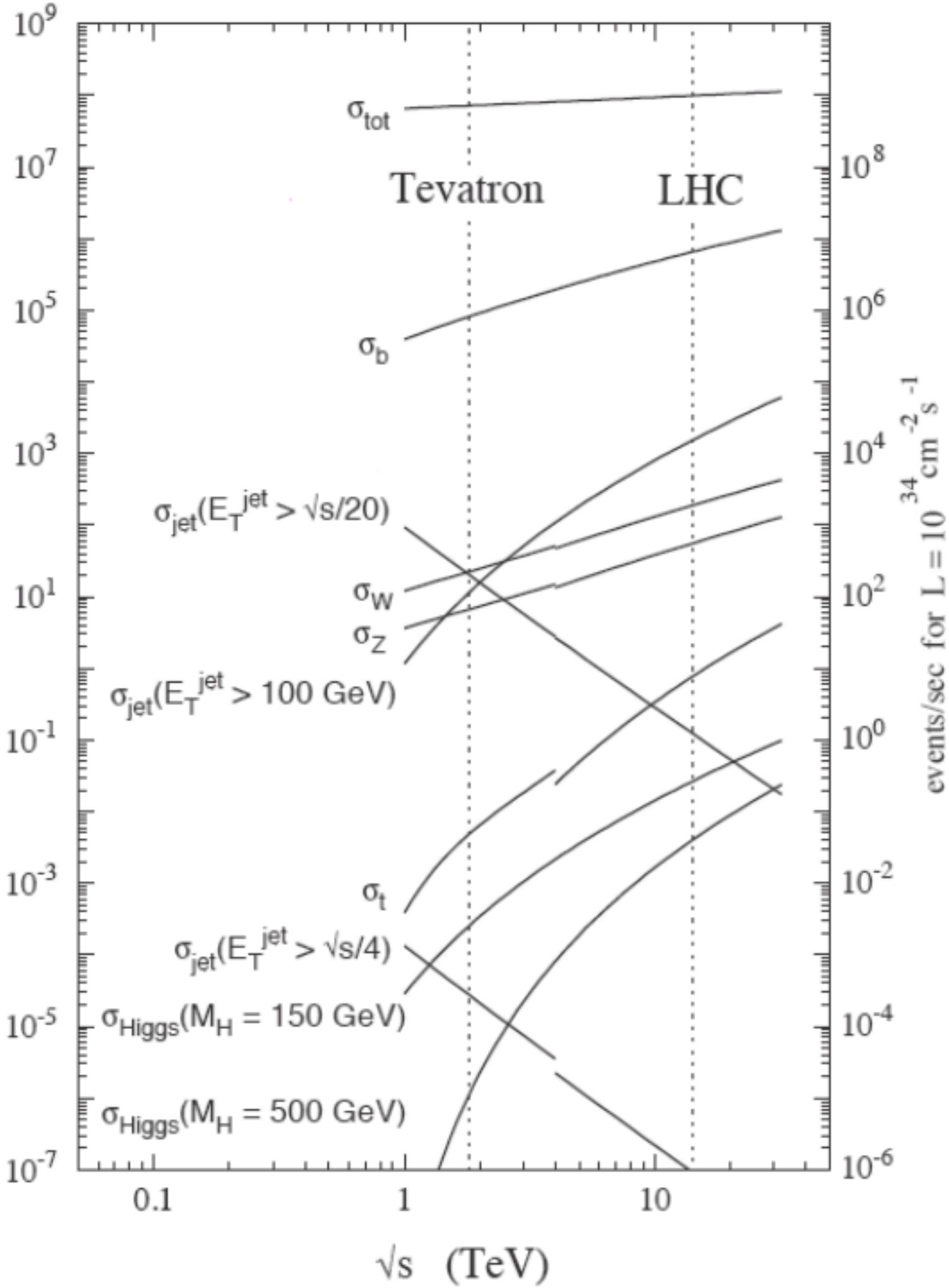


Belle 1999-2010
~800 million BB

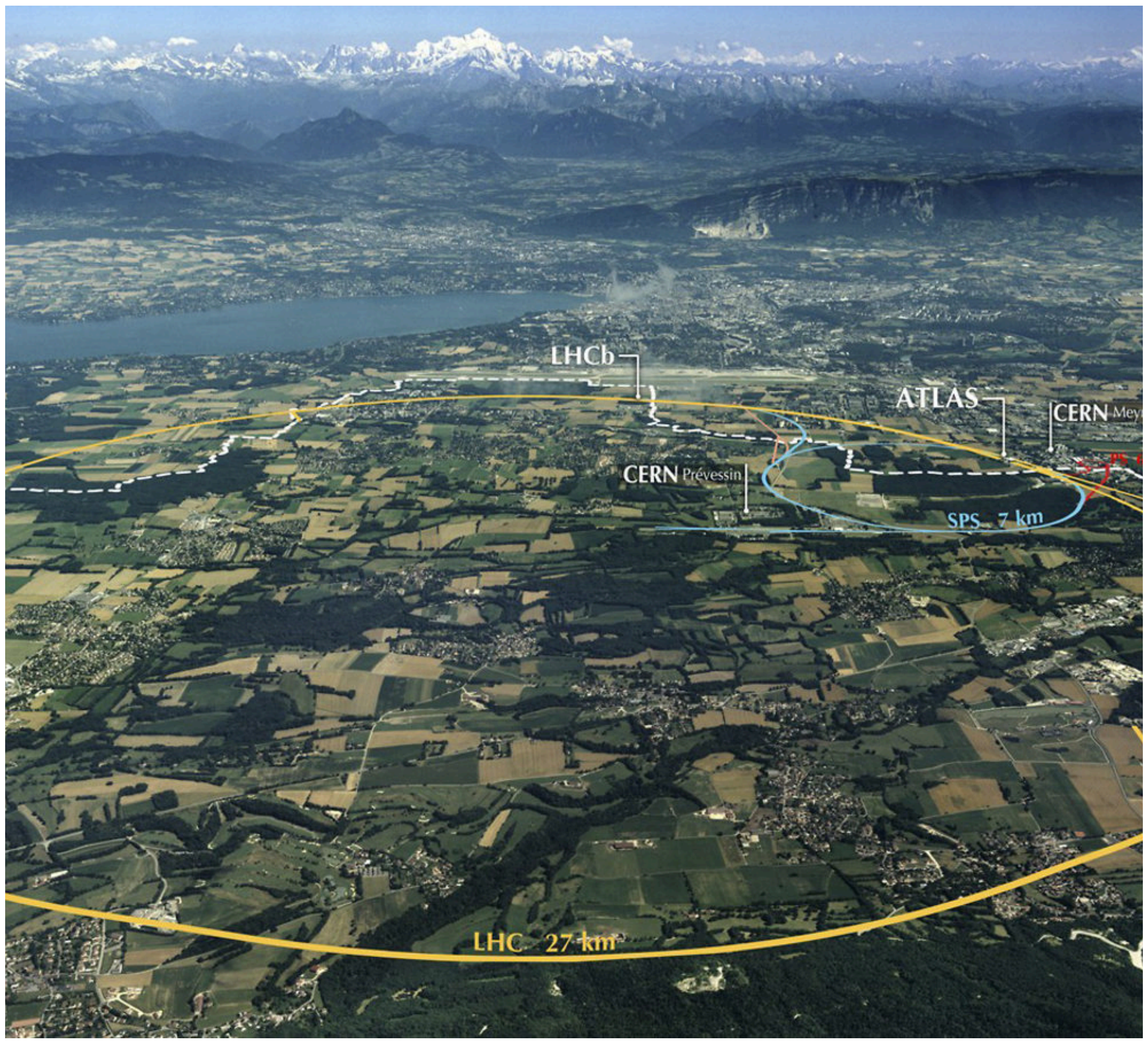
Later I will mention Belle-II, which will collect ~50x more luminosity during 2018-2024

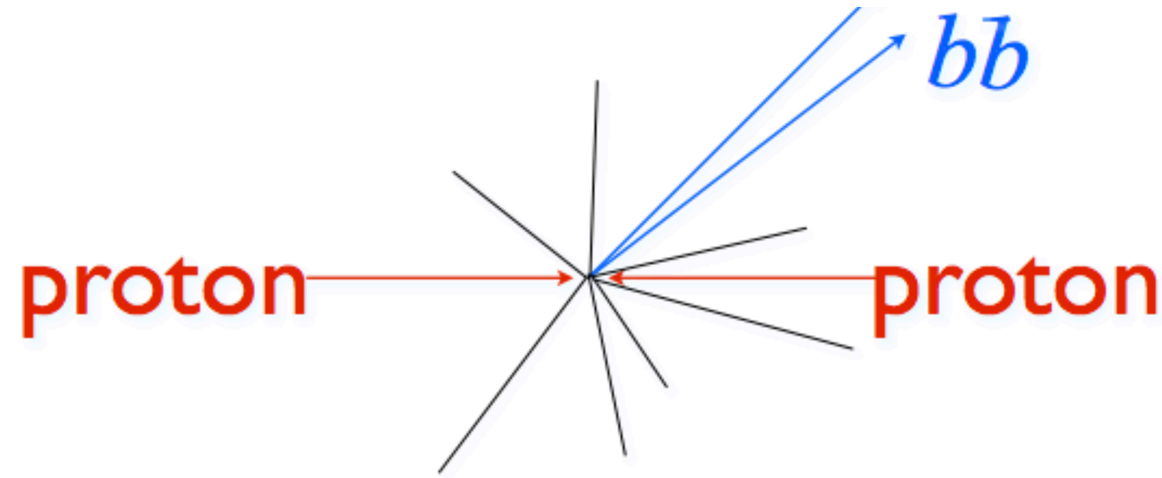
The LHC

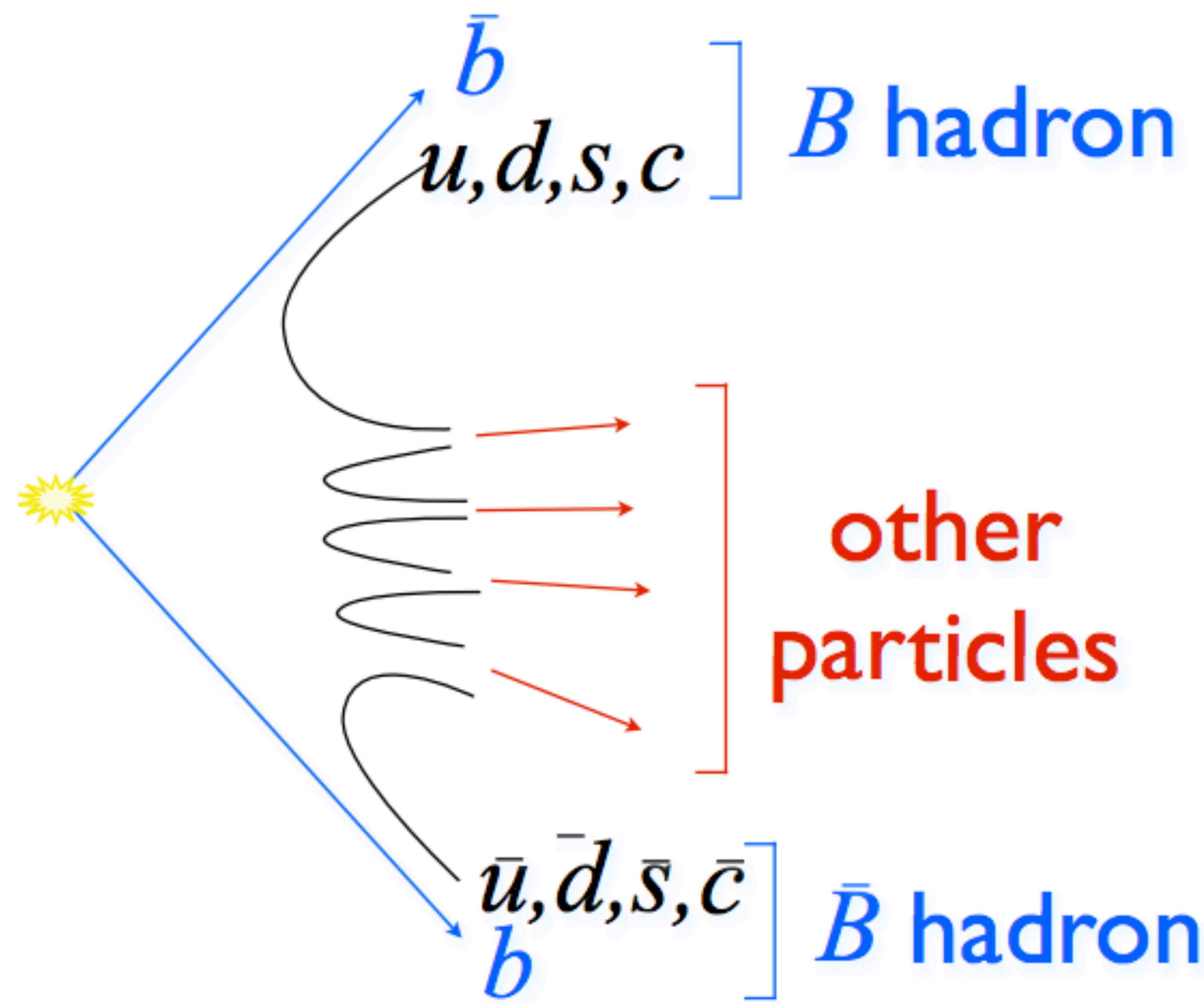

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
LHC 27 km


Tevatron
LHC
σ_{tot}
σ_b
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100\ GeV)$
σ_t
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/4)$
$\sigma_{Higgs}(M_H = 150\ GeV)$
$\sigma_{Higgs}(M_H = 500\ GeV)$
10^9
10^7
10^5
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
0.1
1
10
$\sqrt{s}$ (TeV)
10^8
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
events/sec for $L = 10^{34}\ cm^{-2}\ s^{-1}$

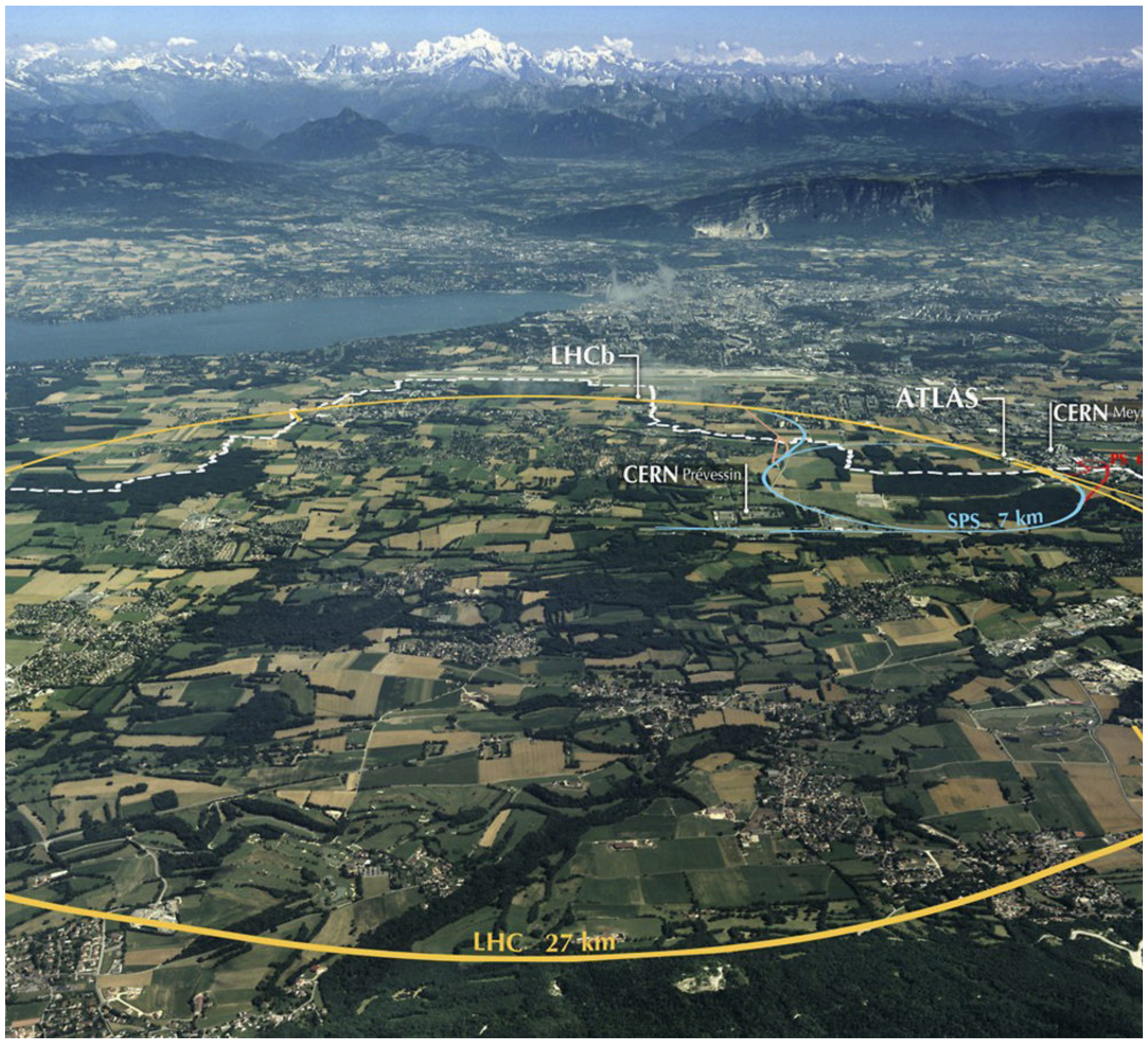
The LHC

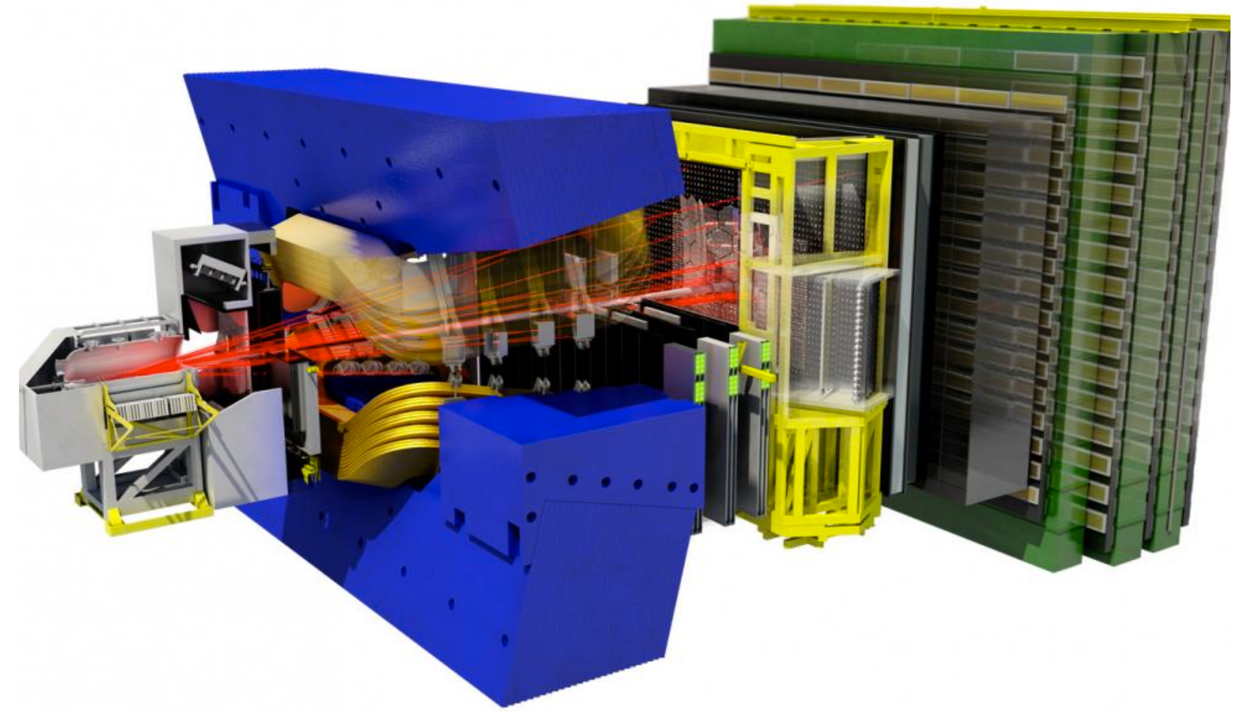

LHCb
ATLAS
CERN Mey
CERN Prévessin
SPS 7 km
LHC 27 km

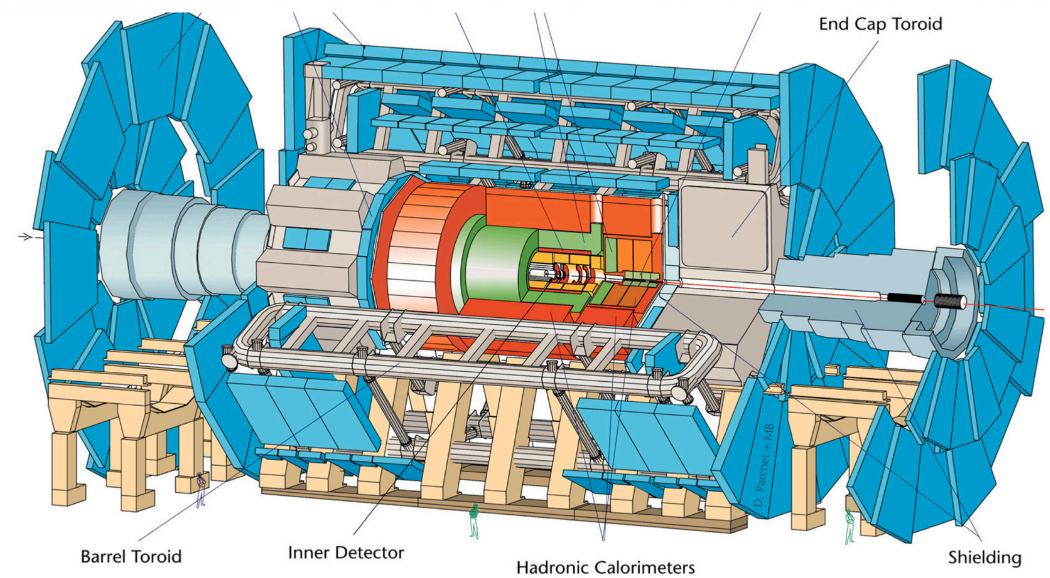

$b\bar{b}$
proton
proton

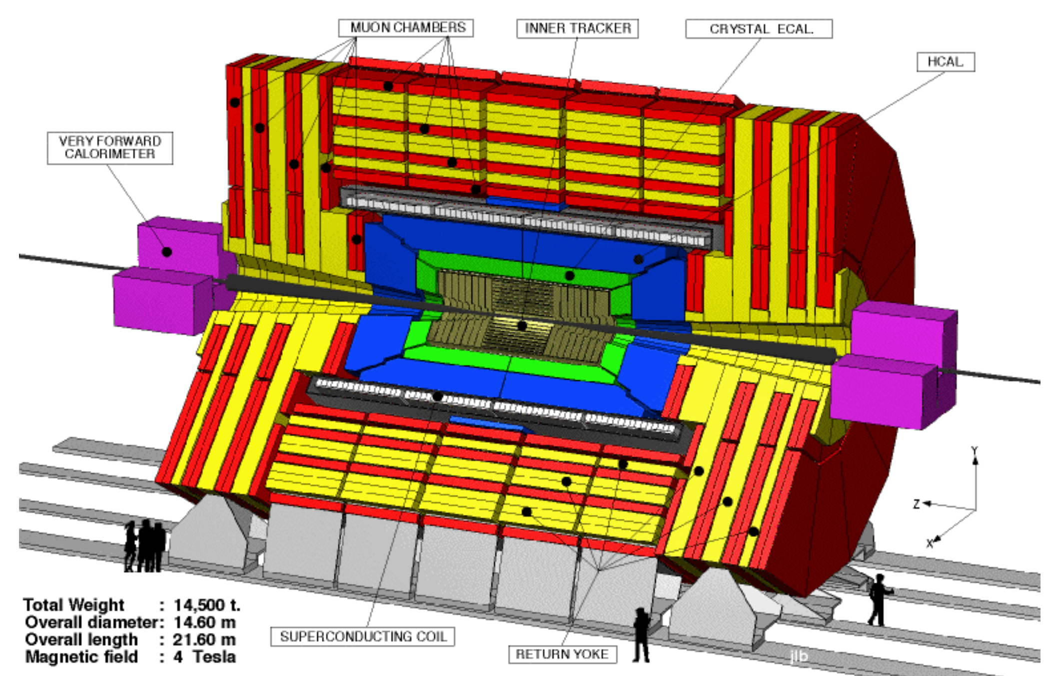

$\bar{b}$
u,d,s,c
B hadron
other particles
$\bar{u},\bar{d},\bar{s},\bar{c}$
b
$\bar{B}$ hadron

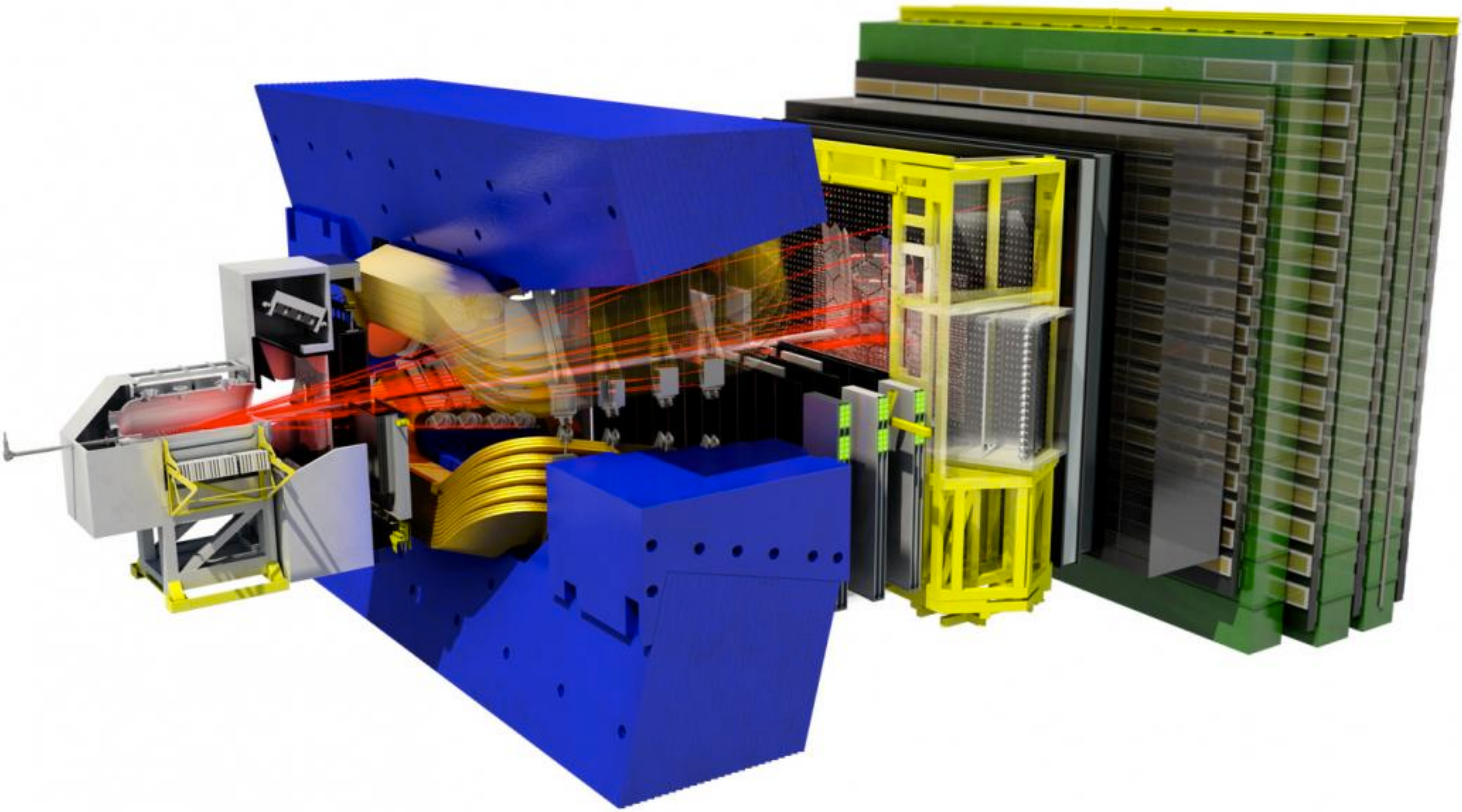
The LHC


LHCb
ATLAS
CERN
CERN Prévessin
SPS 7 km
LHC 27 km

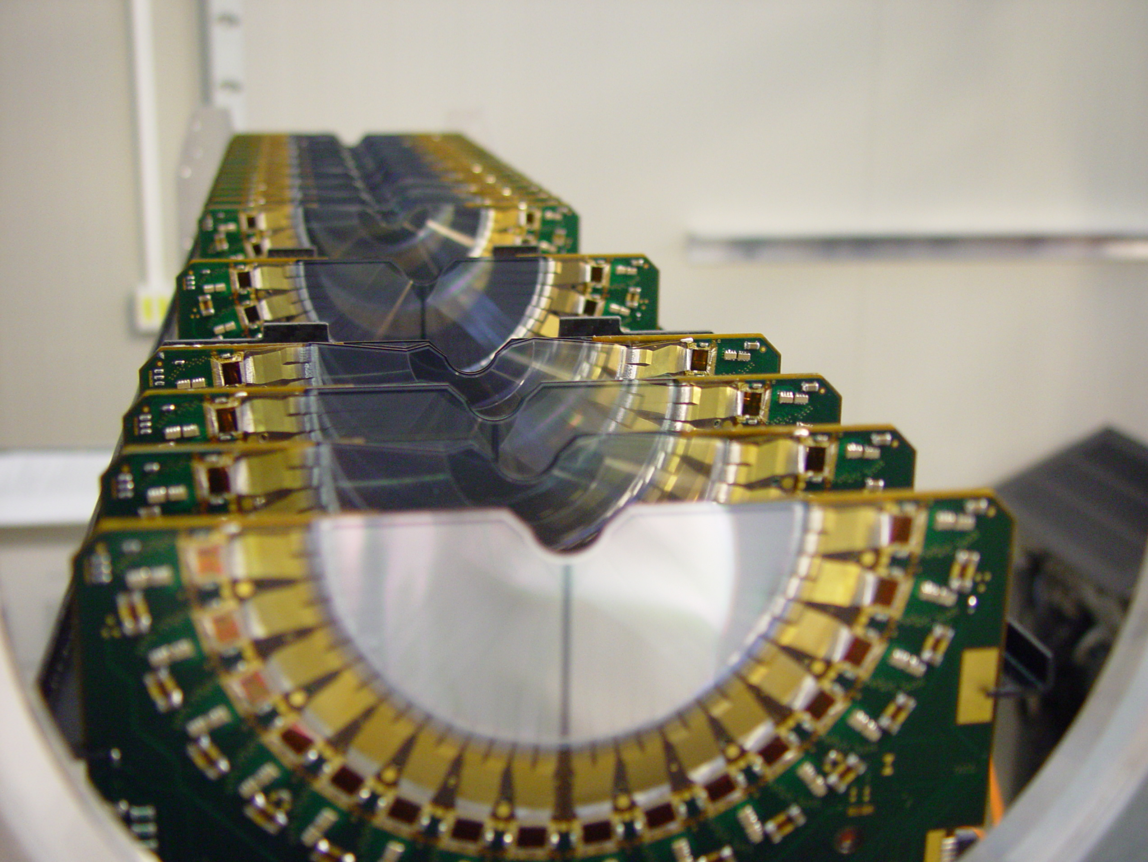


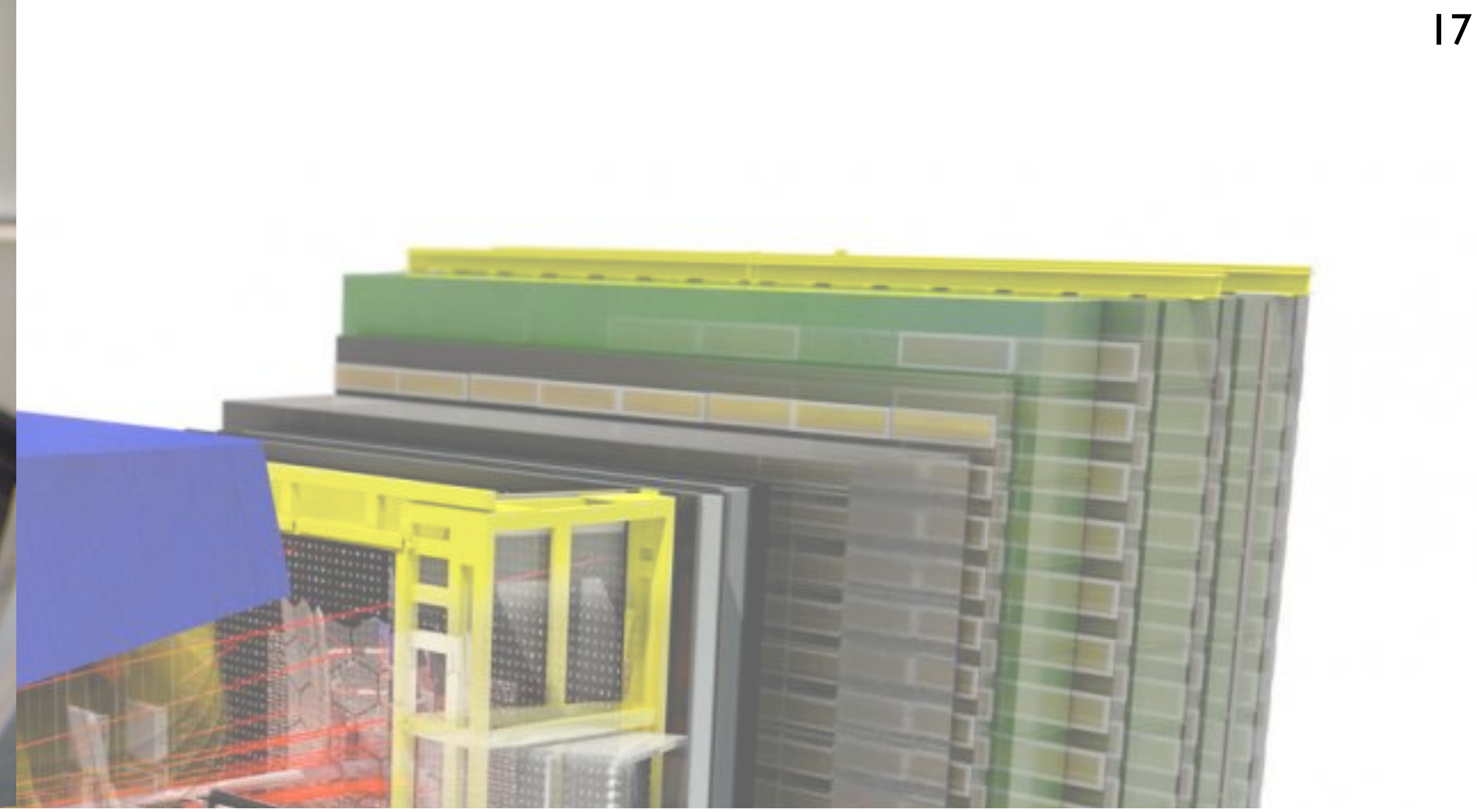

End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

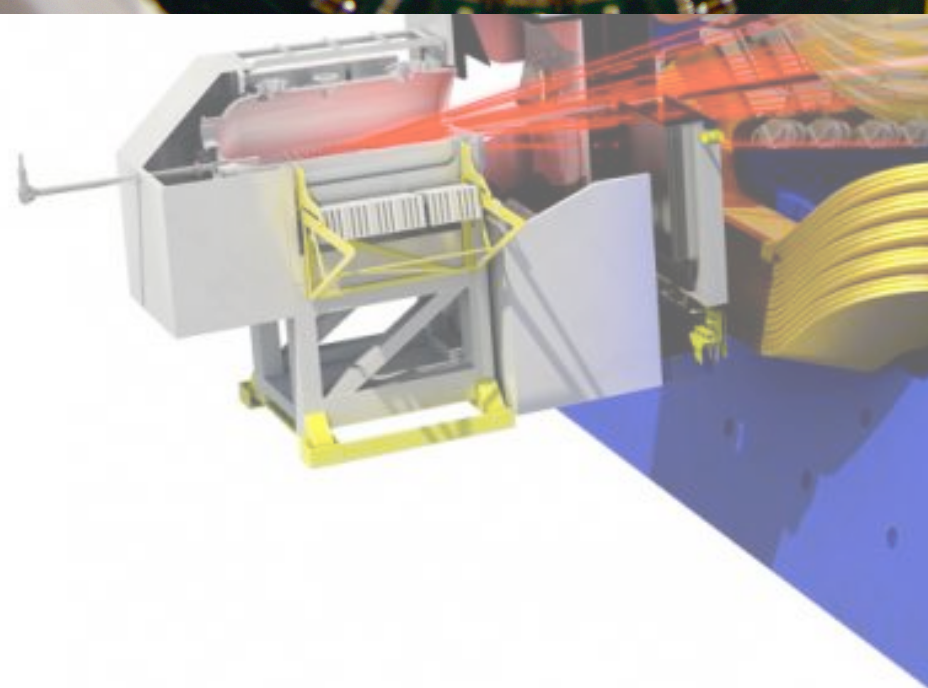

MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

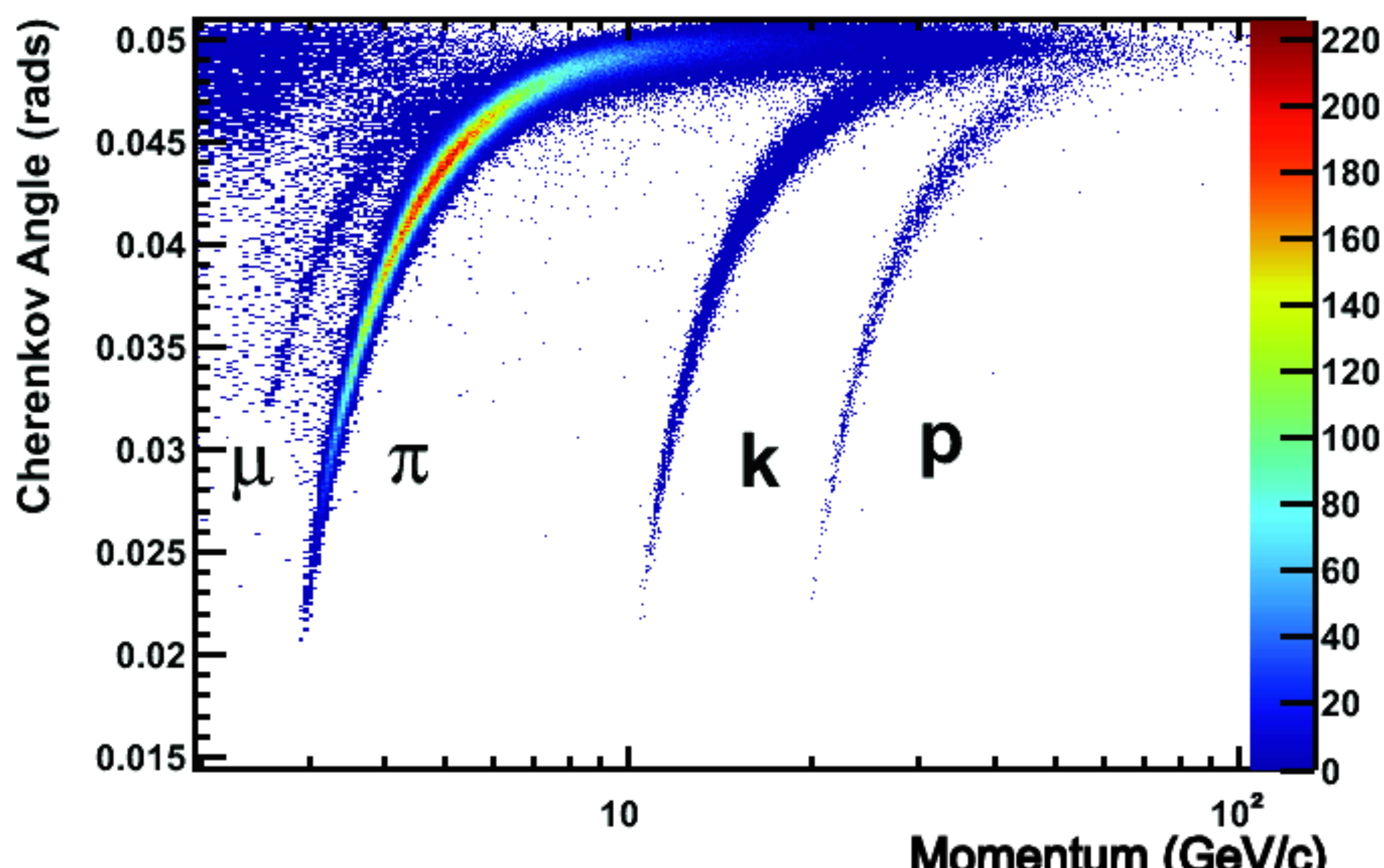


Current dataset ~**10^{12}** b hadrons

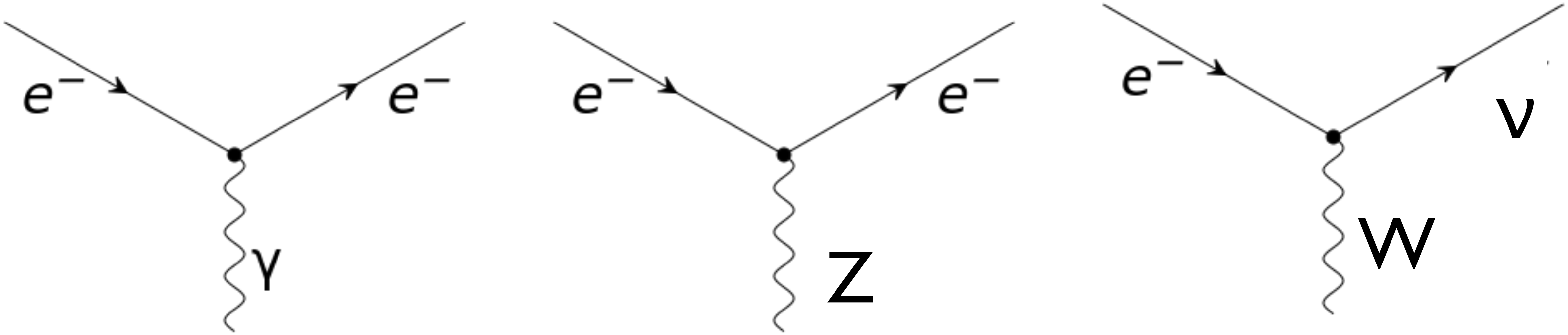







Cherenkov Angle (rads)
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
10
10^2
Momentum (GeV/c)
μ
π
k
p
220
200
180
160
140
120
100
80
60
40
20
0

Lepton universality in the SM



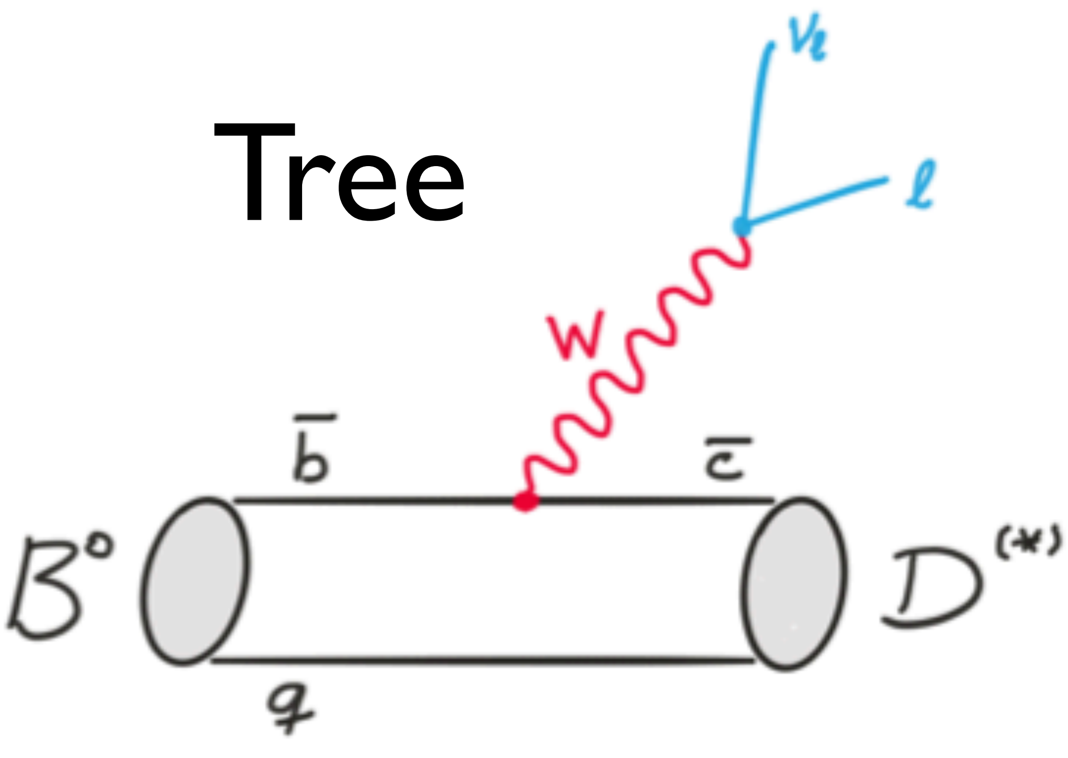
Couplings of above vertices are invariant under exchange of lepton generation.

Tested in W and Z decays at LEP,

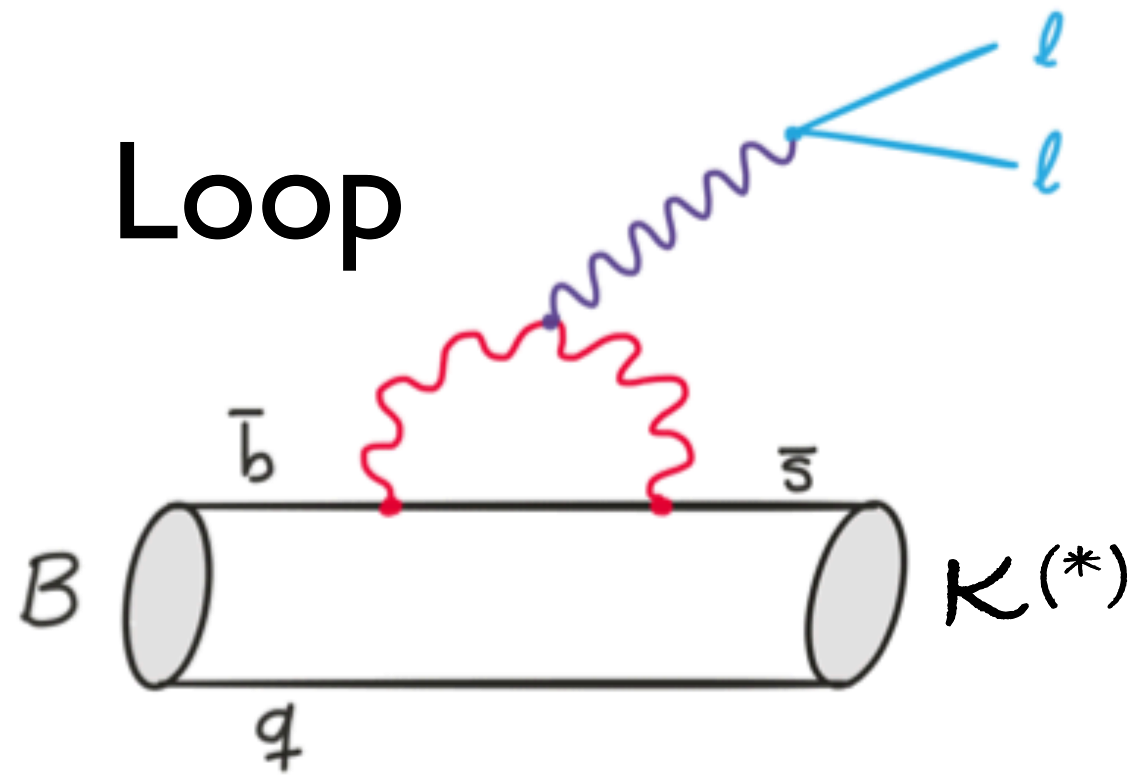
Kaon and pion decays, τ and μ lifetimes…

LU tests with b decays

Tree



Loop



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

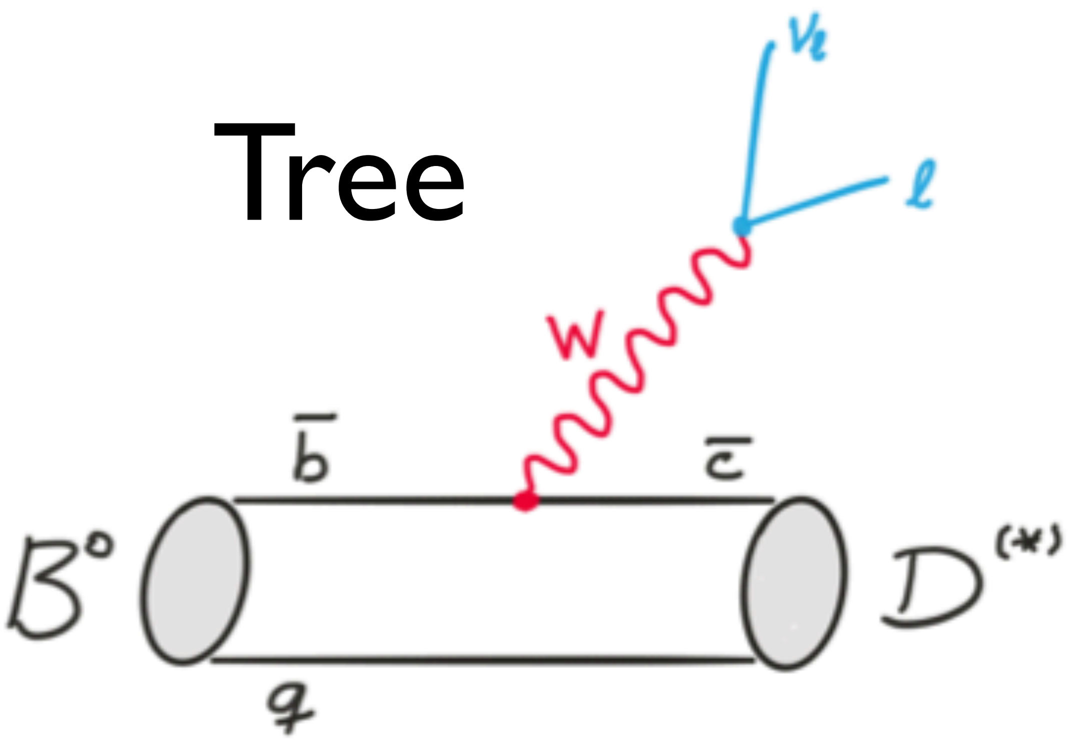
τ versus μ,e ratios

$R(K^{(*)})$

μμ versus ee ratios

LU tests with b decays

Tree

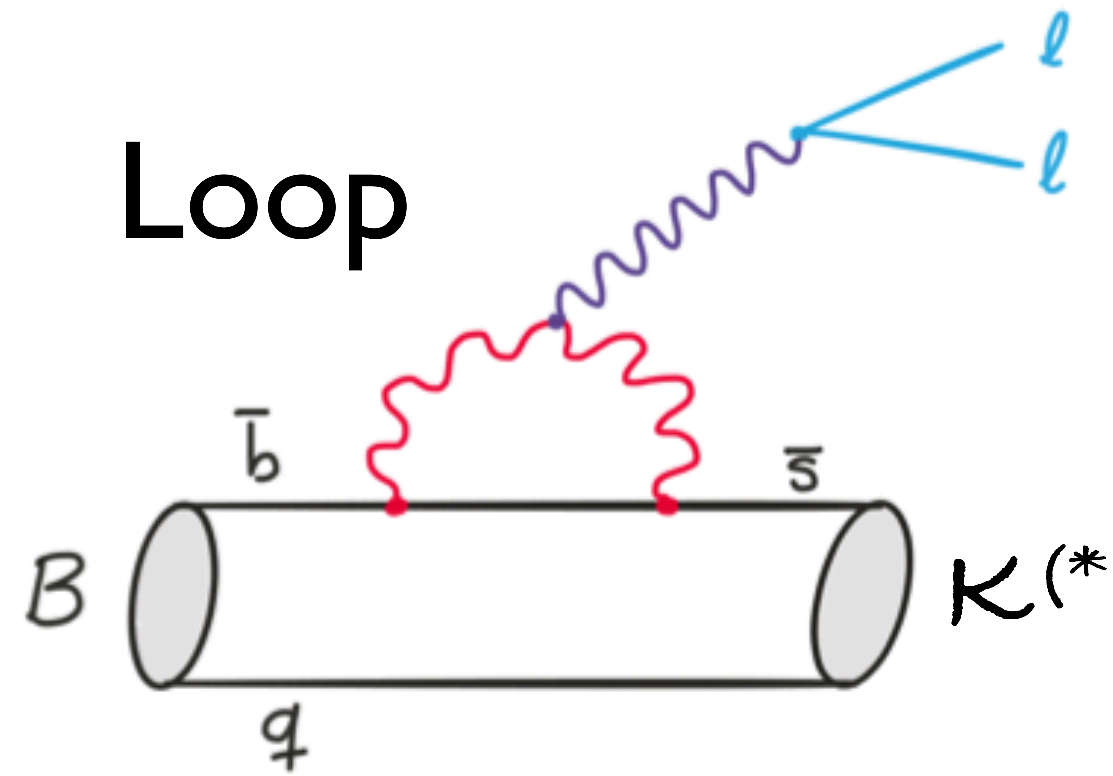


$R(D^{(*)})$

τ versus μ,e ratios

Focus of my talk

Loop

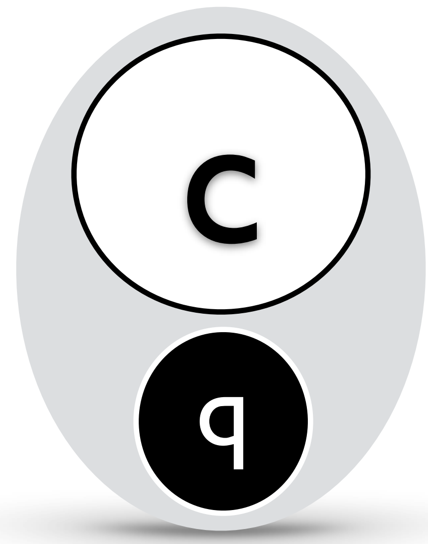


$R(K^{(*)})$

μμ versus ee ratios

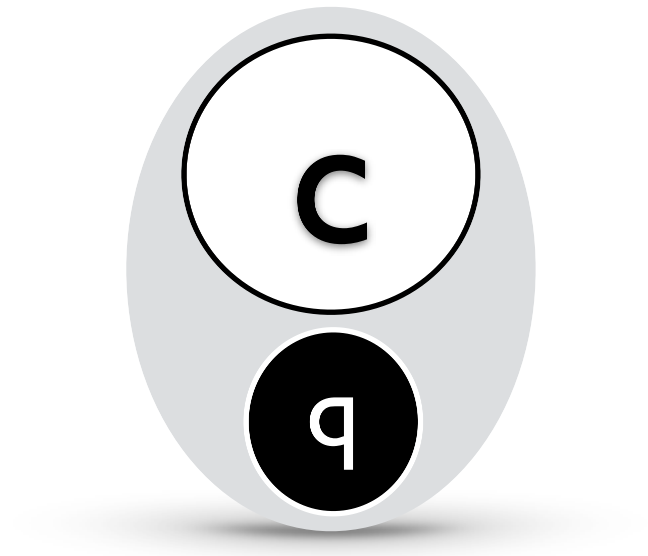
Covered in recent DESY colloquium by Johannes Albrecht

Jargon buster — D^*



$D^{+,0}$ mesons — spin 0

Jargon buster — D^*

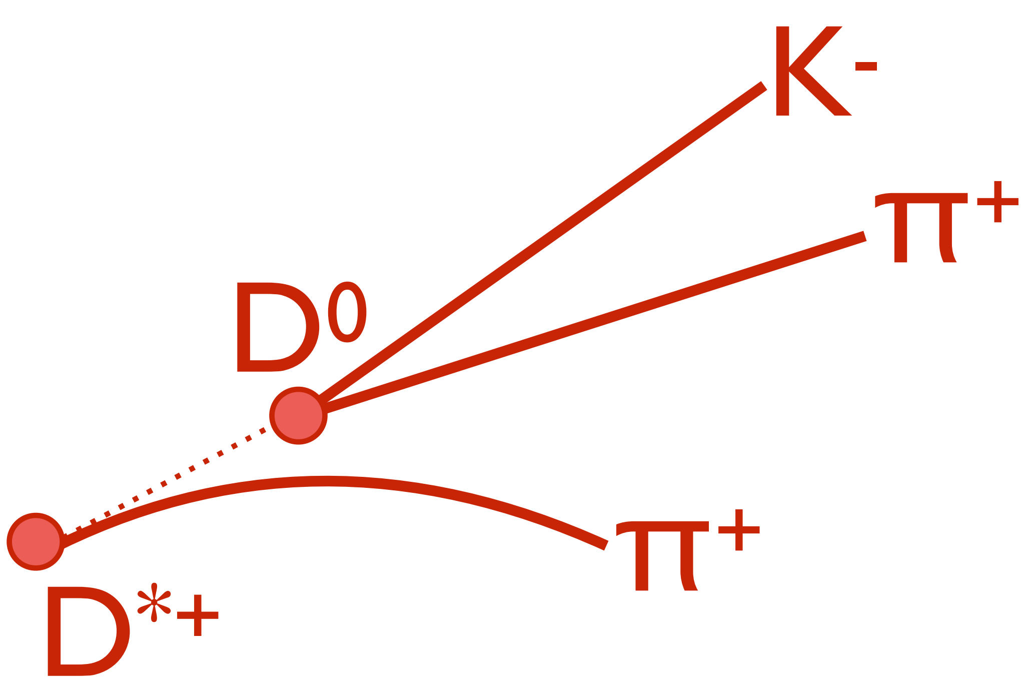


$D^{+,0}$ mesons — spin 0

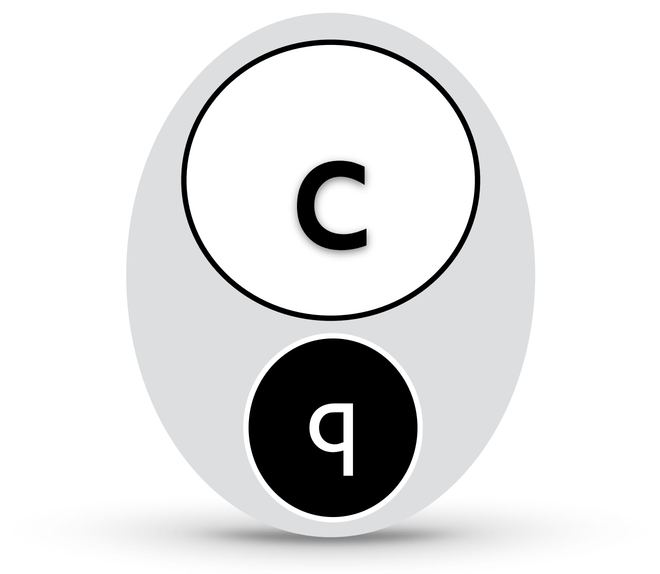
$D^{*+,0}$ mesons — spin 1 excitation

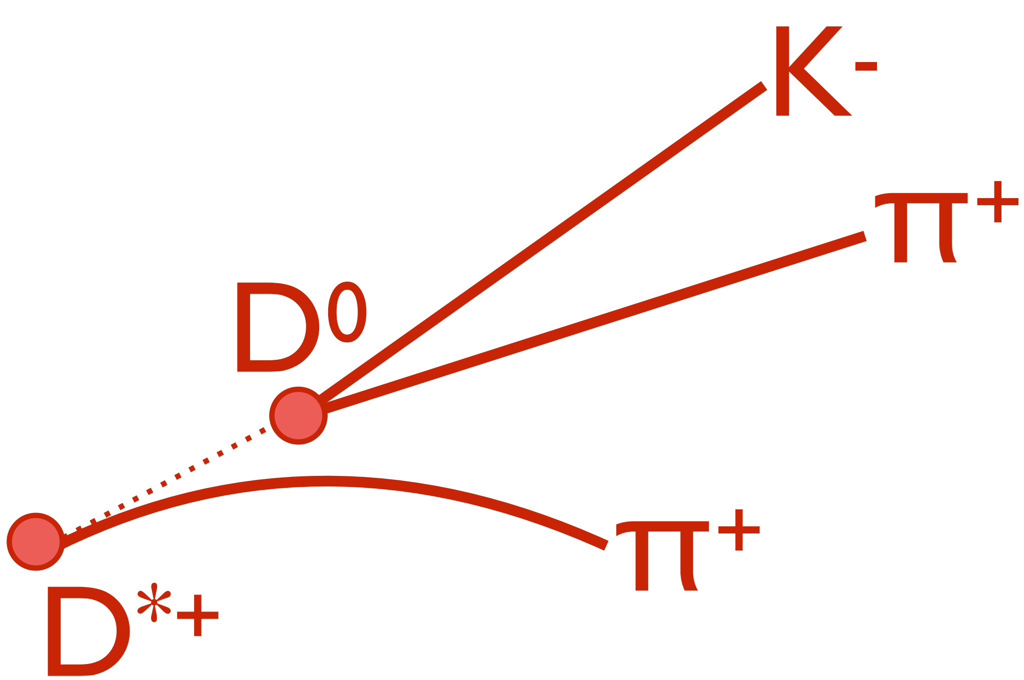
$D^*(2010)^\pm$ $I(J^P) = 1/2(1^-)$

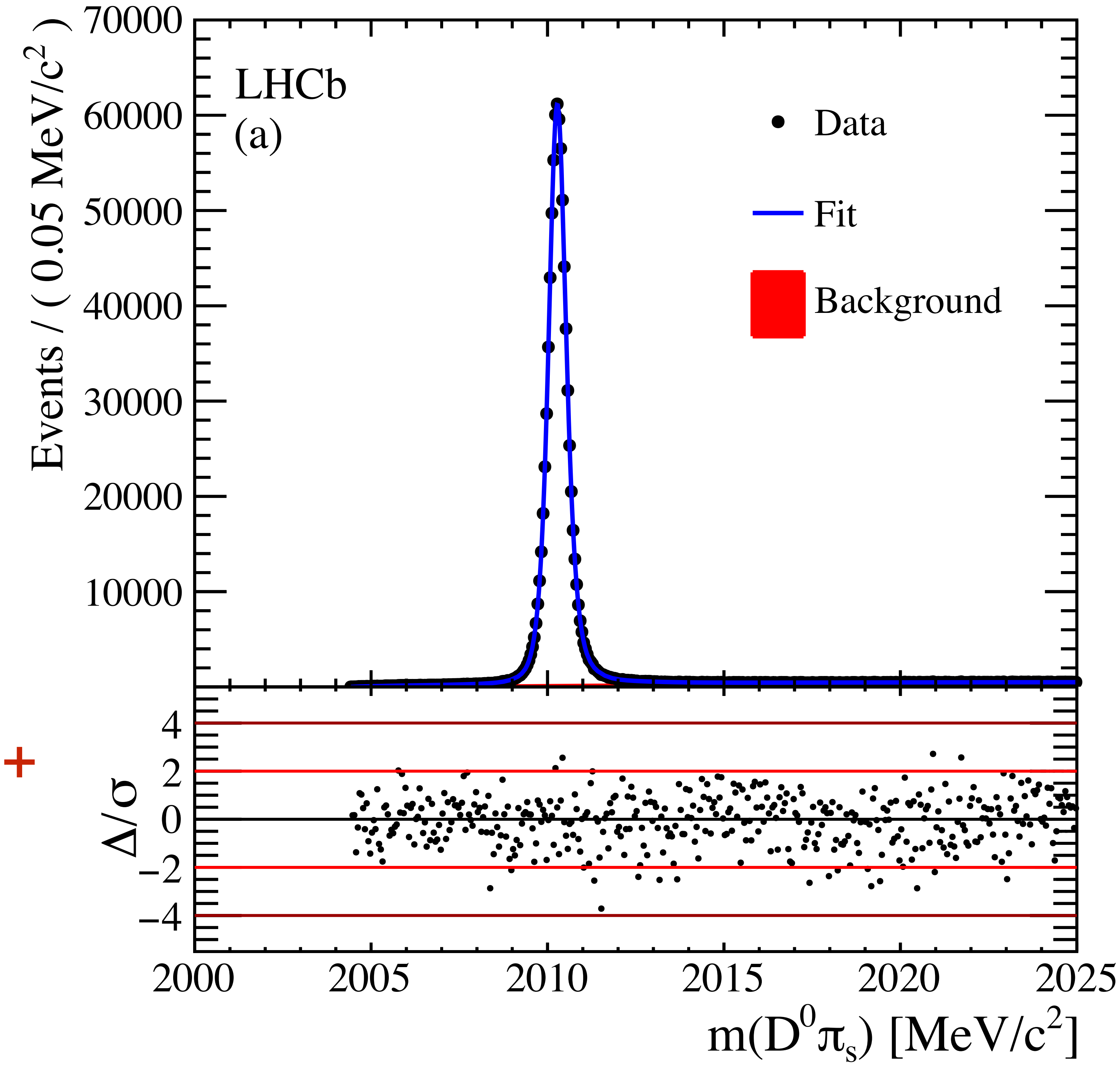
	Fraction (Γ_i / Γ)
$D^0\pi^+$	$(67.7 \pm 0.5)\%$
$D^+\pi^0$	$(30.7 \pm 0.5)\%$
$D^+\gamma$	$(1.6 \pm 0.4)\%$



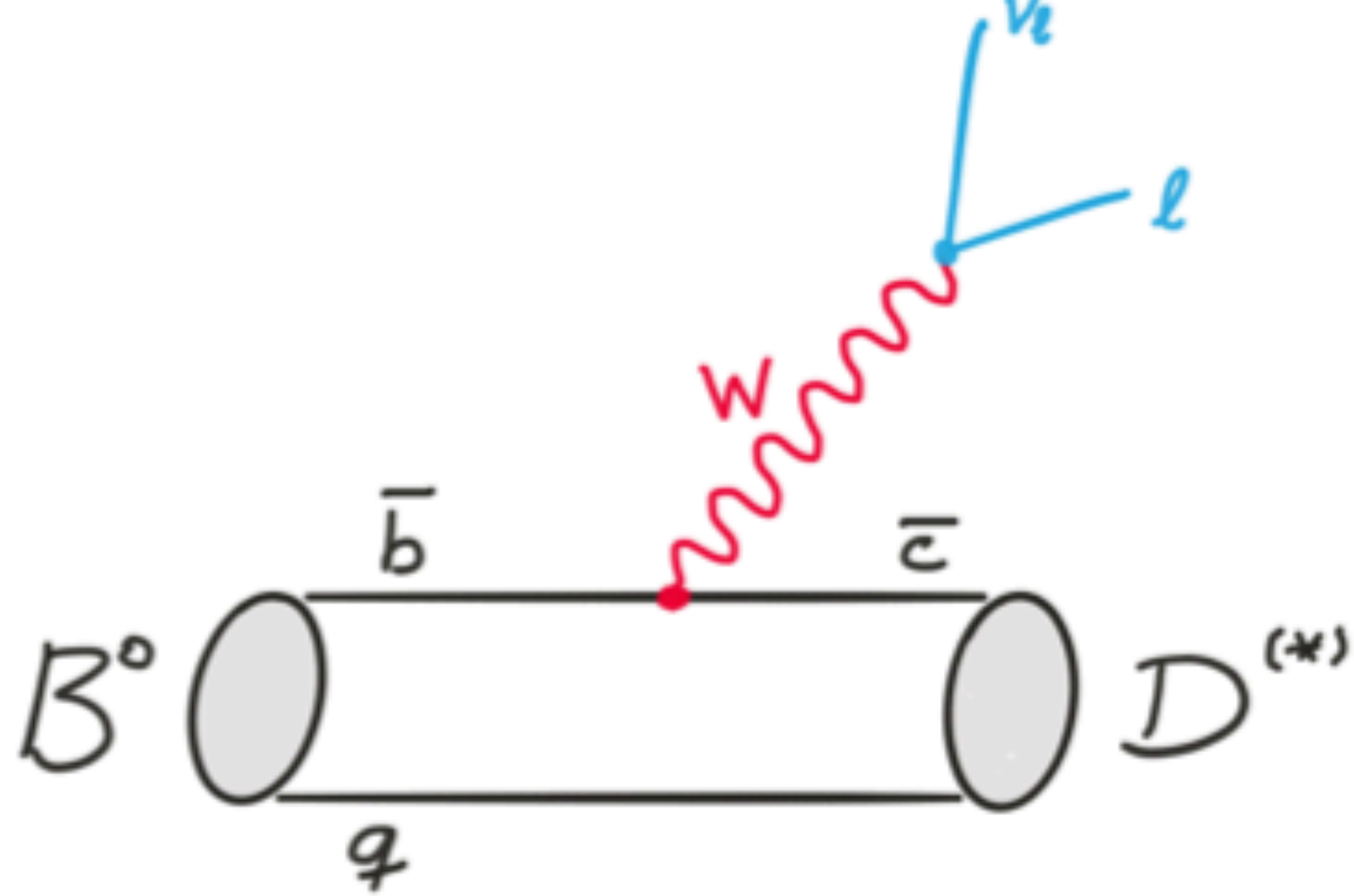
Jargon buster — D^*







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



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

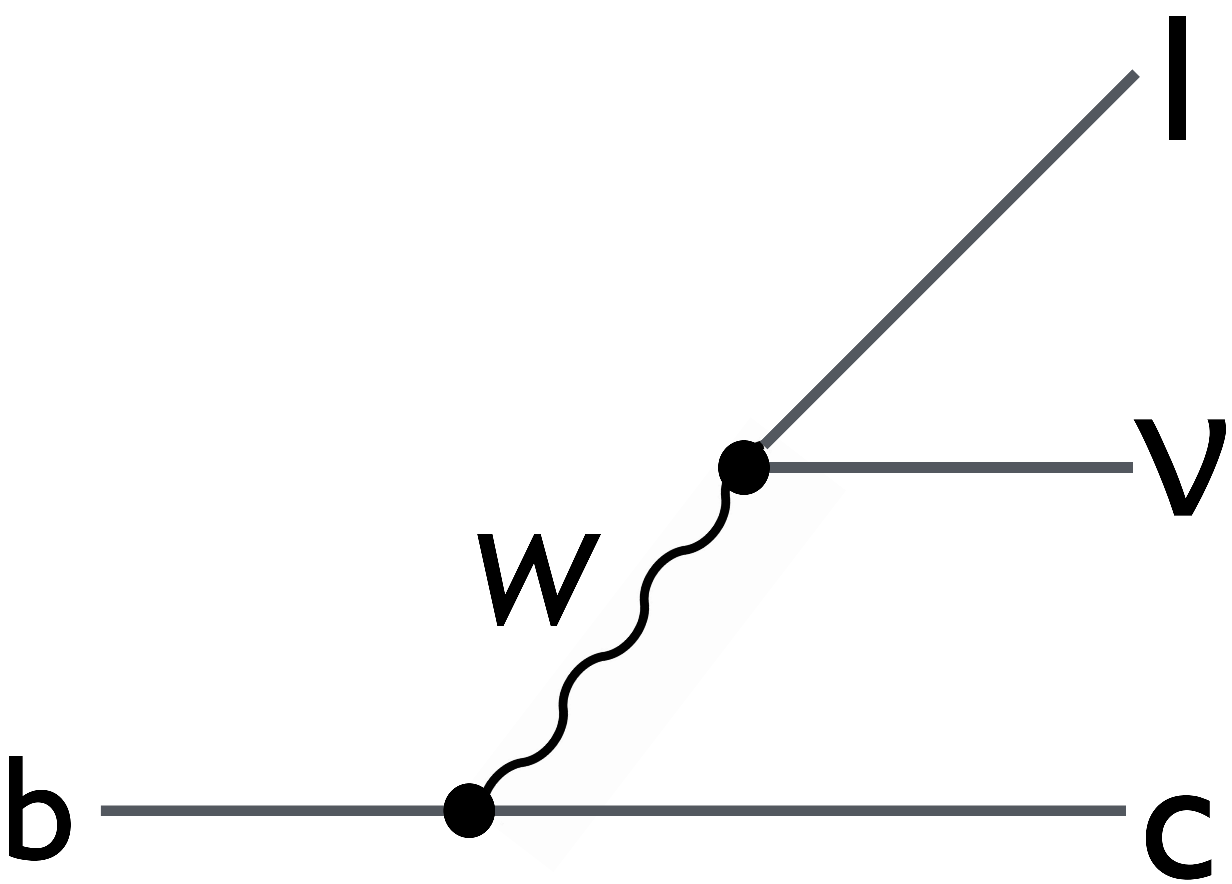
SM predictions:

$R(D) = 0.300 \pm 0.008$

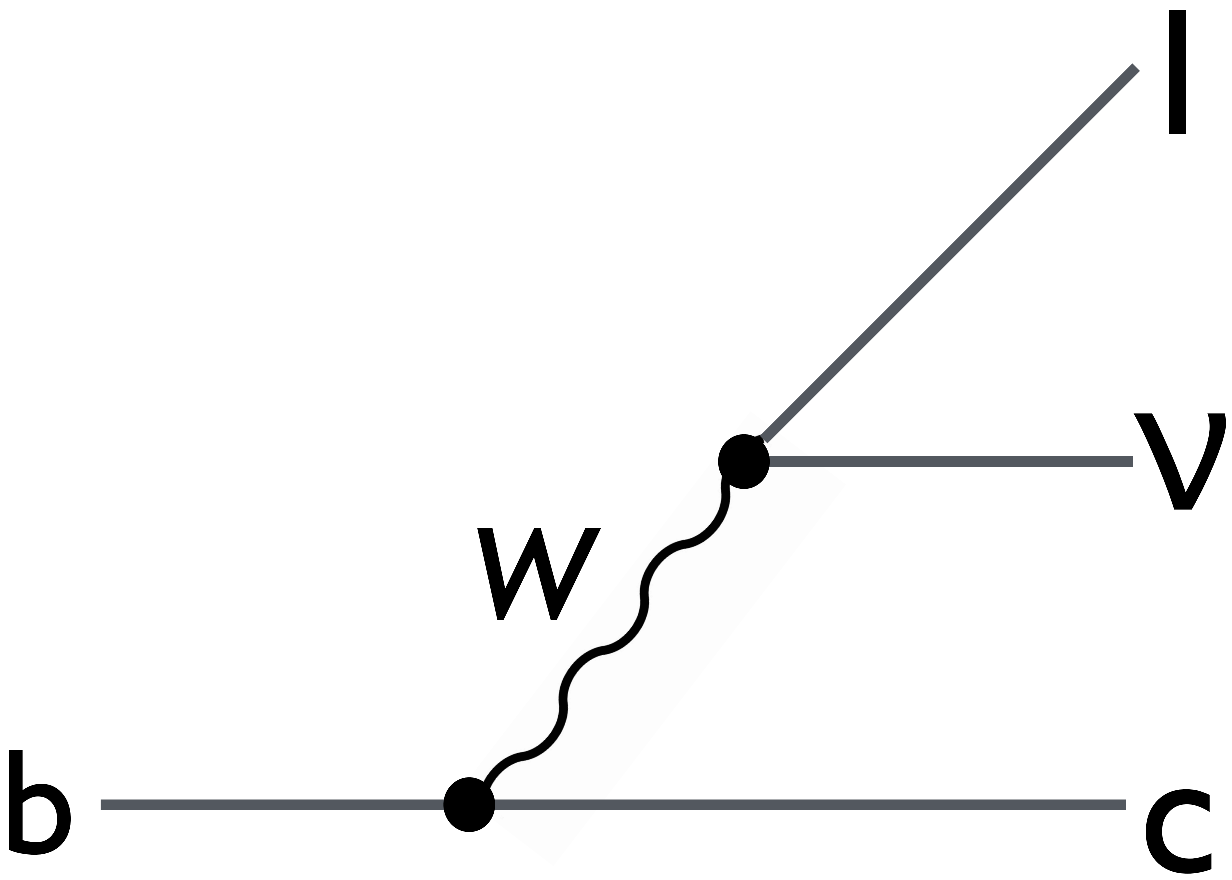
$R(D^*) = 0.252 \pm 0.003$

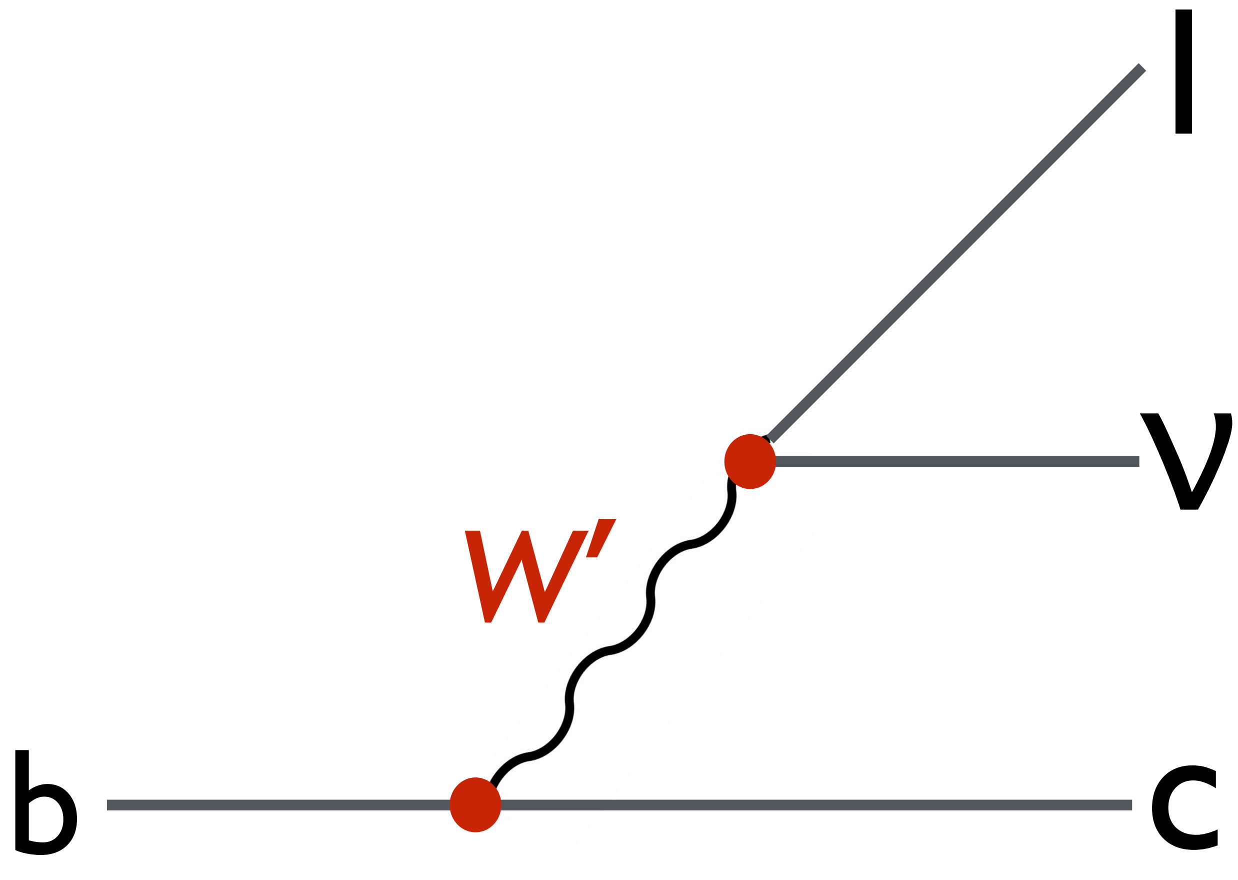
PRD 85 094025 (2012)

$R(D^{(*)})$in SM and beyond

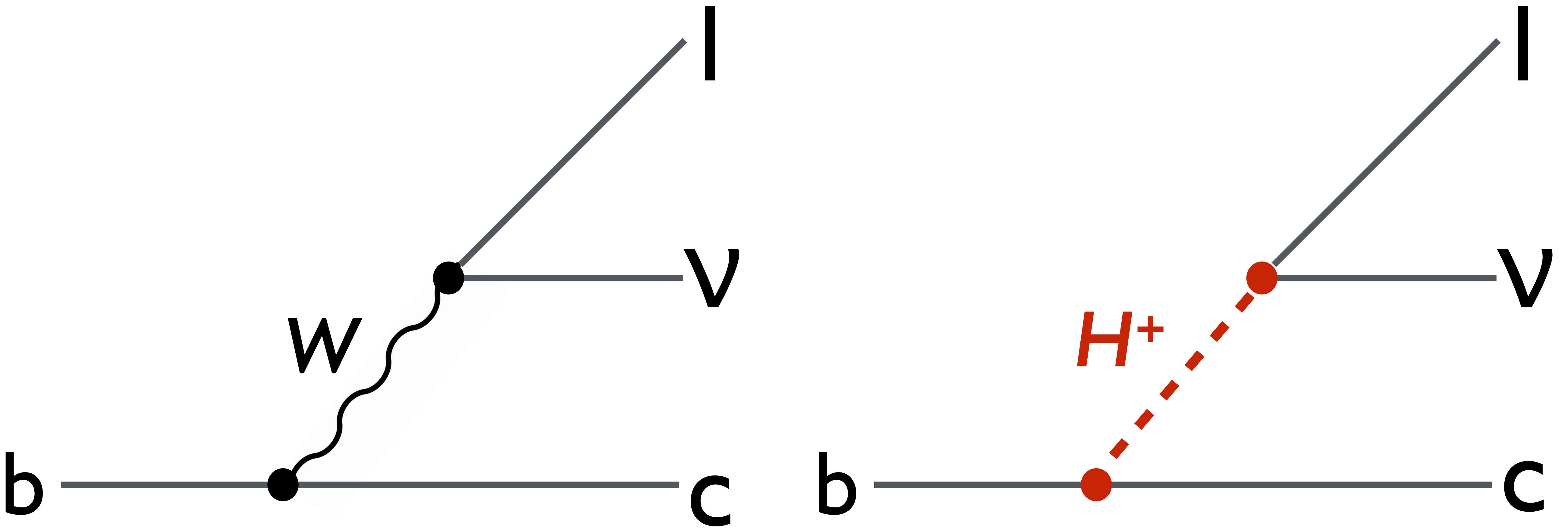


$R(D^{(*)})$ in SM and beyond

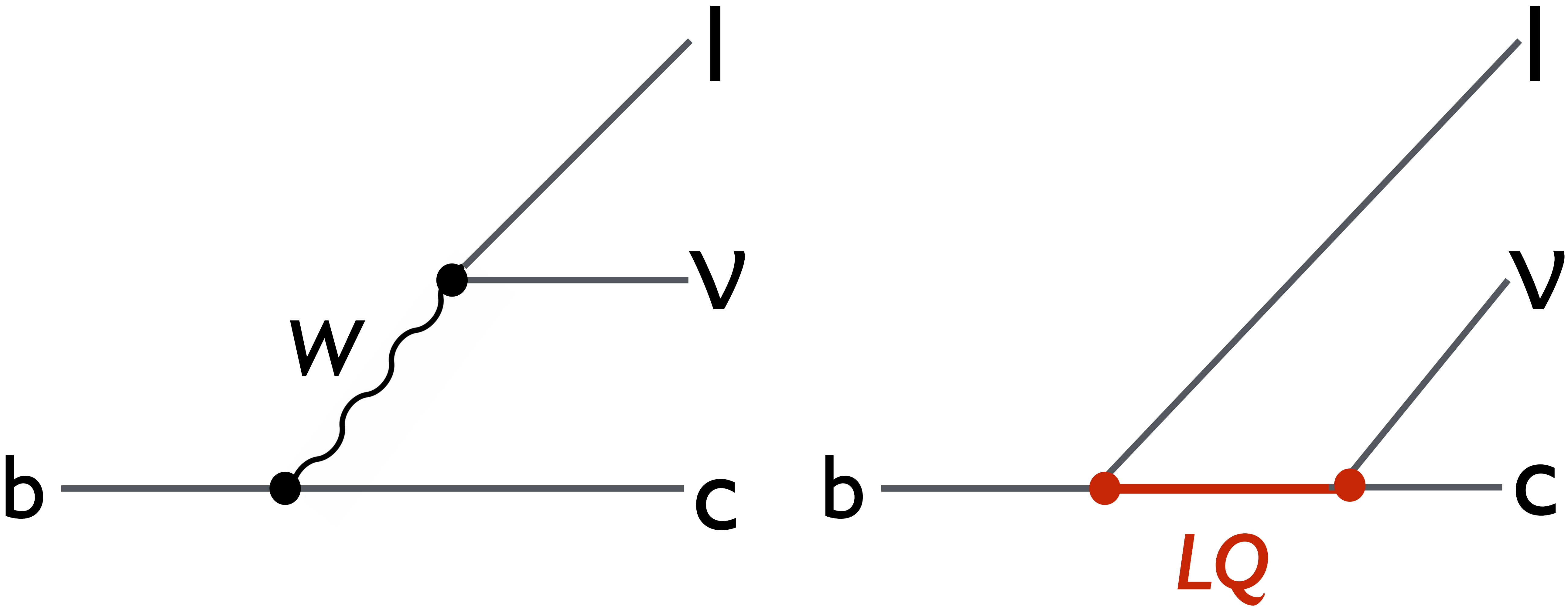




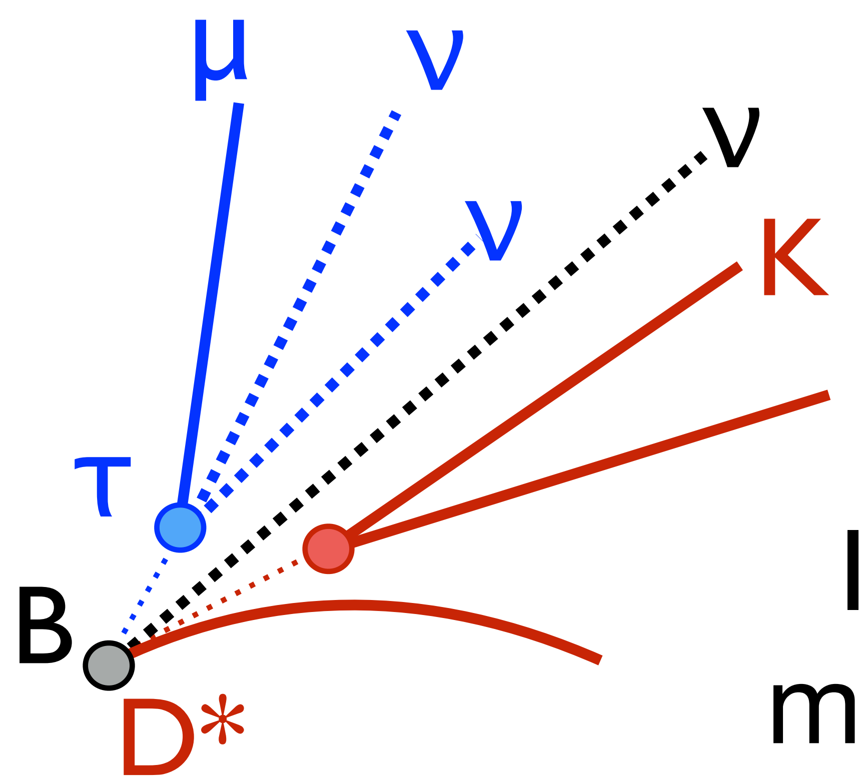
$R(D^{(*)})$ in SM and beyond



$R(D^{(*)})$ in SM and beyond



$R(D^{(*)})$ at B factories



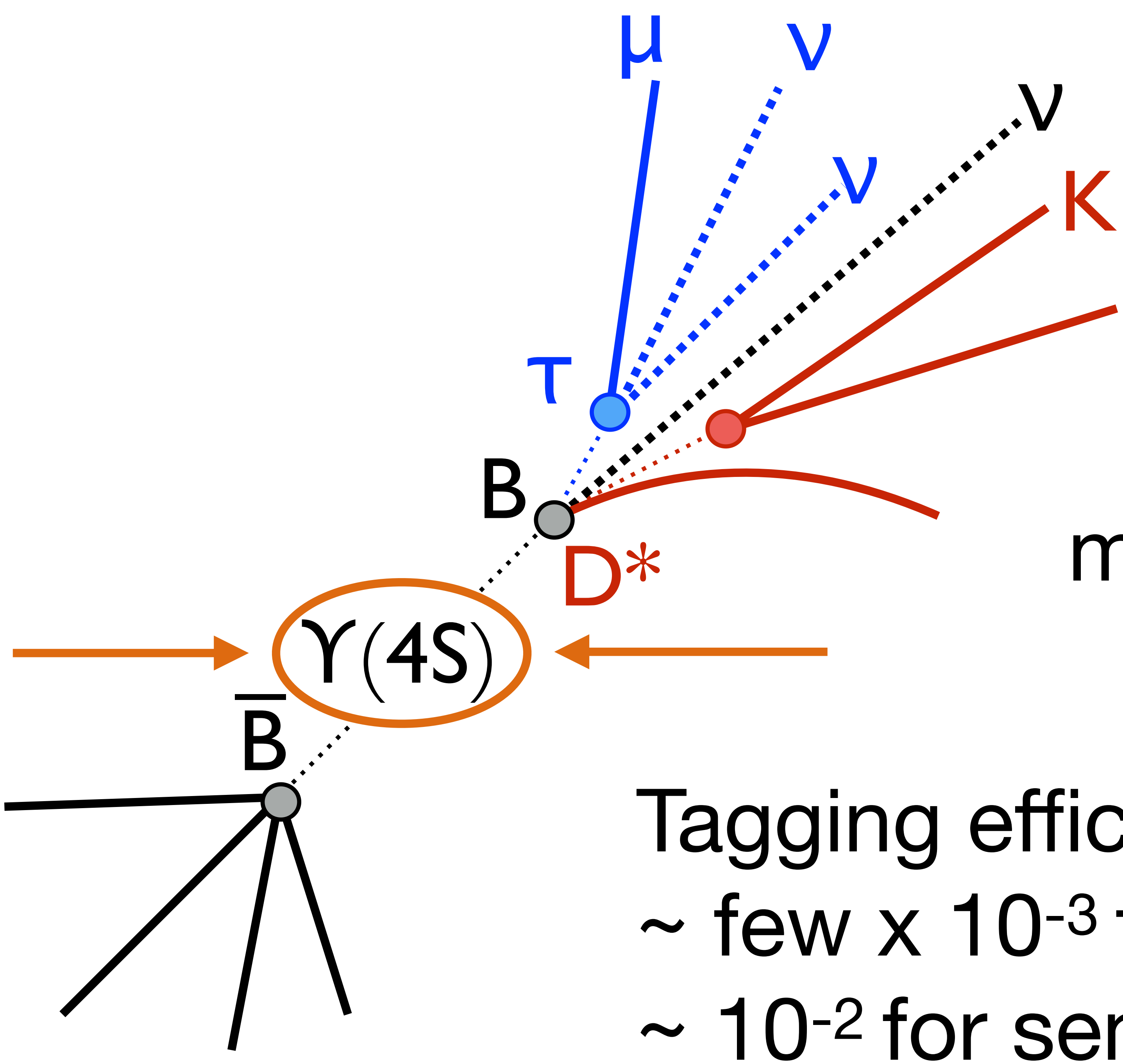
If only we knew the momentum of the B…

Not a rare decay

BR($B \to D^{*} \tau \nu$) ~1%

The problem is the background…

$R(D^{(*)})$ at B factories



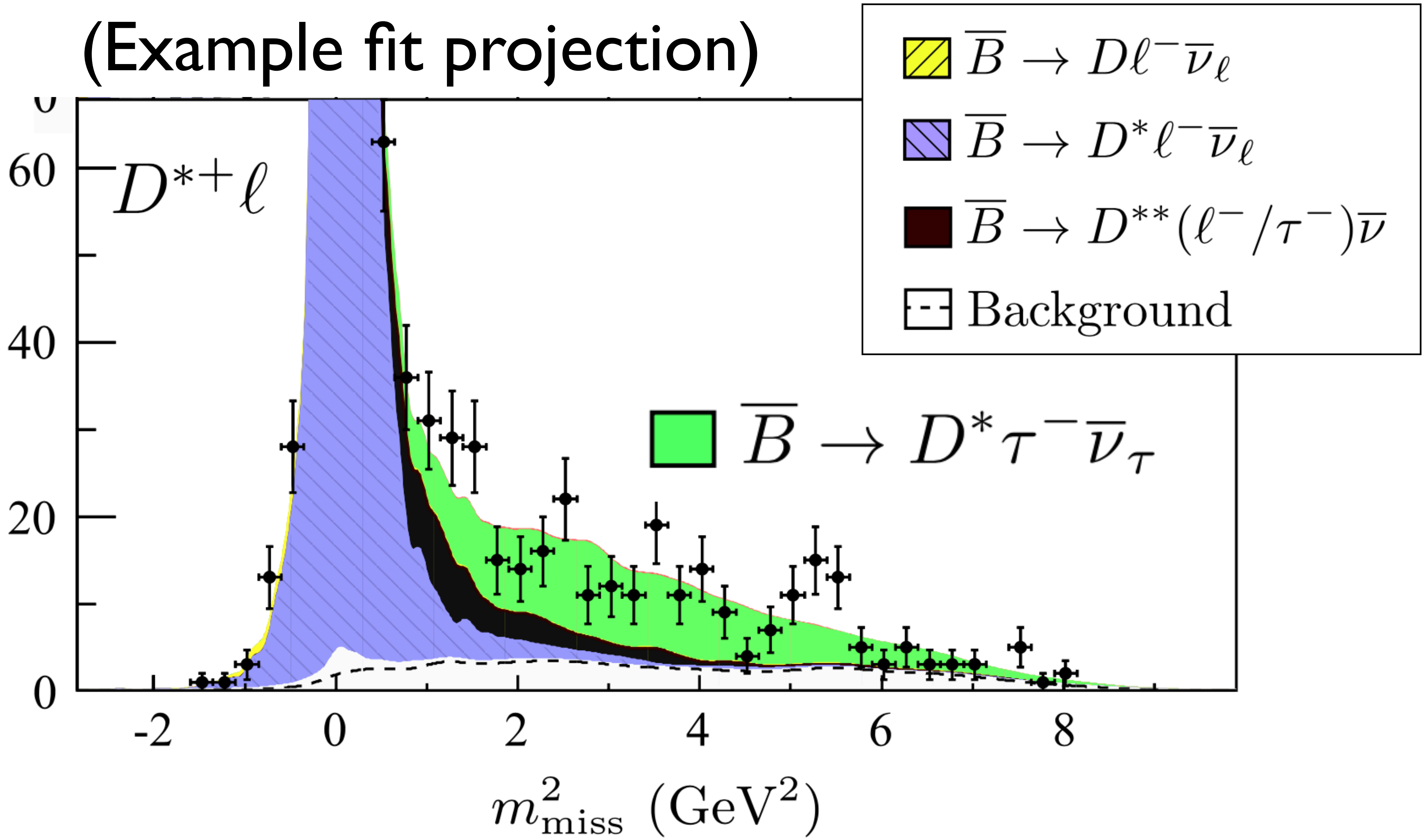
If only we knew the momentum of the B…

Tagging efficiency
~ few x 10^{-3} for full reconstruction
~ 10^{-2} for semileptonic tag

BaBar 2012

PRL 109, 101802 (2012)

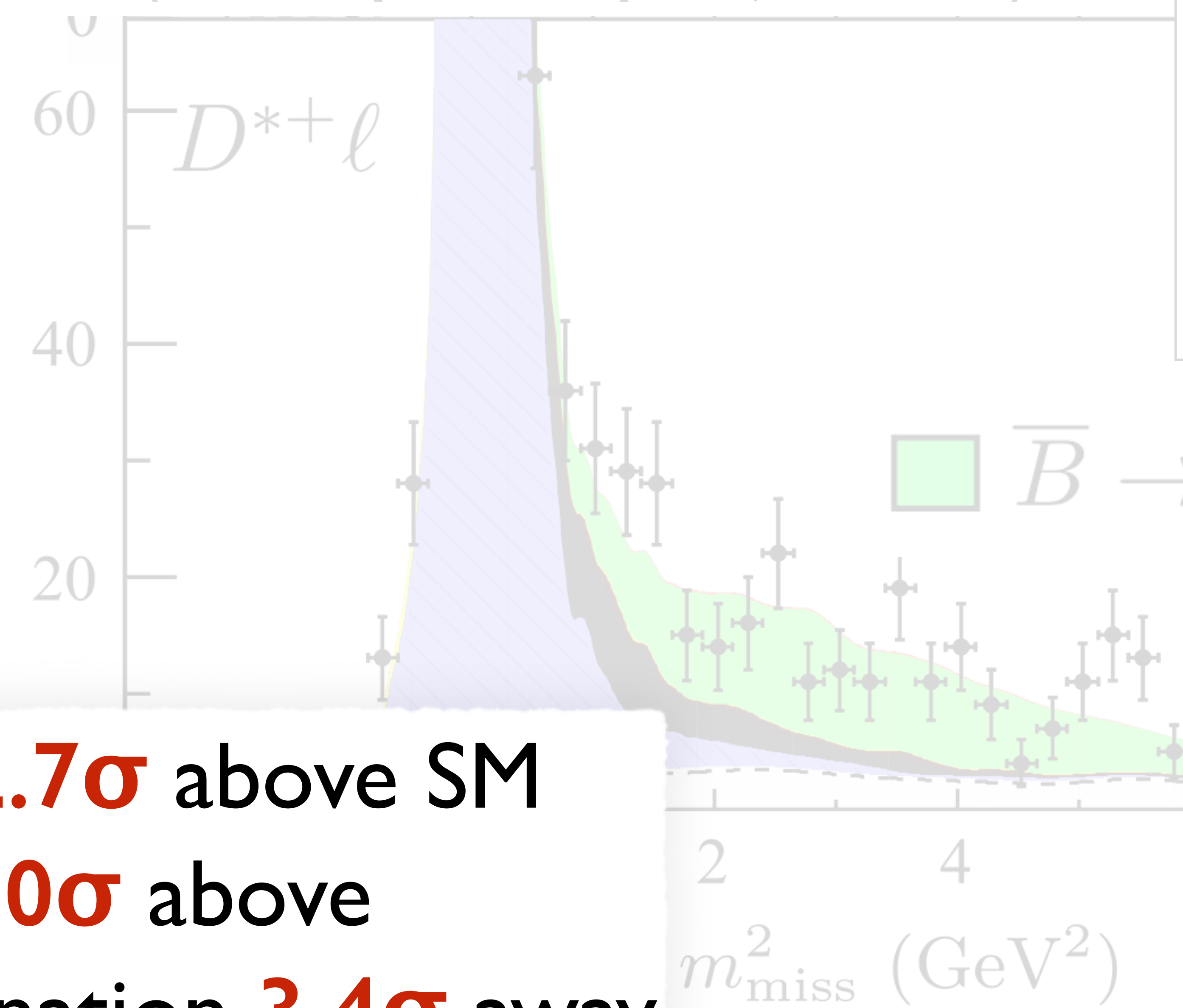
(Example fit projection)



BaBar 2012

PRL 109, 101802 (2012)

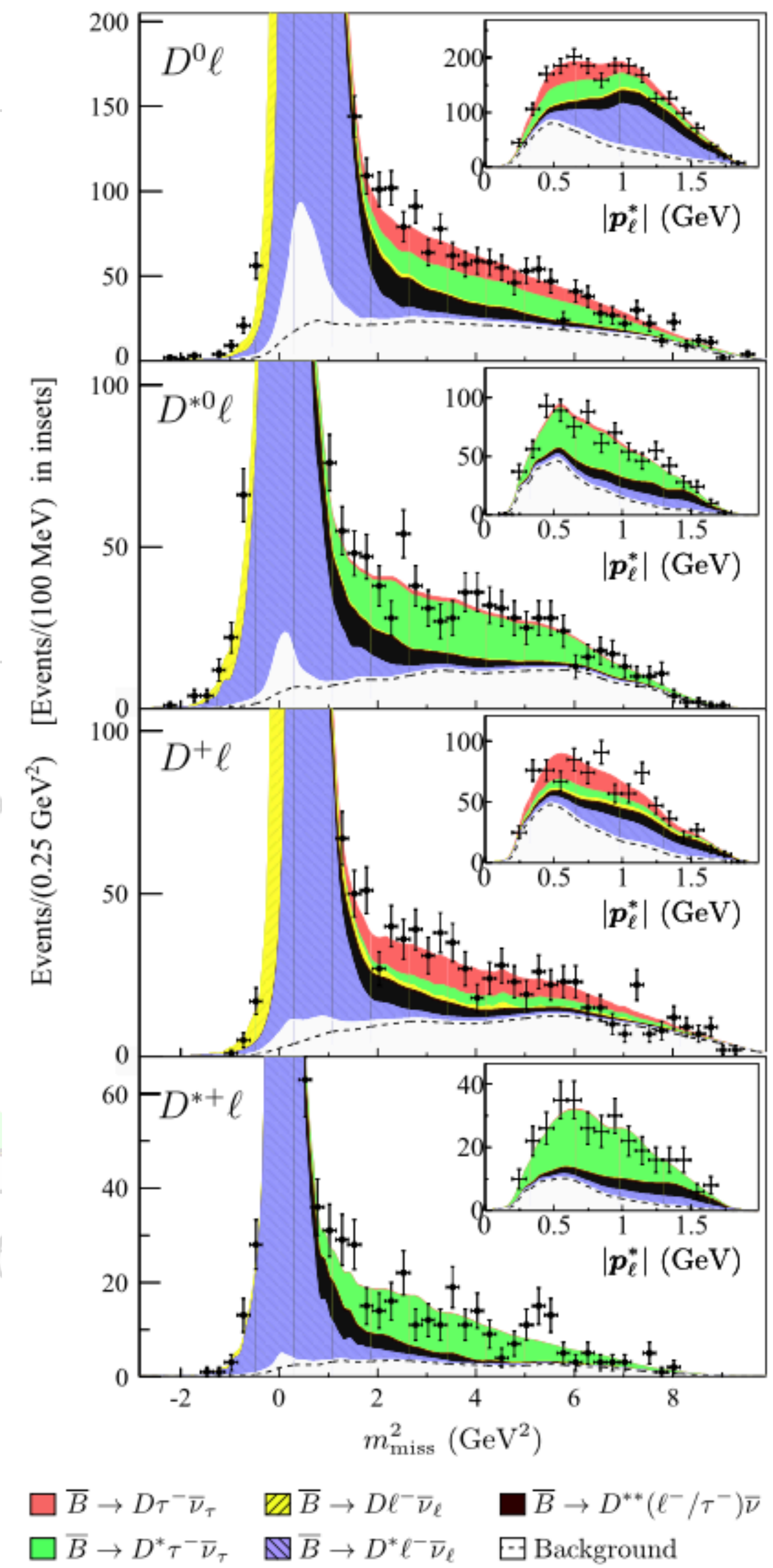
(Example fit projection)



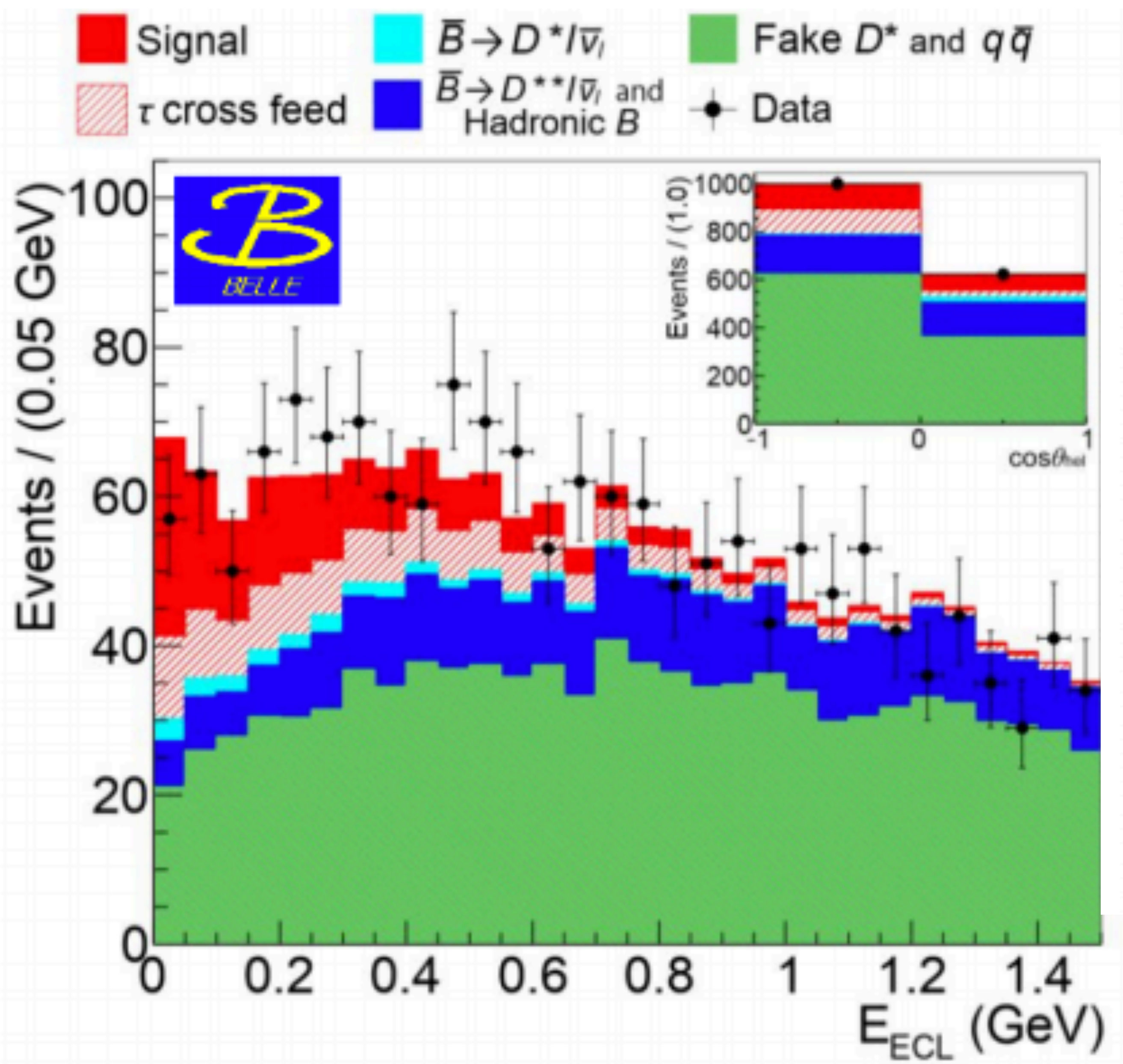
$R(D^*)$ **2.7σ** above SM

$R(D)$ **2.0σ** above

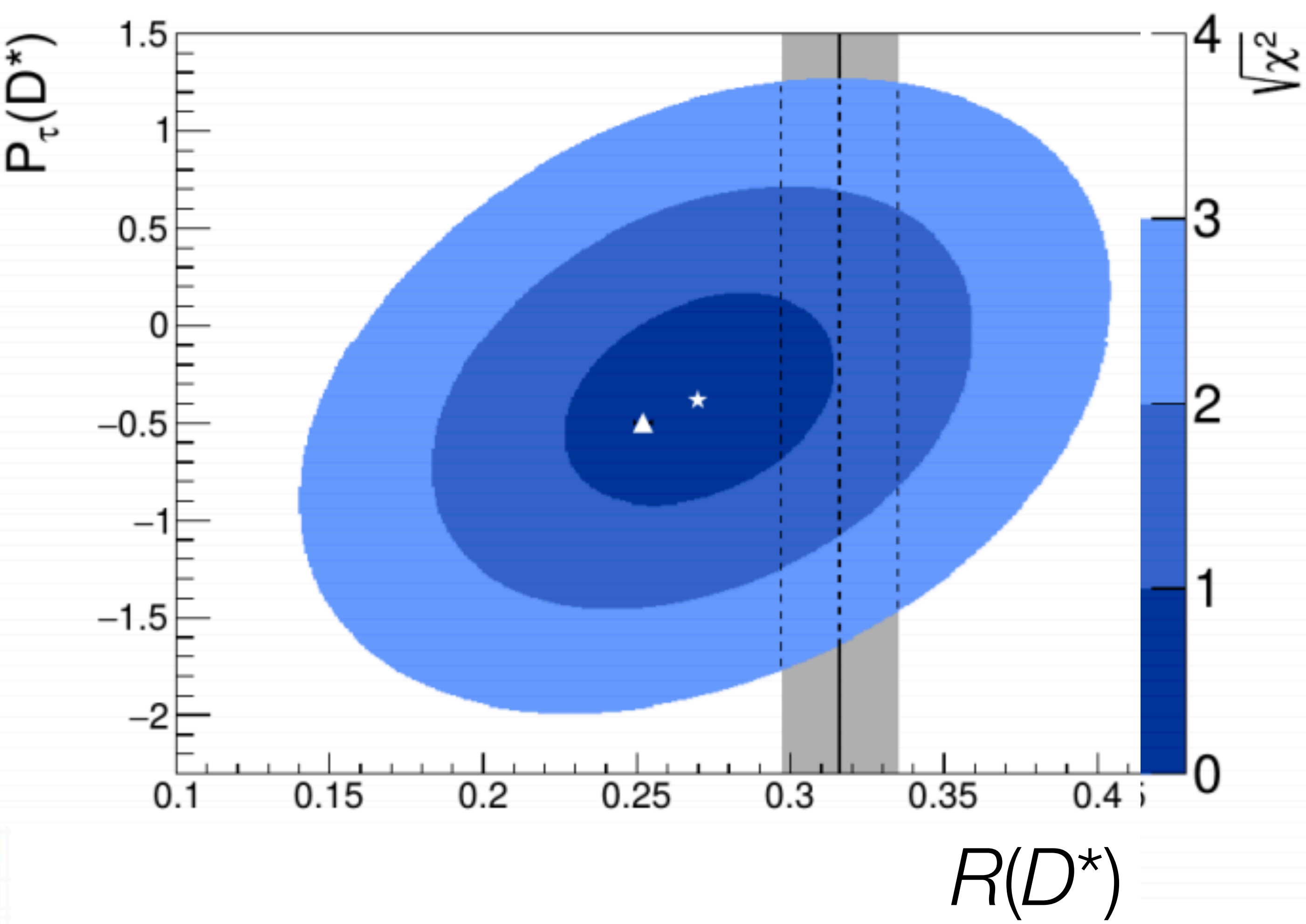
Combination **3.4σ** away



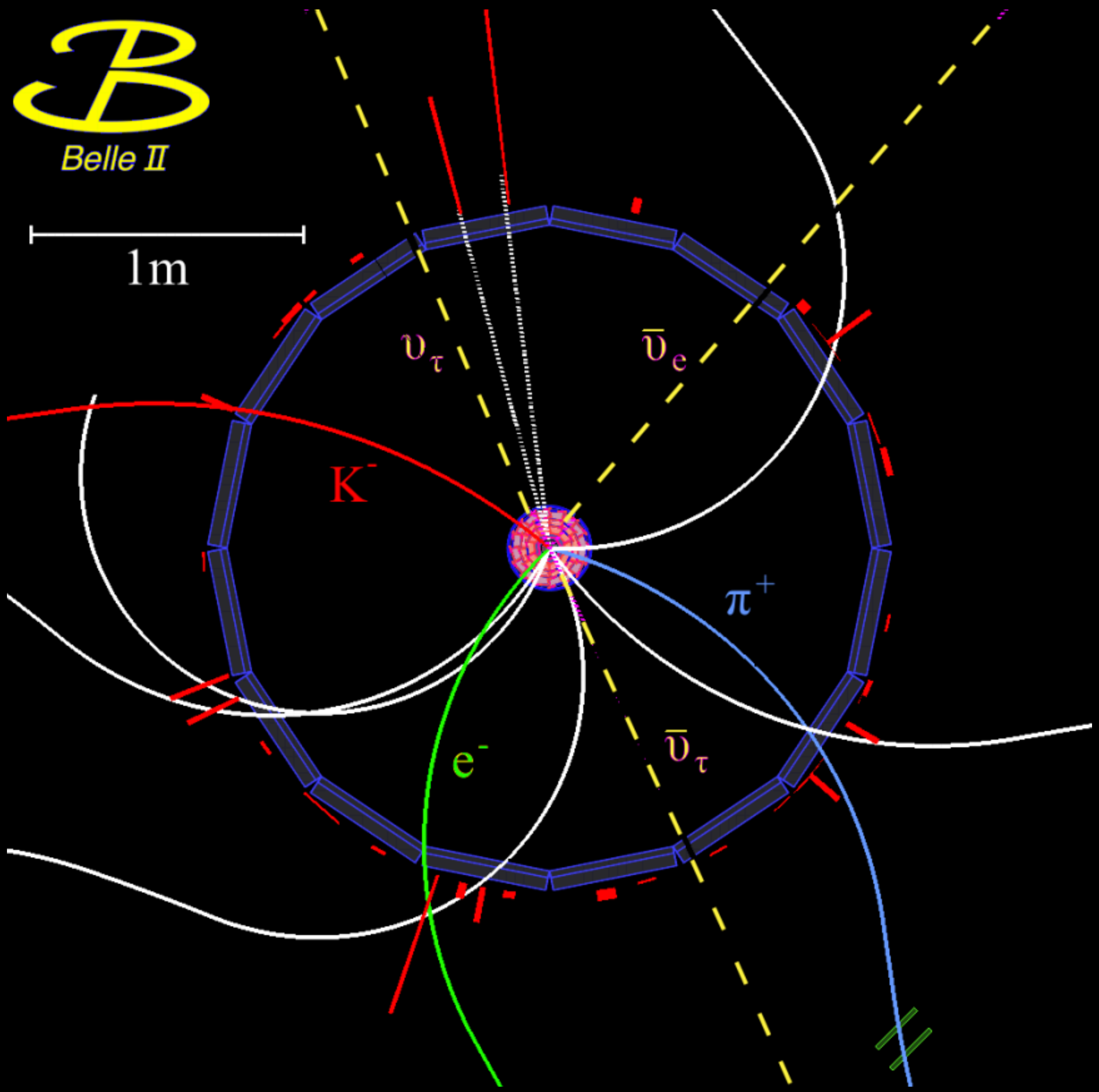
Recent Belle analysis with $\tau \to \pi(\pi^0)\nu$



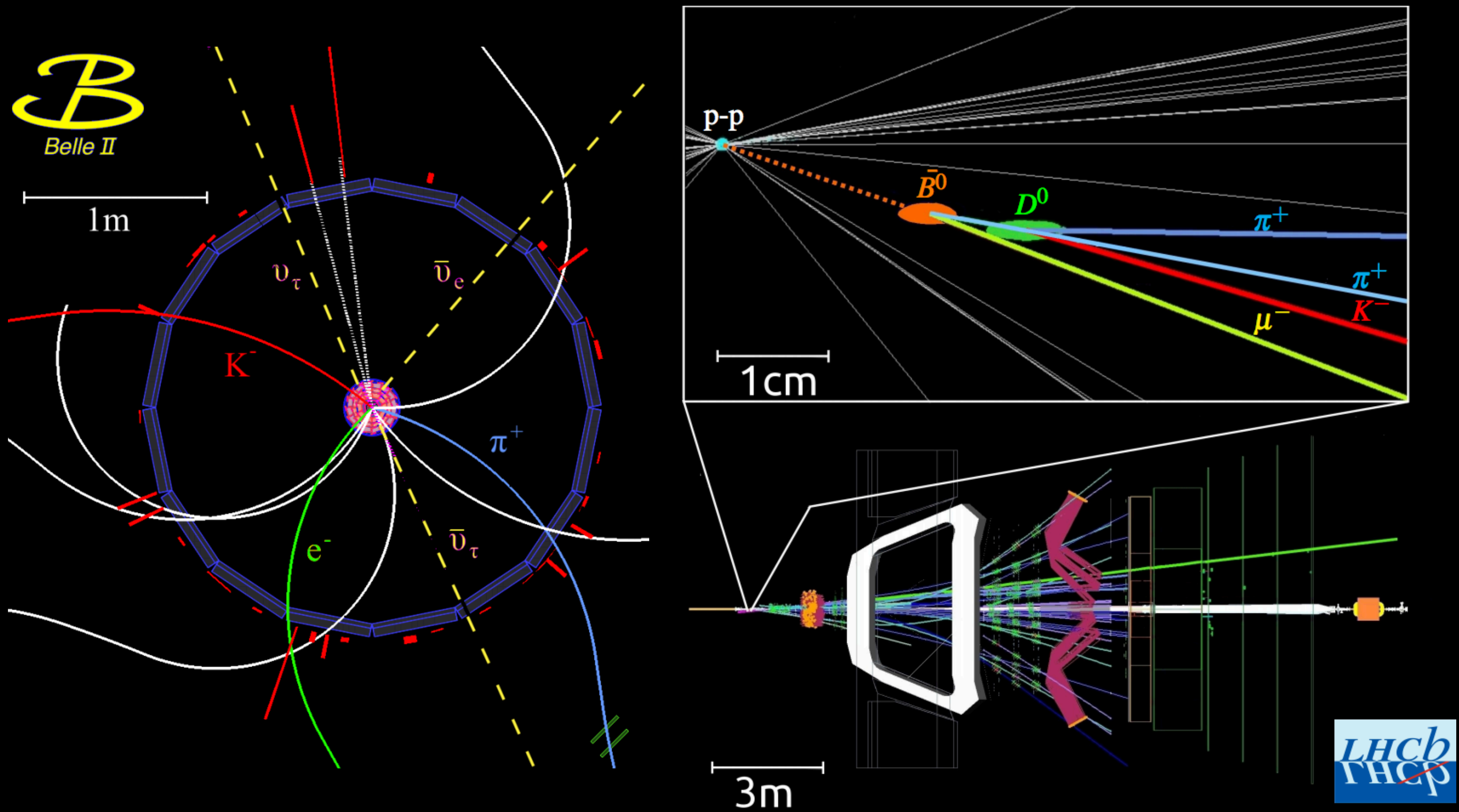
First τ polarisation measurement!



PRL 118, 211801 (2017), PRD 97, 012004 (2018)



Possible at LHCb?



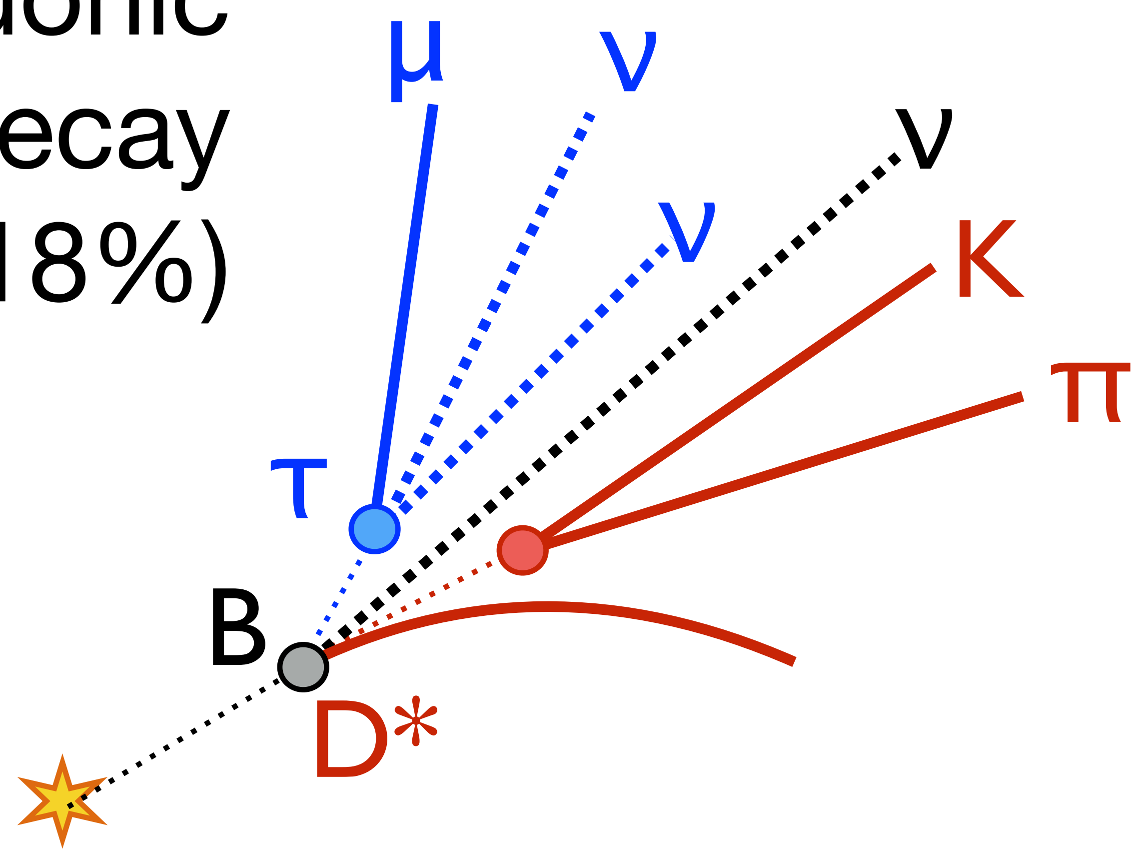
In pp collisions the rest of the event doesn't provide any useful kinematic constraint.

Different approaches required.

$R(D^*)$ from LHCb

*$\pi^- \pi^- \pi^+ \nu X$ (excl. K_s)

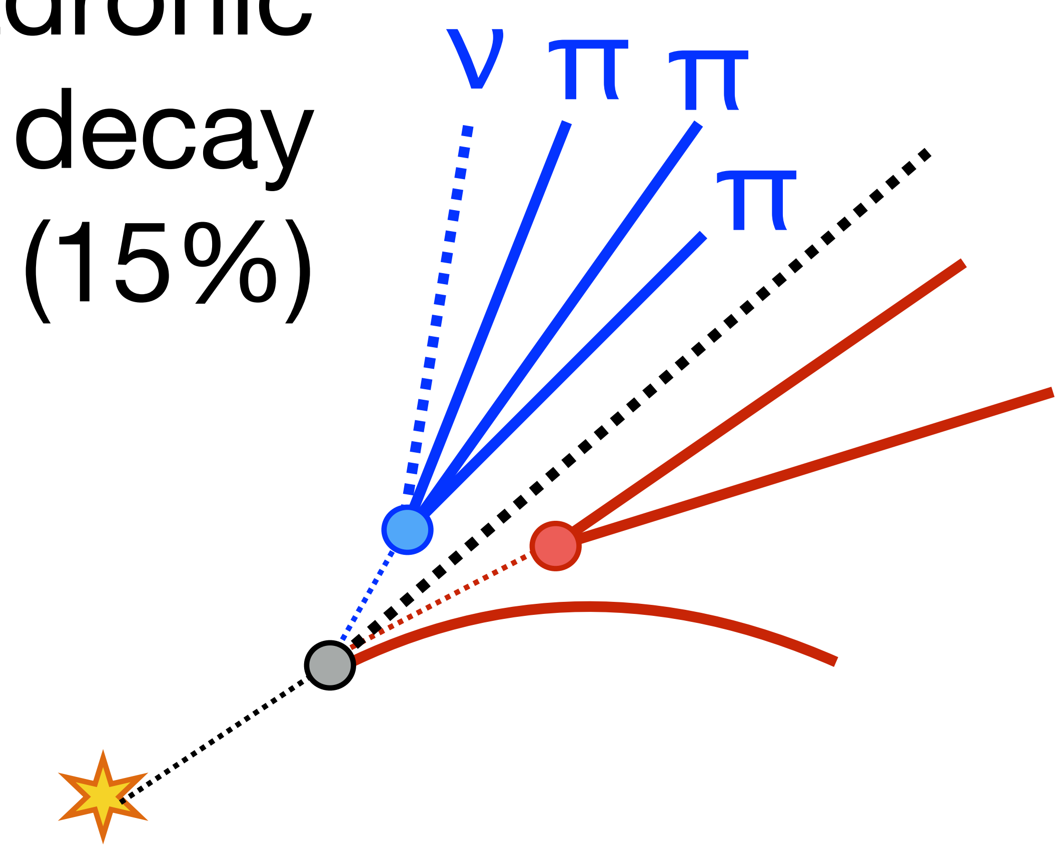
Muonic τ decay (18%)



PRL 115, 111803 (2015)

τ BR = (17.39 ± 0.04)%

Hadronic τ decay (15%)

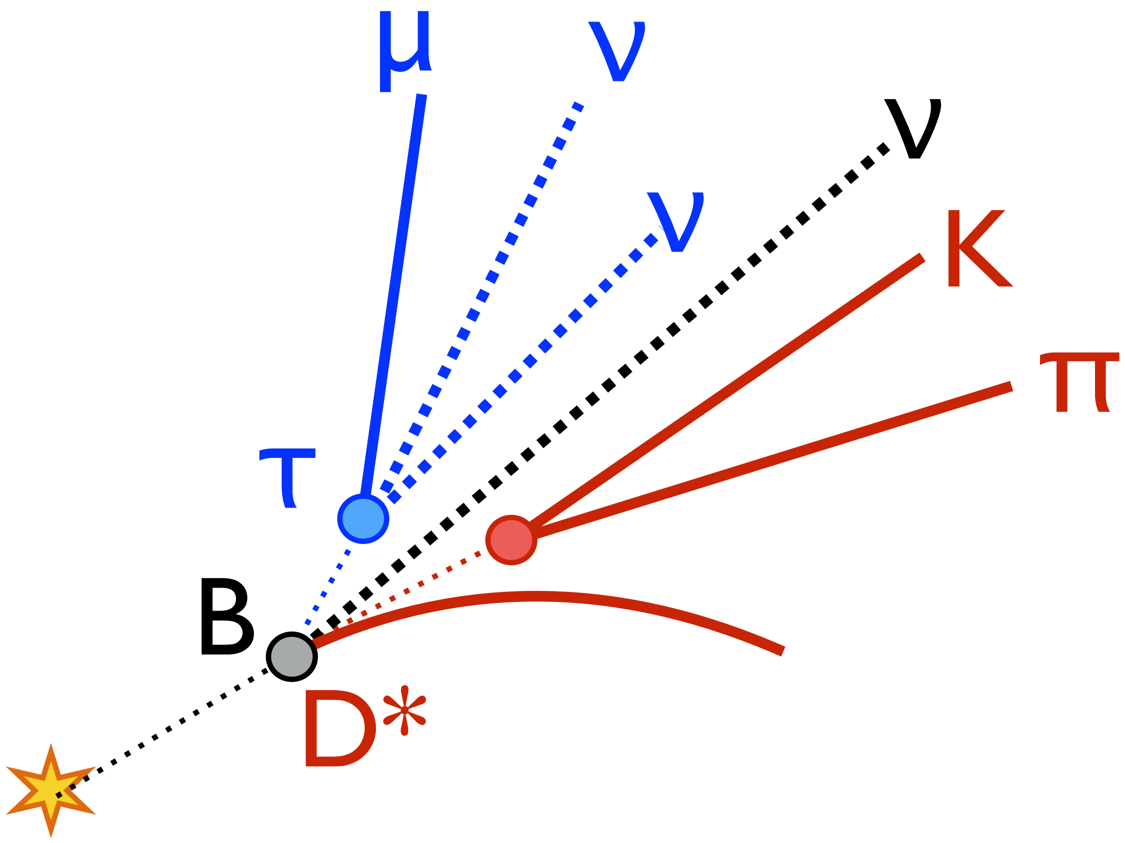


1708.08856v2 (2017)

1711.02505 (2018)

τ BR* = (14.55 ± 0.06)%

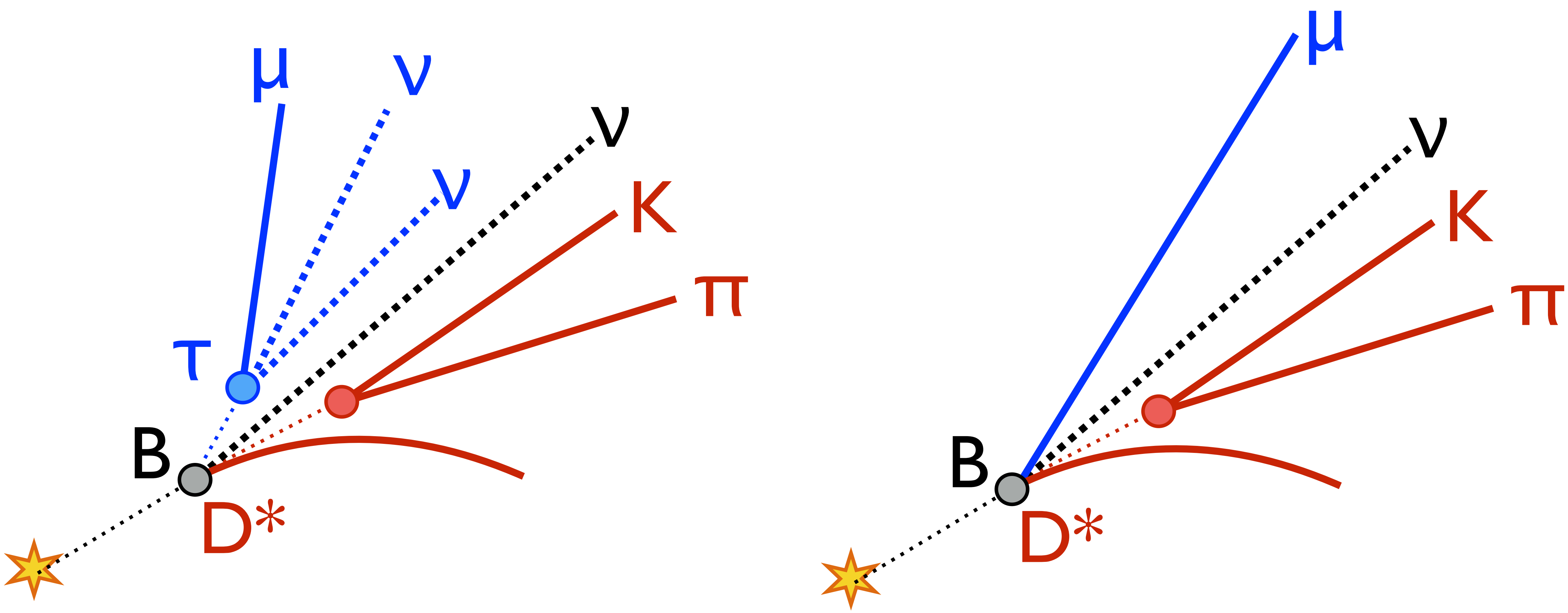
Muonic *R*(*D**) from LHCb



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

Muonic $R(D^*)$ from LHCb

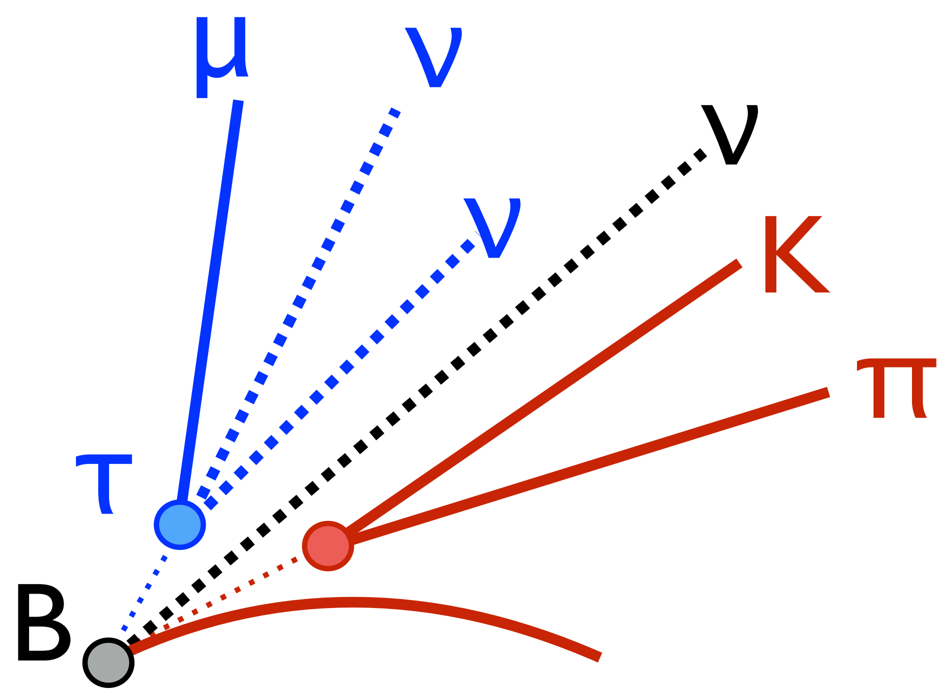
(Normalisation and background)

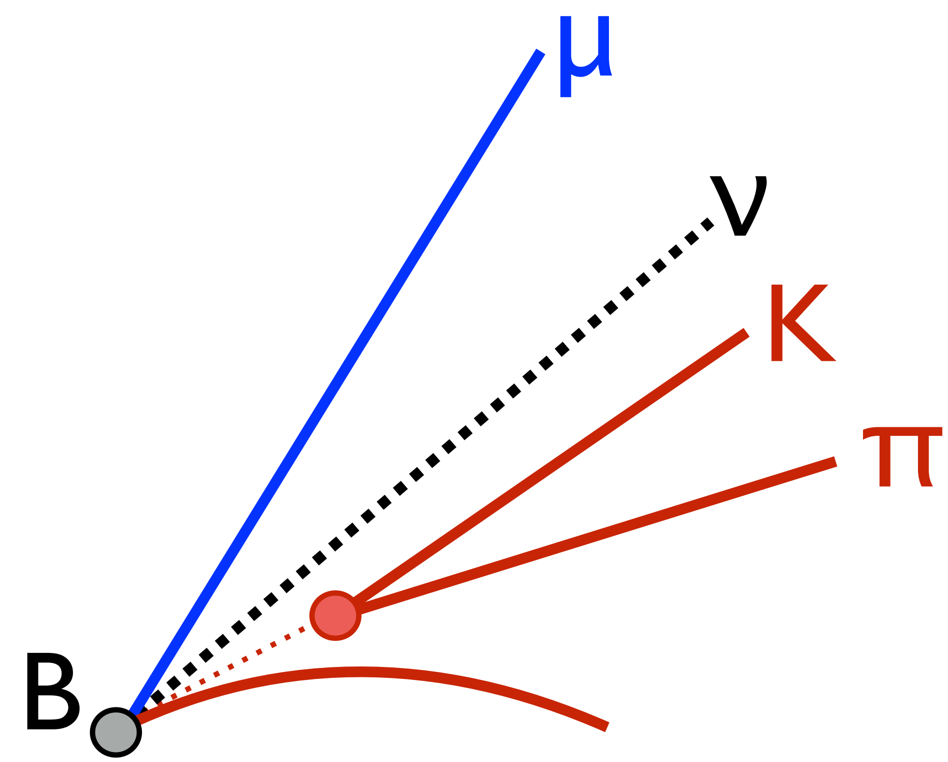


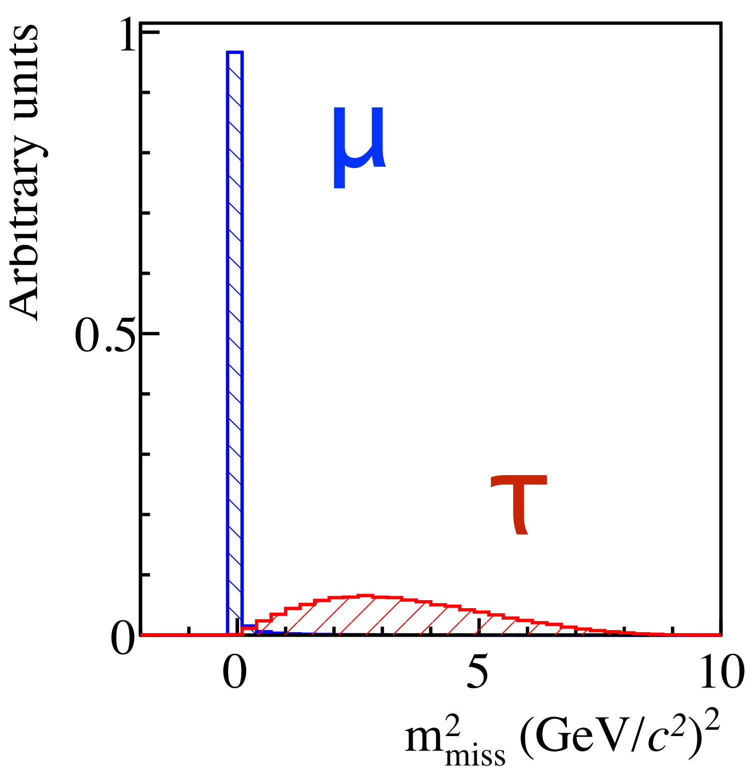
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

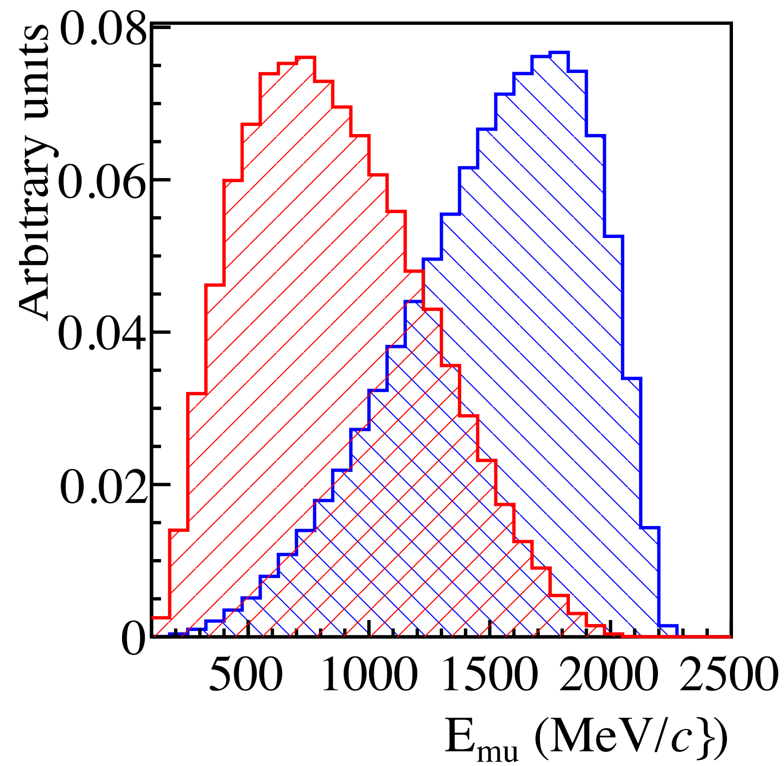
Muonic $R(D^*)$ from LHCb

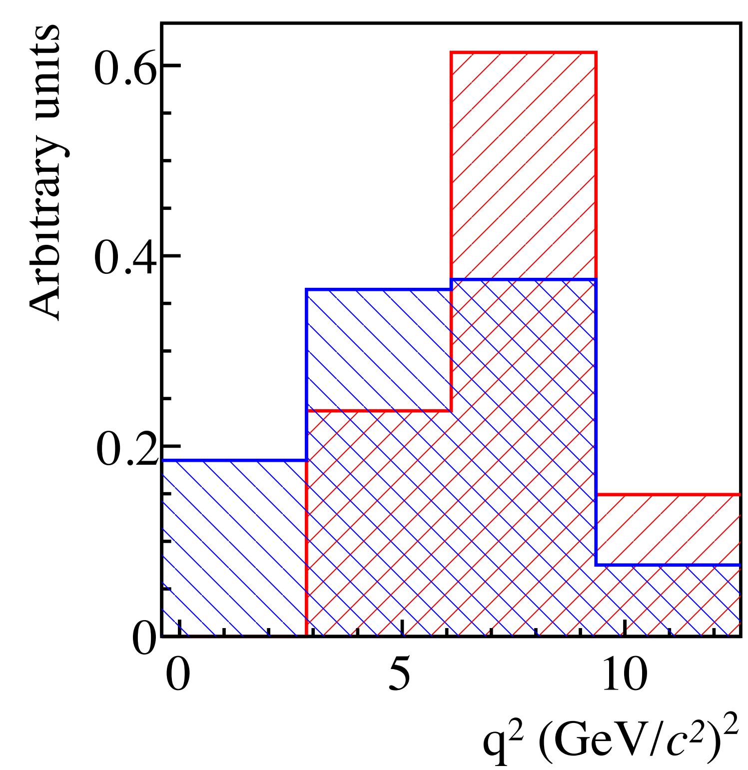
(Normalisation and background)









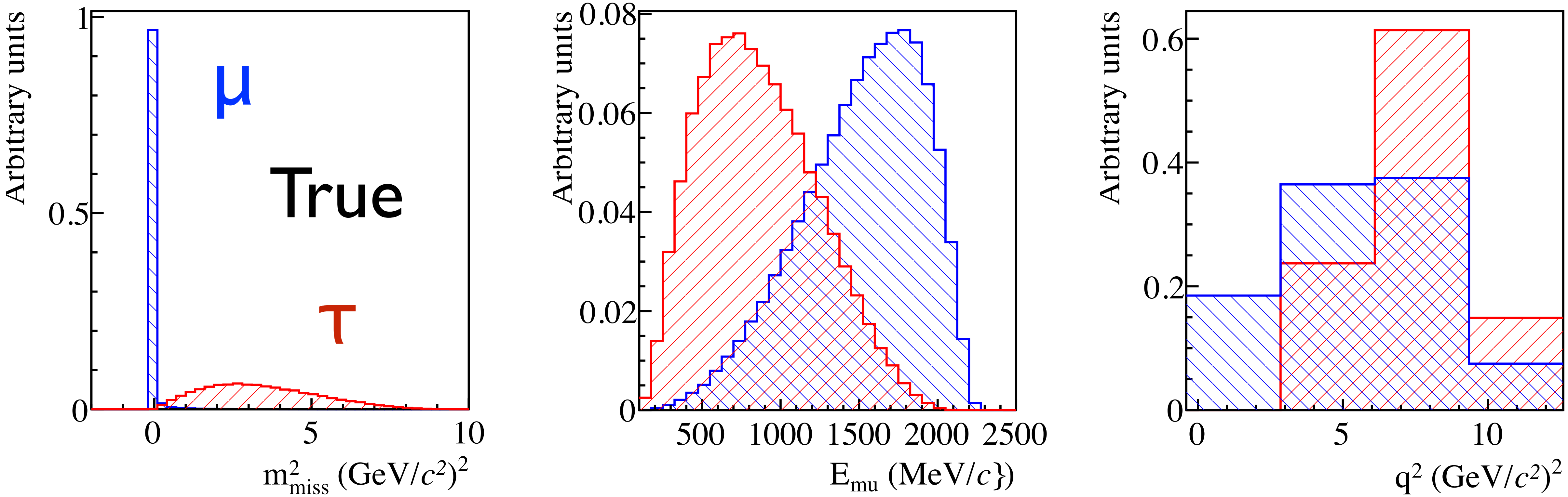


Muonic $R(D^*)$ from LHCb

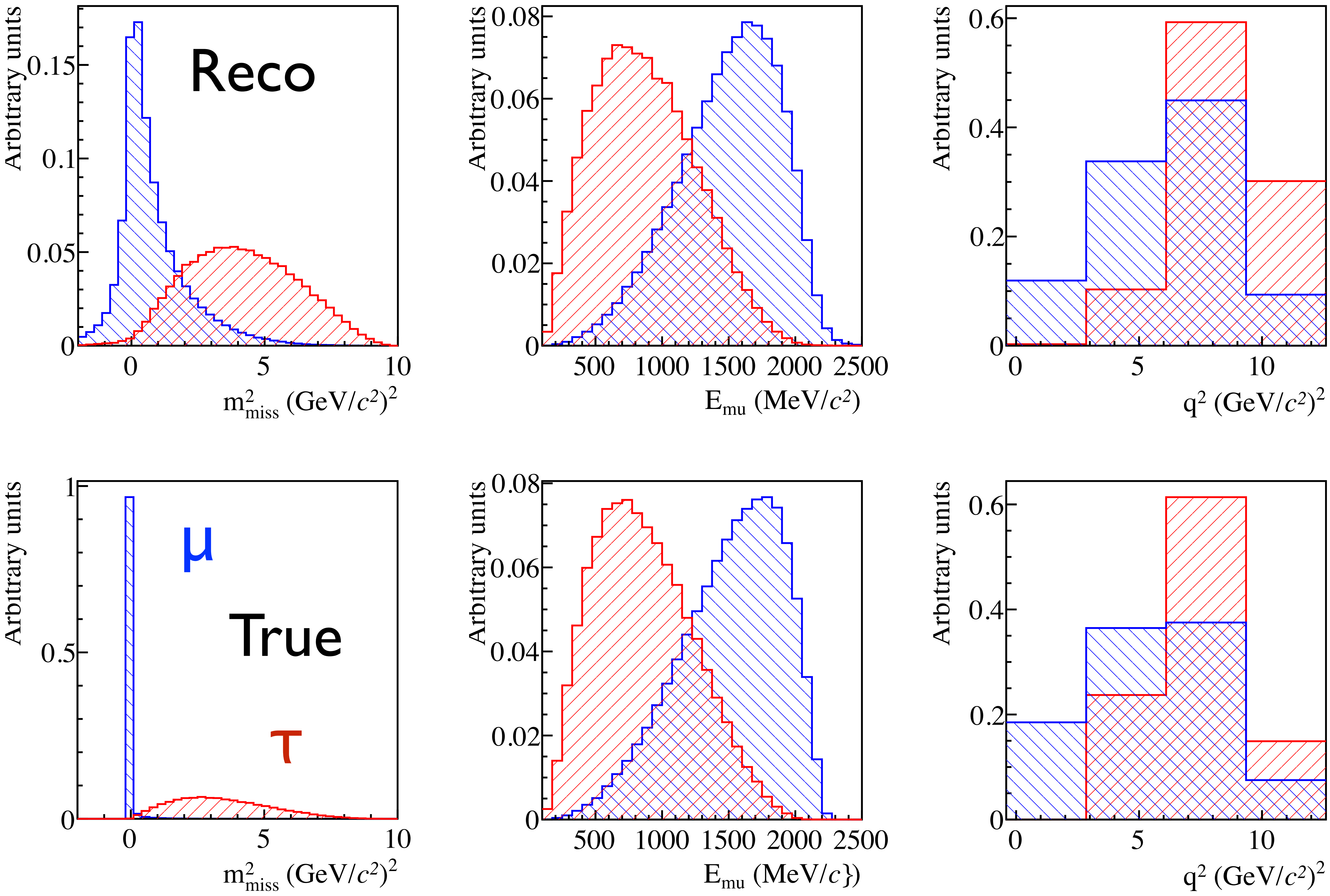
Below we assume knowledge of the b momentum!

Try the approximation $(\gamma\beta_Z)_B = (\gamma\beta_Z)_{visible}$?

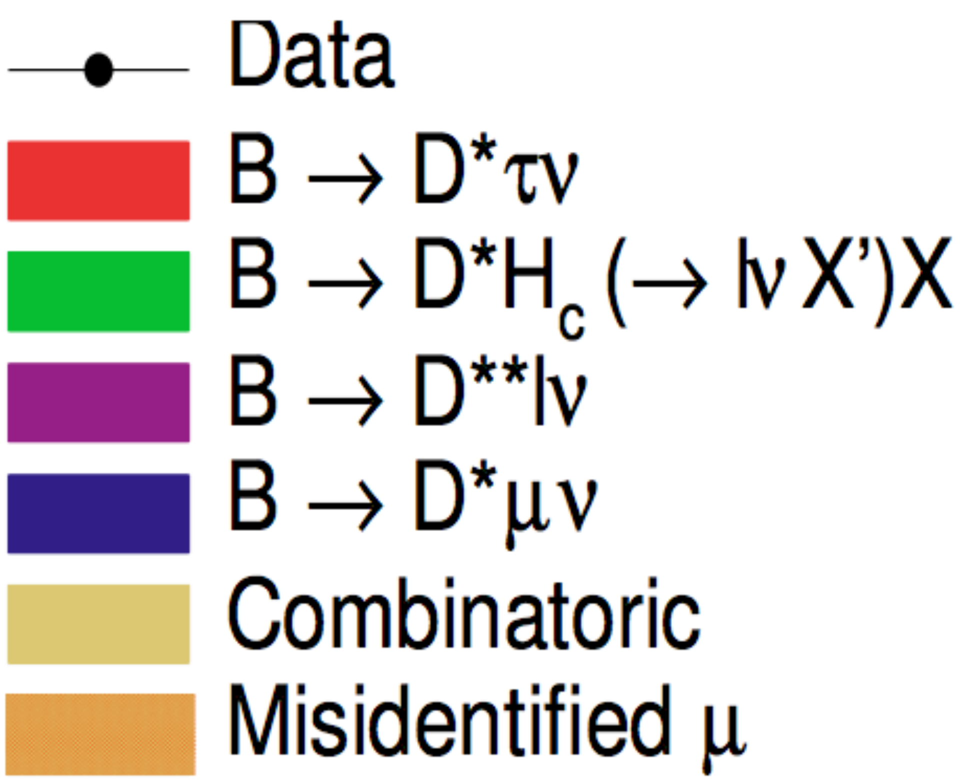
And exploit the measured B flight trajectory.



Muonic $R(D^*)$ from LHCb

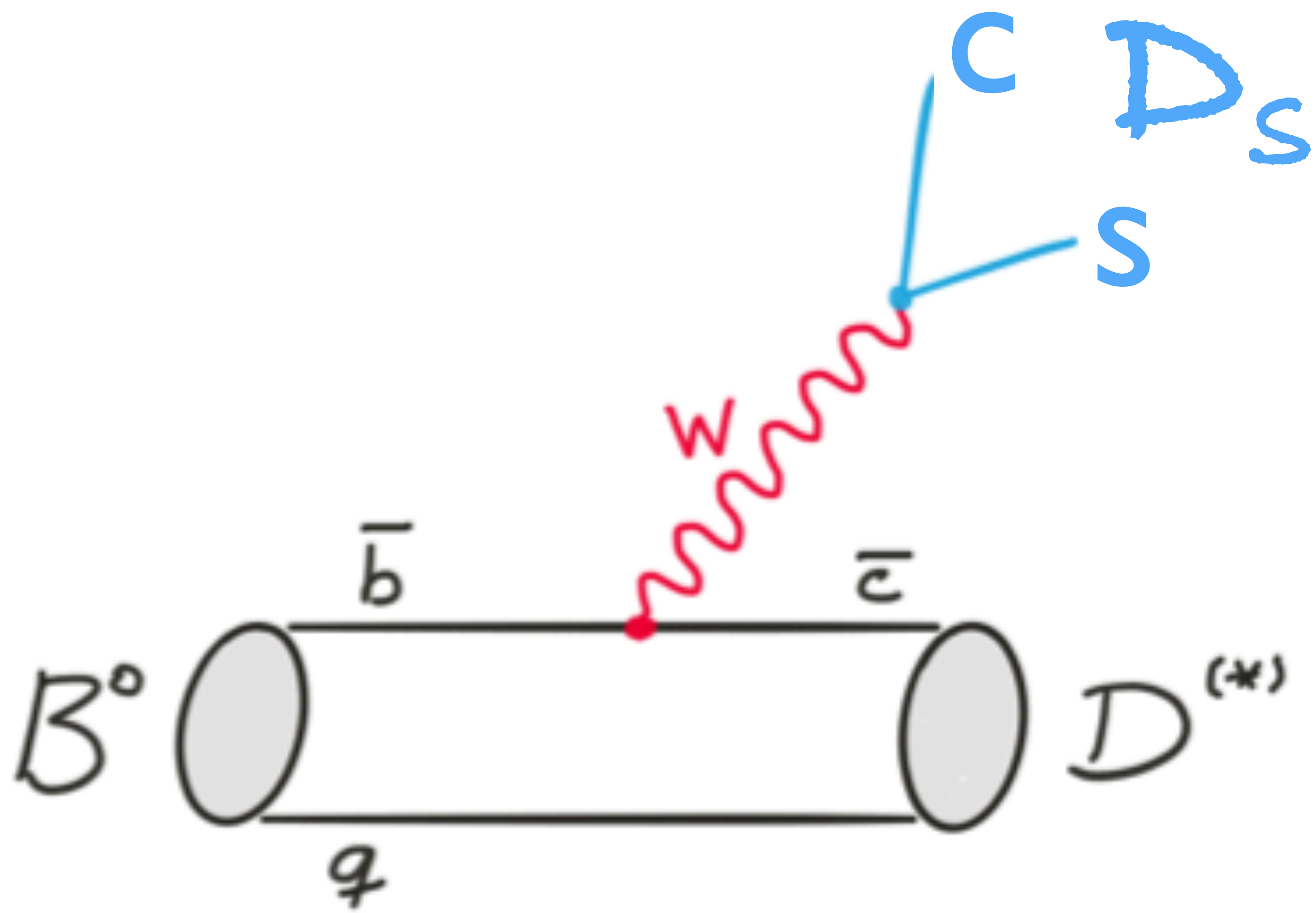


Other backgrounds



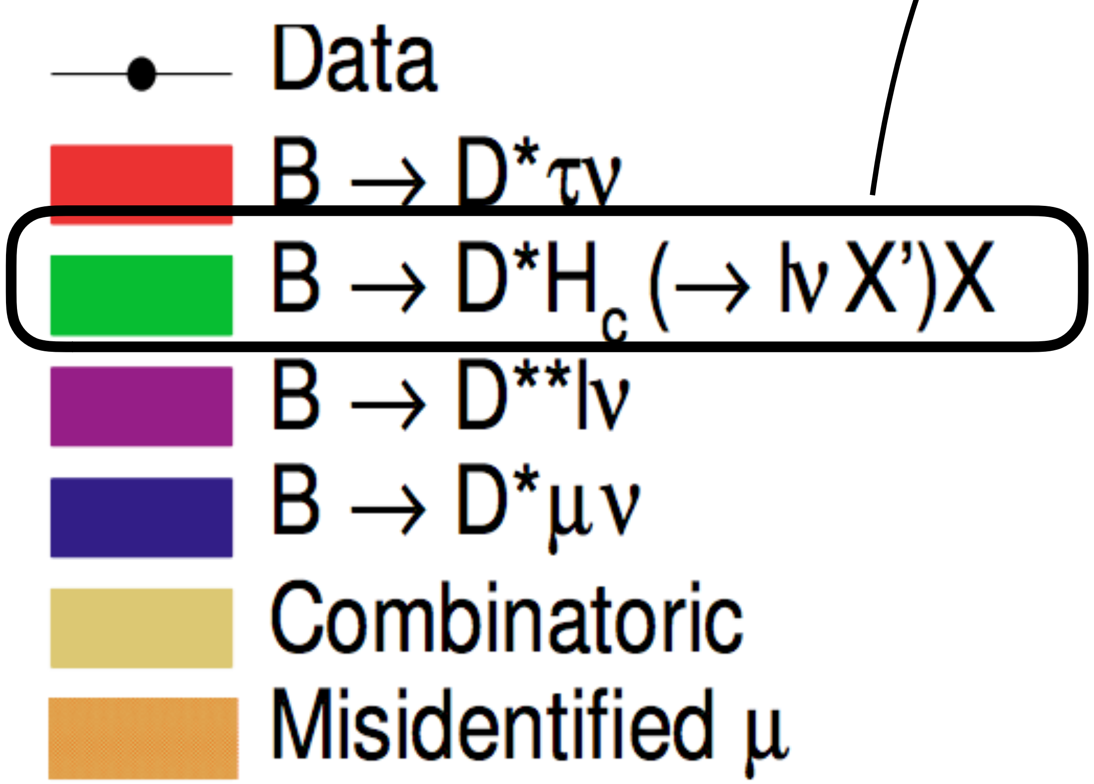
Double charm

- Data
- $B \to D^*\tau\nu$
- $B \to D^*H_c(\to l\nu X')X$
- $B \to D^{**}l\nu$
- $B \to D^*\mu\nu$
- Combinatoric
- Misidentified μ

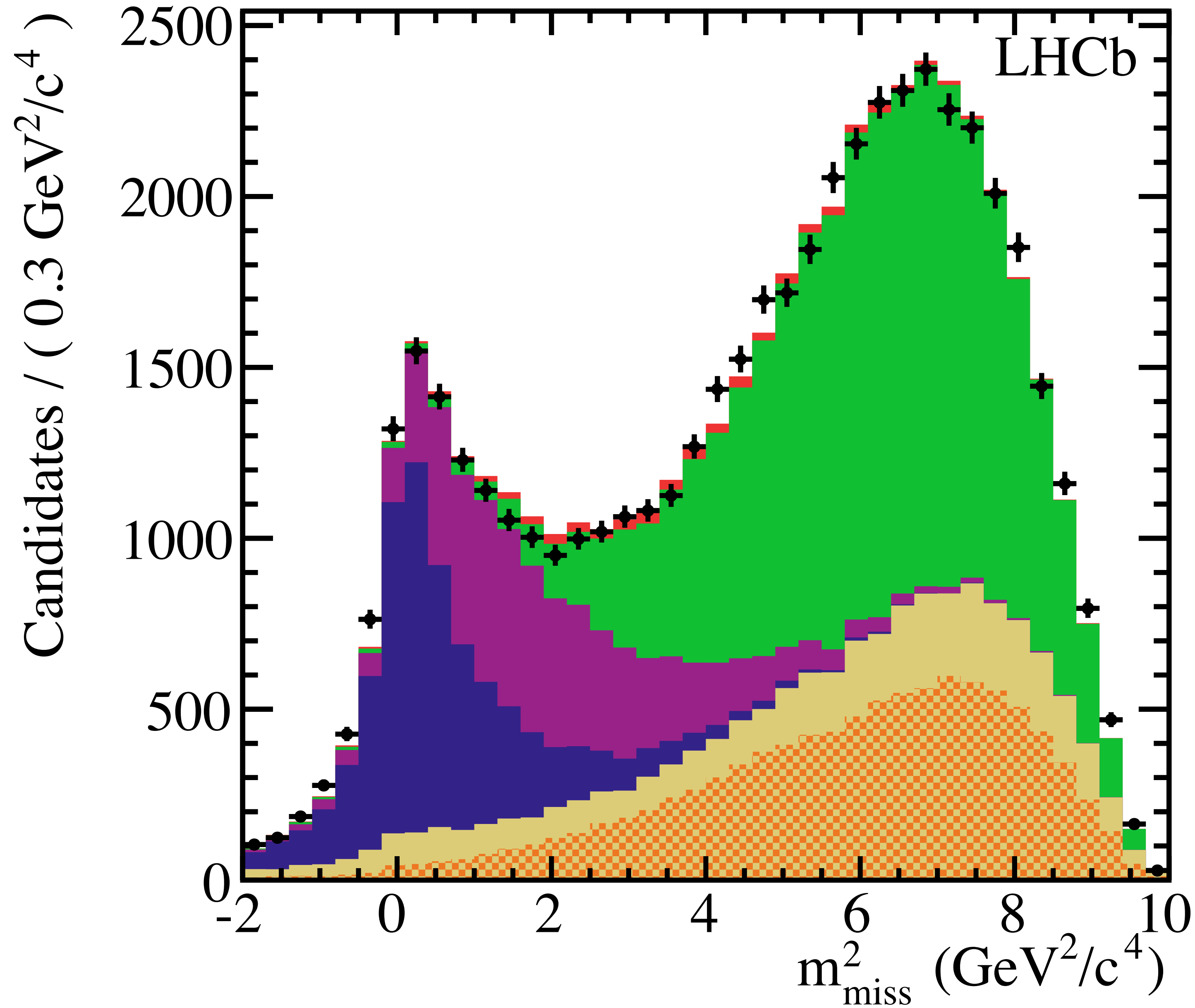


Double charm

“Anti-isolation”
Control region



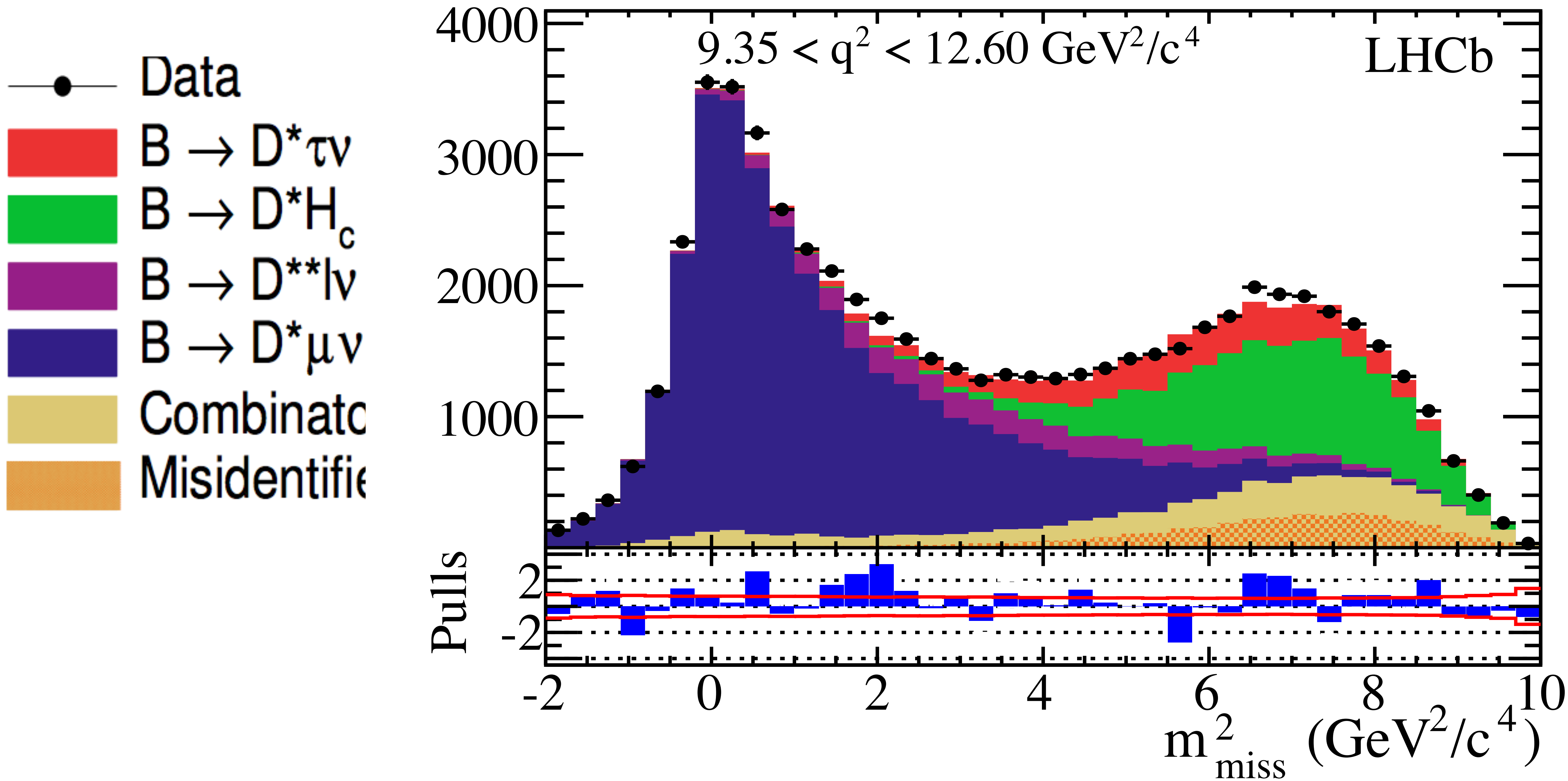
E.g. identified kaon



Fit in (isolated) signal region

4 coarse q^2 bins, and finer bins in m^2_{miss}, E_μ.

Projection of m^2_{miss} in the highest purity q^2 bin:



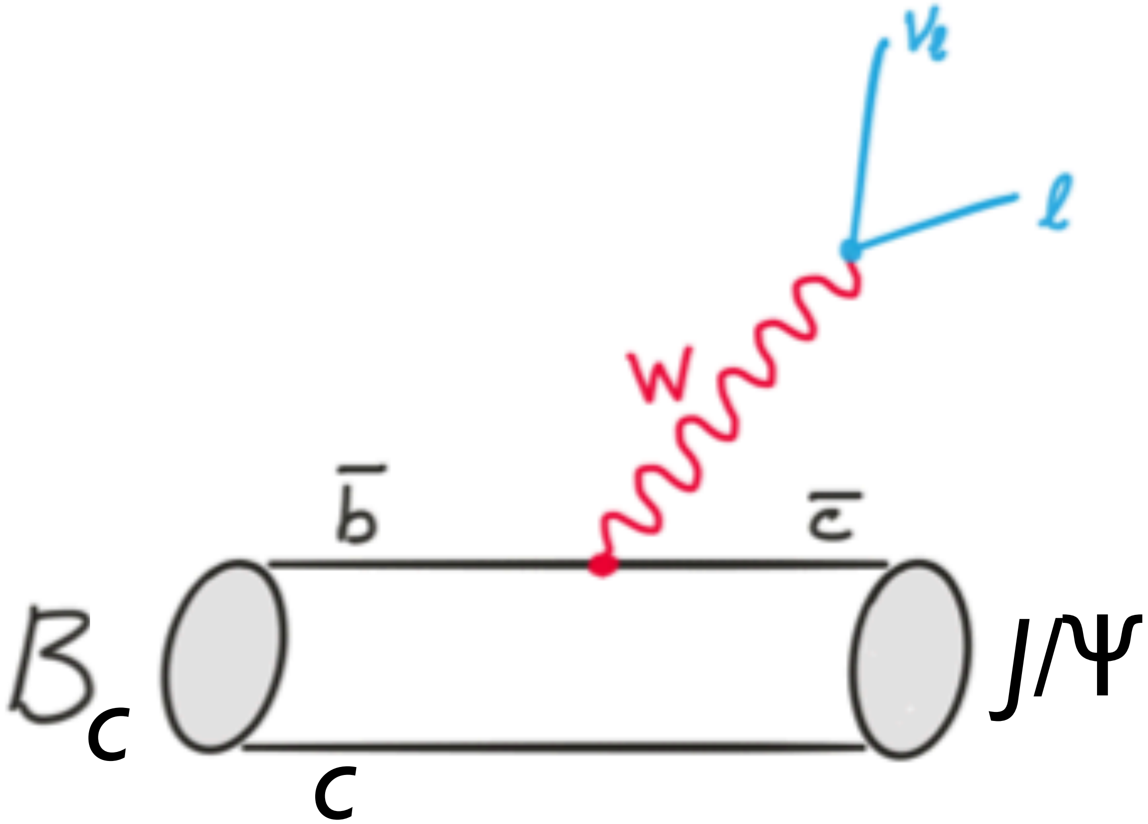
LHCb muonic $R(D^*)$ result

$$R(D^*) = 0.336 \pm 0.027_{\text{stat}} \pm 0.030_{\text{syst}}$$

Consistent with BaBar and Belle results

2.1σ above the SM prediction

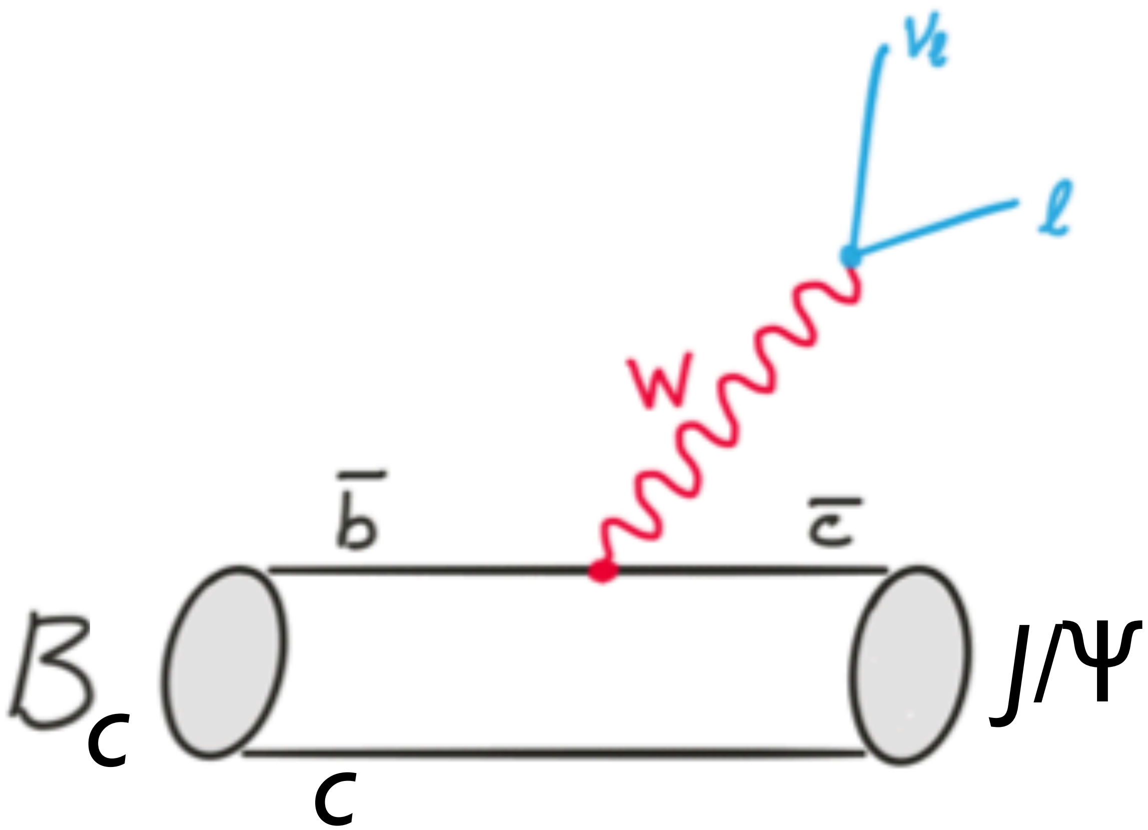
First LHCb analysis with B_c decays

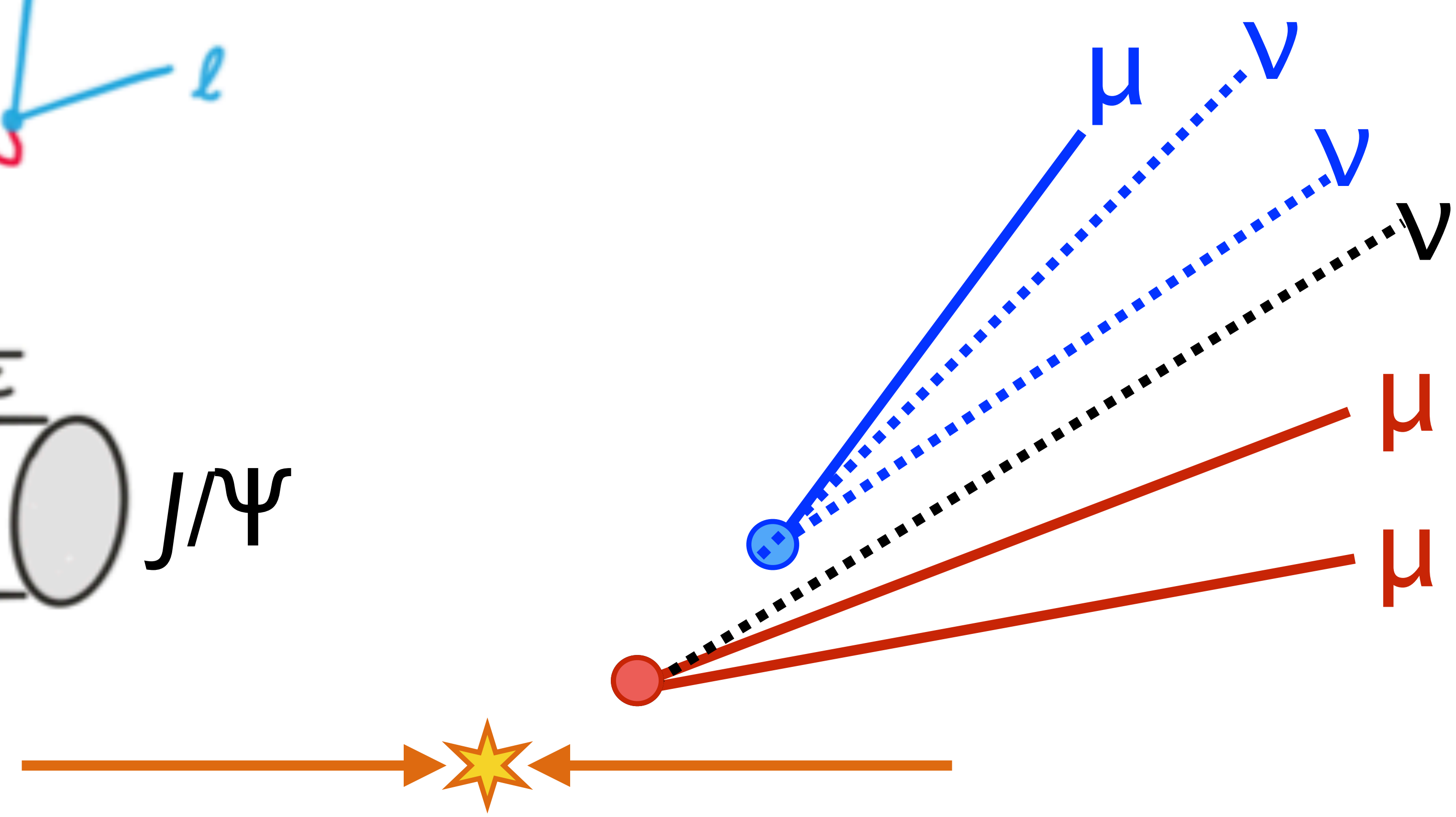


$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

SM predictions for $R(J/\Psi)$ lie in the range 0.25–0.28.

First LHCb analysis with B_c decays

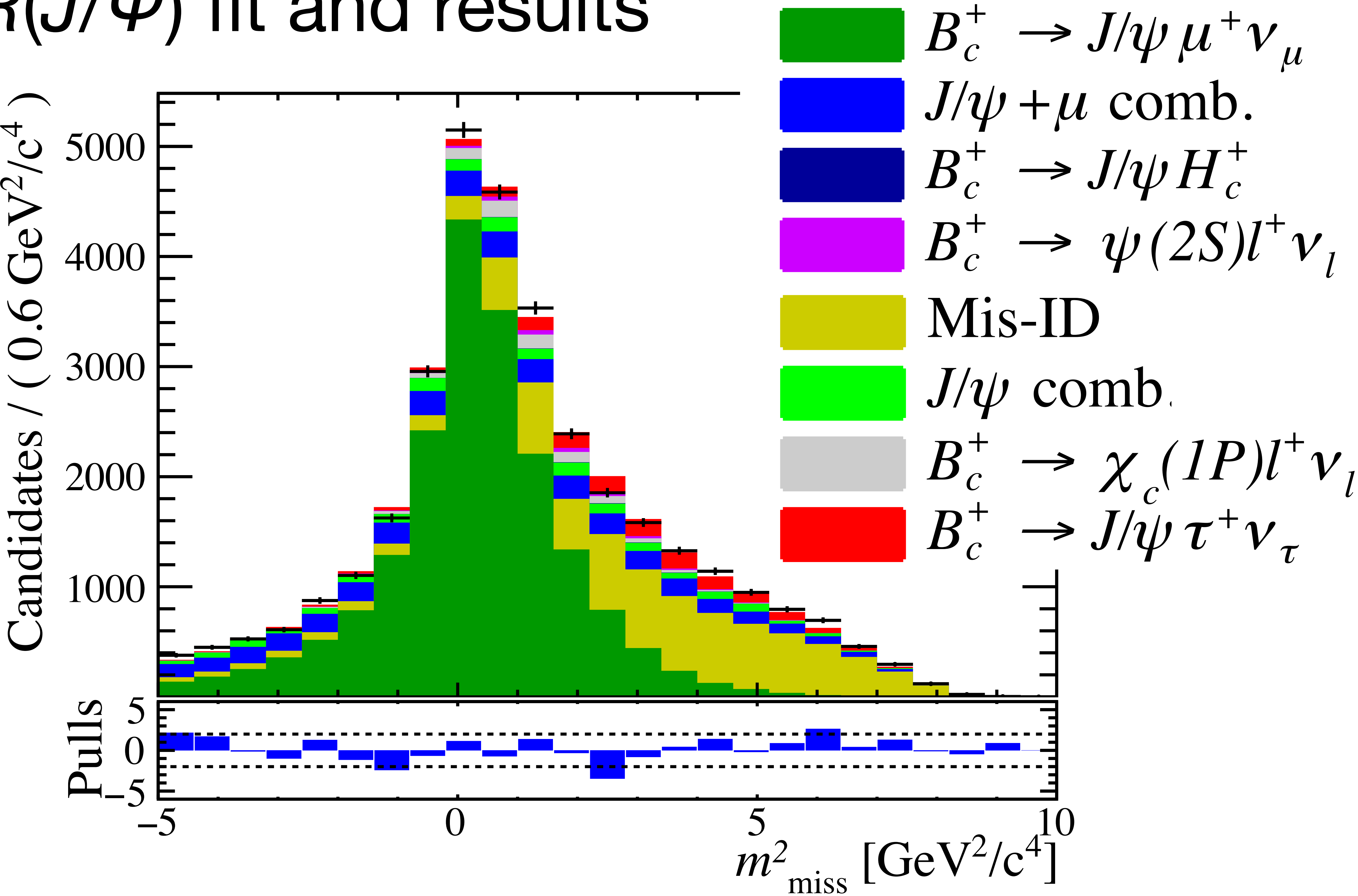




👎Short B_c lifetime

👍No flying charm hadron

$R(J/\Psi)$ fit and results

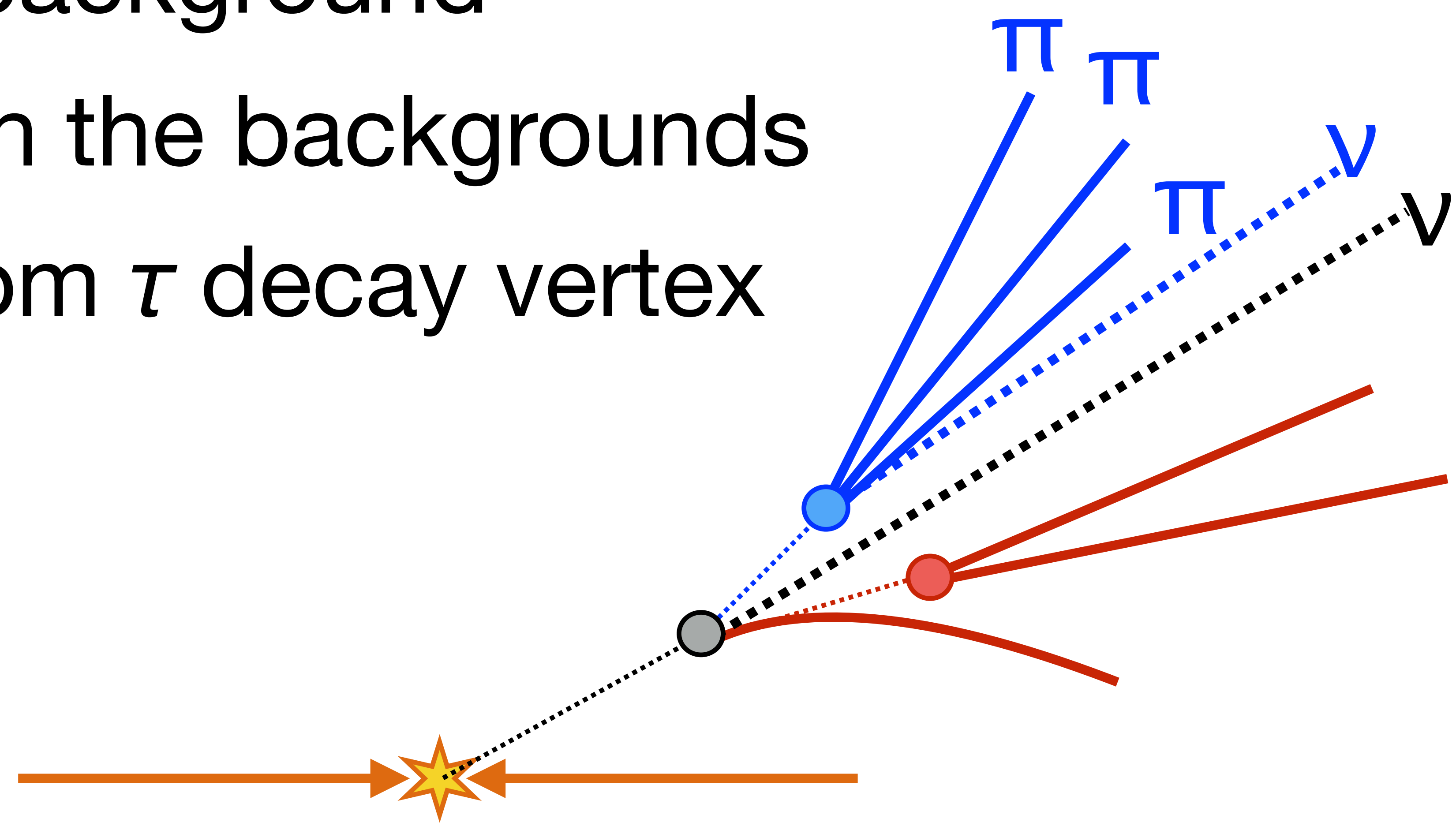


$$R(J/\Psi) = 0.71 \pm 0.17_{\rm stat} \pm 0.18_{\rm syst}$$

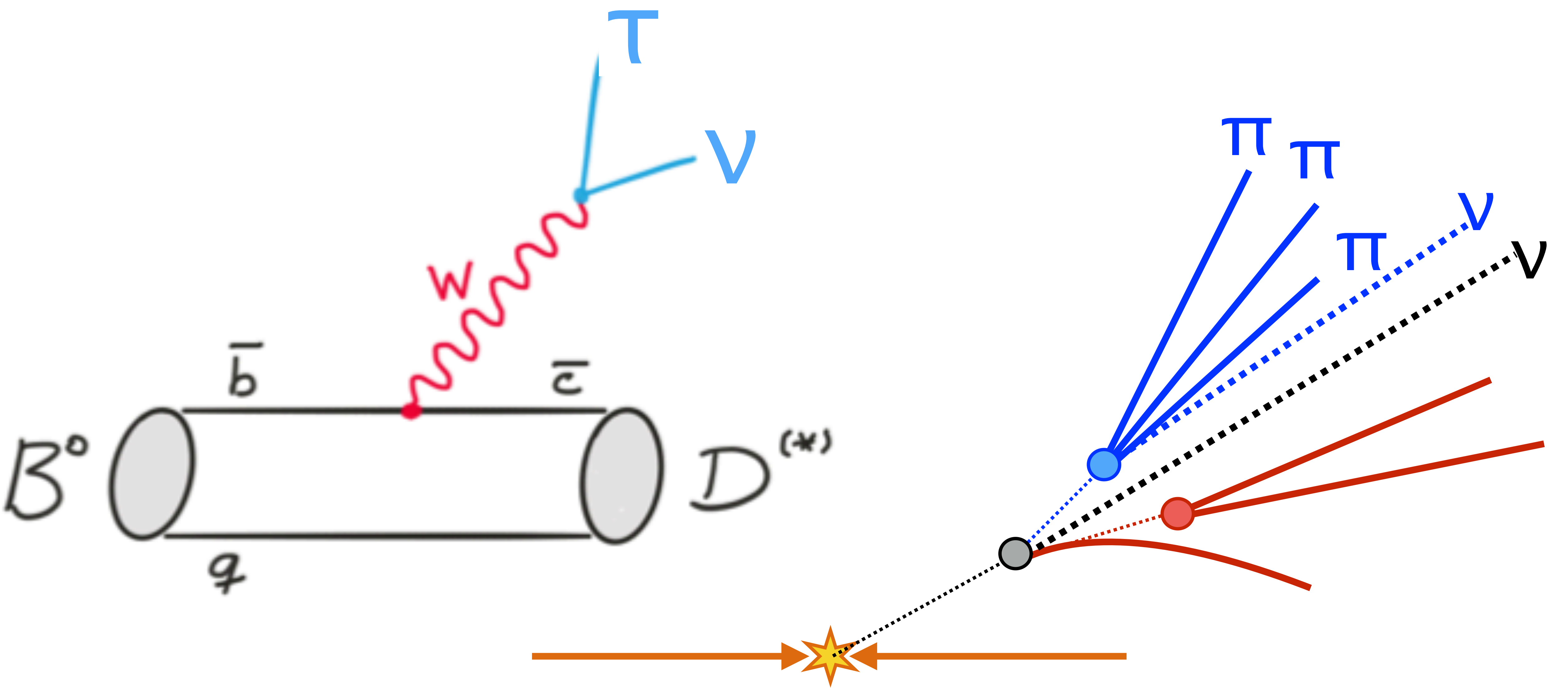
Higher than the predictions, but within 2σ

LHCb $R(D^*)$ with $\tau\to\pi\pi\pi(\pi^0)\nu$

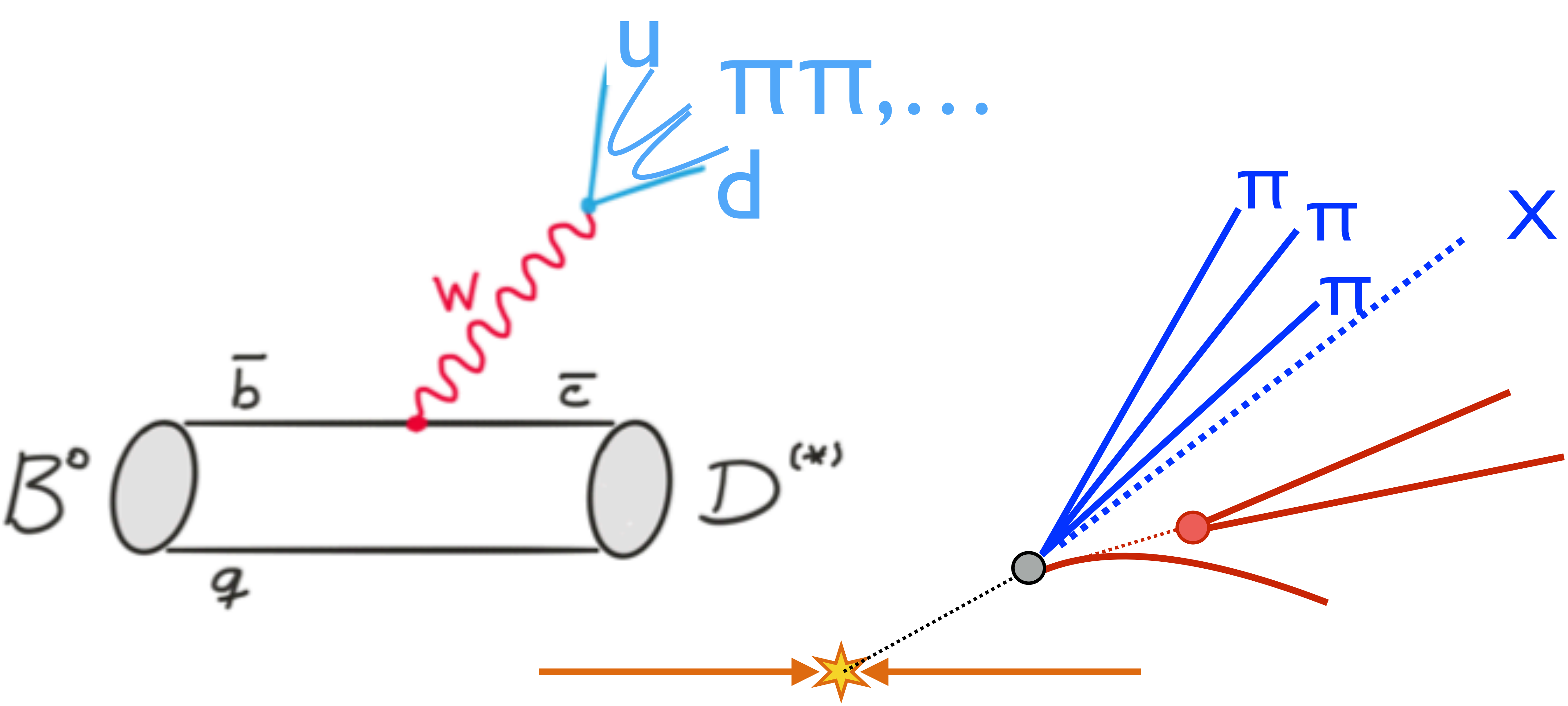
- 👍No $b\to c\mu\nu X$ background
- 👍Mass peaks in the backgrounds
- 👍Only one ν from τ decay vertex



LHCb $R(D^*)$ with $\tau \to \pi\pi\pi(\pi^0)\nu$

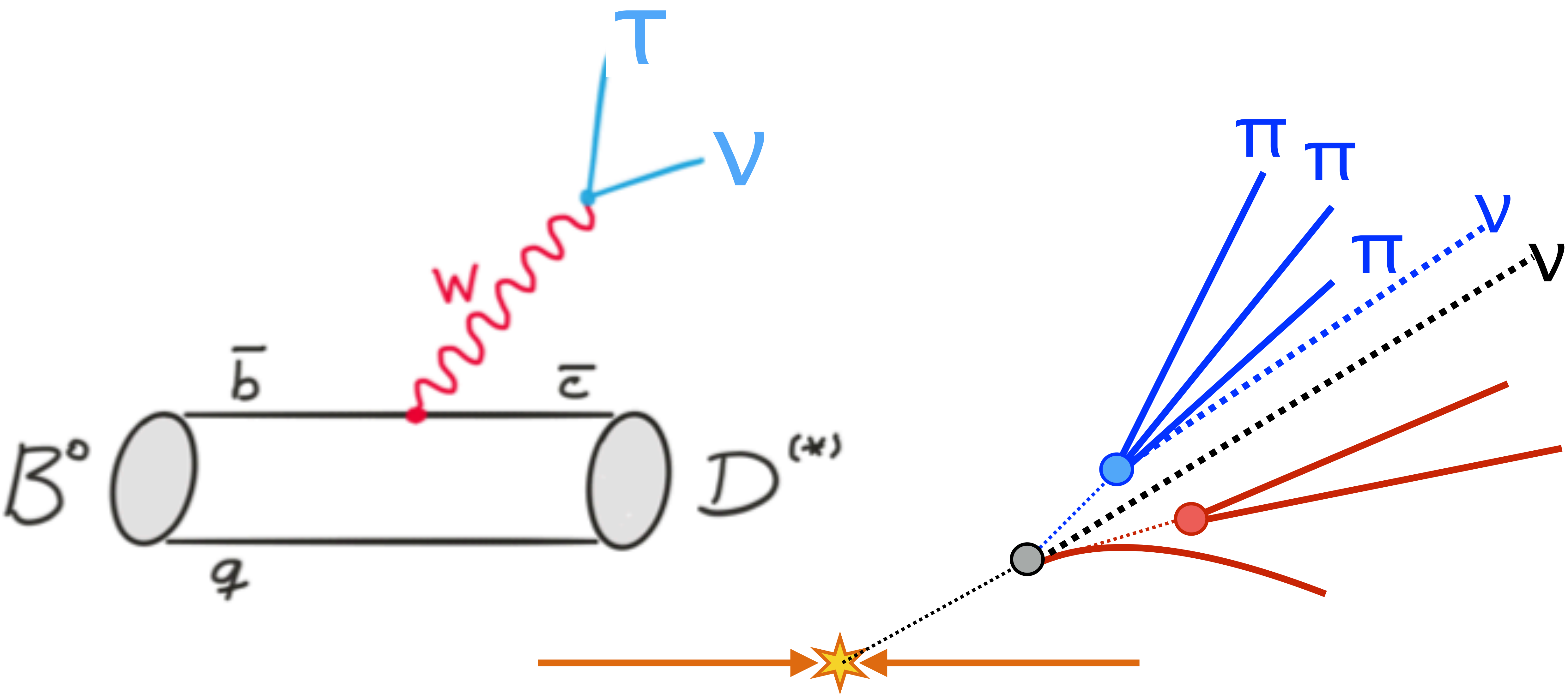


The *prompt* background



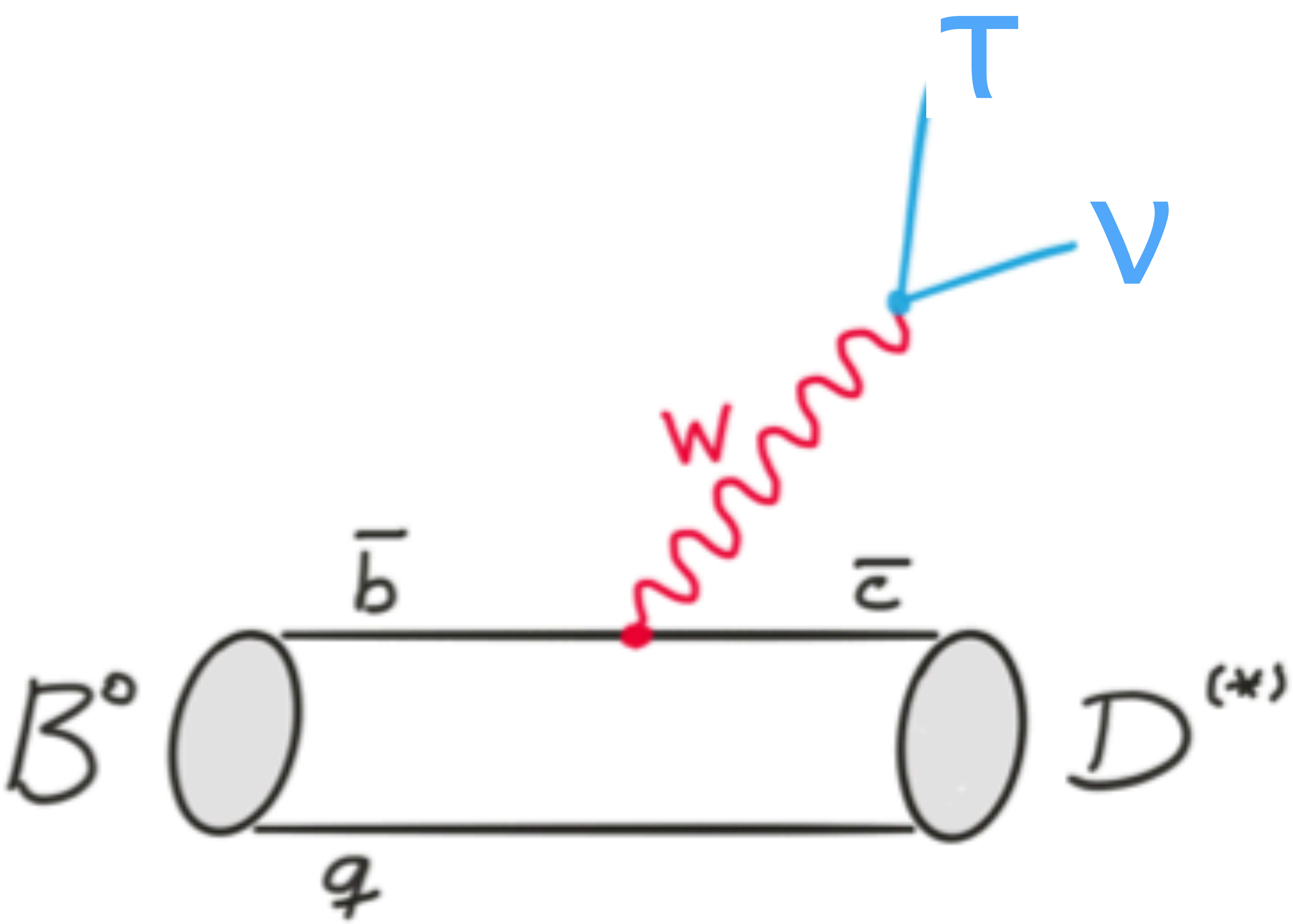
B/S ~ 10^2

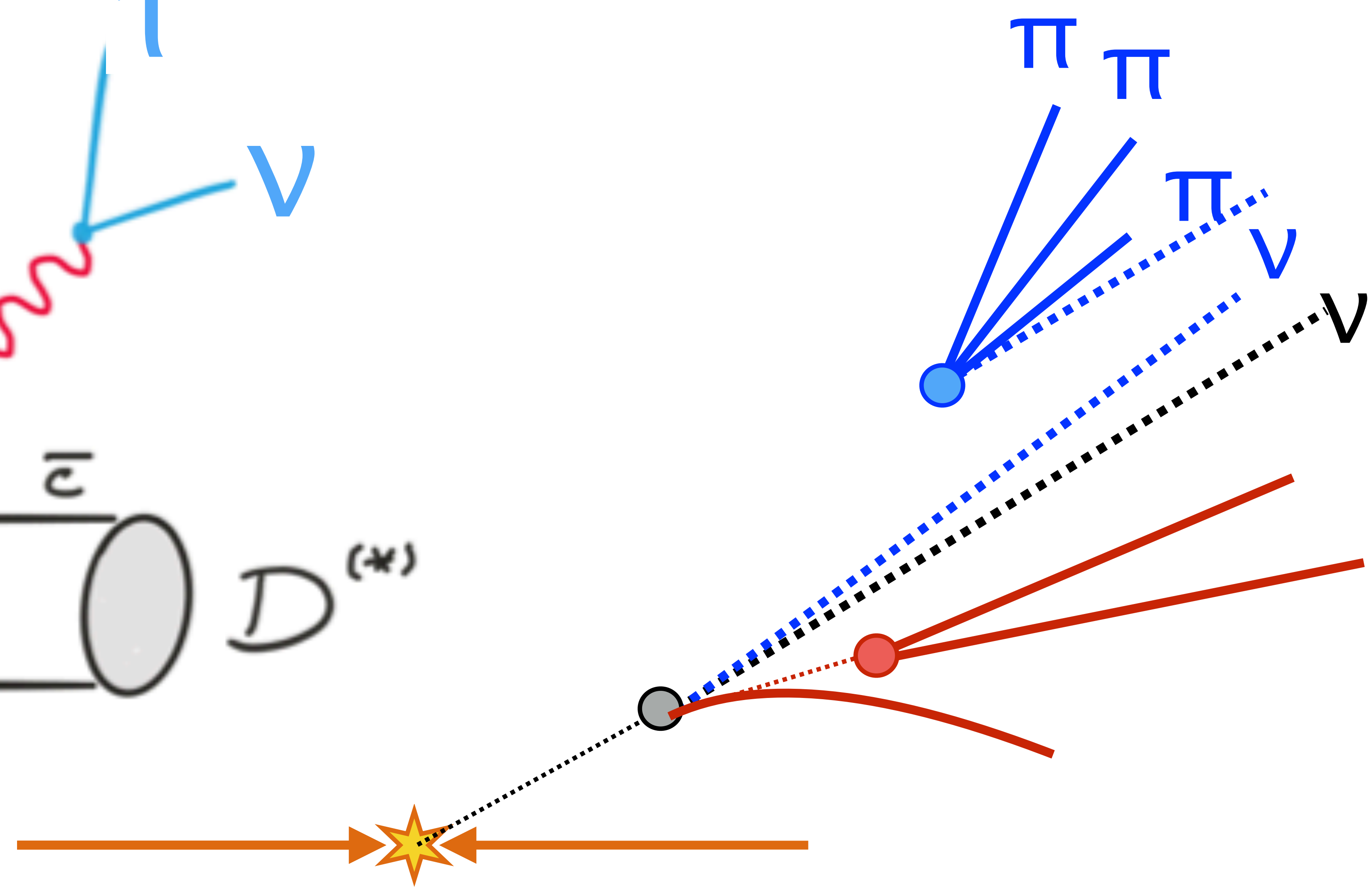
The *prompt* background



B/S ~ 10^2

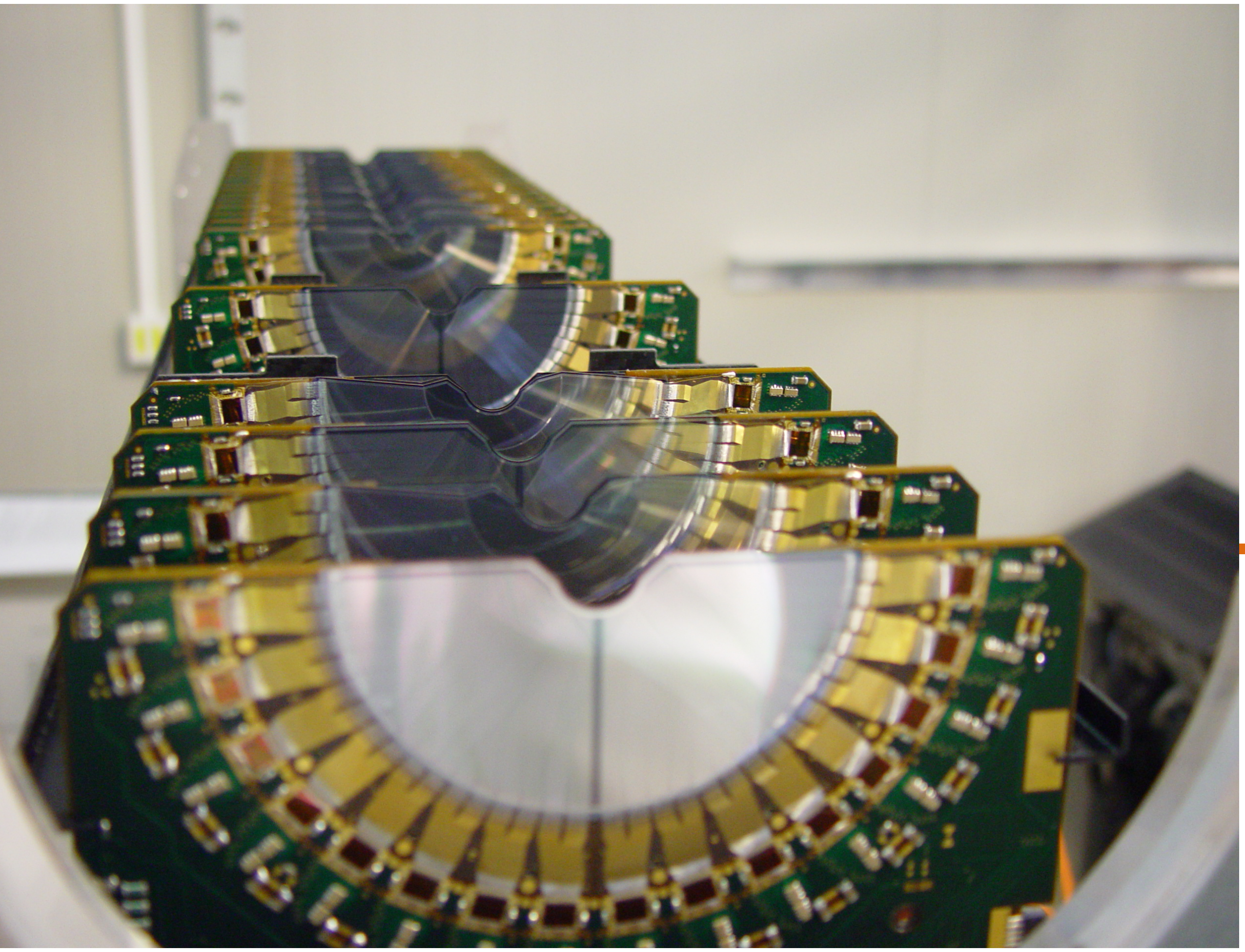
The *prompt* background

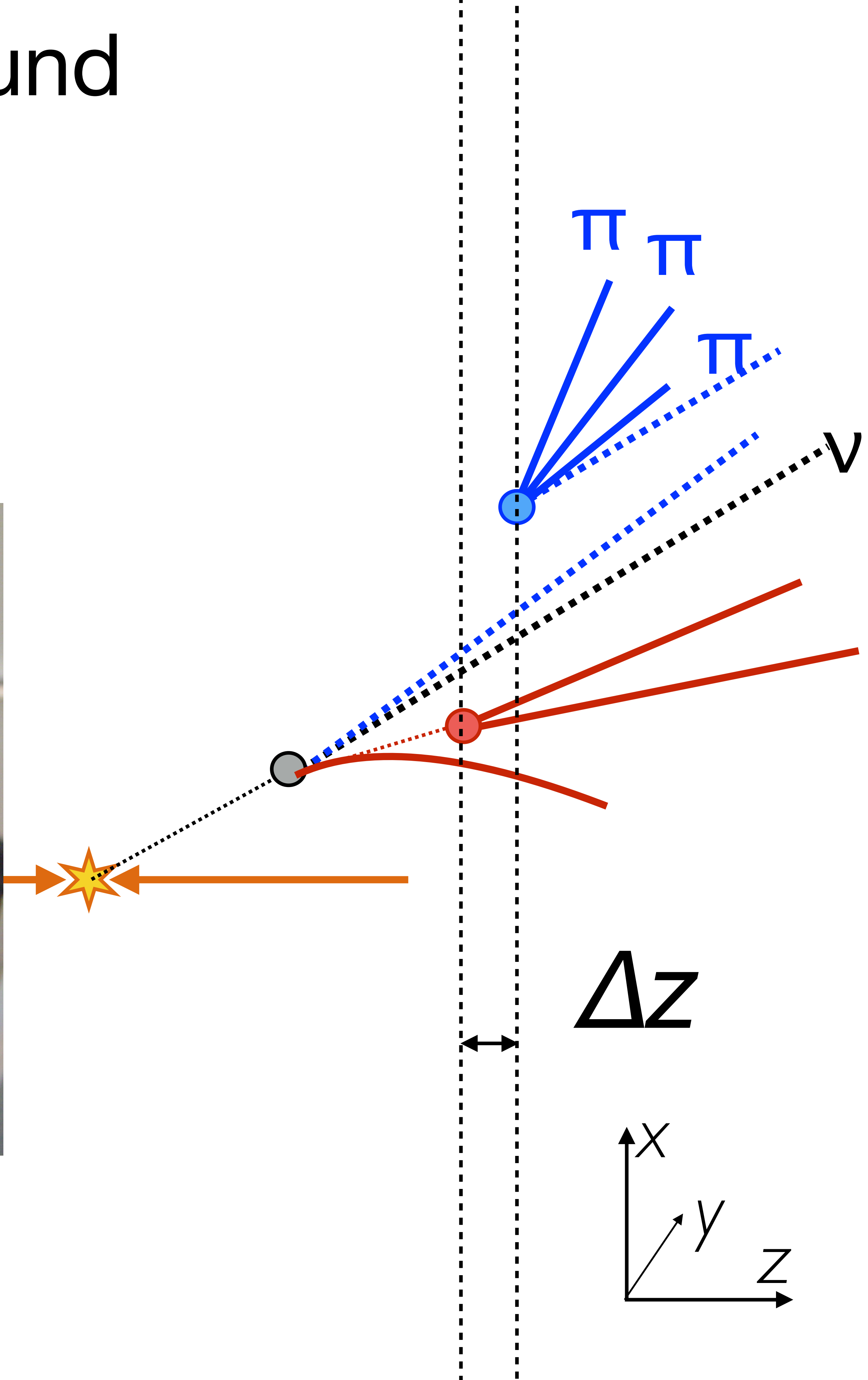




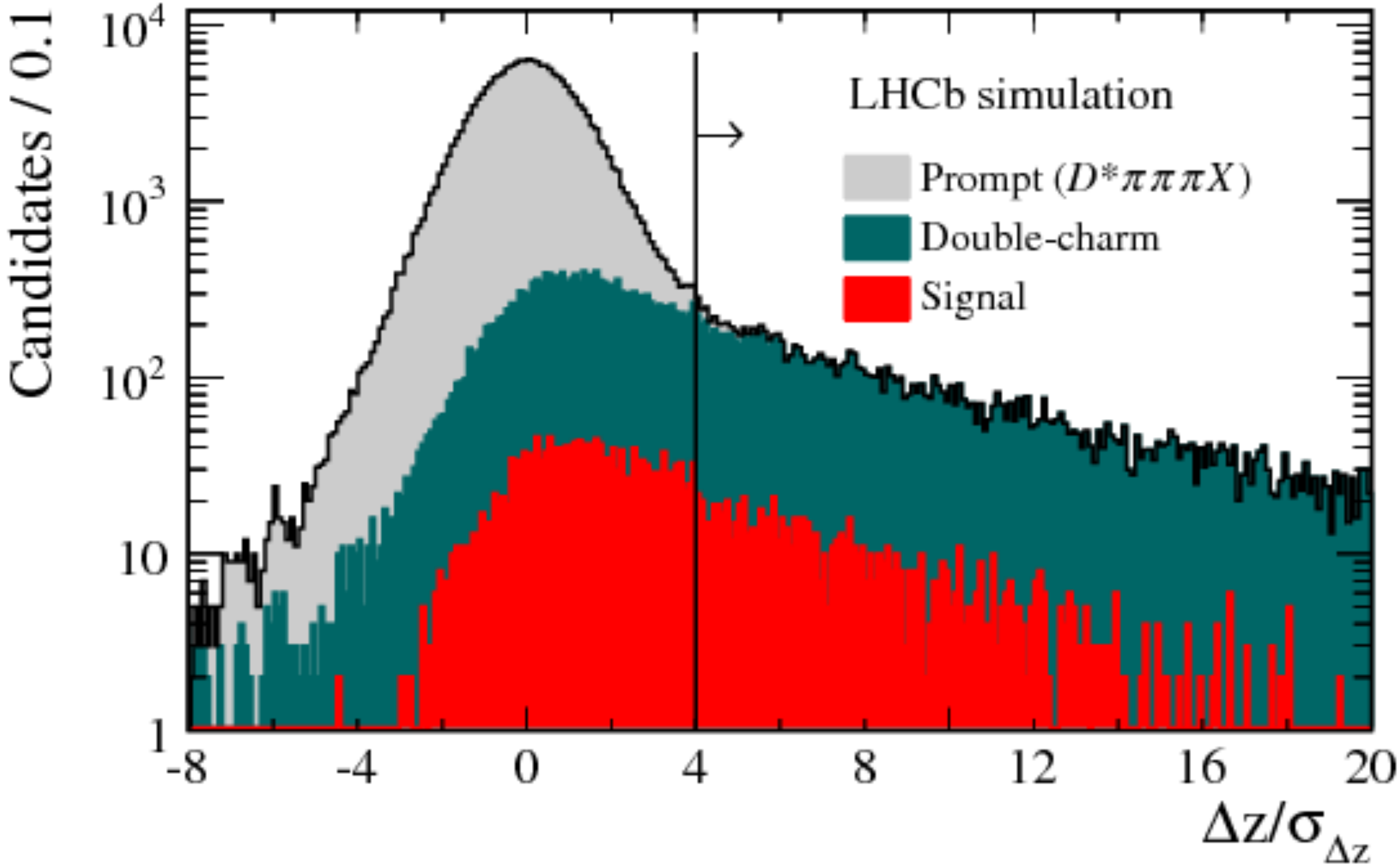
B/S ~ 10^2

The *prompt* background

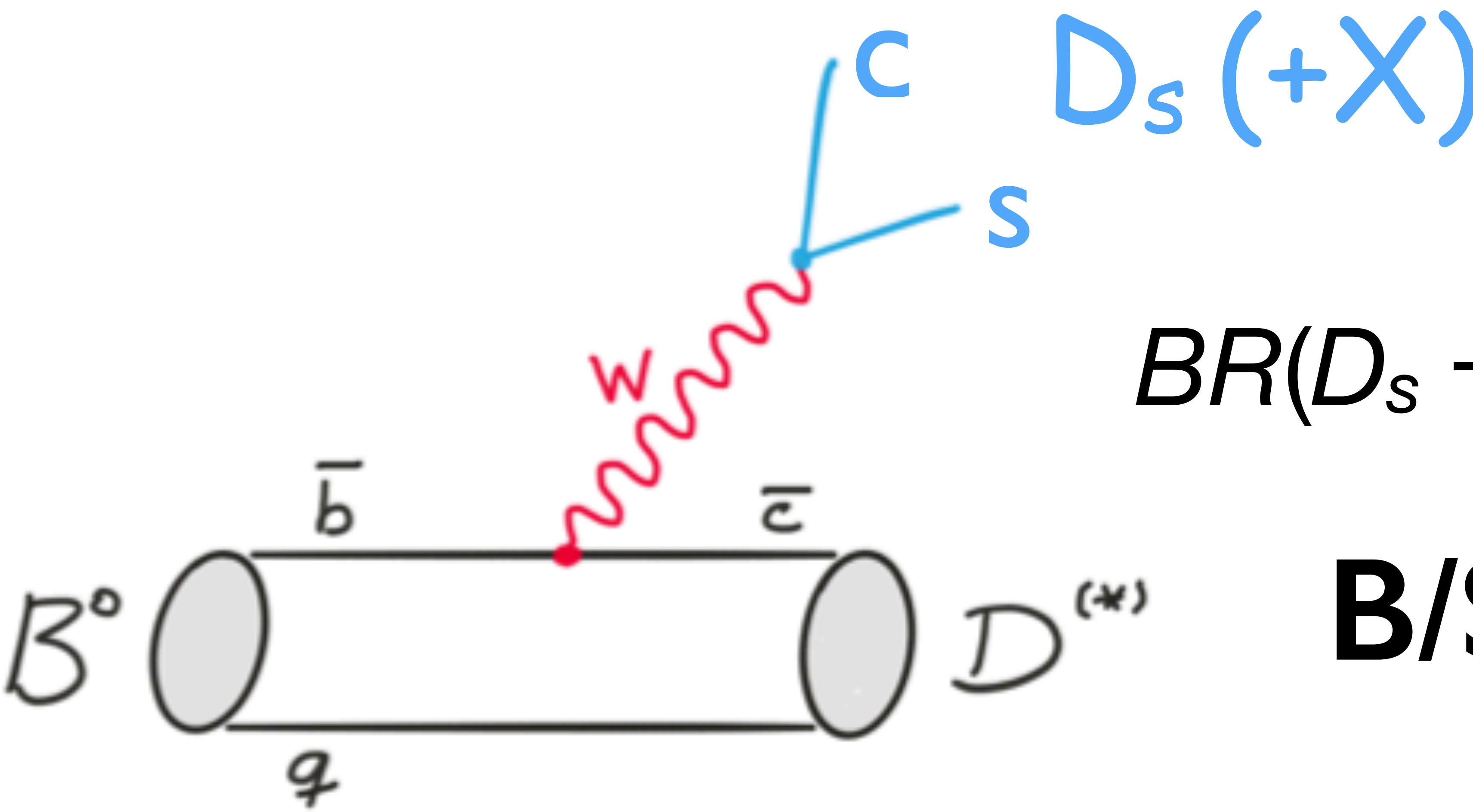




Detached vertex method



Double charm background



$BR(D_s \to 3\pi X)$ ~25%

B/S ~ 10

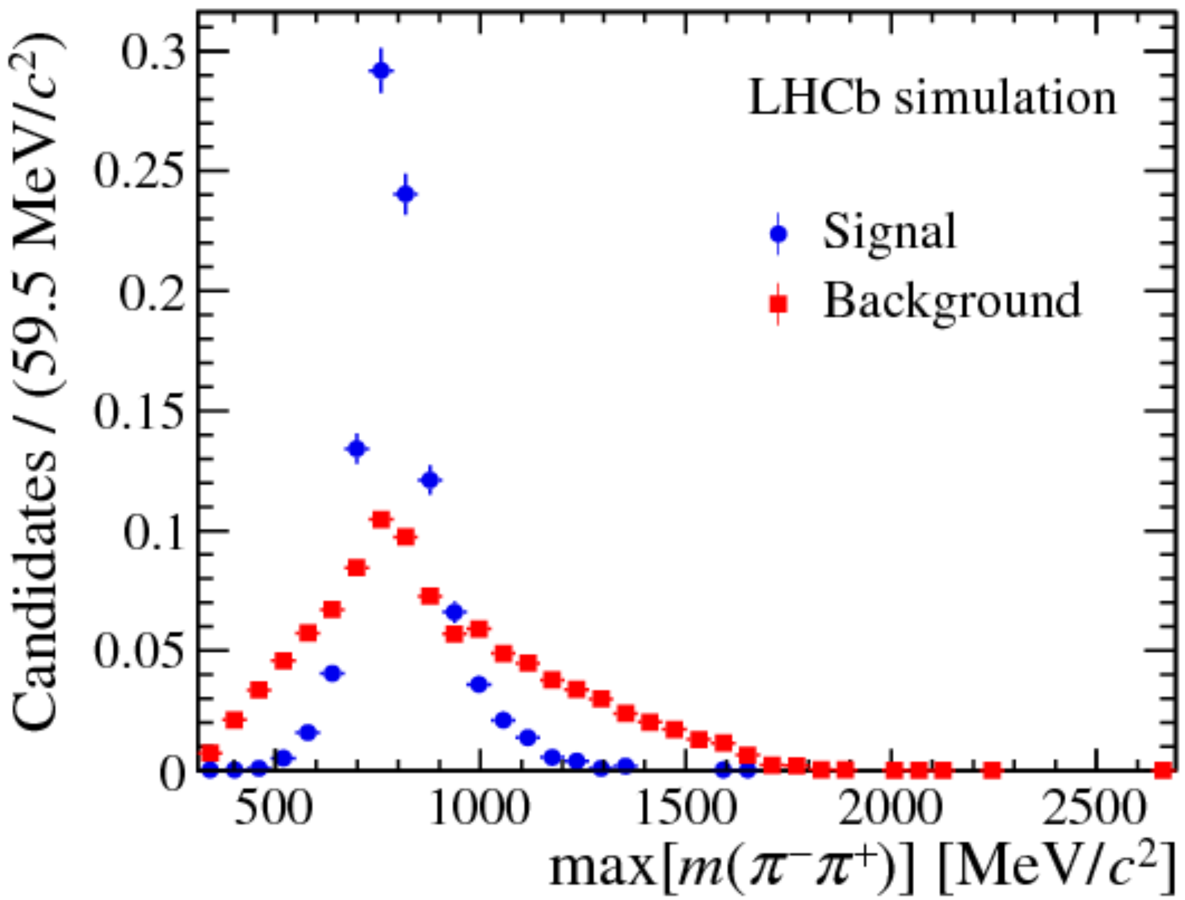
$D_s \to 3\pi X$ dominated by various modes with intermediate $\eta^{(\prime)}, \omega, \rho$, etc…

Some measured, some not…

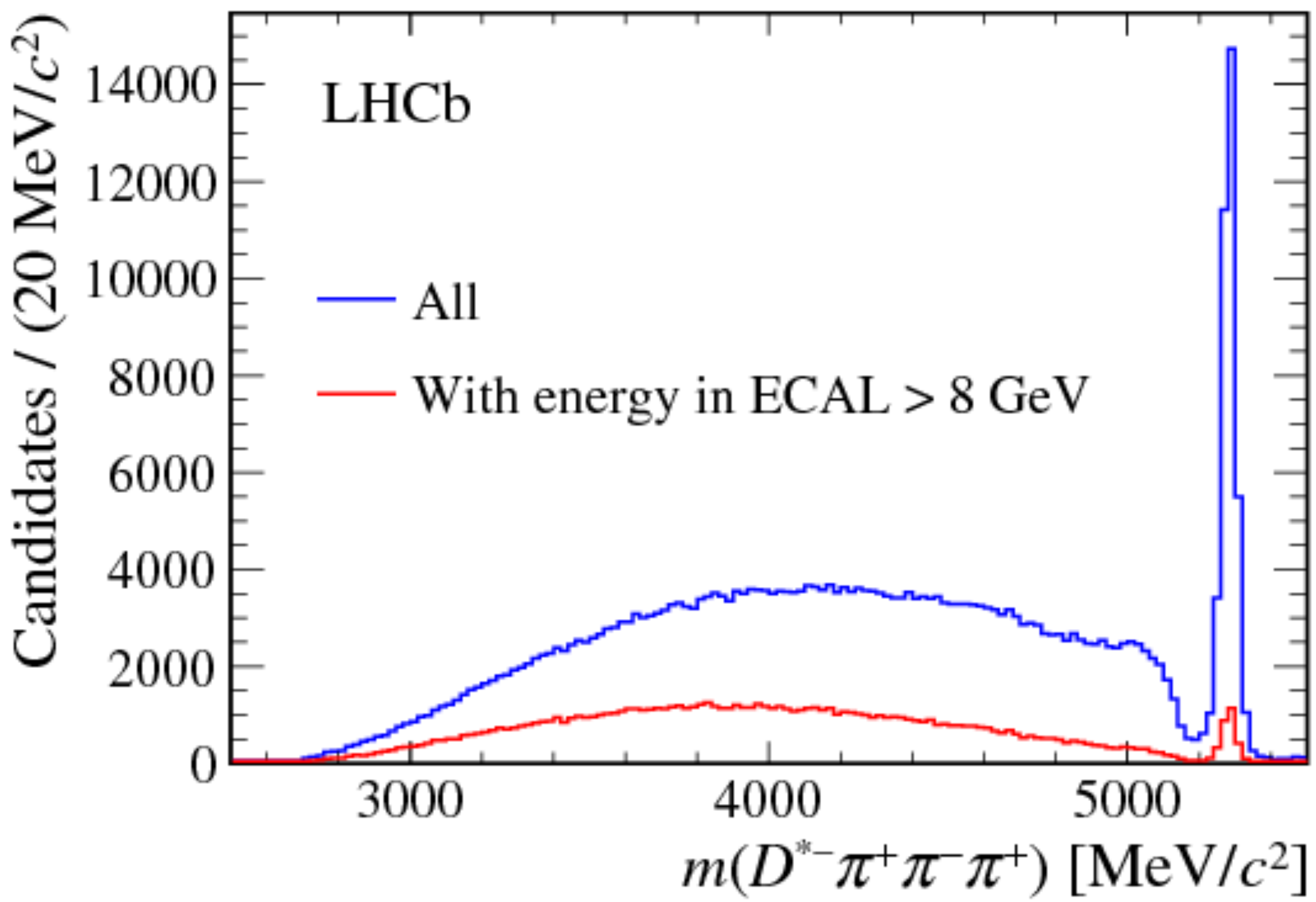
Also contributions with D^*D^+X, D^*D^0X…

The anti-double-charm BDT

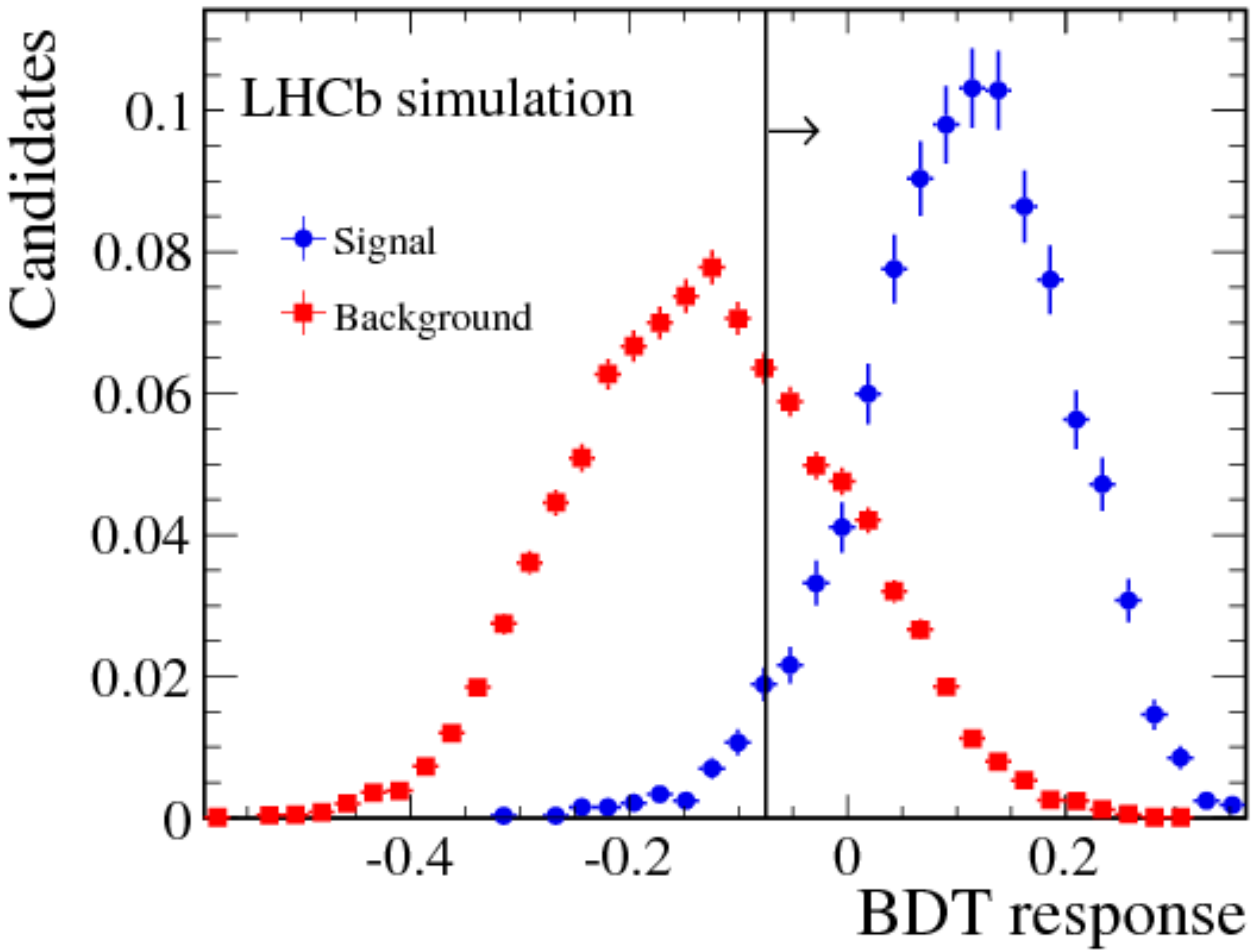
Kinematics, E.g.



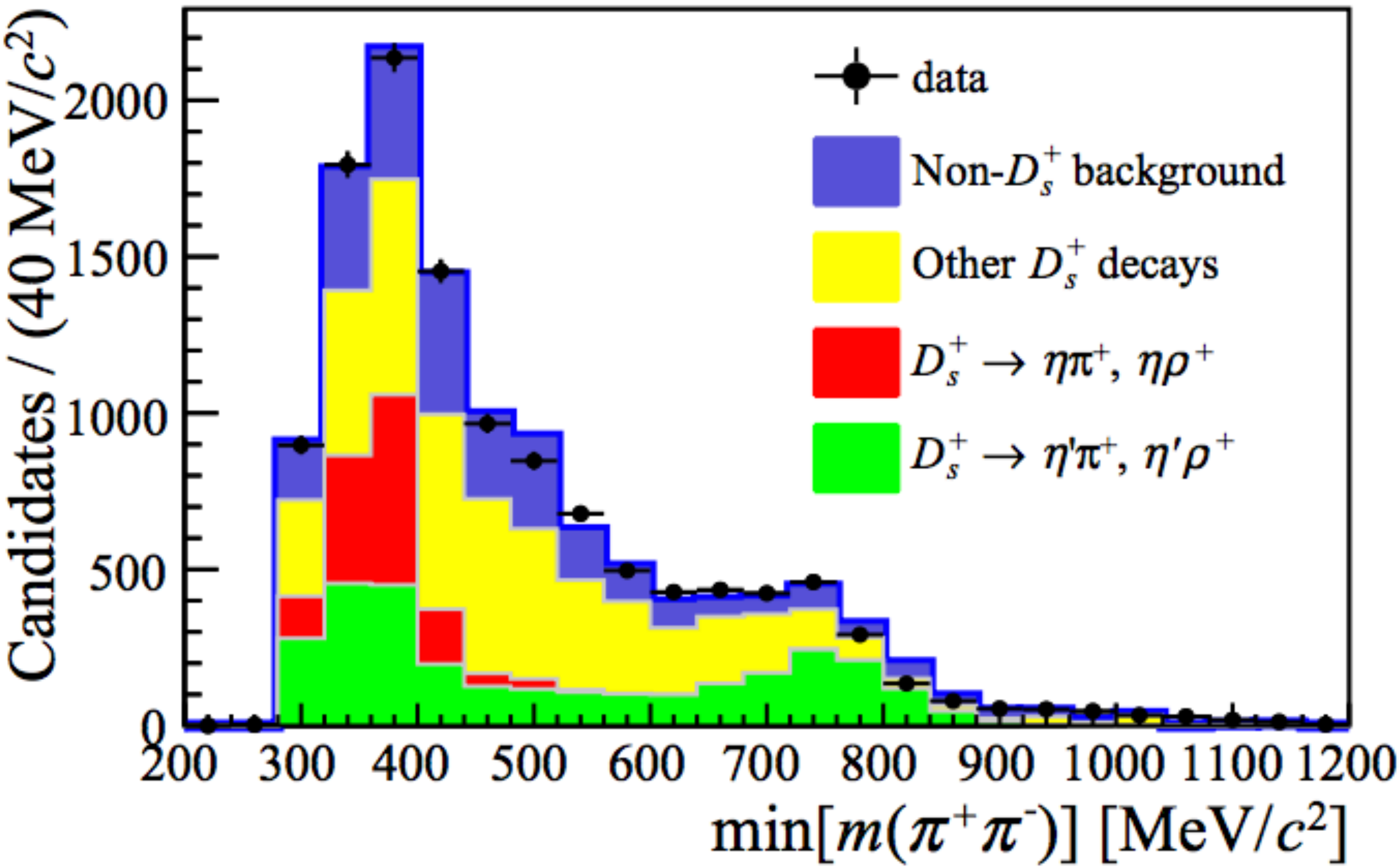
Neutral isolation



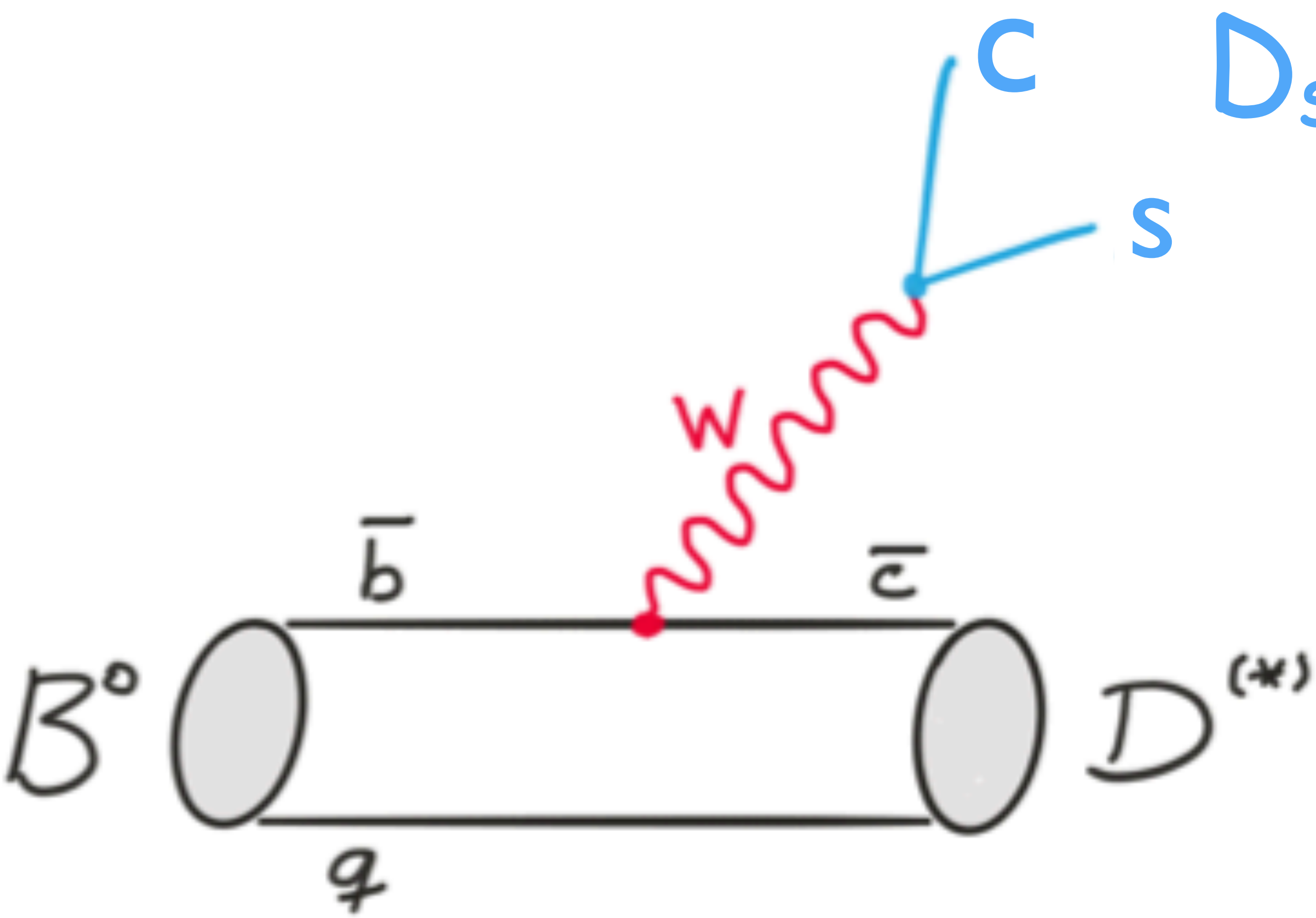
The anti-double-charm BDT



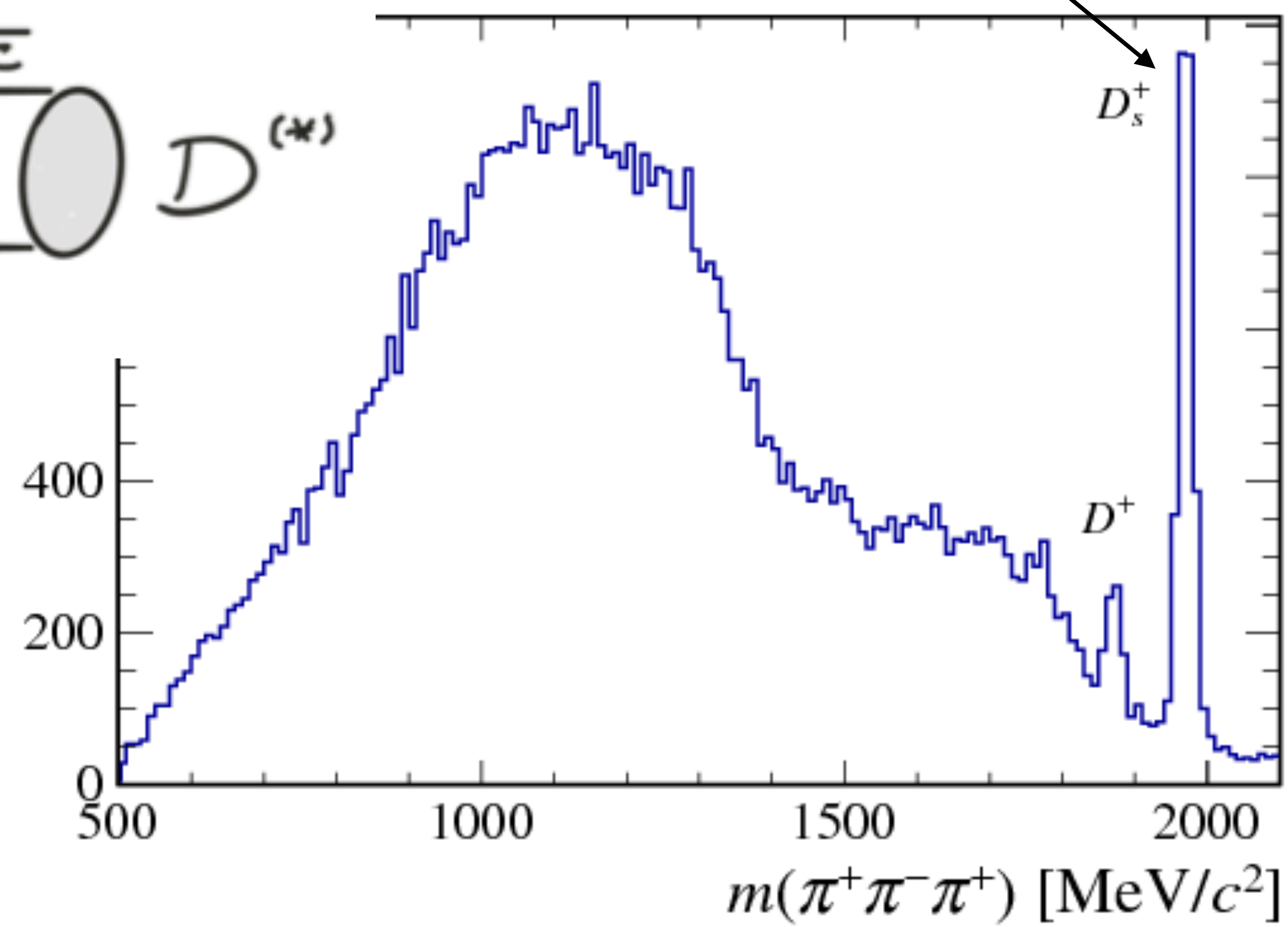
D_s enriched control region



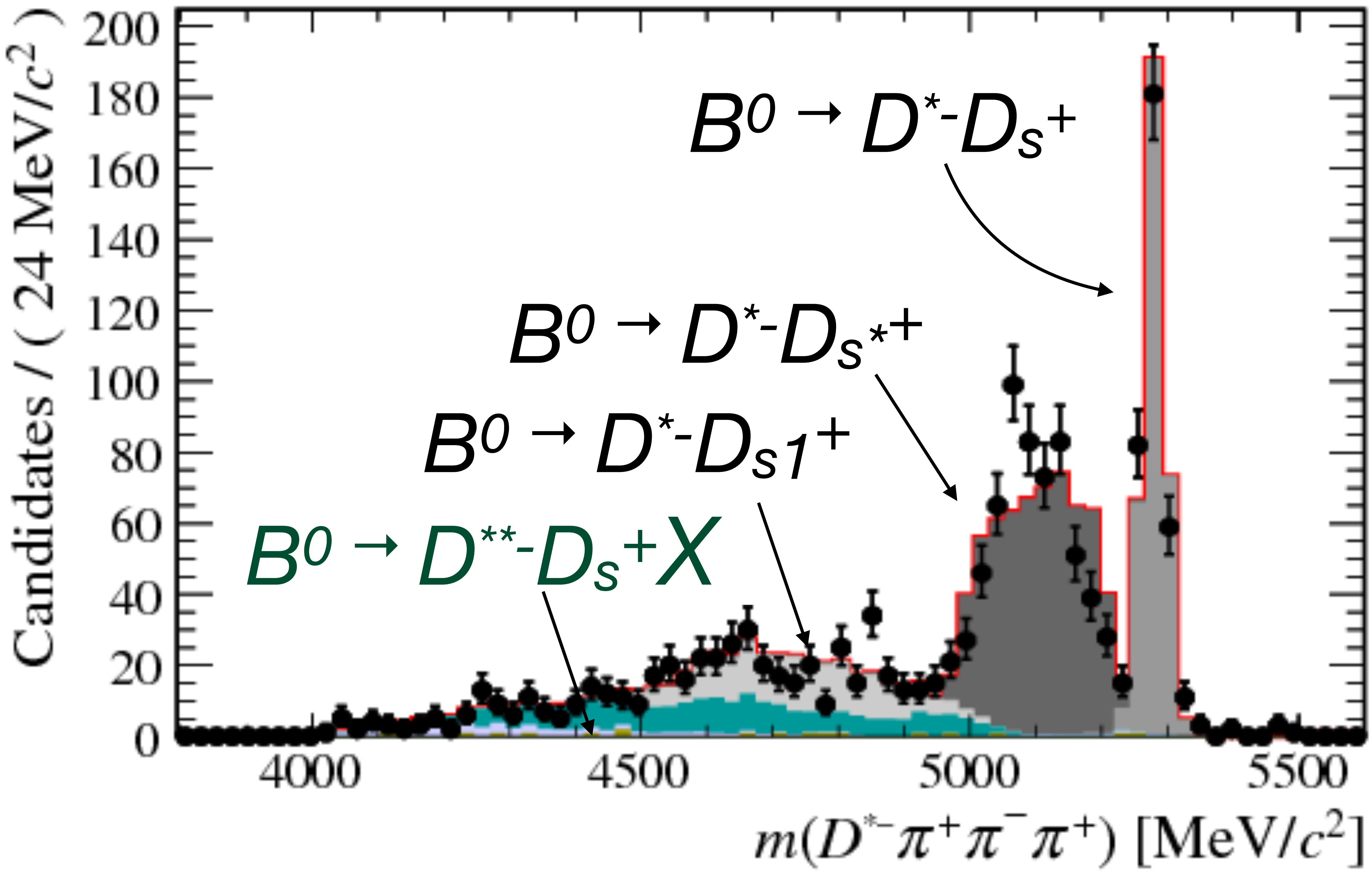
Controlling the double-charm



$D_s^+ \rightarrow \pi^+\pi^-\pi^+$



Controlling the double-charm



Normalisation

Actually measure
$$\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$$

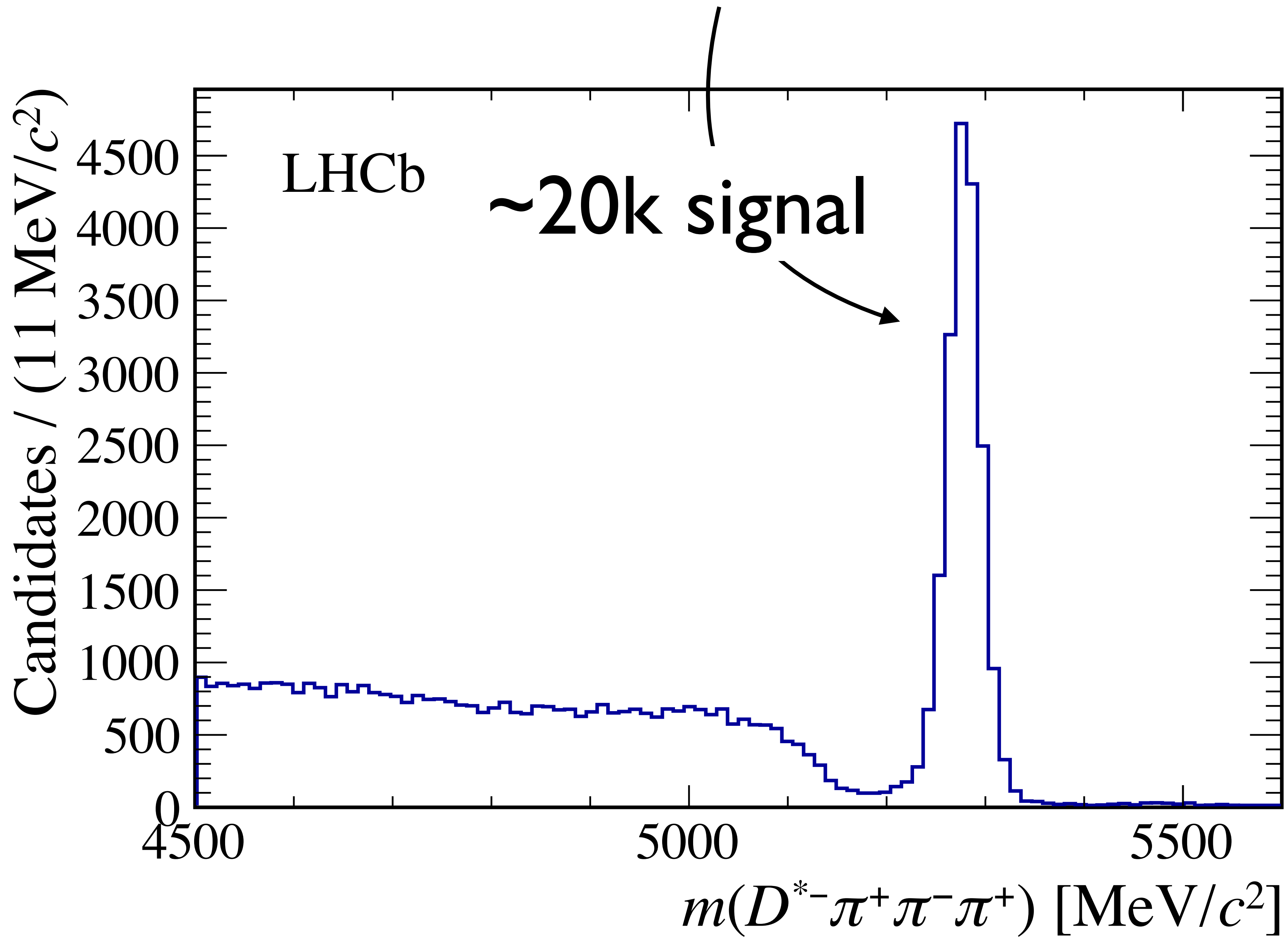
And use external measurements of $B(B \to D^* 3\pi)$ and $B(B \to D^* \mu\nu)$ to get $R(D^*)$.

Benefit from a new (2016) measurement of $B(B \to D^* 3\pi)$ from BaBar. PRD 94 (2016) 091101

$$B(B \to D^* 3\pi) = (0.726 \pm 0.011 \pm 0.031)\%$$

Normalisation

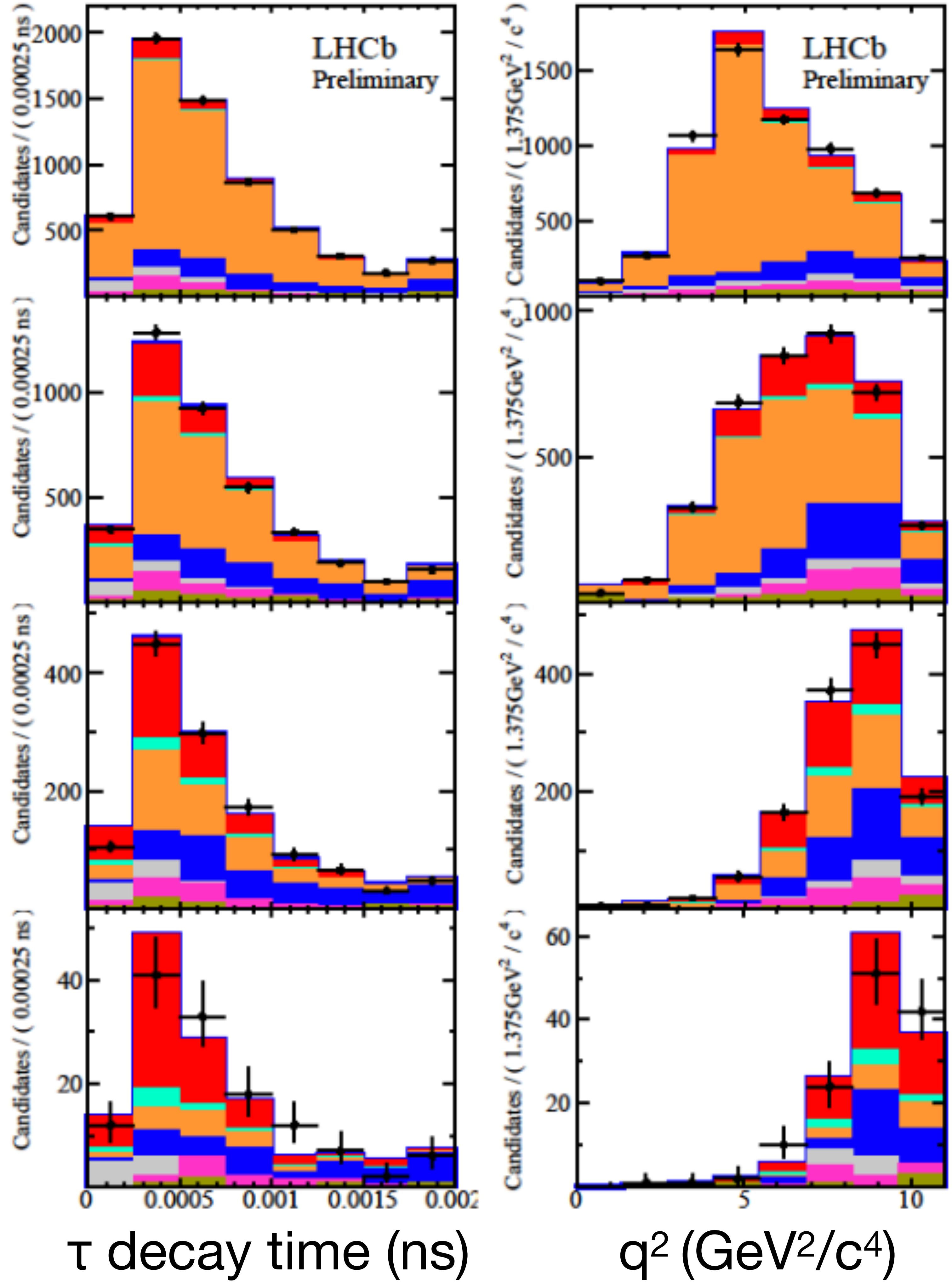
Actually measure $$\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$$



The signal fit

- $D^*\tau\nu$
- $D^{**}\tau\nu$
- D^*D_sX
- D^*D^+X
- $D^*3\pi X$
- D^*D^0X
- comb. bkg

Higher BDT score



The result

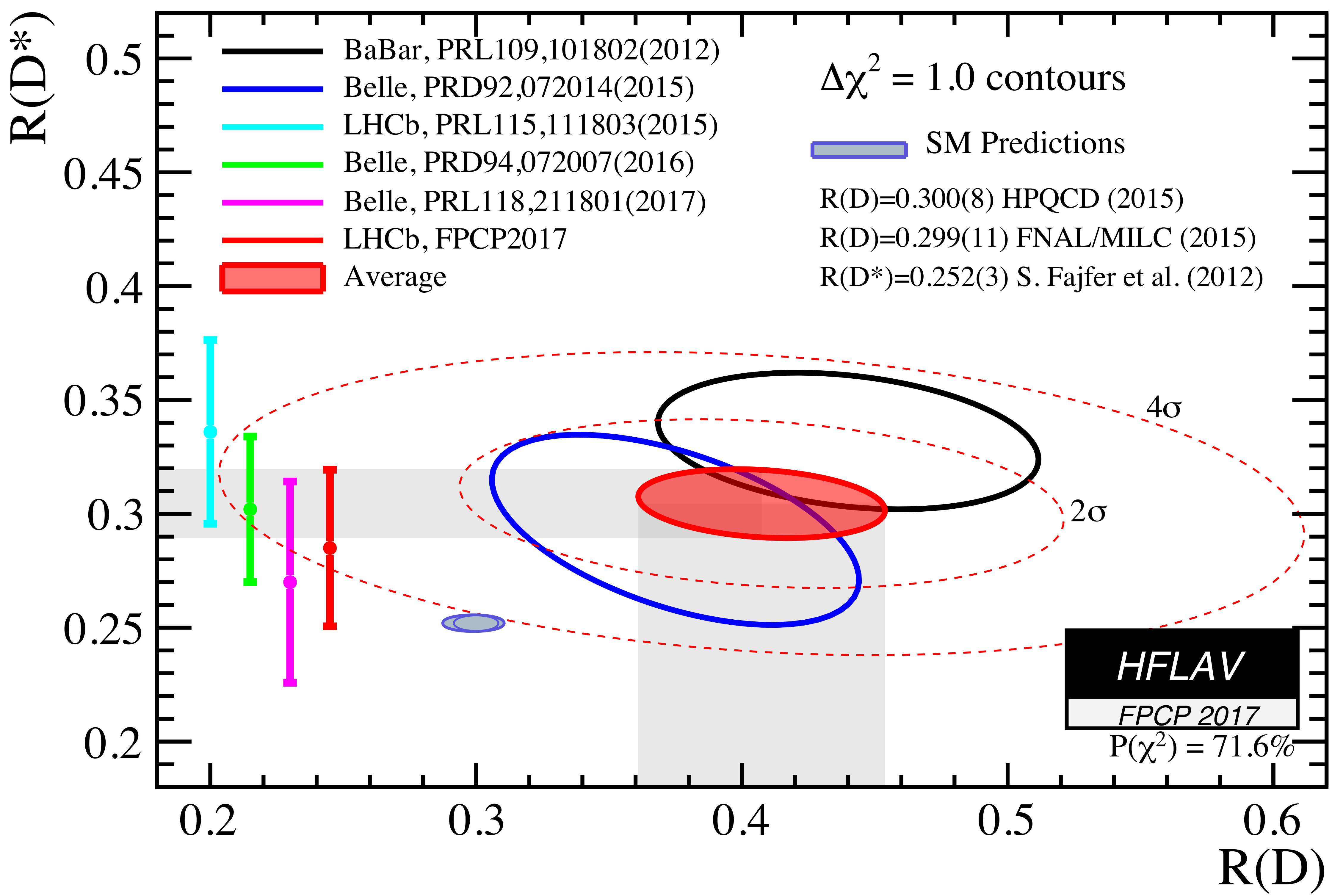
$$B(D^{*}\tau\nu)/B(3D^{*}\pi) = 1.93 \pm 0.13_{stat} \pm 0.17_{syst}$$

$$R(D^{*}) = 0.285 \pm 0.019_{stat} \pm 0.025_{syst} \pm 0.014_{ext}$$

Consistent with the SM and with the previous results

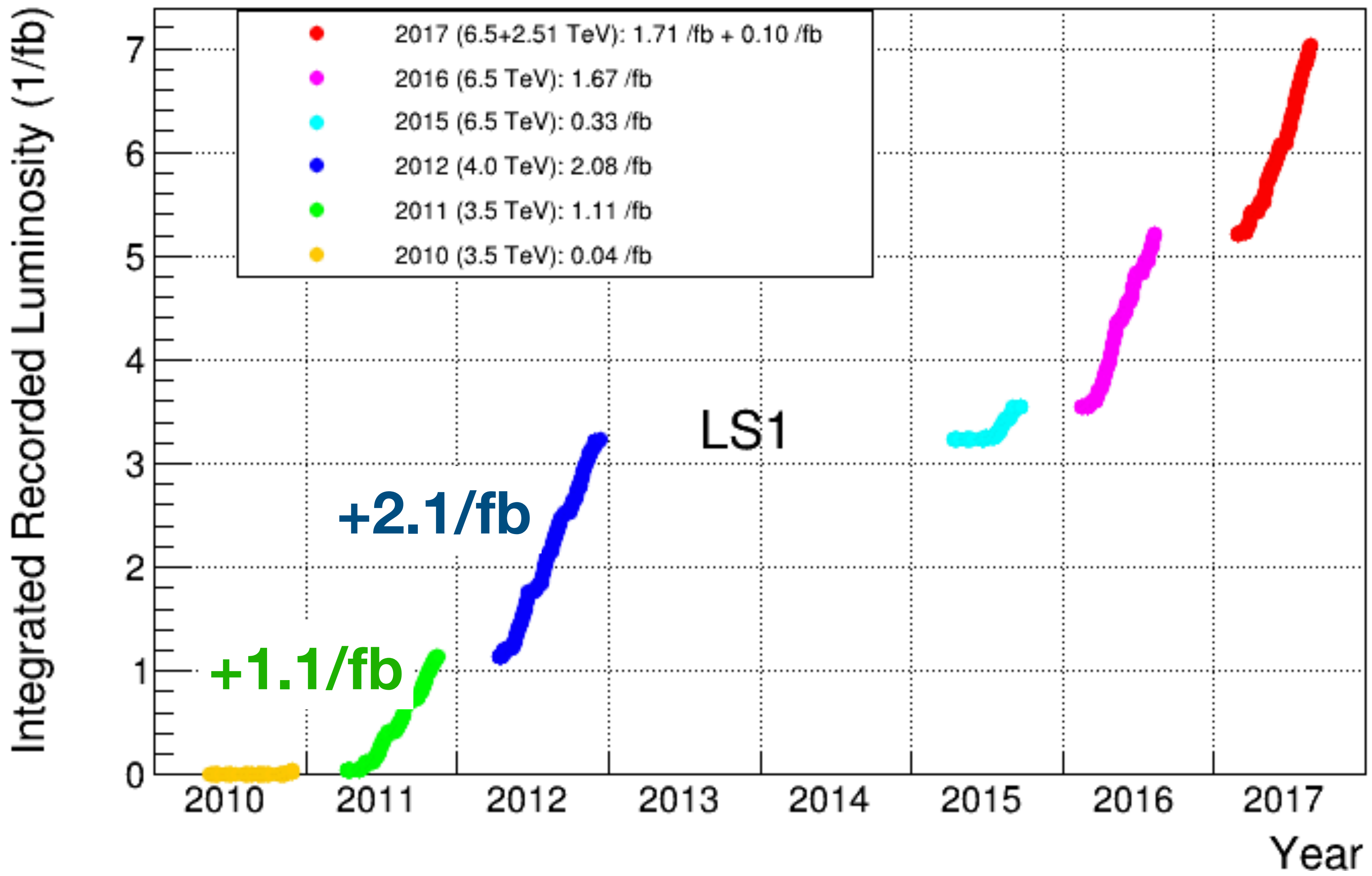
Contribution	Value %
Simulated sample size	4.7
Signal modeling	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feed-downs	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^*3\pi X$ background	2.8
Empty bins in templates	1.3
Efficiency ratio	3.9
Total internal uncertainty	8.9
$\mathcal{B}(B^0 \to D^*3\pi)$ and $\mathcal{B}(B^0 \to D^*\mu\nu_\mu)$	4.8

The state-of-the-art



The tension is now at the level of 4.1σ

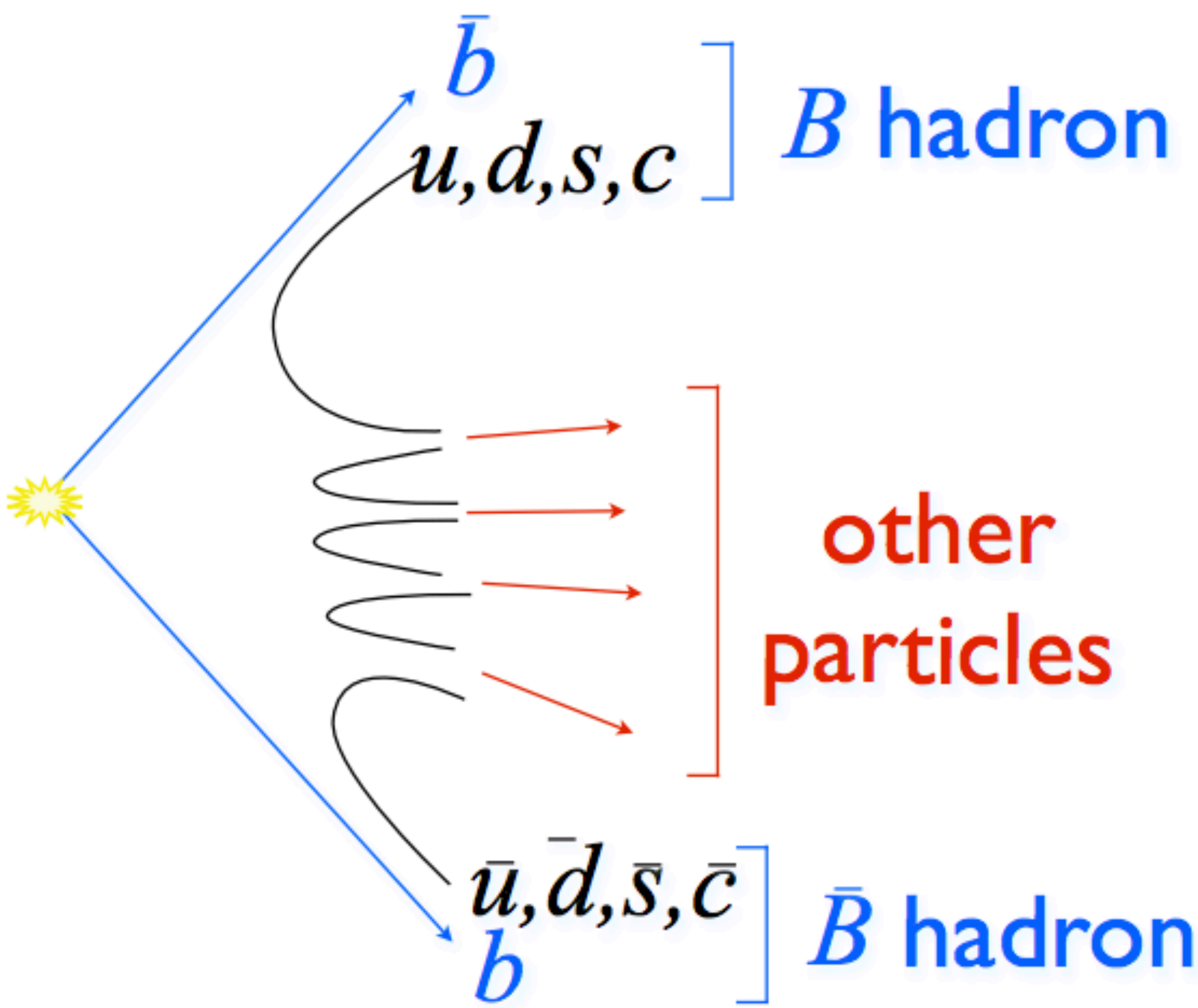
LHCb in the near future



Further 2 fb^{-1} is anticipated in 2018.

Given higher cross sections, and trigger improvements, Run-II typically represents a 4-5x increase over Run-I!

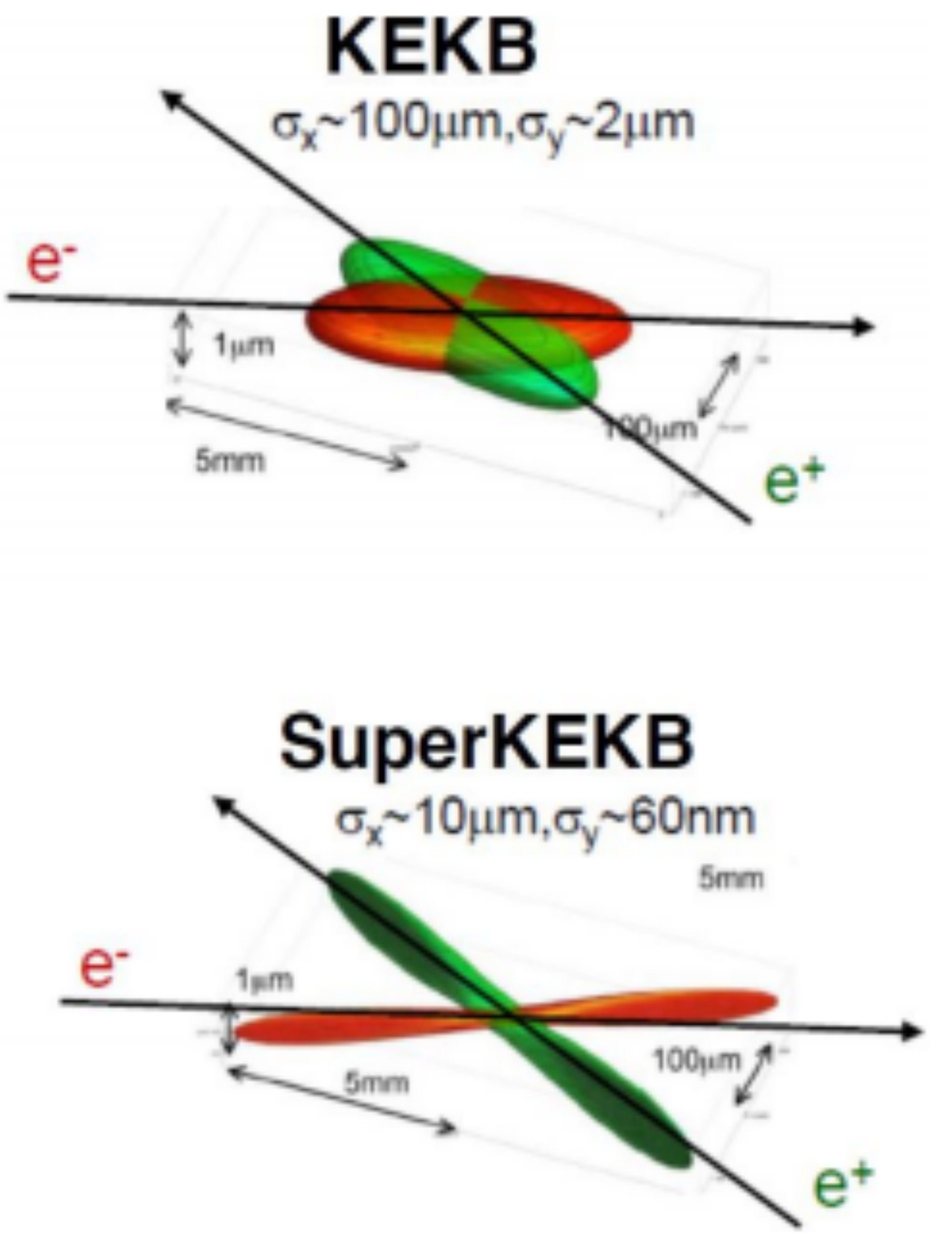
LHCb in the near future

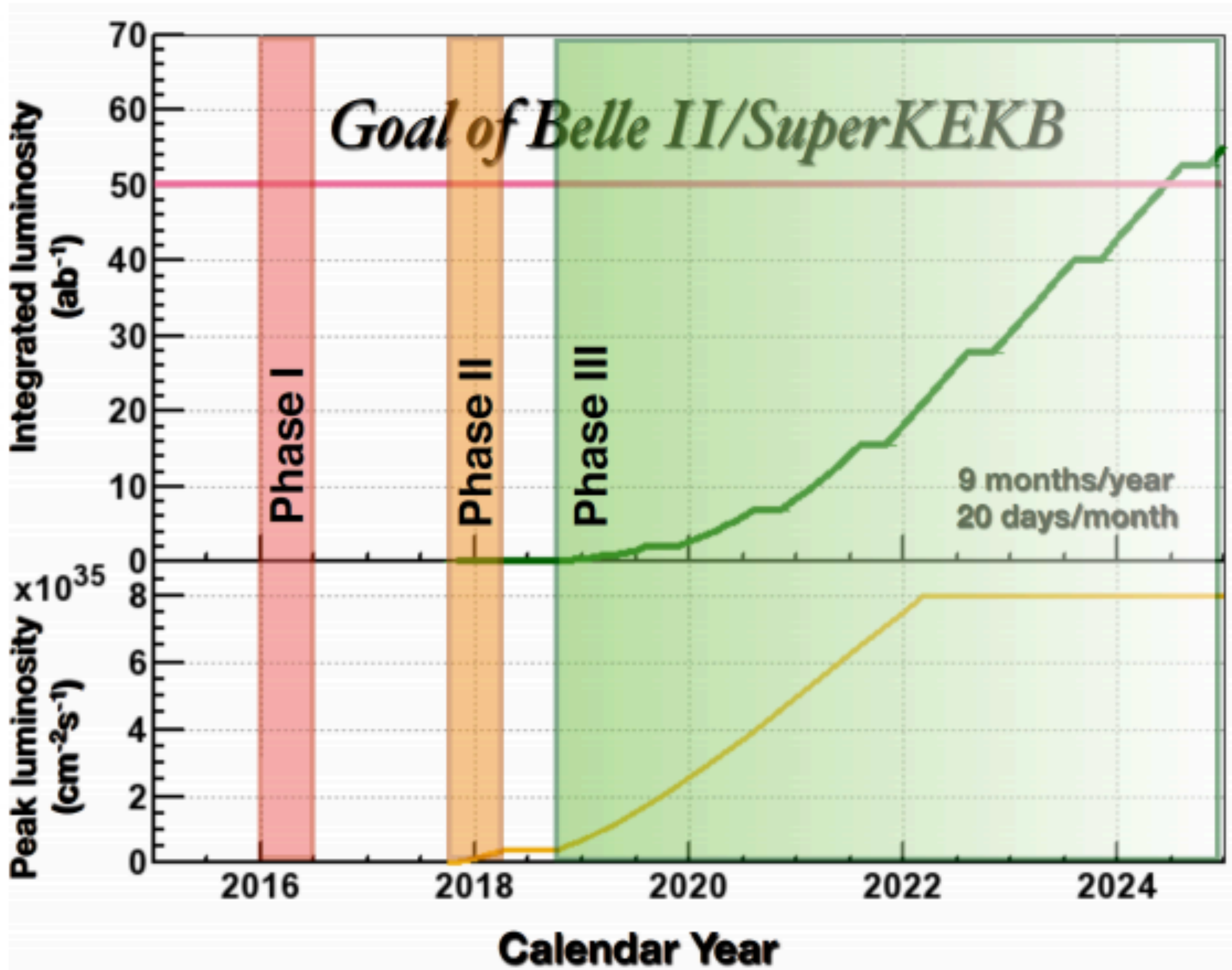


$R_{\tau\mu}$ measurements in progress with

b→c	**b→u**
$B \to D^{*+}\tau\nu$	$\Lambda_b \to p\tau\nu$
$B \to D^{+,0}\tau\nu$	$B \to pp\tau\nu$
$B_s \to D_s\tau\nu$	etc..
$\Lambda_b \to \Lambda^{(*)}_c\tau\nu$	
$B_c \to J/\psi\tau\nu$	
etc…	

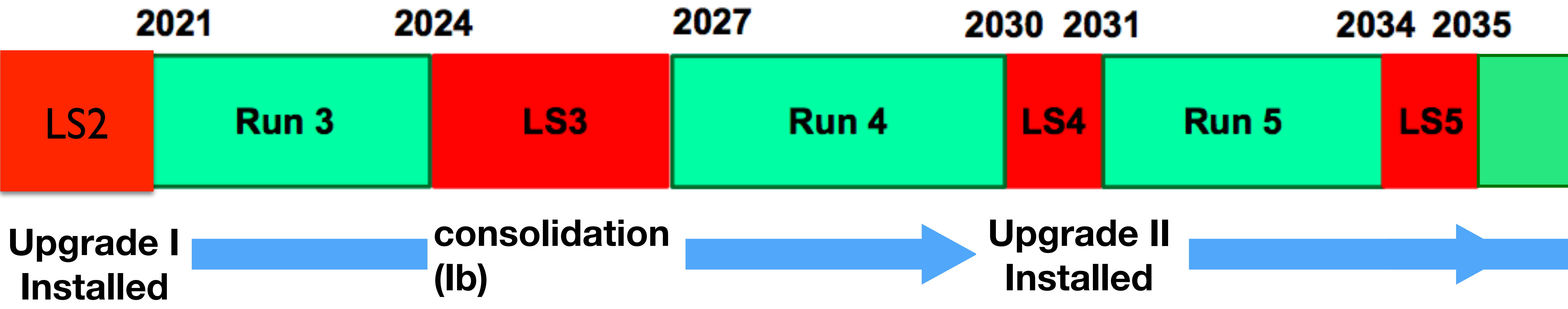
SuperKEKB and Belle II





Aim to record ~50x Belle dataset by 2025!

LHCb upgrades



- Upgrade I (**50 fb**$^{-1}$)

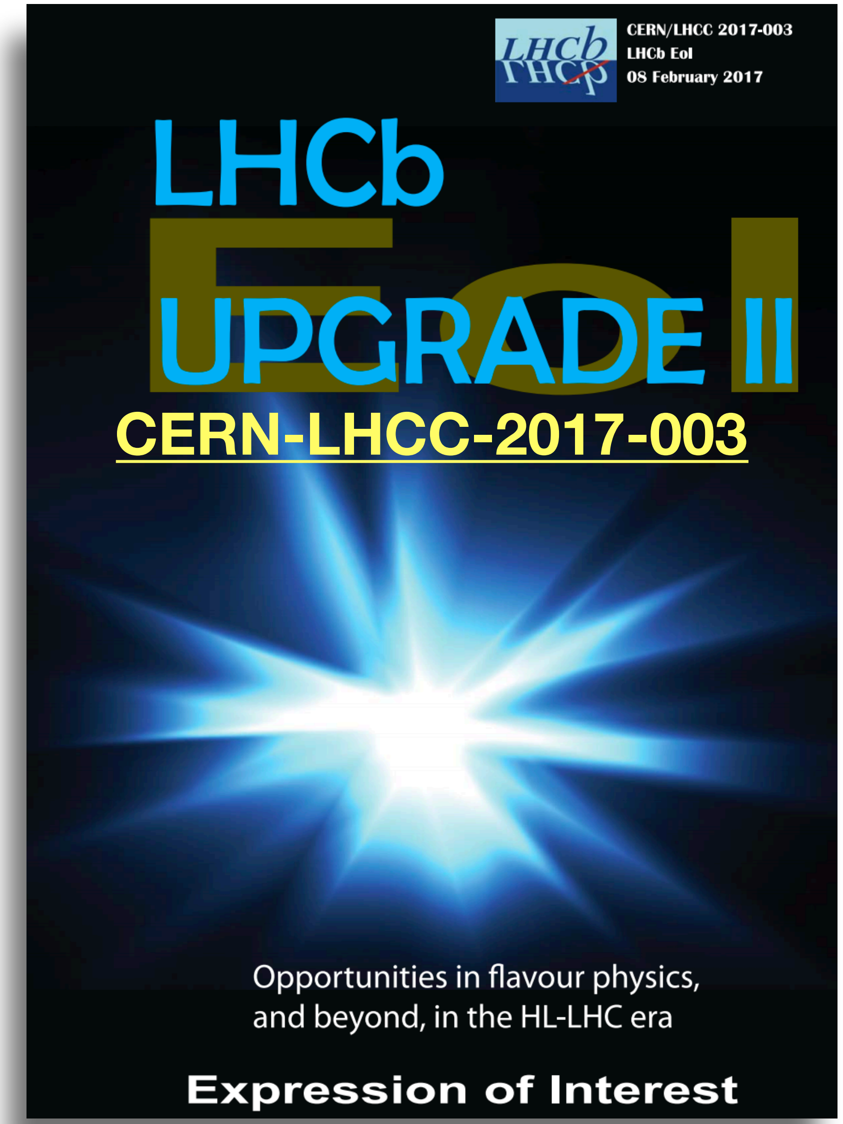
  Full software trigger

  (5x) increase in luminosity to $2\text{x}10^{33}$ $\text{cm}^{-2}\text{s}^{-1}$.

- Upgrade II (**300+ fb**$^{-1}$)

  Increase luminosity to 1—2 x 10^{34} $\text{cm}^{-2}\text{s}^{-1}$.

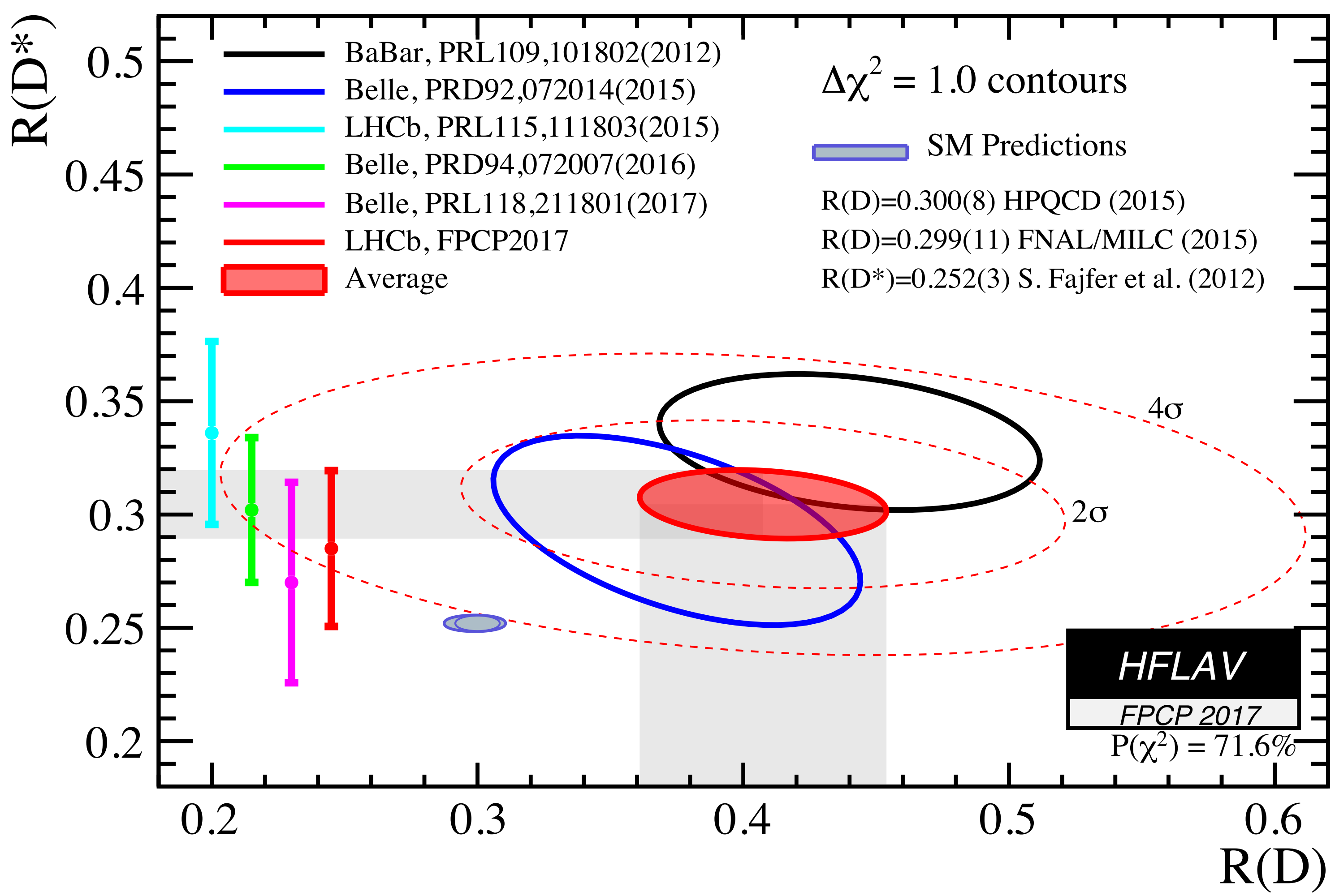
  Fast-timing, higher granularity and rad-hardness.

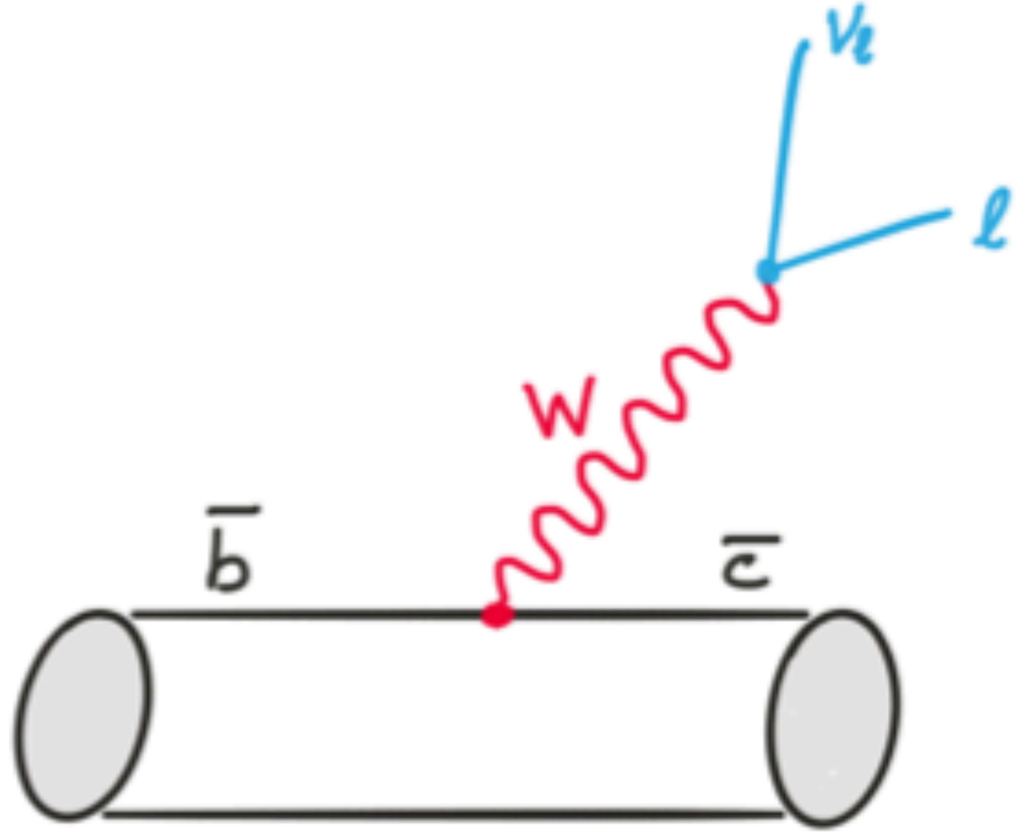


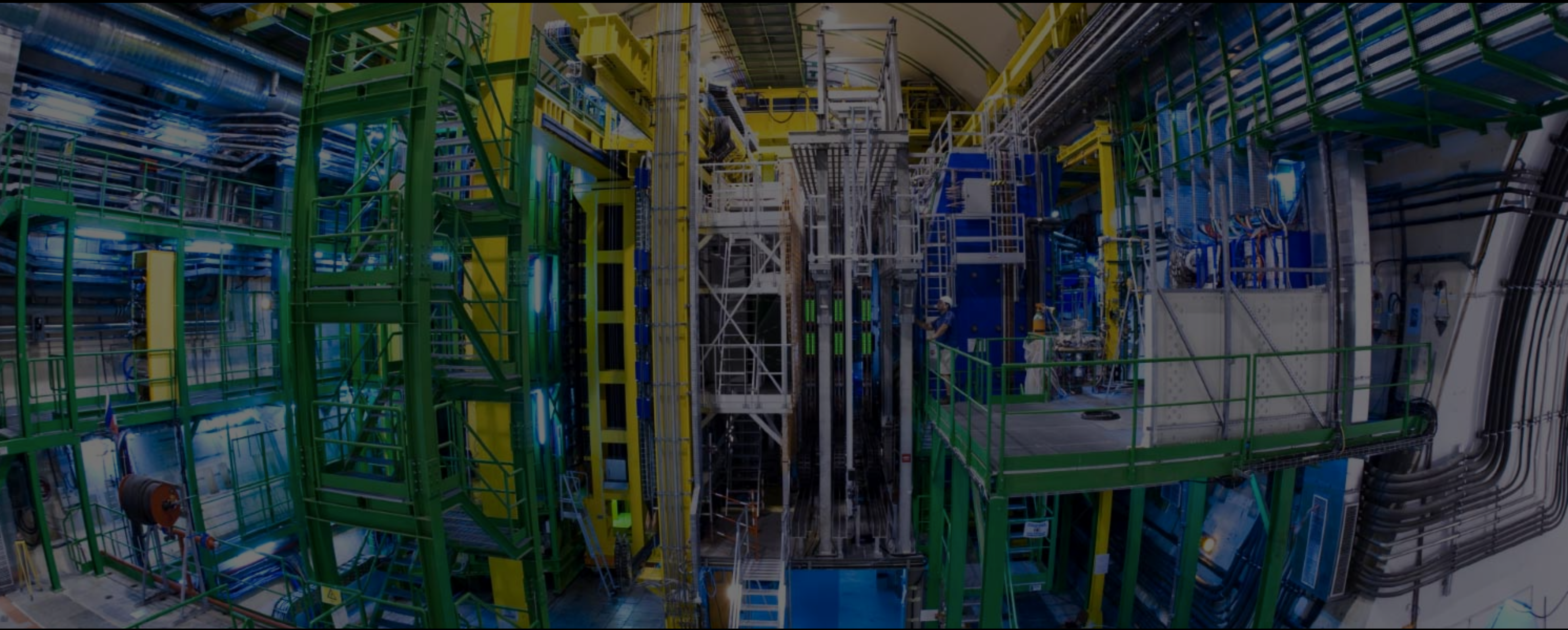
Summary

Do we see breaking of lepton universality in b decays?

Too early to claim any discovery, but exciting prospects from LHCb and Belle II!





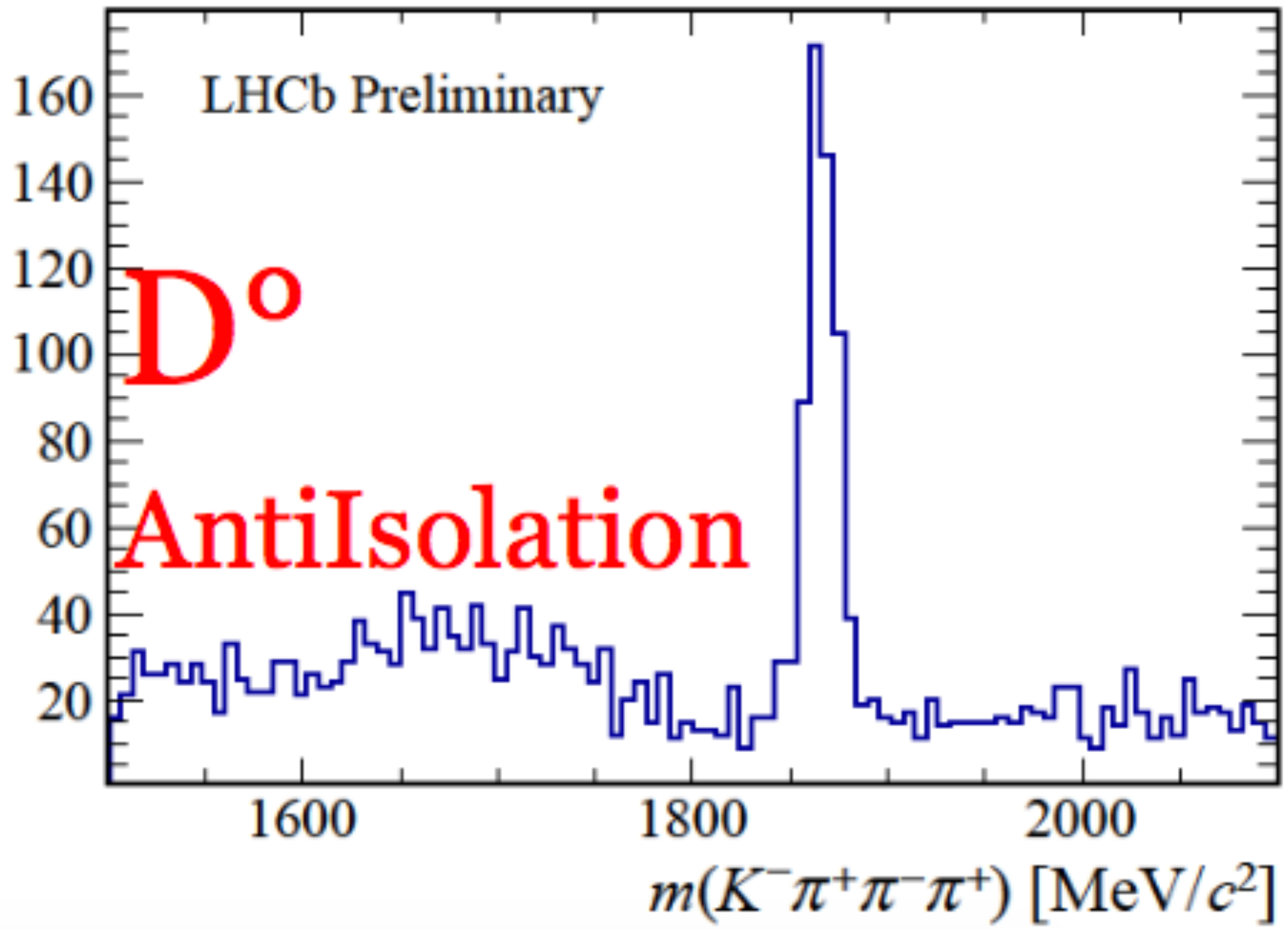


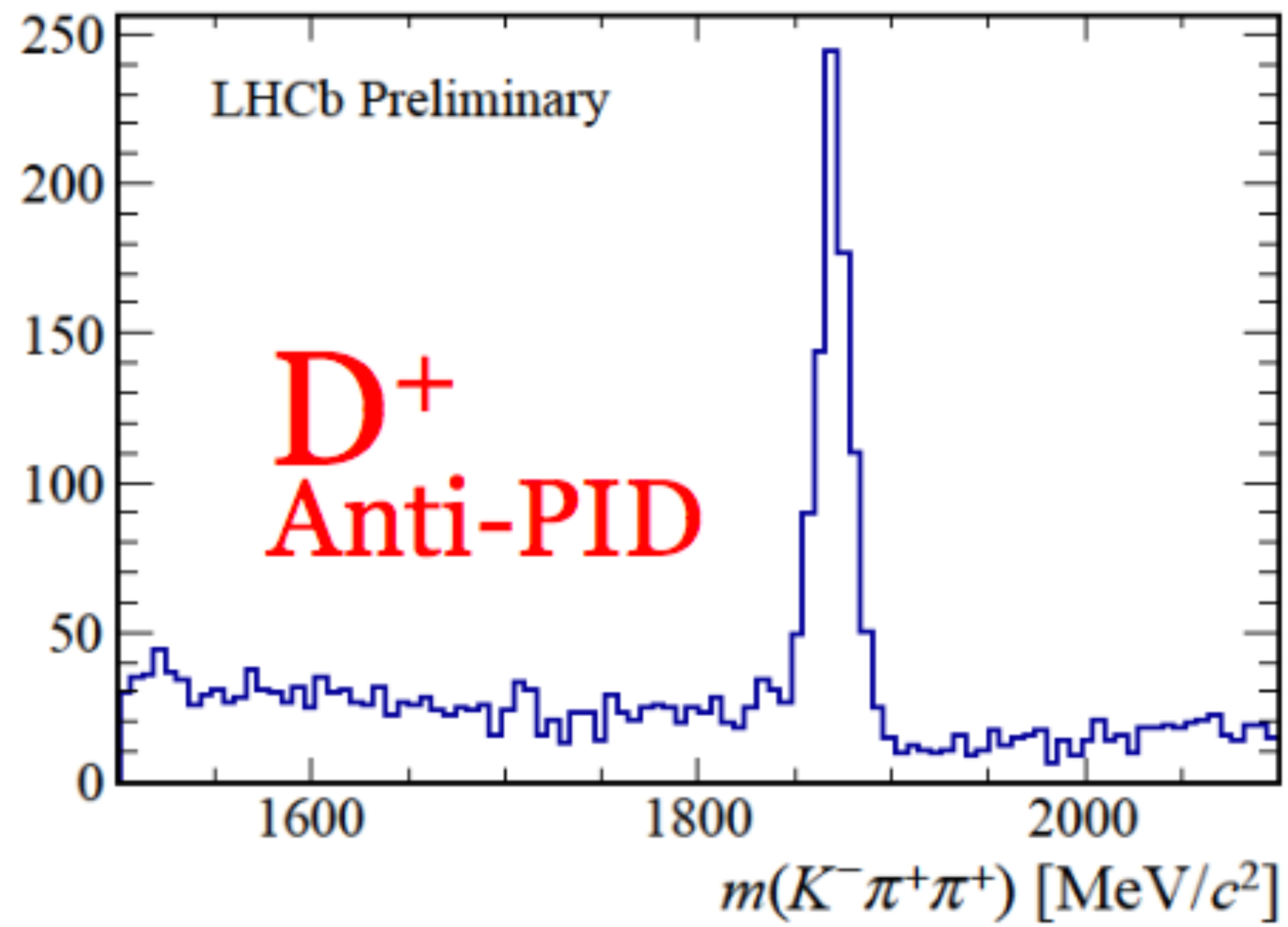
Backup slides start here

$R(D^*)$ muonic systematics

Source	$\sim\delta R_D/R_D$
Template stats	6%
Background muon mis-ID	5%
Form factors	3%
Relative efficiency	3%
Background (DD_s)	1.5%
Background (combinatoric)	1%
Total	9%

Other double-charm

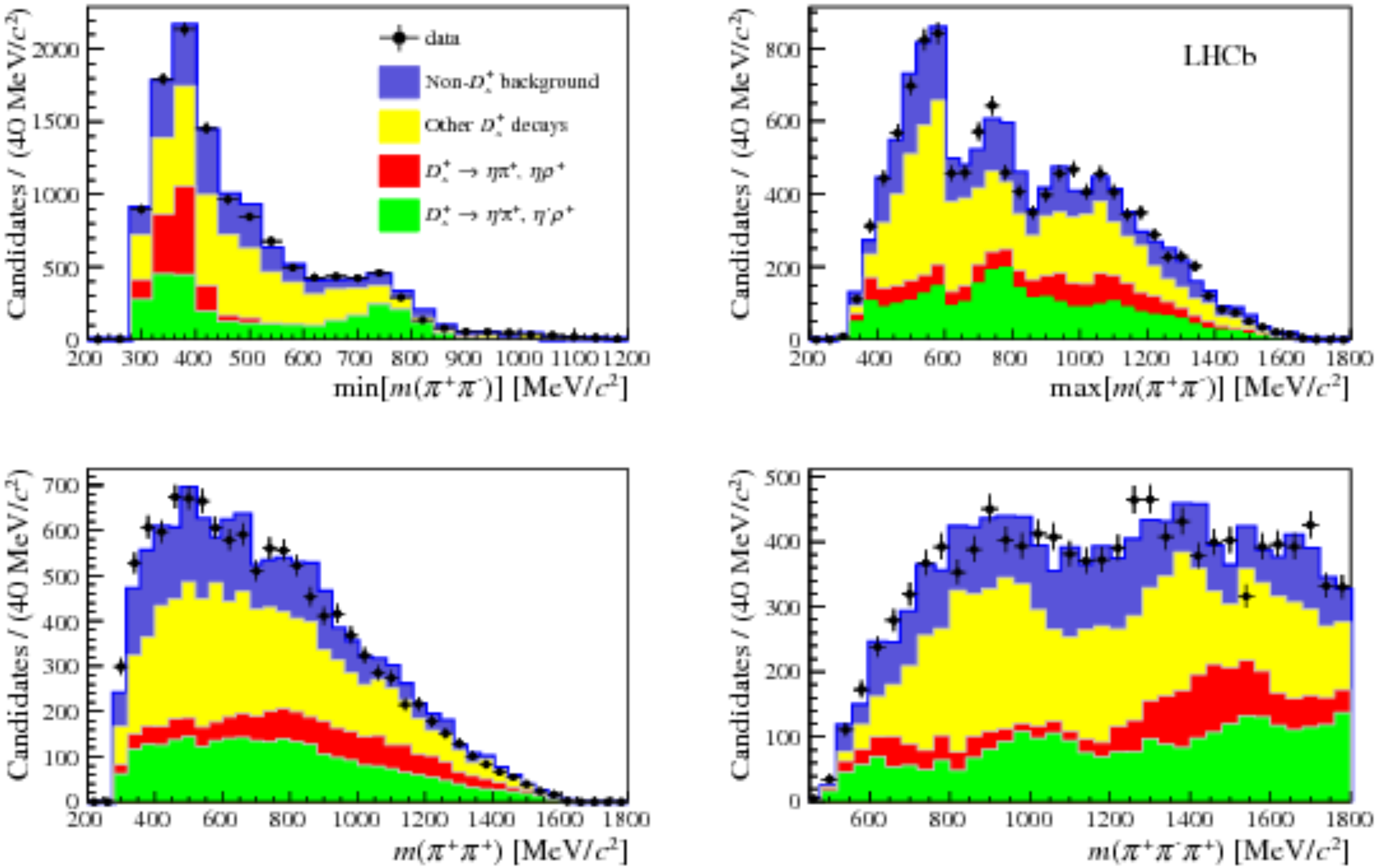


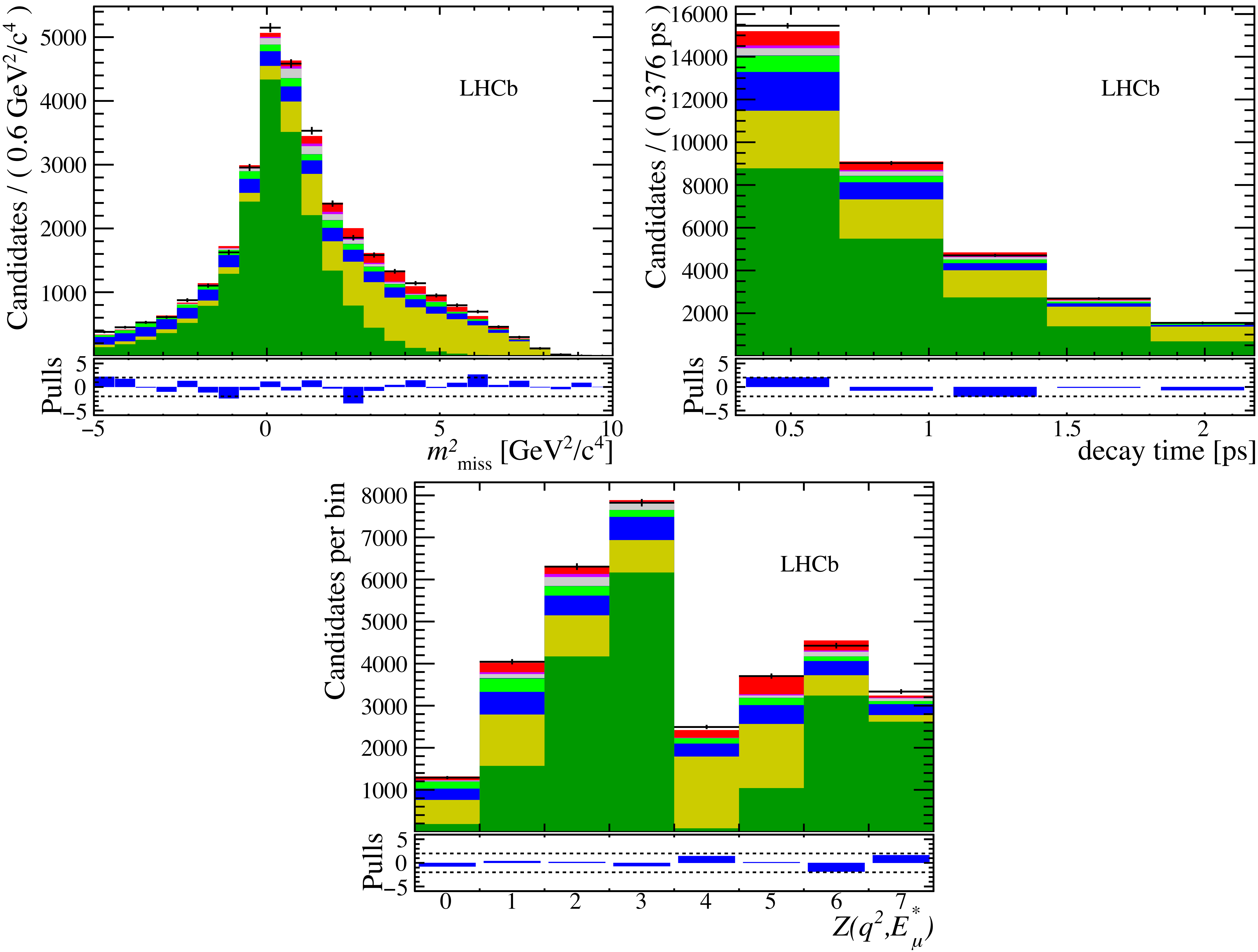


$D^0 \rightarrow 3\pi X$ rate constrained w.r.t. Clean $D^0 \rightarrow K3\pi$ which has well known BR.

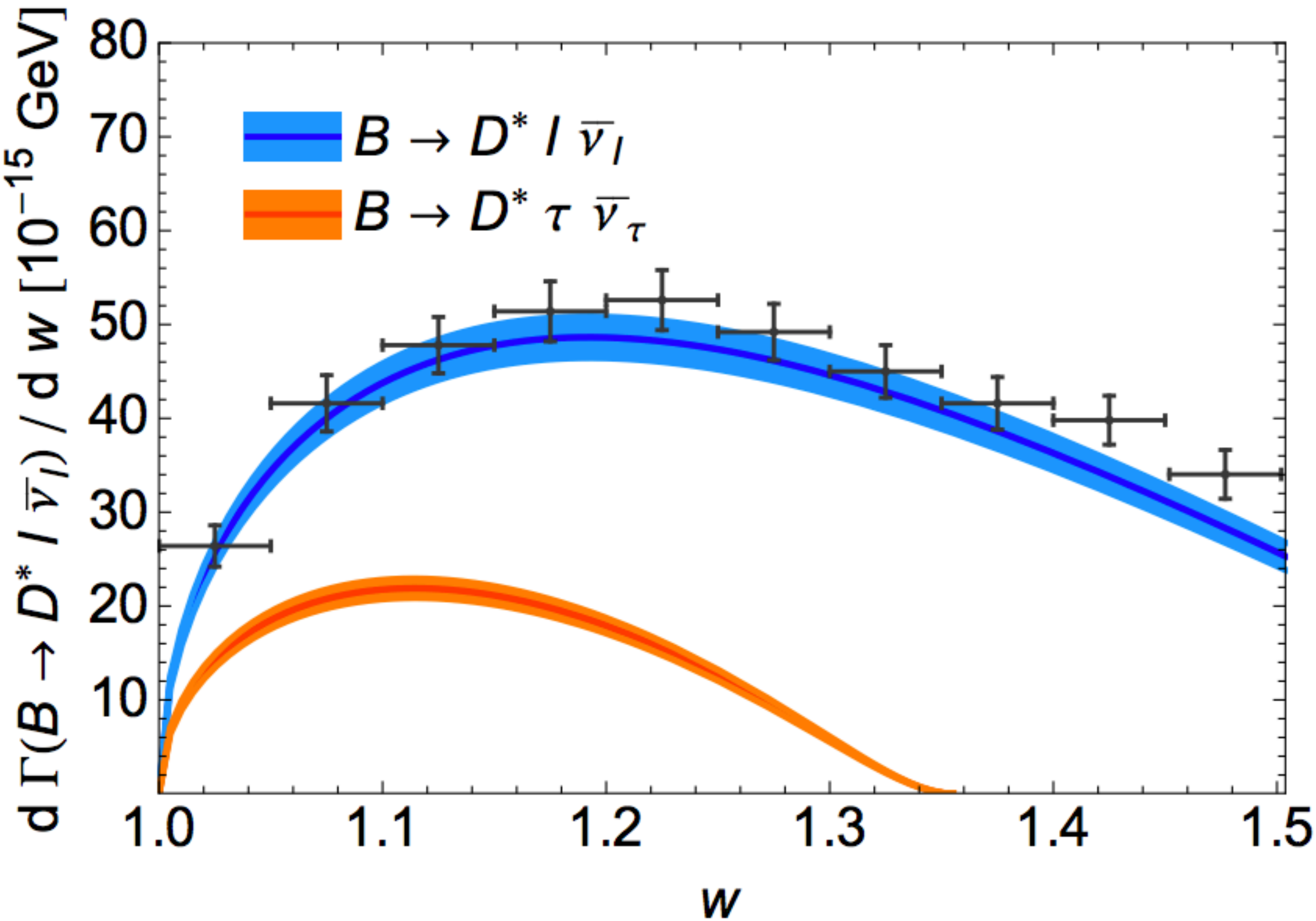
Can't apply same approach to D^+ since relevant BRs aren't well known. More freedom in our final fit.

D_s enriched region





LHCb
Candidates / (0.6 GeV^2/c^4)
Pulls
$m^2_{\rm miss}$ [GeV^2/c^4]
LHCb
Candidates / (0.376 ps)
Pulls
decay time [ps]
LHCb
Candidates per bin
Pulls
$Z(q^2,E^*_\mu)$



Bernlocher, Ligeti, Papucci, Robinson, https://arxiv.org/abs/1703.05330

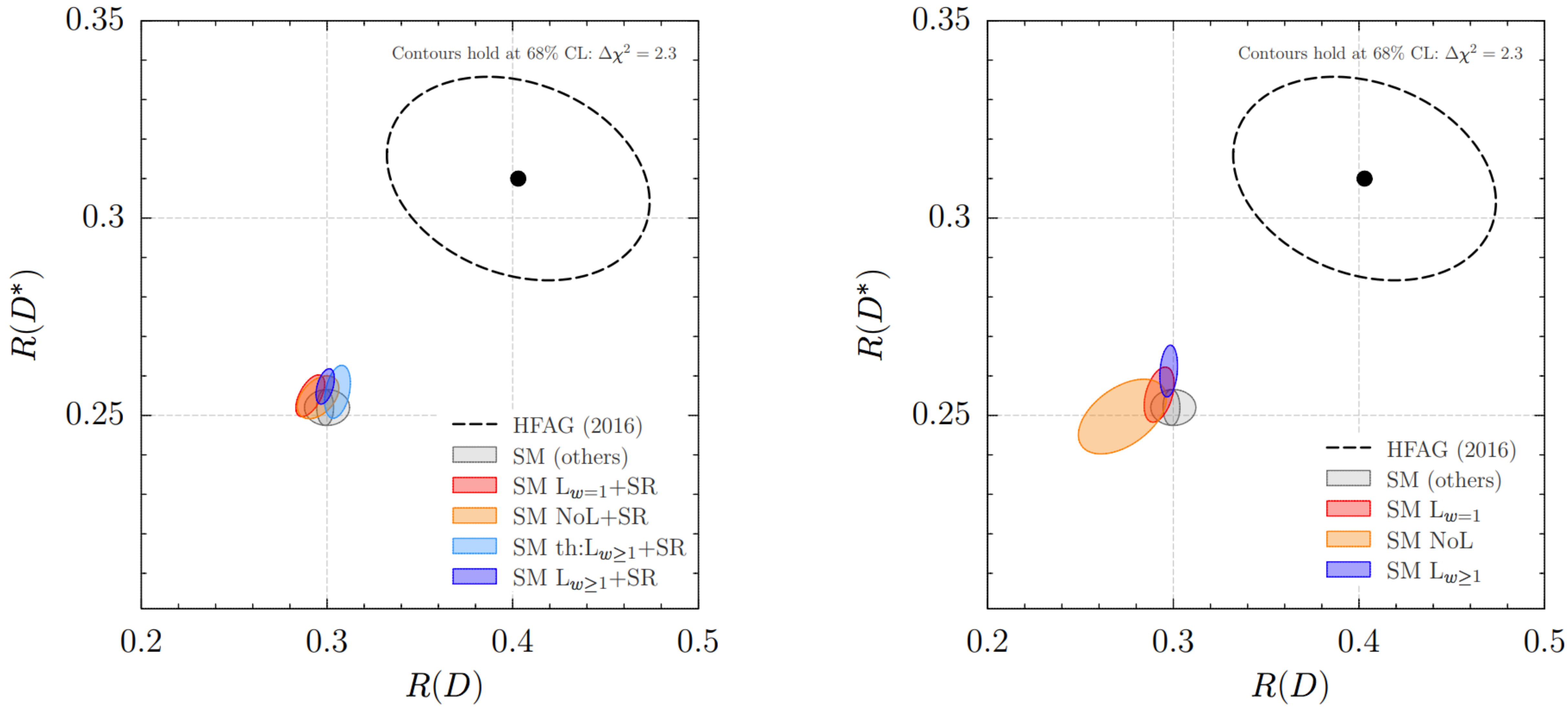
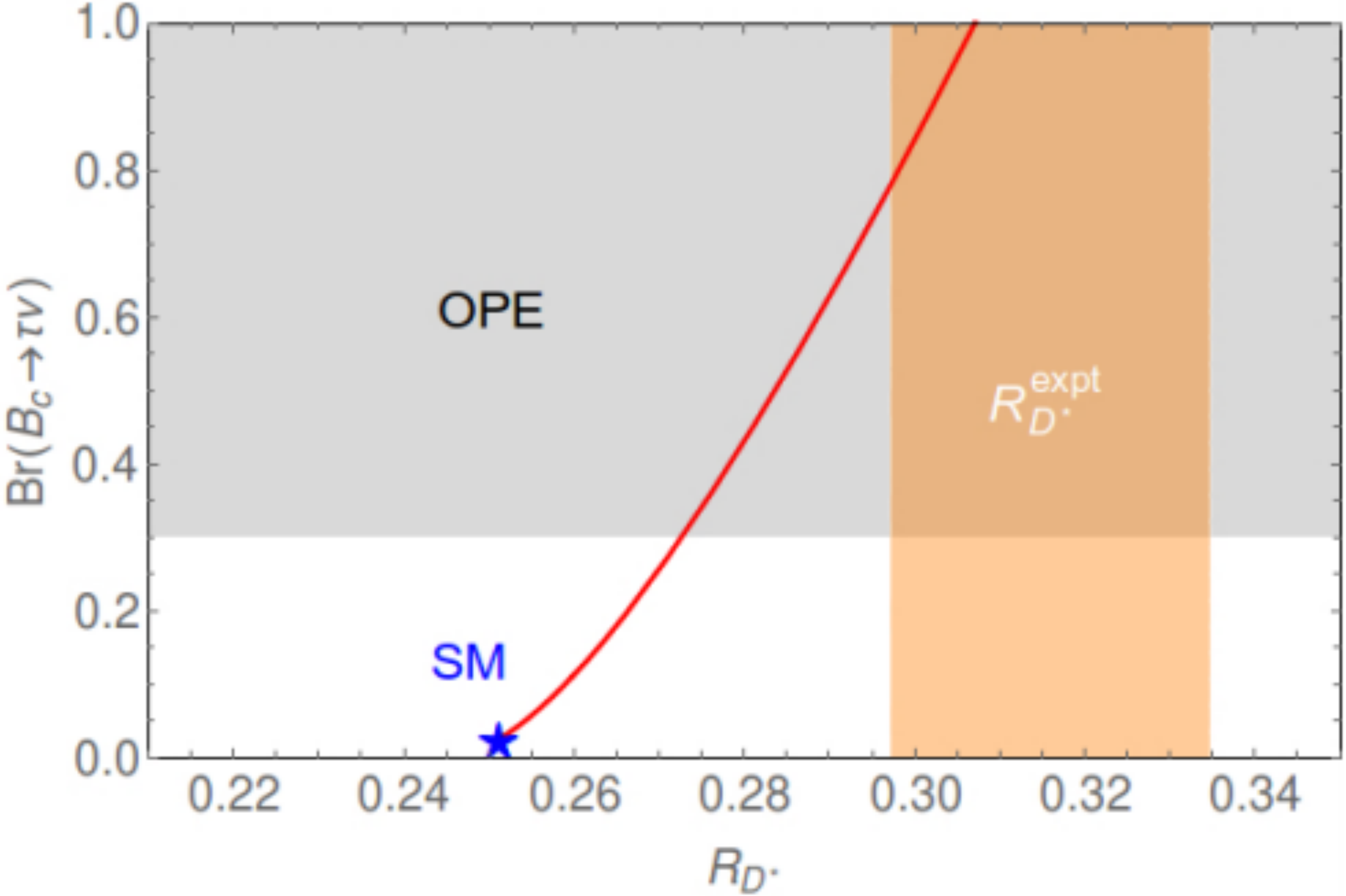


FIG. 4. The SM predictions for $R(D)$ and $R(D^*)$, imposing (left) or not imposing (right) the QCDSR constraints (see Table IV). Gray ellipses show other SM predictions (last three rows of Table IV). The black ellipse shows the world average of the data [9]. The contours are 68% CL ($\Delta\chi^2 = 2.3$), hence the nearly 4σ tension.

Bernlocher, Ligeti, Papucci, Robinson, https://arxiv.org/abs/1703.05330



1.0
0.8
0.6
0.4
0.2
0.0
$Br(B_c \to \tau\nu)$
OPE
SM
$R_{D^*}^{expt}$
0.22
0.24
0.26
0.28
0.30
0.32
0.34
R_{D^*}

Experiment	Method	N evts $B^0 \rightarrow D^* \tau \nu$
BABAR	Leptonic_hadronic tag	245±27
BELLE	Leptonic hadronic tag	0,4x500=200
BELLE	Single pi hadronic tag	88 ±11
LHCb	3π Hadronic	1273±95

R(J/Ψ) systematics

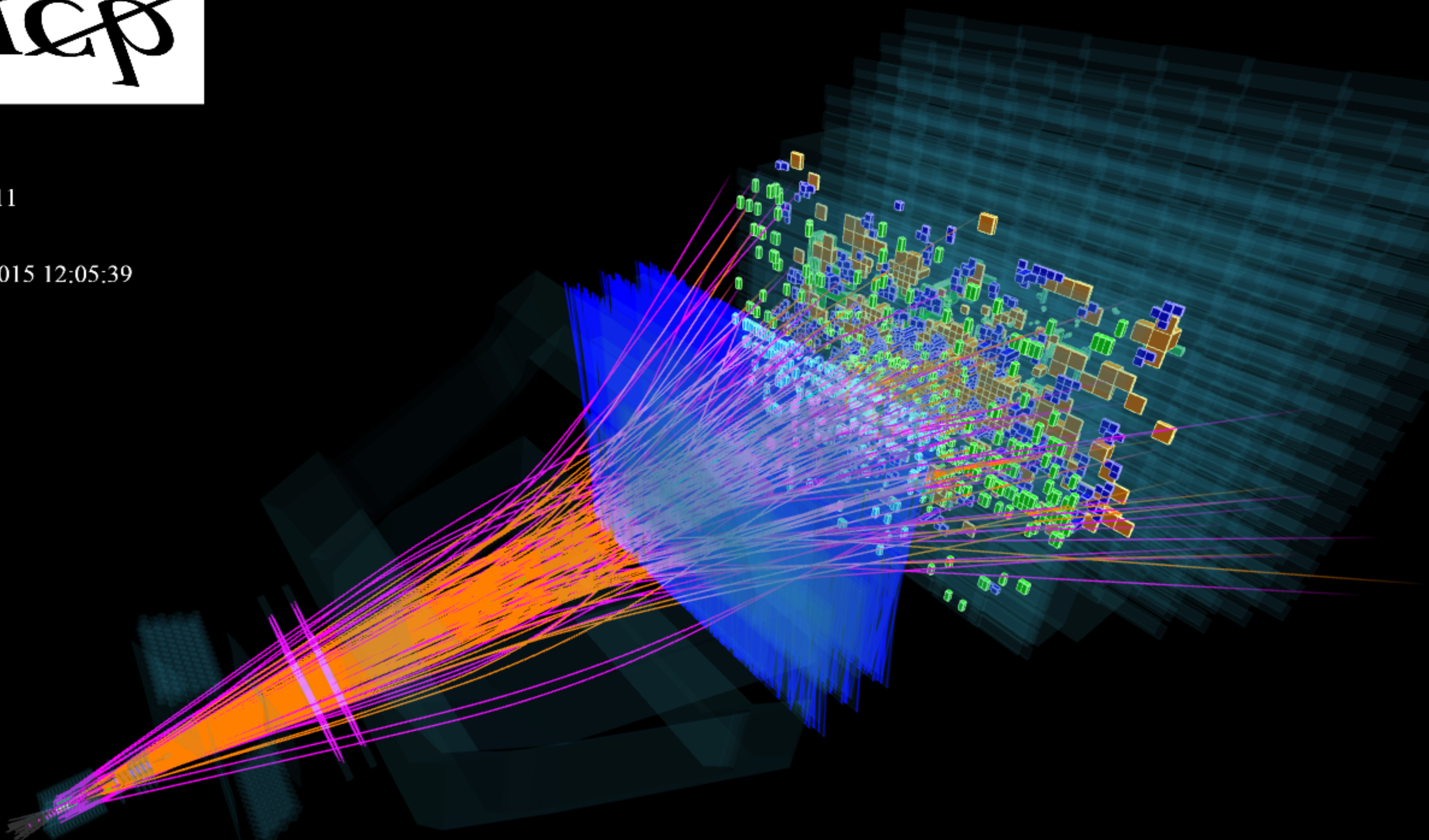
Table 1: Systematic uncertainties in the determination of $\mathcal{R}(J/\psi)$.

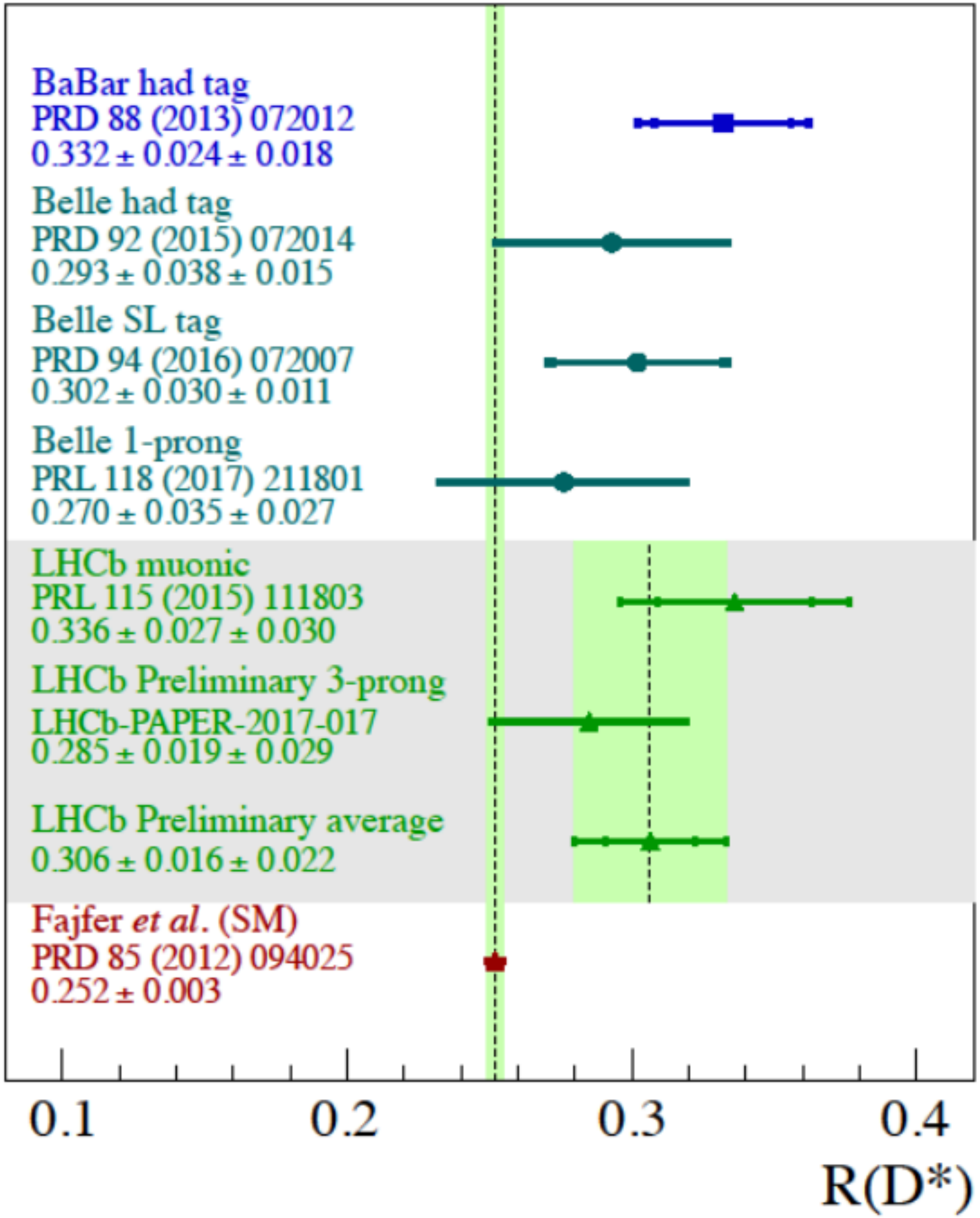
Source of uncertainty	**Size ($\times 10^{-2}$)**
Limited size of simulation samples	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Misidentification background strategy	5.6
Combinatorial background cocktail	4.5
Combinatorial J/ψ sideband scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
Semitauonic $\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau)$	0.2
Total systematic uncertainty	**17.7**
Statistical uncertainty	**17.3**

Event 58049711

Run 153460

Wed, 03 Jun 2015 12:05:39





New result has highest statistical precision.

Naive R(D*) average is 3.4σ above SM.

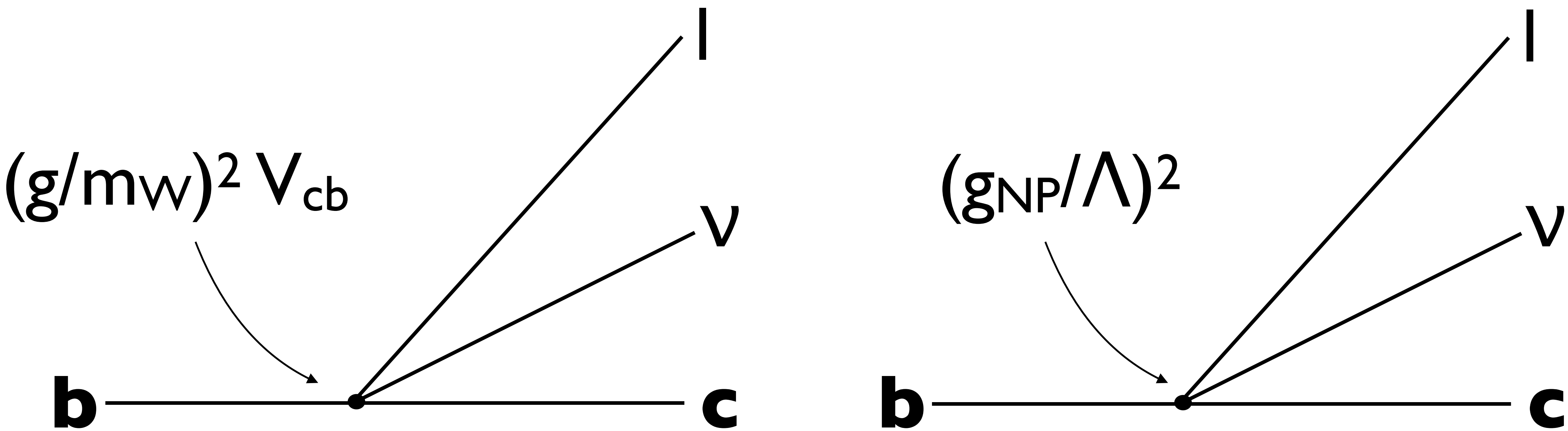
Naive R(D,D*) average is 4.1σ above SM…

$$\frac{\mathrm{d}\Gamma^{SM}(\bar{B} \to D^{(*)}\ell^{-}\overline{\nu}_{\ell})}{\mathrm{d}q^2} = \underbrace{\frac{G_F^2\;|V_{cb}|^2\;|p^*_{D^{(*)}}|\;q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2}_{\text{universal and phase space factors}} \tag{3}$$

$$\times \underbrace{\left[(|H_+|^2+|H_-|^2+|H_0|^2)\left(1+\frac{m_\ell^2}{2q^2}\right)+\frac{3m_\ell^2}{2q^2}|H_s|^2\right]}_{\text{hadronic effects}}\;.$$

Naive NP scale

~30% effect in τ/μ versus SM



$$\left(\frac{g_{\rm NP}}{\Lambda}\right)^2 \sim \sqrt{30\%}\left(\frac{g}{m_W}\right)^2 |V_{cb}|^2$$
$$\sim \left(\frac{g_{\rm NP}}{3\ {\rm TeV}}\right)^2$$