Flavour anomalies & Belle II's impact on the physics landscape

Particle Physics Seminar, University of Zurich

Belle II

Florian U. Bernlochner
florian.bernlochner@cern.ch
University of Bonn, Germany

universitätbonn

About me

- Born and grown up in Bern, CH
- Studied at ETH Zurich (theoretical) physics from 2002-2007
- PhD at Humboldt University in Berlin, Germany working at BaBar
  - 2007-2008 research stay at SLAC, California
  - Finished mid 2011
- Postdoc at University of Victoria, Canada, working on ATLAS
  - 2011-2014 based at CERN
- Junior faculty at University of Bonn, working on Belle (II)
  - Since mid 2014

Belle Belle II

Jochen Dingfelder

universität bonn

Florian Bernlochner

PhD students

Jan Hasenbusch

$B \to X_{c,u} \, \tau \, \bar{\nu}_\tau$

Luis Pesantez

$B \to X_{s,d} \, \gamma$

Stephan Duell

$B \to \pi \, \tau \, \bar{\nu}_\tau$

Belle II tracking

BSc student

Max Rüger

$B \to X \, \ell \, \bar{\nu}_\ell$

MSc students

Saskia Mönig

$B \to D^* \, \ell \, \bar{\nu}_\ell$

Mario Arndt

$B \to D^{(*)} \pi \, \tau \, \bar{\nu}_\tau$

Tarek El Rabbat

$B_s \to K \, \ell \, \bar{\nu}_\ell$

Christian Wessel

Belle II PXD / Datcon

+ Hardware (1 Postdoc + 4 PhDs + …)

Talk Overview

Summary

B-Factories

a quick introduction to the family

Physics done in Bonn

an overview

Belle II Detector

concept and current status

Belle II Physics & LHCb

On complementarity and overlap

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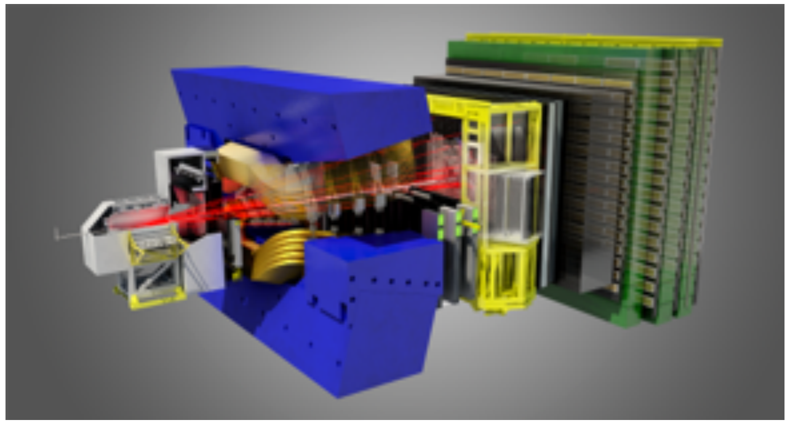
Summary

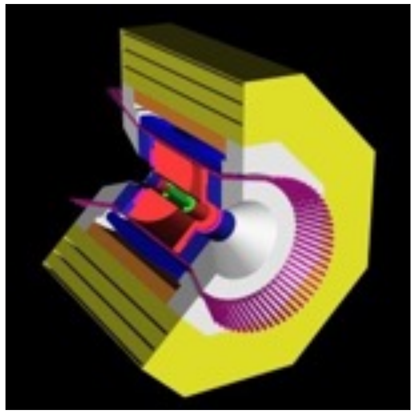
B-Factory Family Album

ARGUS

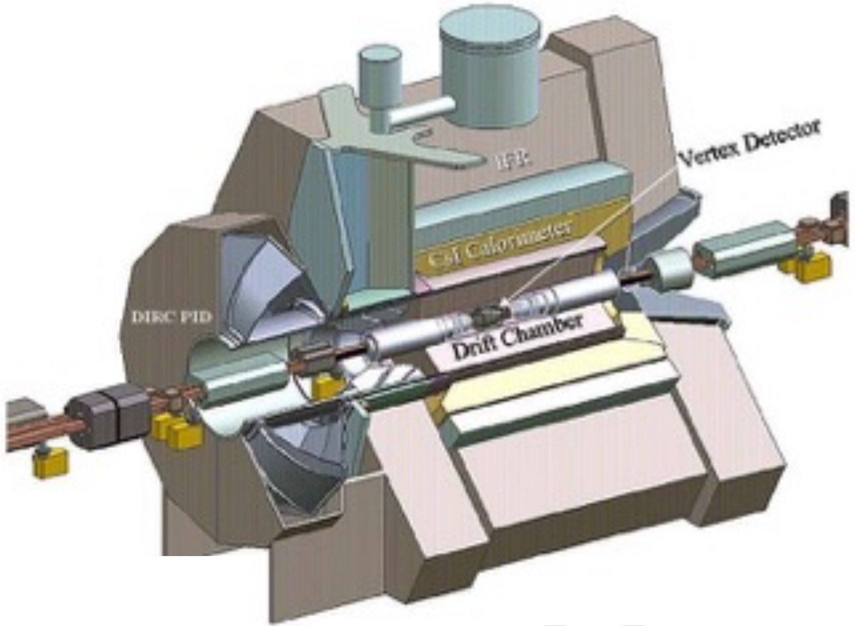
HERA-B



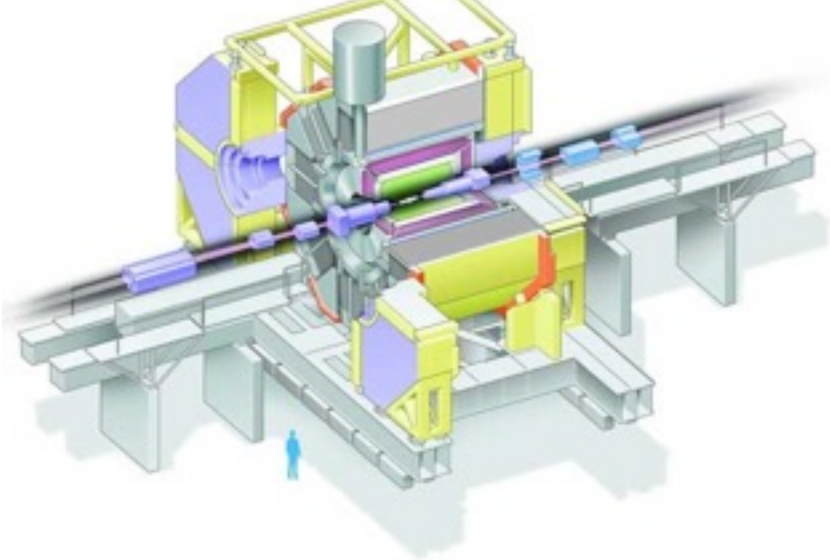
LHCb



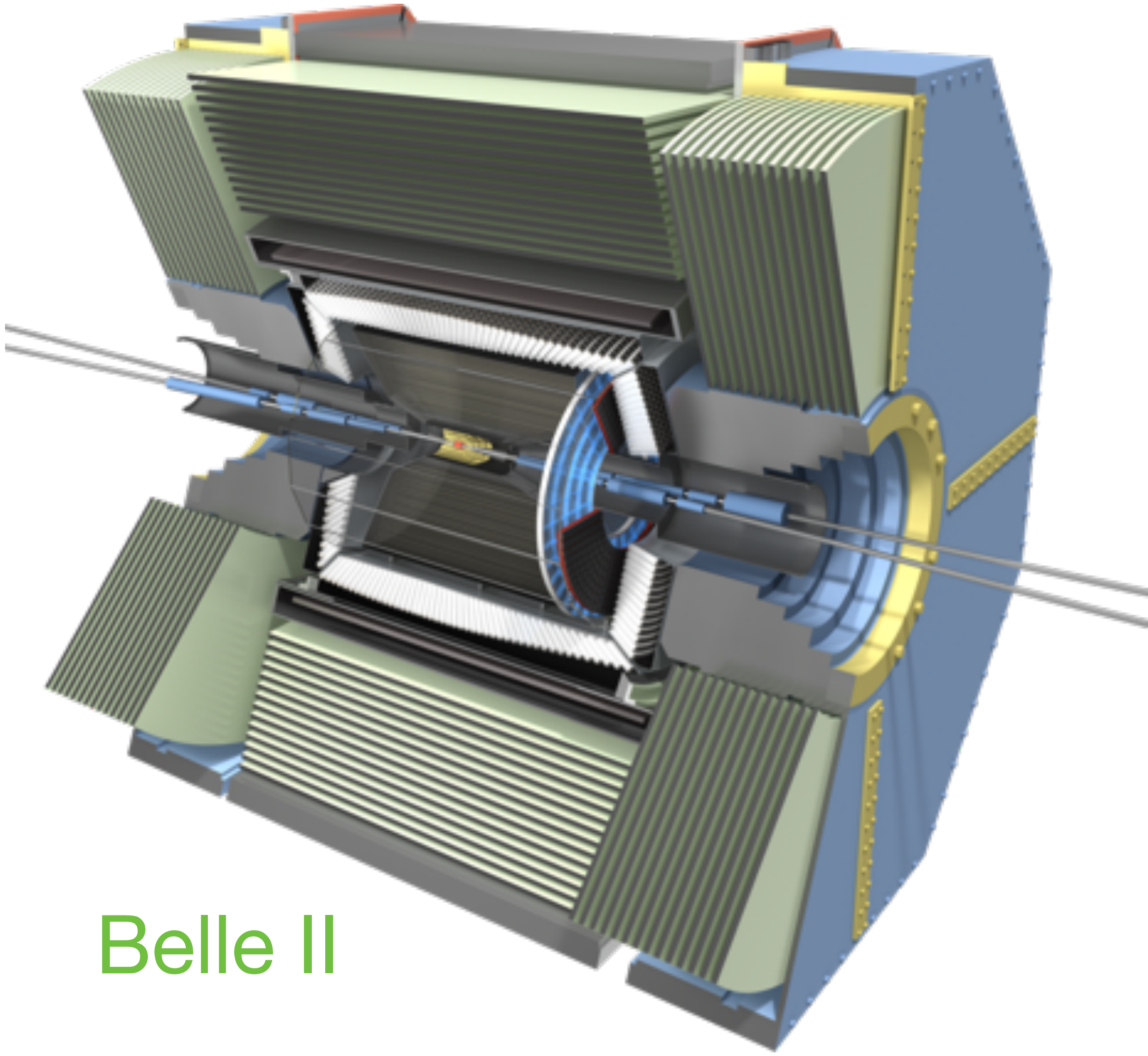
CLEO



BaBar

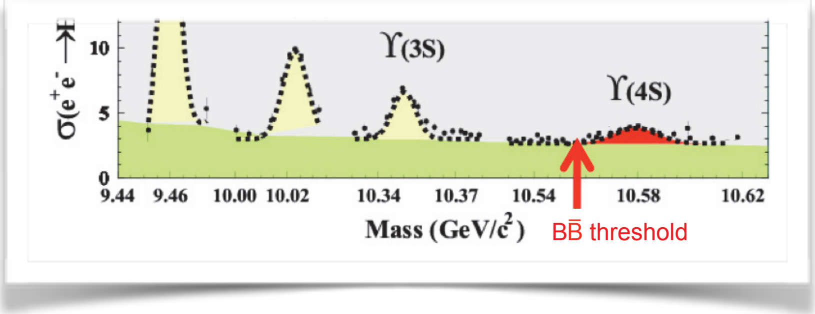


Belle



Belle II

B-Factory Family Album

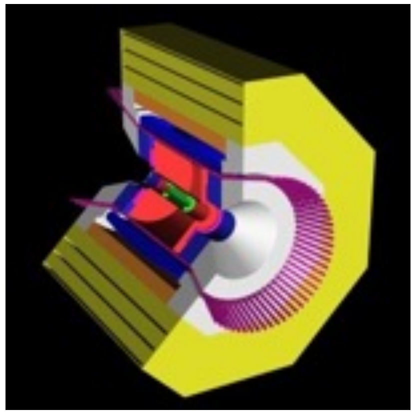


Collision cross section to hadrons in nb

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

$$\langle b\bar{b}\rangle \quad \sqrt{s} = 10.58\,\mathrm{GeV}$$

ARGUS



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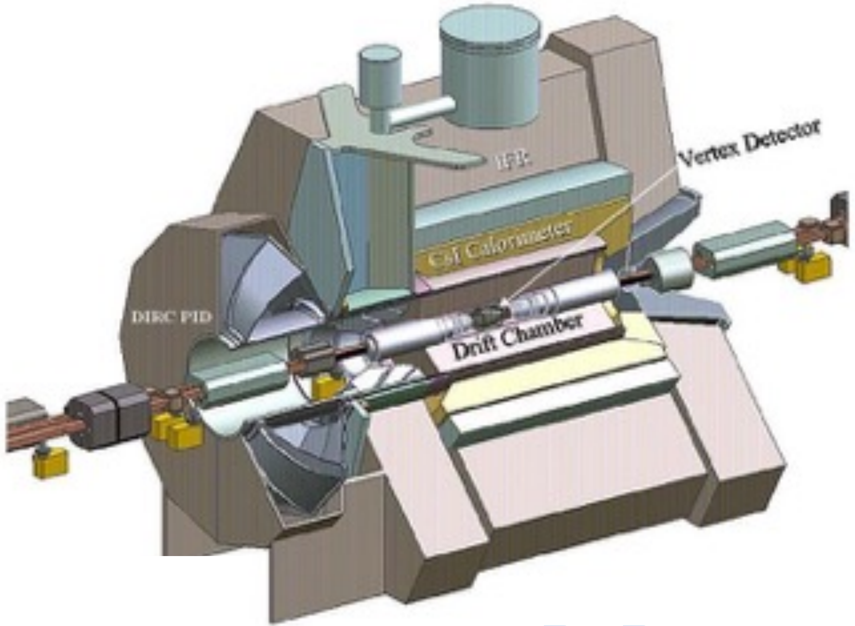
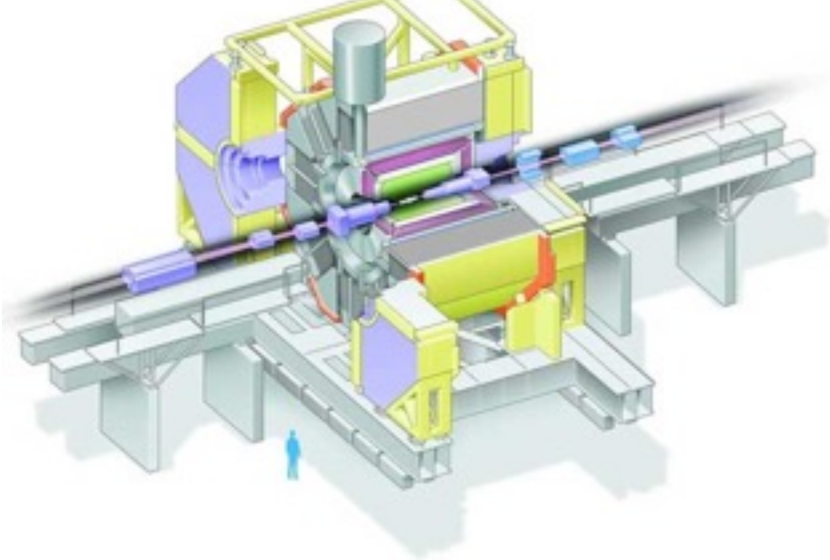


BaBar



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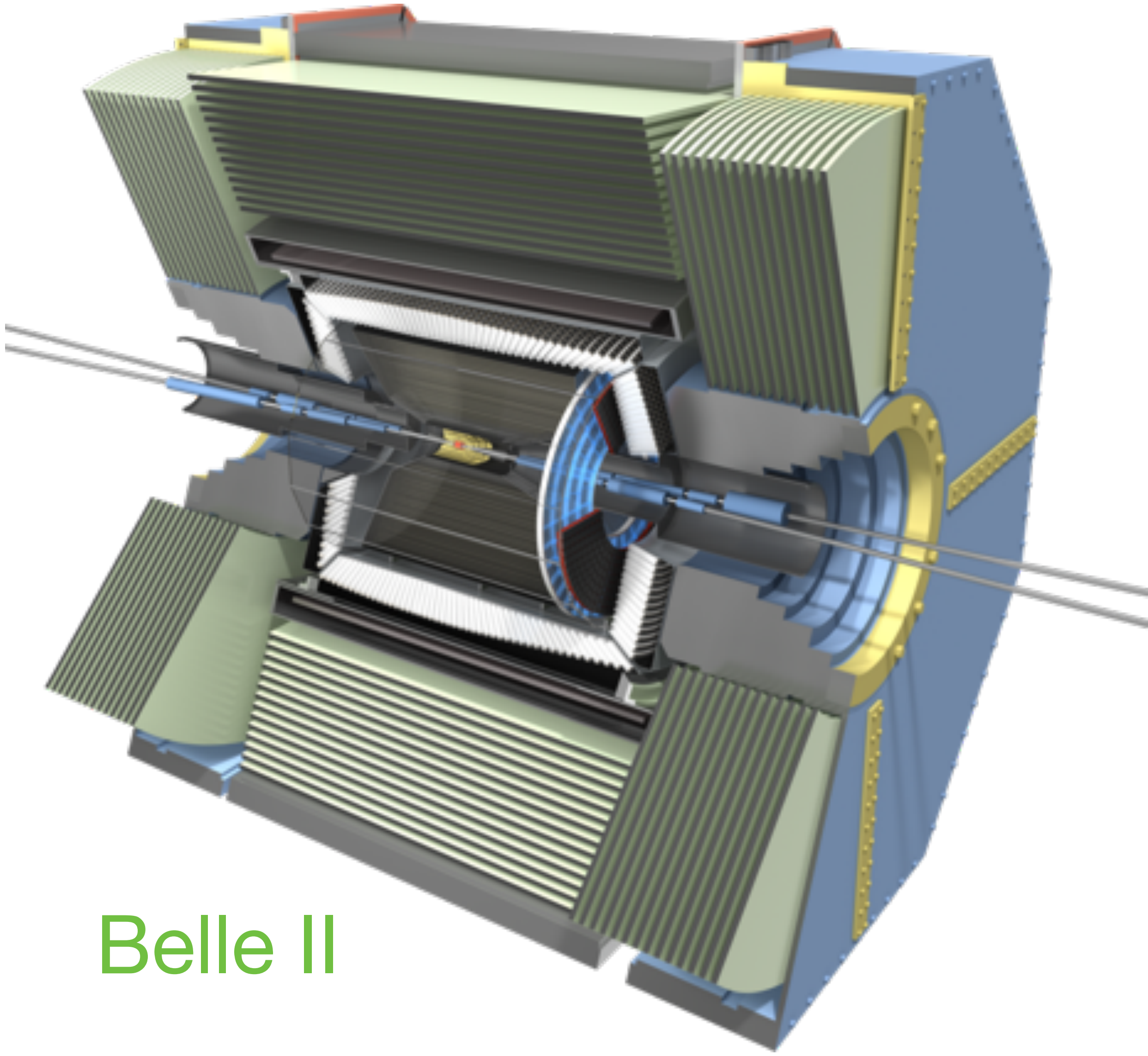
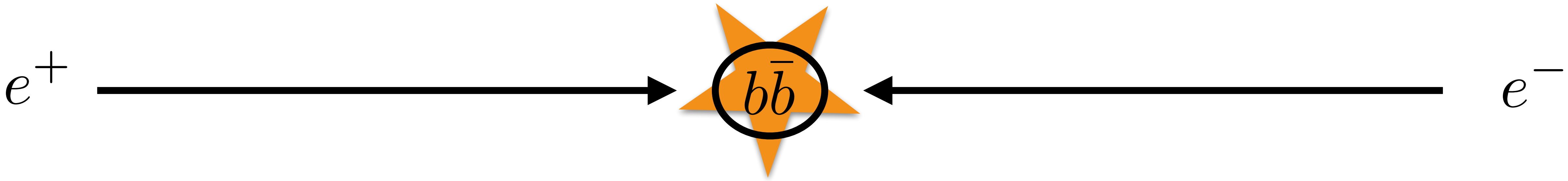
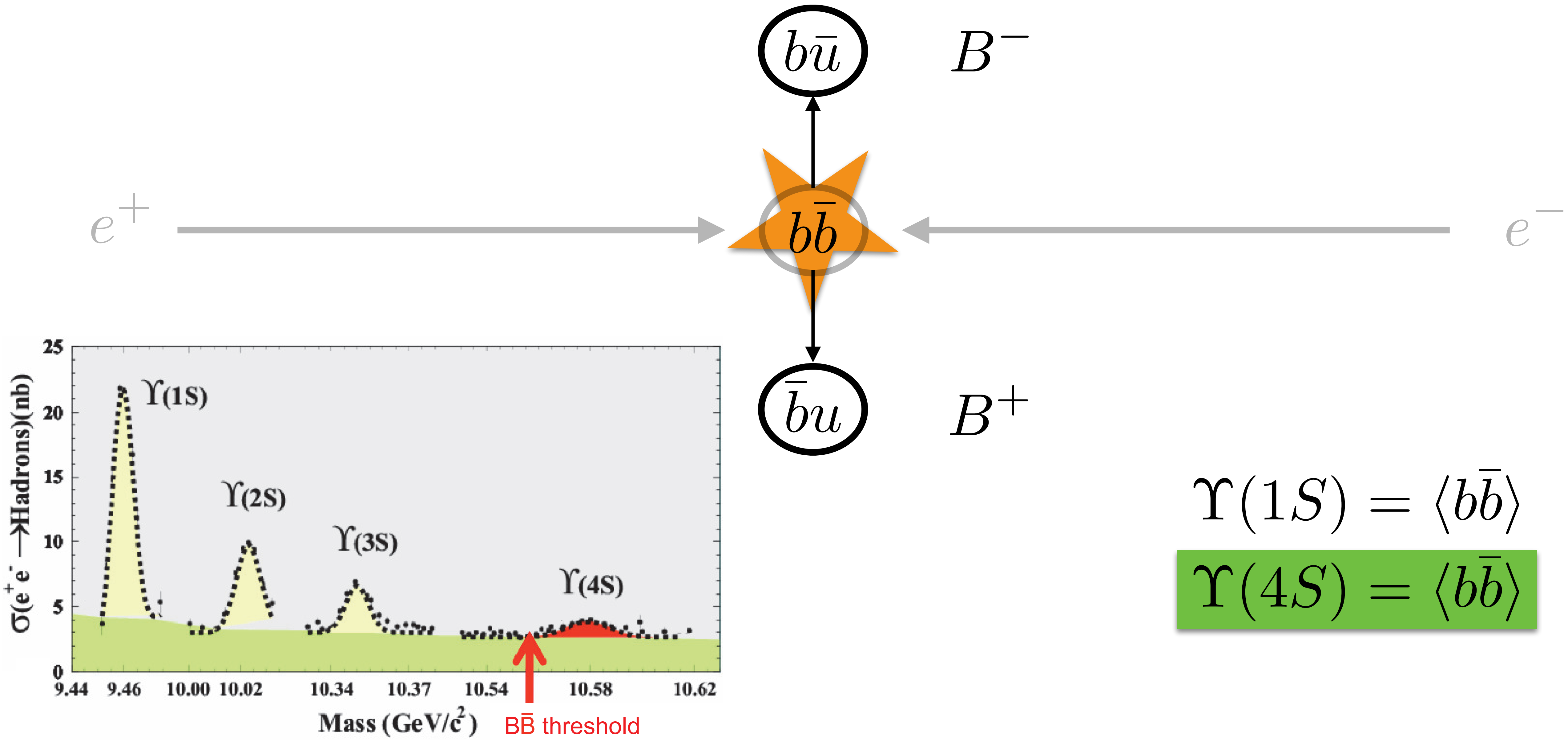


Belle II

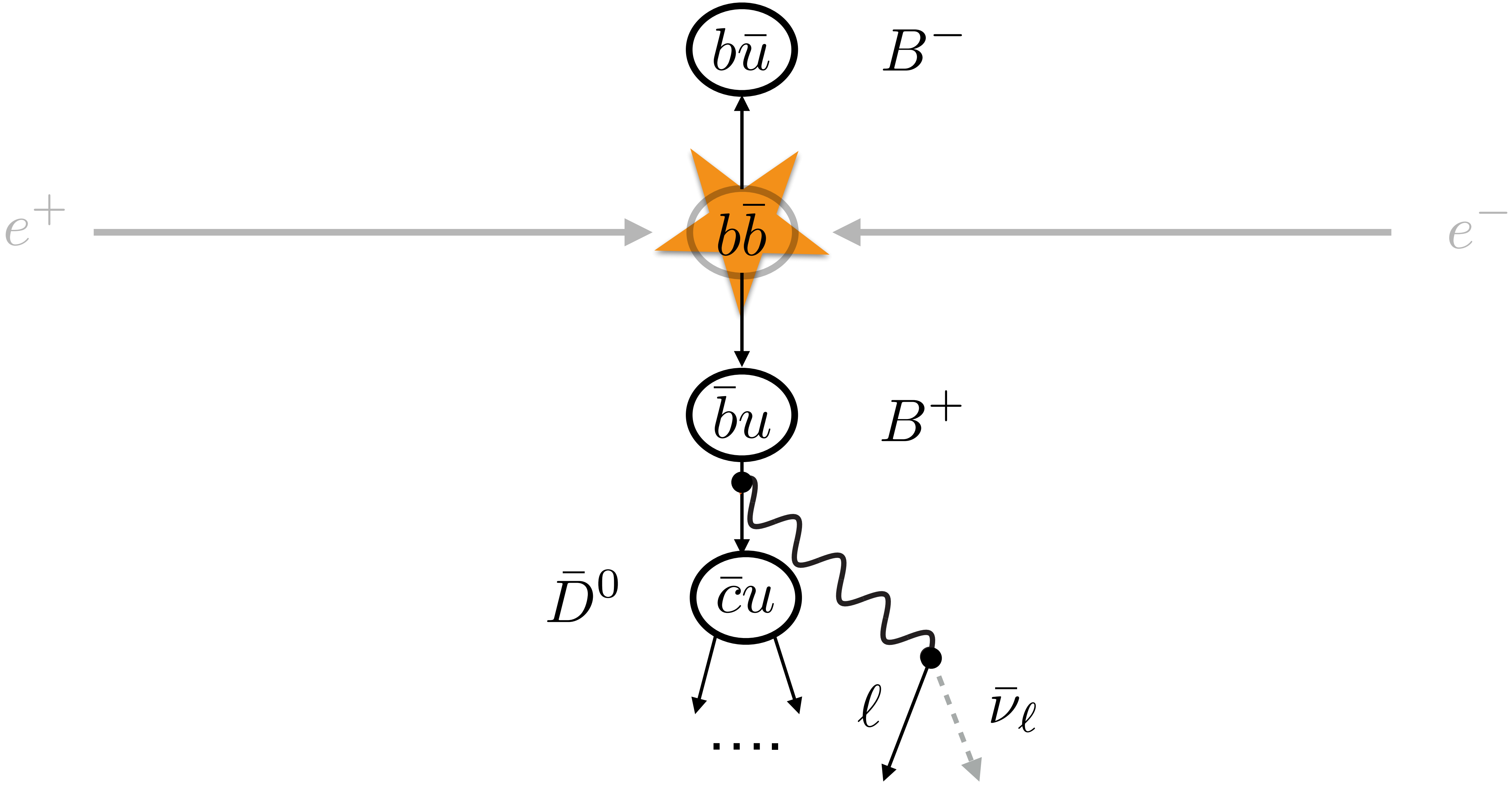
$e^+ e^-$ machines are beautiful

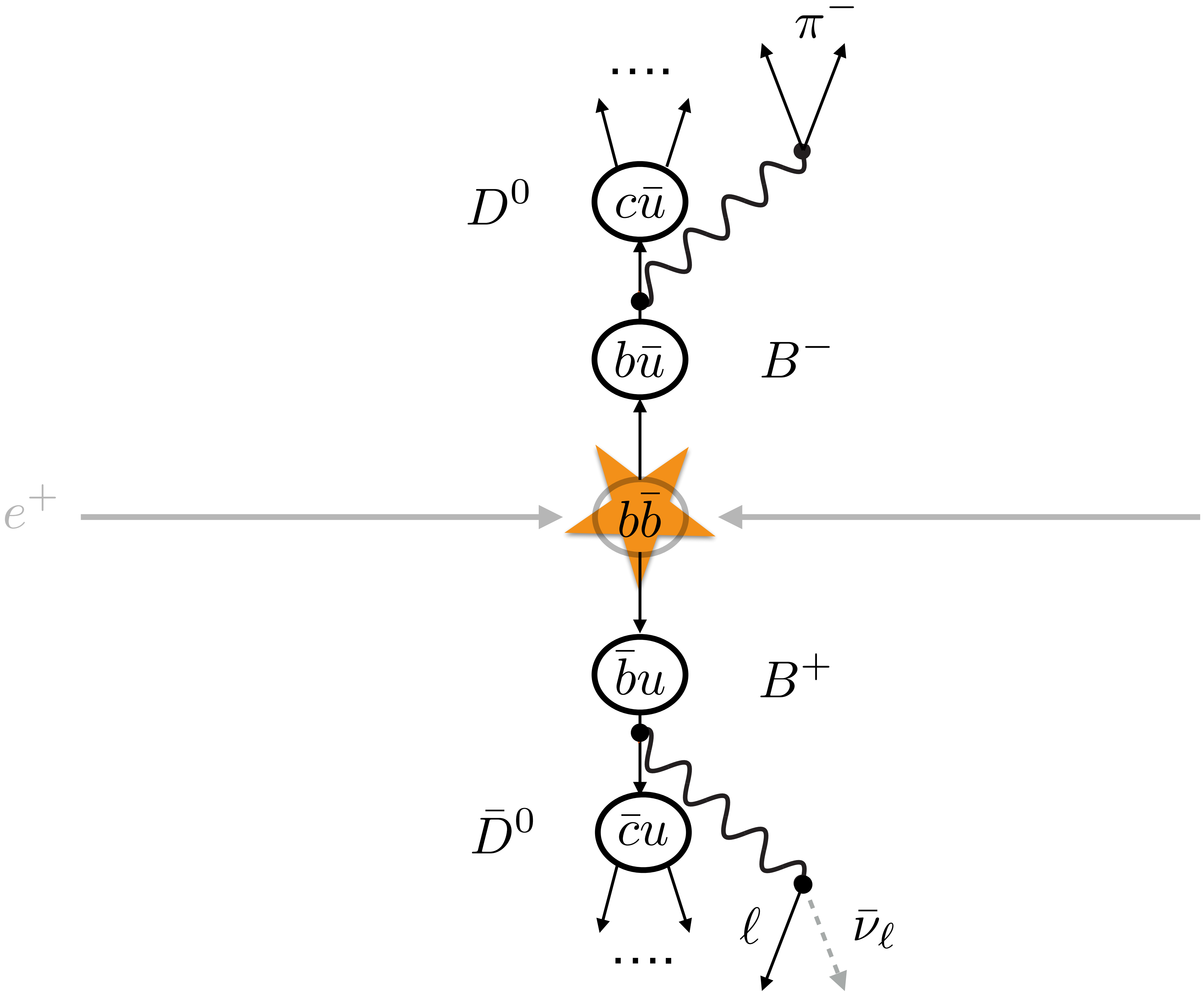


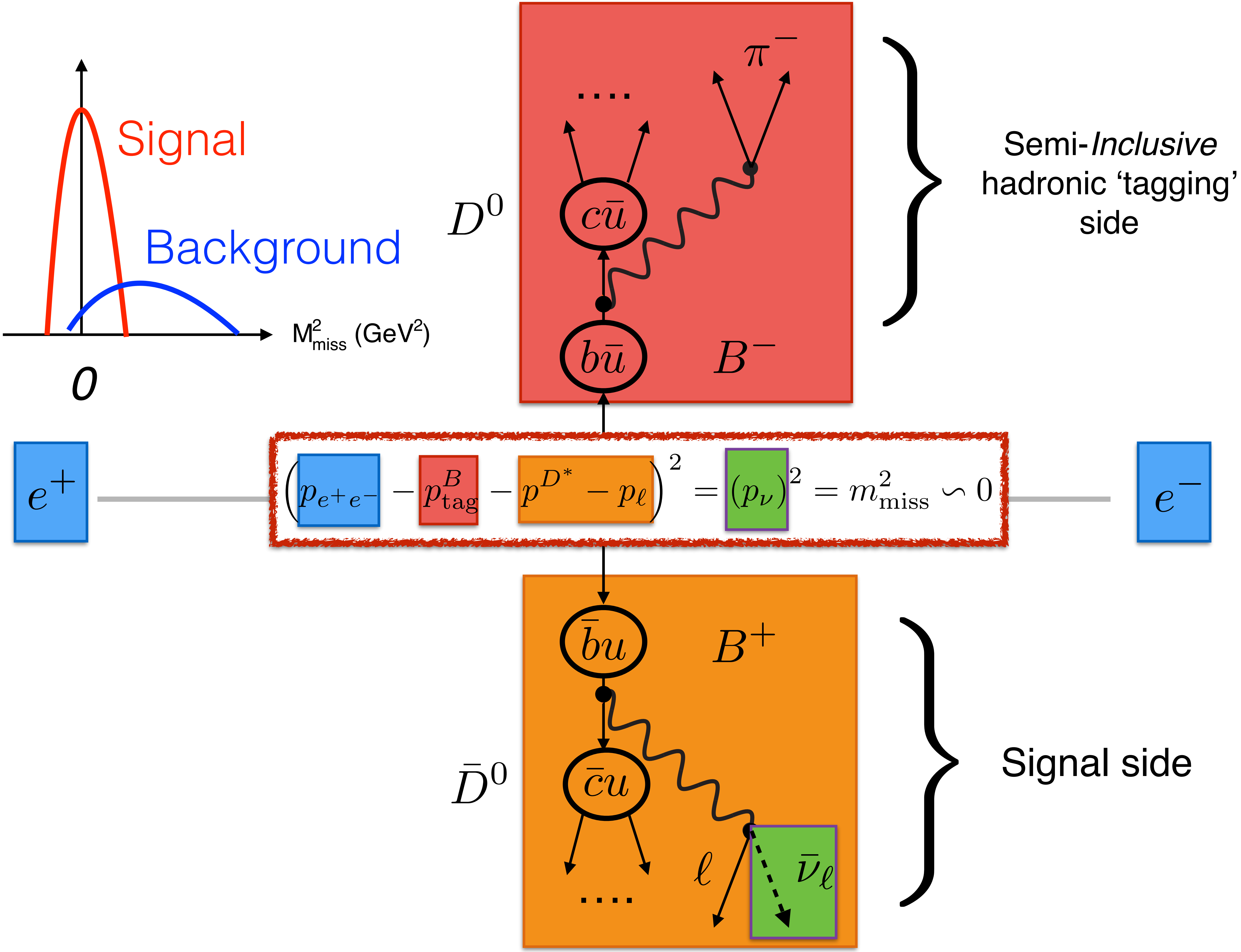


$$\Upsilon(1S) = \langle b\bar{b} \rangle$$

$$\Upsilon(4S) = \langle b\bar{b} \rangle$$


$b\bar{u}$
B^-
e^+
$b\bar{b}$
e^-
$\bar{b}u$
B^+
$\bar{D}^0$
$\bar{c}u$
....
ℓ
$\bar{\nu}_\ell$


π^-
....
D^0
$c\bar{u}$
$b\bar{u}$
B^-
e^+
$b\bar{b}$
$\bar{b}u$
B^+
$\bar{D}^0$
$\bar{c}u$
ℓ
$\bar{\nu}_\ell$
....

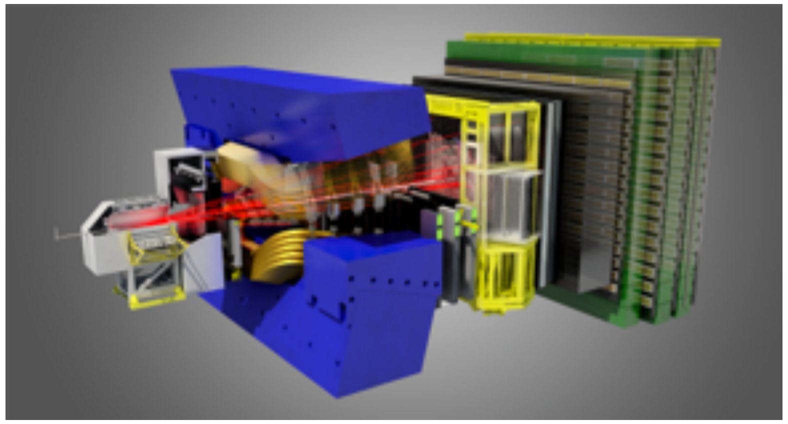


$$\left(p_{e^+e^-} - p^{B}_{\text{tag}} - p^{D^*} - p_\ell\right)^2 = (p_\nu)^2 = m^2_{\text{miss}} \backsim 0$$

B-Factory Family Album

HERA-B

proton-atom collisions

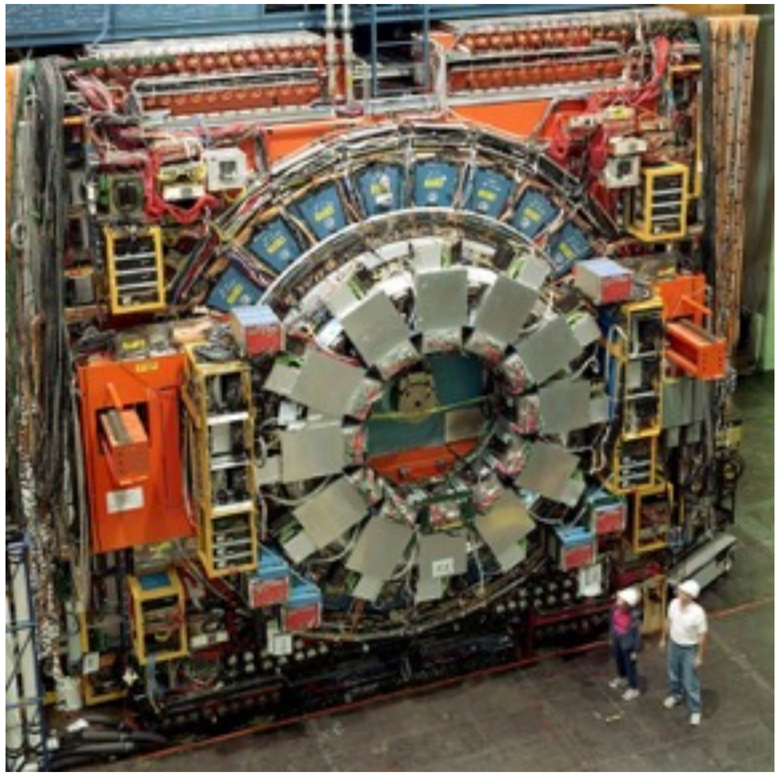


LHCb

proton-proton collisions

Note:

- Also proton-antiproton collision experiments and results from ATLAS & CMS



CDF

D0

The CKM Mechanism

The CKM Mechanism source of *Charge* *Parity* *Violation* in SM

- Unitary 3x3 Matrix, parametrizes rotation between mass and weak interaction eigenstates in Standard Model

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak Eigenstates CKM Matrix Mass Eigenstates

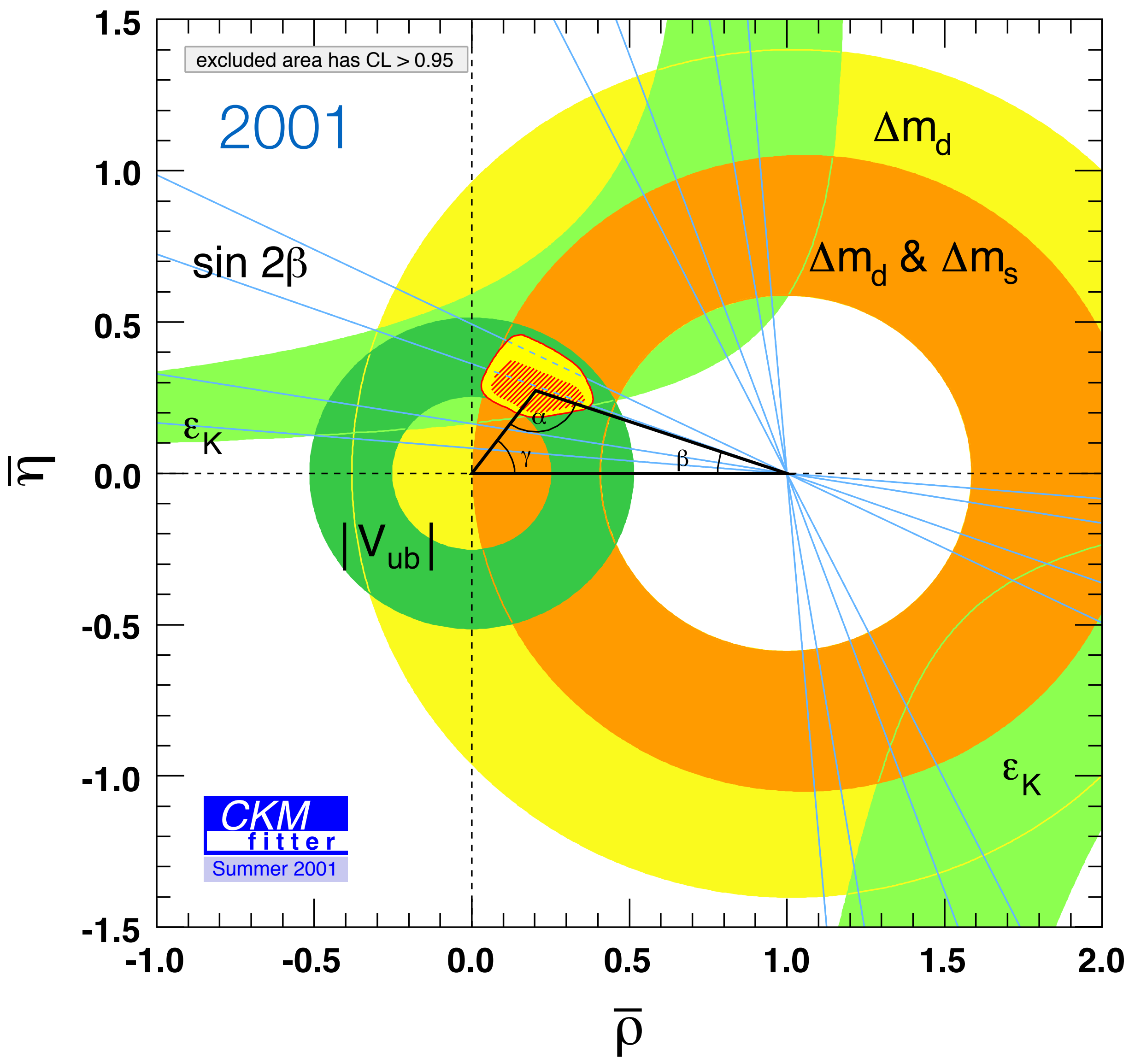
- Fully parametrized by **four** parameters if unitarity holds: three real parameters and one complex phase that if non-zero results in *CPV*
- Unitarity can be visualized using triangle equations, e.g.

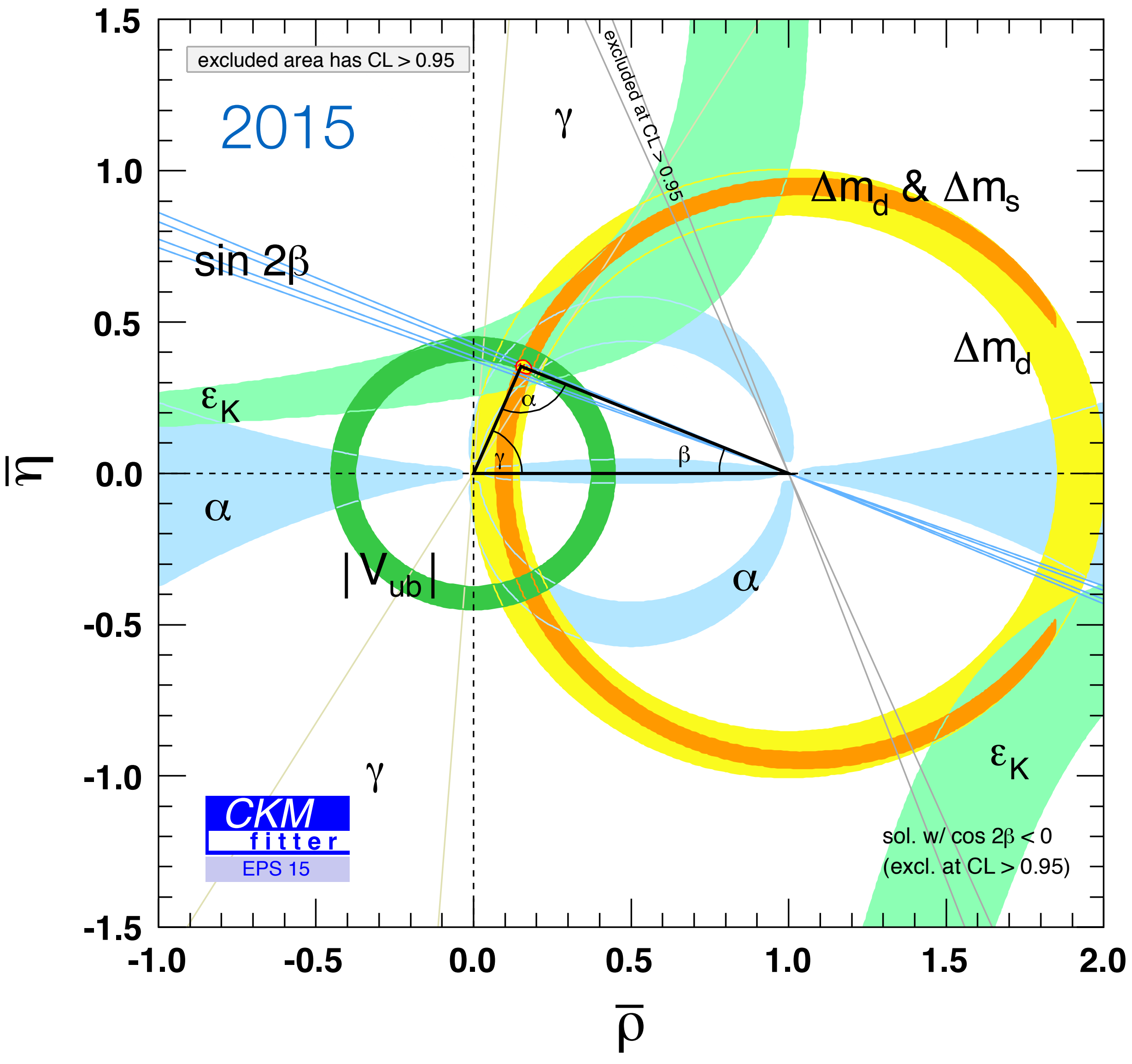
$$V_{CKM} V_{CKM}^{\dagger} = \mathbf{1} \qquad \rightarrow \qquad V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

CKM Picture over the years: *from discovery to precision*

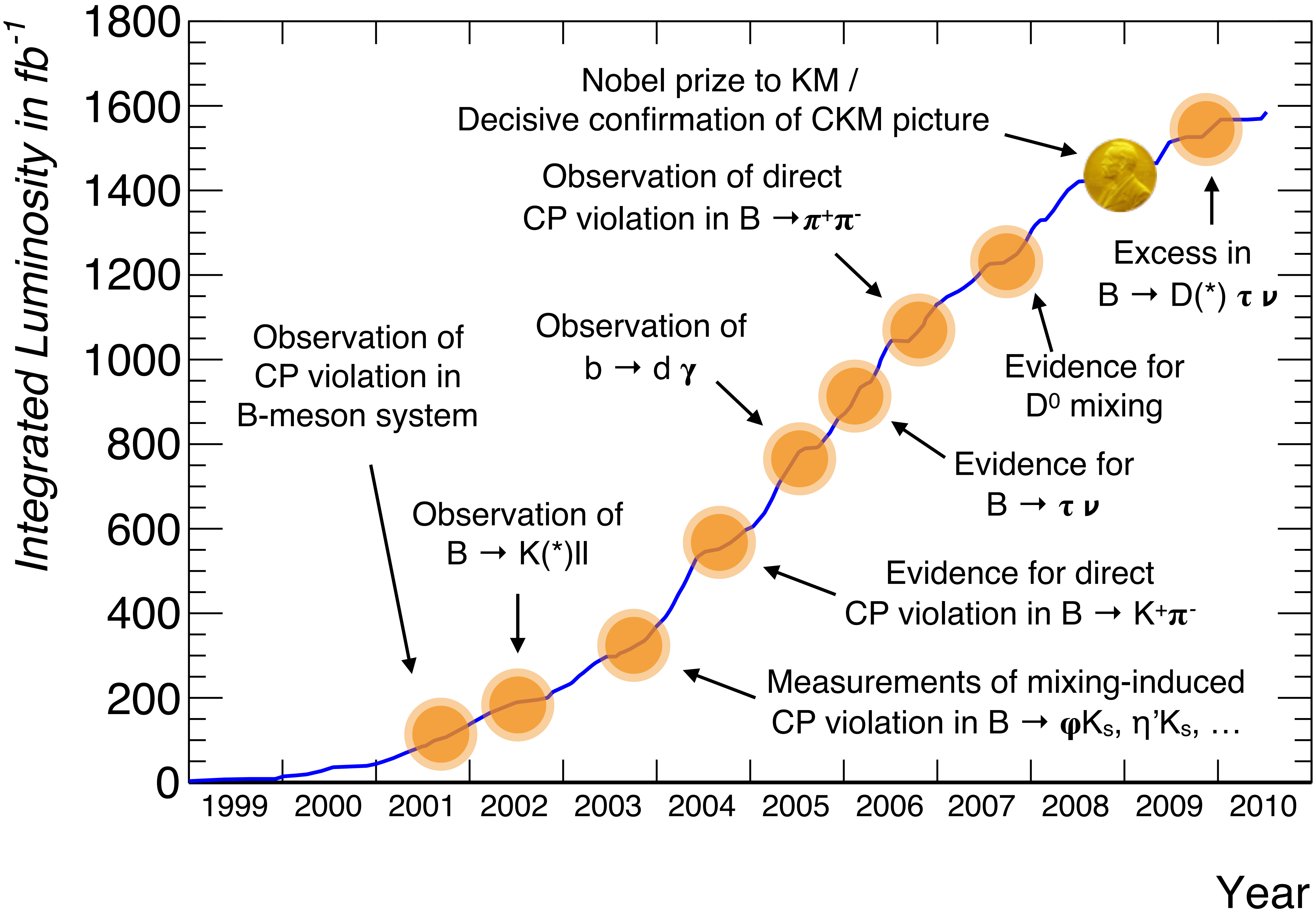
Existence of *CPV* phase established in 2001 by BaBar & Belle

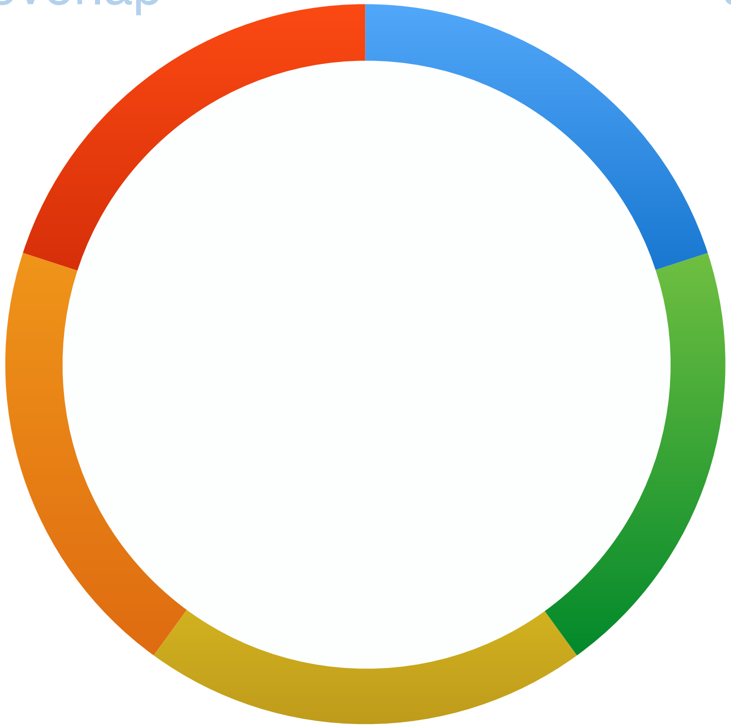
- Picture still holds 15 years later, constrained with remarkable precision
- But: still leaves room for new physics contributions





Recap of the last decade of BaBar & Belle: *a rich harvest*





Belle II & LHCb

On complementarity and overlap

B-Factories

a quick introduction to the family

Belle II Physics

from CPV to dark photons

Physics done in Bonn

an overview

Belle II Detector

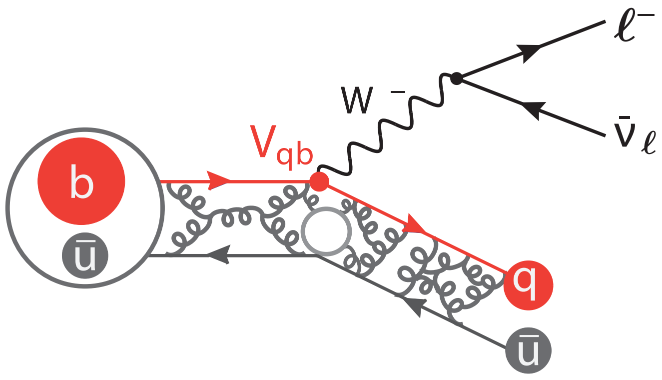
concept and current status

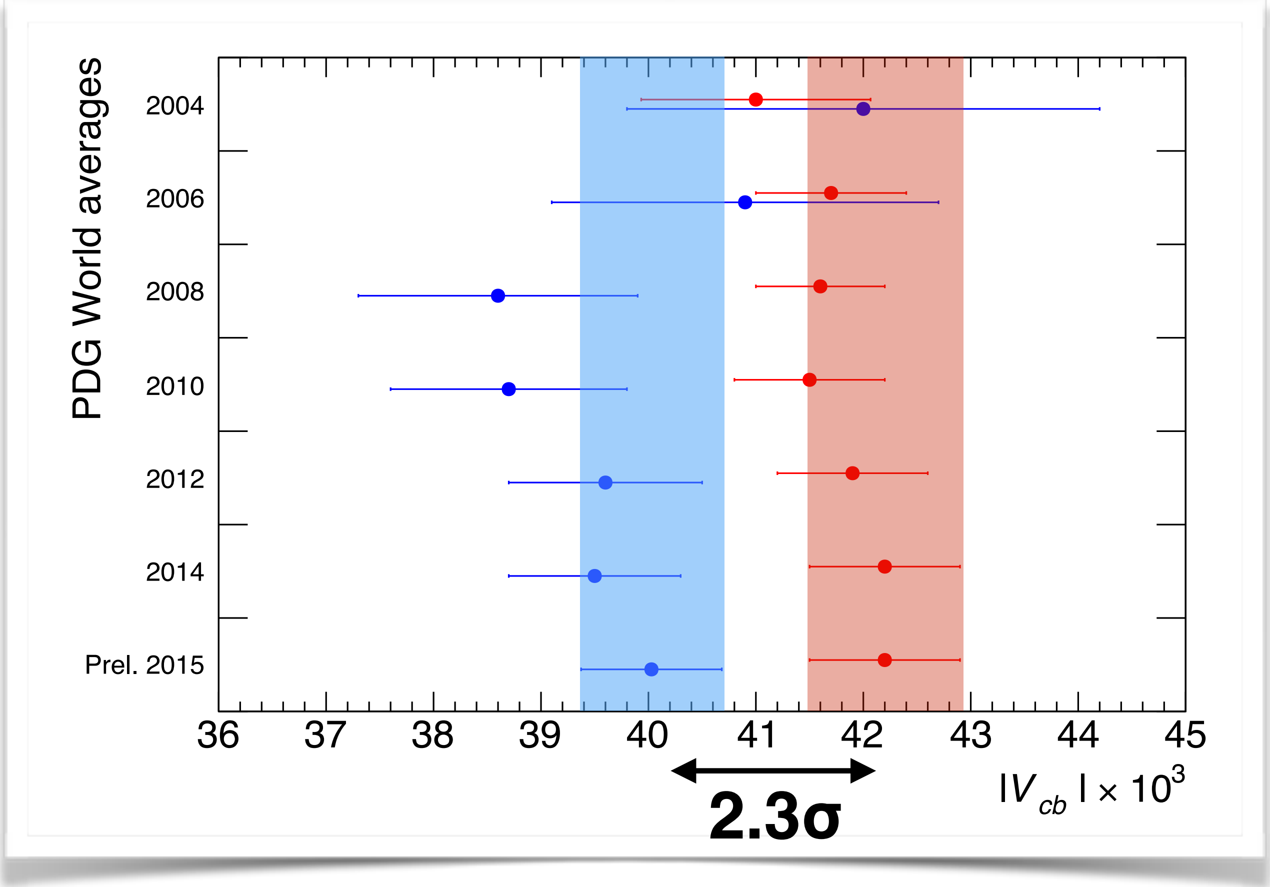
Flavour Anomalies: |V$_{ub}$| & |V$_{cb}$|

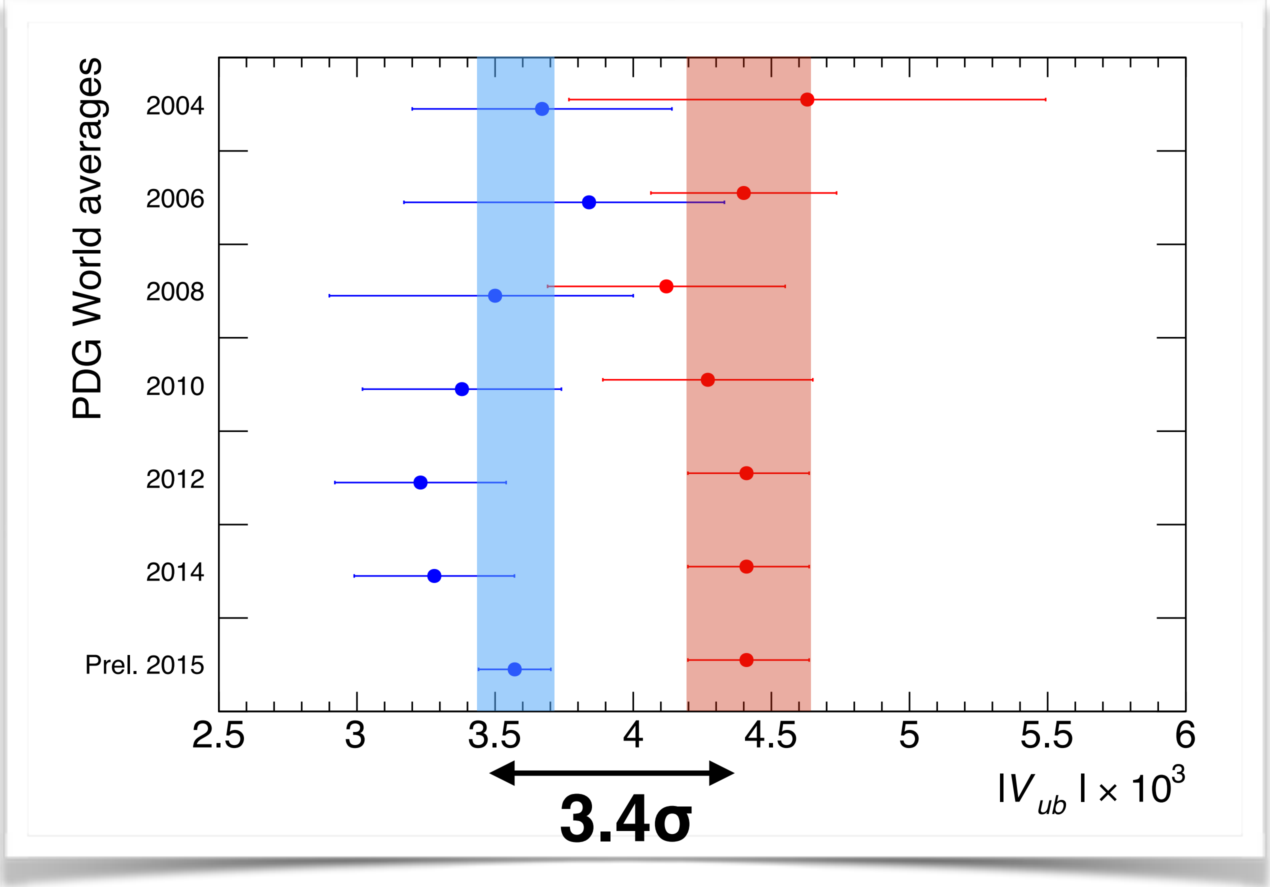
$$|V_{qb}| = \sqrt{\frac{\overset{\text{from experiment}}{\overset{\downarrow}{\mathcal{B}(B \to X_q\, \ell\, \bar{\nu}_\ell)}}}{\underset{\text{from theory}}{\underset{\uparrow}{\Gamma(B \to X_q\, \ell\, \bar{\nu}_\ell)}}\, \tau_B}}$$

Sizeable tension in *exclusive* and *inclusive* |V$_{ub}$| & |V$_{cb}$|

- Both methods considered theoretical and experimental mature
- Individual determinations leave a consistent picture







- About **2.3σ** and **3.4σ** disagreement between incl. and excl. for |V$_{cb}$| & |V$_{ub}$|, respectively

A closer look on the exclusive $|V_{ub}|$ side

Fermilab+MILC: arXiv:1503.07839v2 [hep-lat]

Predominantly measured using

$$B \to \pi\,\ell\,\bar{\nu}_\ell$$

- Tagged and untagged measurements
    - Tagged = fully reconstruct second B meson in decay with hadronic modes
- Some tension between the measurements:
    - P-Value of combined 4 par fit: 2%
    - Fit takes into account correlated uncertainties, but does not allow for systematic pulls.

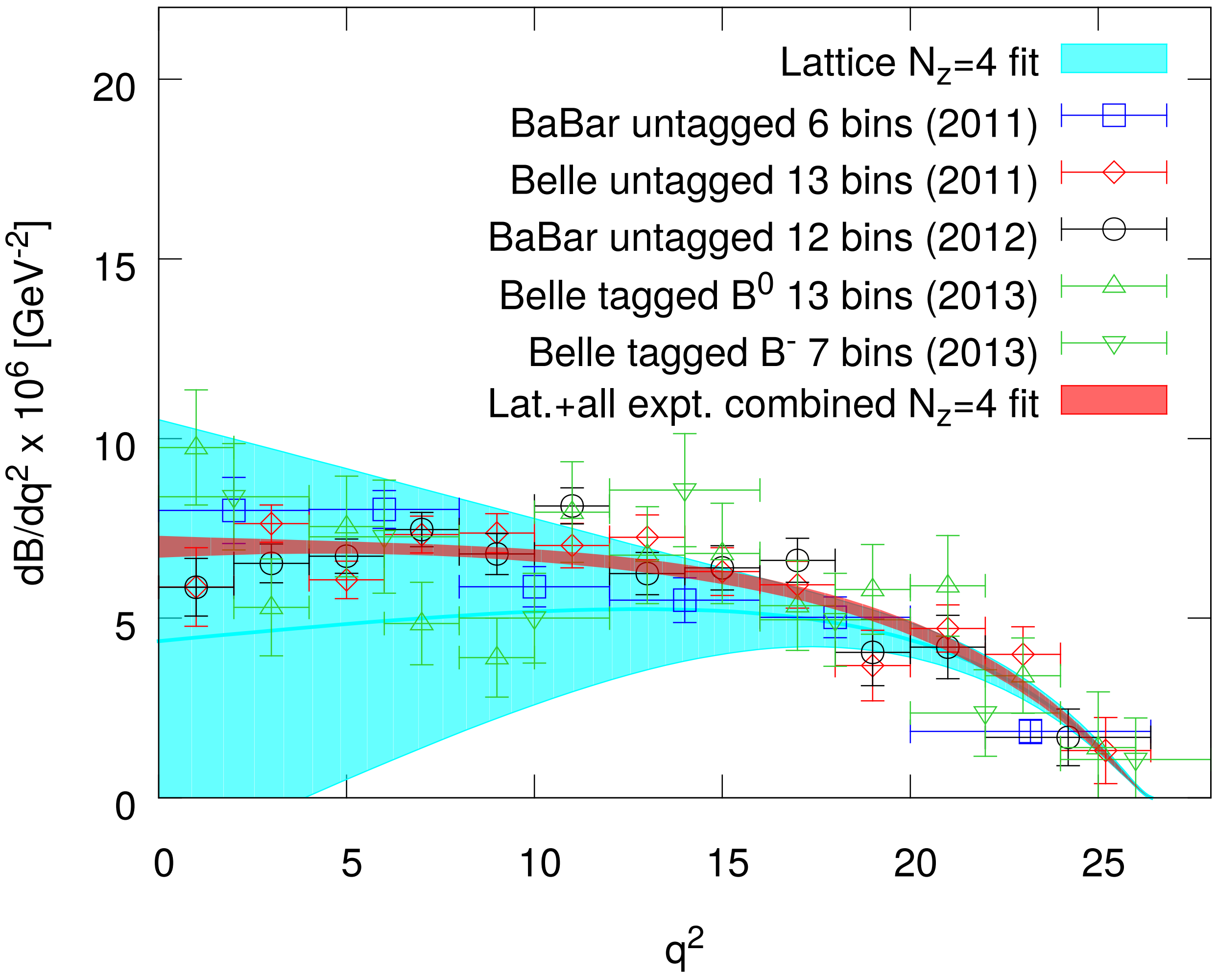


Table XVI. Results of the combined lattice+experiment fits with $N_z = 4$;.

Fit	χ^2/dof	dof	p value	b_0^+	b_1^+	b_2^+	b_3^+	$\|V_{ub}\|(\times 10^3)$
Lattice+exp.(all)	1.4	54	0.02	0.419(13)	−0.495(55)	−0.43(14)	0.22(31)	3.72(16)
Lattice+BaBar11 [7]	1.1	9	0.38	0.414(14)	−0.488(73)	−0.24(22)	1.33(44)	3.36(21)
Lattice+BaBar12 [8]	1.1	15	0.34	0.415(14)	−0.551(72)	−0.45(18)	0.27(41)	3.97(22)
Lattice+Belle11 [9]	0.9	16	0.55	0.412(13)	−0.574(65)	−0.40(16)	0.38(36)	4.03(21)
Lattice+Belle13 [10]	1.0	23	0.42	0.406(14)	−0.623(73)	−0.13(22)	0.92(45)	3.81(25)

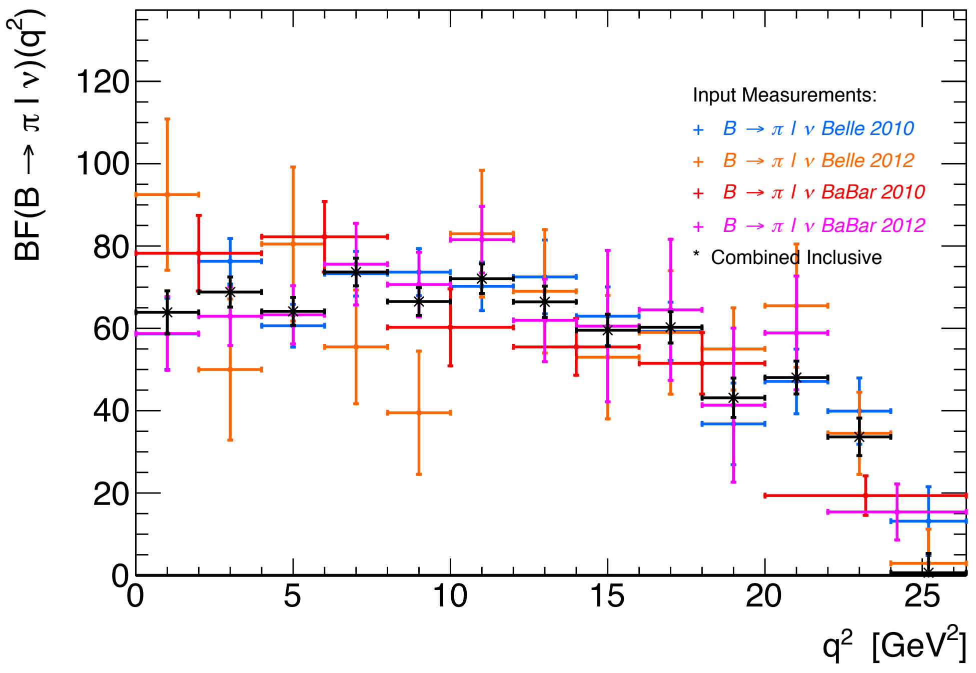
A closer look on the exclusive $|V_{ub}|$ side

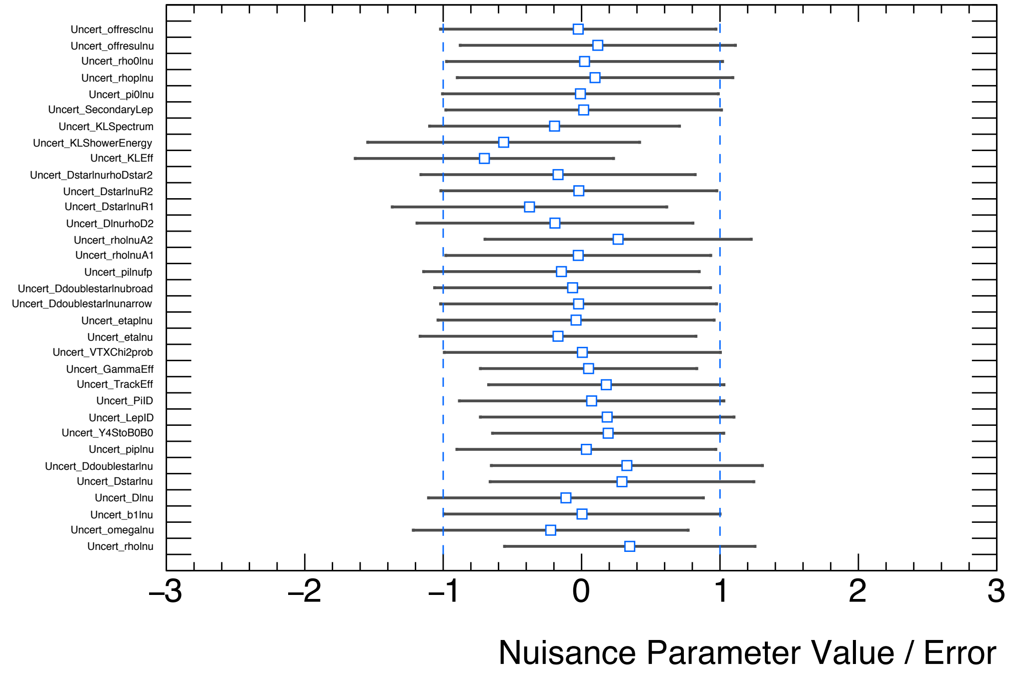
FB, Stephan Duell, Jochen Dingfelder, **in preparation**

New average of experimental input, that allows for systematics to pull on central values:

$$\mathcal{L} = \prod_{i\in\mathrm{meas}} \mathcal{L}_i \prod_{j\in\mathrm{NP}} \mathcal{P}_j$$

- Can average differential branching fractions in finest given granularity
  - Results in one averaged spectrum + correlations that can be analyzed separately
  - Pulls on systematic errors are propagated through to the central values of the measured distributions





A closer look on the exclusive $|V_{ub}|$ side

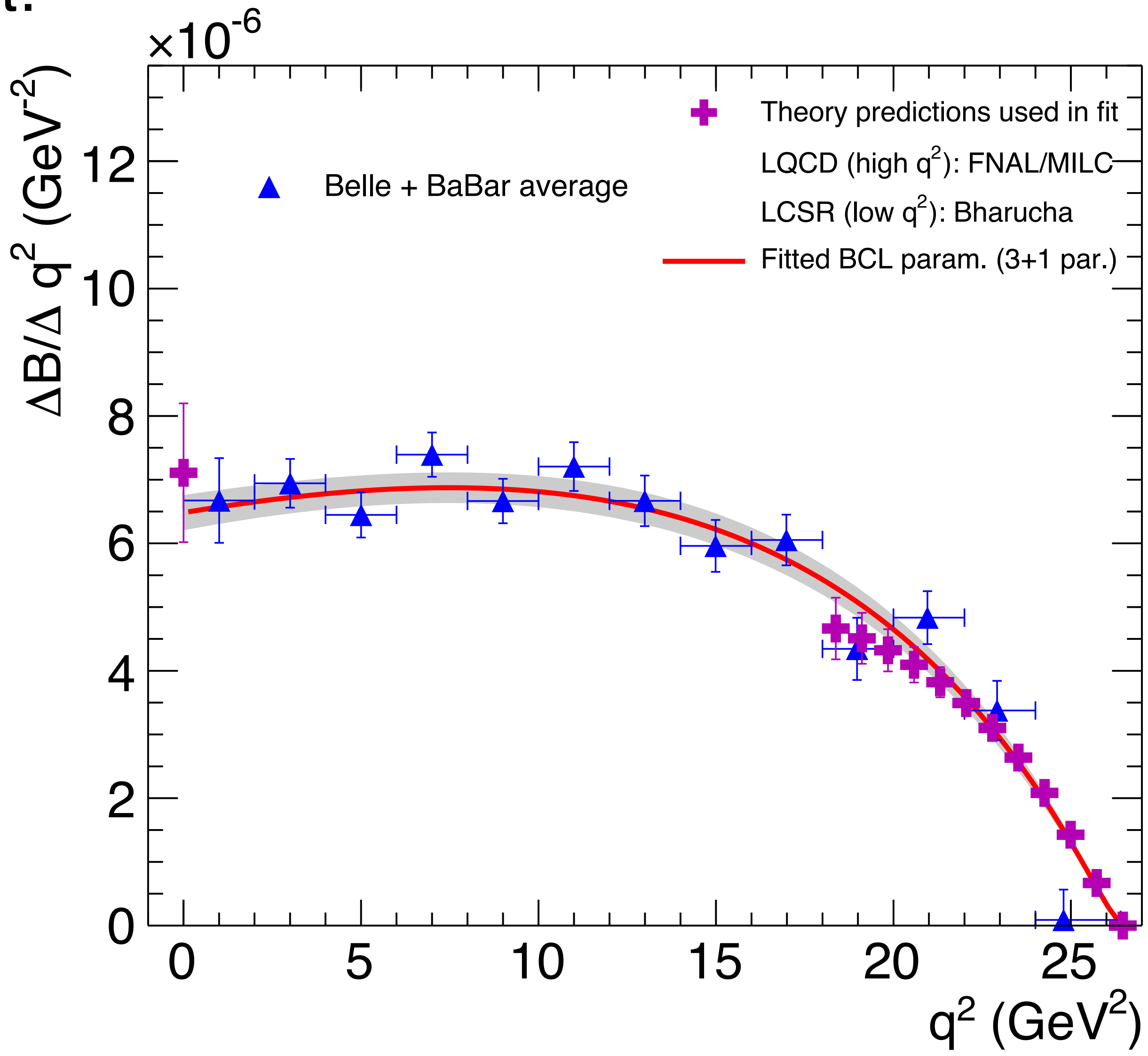
FB, Stephan Duell, Jochen Dingfelder, **in preparation**

Result of BCL + Fermilab/MILC + Bharucha fit:

$$|V_{ub}| \times 10^{-3} = 3.67 \pm 0.13$$

$$\chi^2/\text{ndf} = 21.9/22 \quad P = 0.47$$

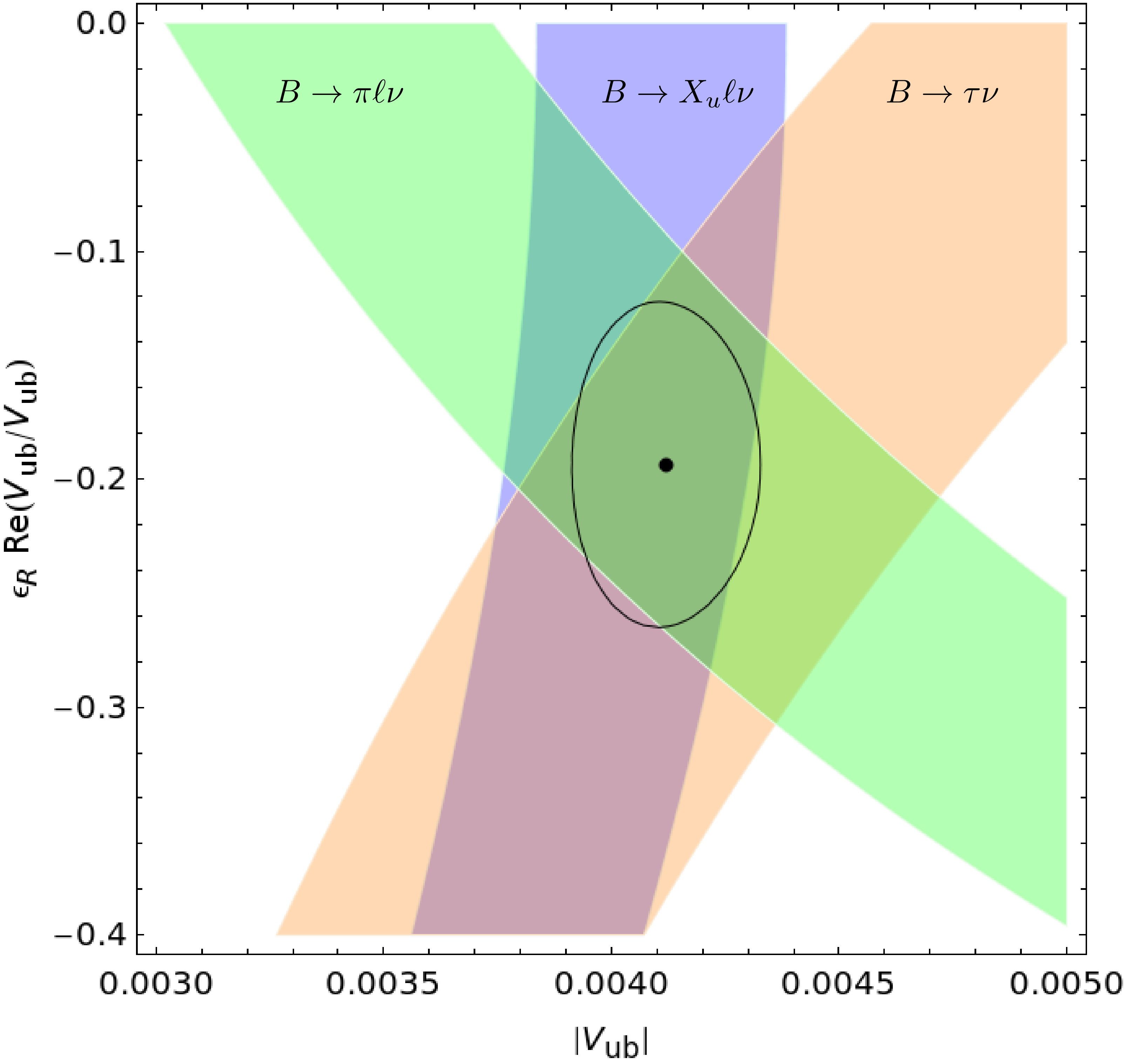
- Used only large q² range for lattice input
  - Some tension in shape between data and lattice
  - High q² region sensitive to modelling of other SL b → u transitions
  - Will need substantially larger data set to improve understanding there.

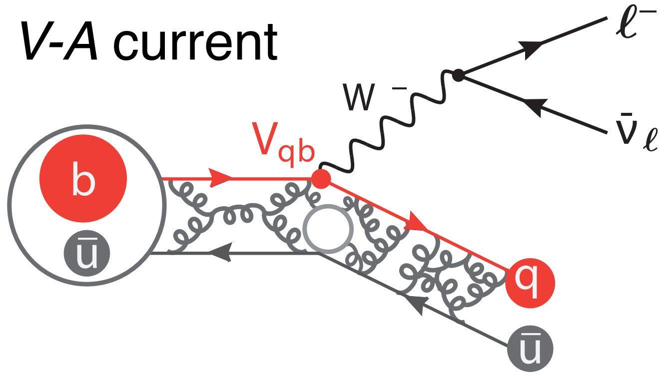


Right-handed currents & $|V_{ub}|$

Quark flavour mixing with right-handed currents: an effective theory approach

Andrzej J. Buras[a,b], Katrin Gemmler[a], Gino Isidori[b,c]



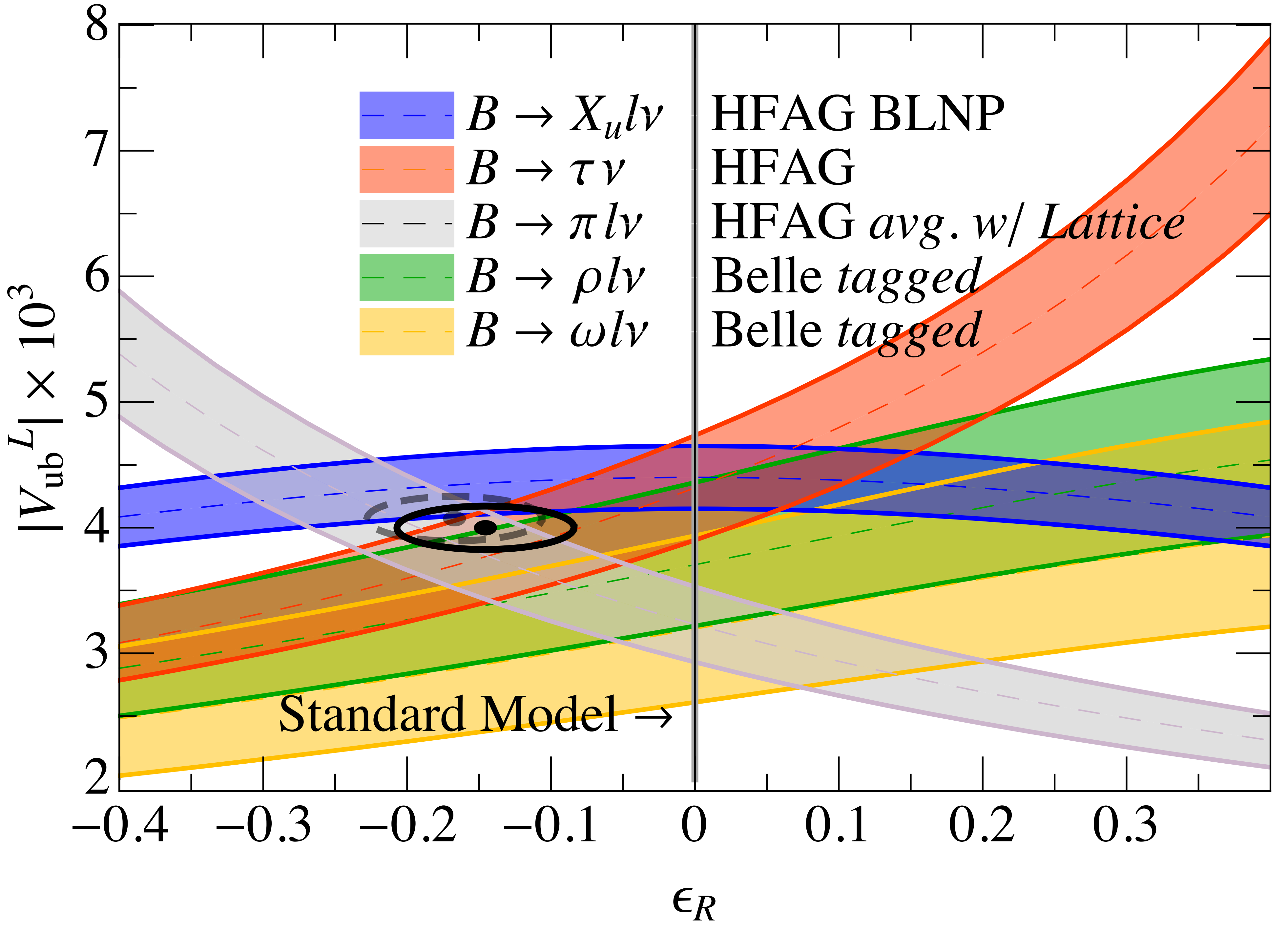


$$V \to (1+\epsilon_R)\,V\,, \qquad A_i \to (1-\epsilon_R)\,A_i\,.$$

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

Right-handed currents & $|V_{ub}|$

Fit	$\lvert V_{ub}^L\rvert \times 10^4$	ϵ_R	χ^2 / ndf	Prob.
3 modes	4.07 ± 0.18	-0.17 ± 0.06	$2.5\,/1$	0.11
4 modes	4.00 ± 0.17	-0.15 ± 0.06	$4.5\,/2$	0.11



FB, Zoltan Ligeti, Sascha Turczyk, **Phys. Rev. D 90, 094003 (2014)**

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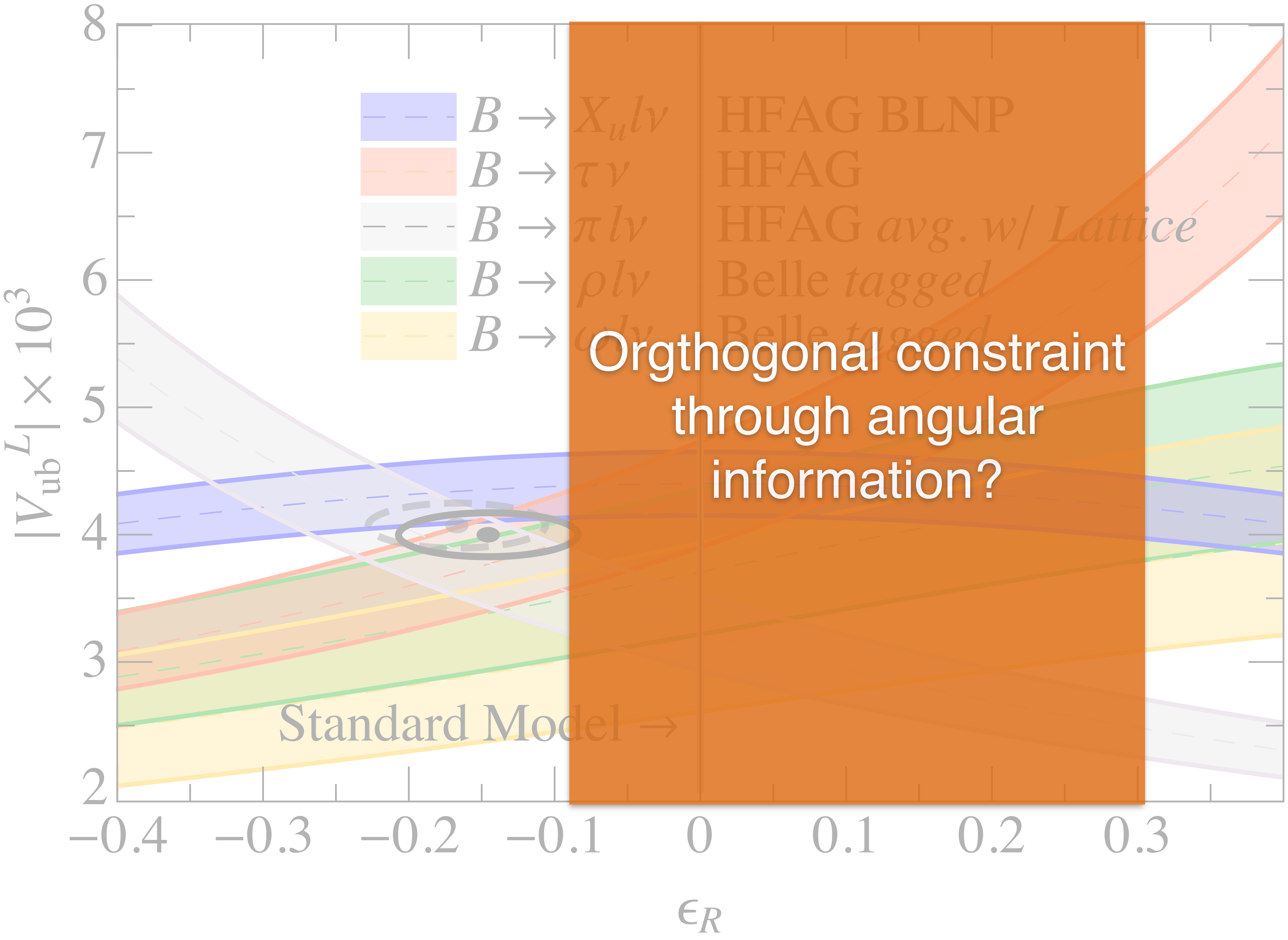


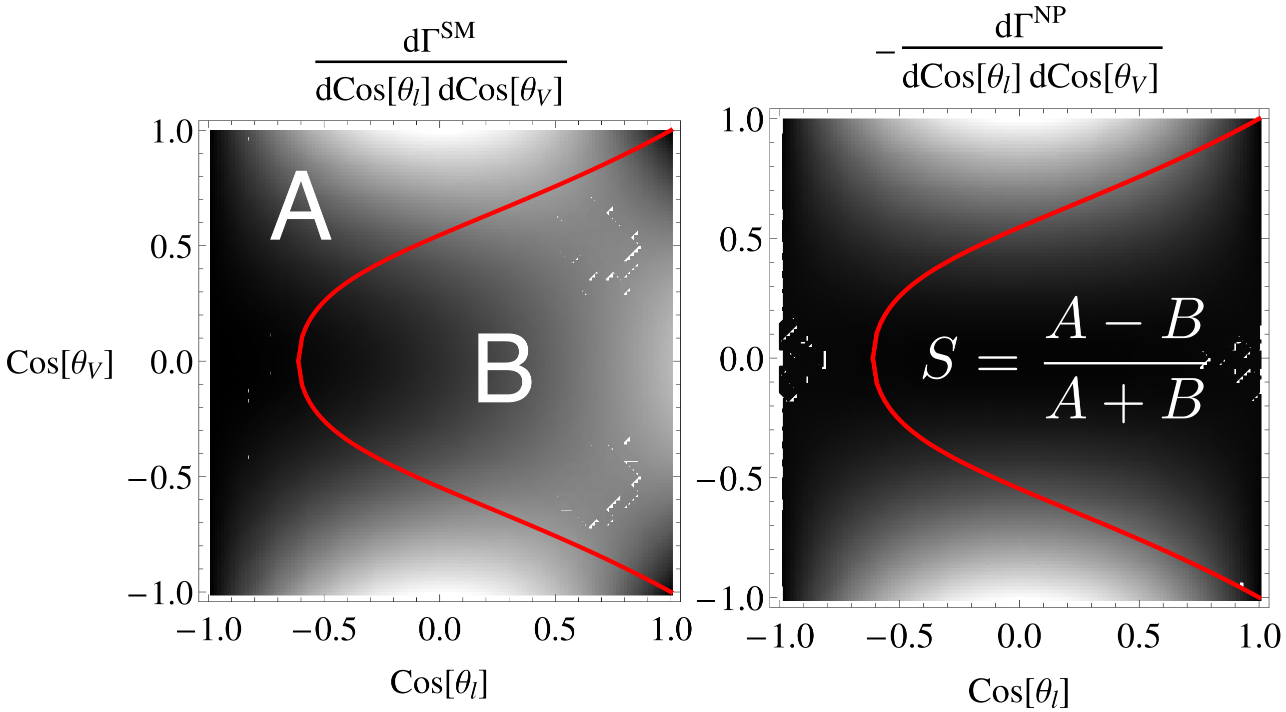
Orgthogonal constraint through angular information?

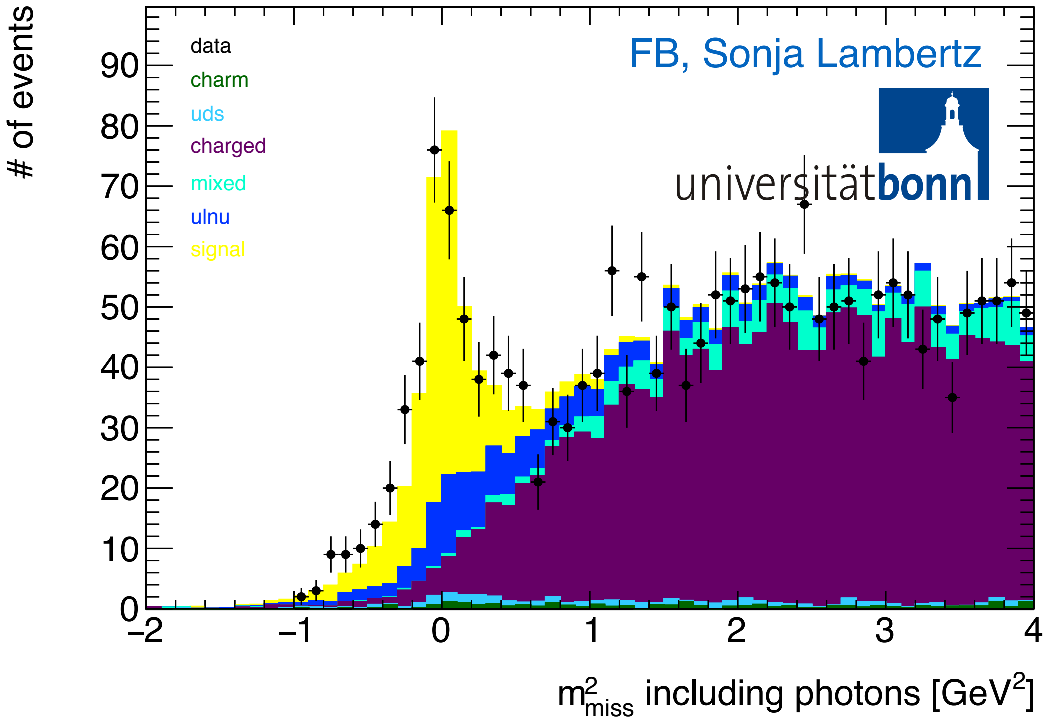
FB, Zoltan Ligeti, Sascha Turczyk, **Phys. Rev. D 90, 094003 (2014)**

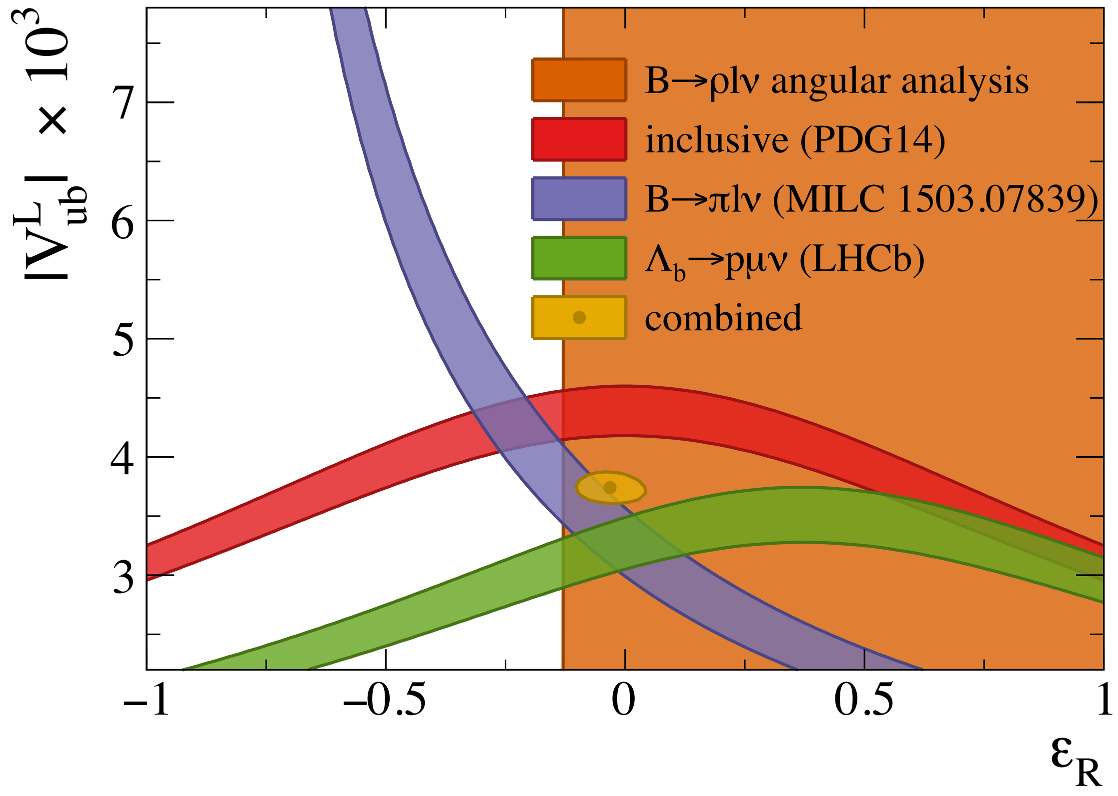
Right-handed currents & $|V_{ub}|$

FB, Zoltan Ligeti, Sascha Turczyk, **Phys. Rev. D 90, 094003 (2014)**

$$
\begin{aligned}
\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_V\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\chi} &= \frac{G_F^2|V_{ub}^L|^2 m_B^3}{2\pi^4} \\
\times \Big\{ & J_{1s}\sin^2\theta_V + J_{1c}\cos^2\theta_V \\
&+ (J_{2s}\sin^2\theta_V + J_{2c}\cos^2\theta_V)\cos 2\theta_\ell \\
&+ J_3\sin^2\theta_V\sin^2\theta_\ell\,\cos 2\chi \\
&+ J_4\sin 2\theta_V\sin 2\theta_\ell\,\cos\chi + J_5\sin 2\theta_V\sin\theta_\ell\,\cos\chi \\
&+ (J_{6s}\sin^2\theta_V + J_{6c}\cos^2\theta_V)\cos\theta_\ell \\
&+ J_7\sin 2\theta_V\sin\theta_\ell\,\sin\chi + J_8\sin 2\theta_V\sin 2\theta_\ell\,\sin\chi \\
&+ J_9\sin^2\theta_V\sin^2\theta_\ell\,\sin 2\chi \Big\}. \qquad (3)
\end{aligned}
$$

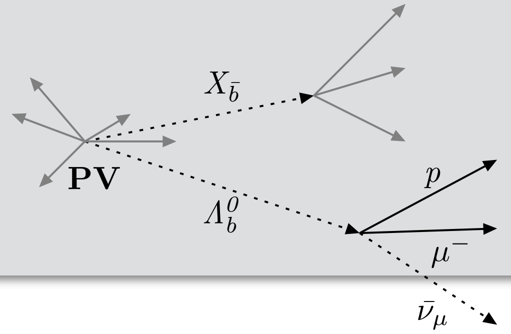






$|V_{ub}|$ from baryonic decays and more on RH currents

LHCb: Nature Physics 10 (2015) 1038



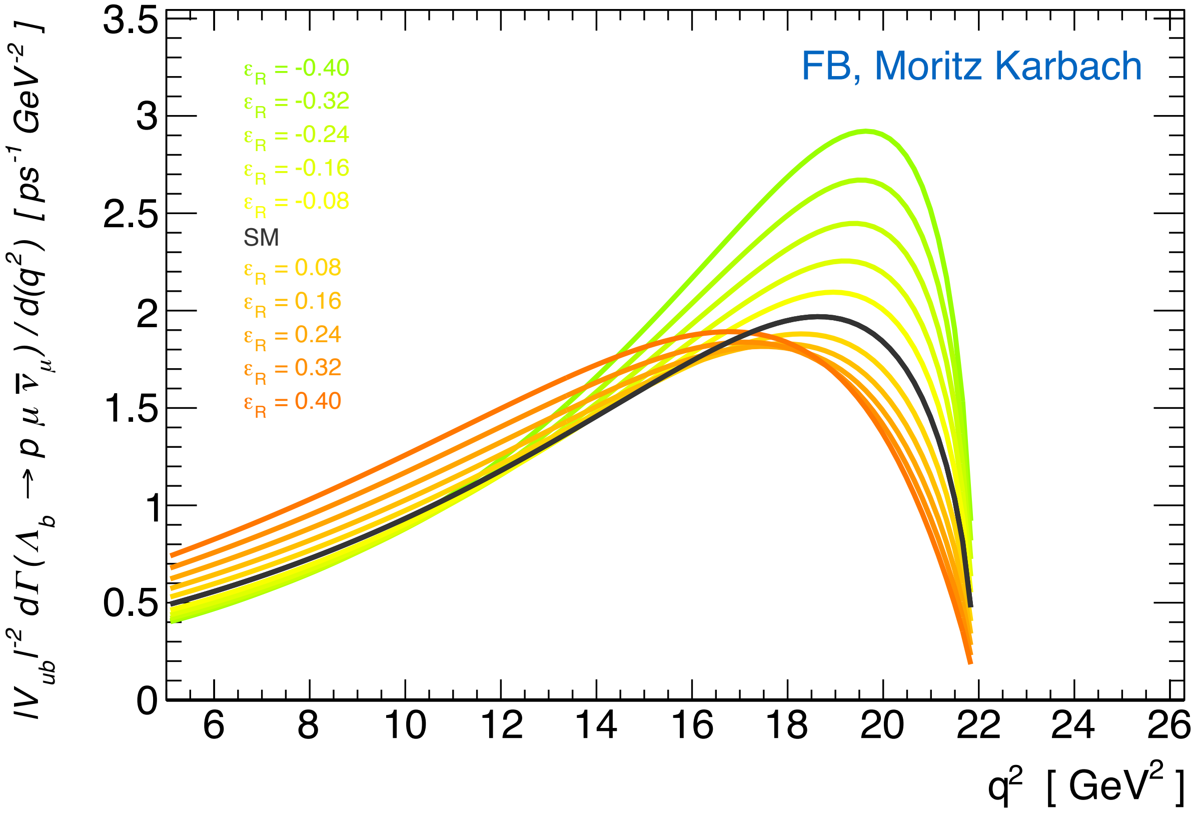
LHCb carried out very nice measurement of

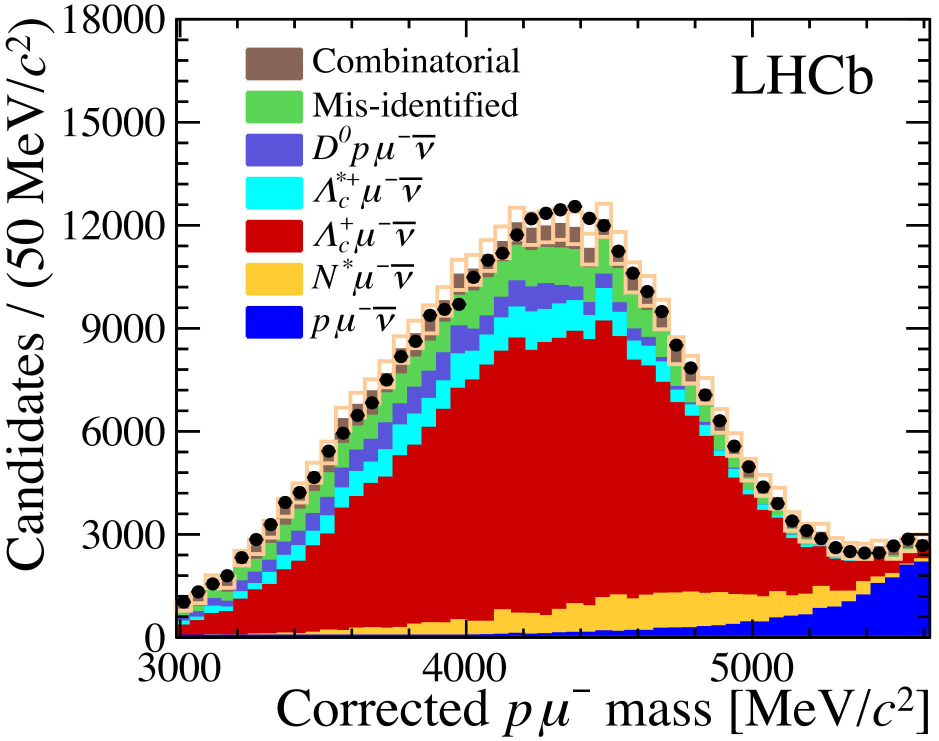
$$\Lambda_b \to p\,\mu\,\bar{\nu}_\mu$$

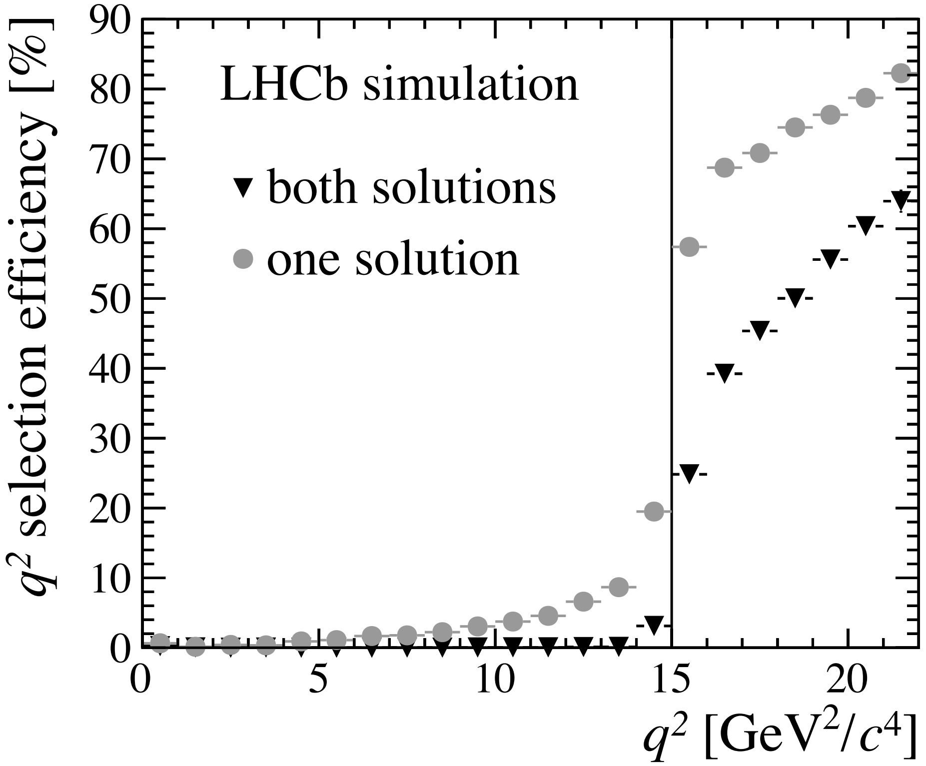
- Can be well reconstructed due to well separated secondary vertex and clean final states
- Signal & background separation in corrected mass:

$$m_{\rm corr} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp,$$

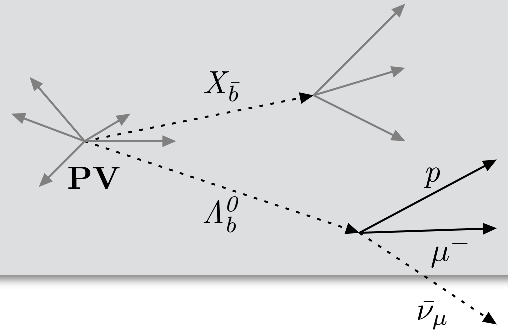
- Helped carrying out an interpretation of RH currents







|V$_{ub}$| from baryonic decays and more on RH currents



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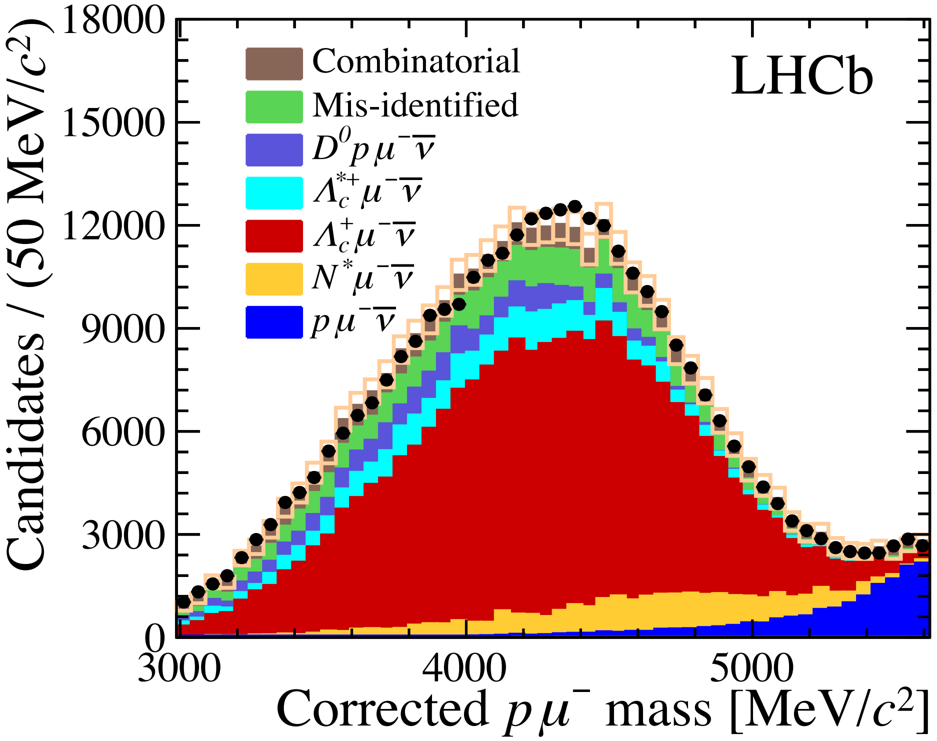
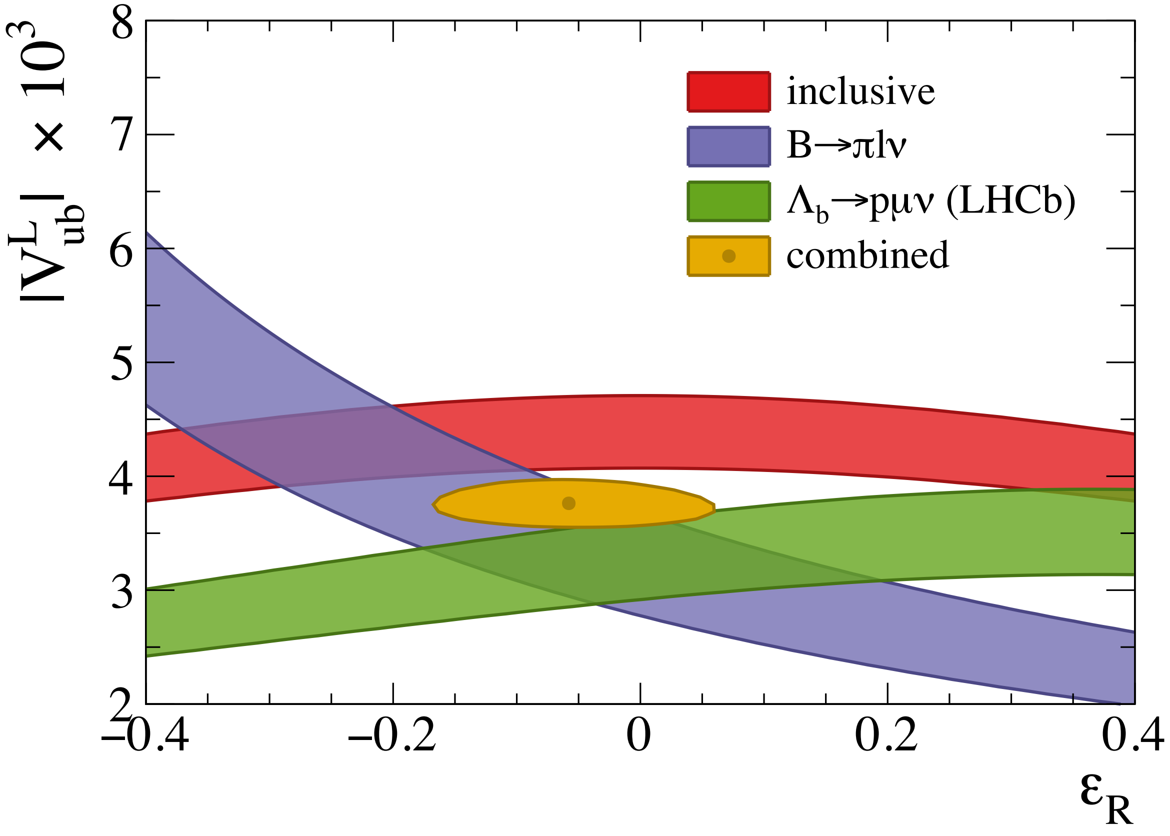
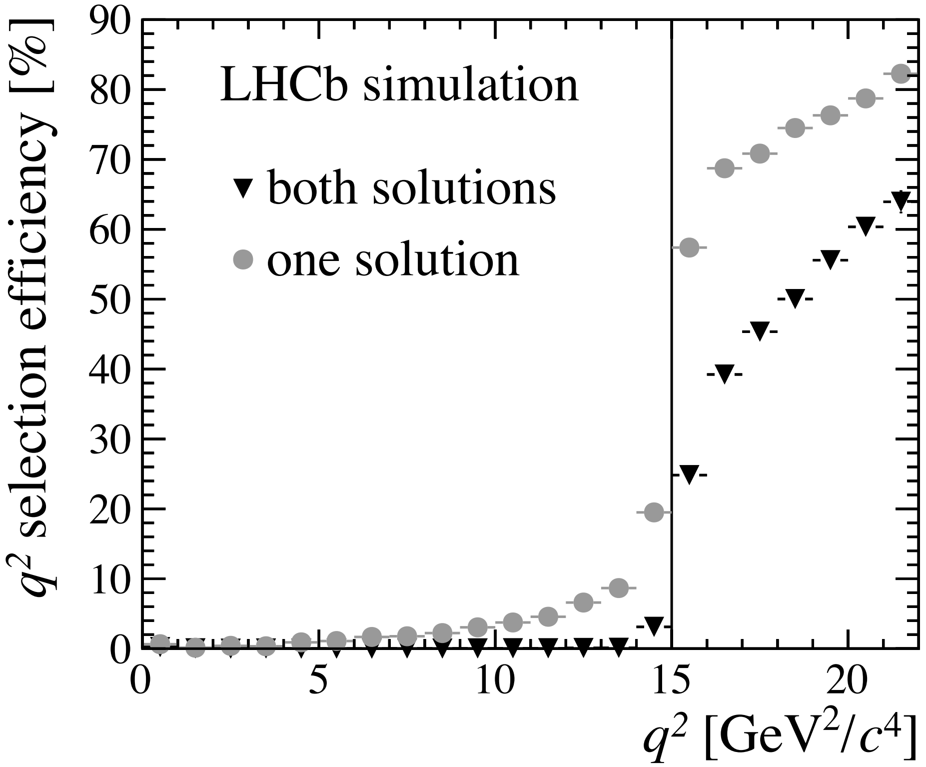


- Helped carrying out an interpretation of RH currents





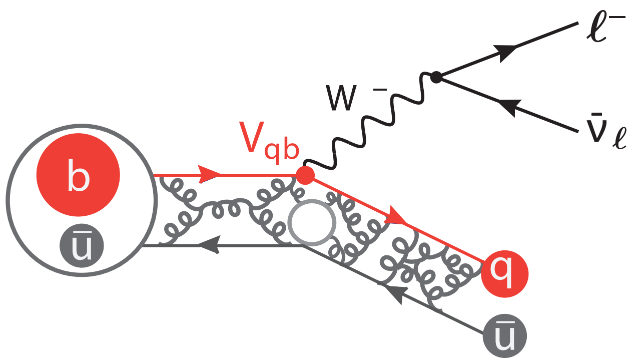
A closer look on the inclusive |V$_{ub}$| side

from experiment

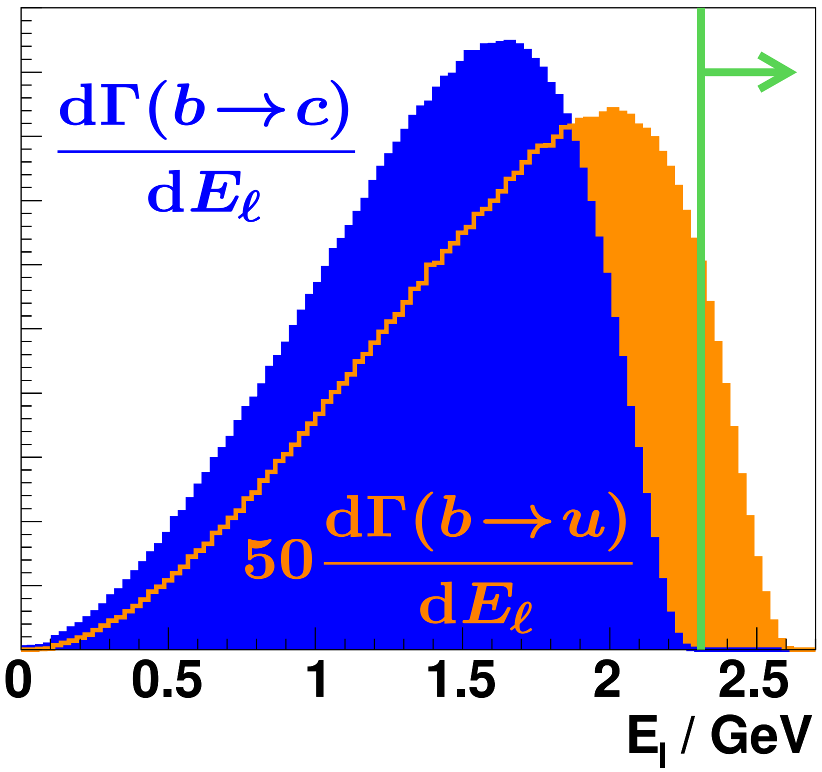
$$|V_{qb}| = \sqrt{\frac{\mathcal{B}(B \to X_q \, \ell \, \bar{\nu}_\ell)}{\Gamma(B \to X_q \, \ell \, \bar{\nu}_\ell) \, \tau_B}}$$

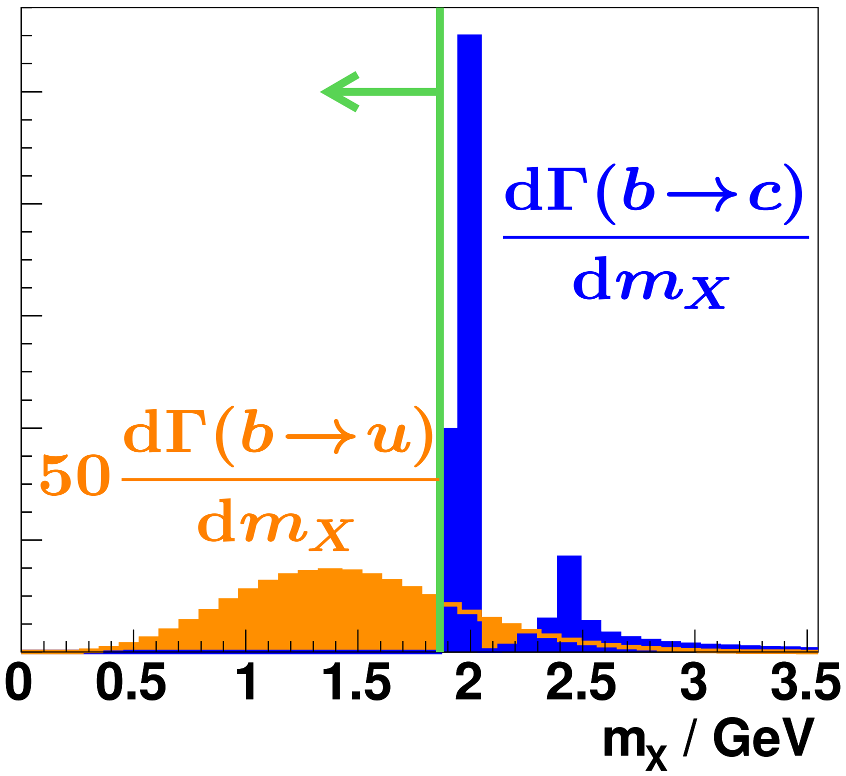
from theory

Inclusive measurements very challenging:



- CKM favoured b → c largest background (50 x larger)
  - Near identical signature: lepton, one missing neutrino
  - Can only be clearly separated near kinematic endpoints





- **Problem**: cannot make reliable theory predictions there
  - Predictions depend on details of B-meson PDF
    - Fermi motion of b-quarks inside the B-meson determine details near kinematic endpoint

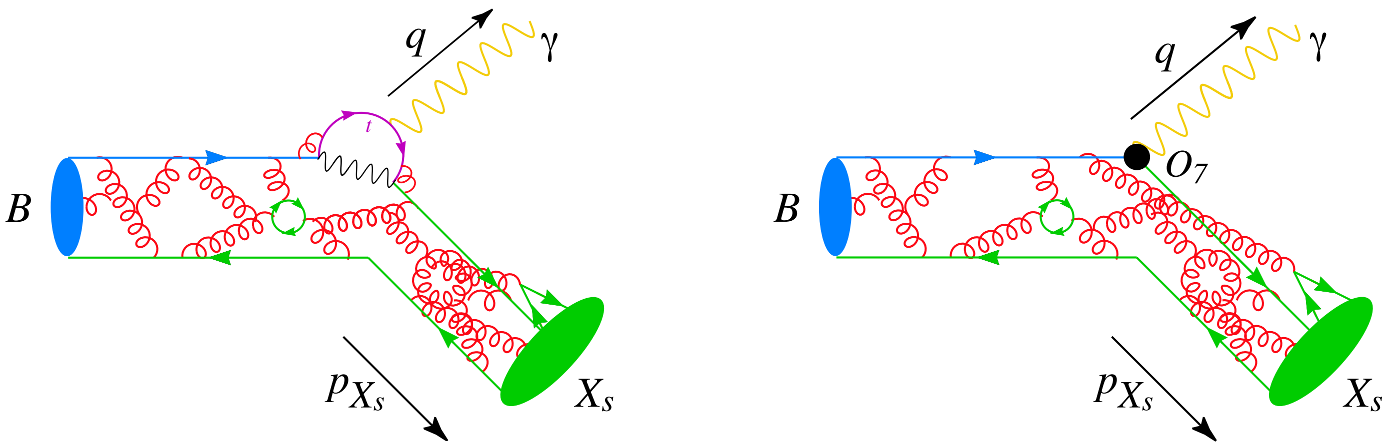
A closer look on the inclusive $|V_{ub}|$ side

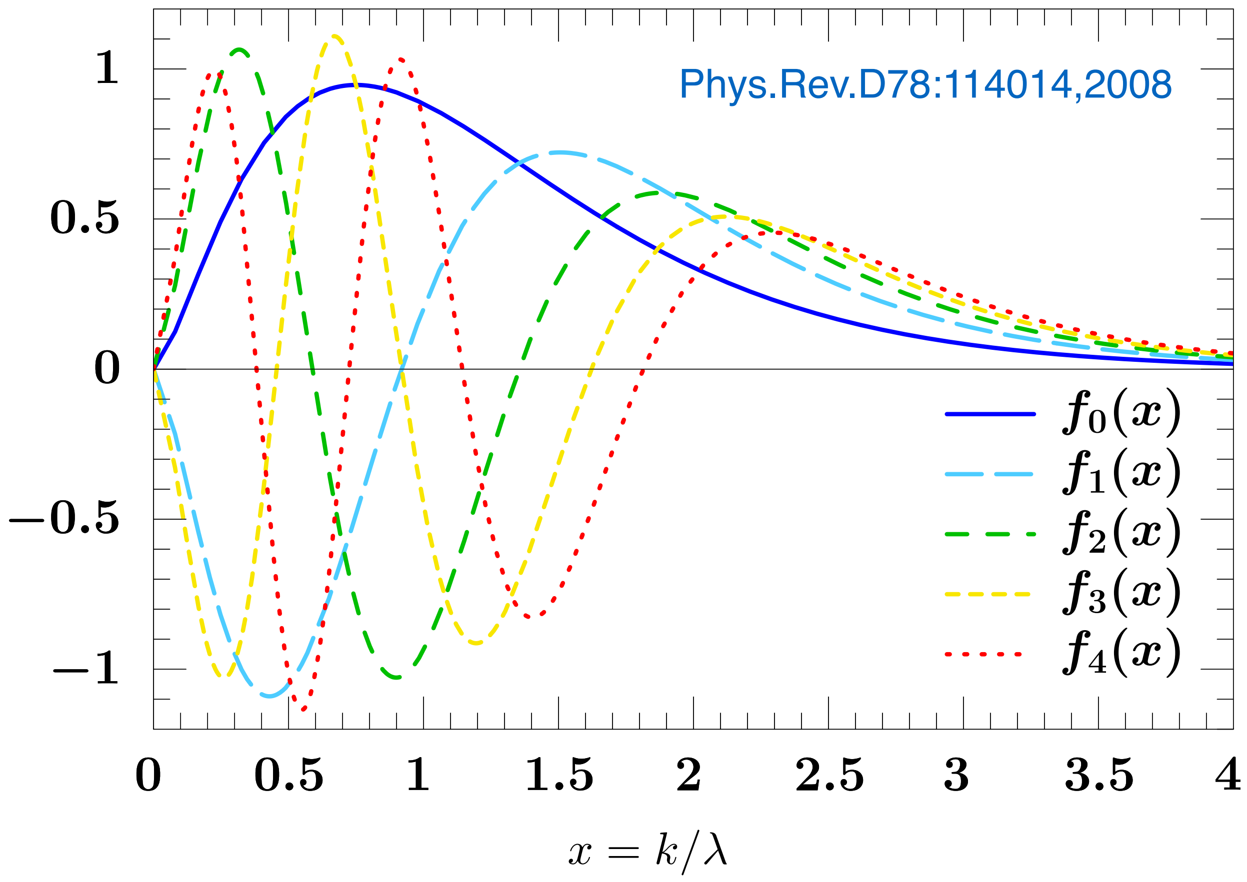
SIMBA idea: measure the non-perturbative details simultaneously with $|V_{ub}|$

orthonormal expansion

$$\boxed{\widehat{F}(k) = \left[\sum_n c_n f_n(k)\right]^2 ,}$$

coefficients contain non-perturbative physics





Phys.Rev.D78:114014,2008

FB, Heiko Lacker, Zoltan Ligeti, Ian Stewart, Kerstin Tackmann, Frank Tackmann, **in preparation**

A closer look on the inclusive |V_{ub}| side

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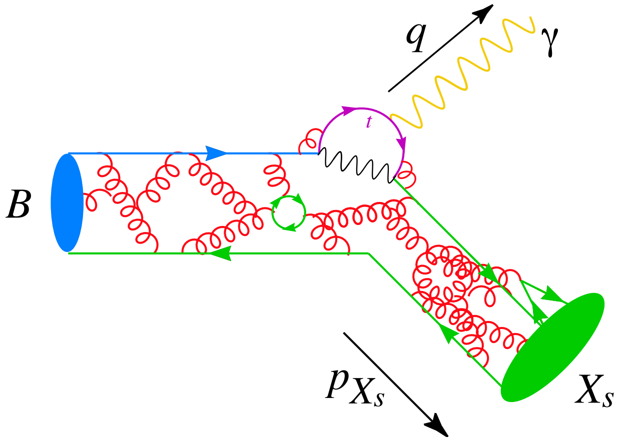
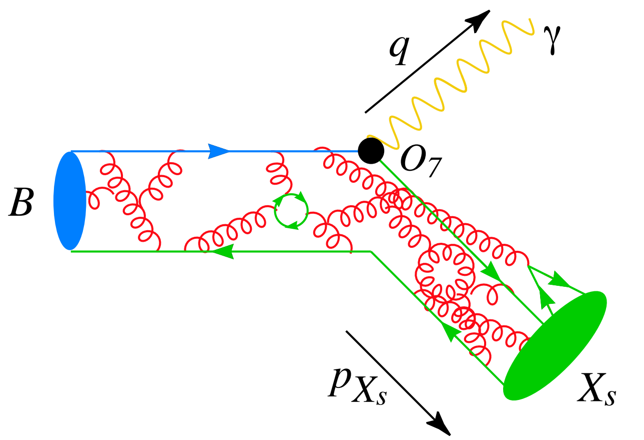
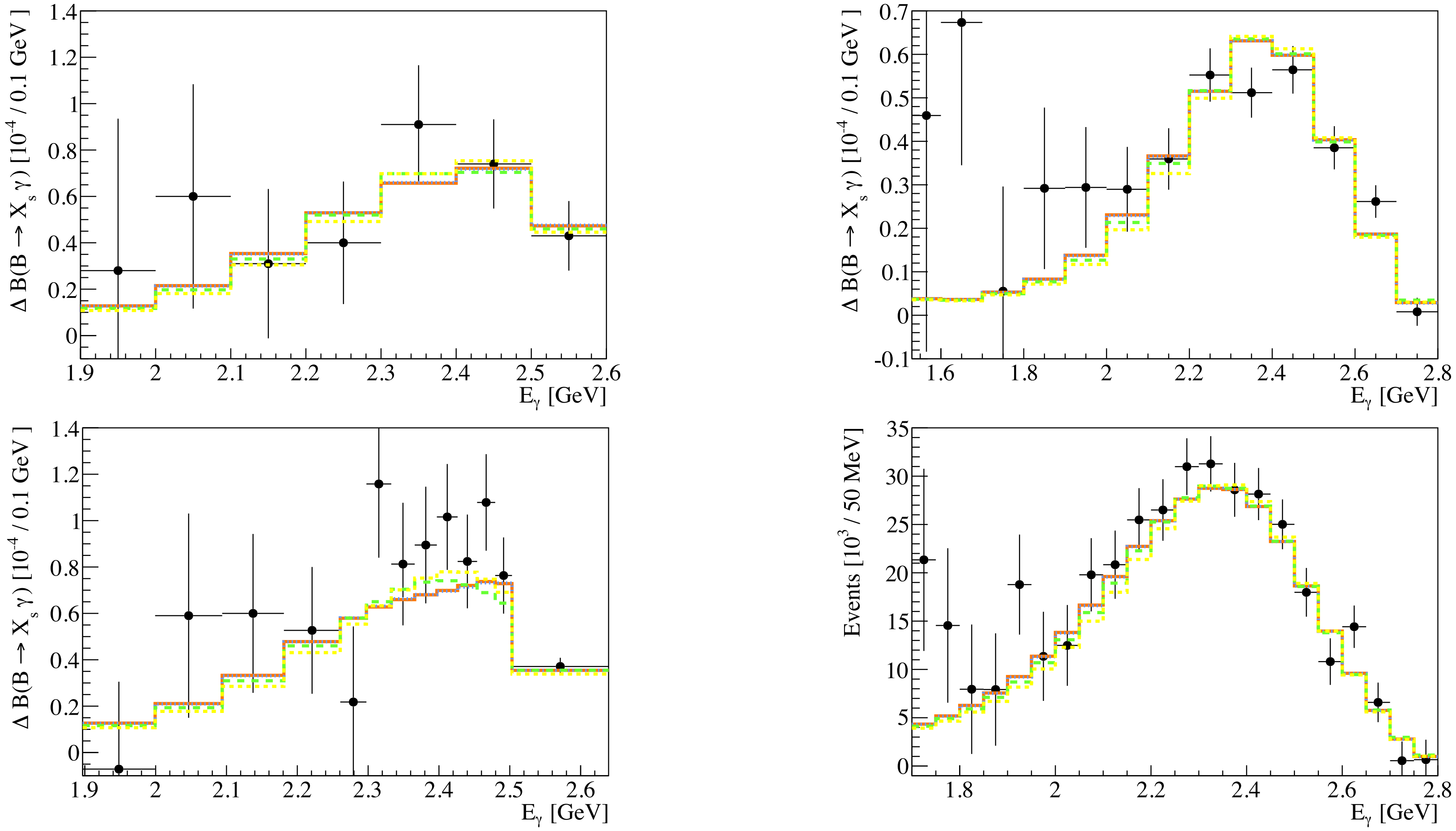


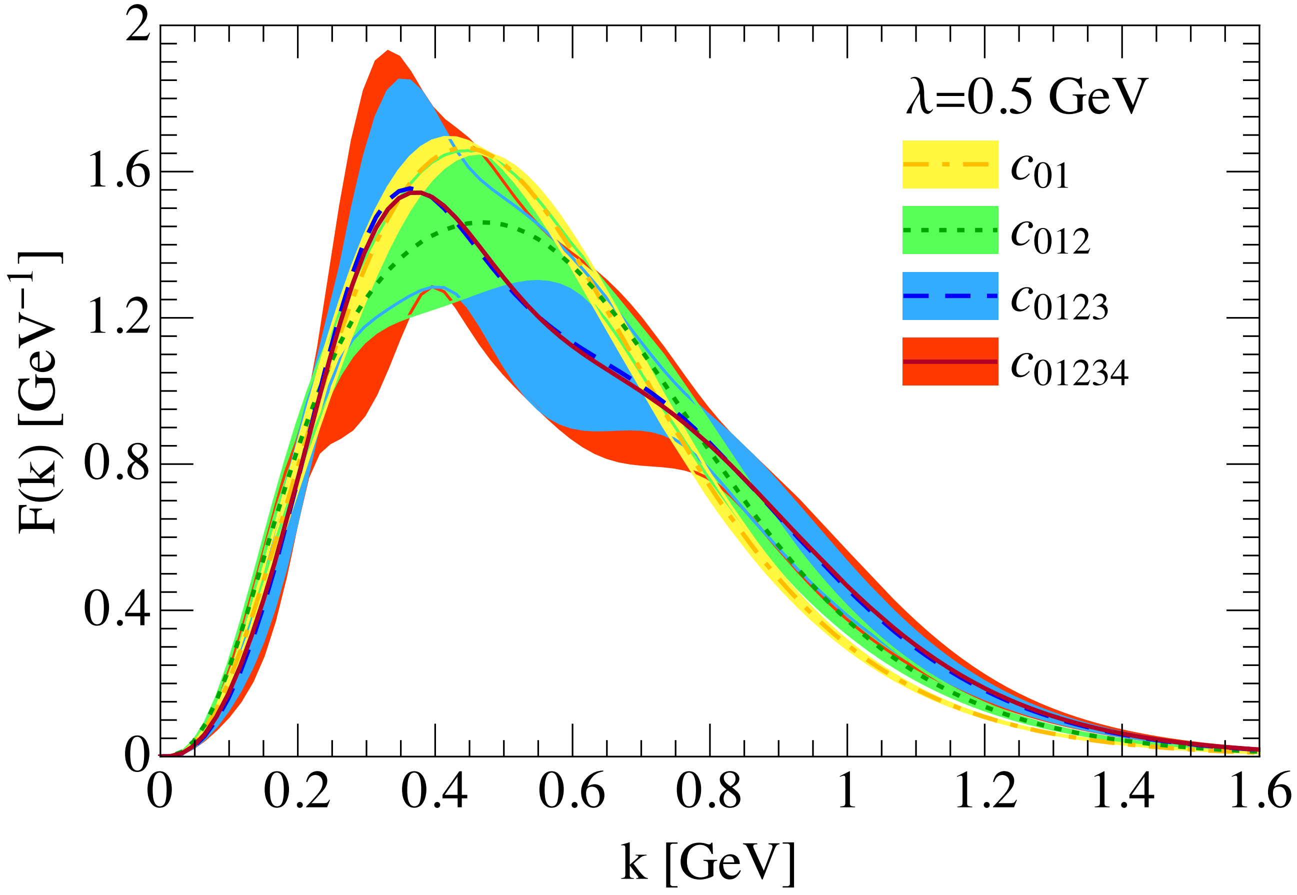


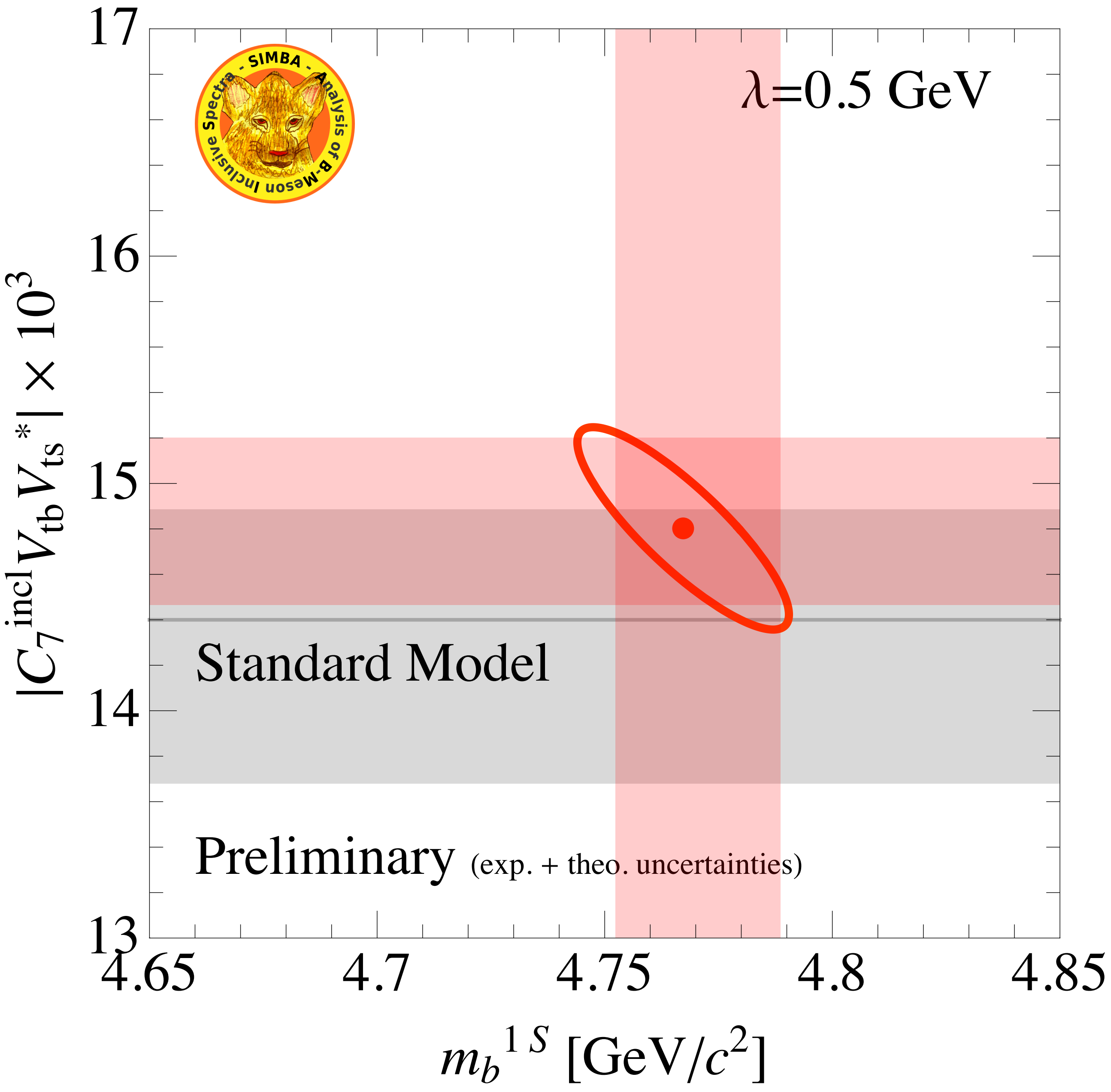


FB, Heiko Lacker, Zoltan Ligeti, Ian Stewart, Kerstin Tackmann, Frank Tackmann, **in preparation**

A closer look on the inclusive $|V_{ub}|$ side

SIMBA idea: measure the non-perturbative details simultaneously with $|V_{ub}|$





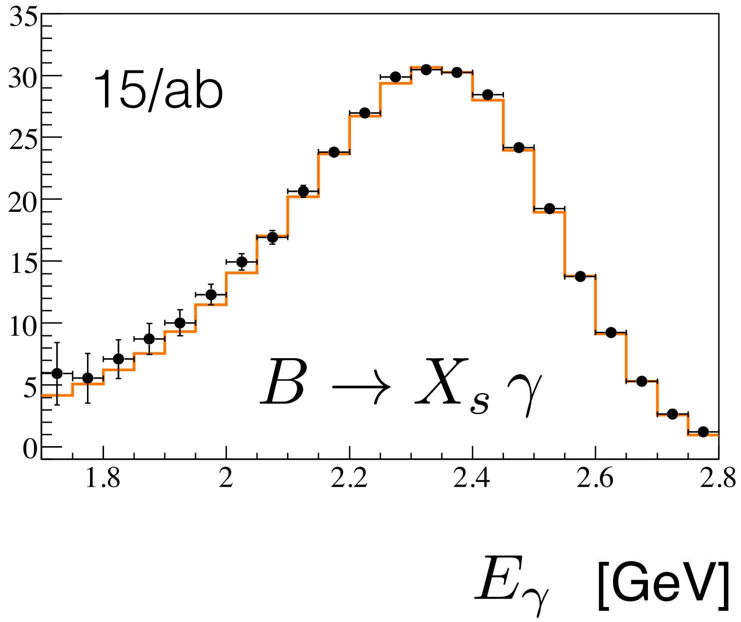
FB, Heiko Lacker, Zoltan Ligeti, Ian Stewart, Kerstin Tackmann, Frank Tackmann, **in preparation**

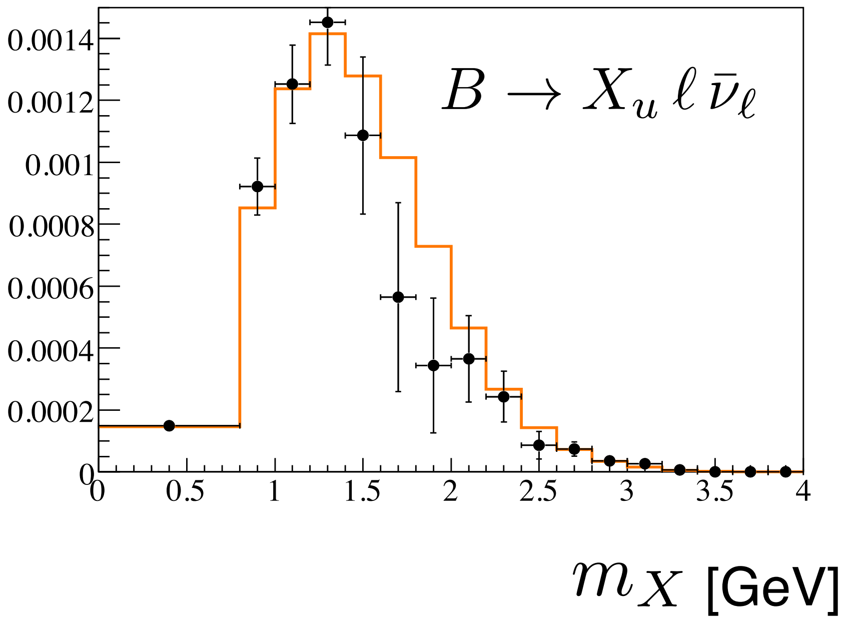
A closer look on the inclusive $|V_{ub}|$ side

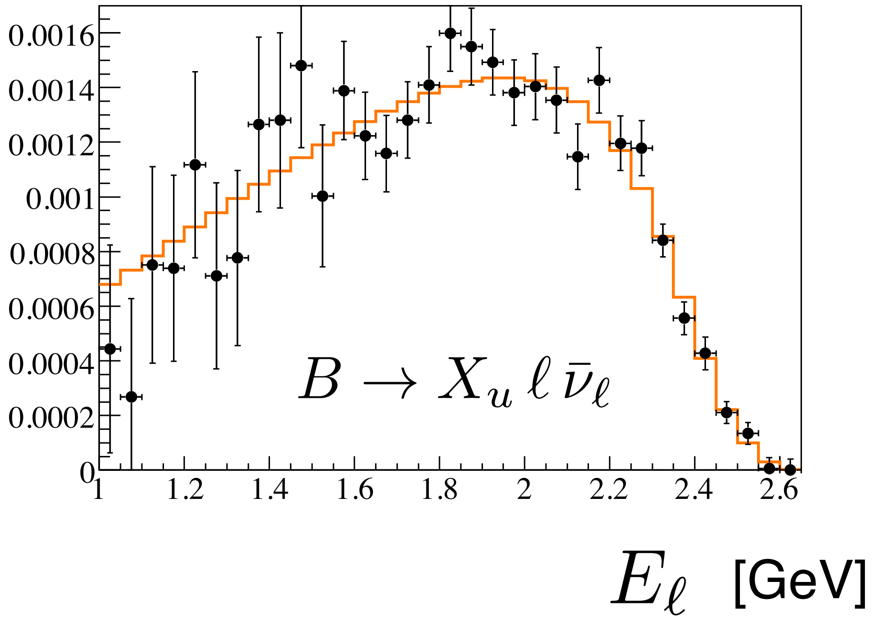
To carry this out to its full potential: need differential measurements

- Differential branching fractions of inclusive SL b → u and b → c decays
  - For SL b → u very difficult, but not impossible with B-Factory data
  - For SL b → c: was never a priority to measure
- Auxiliary input: Differential measurements of inclusive b → s ɣ

$$\frac{d\Gamma(\bar{B} \to X_s\,\gamma)}{dE_\gamma} = 2\,H_s \int dk\,\widehat{P}_s(k)\,\widehat{F}(k)\,, \qquad \frac{d\Gamma(\bar{B} \to X_u\,\ell\,\bar{\nu}_\ell)}{dE_\ell\,dp_X^+\,dp_X^-} = H_u \int dk\,\widehat{P}_u(k)\,\widehat{F}(k)\,.$$







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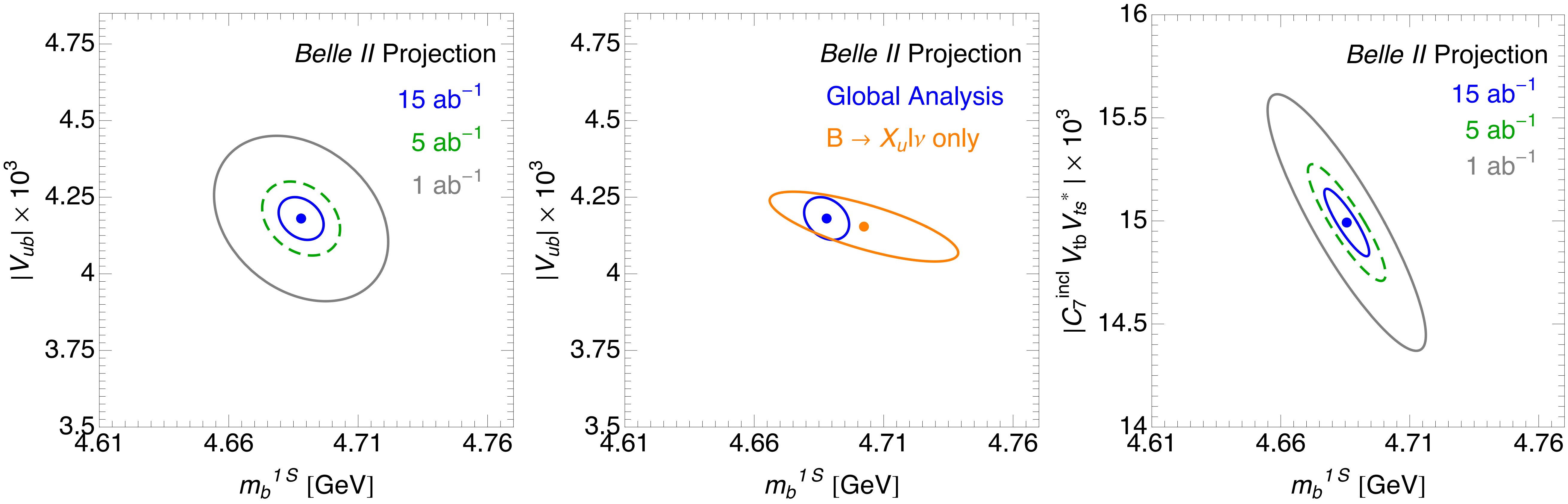
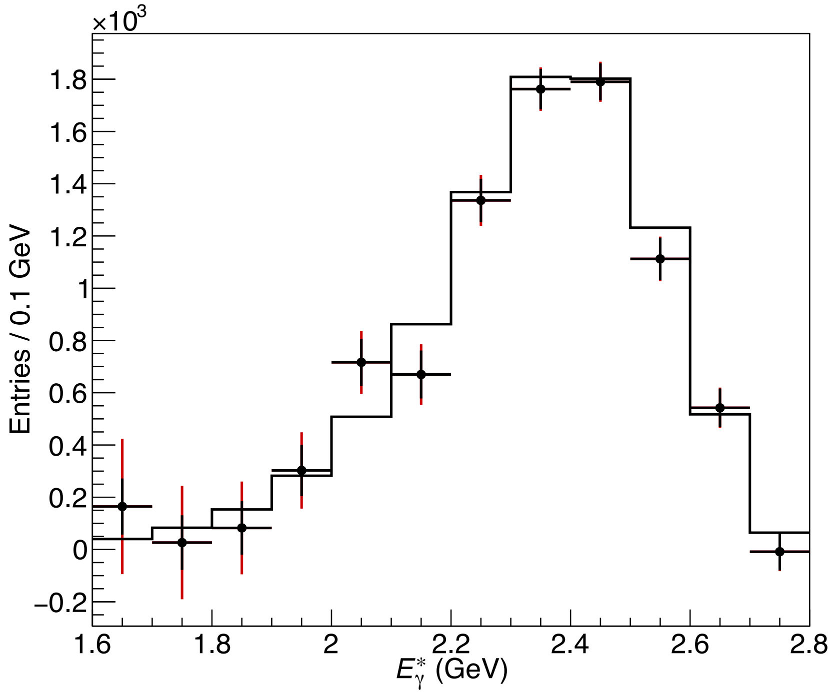
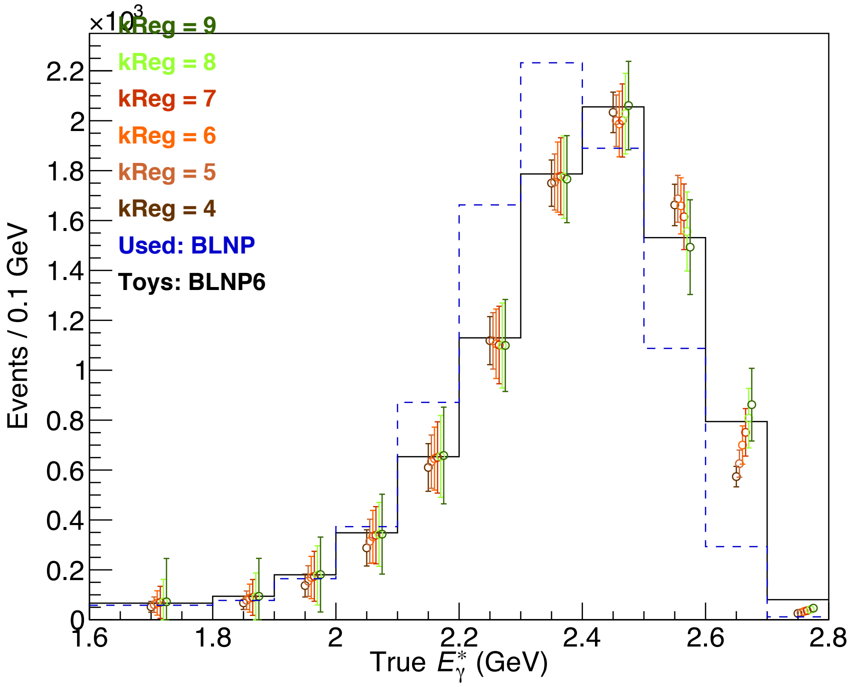


Important auxiliary input:

Currently repeating untagged inclusive b → s ɣ measurement:

- Reconstruct high energetic photon
- Veto events with continuum or B-background signature (multivariate)
  - At low photon energies: mostly background from other B-decays
  - Reliable measurements possible down to about 1.8-2 GeV
  - Theory prediction at NNLO from Misiak et al in B-meson rest frame with Eɣ > 1.6 GeV cut
    - For higher cuts the branching fraction depends on the details of the b-quark PDF / shape function





Unfolded toys in True E_γ^{CM}

Result aims to be out for ICHEP

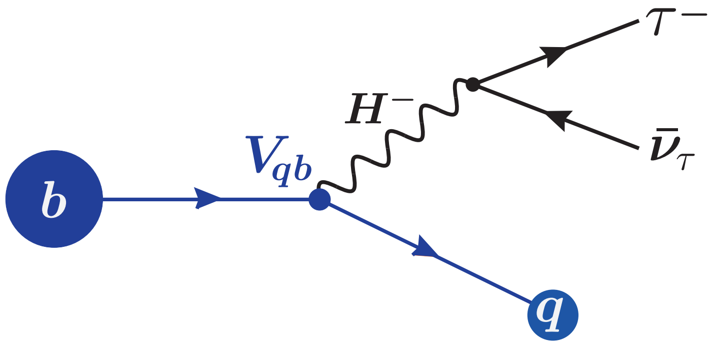
- Working on last details of unfolding
  - ‘Unfolding’ = reverting resolution induced migrations

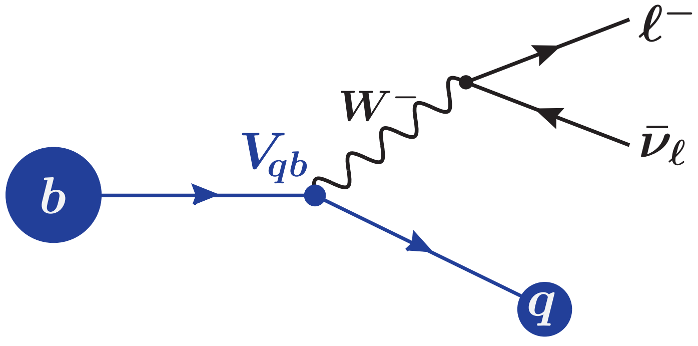
Flavour Anomalies: *R(D) & R(D*)*

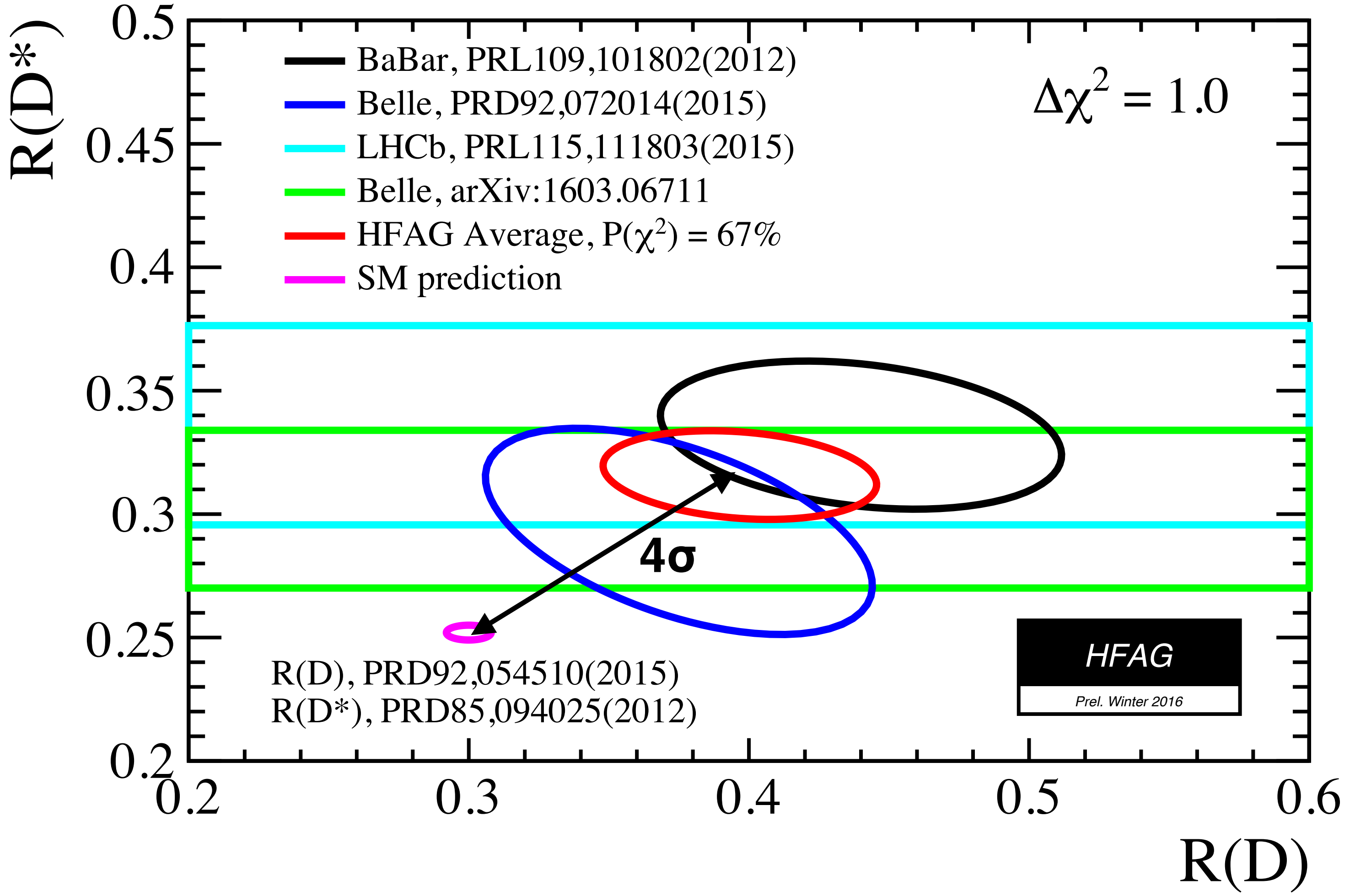
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\,\ell\,\bar{\nu}_\ell)}$$

Another anomaly in the flavour sector is between that ratio of semitauonic and light lepton branching fractions

- Sensitive to for instance to contributions from a charged Higgs Boson
- In the prediction of this ratio, many of the theory uncertainties cancel
- Excess seen by BaBar, Belle and also LHCb







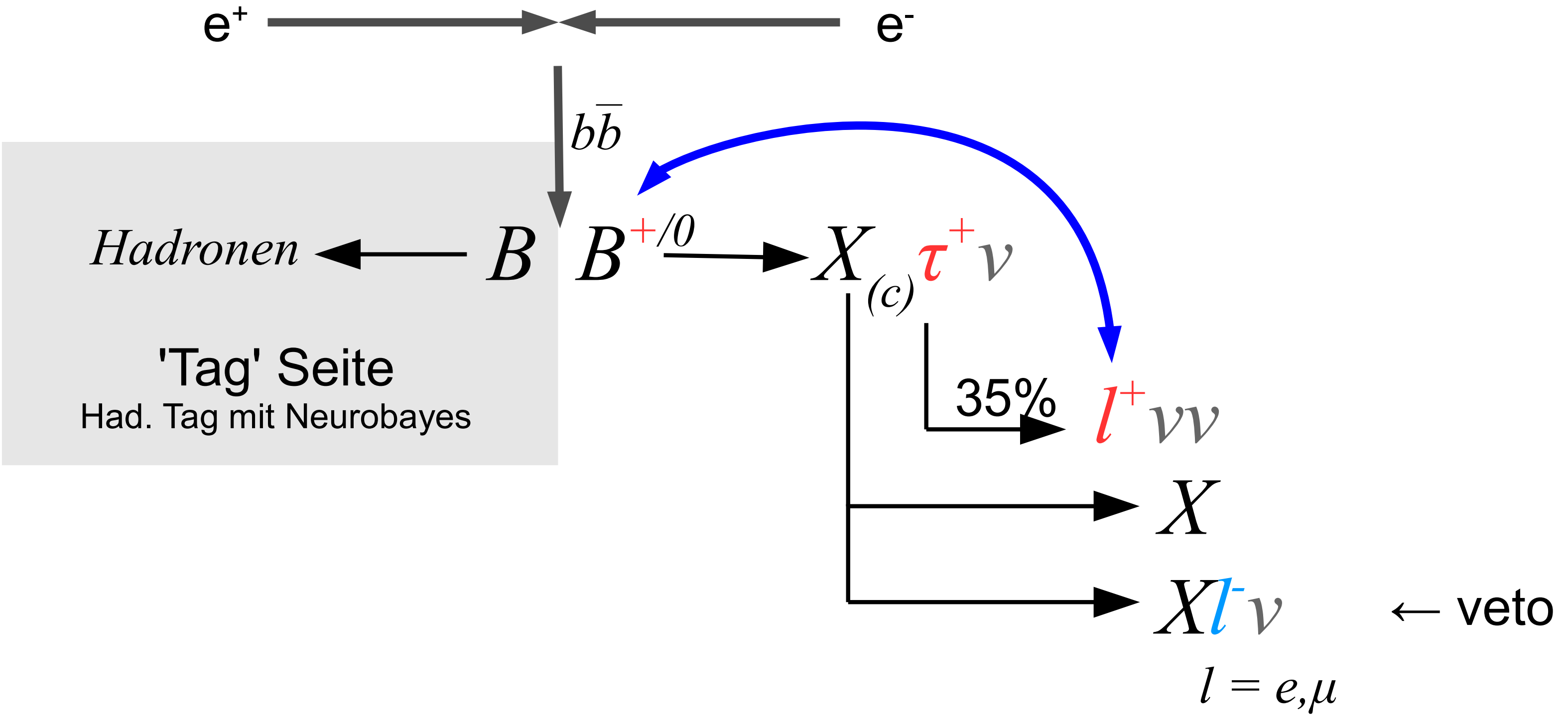
- About **4σ** disagreement between SM expectation and observation
- Deviations not compatible with type II 2HDM, could be accommodated by type III like scenarios

R(X)

Several alternatives to probe the R(D)/R(D*) enhancement:

$$R(X) \quad R(\pi) \quad R(D^{**})$$

Working on an **R(X)** measurement, aiming for ICHEP



e$^+$ e$^-$

$b\bar{b}$

Hadronen ← B $B^{+/0} \rightarrow X_{(c)}\tau^+\nu$

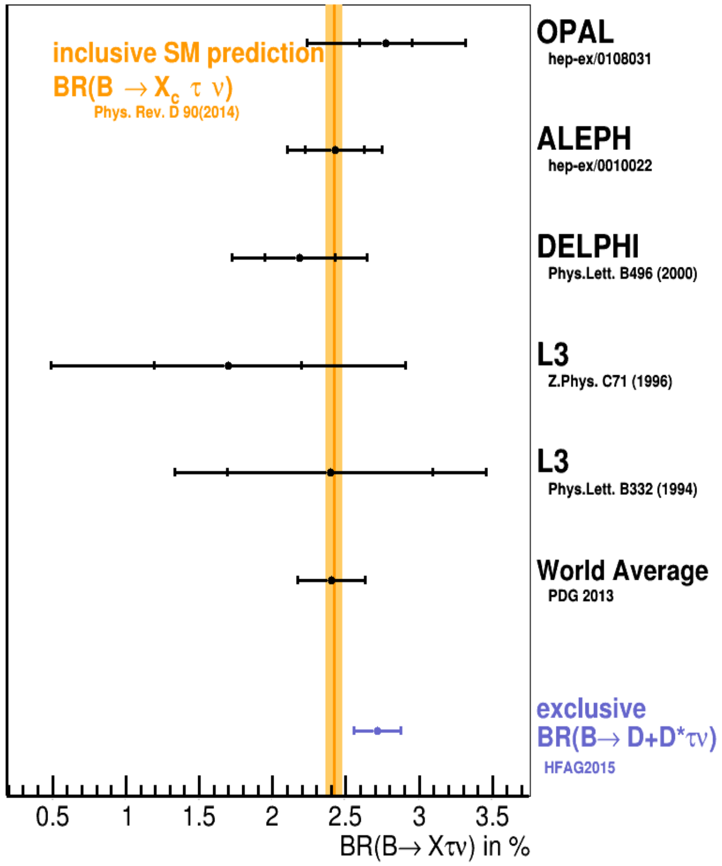
'Tag' Seite
Had. Tag mit Neurobayes

35% → $l^+\nu\nu$

→ X

→ $Xl^-\nu$ ← veto

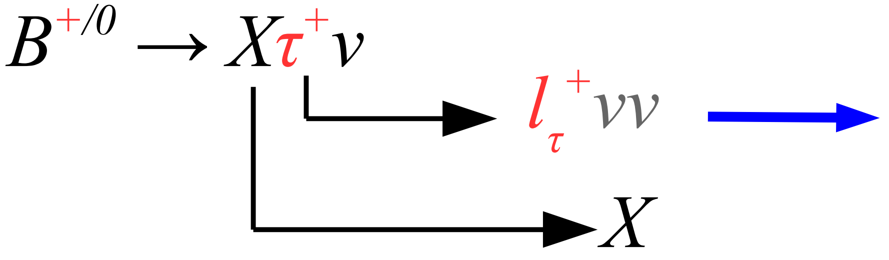
$l = e,\mu$



Diskrepanz zwischen SM und exklusiven B→D$^{(*)}$τν Zerfällen → Neue Physik?

R(X)

Signal


$B^{+/0} \rightarrow X\tau^+\nu$

$\tau^+ \rightarrow l_\tau^+\nu\nu$

X

SL B Zerfälle

$B \rightarrow D^* l\nu$

$B \rightarrow D^* l\nu$

$B \rightarrow D^{**} l\nu$

Andere Zerfälle

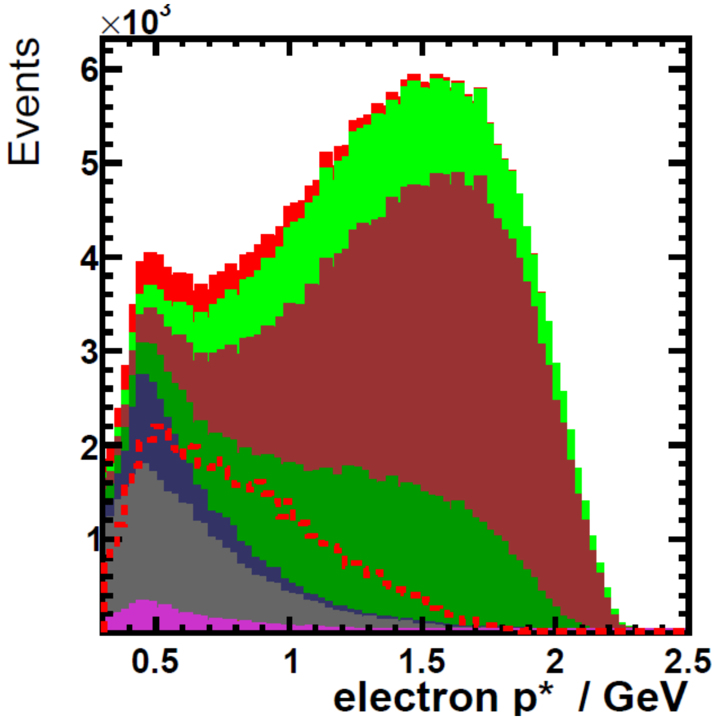
Falsch identifizierte Leptonen

Sekundäre Leptonen

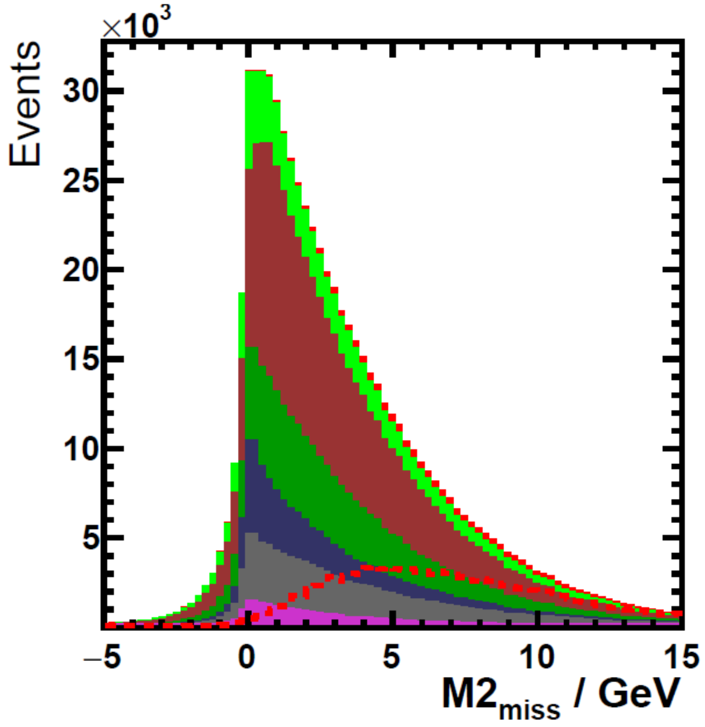
$B \rightarrow X_c(X_c \rightarrow Xl\nu)X$

Kontinuum

$e^+e^- \rightarrow q\bar{q}$ (q = udsc)



Signal-B Ruhesystem



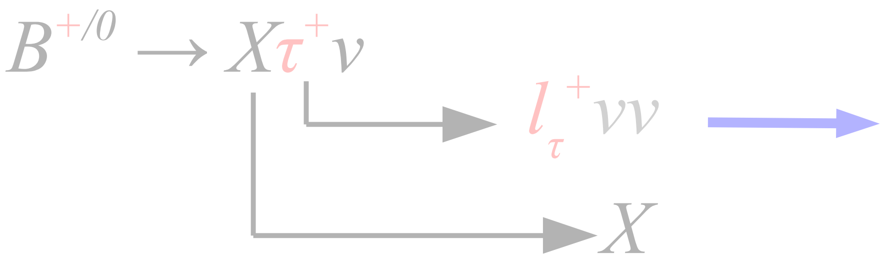
$M^2_{miss} = (p_{tot} - p_{tag} - p^{vis}_{sig})^2$

p^{vis}_{sig} = alle Spuren und Photonen der Signalseite

Peak für Zerfälle ohne oder mit einem Neutrino!

R(X)

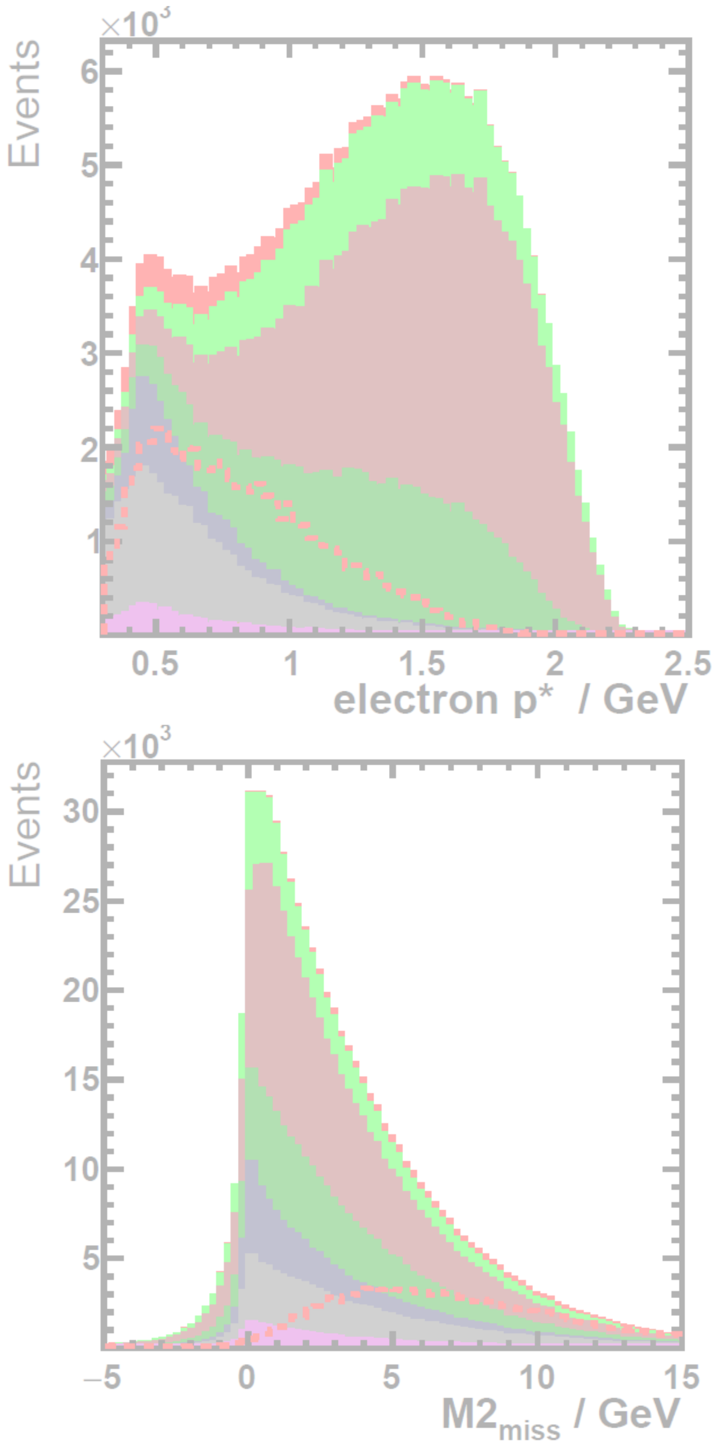
Signal



$B^{+/0} \rightarrow X\tau^{+}\nu$

$l_{\tau}^{+}\nu\nu$

X



Signal composition

D** background

Tagging systematics

Signal-B Ruhesystem

$M^2_{miss} = (p_{tot} - p_{tag} - p^{vis}_{sig})^2$

p^{vis}_{sig} = alle Spuren und Photonen der Signalseite

SL B Zerfälle

$B \rightarrow D^{*} l\nu$

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$e^+e^- \rightarrow q\bar{q}$ (q = udsc)

Peak für Zerfälle ohne oder mit einem Neutrino!

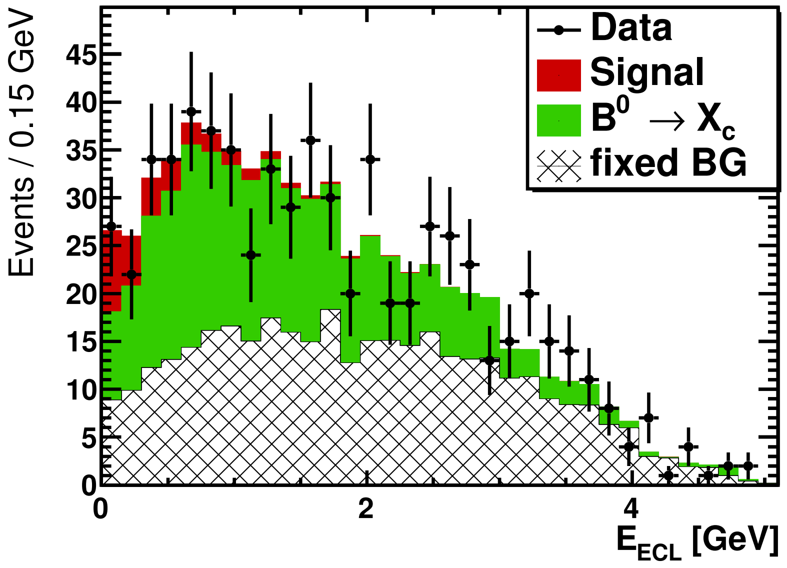
R(π)

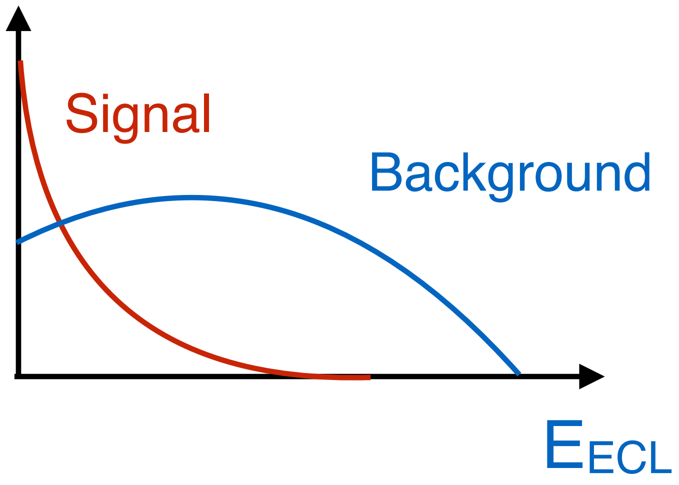
Phys. Rev. D 93, 032007 (2016)

Belle determined a first limit on R(π)

- Hadronic tagging, multivariate background subtraction
- Extraction of signal in E_{ECL}
  - E_{ECL} = extra neutral energy in calorimeter not associated with secondary B or signal decay

$$R_\pi^{\text{meas}} = 1.05 \pm 0.51\,.$$

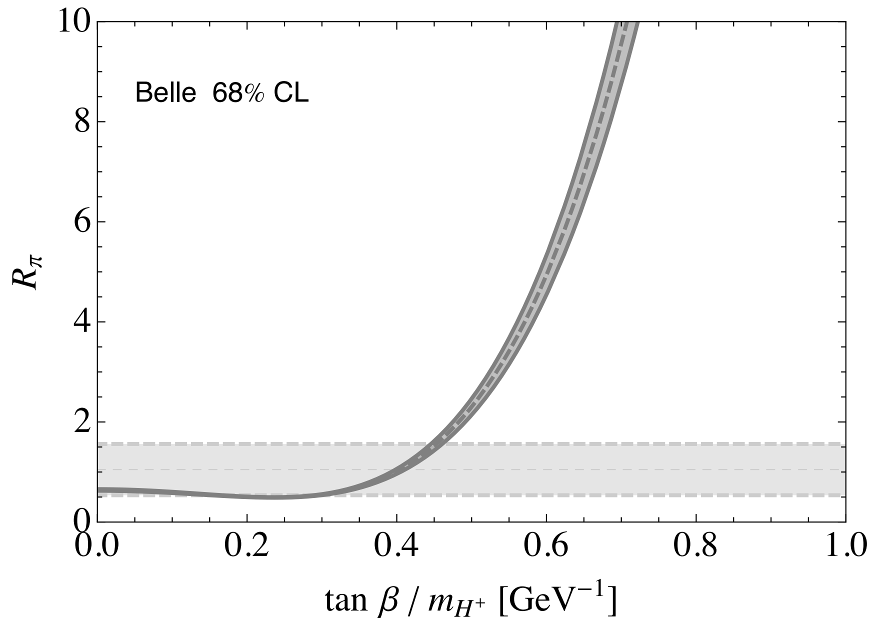


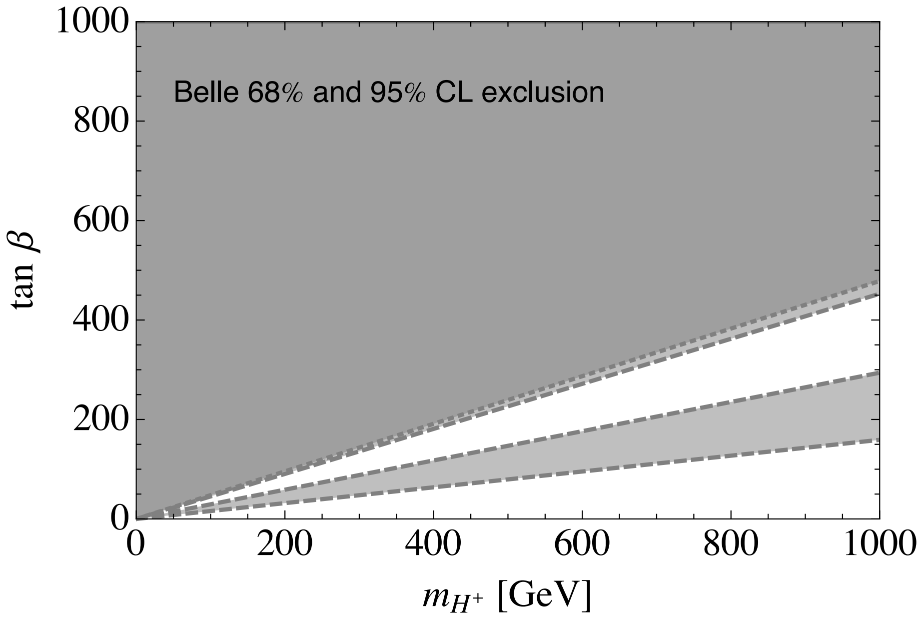


- Can be confronted with SM or 2HDM type II:

$$R_\pi^{\text{SM}} = 0.641 \pm 0.016\,.$$

Fermilab+MILC: arXiv:1503.07839v2 [hep-lat]
FB, **Phys. Rev. D 92, 115019 (2015)**





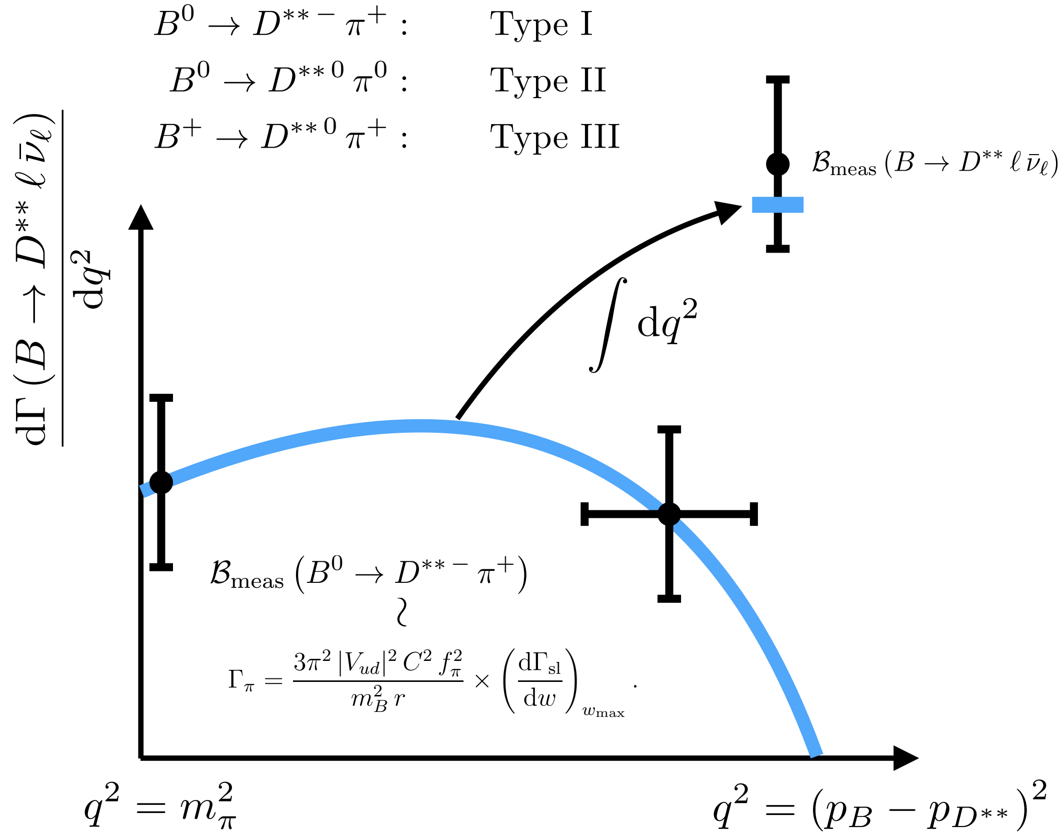
- Studied (MSc. thesis Stephan Duell) if semi-leptonic tag result could add something:
  - Does not look promising

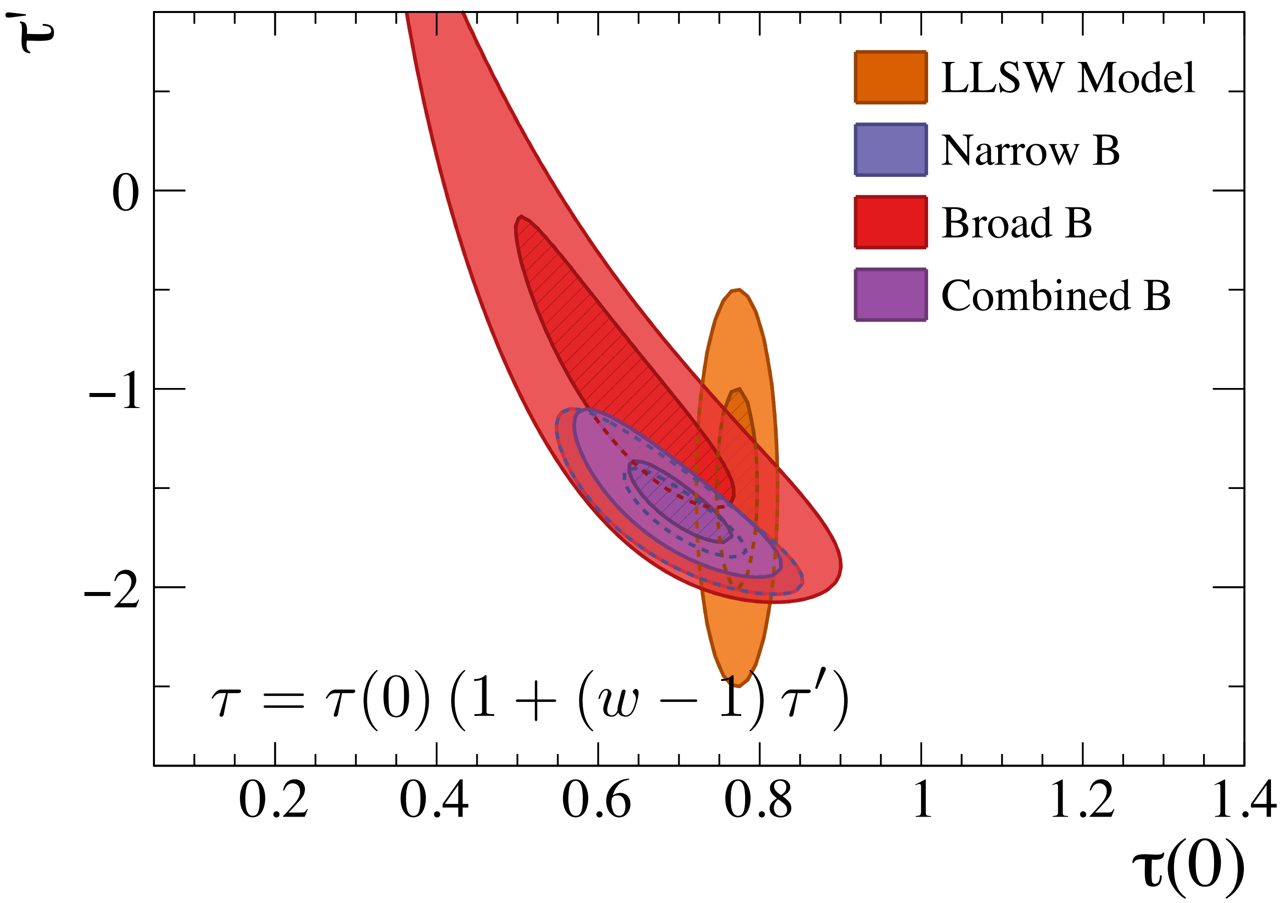
R(D**)

FB, Zoltan Ligeti, **in Preparation**

Most analyses model D** backgrounds using LLSW PRL 78 (1997) 3995, Phys.Rev.D57:308-330,1998

- Currently working with Zoltan Ligeti on updating this
  - Some of the underlying assumptions changed; we know a tad more
  - Use LLSW expansion and fit slope and normalization of leading form factors



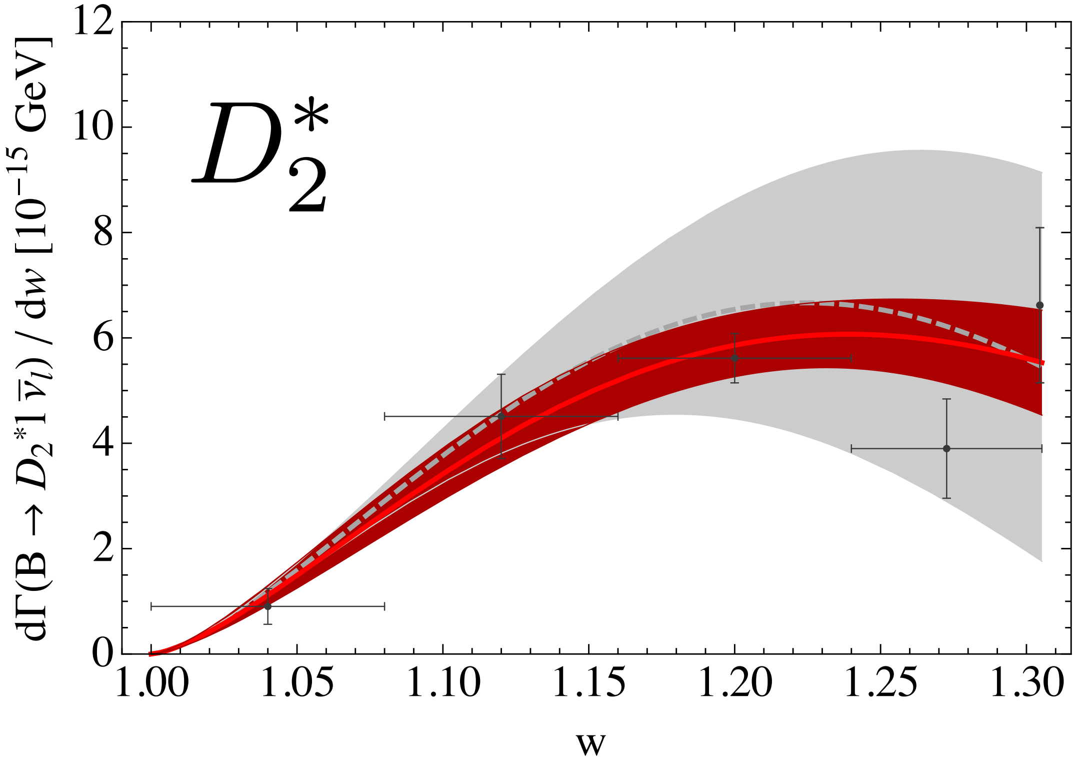


R(D**)

FB, Zoltan Ligeti, **in Preparation**

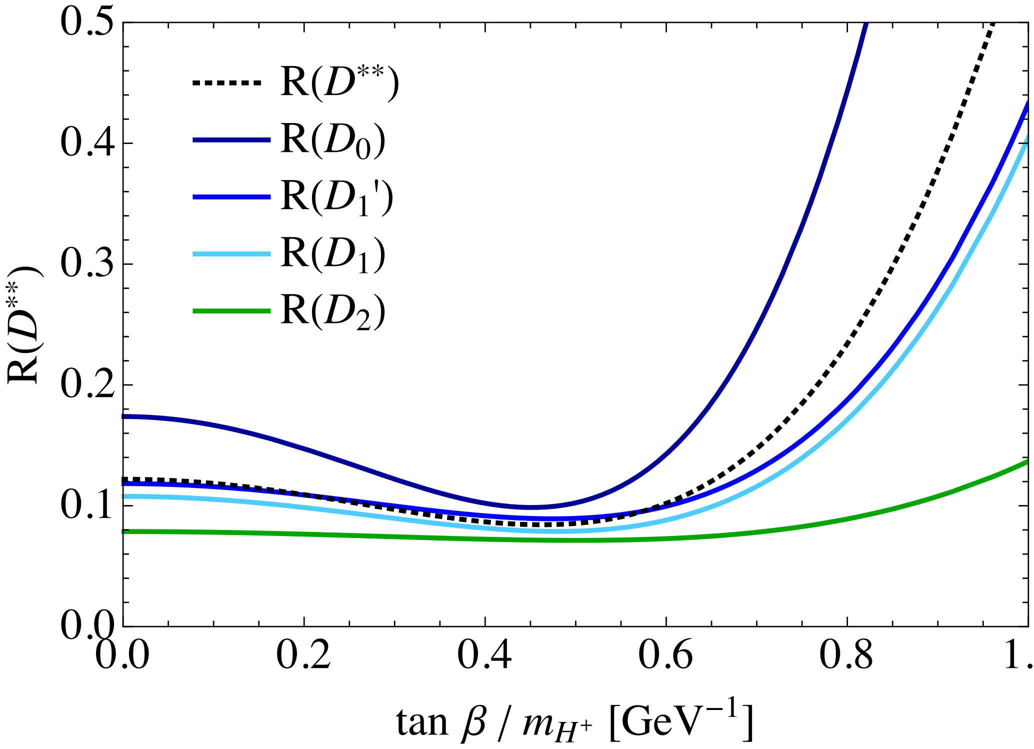
Reduces error on modelling

- ‘Postdiction’, as using measured differential and total branching fractions
- But: coherent prediction of the dynamics of the decays. Form factors and observed branching fractions do not decouple
- Can be used to predict R(D**)



Important for signal modelling in R(X) measurements.

- Plan to measure R(D**) using Belle data and hadronic tagging, today Mario Arndt started working on this.



B-Factories

a quick introduction to the family

Physics done in Bonn

an overview

Belle II Detector

concept and current status

Belle II Physics & LHCb

On complementarity and overlap

Summary

Transformation of a *B*-Factory into a **Super** *B*-Factory

To further push the intensity frontier need substantial instantaneous luminosity increase

KEK to SuperKEKB: **2.1x 10^{34} cm^{-2} s^{-1} to 8 x 10^{35} cm^{-2} s^{-1}**

Key: **nano-beam scheme** — squeeze the beam to very small vertical spot size of ~50 nm

LER / HER	KEKB	SuperKEKB
Energy [GeV]	3.5 / 8	4.0 / 7.0
β_y^* [mm]	5.9 / 5.9	**0.27 / 0.30**
β_x^* [mm]	1200	**32 / 25**
I± [A]	1.64 / 1.19	**3.6 / 2.6**
$\zeta_{\pm y}$	0.129 / 0.09	**0.09 / 0.09**
ε [nm]	18 / 24	**3.2 / 4.6**
# of bunches	1584	2500
Luminosity [10^{34} cm^{-2} s^{-1}]	2.1	80

Needs major upgrade of KEKB accelerator

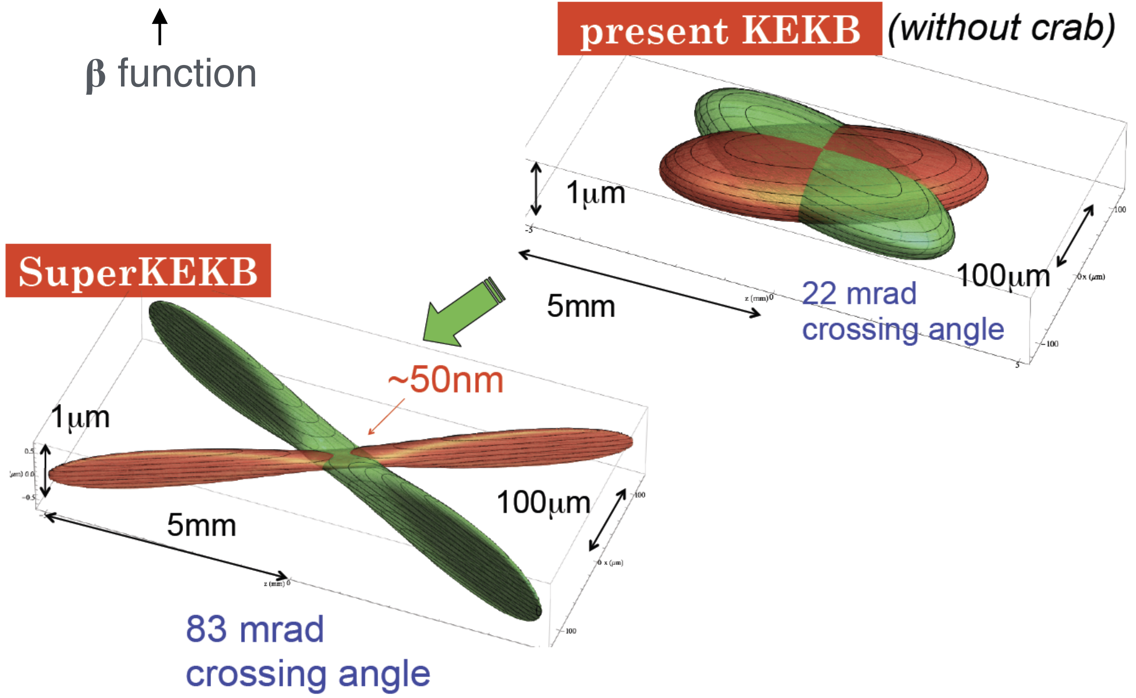
Lorentz factor   beam current   beam-beam parameter

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\boxed{\left(\frac{I_\pm \zeta_{\pm y}}{\beta_y^*}\right)}\left(\frac{R_L}{R_y}\right)$$

beam size aspect ratio   vertical β function   geometric factors

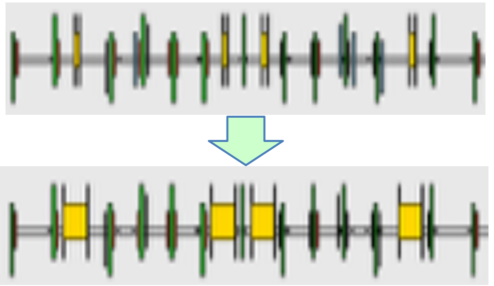
$$\zeta_{\pm y} \sim \sqrt{\beta^*/\epsilon} \longleftarrow \text{emittance}$$

β function



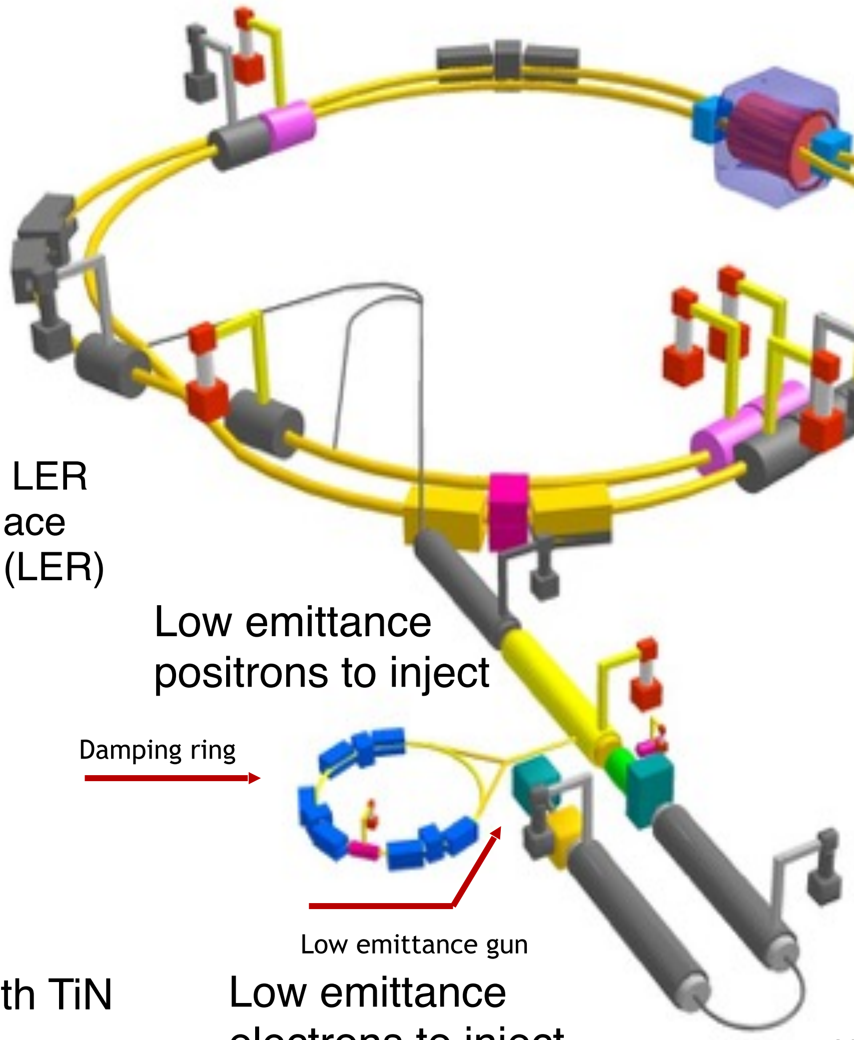
Transformation of a *B*-Factory into a **Super** *B*-Factory

Redesign the lattices of HER & LER to squeeze the emittance. Replace short dipoles with longer ones (LER)



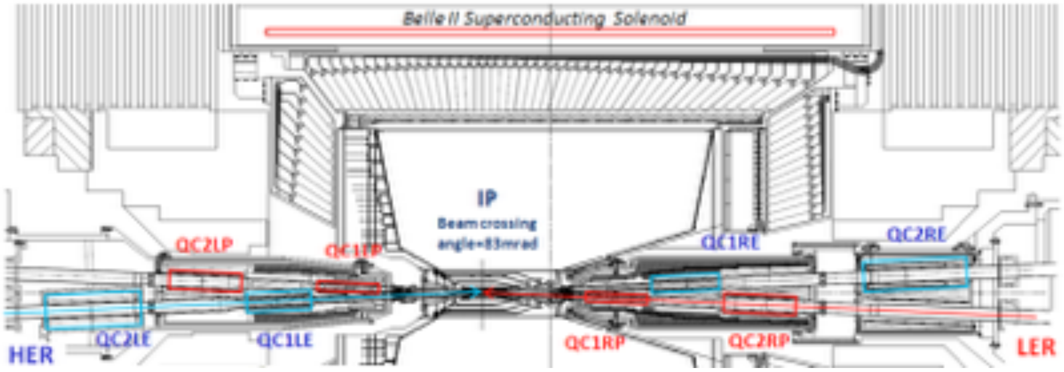
Replaced old beam pipes with TiN coated beam pipes with antechambers

New superconducting final focusing magnets near the IP



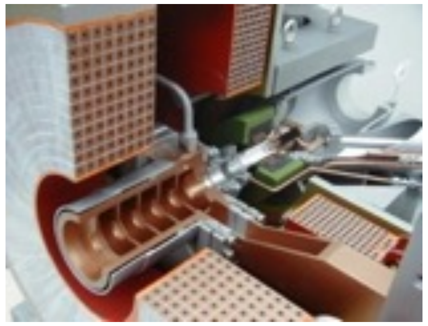
Low emittance positrons to inject

Low emittance electrons to inject



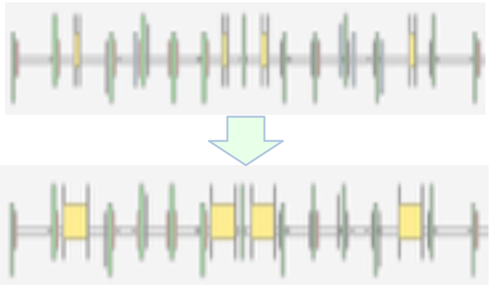
Reinforced RF (radio frequency) system for higher beam currents, improved monitoring & control system

Upgrade positron capture section



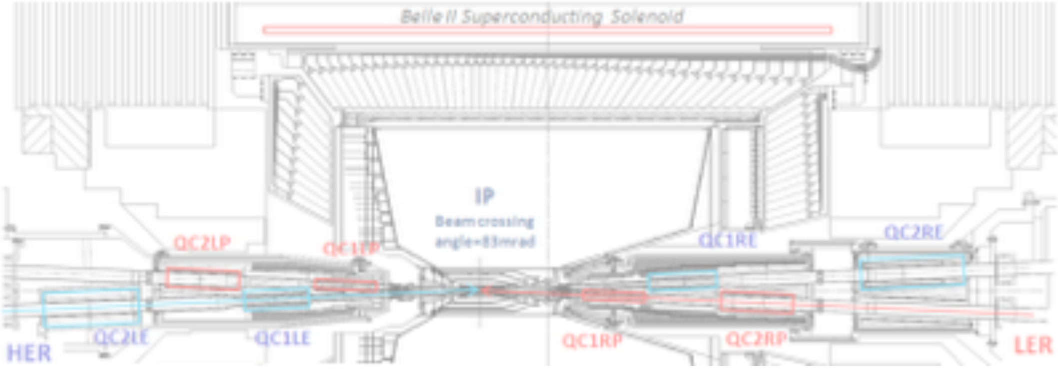
Transformation of a *B*-Factory into a **Super** *B*-Factory

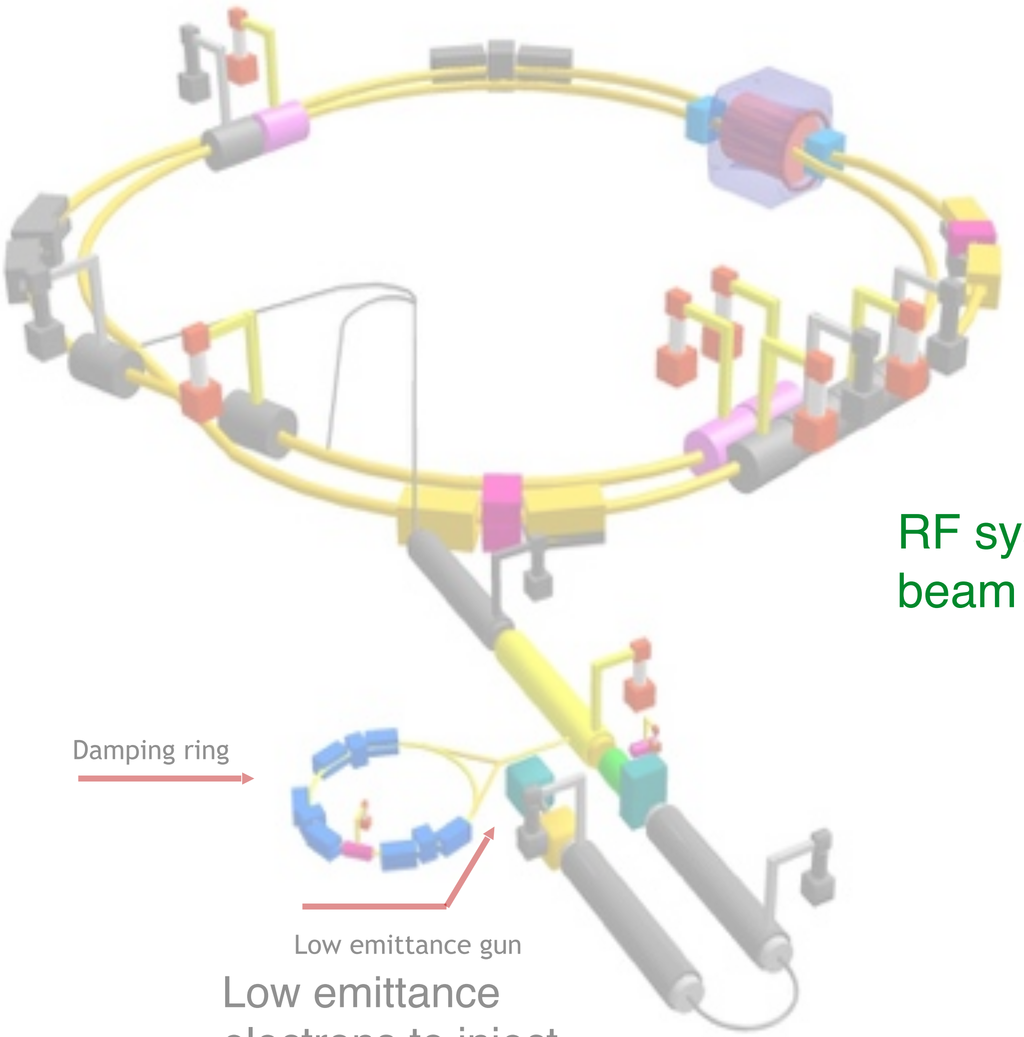
All magnets installed ✔



Beam pipes replaced ✔

Work on final focus magnets progressing well

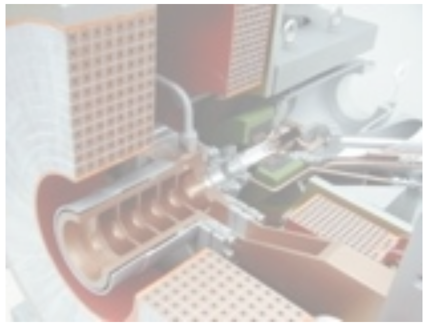




Low emittance electrons to inject

RF system for higher beam currents upgraded ✔

Upgrade positron capture section

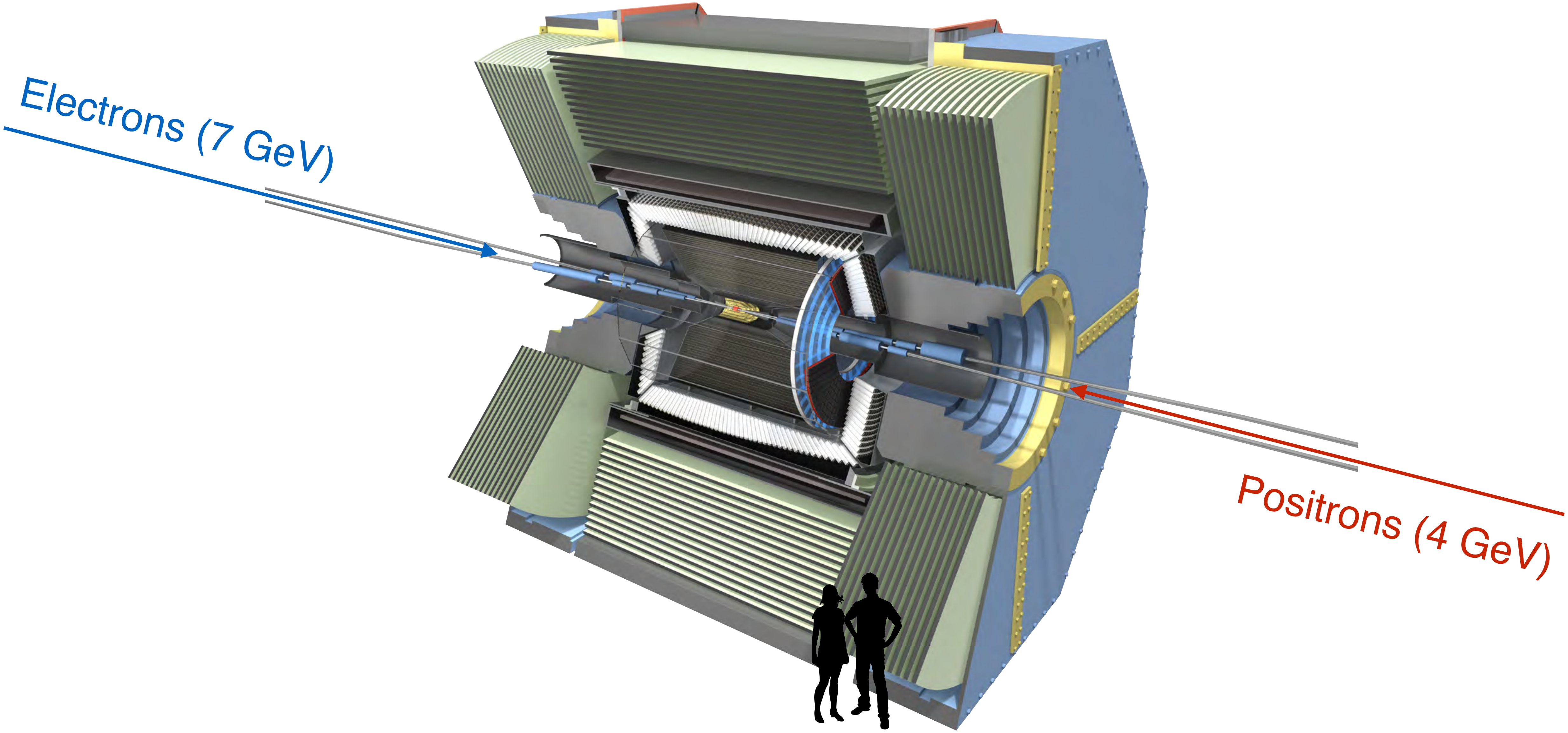


new positron dampening ring is being constructed

The Belle II Detector

To cope with higher luminosity: **need new detector**

Design concept similar to Belle and BaBar



Needs to cope with 20 times larger beam backgrounds, many technological challenges

The Belle II Detector

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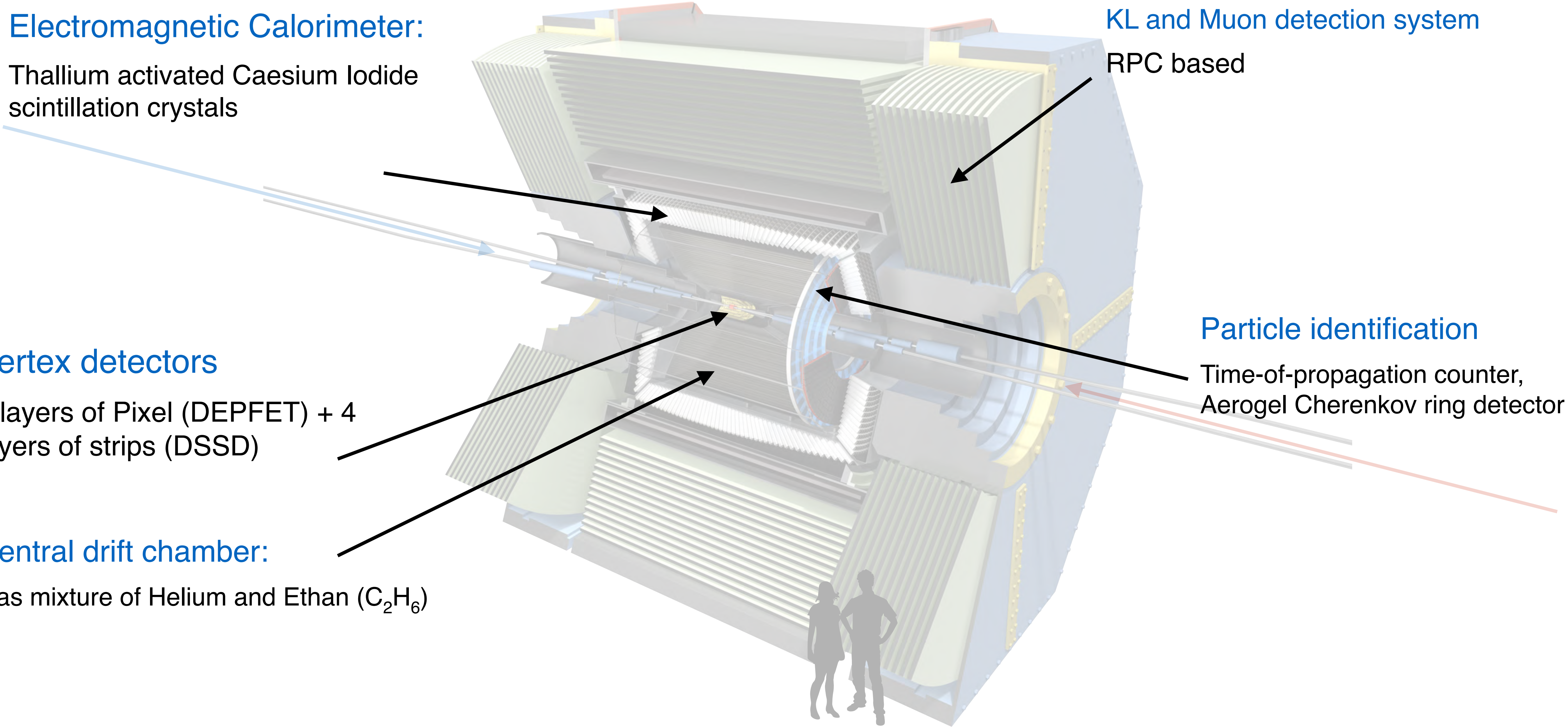


Electromagnetic Calorimeter:

Thallium activated Caesium Iodide scintillation crystals

KL and Muon detection system

RPC based

Particle identification

Time-of-propagation counter, Aerogel Cherenkov ring detector

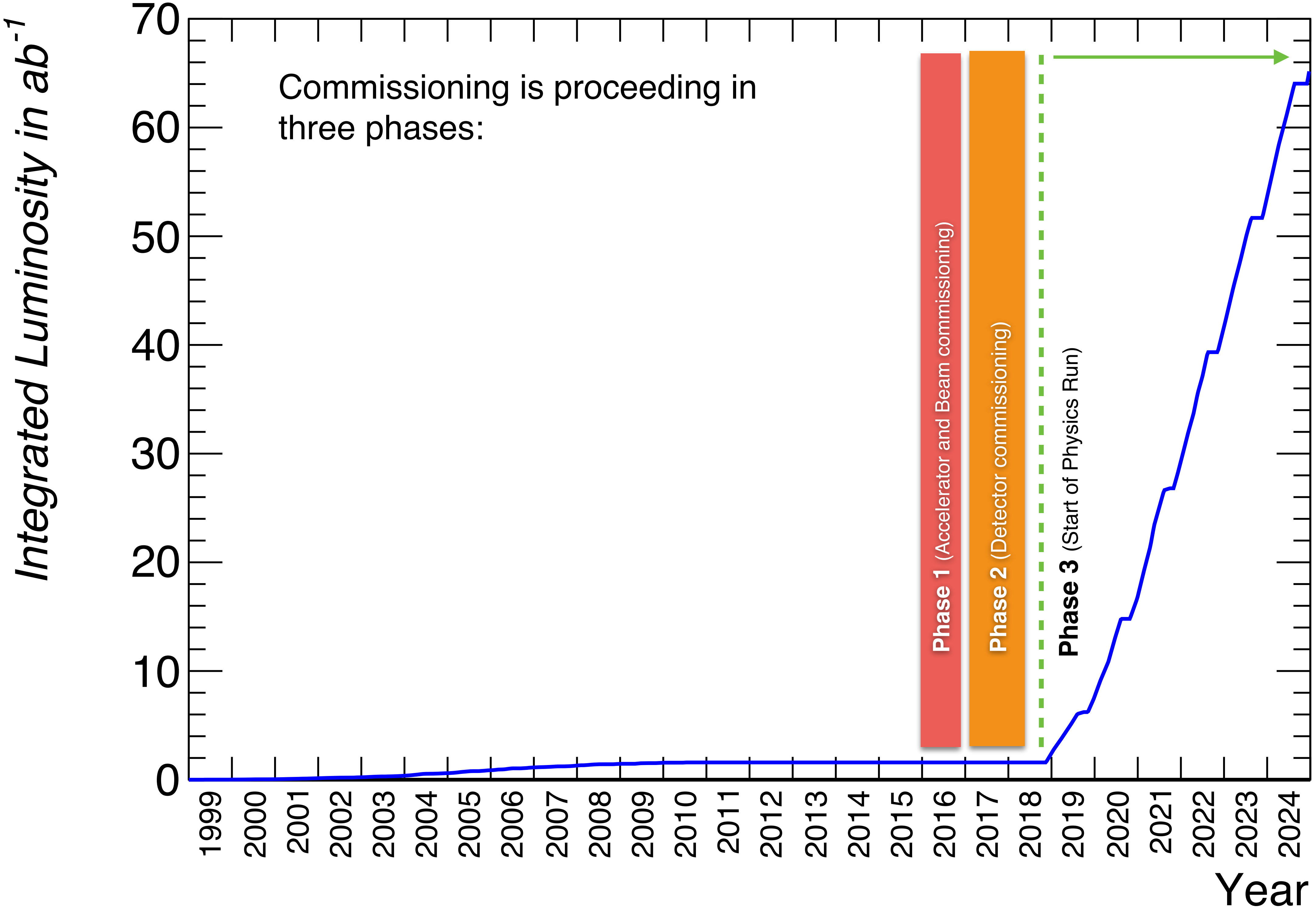
Vertex detectors

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

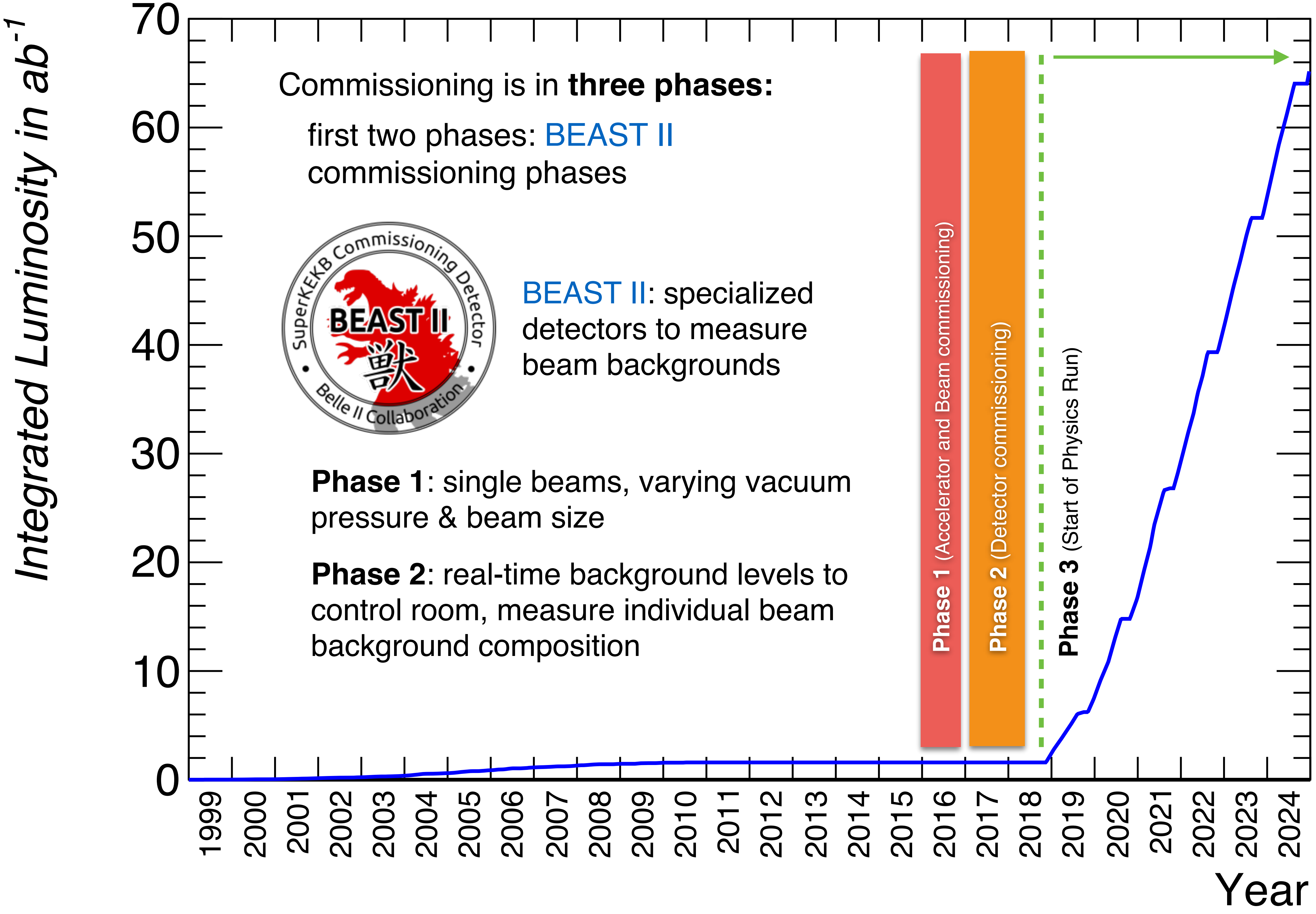
Central drift chamber:

Gas mixture of Helium and Ethan (C_2H_6)

Belle II / SuperKEKB Luminosity projections



Belle II / SuperKEKB Luminosity projections



Commissioning is in **three phases:**

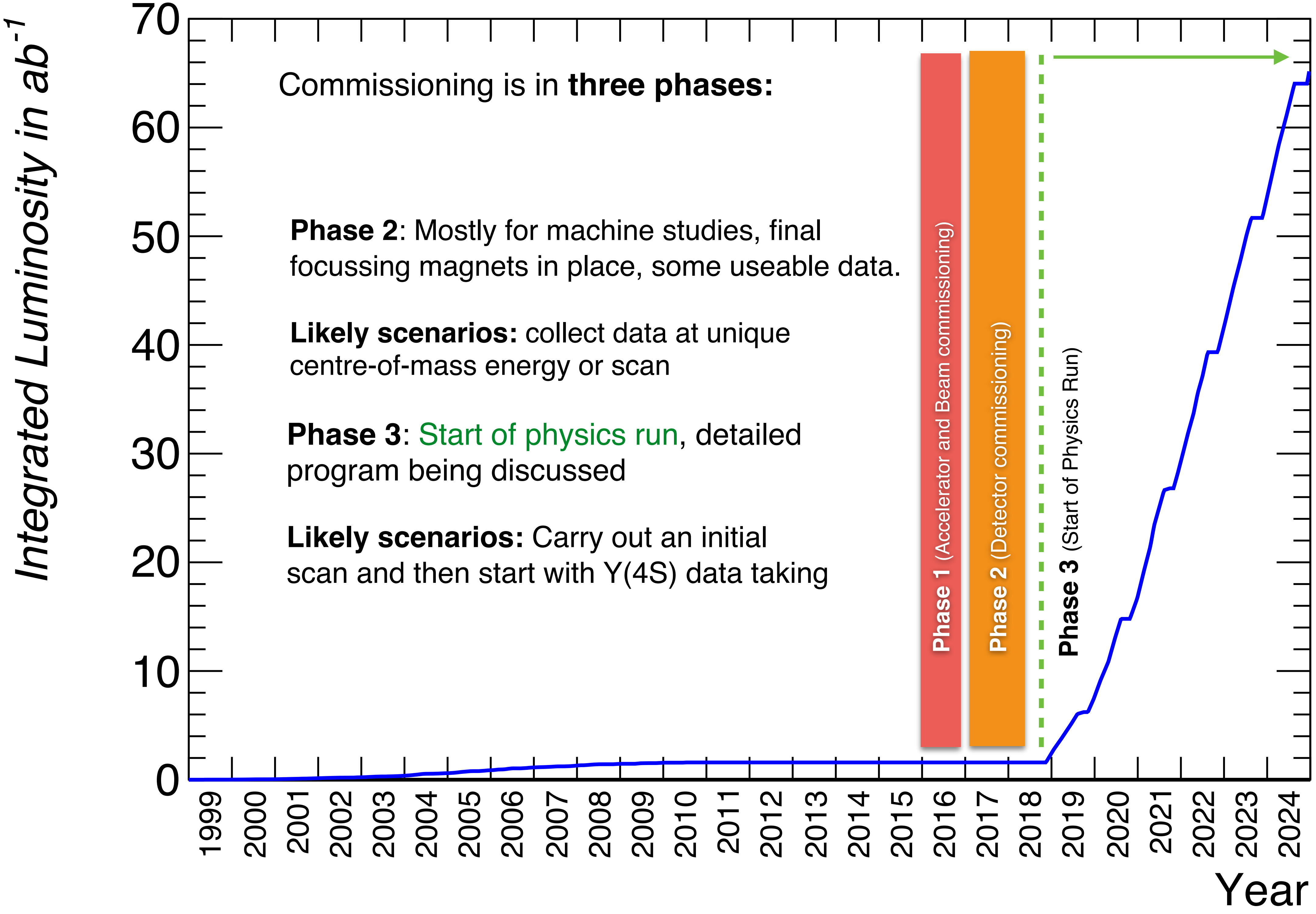
first two phases: BEAST II commissioning phases

BEAST II: specialized detectors to measure beam backgrounds

Phase 1: single beams, varying vacuum pressure & beam size

Phase 2: real-time background levels to control room, measure individual beam background composition

Belle II / SuperKEKB Luminosity projections



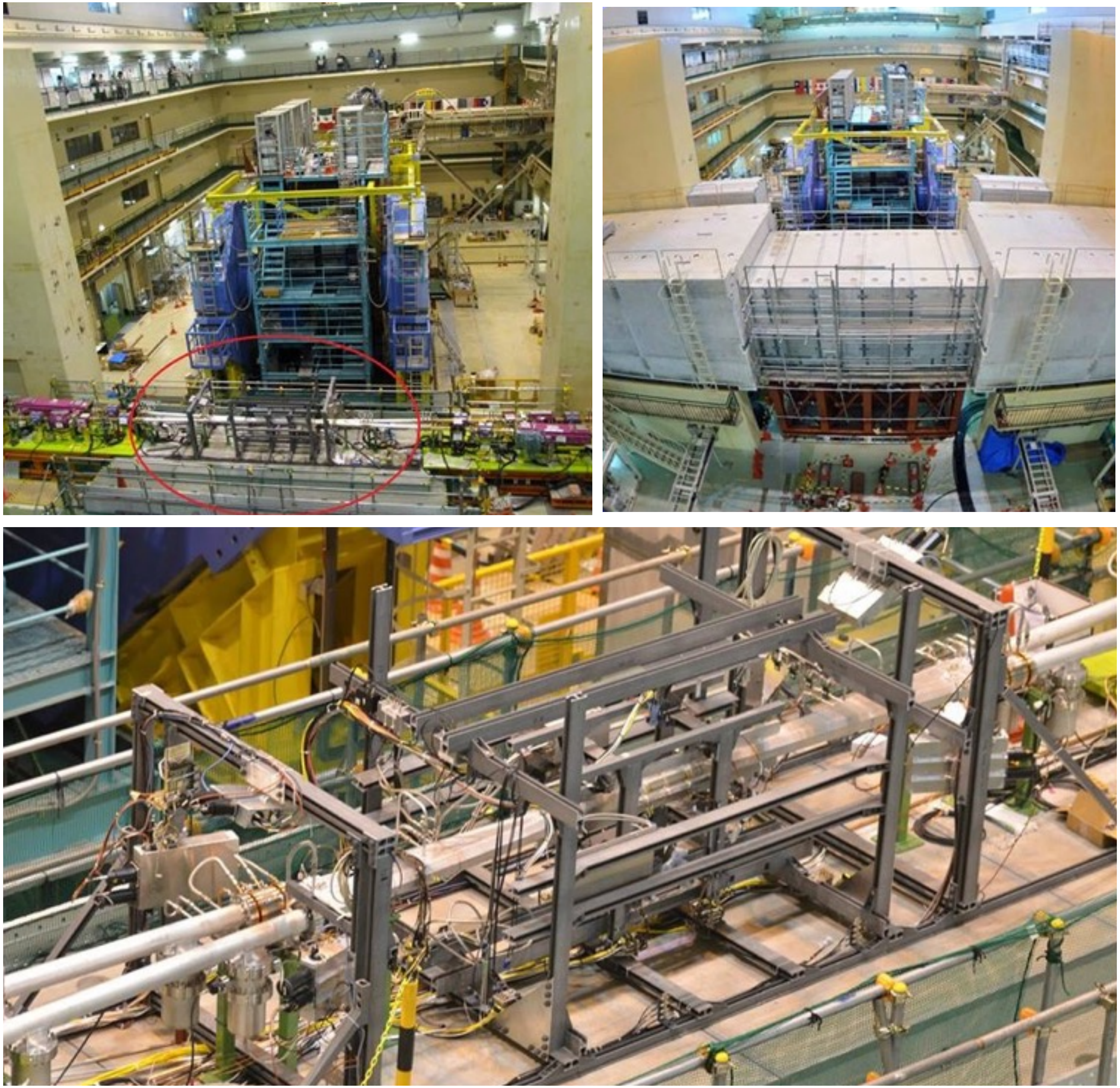
Commissioning is in **three phases:**

Phase 2: Mostly for machine studies, final focussing magnets in place, some useable data.

Likely scenarios: collect data at unique centre-of-mass energy or scan

Phase 3: Start of physics run, detailed program being discussed

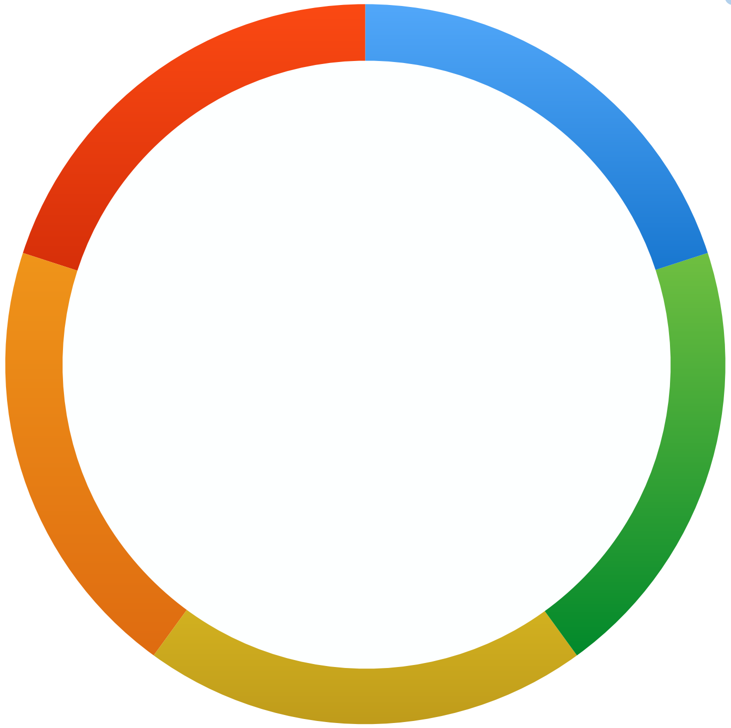
Likely scenarios: Carry out an initial scan and then start with Υ(4S) data taking



Summary

B-Factories

a quick introduction to the family



Belle II Physics & LHCb

On complementarity and overlap

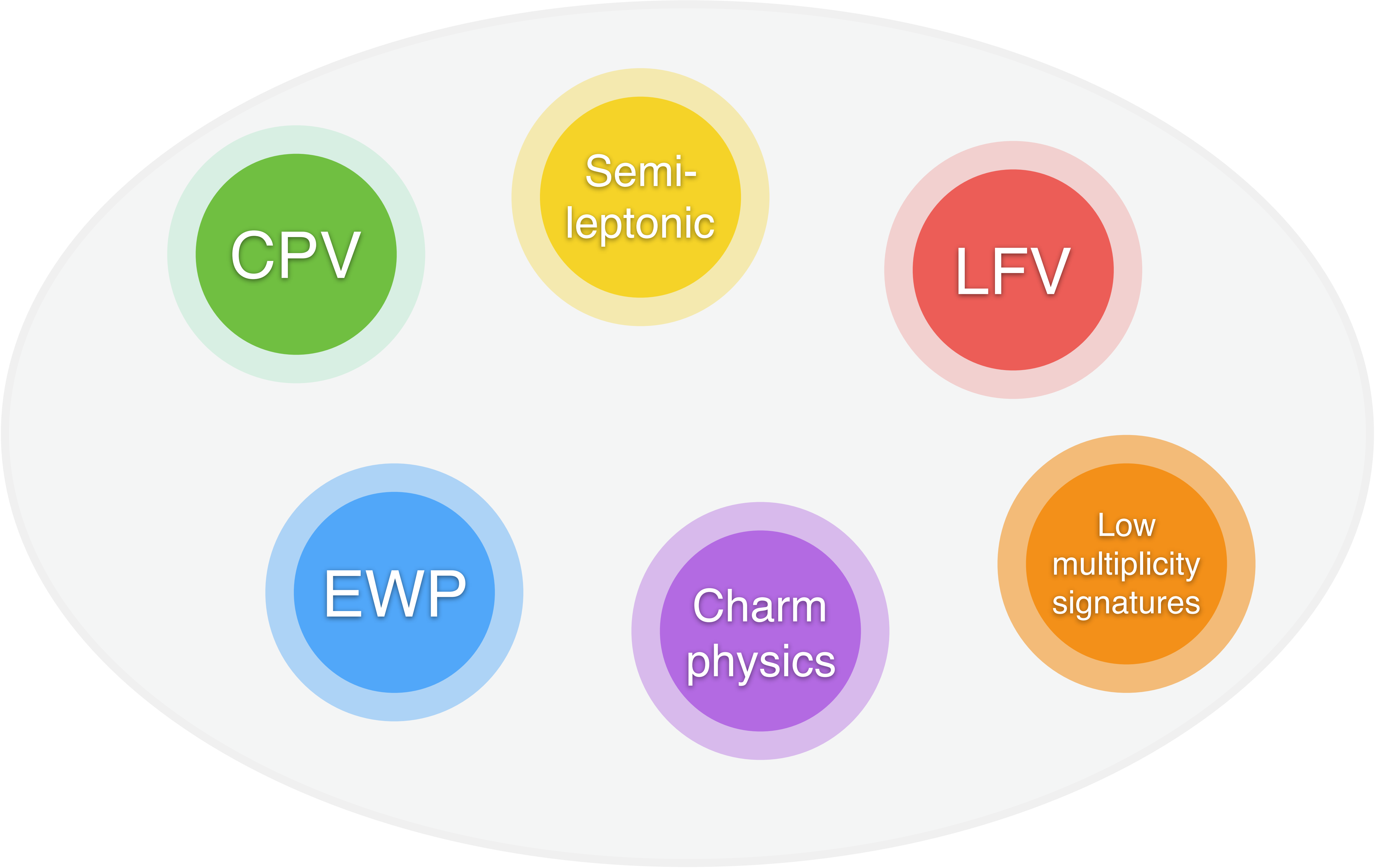
Physics done in Bonn

an overview

Belle II Detector

concept and current status

Super B-Factory measurement candy bowl



CPV

Semi-leptonic

LFV

EWP

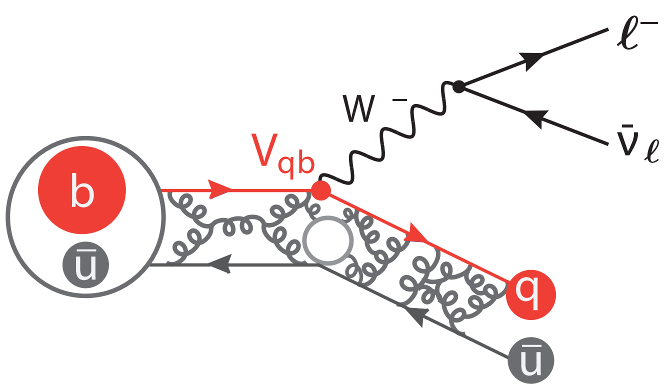
Charm physics

Low multiplicity signatures

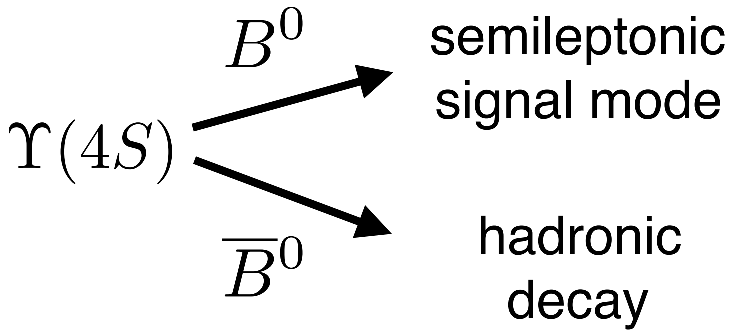
Semi-leptonic

Precision measurements of CKM matrix elements priority

Exclusive measurements profit from large Belle II data samples



- Established measurement method: ***fully hadronic reconstruction of second B-meson***
- Very low efficiency due to low hadronic Branching Fractions (of the order 0.2-0.3%)



$\Upsilon(4S)$

B^0 semileptonic signal mode

$\overline{B}^0$ hadronic decay

Neutrino of signal decay the only missing particle!

had. tagged

$B \to D^* \ell \,\bar{\nu}_\ell$

Error on IV_{cb}I	stat.	tot.
B-Factories	0.6%	3.6%
Belle II 5/ab	0.2%	1.8%
Belle II 50/ab	0.1%	**1.4%**

had. tagged

$B \to \pi \,\ell \,\bar{\nu}_\ell$

Error on IV_{ub}I	stat.	tot.
B-Factories	5.8%	10.8%
Belle II 5/ab	2.2%	4.7%
Belle II 50/ab	0.7%	**2.4%**

untagged

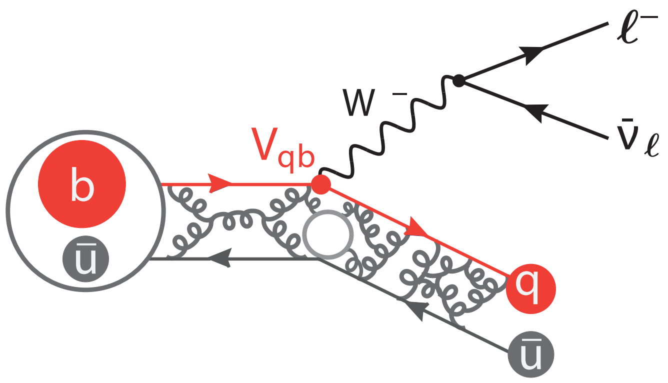
$B \to \pi \,\ell \,\bar{\nu}_\ell$

Error on IV_{ub}I	stat.	tot.
B-Factories	2.7%	9.4%
Belle II 5/ab	1.0%	4.2%
Belle II 50/ab	0.3%	**2.2%**

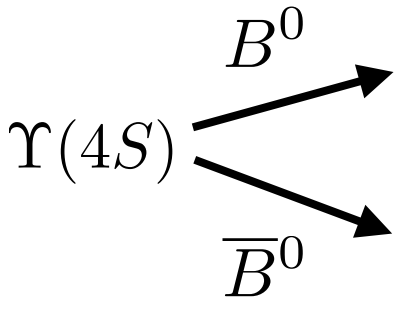
Semi-
leptonic

Precision measurements of CKM matrix elements a priority

Improvements on *inclusive measurements* less clear.



- $|V_{cb}|$ systematically and theory limited; need new approaches and ideas
- $|V_{ub}|$ will gain; but need to improve on understanding of background and methodology



$\Upsilon(4S)$

B^0 → semileptonic signal mode

$\overline{B}^0$ → hadronic decay

Neutrino of signal decay the only missing particle!

$$B \to X_c \ell \, \bar{\nu}_\ell$$

Error on $\lvert V_{cb} \rvert$	stat.	tot.
B-Factories	1.5%	1.8%
Belle II 50/ab	0.5%	**1.2%**

$$B \to X_u \, \ell \, \bar{\nu}_\ell$$

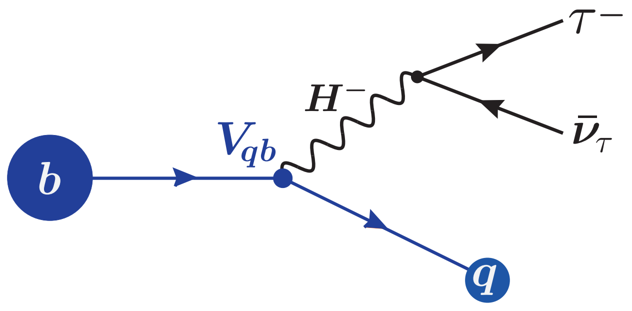
Error on $\lvert V_{ub} \rvert$	stat.	tot.
B-Factories	4.5%	6.5%
Belle II 5/ab	1.1%	3.4%
Belle II 50/ab	0.4%	**3%**

Semi-leptonic

Semi-tauonic decay modes highly sensitive to new physics

Clean measurement is a major Belle II goal

Target: $R(X)$ $R(\pi)$ $R(D^{**})$



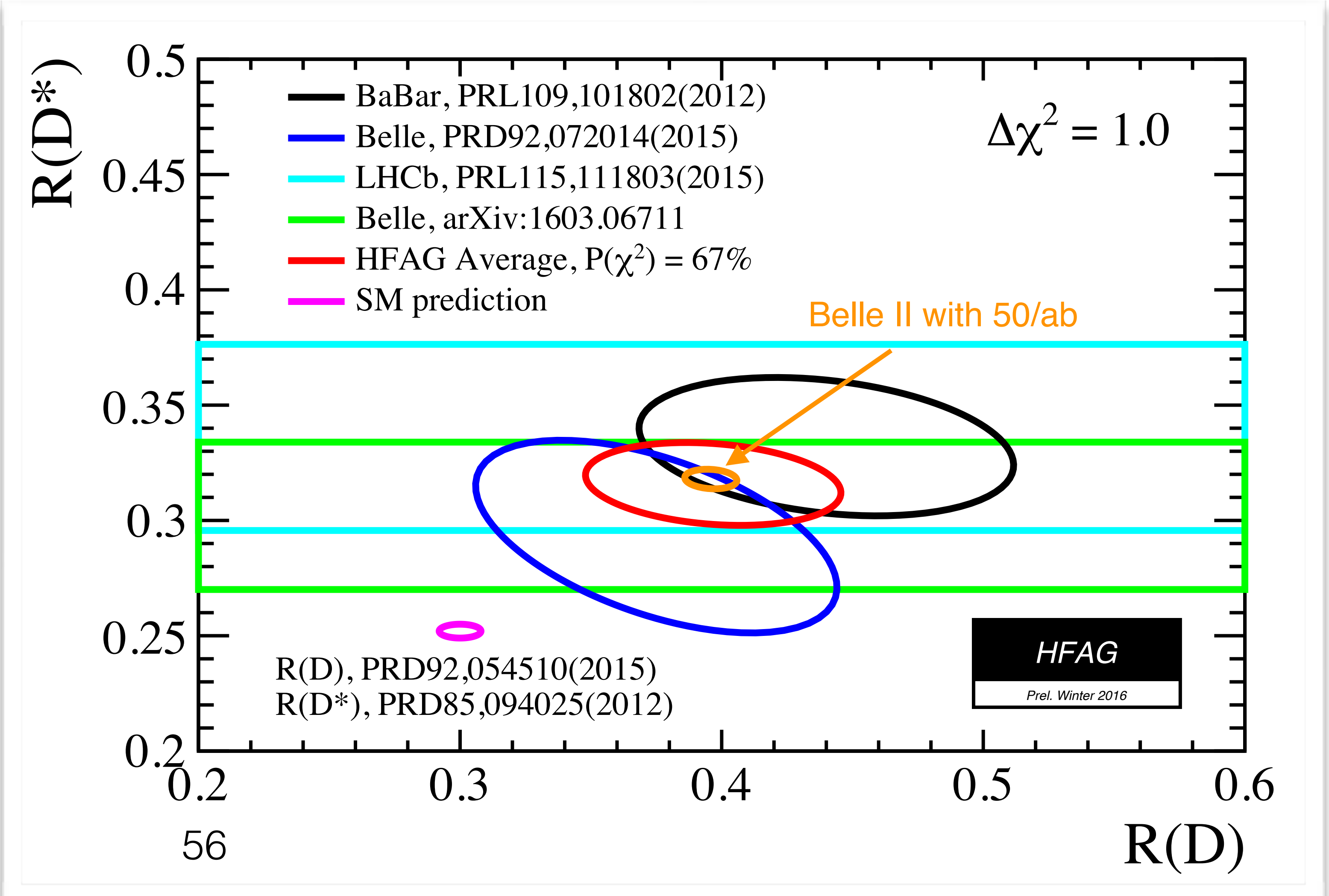
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\,\ell\,\bar{\nu}_\ell)}$$

$R(D)$

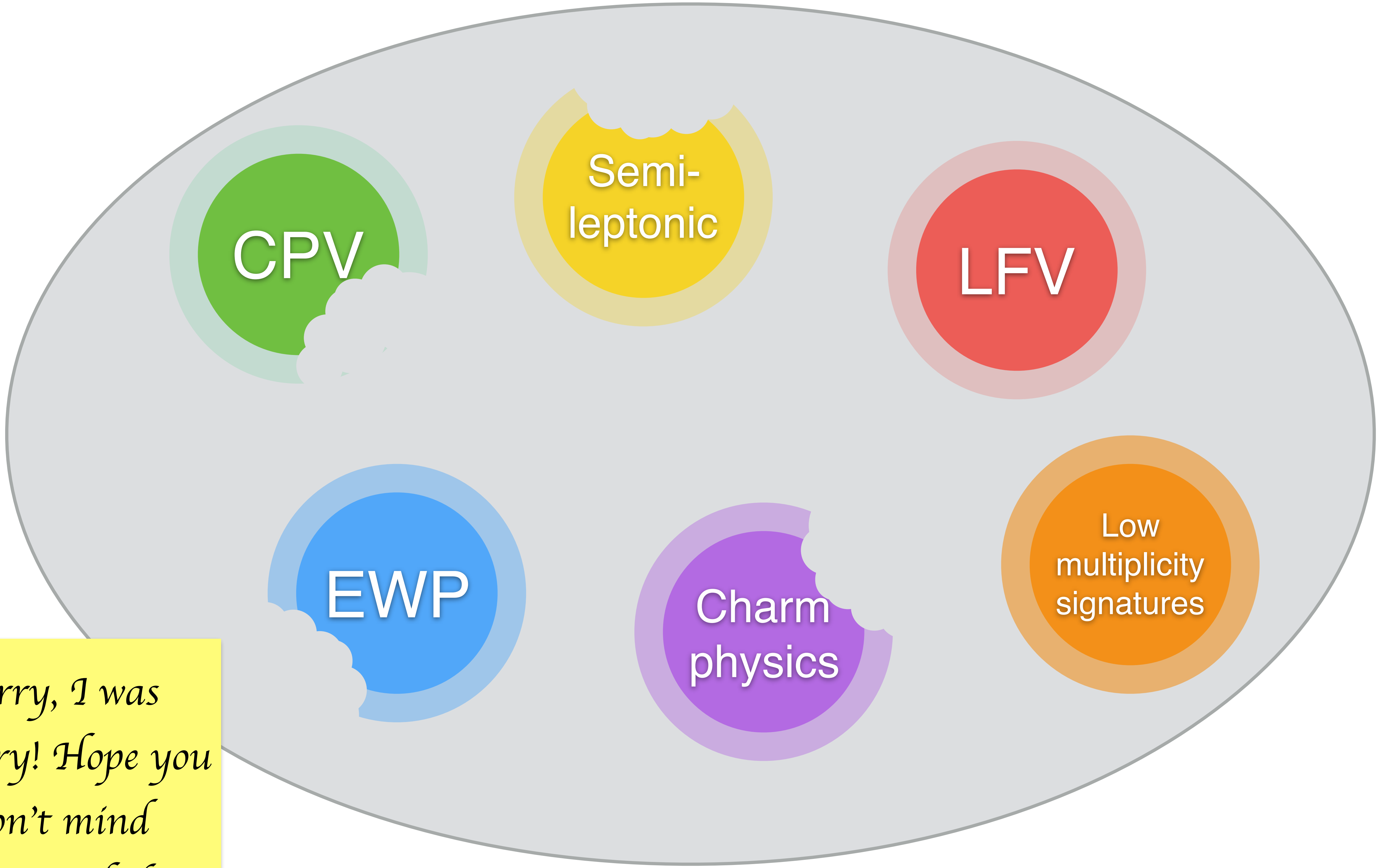
Error	stat.	tot.
B-Factories	13%	16.2%
Belle II 5/ab	3.8%	5.6%
Belle II 50/ab	1.2%	**3.4%**

$R(D^*)$

Error	stat.	tot.
B-Factories	7.1%	9.0%
Belle II 5/ab	2.1%	3.2%
Belle II 50/ab	0.7%	**2.1%**



Super B-Factory measurement candy bowl after LHCb had a treat



CPV

Semi-leptonic

LFV

EWP

Charm physics

Low multiplicity signatures

Sorry, I was hungry! Hope you don't mind

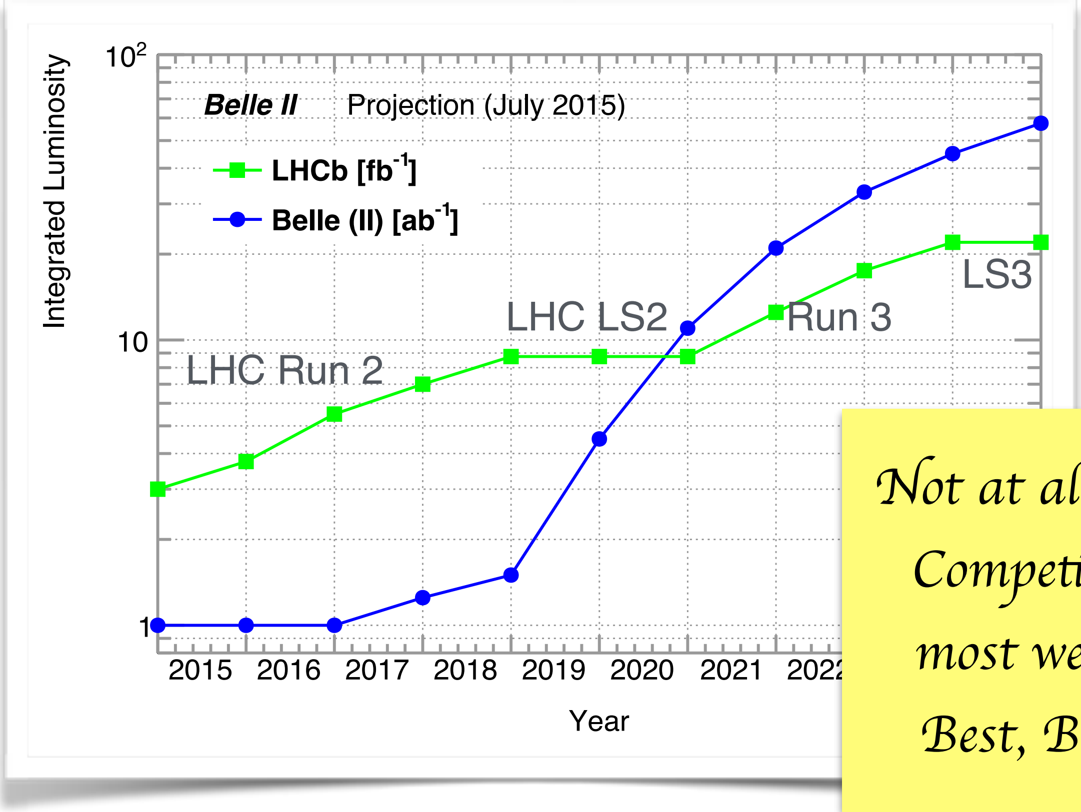
Best, LHCb

Belle II & LHCb: *On complementarity and overlap*

Rivalry and competition — a good thing:

- *B*-factories profited from scrutiny of other team
- In past schedules lined up — with LHCb and Belle II things lie differently
  - LHCb: running and very successful
  - Belle II: first collisions 2017, first Υ(4S) physics 2018
- Provocative question: **’Will there be anything interesting left to measure?’**

- Clear *overlaps* between *physics programs*, but also unique strengths
  - *Large Baryonic samples* and *decays into visible particles:* LHCb’s strength
  - *Missing particles, inclusive measurements, low multiplicity final states:* Belle II’s forte
  - Some channels will be head-and-neck run — great!



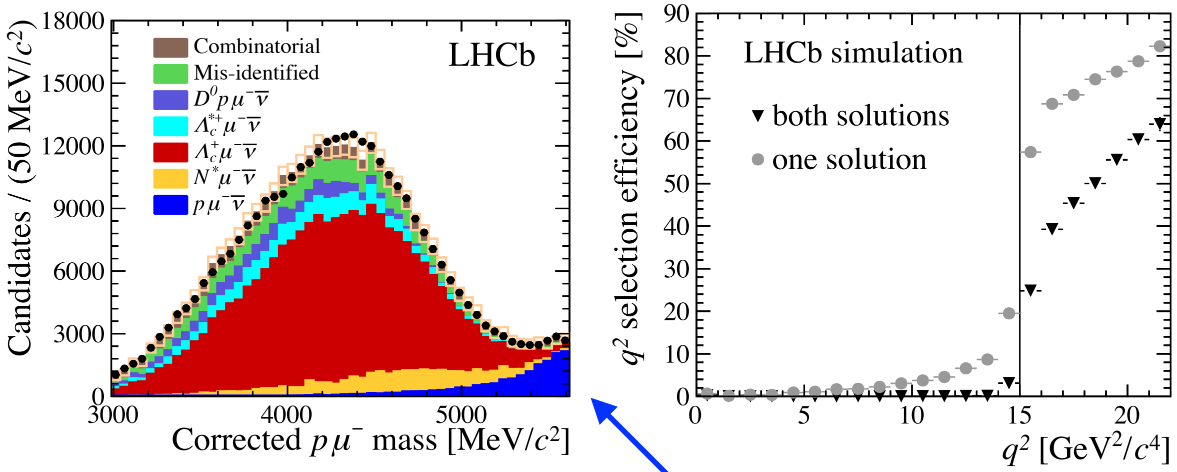
Estimates for 2024 data sets

LHCb 22/fb
Belle II 50/ab

Not at all LHCb,
Competition is
most welcome!
Best, Belle II

Semi-leptonic

Nature Physics 10 (2015) 1038



Signal(!)

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004\,,$$

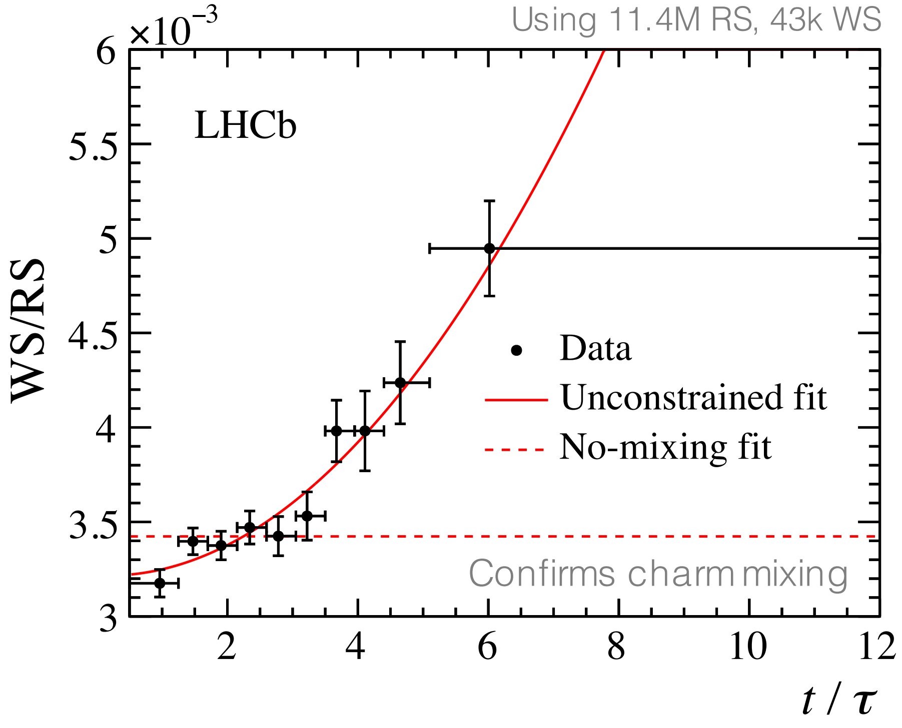
$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}\,,$$

Error on $\|V_{ub}\|$	tot.
LHCb 22/fb	**3.6%**
Belle II 50/ab	**2.2%**

2024 data sets

Charm physics

Using 11.4M RS, 43k WS



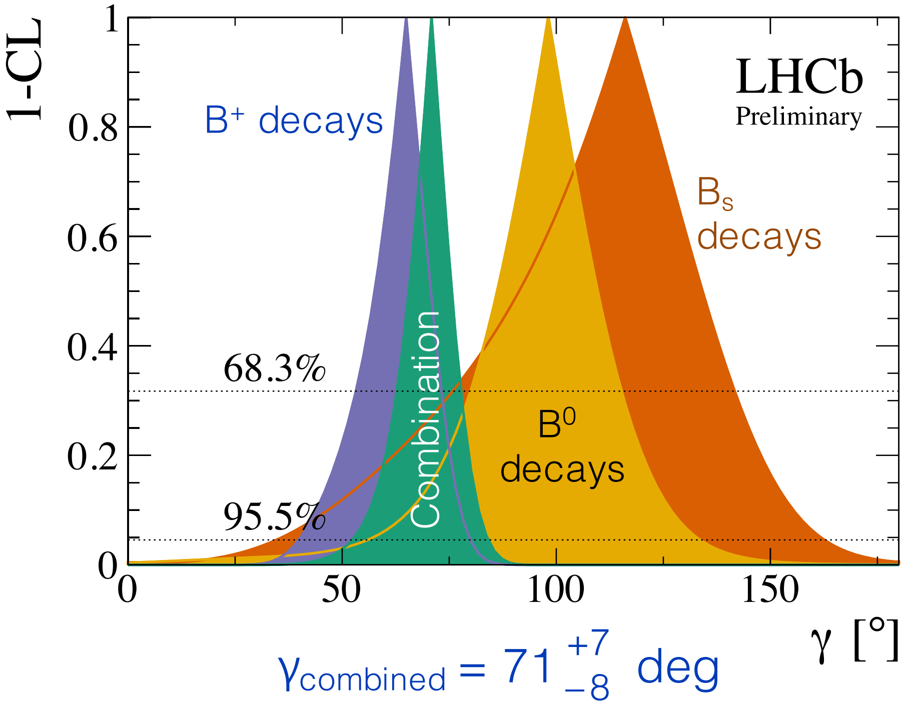
Confirms charm mixing

Error on ΔA_{CP}	tot.
LHCb 22/fb	**0.03%**
Belle II 50/ab	**0.03%**

New, full 3 fb^{-1} result:

$$\Delta A_{CP} = -0.10 \pm 0.08_{\text{stat}} \pm 0.03_{\text{syst}}\ \%$$

CPV



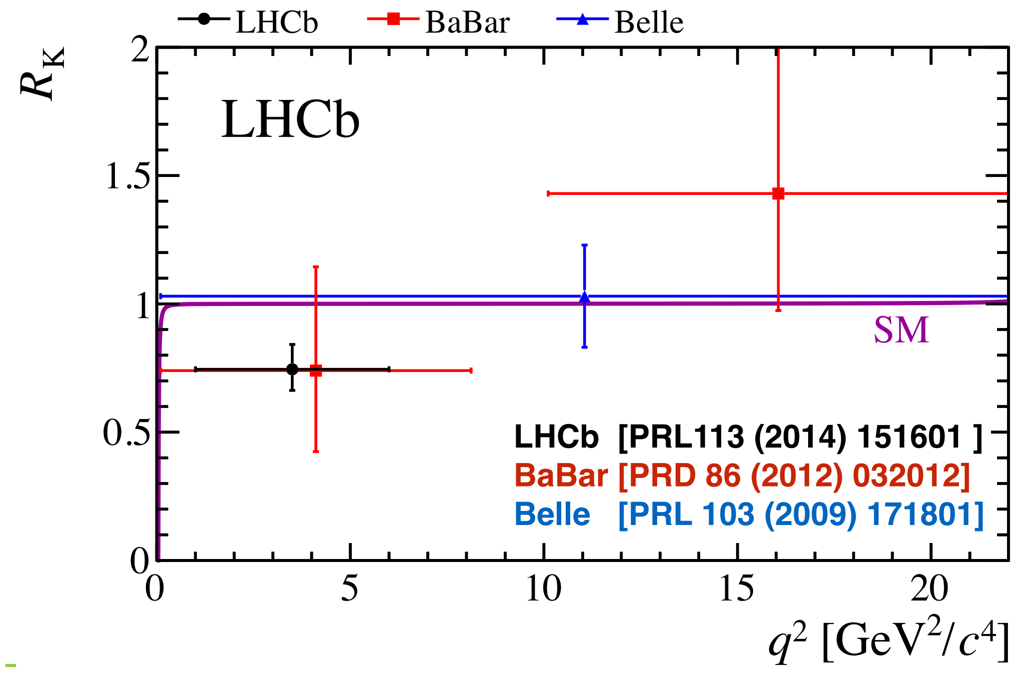
$\gamma_{\text{combined}} = 71^{+7}_{-8}$ deg

CKM fit: 68 ± 2 deg

Error on γ	tot.
LHCb 22/fb	**2°**
Belle II 50/ab	**1.5°**

Error on sin(2β) from B → J/ψ K_s	tot.
LHCb 22/fb	**0.014**
Belle II 50/ab	**0.007**

EWP



LHCb [PRL113 (2014) 151601]
BaBar [PRD 86 (2012) 032012]
Belle [PRL 103 (2009) 171801]

$$R_K = \frac{BR(B^+ \rightarrow K^+\mu^+\mu^-)}{BR(B^+ \rightarrow K^+e^+e^-)}$$

R_K	low q^2	high q^2
LHCb 22/fb	**4.4%**	**-**
Belle II 50/ab	**3%**	**3%**

R_{K^*}	low q^2	high q^2
Belle II 50/ab	**4%**	**4%**

R_{Xs}	low q^2	high q^2
Belle II 50/ab	**5%**	**5%**

Summary

B-Factories

a quick introduction

Physics done in Bonn

an overview

Belle II Detector

concept and current status

Belle II Physics
& LHCb

On complementarity and overlap

Summary

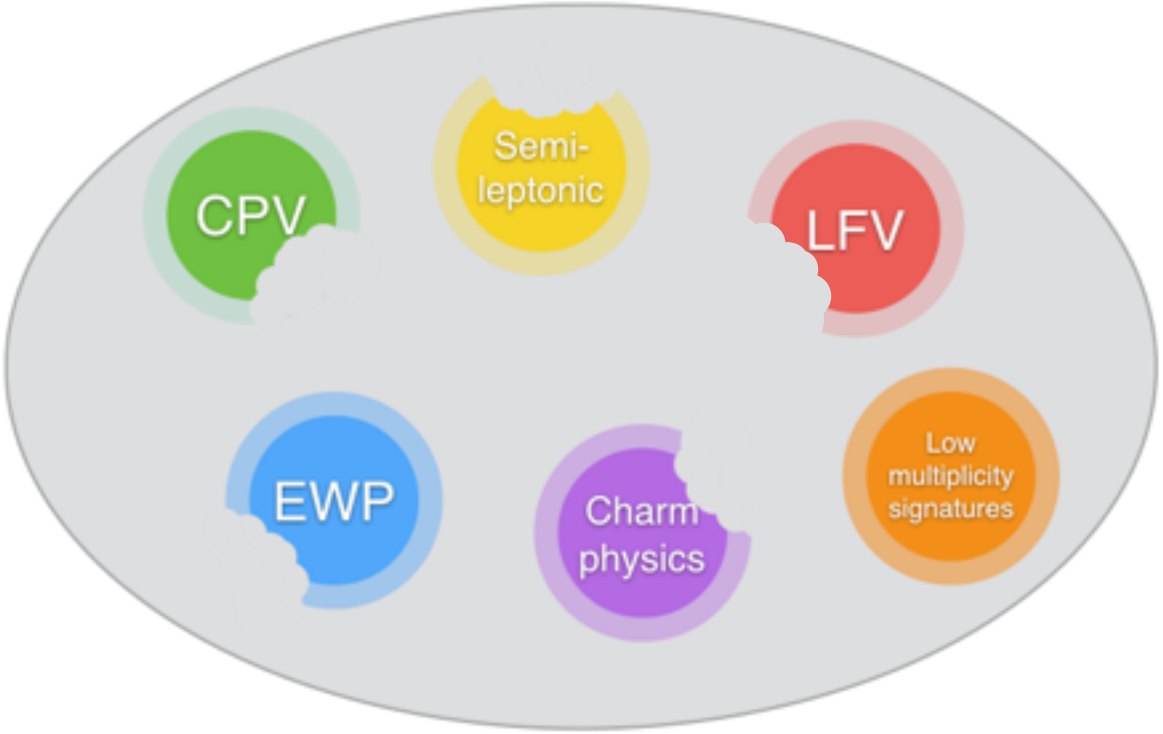
Brief overview about the Bonn Belle (II) physics activities

I hope you also got a tad excited about Belle II

- Increasingly interesting physics at the intensity frontier with LHCb upgrade & Belle II
- Both experiments have competing topics, but also unique focal points & strengths

Era of the Super B-Factories will keep things interesting

- Significant sensitivity gain on many precision observables — will the SM remain?



Stay tuned

and

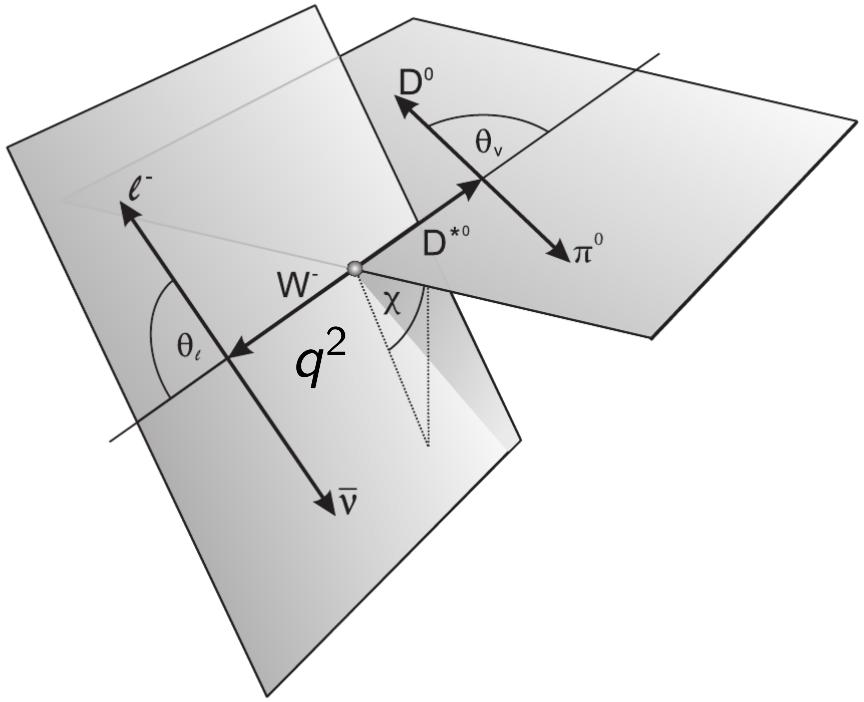
keep snacking!

Backup

A closer look on the exclusive $|V_{cb}|$ side

kinematic variables:

- $w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$ with $q^2 = p_W^2$: momentum transfer
- $\cos\theta_v$ & $\cos\theta_\ell$: helicity angles
- χ: angle D^* and W decay planes



Differential branching fractions:

$$\frac{d^4\Gamma(B \to D^* \ell \nu)}{dw\, d\cos\theta_v\, d\cos\theta_\ell\, d\chi} (|V_{cb}|, \rho_{D^*}, R_1, R_2) \to \text{use 1D} - \text{projections}$$

→ measurement of $|V_{cb}|$ and $B \to D^* l \nu$ form factor paramters

→ search for deviations (in shape) from SM → new Physics?

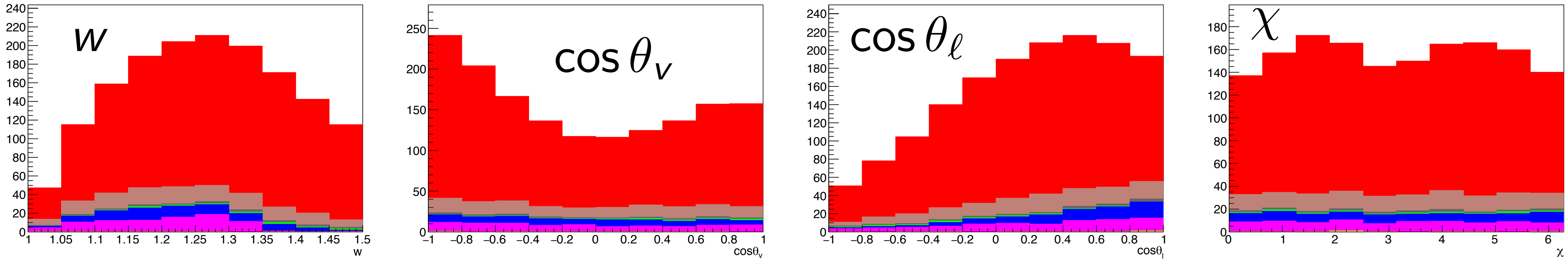
→ unfolding of the spectra

A closer look on the exclusive $|V_{cb}|$ side

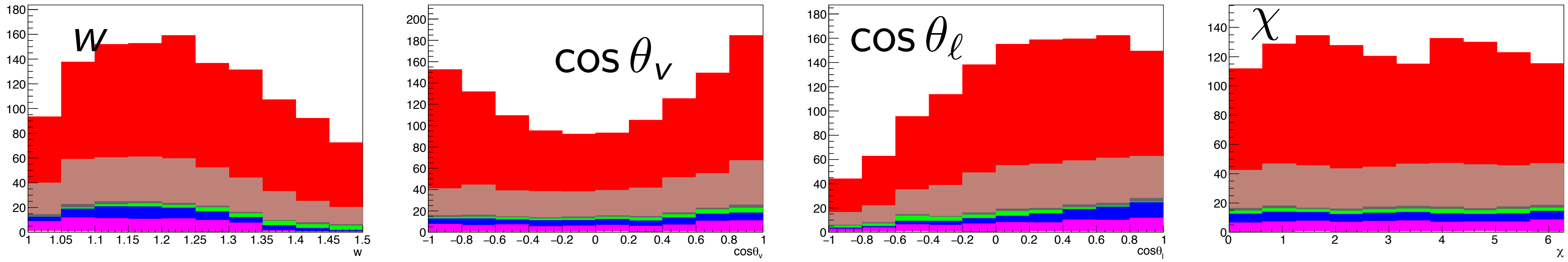
Saskia Mönig, FB

🟥 B→ D*lν (signal)
🟫 B→ D*lν (wrong D/D*)
⬛ fake lepton
🟩 B→ Dlν
🟦 B→ D**lν
🟪 Other B decays
🟨 Continuum

Neutral Bs:

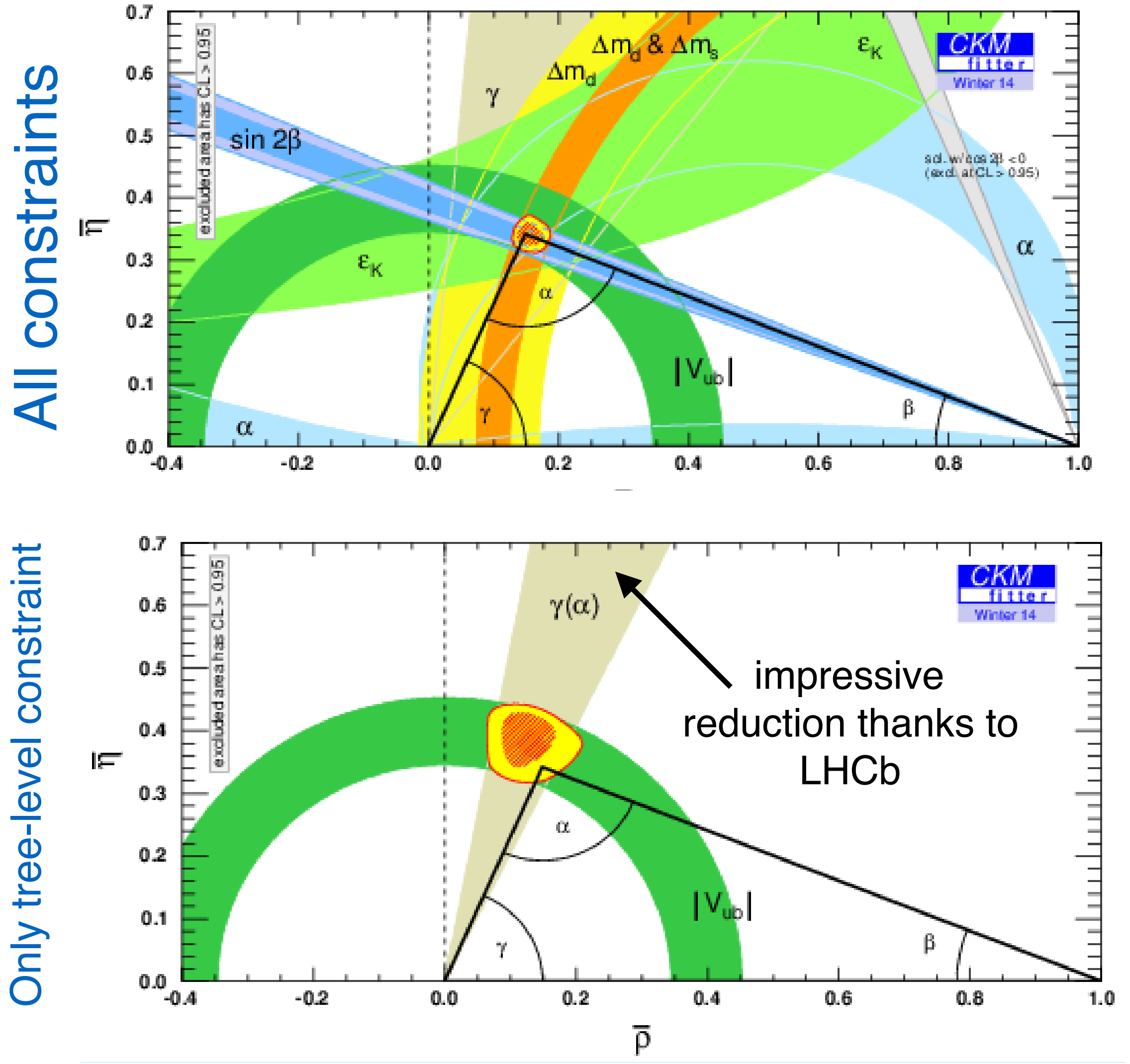


Charged Bs:



CPV

$$\phi_1 \equiv \beta \equiv \arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)].$$


All constraints

Only tree-level constraint

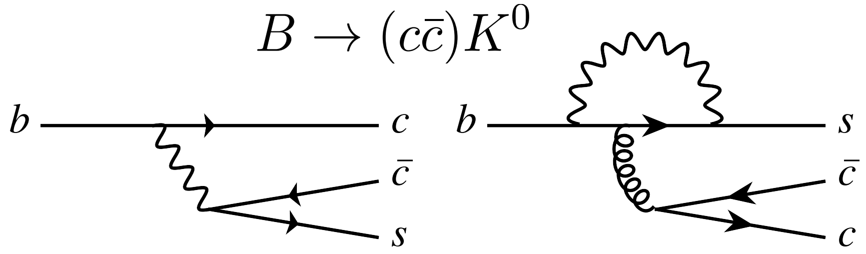
impressive reduction thanks to LHCb

Search for new sources of CPV

- CKM fit dominated by sin(2β = 2 ϕ_1) precision
- If new sources of CPV is present expect tree-constraints and loop constraints to not agree
- Current precision leaves room for new CPV physics

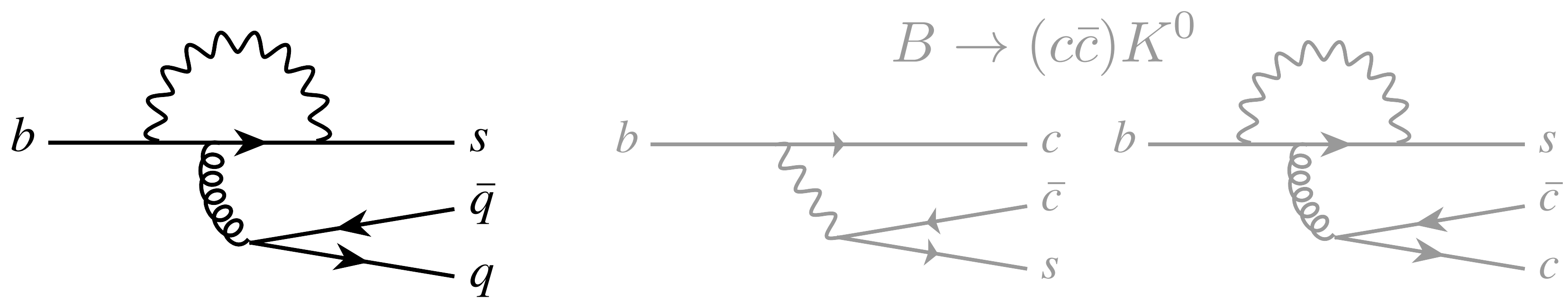
Precision measurements of sin(2β) will remain an important topic to check the consistency of the Unitary triangle and for the search of new physics

$B \to (c\bar{c})K^0$



Error on sin(2β)	stat.	tot.
B-Factories	3.5%	3.9%
Belle II 5/ab	1.3%	1.8%
Belle II 50/ab	0.4%	**1.2%**

CPV



One of the most promising ways to search for new sources of CPV is to compare the mixing-induced CP asymmetries in penguin transitions with tree-dominated modes

$$B \to \eta' K^0$$

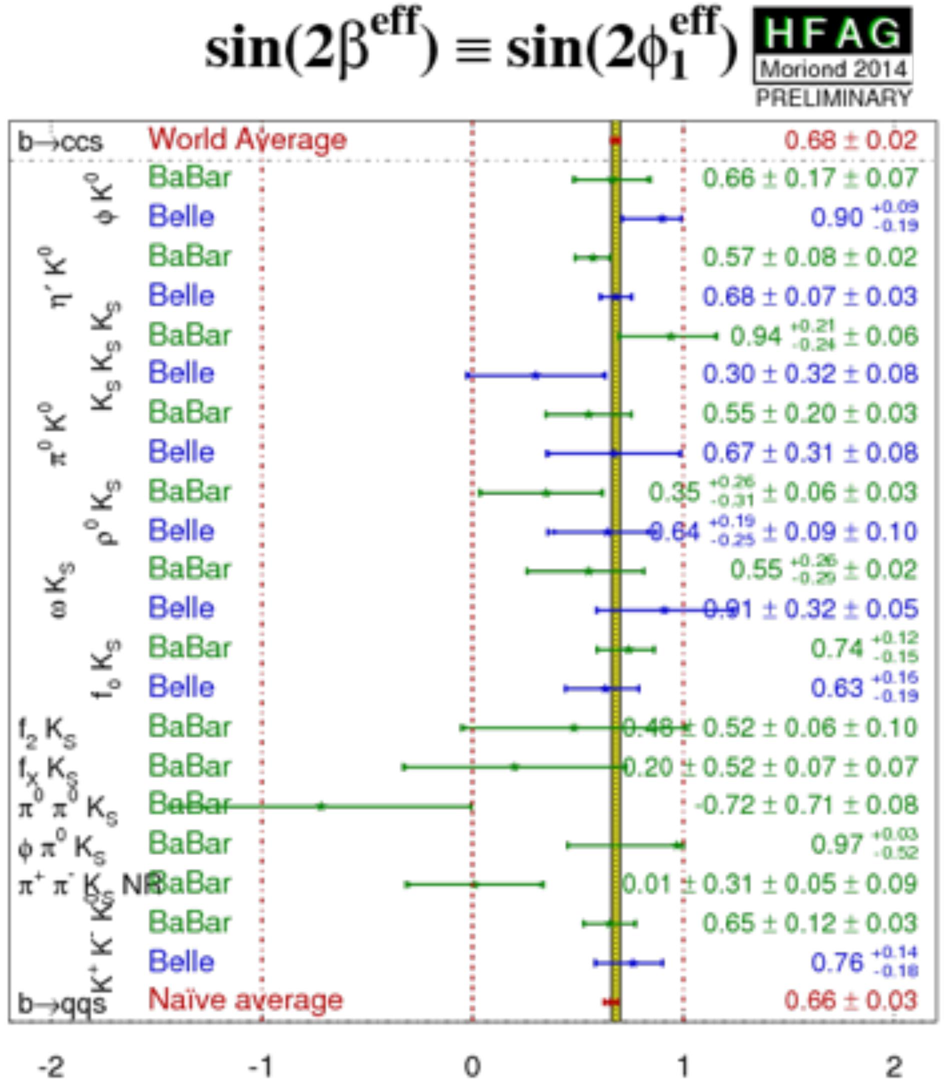
Error on sin(2β)	tot.
B-Factories	9.4%
Belle II 5/ab	4.2%
Belle II 50/ab	**1.6%**

$$B \to \phi K^0$$

Error on sin(2β)	tot.
B-Factories	17.8%
Belle II 5/ab	7.9%
Belle II 50/ab	**2.7%**

$$B \to K^0 K^0 K^0$$

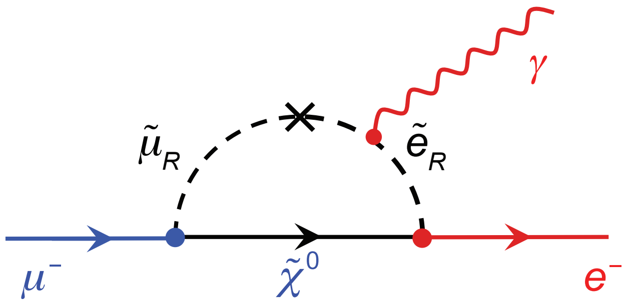
Error on sin(2β)	tot.
B-Factories	33.9%
Belle II 5/ab	15.1%
Belle II 50/ab	**4.9%**



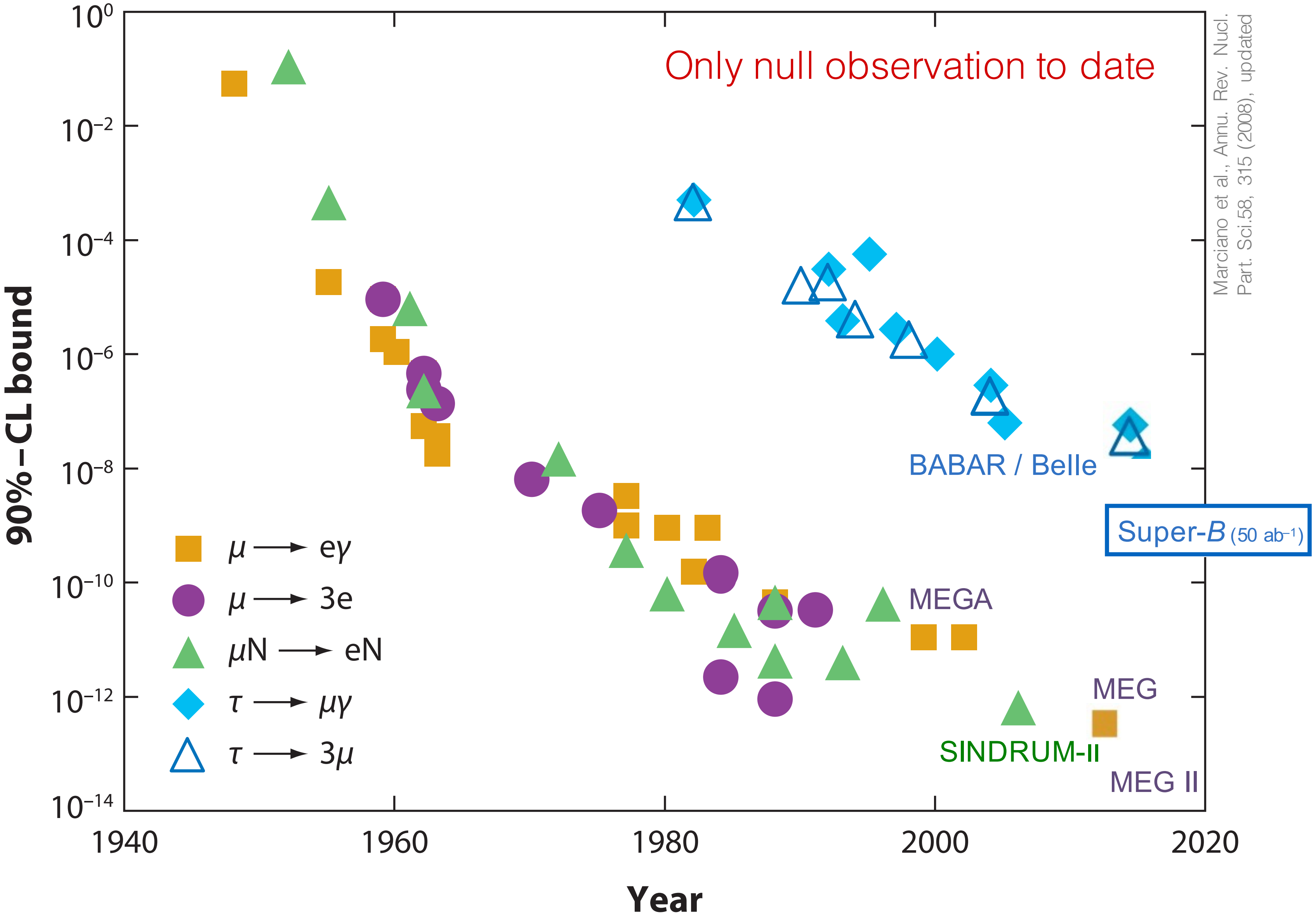
LFV

Charged lepton flavour violation:

SM-free signals!



LFV signals are expected in many BSM scenarios, such as the MSSM or as a consequence of Seesaw models

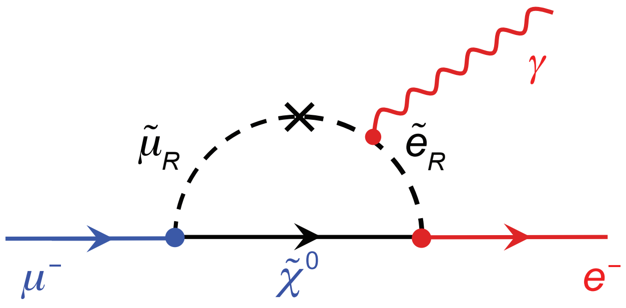


Marciano et al., Annu. Rev. Nucl. Part. Sci.58, 315 (2008), updated

Spectacular perspectives: Mu2e / COMET PRISM / PRIME

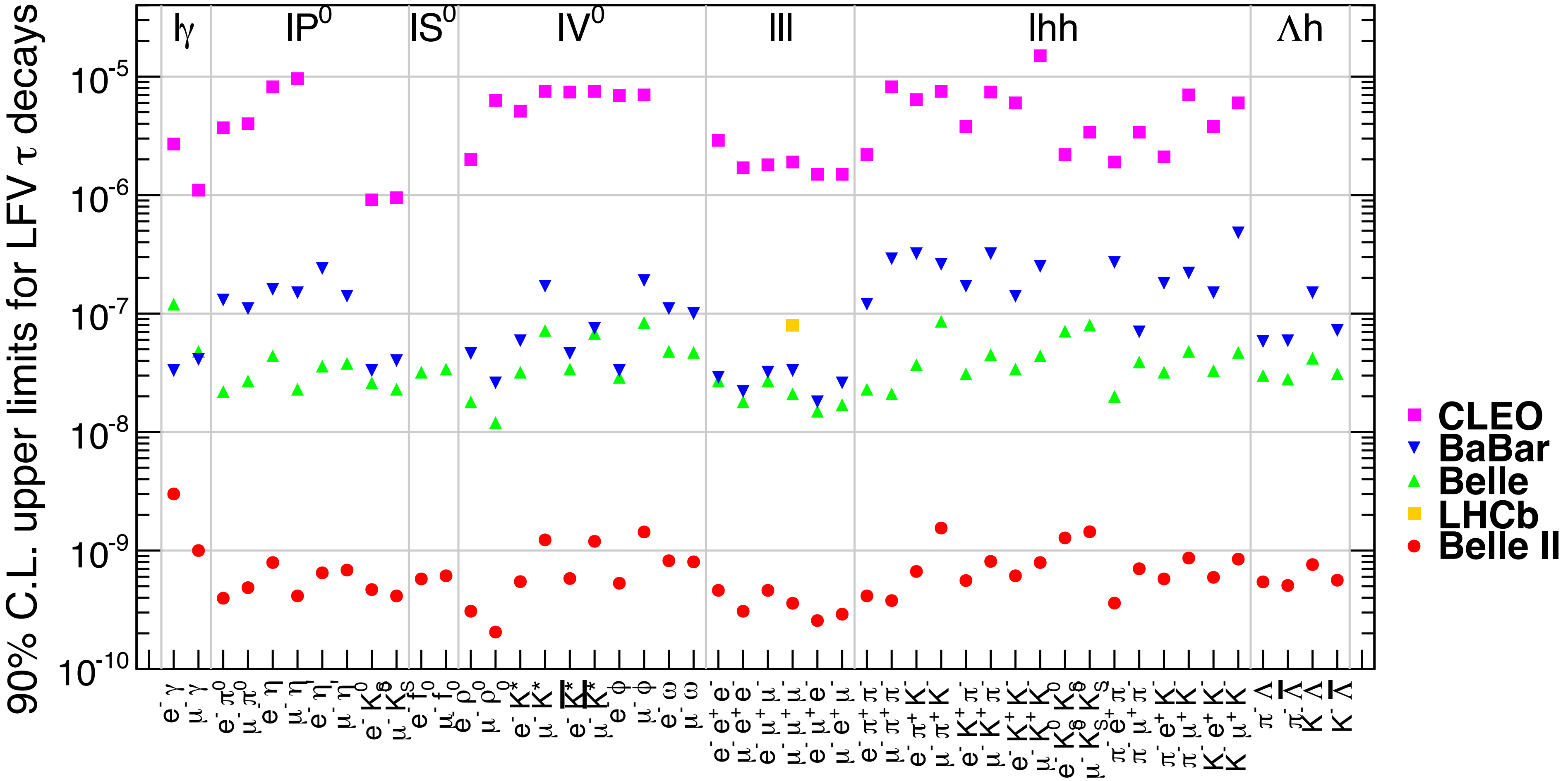
LFV

Charged lepton flavour violation:
SM-free signals!



LFV signals are expected in many BSM scenarios, such as the MSSM or as a consequence of Seesaw models

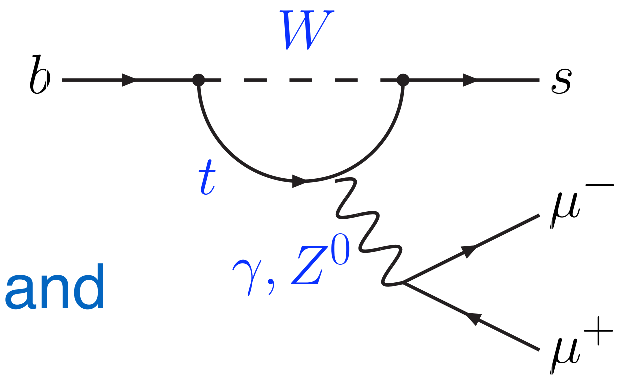
Belle II will be able to improve current limits by a factor of 100 for $\tau \rightarrow 3l$ and a factor of >10 for $\tau \rightarrow l\,\gamma$



EWP

Electroweak penguin production very sensitive to New Physics

- Radiative penguins offer interesting probe for $|C_7|$
  - A_{CP} measurements of $B \to X_{d/s}\, \gamma$ and $B \to X_{d+s}\, \gamma$
- Leptonic penguins access $|C_7|$, $|C_9|$ and $|C_{10}|$
  - Can measure full repertoire of kinematic, angular and CP observables
- Belle II can access inclusive and exclusive decays
  - Way to deal with QCD independent; valuable cross check when anomalies show up *(cf. slide 19)*
  - Measured $B \to X_s\, ll$ A_{FB} *sensitive to* $|C_7|$, $|C_9|$ *ratio*



untagged

$B \to X_s \gamma$

Error	stat.	tot.
B-Factories	4.2%	12.3%
Belle II 5/ab	1.5%	6.6%
Belle II 50/ab	0.5%	**5.4%**

had. tagged

$B \to X_s \gamma$

Error	stat.	tot.
B-Factories	13.4%	16.8%
Belle II 5/ab	4.8%	7.5%
Belle II 50/ab	1.5%	**5.1%**

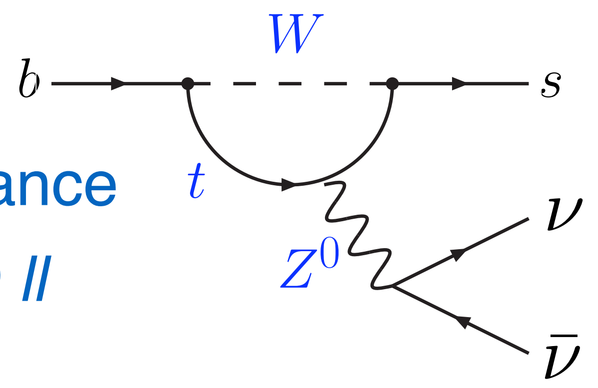
$B \to X_s \ell\ell$ C_7/C_9 ratio

Error	tot.
B-Factories	19%
Belle II 5/ab	9%
Belle II 50/ab	**6%**

EWP

Electroweak penguin production very sensitive to New Physics

- Belle II will be able to probe modes with neutrinos and τ leptons
  - $B \to K(^*)\, \nu\nu$ theoretically very clean, no long distance effects from resonances (J/ψ, etc.) as for $B \to K(^*)\, ll$



had. tagged

$B \to \tau\tau$ SM ~ 2 x 10^{-10}

Error	90% CL
B-Factories	< 4.1 x 10^{-3}
Belle II 5/ab	< 0.8 x 10^{-3}
Belle II 50/ab	**< 0.3 x 10^{-3}**

$B_s \to \tau\tau$ SM ~ 9 x 10^{-7}

Error	90% CL
B-Factories	< 13 x 10^{-3}
Belle II 5/ab	**< 2 x 10^{-3}**

had. tagged

$B^0 \to K_S \nu\bar{\nu}$ SM ~ 2.2 x 10^{-6}

Error	stat.
B-Factories	590%
Belle II 5/ab	220%
Belle II 50/ab	**94%**

$B^0 \to K^{*0} \nu\bar{\nu}$ SM ~ 9.5 x 10^{-6}

Error	stat.
B-Factories	112%
Belle II 5/ab	42%
Belle II 50/ab	**22%**

$B^+ \to K^+ \nu\bar{\nu}$ SM ~ 4.7 x 10^{-6}

Error	stat.
B-Factories	130%
Belle II 5/ab	49%
Belle II 50/ab	**22%**

$B^+ \to K^{*+} \nu\bar{\nu}$ SM ~ 10.2 x 10^{-6}

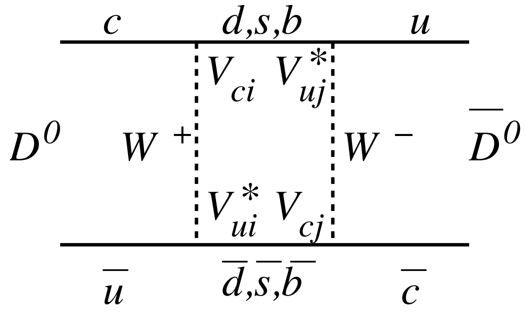
Error	stat.
B-Factories	120%
Belle II 5/ab	45%
Belle II 50/ab	**22%**

Charm physics

Charm physics experienced a large boost in interest from the theory side as well from experimental efforts.

Charm will be one of the important subjects to be studied by Belle II

- Leptonic charm decays are sensitive to NP contributions
- Measurement of D^0 mixing and CPV parameter measurement



- Charm mixing frequency extremely low, challenging high-statistics measurement

y_{CP}

Error	tot. (in 10^{-3})
B-Factories	2.4
Belle II 5/ab	1.1
Belle II 50/ab	**0.5**

A_Γ SM ~ < x 10^{-4}

Error	tot. (in 10^{-4})
B-Factories	22
Belle II 5/ab	10
Belle II 50/ab	**3**

Low multiplicity signatures

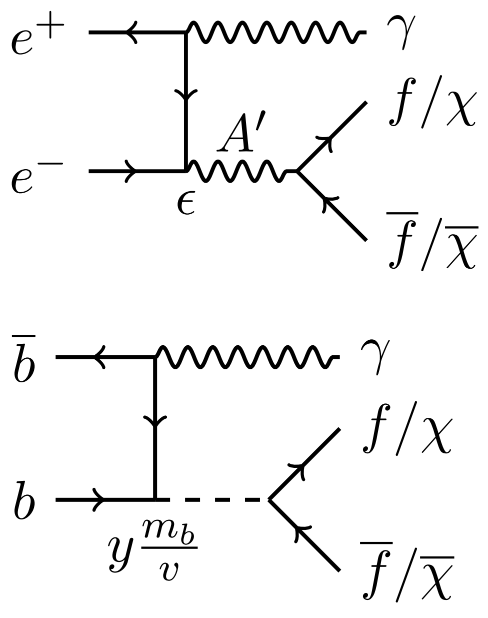
Belle II can probe ‘dark forces’ with dedicated Triggers

- ‘dark forces’: involving dark-matter particles that serve as ‘portals' between the SM and a dark-matter sector

dark photon mass coupling strength

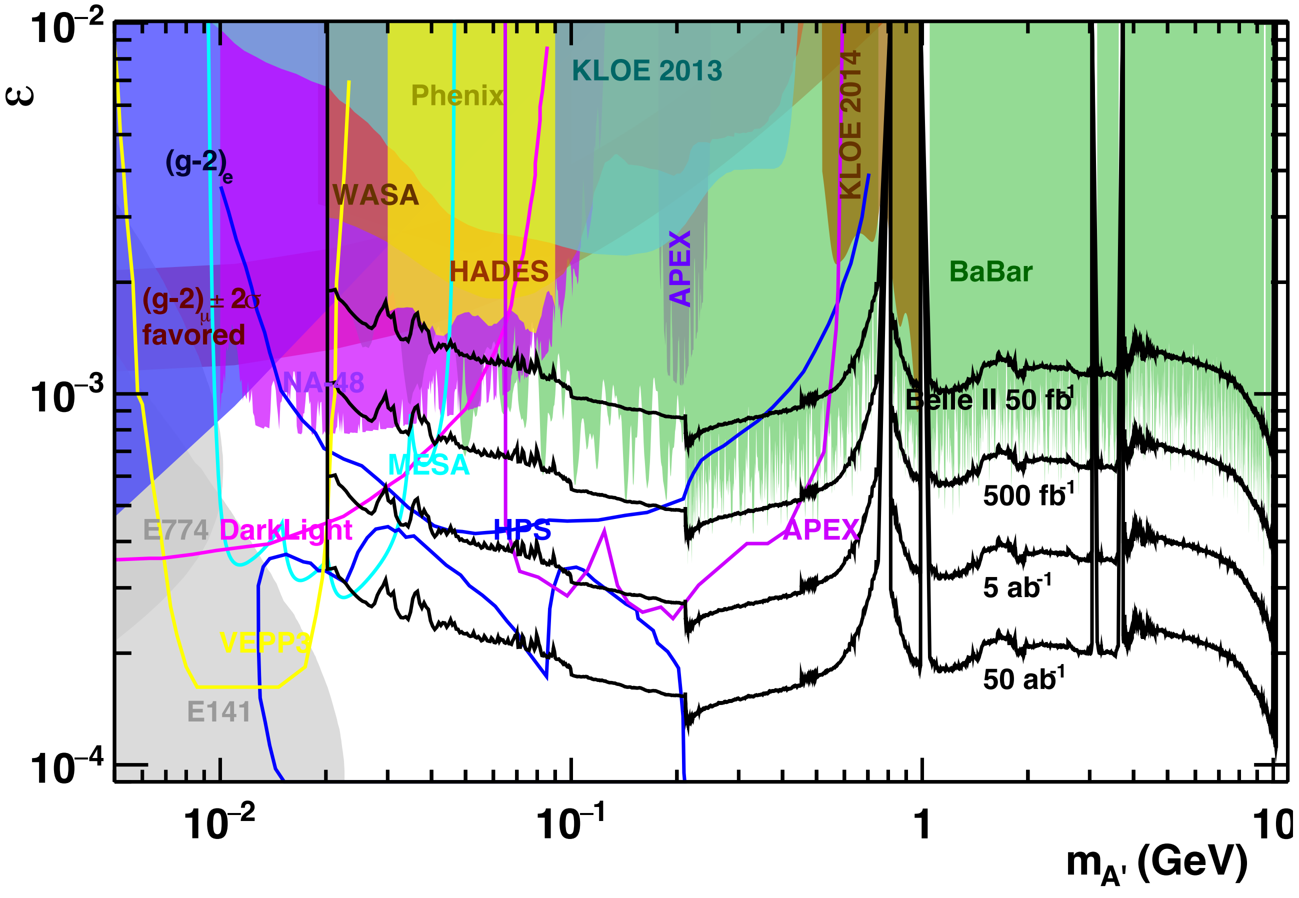
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'^\mu - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

- Motivated by rise in cosmic-ray positron fraction (which does not necessarily have to be due to New Physics)
- Also models with dark Higgs bosons that could be produced in Y(nS) decays.

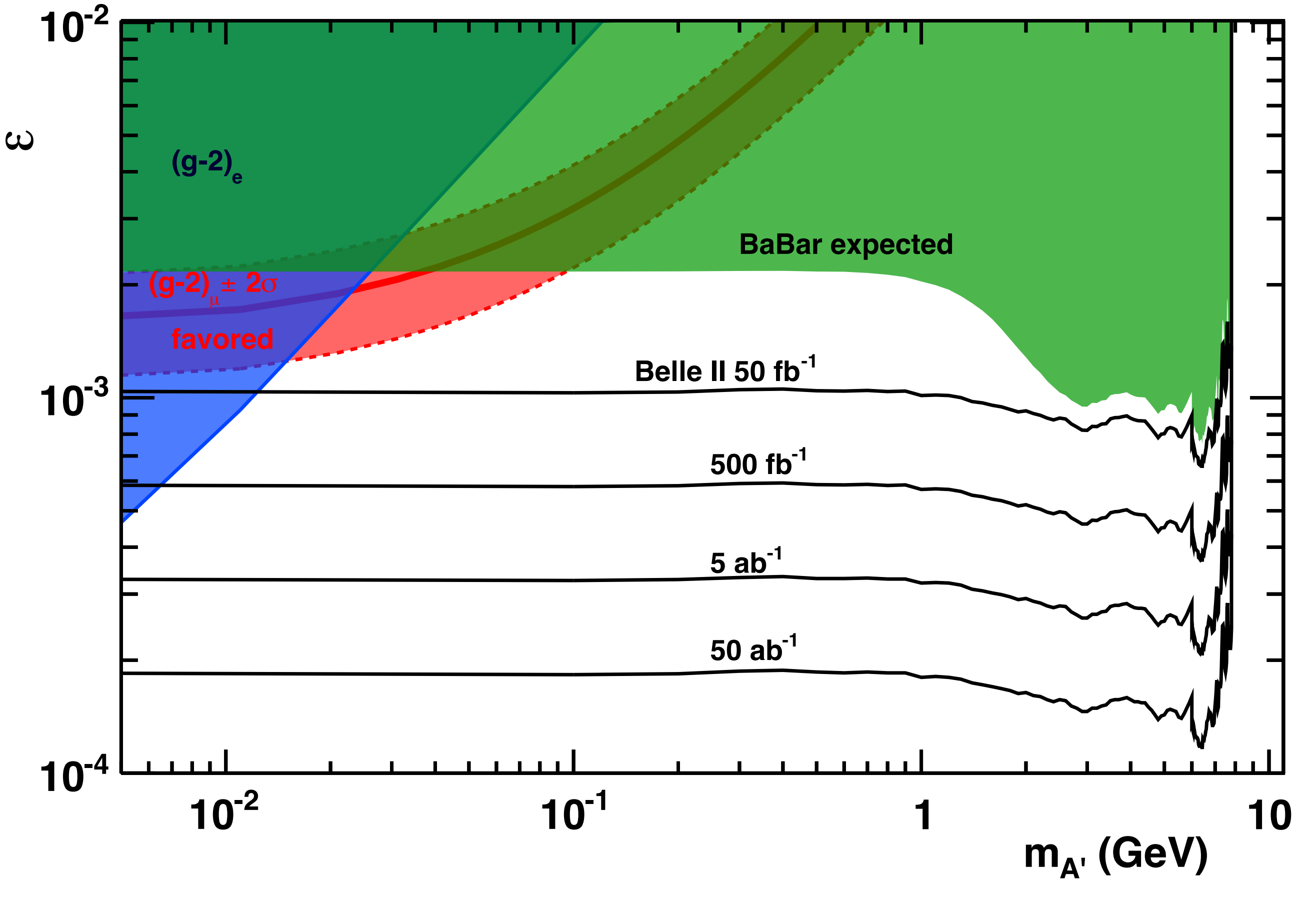


Belle II will probe a unique piece of phase space, and even a small data sample will have a sizeable impact on todays limits

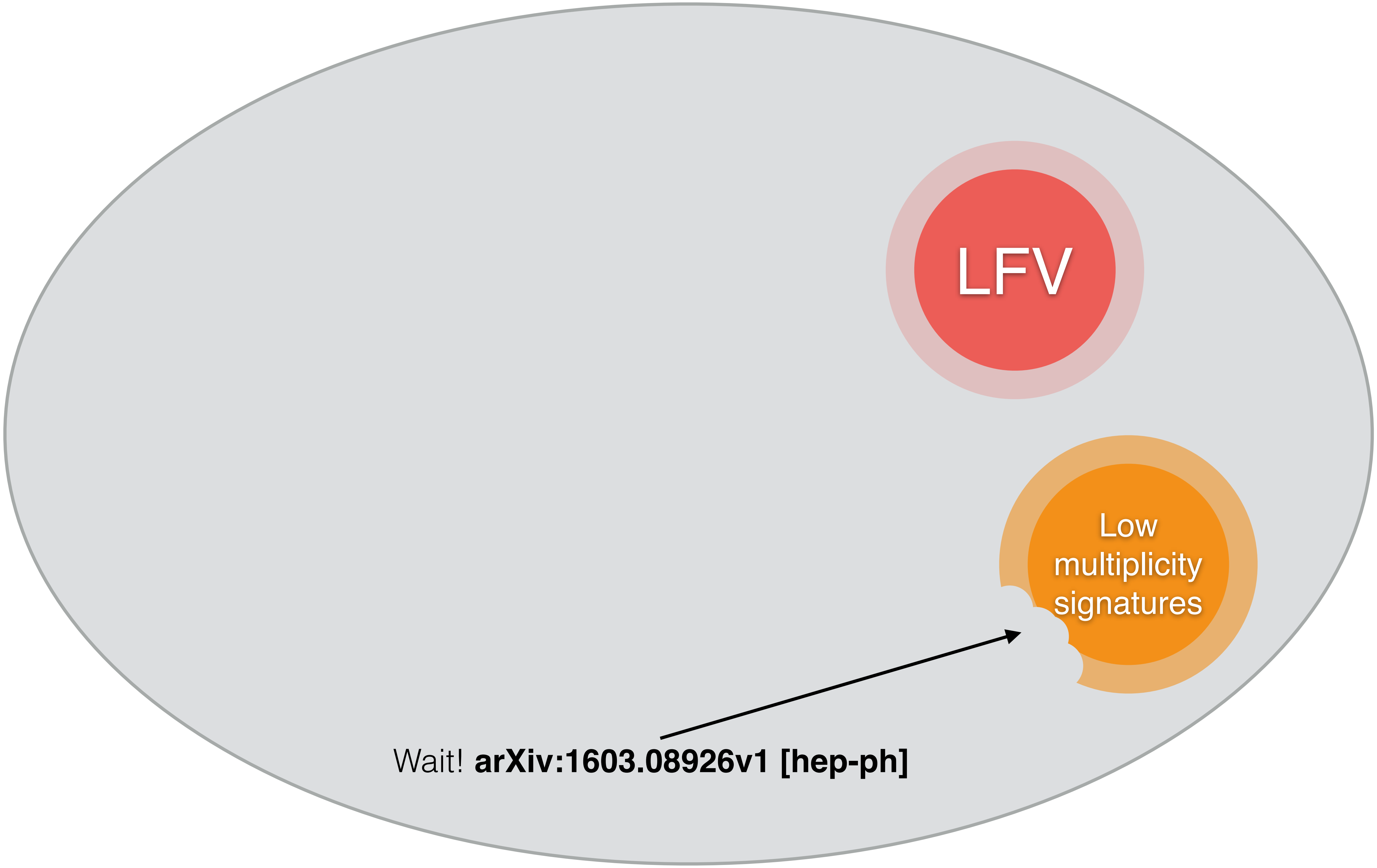
(Prompt) dilepton final state



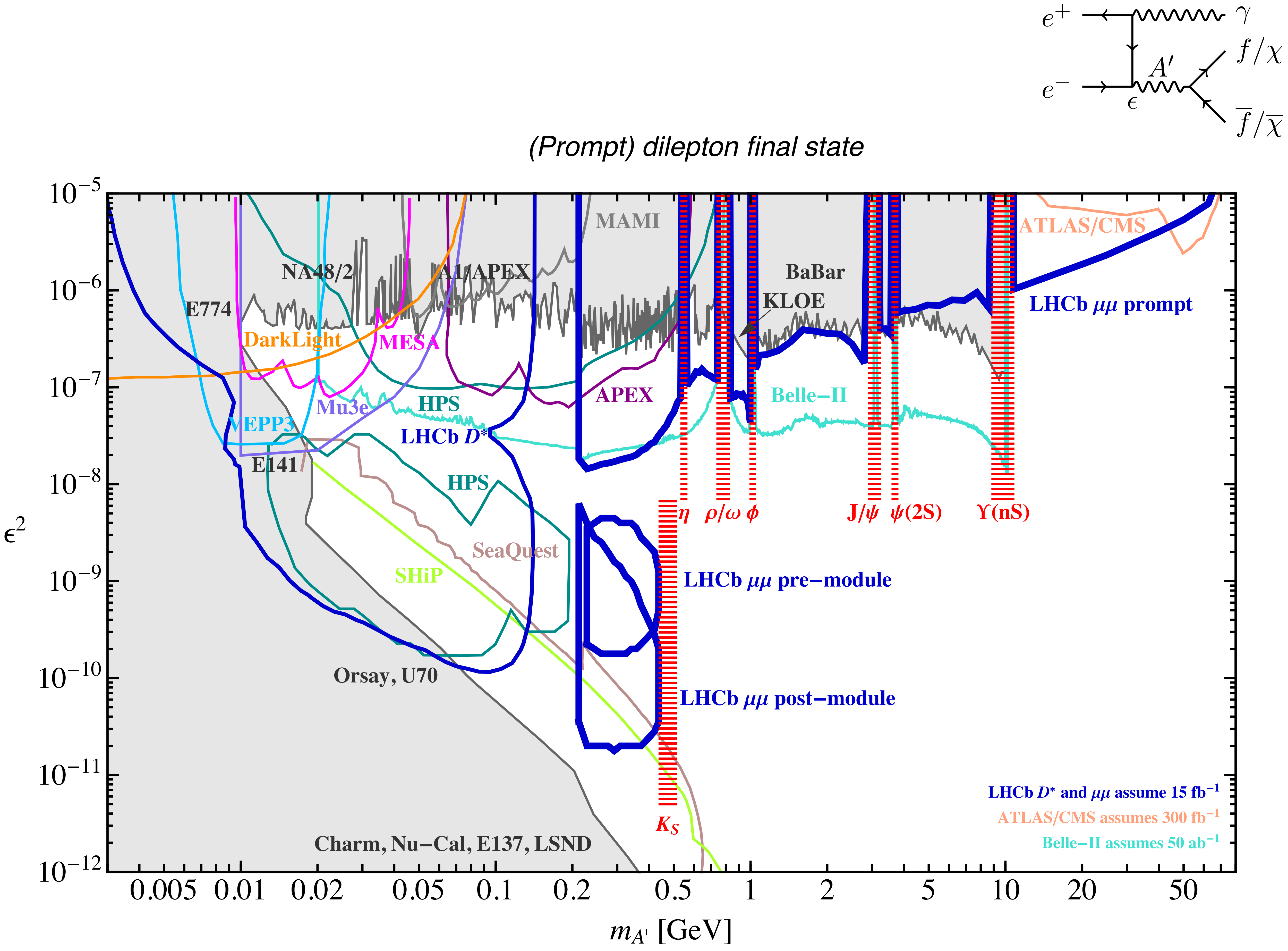
invisible final state



And there are the untouched pieces…



Wait! **arXiv:1603.08926v1 [hep-ph]**



e^+
γ
A'
f/χ
e^-
ϵ
$\overline{f}/\overline{\chi}$
(Prompt) dilepton final state
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
ϵ^2
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1
2
5
10
20
50
$m_{A'}$ [GeV]
MAMI
ATLAS/CMS
NA48/2
A1/APEX
BaBar
KLOE
E774
LHCb $\mu\mu$ prompt
DarkLight
MESA
APEX
Belle−II
HPS
Mu3e
VEPP3
LHCb D^*
E141
HPS
η
ρ/ω
ϕ
J/ψ
ψ(2S)
Υ(nS)
SeaQuest
SHiP
LHCb $\mu\mu$ pre−module
Orsay, U70
LHCb $\mu\mu$ post−module
K_S
Charm, Nu−Cal, E137, LSND
LHCb D^* and $\mu\mu$ assume 15 fb^{-1}
ATLAS/CMS assumes 300 fb^{-1}
Belle−II assumes 50 ab^{-1}

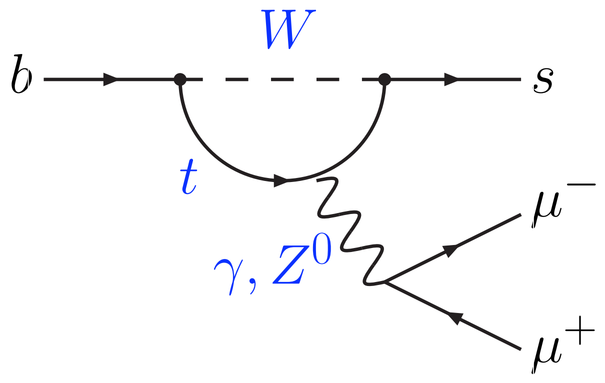
Flavour Anomalies: $b \rightarrow s\mu\mu$

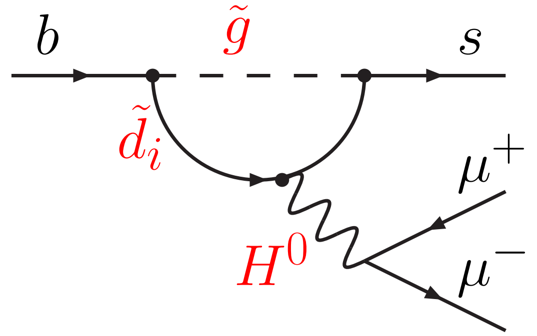
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

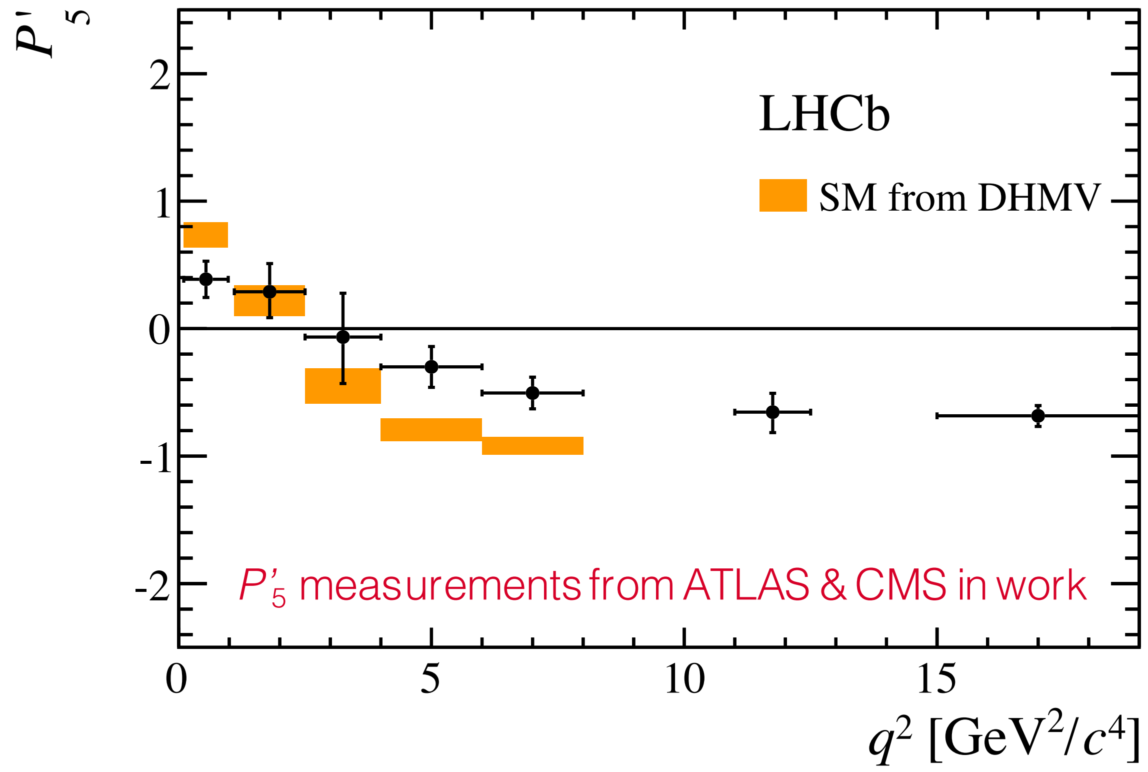
Penguin decays are very sensitive to new physics contributions

In $b \rightarrow s\mu\mu$ new physics can enter via new mediators and alter the total rate, but also the angular correlations

- P_5' is one particular observable depending on the helicity angle and the tilting angle of the decay planes, normalized by the fraction of longitudinal polarized K* mesons
- P_5' can be predicted reliably as many form factor uncertainties cancel



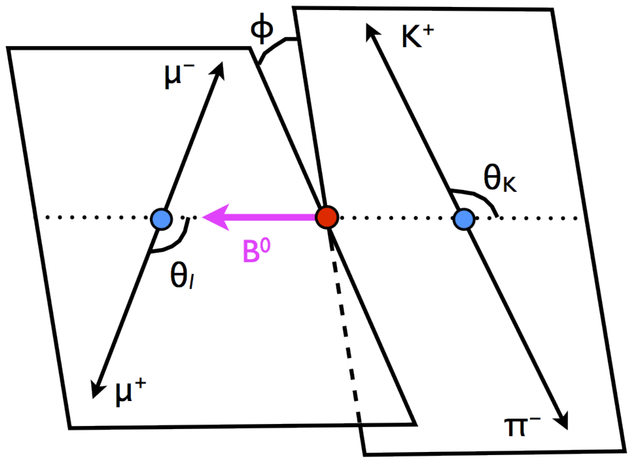




P_5' measurements from ATLAS & CMS in work

- Deviation from SM of the order **3.4σ**

$$B \rightarrow K^* \mu\, \mu$$



$$q^2 = (p_B - p_{K^*})^2 = (p_\mu + p_\mu')^2 = m_{\mu\mu}^2$$

Flavour Anomalies: $b \to s\mu\mu$

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

The reconstruction of $B \to K^{(*)}\ell^+\ell^-$ is challenging!

- The branching ratio for $B^0 \to K^*(892)^0\ell^+\ell^-$ is in the order of 10^{-7}
- There is irreducible background from $B \to K^* J/\psi$ and $B \to K^*\psi(2S)$
- We expect $\mathcal{O}(100)$ candidates in the Belle data-sample

Solution:

- Highly efficient reconstruction algorithms to find as many candidates as possible
- Robust fitting technique – suitable for low statistics
  - $\to$ folding method introduced by LHCb in 2013 (arXiv:1308.1707)

Flavour Anomalies: $b \to s\mu\mu$

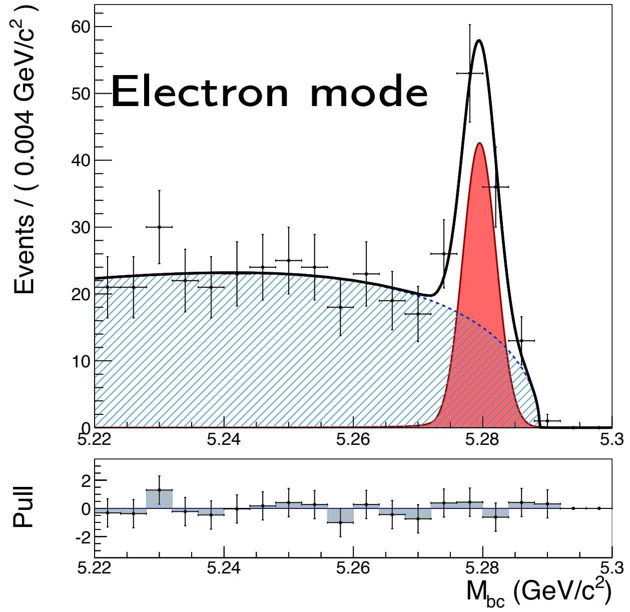
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

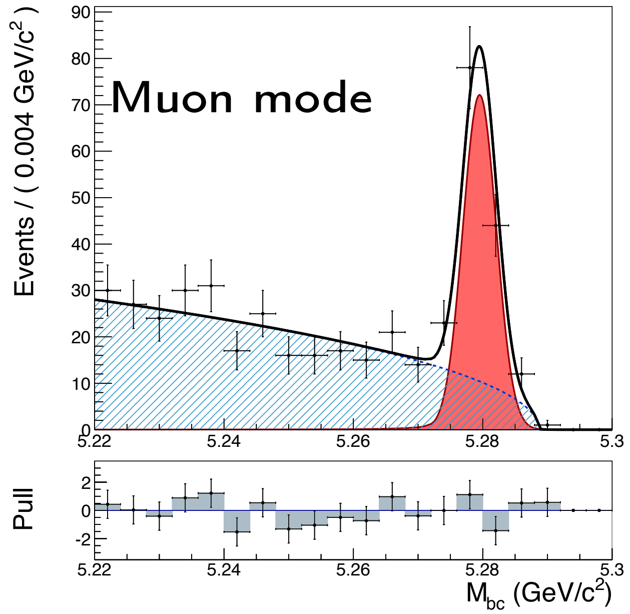
Multivariate approach

- Neural networks for identifying all primary particles and K^*
- K^* is reconstructed in $K^*(892)^0 \to K^+\pi^-$
- Neural networks for signal selection (one for each B decay channel)
- Signal is identified in the beam constrained mass

$$M_{\mathrm{bc}} \equiv \sqrt{E_{\mathrm{Beam}}^2 - |\vec{p}_B|^2}$$

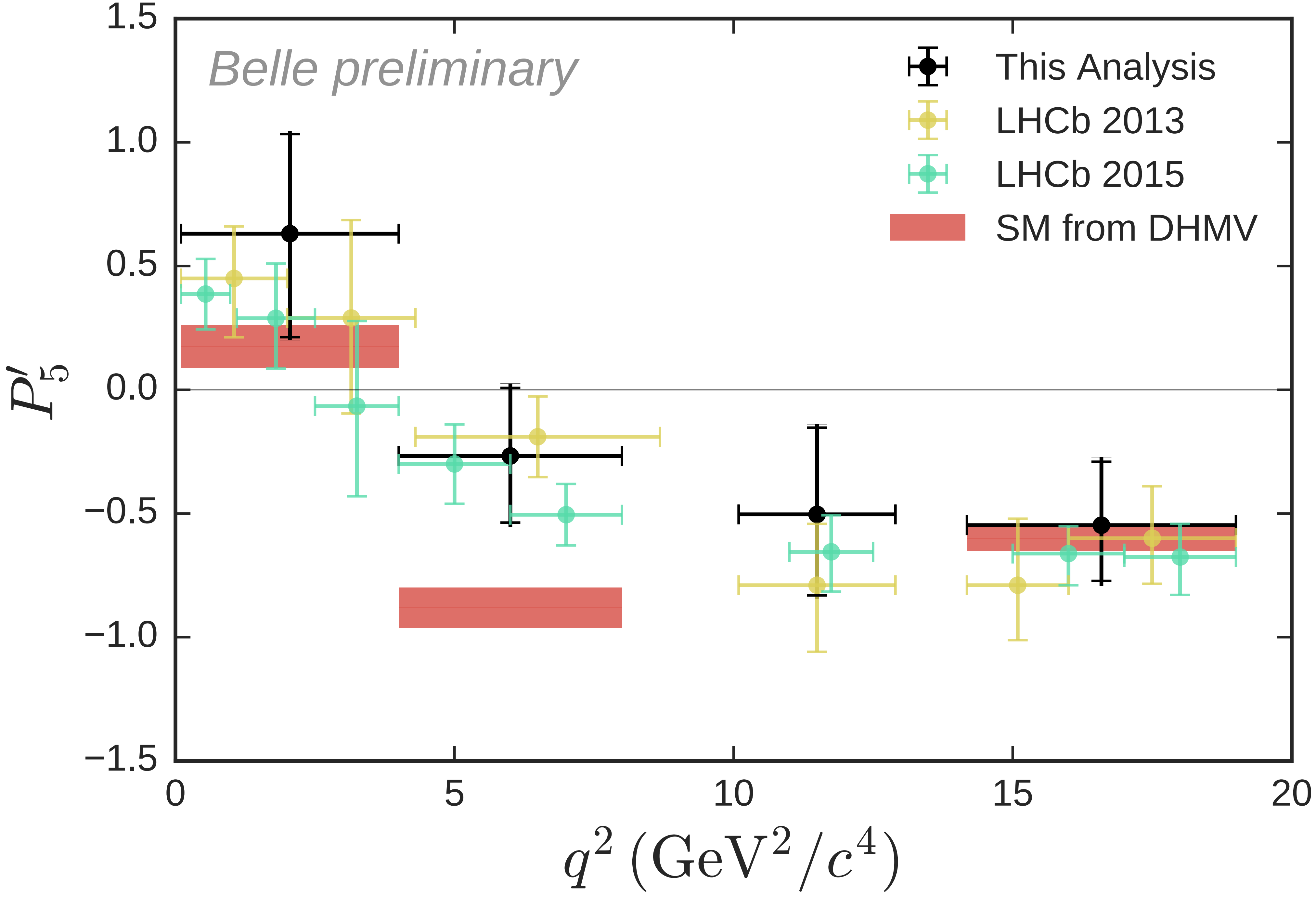
We find:
117.6 ± 12.4 signal candidates for $B^0 \to K^*(892)^0\mu^+\mu^-$
69.4 ± 12.0 for $B^0 \to K^*(892)^0e^+e^-$





Flavour Anomalies: $b \to s\mu\mu$

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$



B-Factories and LHCb $|V_{ub}|$ Systematics

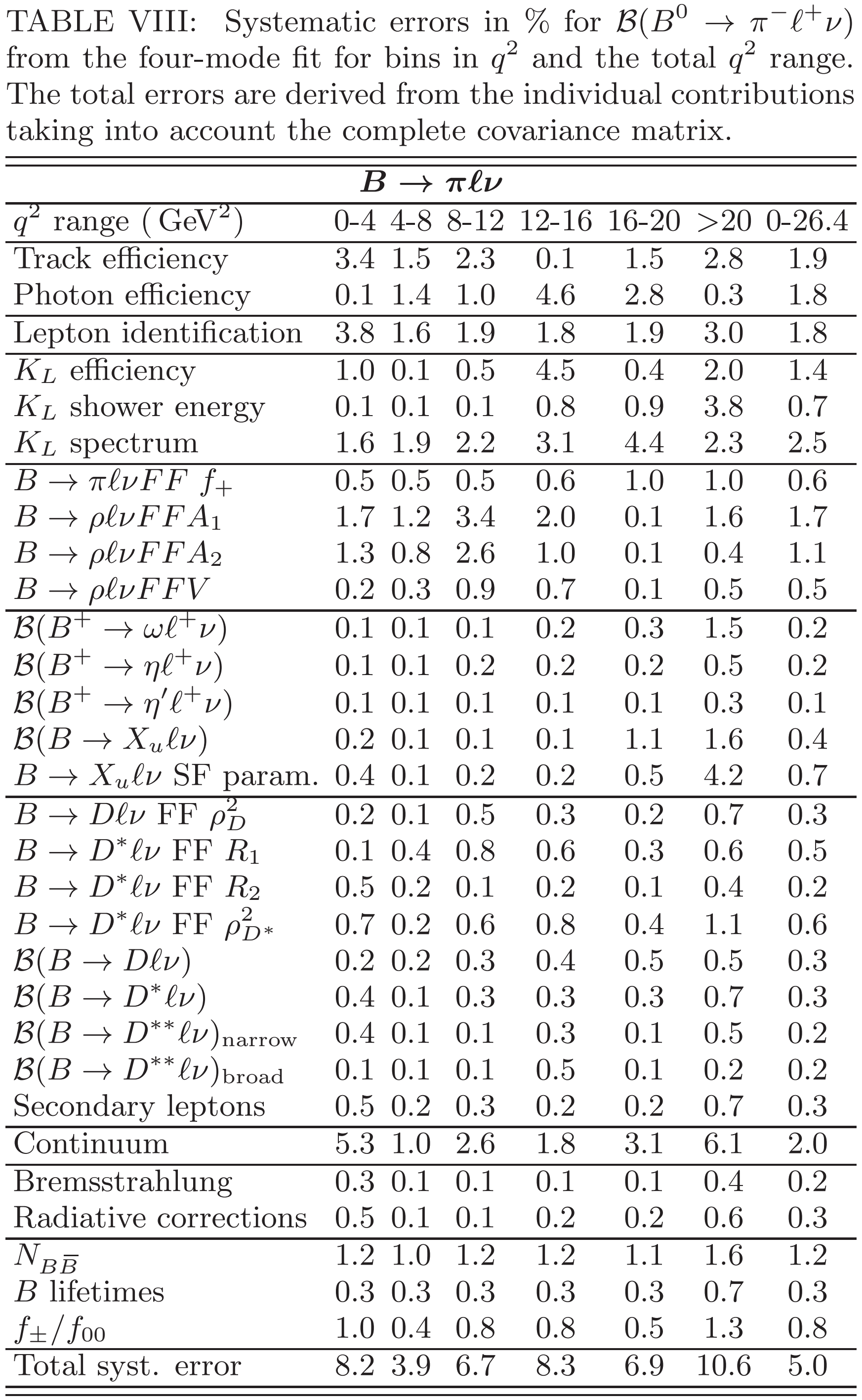
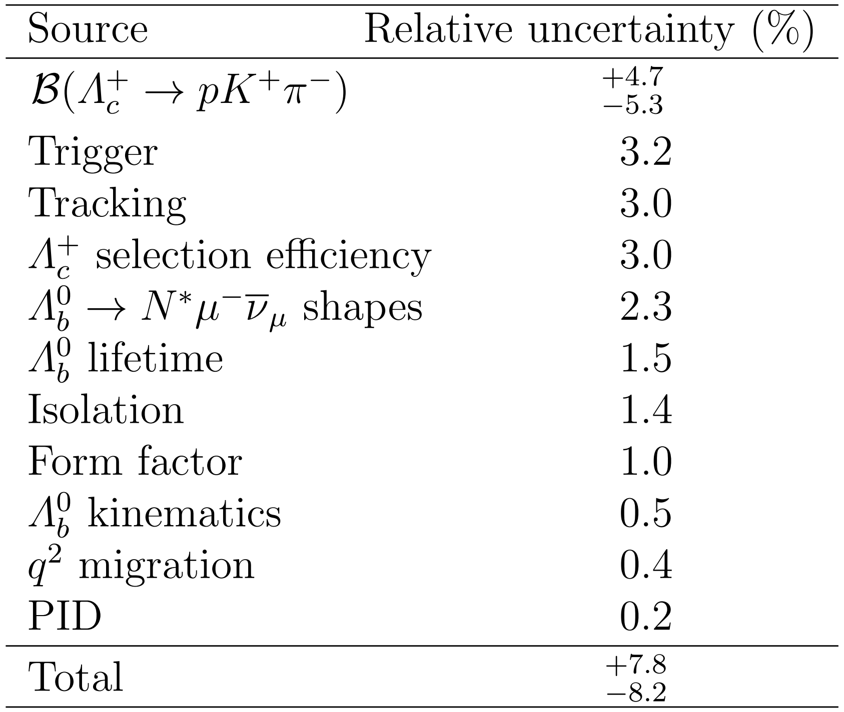


TABLE VIII: Systematic errors in % for $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu)$ from the four-mode fit for bins in q^2 and the total q^2 range. The total errors are derived from the individual contributions taking into account the complete covariance matrix.

	$B \to \pi\ell\nu$						
q^2 range (GeV^2)	0-4	4-8	8-12	12-16	16-20	>20	0-26.4
Track efficiency	3.4	1.5	2.3	0.1	1.5	2.8	1.9
Photon efficiency	0.1	1.4	1.0	4.6	2.8	0.3	1.8
Lepton identification	3.8	1.6	1.9	1.8	1.9	3.0	1.8
K_L efficiency	1.0	0.1	0.5	4.5	0.4	2.0	1.4
K_L shower energy	0.1	0.1	0.1	0.8	0.9	3.8	0.7
K_L spectrum	1.6	1.9	2.2	3.1	4.4	2.3	2.5
$B \to \pi\ell\nu FF\ f_+$	0.5	0.5	0.5	0.6	1.0	1.0	0.6
$B \to \rho\ell\nu FF A_1$	1.7	1.2	3.4	2.0	0.1	1.6	1.7
$B \to \rho\ell\nu FF A_2$	1.3	0.8	2.6	1.0	0.1	0.4	1.1
$B \to \rho\ell\nu FFV$	0.2	0.3	0.9	0.7	0.1	0.5	0.5
$\mathcal{B}(B^+ \to \omega\ell^+\nu)$	0.1	0.1	0.1	0.2	0.3	1.5	0.2
$\mathcal{B}(B^+ \to \eta\ell^+\nu)$	0.1	0.1	0.2	0.2	0.2	0.5	0.2
$\mathcal{B}(B^+ \to \eta'\ell^+\nu)$	0.1	0.1	0.1	0.1	0.1	0.3	0.1
$\mathcal{B}(B \to X_u\ell\nu)$	0.2	0.1	0.1	0.1	1.1	1.6	0.4
$B \to X_u\ell\nu$ SF param.	0.4	0.1	0.2	0.2	0.5	4.2	0.7
$B \to D\ell\nu$ FF ρ_D^2	0.2	0.1	0.5	0.3	0.2	0.7	0.3
$B \to D^*\ell\nu$ FF R_1	0.1	0.4	0.8	0.6	0.3	0.6	0.5
$B \to D^*\ell\nu$ FF R_2	0.5	0.2	0.1	0.2	0.1	0.4	0.2
$B \to D^*\ell\nu$ FF $\rho_{D^*}^2$	0.7	0.2	0.6	0.8	0.4	1.1	0.6
$\mathcal{B}(B \to D\ell\nu)$	0.2	0.2	0.3	0.4	0.5	0.5	0.3
$\mathcal{B}(B \to D^*\ell\nu)$	0.4	0.1	0.3	0.3	0.3	0.7	0.3
$\mathcal{B}(B \to D^{**}\ell\nu)_{\text{narrow}}$	0.4	0.1	0.1	0.3	0.1	0.5	0.2
$\mathcal{B}(B \to D^{**}\ell\nu)_{\text{broad}}$	0.1	0.1	0.1	0.5	0.1	0.2	0.2
Secondary leptons	0.5	0.2	0.3	0.2	0.2	0.7	0.3
Continuum	5.3	1.0	2.6	1.8	3.1	6.1	2.0
Bremsstrahlung	0.3	0.1	0.1	0.1	0.1	0.4	0.2
Radiative corrections	0.5	0.1	0.1	0.2	0.2	0.6	0.3
$N_{B\overline{B}}$	1.2	1.0	1.2	1.2	1.1	1.6	1.2
B lifetimes	0.3	0.3	0.3	0.3	0.3	0.7	0.3
$f_{\pm}/f_{00}$	1.0	0.4	0.8	0.8	0.5	1.3	0.8
Total syst. error	8.2	3.9	6.7	8.3	6.9	10.6	5.0



Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

B-Factories R(D) / R(D) Systematics*

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

LHCb R(D) Systematics*

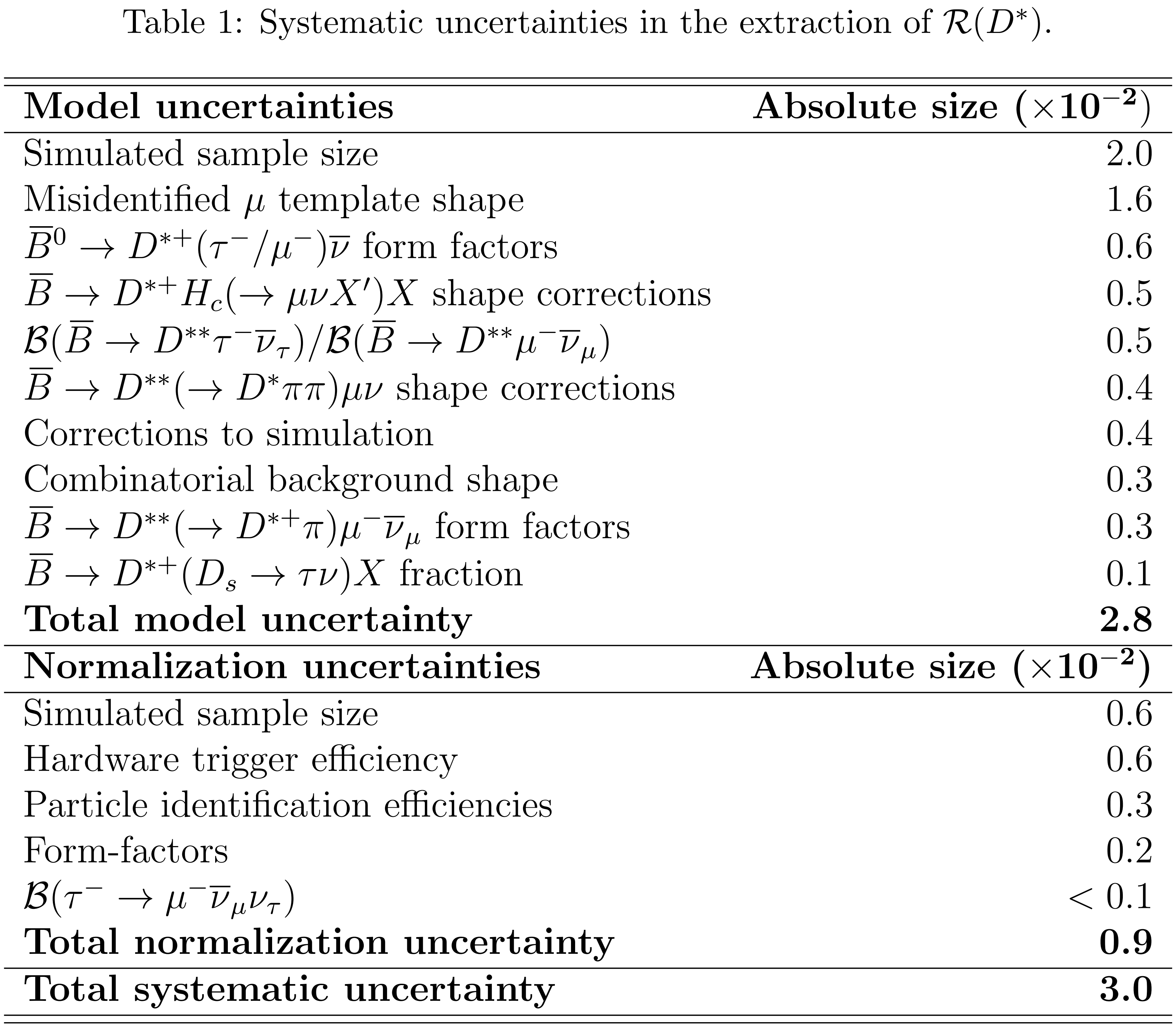


Table 1: Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

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**

LHCb and Belle sin(2β = 2 ϕ₁)

Origin	$\sigma(S_{J/\psi\, K^0_S})$	$\sigma(C_{J/\psi\, K^0_S})$
Tagging calibration	0.034	0.001
Tagging efficiency difference	0.002	0.002
Decay time resolution	0.001	0.002
Decay time acceptance	0.002	0.006
Background model	0.012	0.009
Fit bias	0.004	0.005
Total	0.036	0.012

$$S_{J/\psi\, K^0_S} = 0.73 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{syst}),$$

$$C_{J/\psi\, K^0_S} = 0.03 \pm 0.09\,(\text{stat}) \pm 0.01\,(\text{syst}),$$

TABLE III: Systematic errors in $\mathcal{S}_f$ and $\mathcal{A}_f$ in each f_{CP} mode and for the sum of all modes.

		$J/\psi K^0_S$	$\psi(2S)K^0_S$	$\chi_{c1}K^0_S$	$J/\psi K^0_L$	All
Vertexing	$\mathcal{S}_f$	±0.008	±0.031	±0.025	±0.011	±0.007
	$\mathcal{A}_f$	±0.022	±0.026	±0.021	±0.015	±0.007
Δt resolution	$\mathcal{S}_f$	±0.007	±0.007	±0.005	±0.007	±0.007
	$\mathcal{A}_f$	±0.004	±0.003	±0.004	±0.003	±0.001
Tag-side interference	$\mathcal{S}_f$	±0.002	±0.002	±0.002	±0.001	±0.001
	$\mathcal{A}_f$	${}^{+0.038}_{-0.000}$	${}^{+0.038}_{-0.000}$	${}^{+0.038}_{-0.000}$	${}^{+0.000}_{-0.037}$	±0.008
Flavor tagging	$\mathcal{S}_f$	±0.003	±0.003	±0.004	±0.003	±0.004
	$\mathcal{A}_f$	±0.003	±0.003	±0.003	±0.003	±0.003
Possible fit bias	$\mathcal{S}_f$	±0.004	±0.004	±0.004	±0.004	±0.004
	$\mathcal{A}_f$	±0.005	±0.005	±0.005	±0.005	±0.005
Signal fraction	$\mathcal{S}_f$	±0.004	±0.016	< 0.001	±0.016	±0.004
	$\mathcal{A}_f$	±0.002	±0.006	< 0.001	±0.006	±0.002
Background Δt PDFs	$\mathcal{S}_f$	< 0.001	±0.002	±0.030	±0.002	±0.001
	$\mathcal{A}_f$	< 0.001	< 0.001	±0.014	< 0.001	< 0.001
Physics parameters	$\mathcal{S}_f$	±0.001	±0.001	±0.001	±0.001	±0.001
	$\mathcal{A}_f$	< 0.001	< 0.001	±0.001	< 0.001	< 0.001
Total	$\mathcal{S}_f$	±0.013	±0.036	±0.040	±0.021	±0.012
	$\mathcal{A}_f$	${}^{+0.045}_{-0.023}$	${}^{+0.047}_{-0.027}$	${}^{+0.046}_{-0.026}$	${}^{+0.017}_{-0.041}$	±0.012

Decay mode	$\sin 2\phi_1 \equiv -\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
$J/\psi K^0_S$	$+0.670 \pm 0.029 \pm 0.013$	$-0.015 \pm 0.021^{+0.045}_{-0.023}$
$\psi(2S)K^0_S$	$+0.738 \pm 0.079 \pm 0.036$	$+0.104 \pm 0.055^{+0.047}_{-0.027}$
$\chi_{c1}K^0_S$	$+0.640 \pm 0.117 \pm 0.040$	$-0.017 \pm 0.083^{+0.046}_{-0.026}$
$J/\psi K^0_L$	$+0.642 \pm 0.047 \pm 0.021$	$+0.019 \pm 0.026^{+0.017}_{-0.041}$
All modes	$+0.667 \pm 0.023 \pm 0.012$	$+0.006 \pm 0.016 \pm 0.012$

LHCb γ Systematics for B -> Dh

$$A^{K\pi\pi^0}_{\mathrm{ADS}(K)} = -0.20 \pm 0.27 \pm 0.04$$

$$A^{K\pi\pi^0}_{\mathrm{ADS}(\pi)} = 0.438 \pm 0.190 \pm 0.011$$

$$A^{KK\pi^0}_{\mathrm{qGLW}(K)} = 0.30 \pm 0.20 \pm 0.02$$

$$A^{\pi\pi\pi^0}_{\mathrm{qGLW}(K)} = 0.054 \pm 0.091 \pm 0.011$$

$$A^{KK\pi^0}_{\mathrm{qGLW}(\pi)} = -0.030 \pm 0.040 \pm 0.005$$

$$A^{\pi\pi\pi^0}_{\mathrm{qGLW}(\pi)} = -0.016 \pm 0.020 \pm 0.004$$

$$A^{K\pi\pi^0}_{K} = 0.010 \pm 0.026 \pm 0.005$$

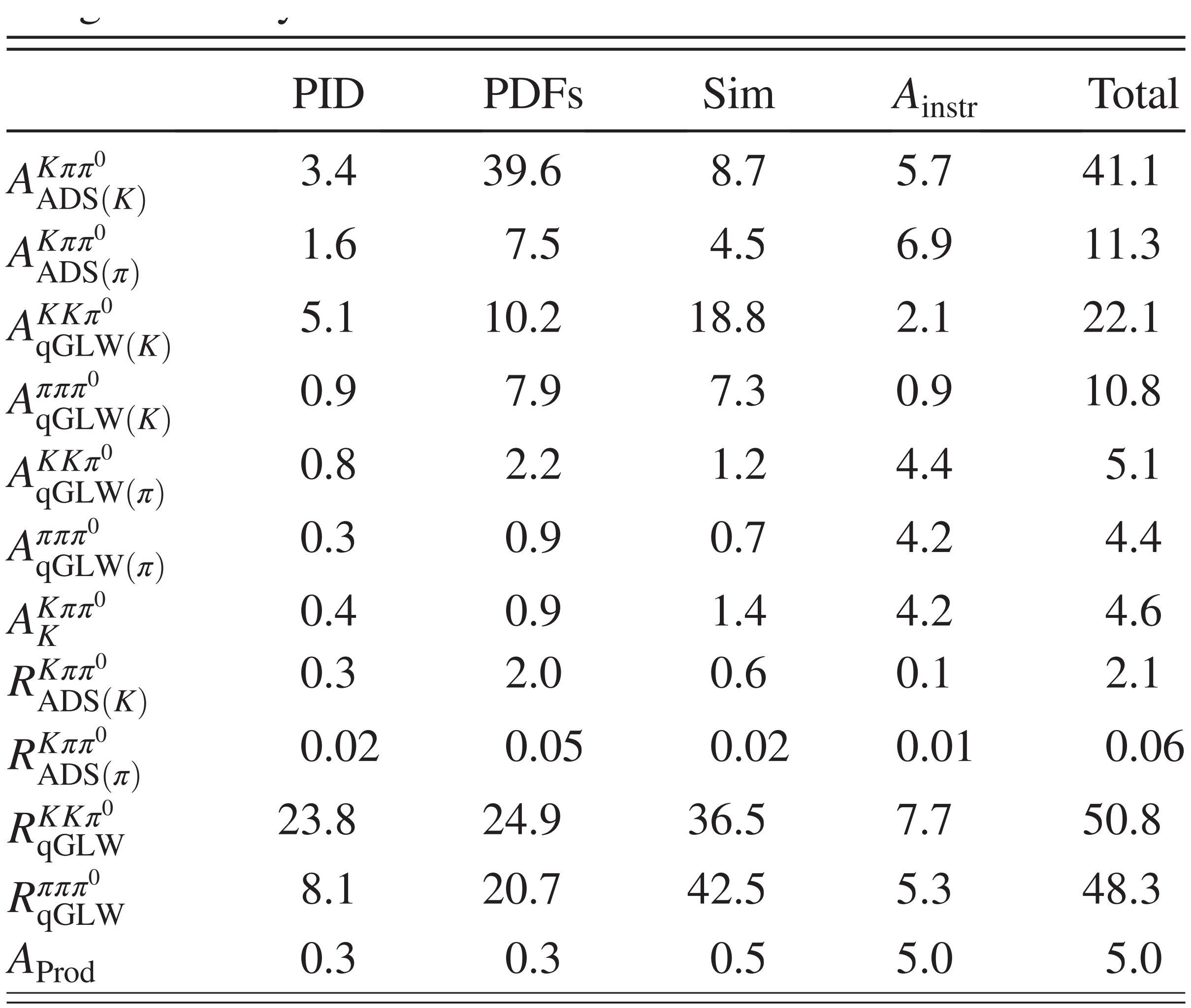
$$R^{K\pi\pi^0}_{\mathrm{ADS}(K)} = 0.0140 \pm 0.0047 \pm 0.0021$$

$$R^{K\pi\pi^0}_{\mathrm{ADS}(\pi)} = 0.00235 \pm 0.00049 \pm 0.00006$$

$$R^{KK\pi^0}_{\mathrm{qGLW}} = 0.95 \pm 0.22 \pm 0.05$$

$$R^{\pi\pi\pi^0}_{\mathrm{qGLW}} = 0.98 \pm 0.11 \pm 0.05$$

$$A_{\mathrm{Prod}} = -0.0008 \pm 0.0055 \pm 0.0050,$$



	PID	PDFs	Sim	A_{instr}	Total
$A^{K\pi\pi^0}_{\mathrm{ADS}(K)}$	3.4	39.6	8.7	5.7	41.1
$A^{K\pi\pi^0}_{\mathrm{ADS}(\pi)}$	1.6	7.5	4.5	6.9	11.3
$A^{KK\pi^0}_{\mathrm{qGLW}(K)}$	5.1	10.2	18.8	2.1	22.1
$A^{\pi\pi\pi^0}_{\mathrm{qGLW}(K)}$	0.9	7.9	7.3	0.9	10.8
$A^{KK\pi^0}_{\mathrm{qGLW}(\pi)}$	0.8	2.2	1.2	4.4	5.1
$A^{\pi\pi\pi^0}_{\mathrm{qGLW}(\pi)}$	0.3	0.9	0.7	4.2	4.4
$A^{K\pi\pi^0}_{K}$	0.4	0.9	1.4	4.2	4.6
$R^{K\pi\pi^0}_{\mathrm{ADS}(K)}$	0.3	2.0	0.6	0.1	2.1
$R^{K\pi\pi^0}_{\mathrm{ADS}(\pi)}$	0.02	0.05	0.02	0.01	0.06
$R^{KK\pi^0}_{\mathrm{qGLW}}$	23.8	24.9	36.5	7.7	50.8
$R^{\pi\pi\pi^0}_{\mathrm{qGLW}}$	8.1	20.7	42.5	5.3	48.3
A_{Prod}	0.3	0.3	0.5	5.0	5.0