Precision flavour physics

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My (almost) flavour timeline

1995-1999 Univ. of Oxford - PhD on not so tasty W/Z physics with Delphi at LEP

1999-2002 Univ. of Oxford/CERN – post-doc/fellow on R&D for **LHCb RICH and vertex detector**

2002-2005 SLAC – post-doc **BaBar RICH and physics**

2005-2009 Univ. of Oxford – faculty on LHCb **building RICH and physics preparation**, plus **CLEO-c (charm factory)**

2009-2024 Indian Institute of Technology Madras – faculty on **Belle (II), CLEO-c** and **BESIII (another charm factory) – mainly analysis and Belle II vertex detector**

2023-2025 – physics coordinator of Belle II – some bias may appear

Beets and Leeks
signature dish of
‘The French Laundry’ in
the nearby Napa Valley

Precision flavour

However perhaps more apt
my local South Indian thali
…many diverse things lead to precision flavour

Lecture plan

- A brief introduction to flavour
- Cabibbo-Kobayashi-Maskawa quark-mixing matrix
- Main experimental players: Belle II and LHCb
- **Case study 1:** V_{cb}
- **Case study 2:** γ – *CP* violating phase ← **HALFTIME somewhere here**
- Beyond the *b* quark: charm physics
- **Case study 3:** *CP* violation in *D* mesons
- Beyond the quarks: tau physics
- **Case study 4:** lepton-flavour universality and tau mass
- Outlook

Flavour – the essence

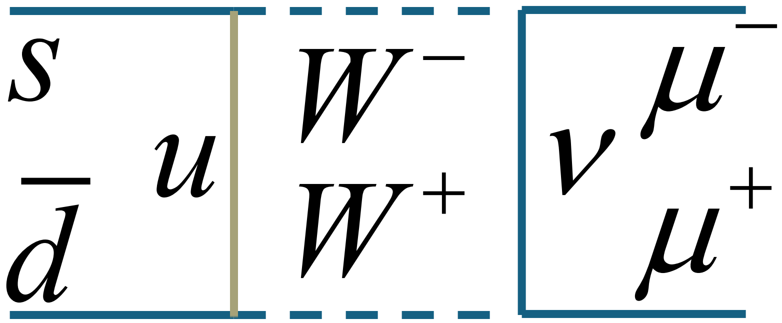
- QED and QCD parts of the standard model don’t care whether a quark is u, d, c, s, t or b
  - QED doesn’t care whether a lepton is tau, muon or electron
- But their masses are different, so the Higgs (Yukawa) part of the SM does care
  - With electroweak symmetry breaking this leads to the weak basis of quarks not necessarily aligning with the mass basis
  - **Cabbibo-Kobayashi-Maskawa (CKM) mixing matrix**
- Flavour physics is the study of interactions that distinguish between flavour
  - We will begin with the quark sector

Why flavour? History of discovery

- Particle zoo of mesons and baryons discovered in 1950s and early 1960s lead to the quark model
  - up (u)
  - down (d)
  - strange (s)
- An allowed but rare decay such as

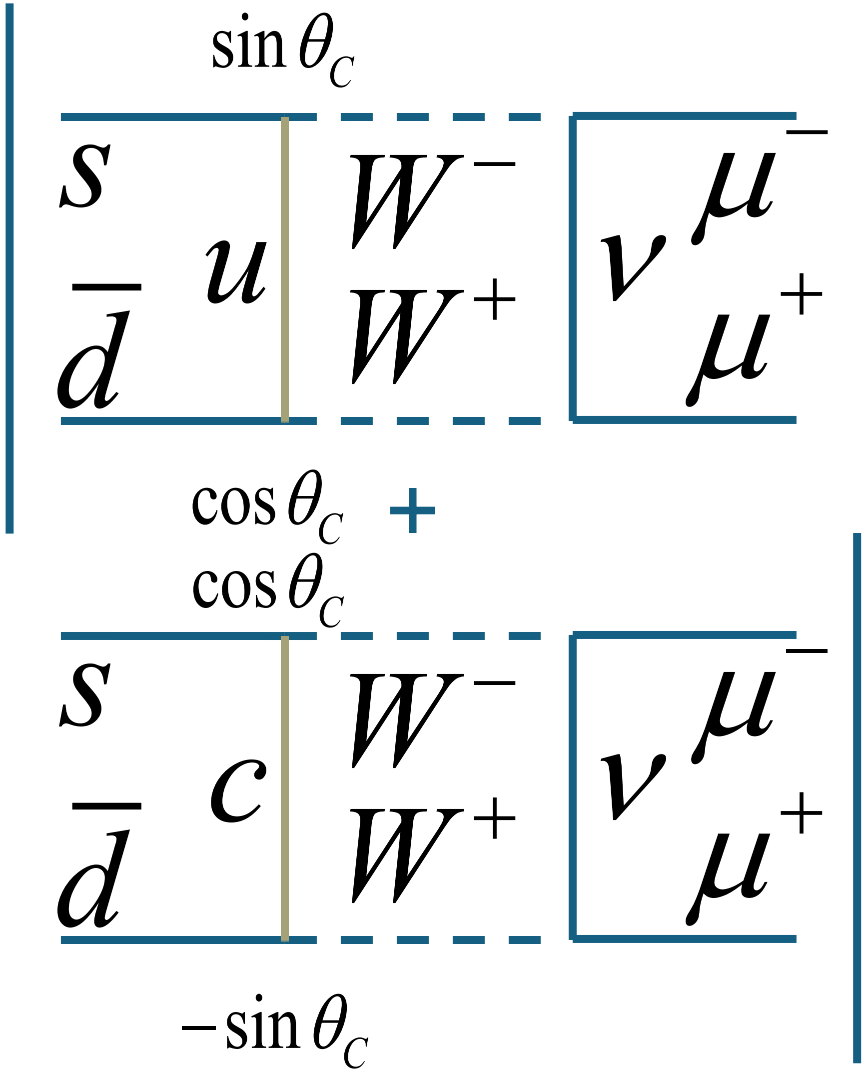
$$K_L^0(s\bar{d}) \to \mu^+\mu^-$$

was predicted **but not seen!**

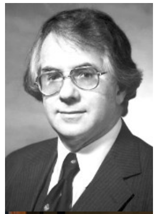


Why flavour? history of discovery

$$(u\ c)\begin{pmatrix}\cos\theta_C & \sin\theta_C\\ -\sin\theta_C & \cos\theta_C\end{pmatrix}\begin{pmatrix}d\\ s\end{pmatrix}$$



$^2 \propto \text{Rate} \sim 0$



Glashow

Iliopoulos

Maiani

Phys. Rev. **D** 2, 1285 (1970)

$m_c \sim 3\ m_K$

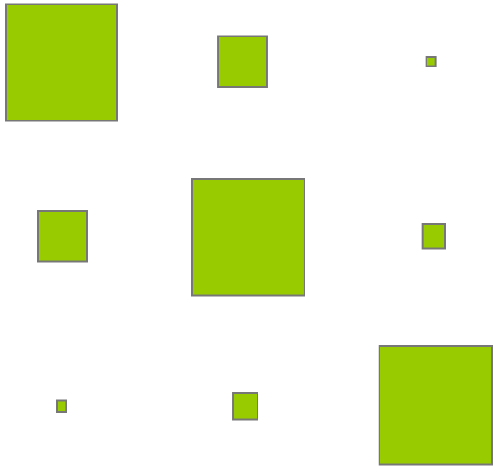
Such rare virtual processes tell you about higher energy particles

CKM matrix

- Two by two mixing matrix proposed by Cabibbo
  - Kobayashi-Maskawa proposed **third generation** to explain observed CP violation by Cronin and Fitch
- 3×3 unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase
- Intergenerational coupling disfavoured

$$\begin{pmatrix} u & c & t \end{pmatrix}\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Relative magnitude of elements



Responsible for CP violation

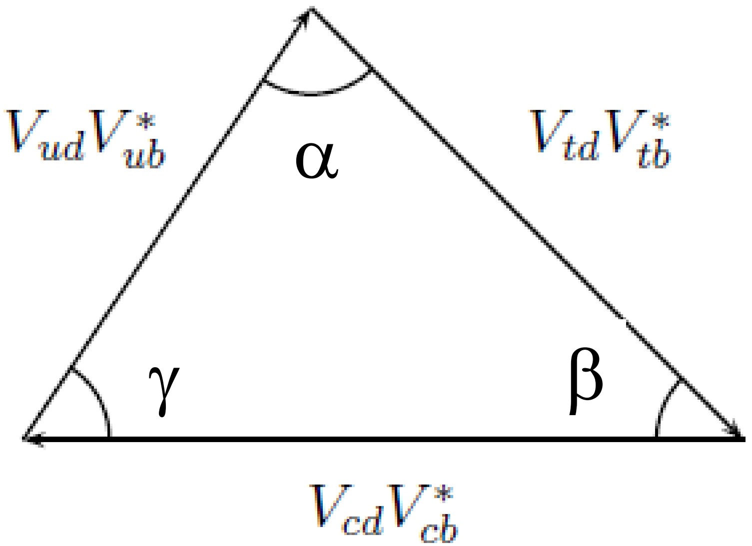
Visualising CP violation: the unitarity triangle

$\lambda = \sin\theta_c = 0.22$

1) $$\left(\boxed{\begin{matrix} 1-\lambda^2/2 \\ -\lambda \\ A\lambda^3\left[1-(\rho-i\eta)\right] \end{matrix}} \quad \begin{matrix} \lambda \\ 1-\lambda^2/2 \\ -A\lambda^2 \end{matrix} \quad \boxed{\begin{matrix} A\lambda^3(\rho-i\eta) \\ A\lambda^2 \\ 1 \end{matrix}}\right) + O(\lambda^4)$$

2) Exploit unitarity (1st and 3rd col.) $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

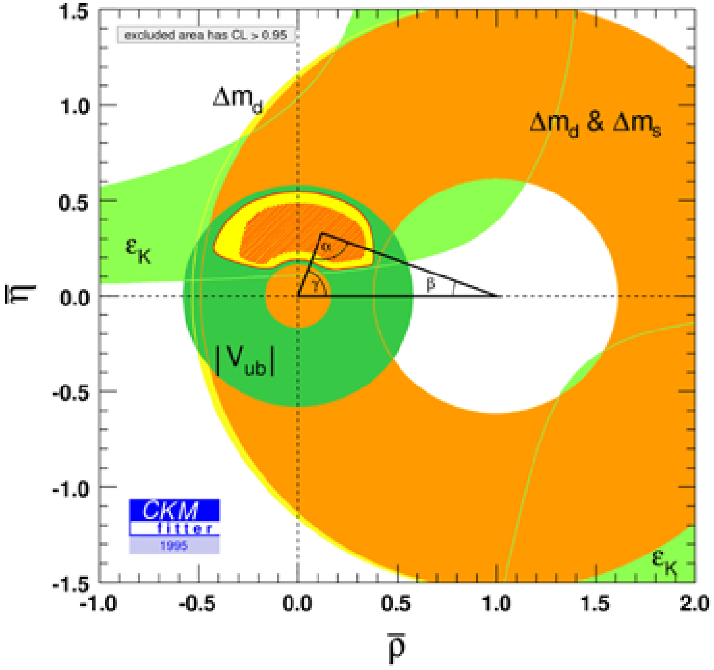
3)



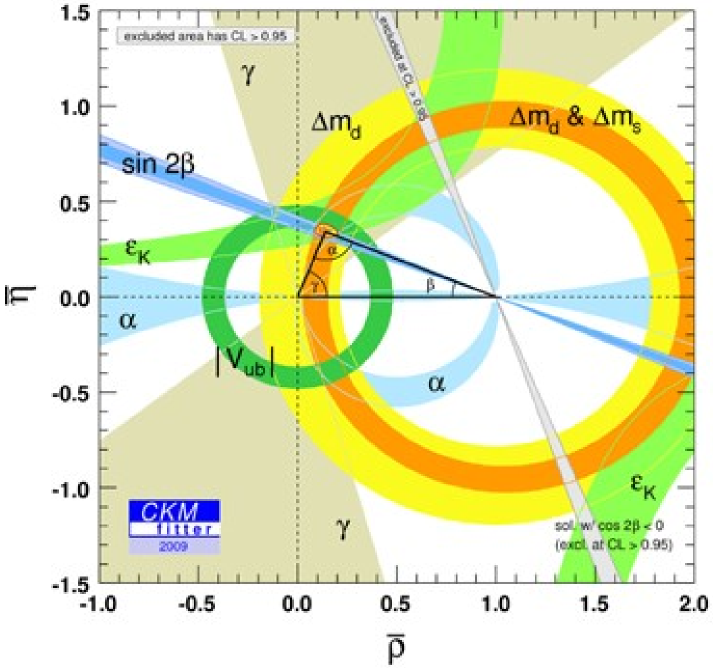
Each side prop to λ^3

$$\begin{aligned} \phi_1 &= \beta \\ &= \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \\ &\simeq \arg\left(\frac{1}{1-\rho-i\eta}\right) \end{aligned}$$

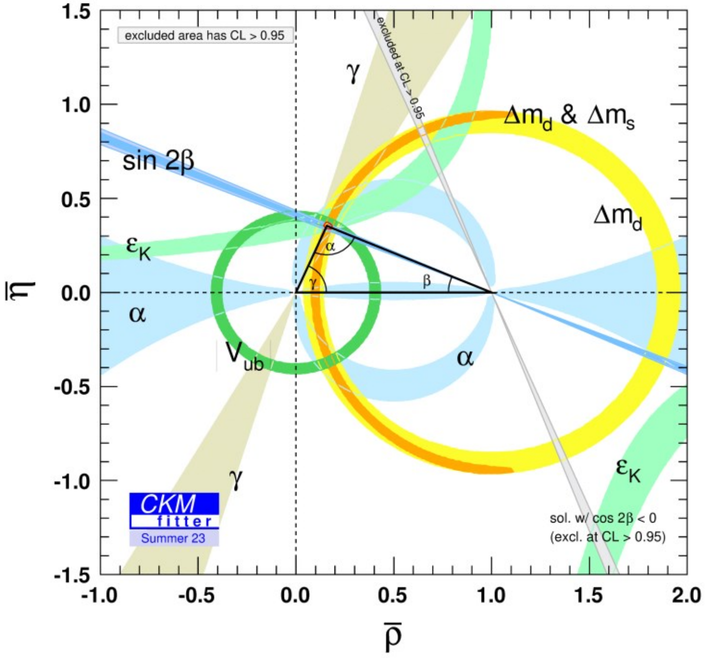
CKM/Unitarity triangle measurements



Pre 1st generation *B* factories
1999

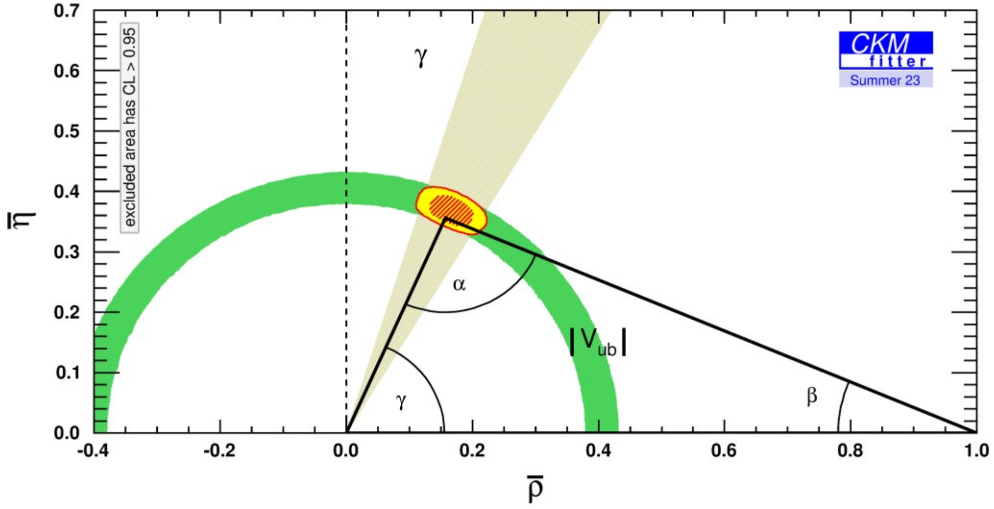


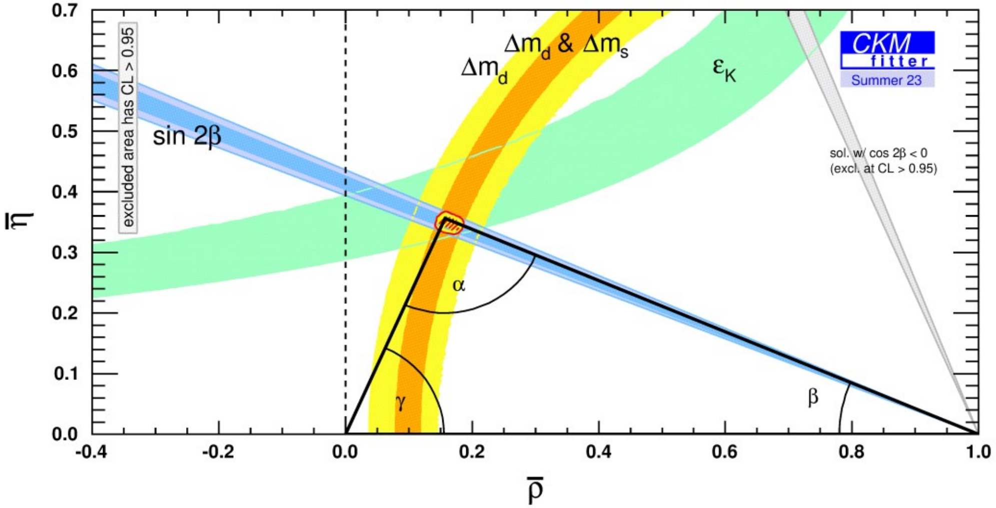
Post 1st generation *B* factories
+ CDF B_s mixing
2009



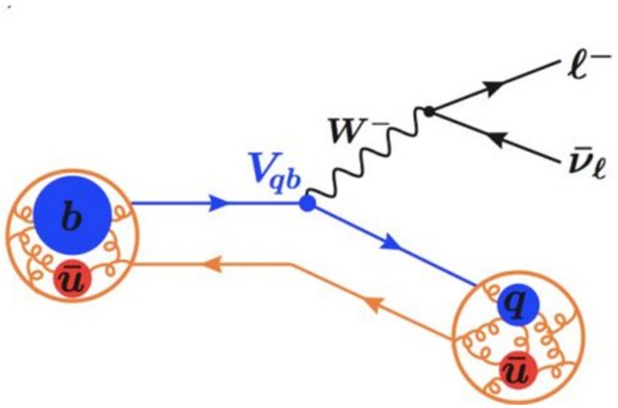
Today
+ LHCb and improved theory

Today the goal is over constraint – loop sensitivity

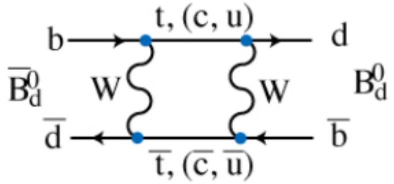




Tree level only

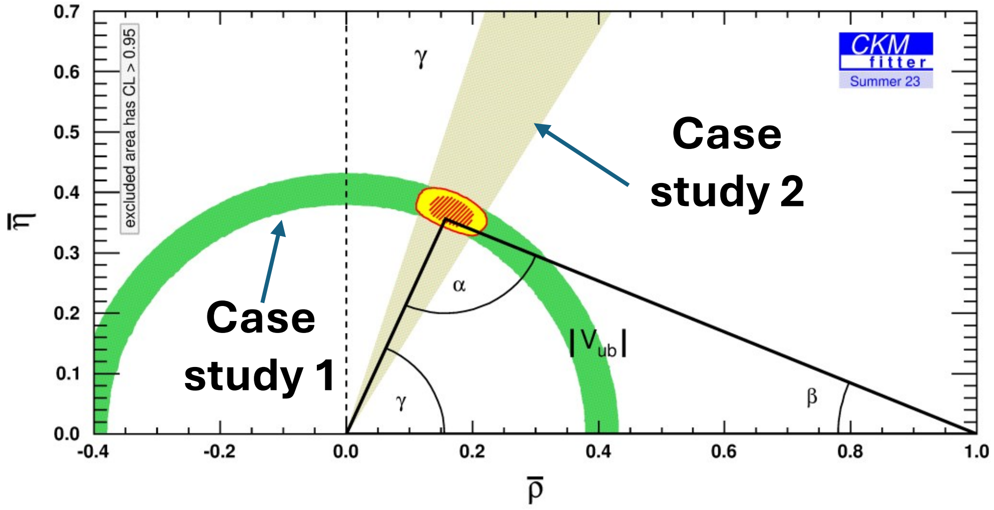


Loop-level only



NP at
O(>TeV)?

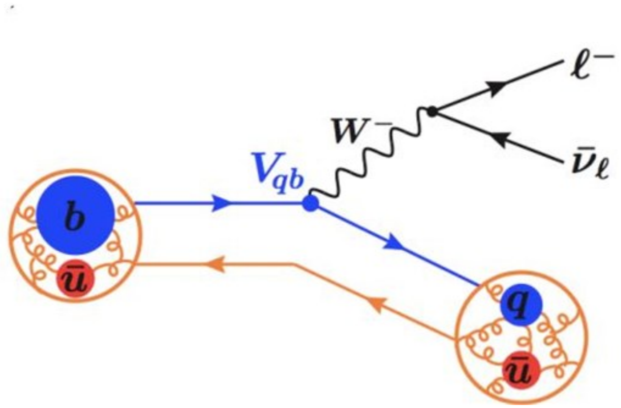
Today the goal is over constraint – loop sensitivity

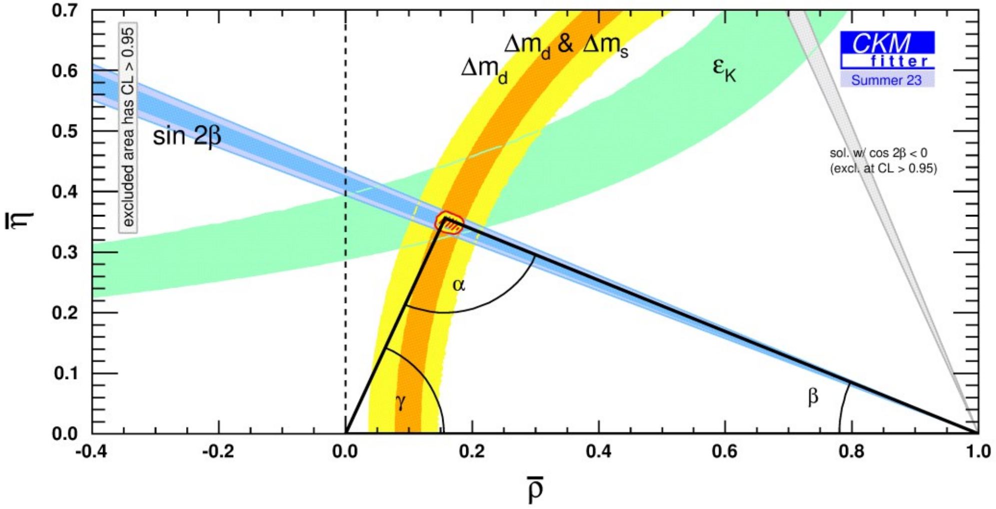


Case study 2

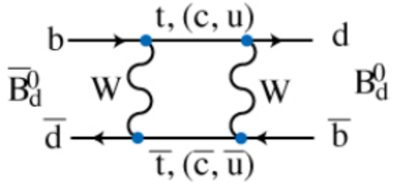
Case study 1

Tree level only



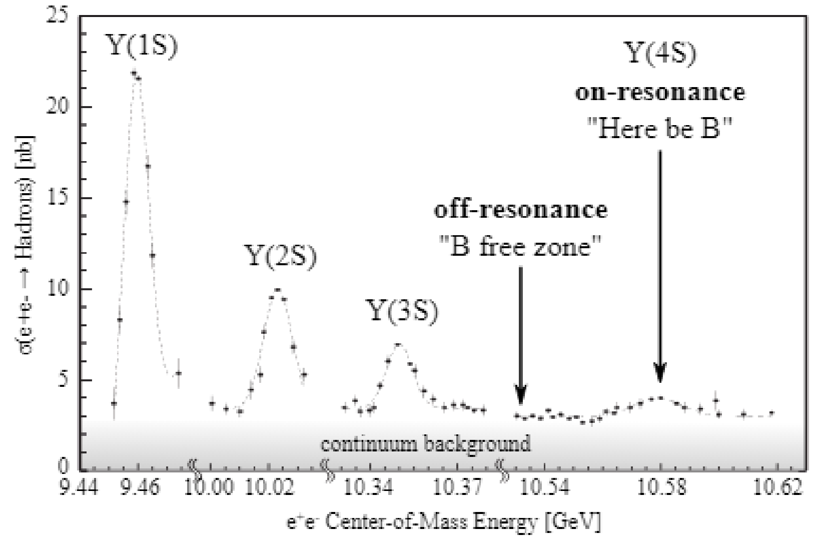


Loop-level only

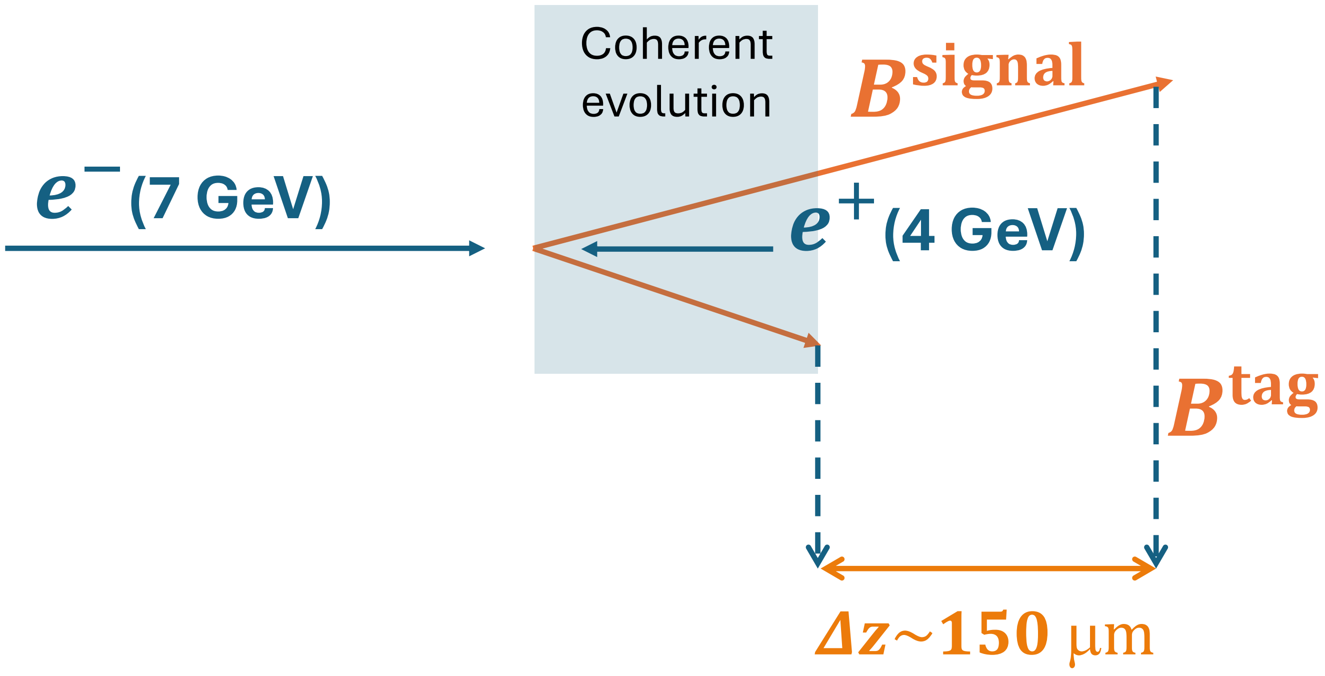


NP at O(>TeV)?

Why asymmetric e^+e^- at Y(4S)?

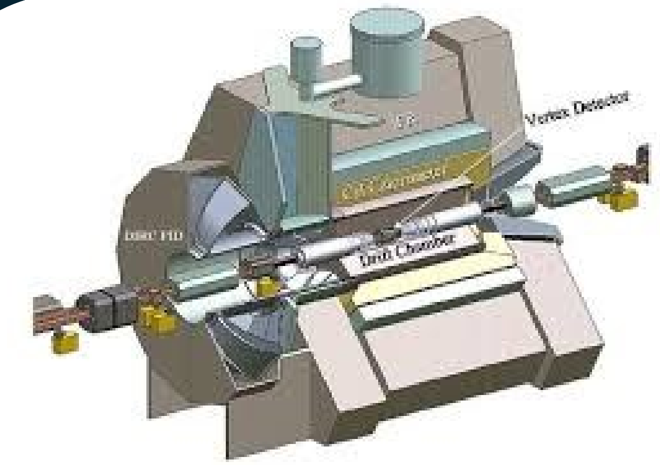


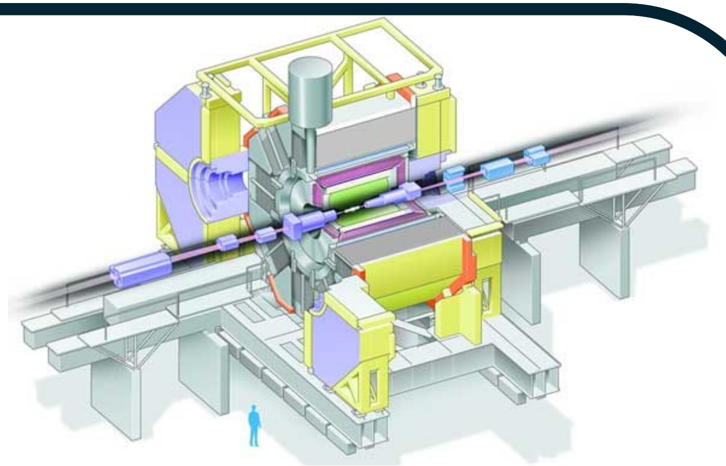
- **Y(4S)** – cross section of $B\bar{B}$ **one quarter** of continuum: $e^+e^- \rightarrow q\bar{q}, q = u, d, s, c$
- **e⁺e⁻** - constrained kinematics and **no other particles** at threshold
  - Excellent neutral and missing four-momentum reconstruction
  - Full event reconstruction – **hadronic *B* tagging**



- **Asymmetric** – boosted *B*s to allow measurements of time-dependent *CP* violation
  - Tagging power increased by quantum **coherent production** from Y(4S)

The protagonists





SLAC - PEP II collider

462 fb^{-1} at Υ(4S) [1999-2008]

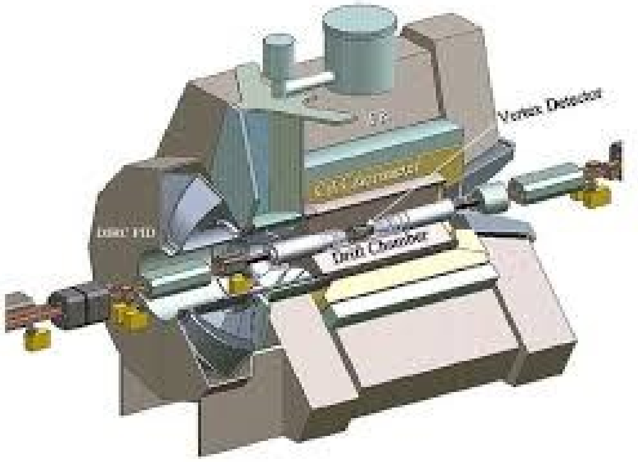
KEK – KEKB collider

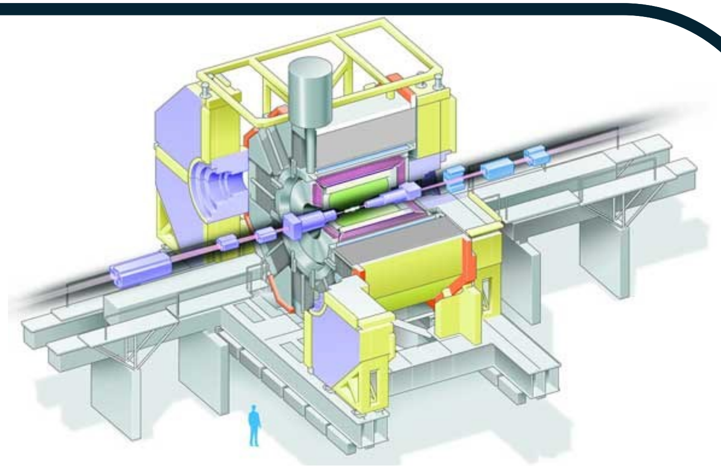
711 fb^{-1} at Υ(4S) [1999-2010]

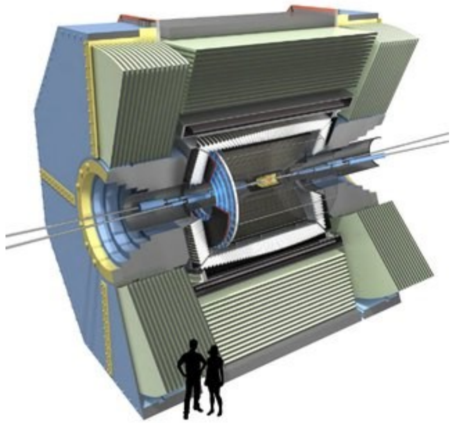
1st generation *B* factory

The protagonists

2nd generation *B* factory







SLAC - PEP II collider

462 fb^{-1} at Υ(4S) [1999-2008]

KEK – KEKB collider

711 fb^{-1} at Υ(4S) [1999-2010]

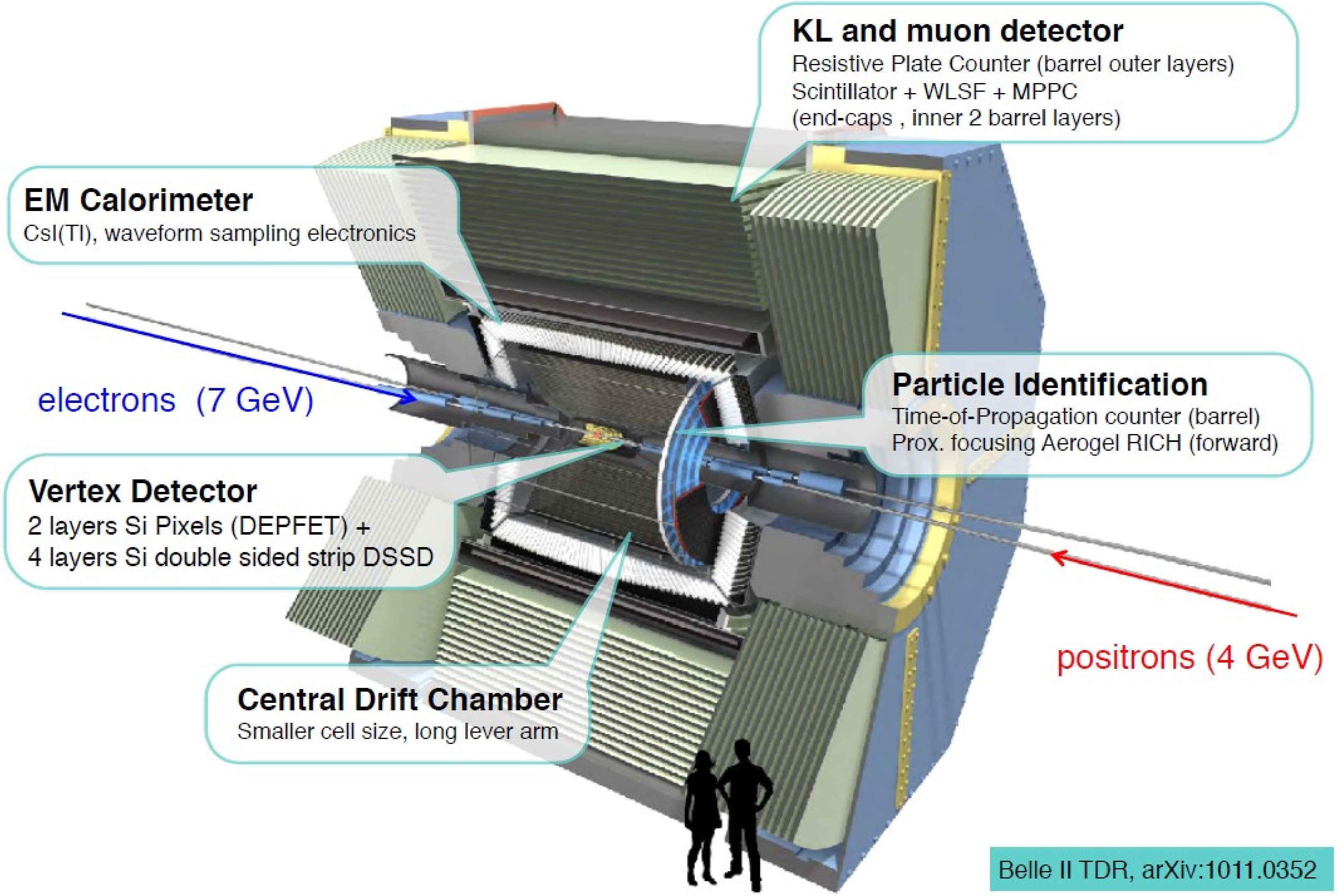
KEK – Super KEKB collider

450 fb^{-1} at Υ(4S) [2019-2024+]

364 fb^{-1} or less used for results presented here

1st generation *B* factory

Belle II



Belle II TDR, arXiv:1011.0352

Key advantages

Hermiticity

Known initial state kinematics, i.e., good missing momentum resolution

Full event reconstruction

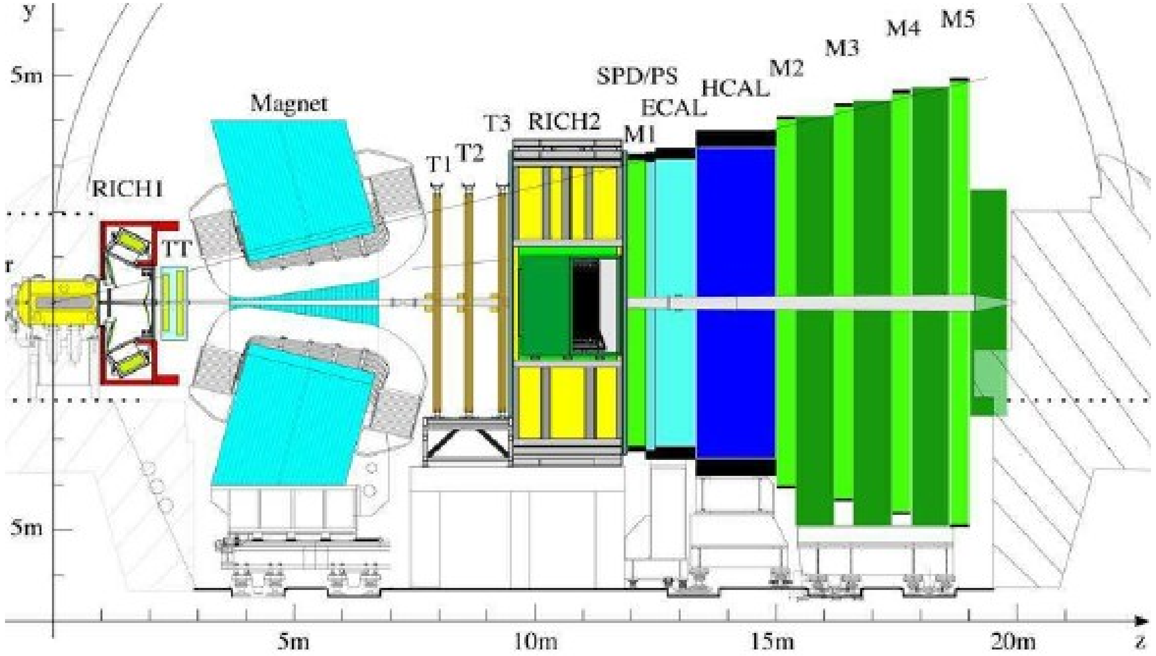
Similar electron and muon identification efficiencies

Disadvantage: sample size

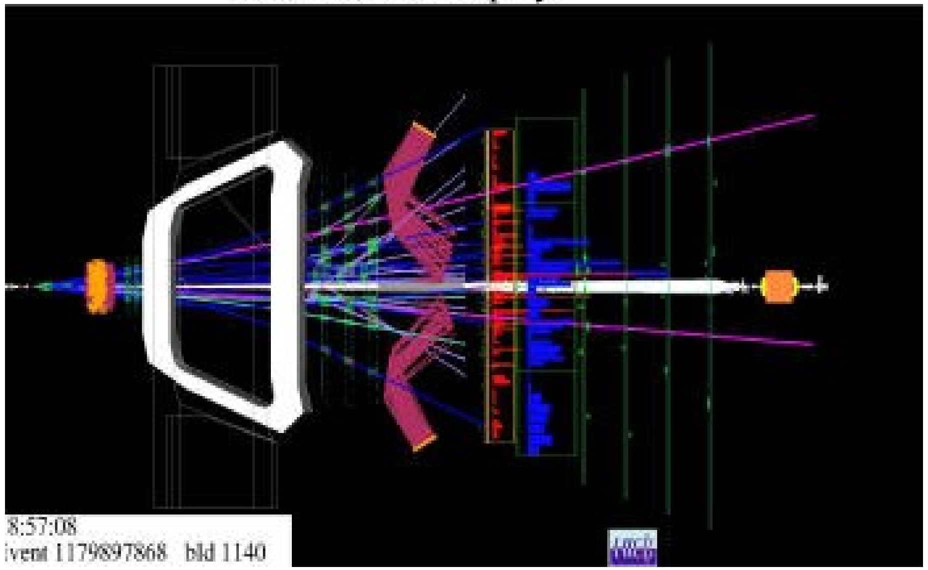
Luminosity goal 30x (instantaneous) and 50x (integrated) that of KEKB/Belle

LHCb in a slide

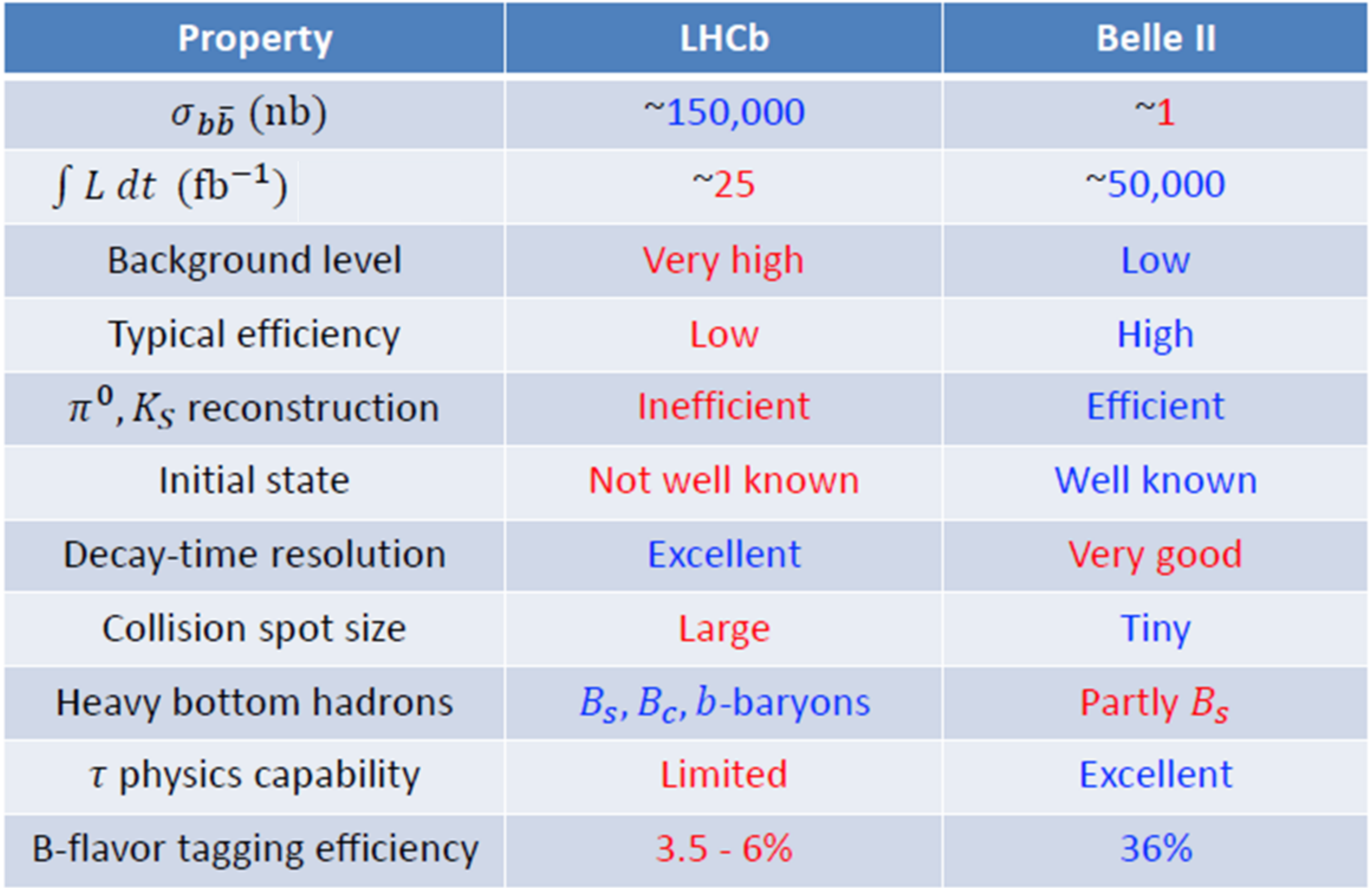
- 13 TeV *pp* collisions
  - trillion *bb*/2 fb^{-1}
  - 6 fb^{-1} @ 13 TeV
  - + 3 fb^{-1} @ 7/8 TeV
  - Run 3 started 2023
    - upgraded detector
- Forward geometry gets both *b* quarks in acceptance and boosted
  - exploit b lifetime to separate background
- RICHes for π/K separation
- Full trigger bandwidth for *B* physics



LHCb Event Display



Complementary competition (oxymoron?)



Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1})	~25	~50,000
Background level	Very high	Low
Typical efficiency	Low	High
π^0, K_S reconstruction	Inefficient	Efficient
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Very good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	36%

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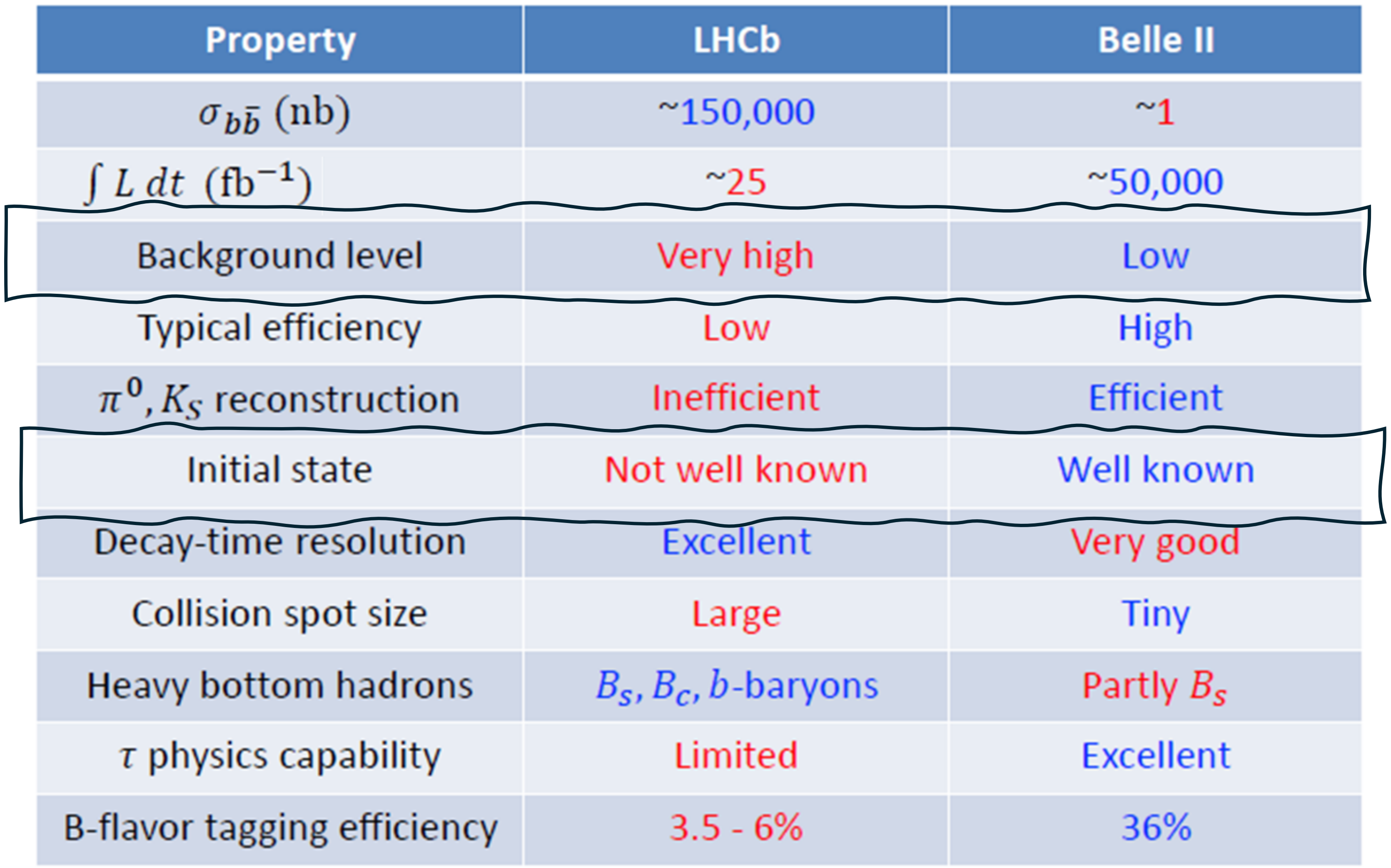

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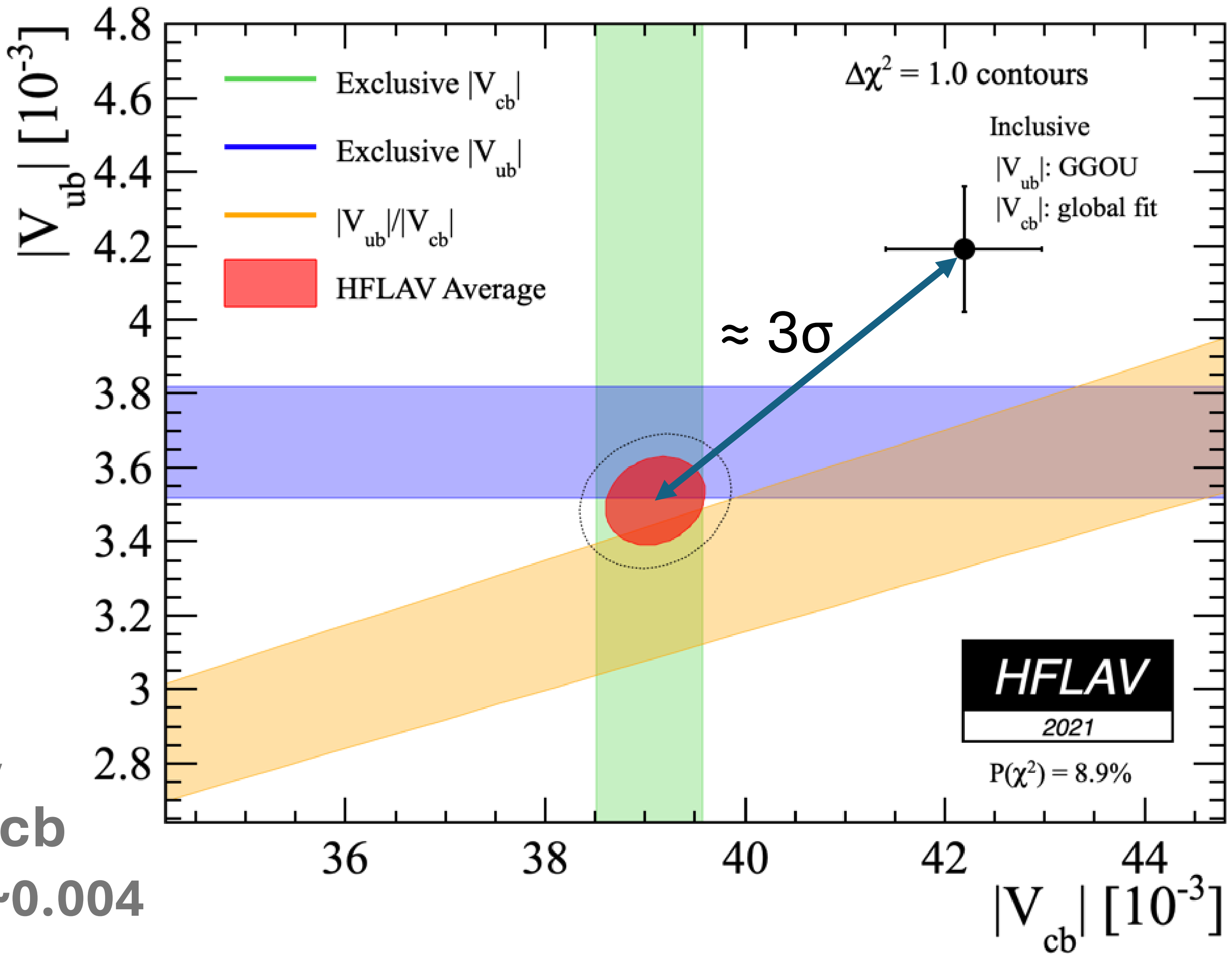
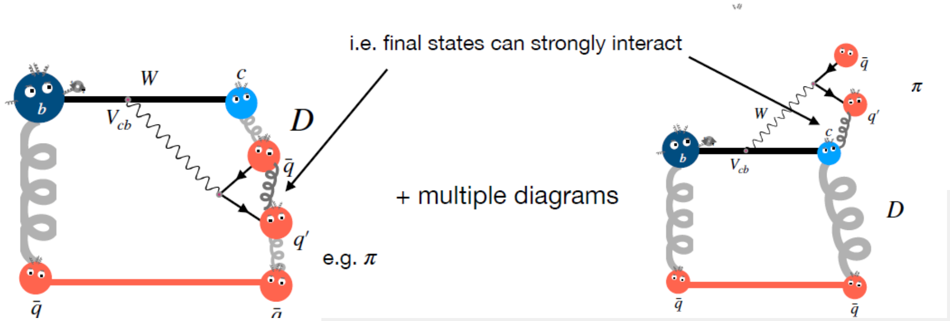
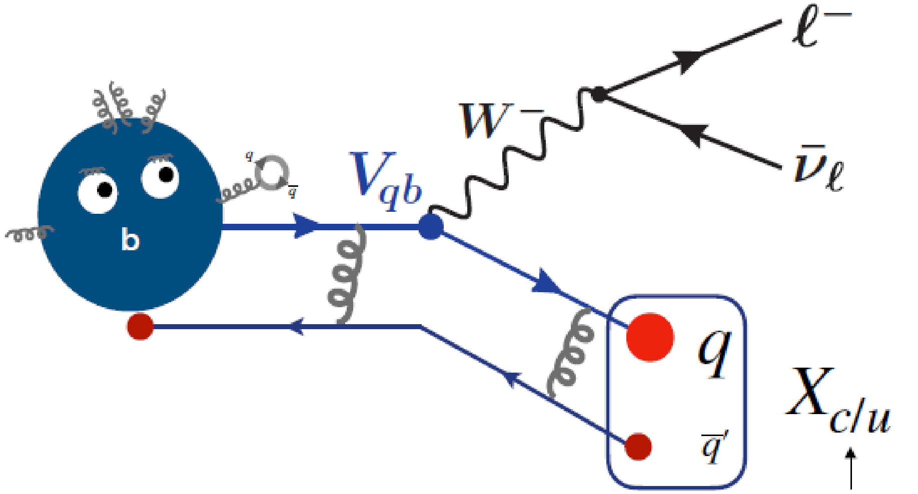


Case study 1: V_{cb}

Fix V_{cb}~0.04 first then V_{ub}~0.004

$|V_{qb}|$: three different ways





hadronic states with
a charm or up quark

Experimentally Easy

1) **Hadronic decays**

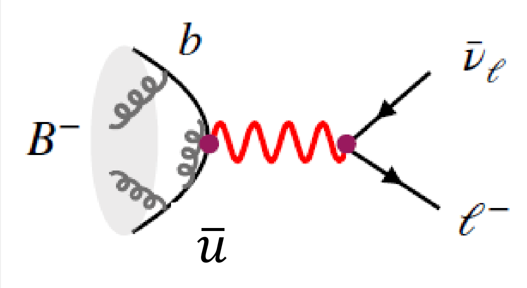
3) **Semi-leptonic decays** → theory doable, experimentally doable

Theory Hard

Theory Easy

No one cares what
is in this corner :-)

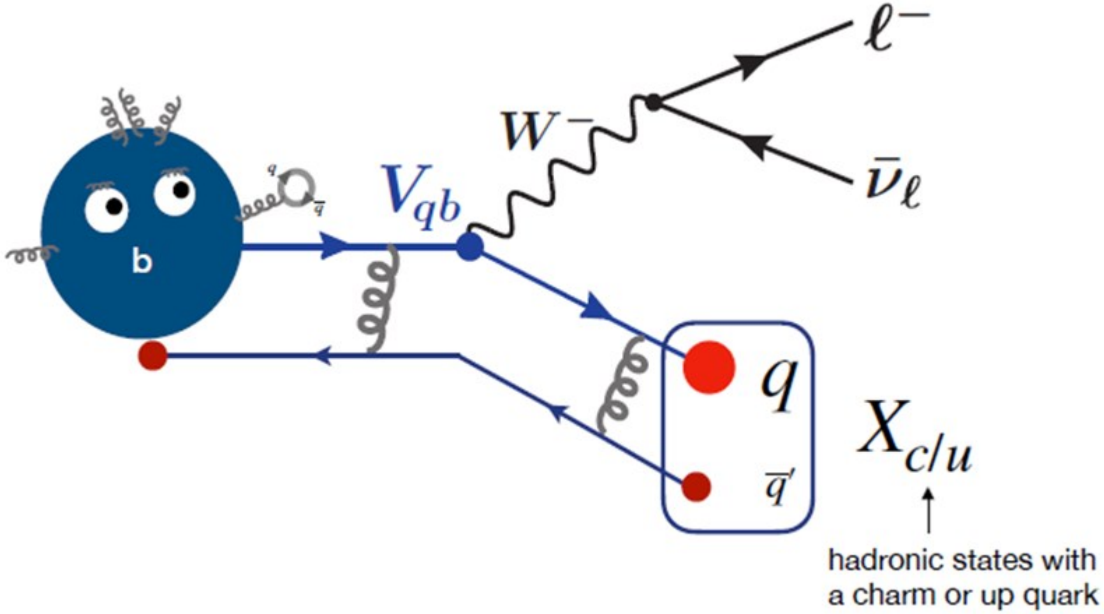
2) **Leptonic decays**



Experimentally Hard

F. Bernlochner – Belle II Physics Week

Inclusive vs. exclusive



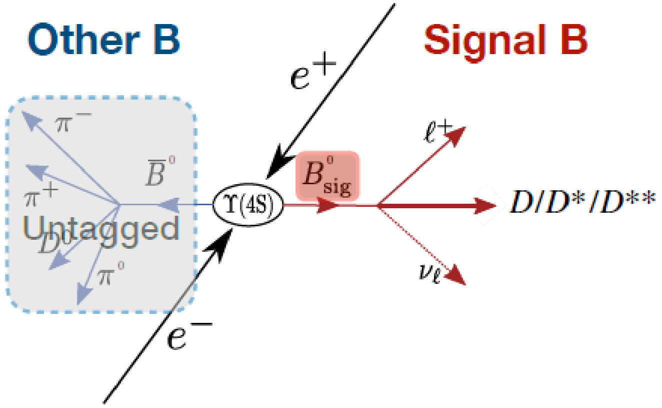
- $X_{c/u}$ is **exclusively** reconstructed as *D*, *D**, π, etc

$$BF \propto |V_{qb}|^2 f(q^2)^2$$

  - $f(q^2)$ is a form factor that describes the hadronic transition of B meson to exclusively reconstructed hadron – depends on invariant mass of leptons q^2
  - Calculated from lattice QCD or parameterized in fit to data
- $X_{c/u}$ is not fully reconstructed – this is **inclusive** – quark-hadron duality (a little more later)

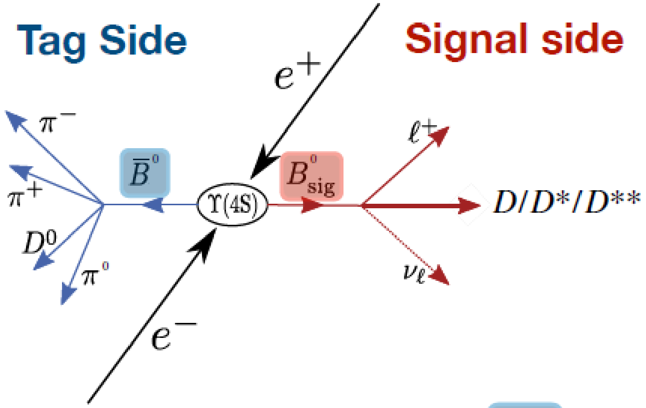
$$\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q\,\ell\,\bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \ldots \right]$$

Exclusive: untagged or tagged



- \+ Very high efficiency
- \+ Measurement of absolute branching fractions straightforward
  (depends on total # of $N_{B\bar{B}}$, understanding efficiencies)

- \- Less experimental control, e.g. more background from $e^+e^+ \to q\bar{q}$
- \- Cannot directly access signal B rest frame, need tricks



$$p_{\rm sig} = p_{e^+e^-} - p_{\rm tag}$$

- \+ High degree of experimental control, e.g. can identify all final state particles with either the signal or the tag side
- \+ If hadronic modes for tagging are used, can reconstruct B rest frame

- \- Understanding efficiencies is difficult
- \- Low efficiency reduces the effective statistical power

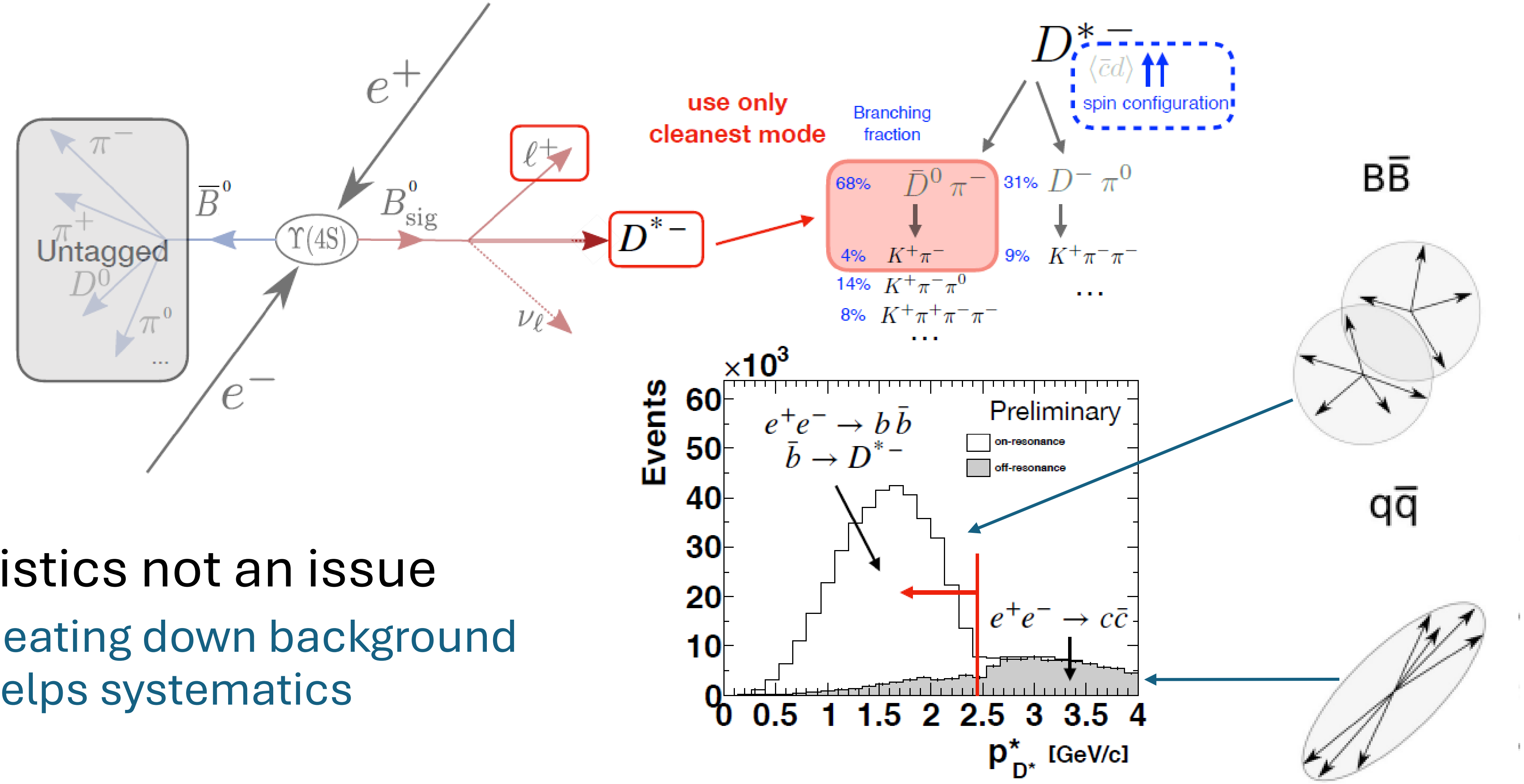
Absolute BF from here

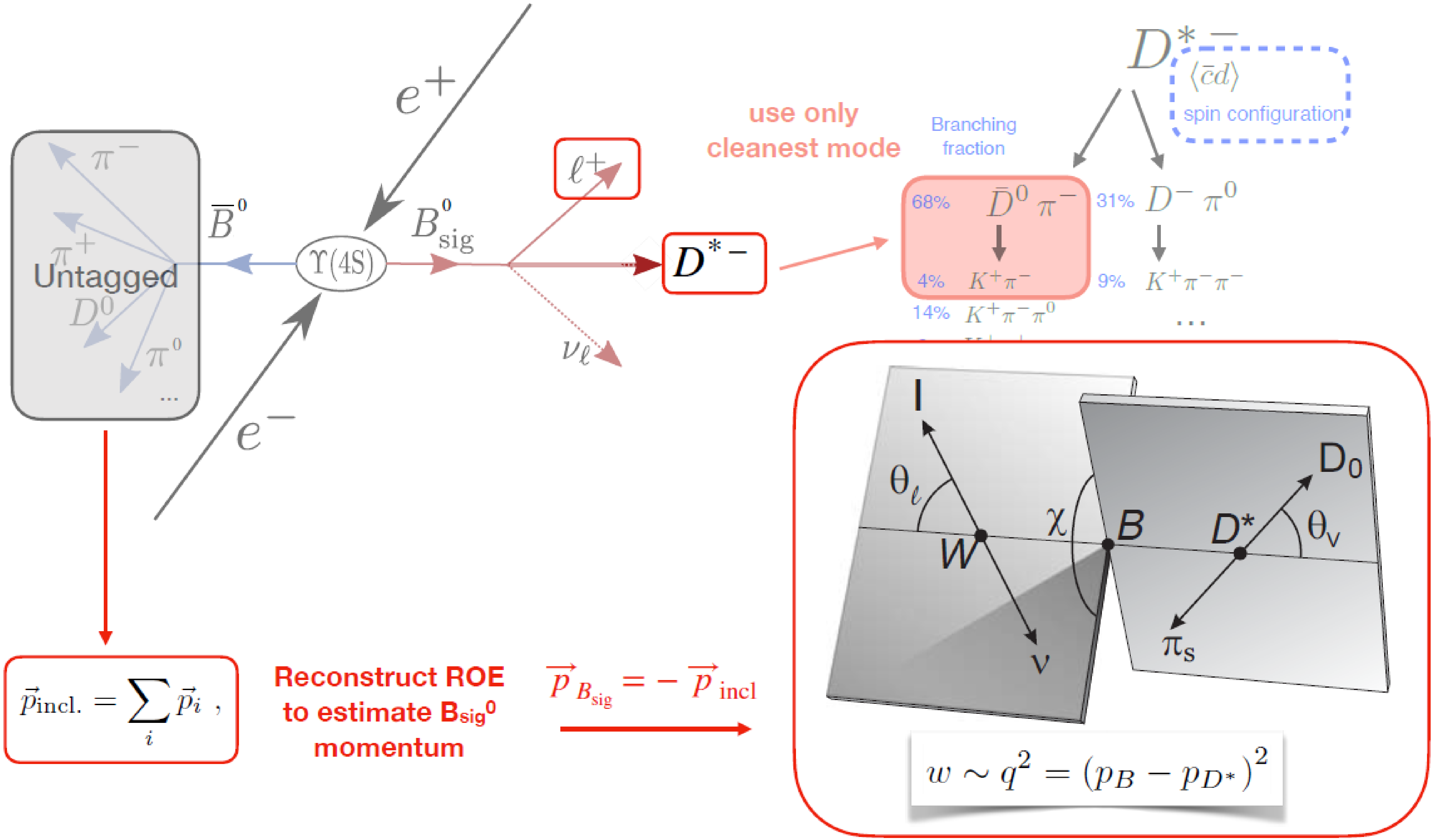
↓

Angular analysis to better constrain theory

Untagged example – Belle II https://arxiv.org/abs/2310.01170

- Statistics not an issue
  - Beating down background helps systematics





use only cleanest mode

$$\vec{p}_{\text{incl.}} = \sum_i \vec{p}_i \,,$$

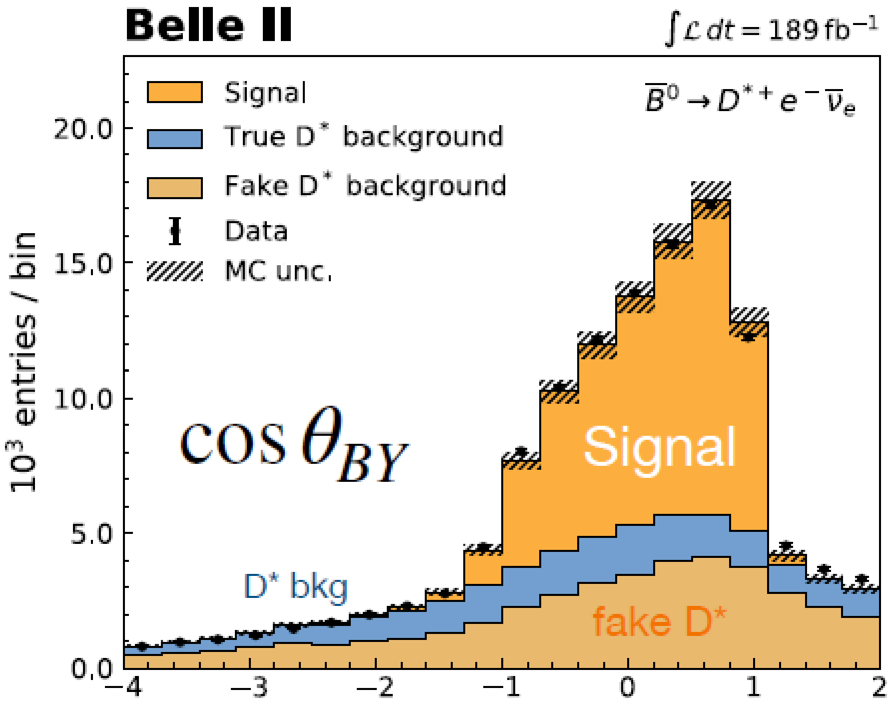
Reconstruct ROE to estimate B_{sig}^0 momentum

$$\vec{p}_{B_{\text{sig}}} = -\,\vec{p}_{\text{incl}}$$

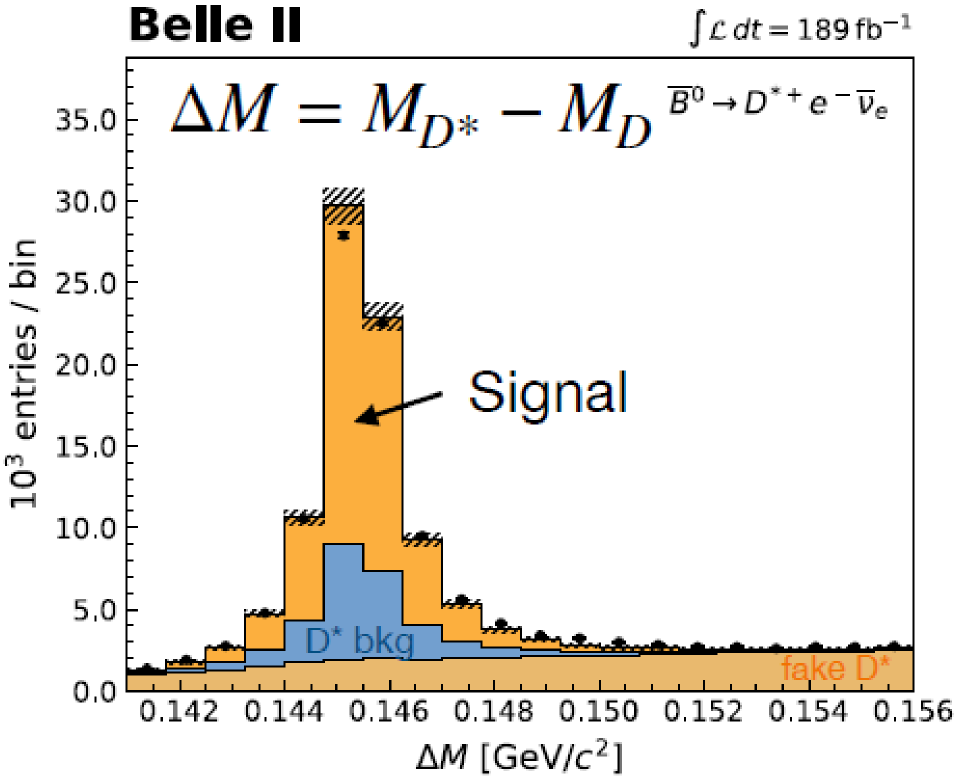
$$w \sim q^2 = (p_B - p_{D^*})^2$$

Signal extraction

Fit in bins of angles and q^2 and sum partial rates – accounts for variable efficiency and can be unfolded to account for resolution



$$\cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\mathbf{p}_B||\mathbf{p}_{D^*\ell}|}$$



PDG masses give Δm = 145 MeV

Slow pion

Systematic uncertainties I

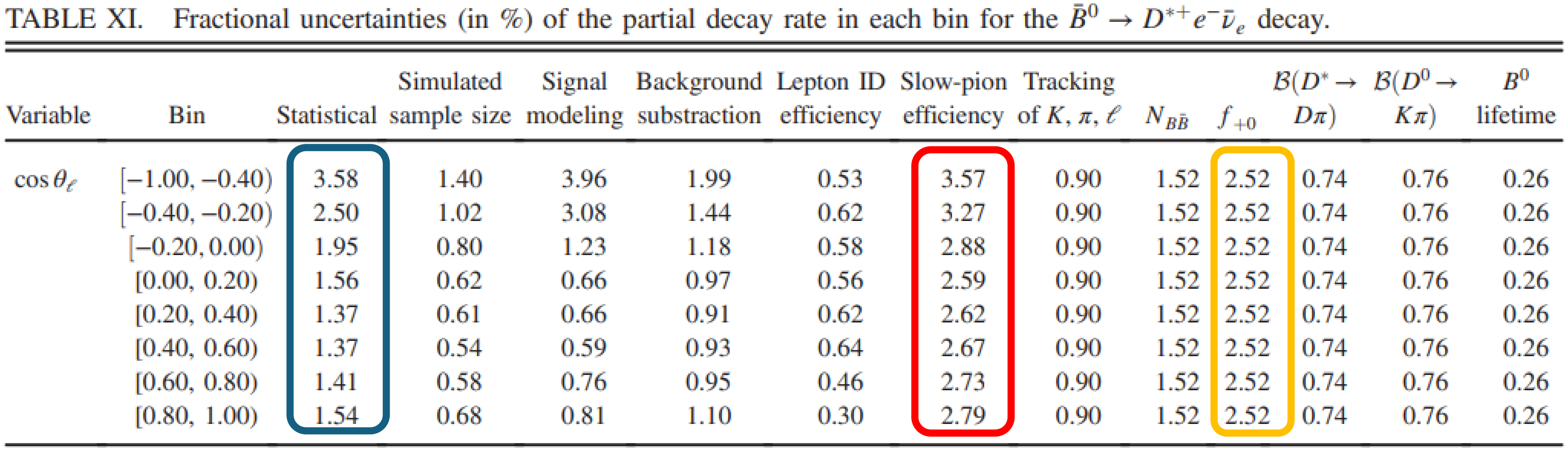


TABLE XI. Fractional uncertainties (in %) of the partial decay rate in each bin for the $\bar{B}^0 \to D^{*+} e^- \bar{\nu}_e$ decay.

Variable	Bin	Statistical	Simulated sample size	Signal modeling	Background substraction	Lepton ID efficiency	Slow-pion efficiency	Tracking of K, π, ℓ	$N_{B\bar{B}}$	f_{+0}	$\mathcal{B}(D^* \to D\pi)$	$\mathcal{B}(D^0 \to K\pi)$	B^0 lifetime
$\cos\theta_\ell$	$[-1.00, -0.40)$	3.58	1.40	3.96	1.99	0.53	3.57	0.90	1.52	2.52	0.74	0.76	0.26
	$[-0.40, -0.20)$	2.50	1.02	3.08	1.44	0.62	3.27	0.90	1.52	2.52	0.74	0.76	0.26
	$[-0.20, 0.00)$	1.95	0.80	1.23	1.18	0.58	2.88	0.90	1.52	2.52	0.74	0.76	0.26
	$[0.00, 0.20)$	1.56	0.62	0.66	0.97	0.56	2.59	0.90	1.52	2.52	0.74	0.76	0.26
	$[0.20, 0.40)$	1.37	0.61	0.66	0.91	0.62	2.62	0.90	1.52	2.52	0.74	0.76	0.26
	$[0.40, 0.60)$	1.37	0.54	0.59	0.93	0.64	2.67	0.90	1.52	2.52	0.74	0.76	0.26
	$[0.60, 0.80)$	1.41	0.58	0.76	0.95	0.46	2.73	0.90	1.52	2.52	0.74	0.76	0.26
	$[0.80, 1.00)$	1.54	0.68	0.81	1.10	0.30	2.79	0.90	1.52	2.52	0.74	0.76	0.26

- Systematically dominated – **the true heart of precision**
- **Slow pion efficiency – correct for any disagreement between simulation and data in their reconstruction efficiency**
  - **Use constrained kinematics of $B^0 \to D^{*-}\pi^+$, $D^{*-} \to D^0\pi_{slow}$ to estimate difference – control sample size will scale with increased luminosity**

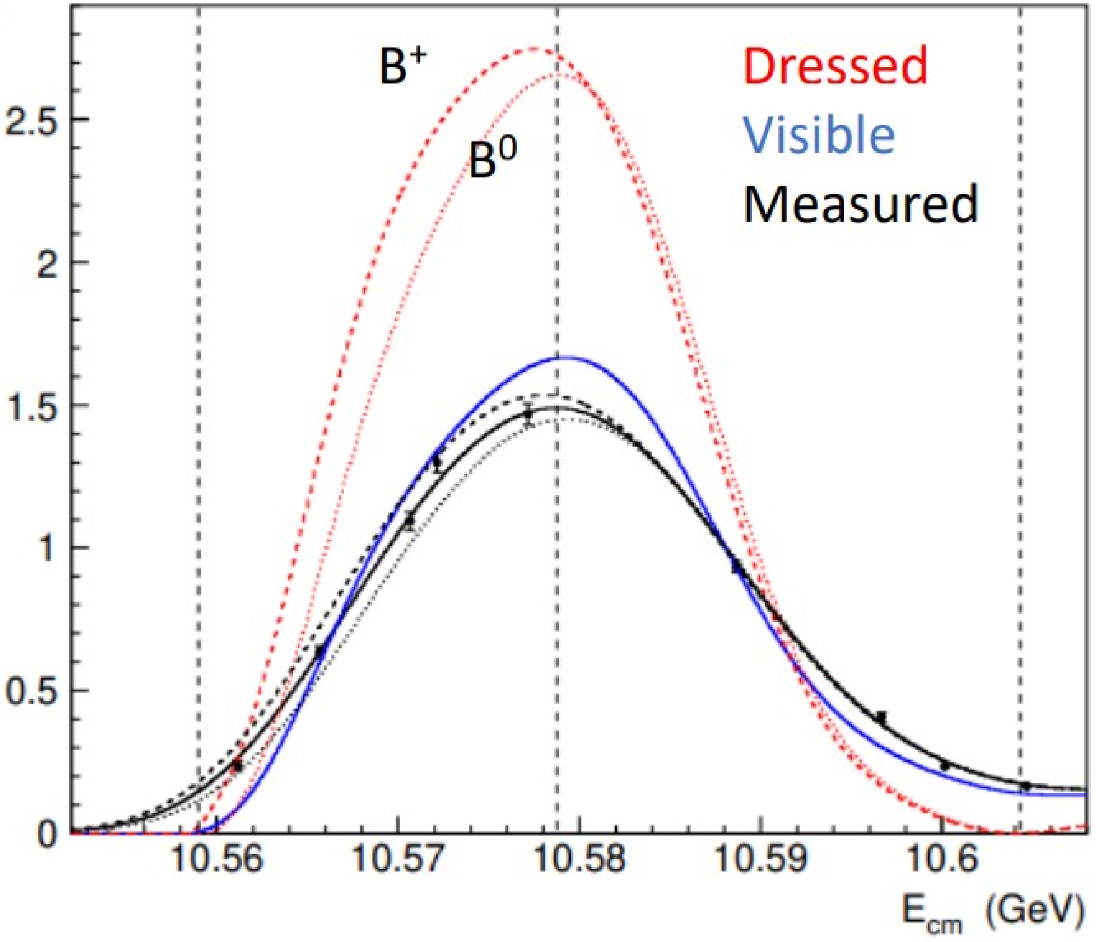
Systematic uncertainties II

$$\Delta\Gamma_x = \frac{\nu_x^{\text{unfolded}}\,\hbar}{\epsilon_x \boxed{N_{B^0}} \mathcal{B}(D^{*+} \to D^0\pi^+)\,\mathcal{B}(D^0 \to K^-\pi^+)\,\tau_{B^0}}$$

- Need to know the number of B^0
- We can count the total number of BB pairs using event shape

$$N_{B^0} = 2N_{B\bar{B}}\,(1+\boxed{f_{+0}})^{-1}$$

- f_{+0}=ratio of Υ(4S) to B^+B^- compared to B^0B^0
  - Naively you would think was 1
  - But it is not exact



Our current best estimate:

PRD **107**, L031102 (2023) [Belle Collaboration]

- Uses B→J/ψK events and isospin assumptions

$$N^{+}_{\mathrm{sig}} = 2N_{B\bar{B}}f^{+-}\varepsilon^{+}\mathcal{B}[B^{+} \to J/\psi(\ell\ell)K^{+}]$$

$$N^{0}_{\mathrm{sig}} = 2N_{B\bar{B}}f^{00}\varepsilon^{0}\mathcal{B}[B^{0} \to J/\psi(\ell\ell)K^{0}]$$

$$\begin{aligned}\frac{N^{+}_{\mathrm{sig}}/\varepsilon^{+}}{N^{0}_{\mathrm{sig}}/\varepsilon^{0}} &= R^{+/0}\frac{\mathcal{B}[B^{+} \to J/\psi(\ell\ell)K^{+}]}{\mathcal{B}[B^{0} \to J/\psi(\ell\ell)K^{0}]} \\ &= R^{+/0}\frac{\Gamma[B^{+} \to J/\psi(\ell\ell)K^{+}]\tau^{+}}{\Gamma[B^{0} \to J/\psi(\ell\ell)K^{0}]\tau^{0}} \\ \Rightarrow R^{+/0} &= \frac{N^{+}_{\mathrm{sig}}\varepsilon^{0}\tau_{0}}{N^{0}_{\mathrm{sig}}\varepsilon^{+}\tau_{+}},\end{aligned}$$

Note that

$R^{+/0} \equiv f_{+0}$

But how good is the assumption $\Gamma(B^{+} \to J/\psi K^{+}) = \Gamma\left(B^{0} \to J/\psi K^{0}\right)$?

Our current best estimate:

PRD **107**, L031102 (2023) [Belle Collaboration]

- The assumption is that it is of the order $\bar{\lambda}^3$ from isospin breaking rescattering [Fleischer and Mannel, 2001]
  - $\bar{\lambda}$ = 0.2 is a generic expansion parameter the same order as sin θ_C=0.22
- This results in

$$f_{+0} = 1.065 \pm 0.012\ (\text{stat}) \pm 0.019\ (\text{syst}) \pm \mathbf{0.043\ (Isospin)}$$

So, it is isospin breaking assumption that dominates the current estimate on V_{cb}

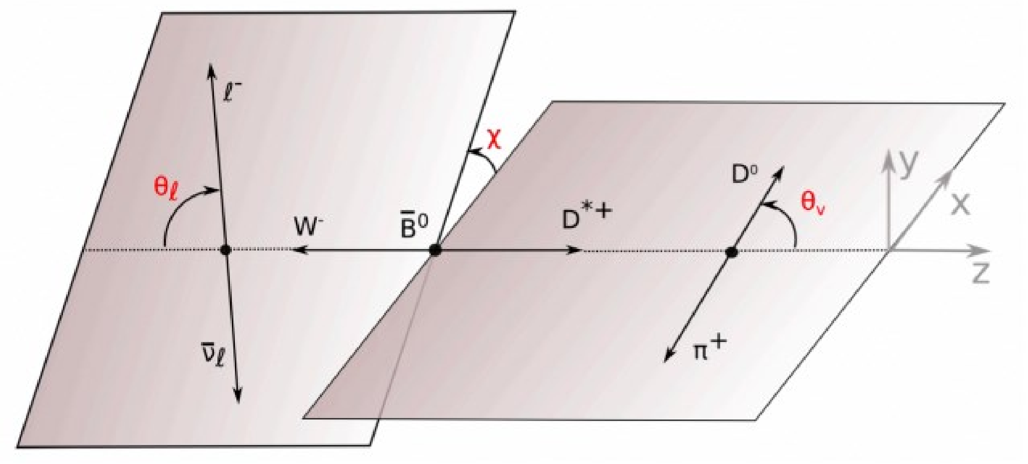
We are actively pursuing other methods such as double semileptonic decay (Babar PRL **95**, 042001 (2005)) or as nuisance parameter in a combined analysis of D and D*

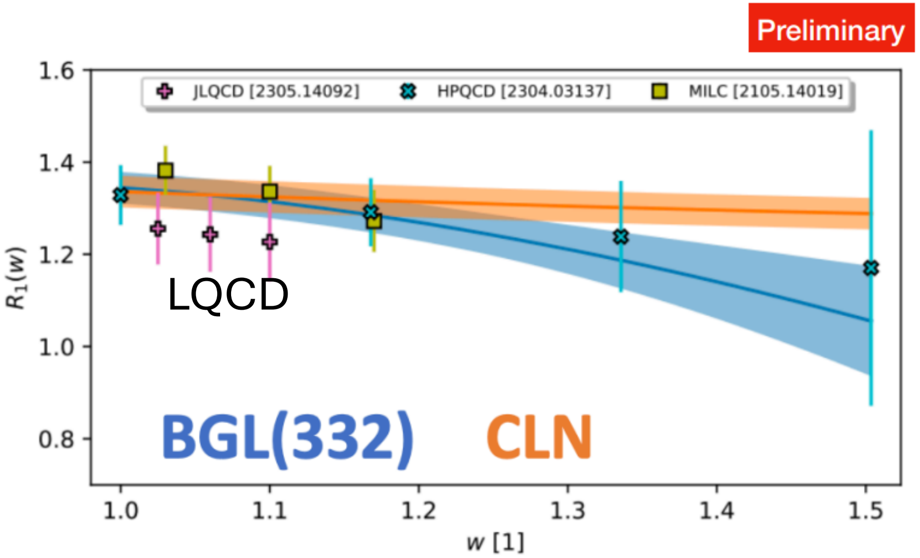
Otherwise this will be the experimental limitation on exclusive V_{cb} in the future

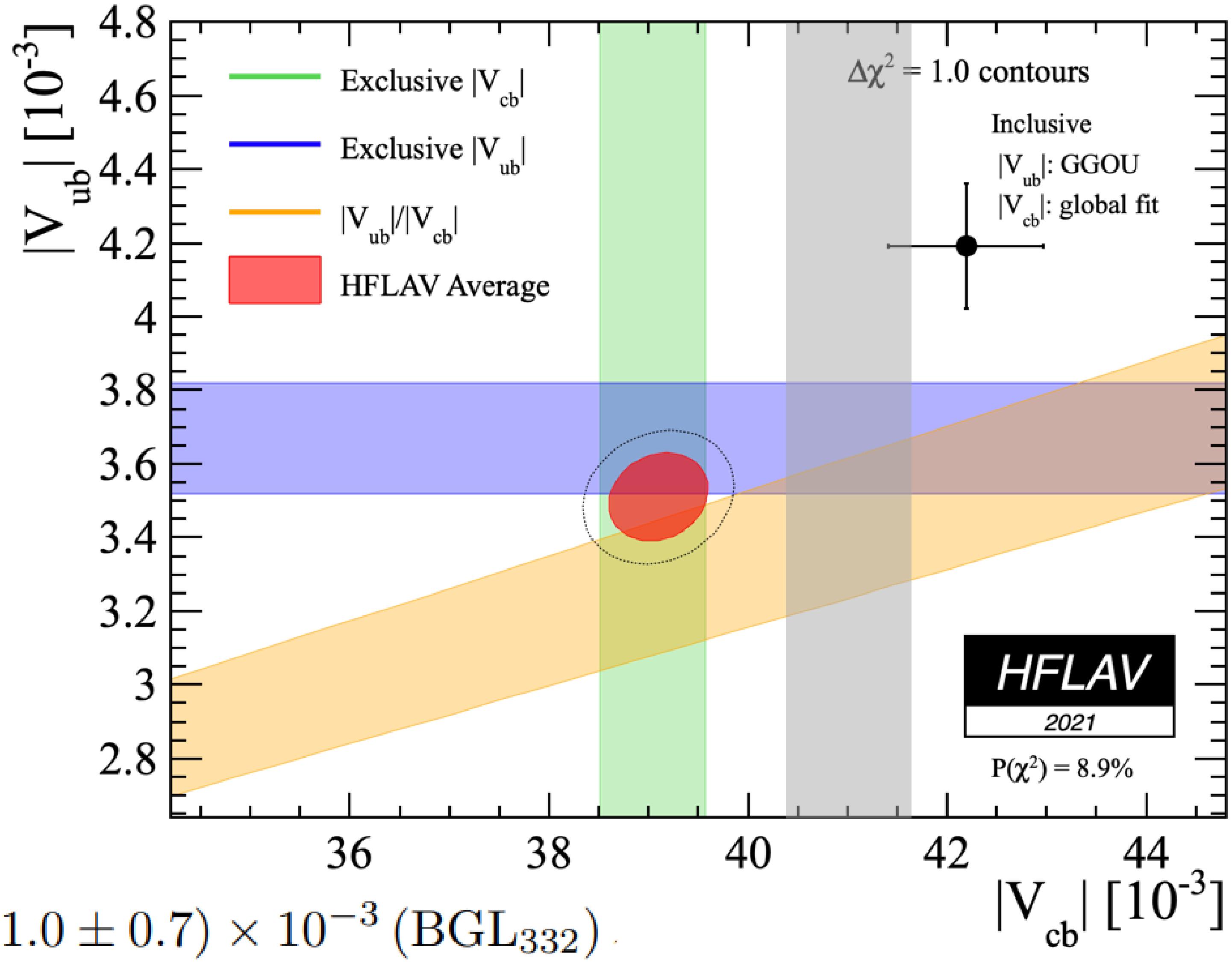
Belle paper accepted by PRL

Angular coefficients in $B \to D^* l \nu$ and V_{cb}

- Measure 4D-differential distribution in terms of decay angles and $w \sim q^2$
  - overall proportionality to $|V_{cb}|^2$
  - $w \geq 1$ is the hadronic recoil parameter – relates to mom. transfer to the leptonic system
- Extract 12 angular coefficients of the distribution in bins of w for the first time using full Belle 711 fb^{-1} sample
  - hadronically tagged
- Fit performed to coefficients in different form-factor parameterizations and with LQCD inputs to extract V_{cb} as well as parameters of the form-factor model
  - WA BF also taken externally





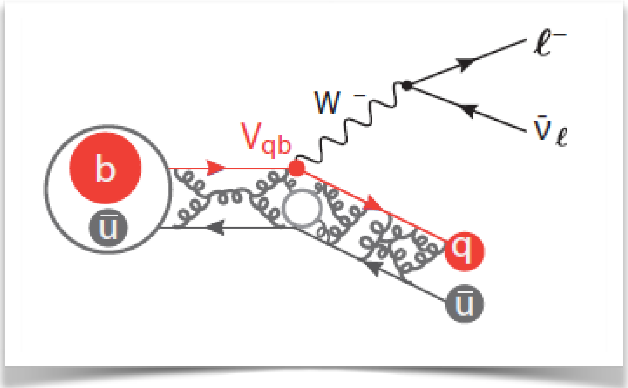


$$|V_{\rm cb}| = (41.0 \pm 0.7) \times 10^{-3}\ ({\rm BGL}_{332})$$

$$|V_{\rm cb}| = (40.9 \pm 0.7) \times 10^{-3}\ ({\rm CLN})$$

Angular analysis of $B \rightarrow D l \nu$ also more compatible

Babar paper accepted by PRD



Inclusive $|V_{cb}|$

F. Bernlochner – Belle II Physics Week

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

Operator Product Expansion (OPE)

$$\boxed{\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q \, \ell \, \bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \dots \right]}$$

Established approach: Use **spectral moments** (hadronic mass moments, lepton energy moments etc.) to determine non-perturbative matrix elements (ME) of OPE and extract $|V_{cb}|$

$$d\Gamma = d\Gamma_0 + d\Gamma_{\mu_\pi} \frac{\mu_\pi^2}{m_b^2} + d\Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + d\Gamma_{\rho_D} \frac{\rho_D^3}{m_b^3} + d\Gamma_{\rho_{LS}} \frac{\rho_{LS}^3}{m_b^3} + \mathcal{O}(1/m_b^4)$$

$d\Gamma$ are calculated perturbatively

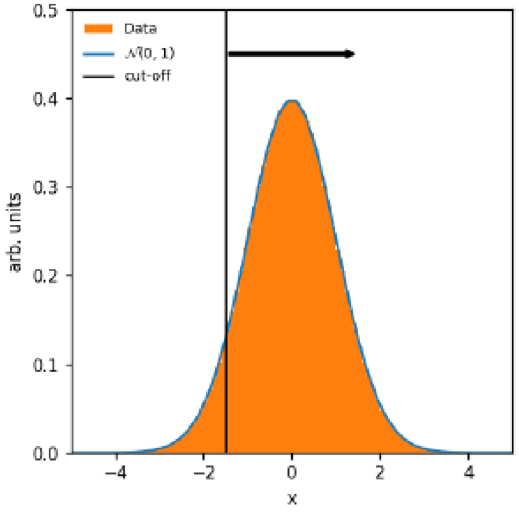
- Available at $\mathcal{O}(\alpha_s^3)$
  Fael, Schönwald, Steinhauser
  Phys. Rev. D 104, 016003 (2021)

$\mu_\pi, \mu_G, \rho_D, \rho_{LS}$ encapsulate non-perturbative dynamics

- HQE parameters must be extracted from data
  - requires the spectral moments of $B \to X_c \ell \nu$

Challenge: Proliferation of HQE parameters at higher order

Bad news: number of these matrix elements increases if one increases expansion in $1/m_{b,c}$



$$\mu_n = \int_{-\infty}^{-\infty} (x-c)^n f(x)dx$$

Raw moment: $c = 0$

Central moment: $c =$ Mean

First raw moment: Mean

Measures the location

Second central moment: Variance

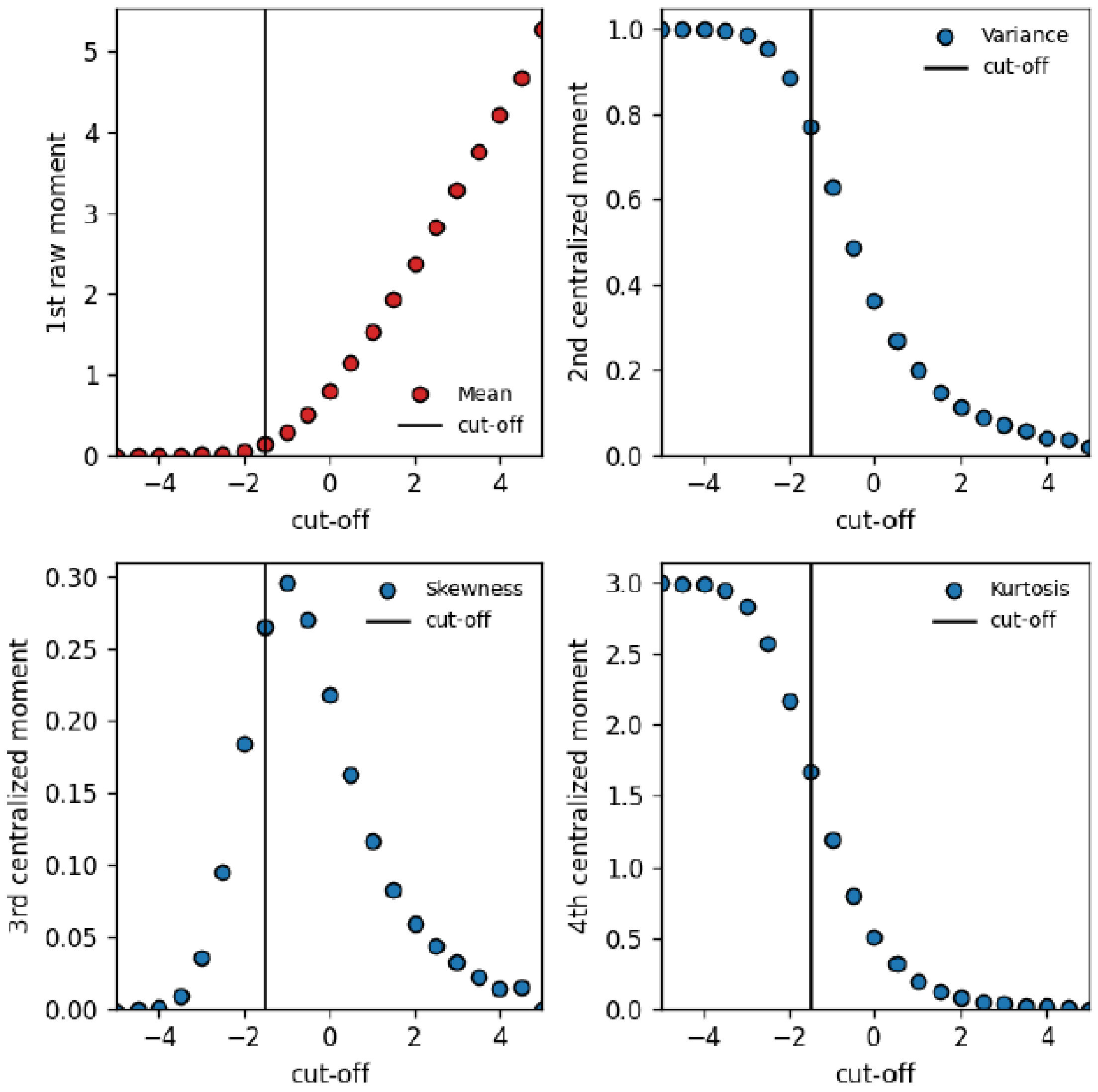
Measures the spread

Third central moment: Skewness

Measures asymmetry

Fourth central moment: Kurtosis

Measures "tailedness"

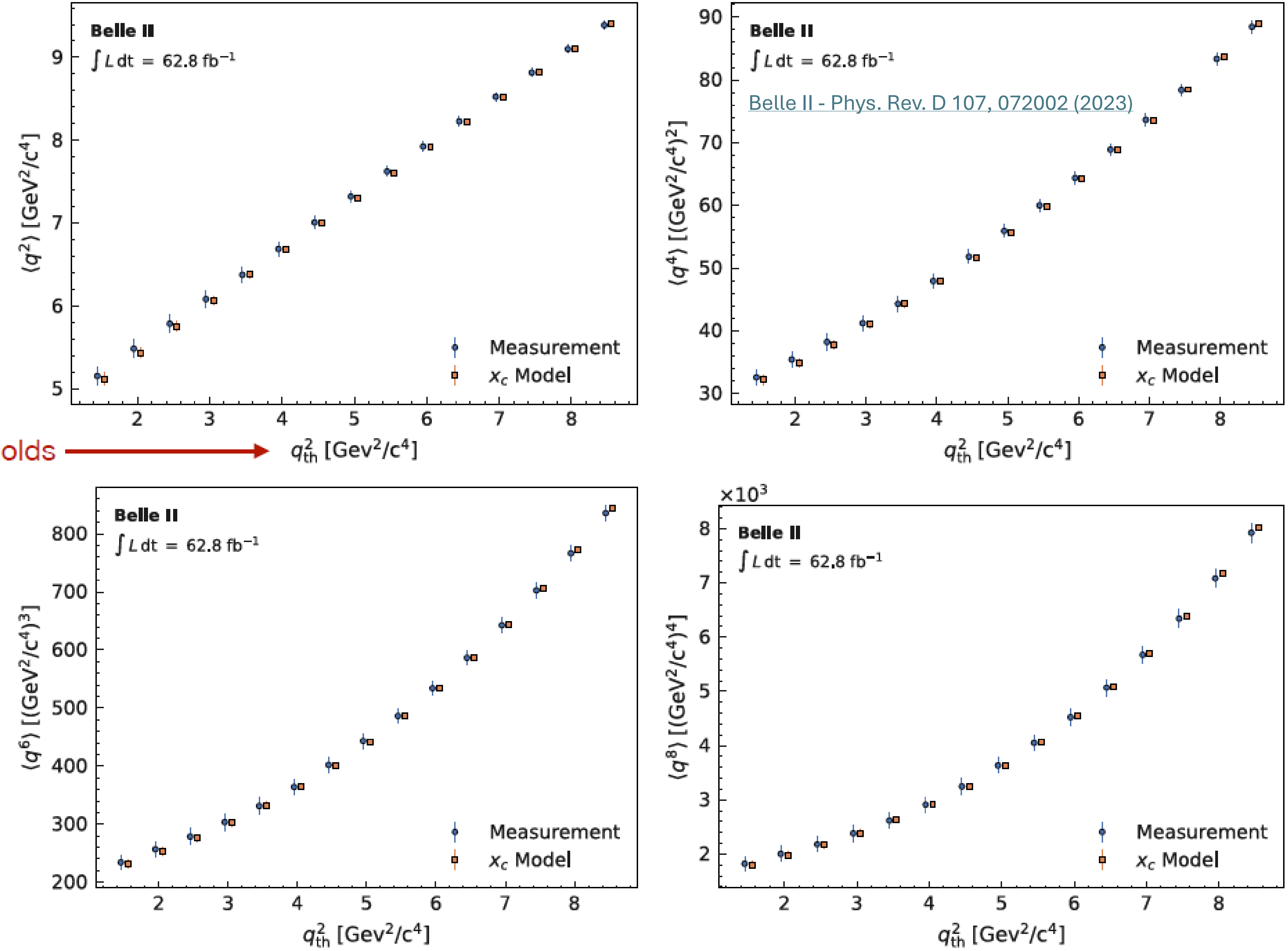


- Essentially their variation tells you about the dynamics of inclusive system, which can be related to the underlying QCD parameters in the expansion

Moments are measured with progressive cuts in the distribution

→ **highly correlated measurements**

q^2 thresholds



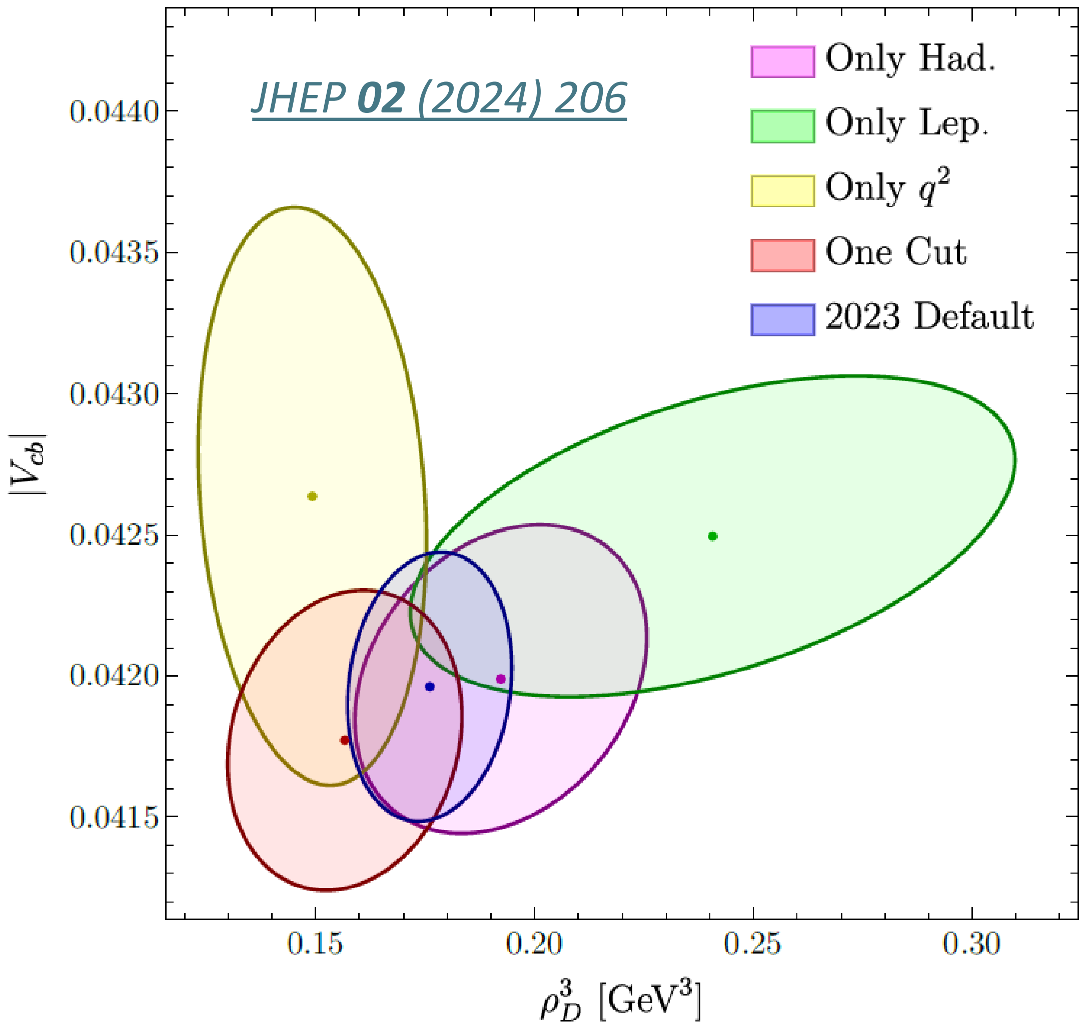
Belle II - Phys. Rev. D 107, 072002 (2023)

Inclusive V_{cb} and outlook

- The OPE is fit to the inclusive branching fraction and moments
- QCD parameters and V_{cb} extracted simultaneously

$$|V_{cb}| = (41.97 \pm 0.48) \times 10^{-3}\,.$$

- Agrees with recent exclusive
- Further improvement from experimental inputs possible or extending expansion to higher order
- Overall V_{xb} showcases work between experiment and theory leads to precision
  - Also, clear different techniques or measurements important to get the full picture
  - Beware a single measurement or experiment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