Quark flavor physics
(to overcome the standard model)
— part 2 —

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The KM framework

The weak interactions between quarks

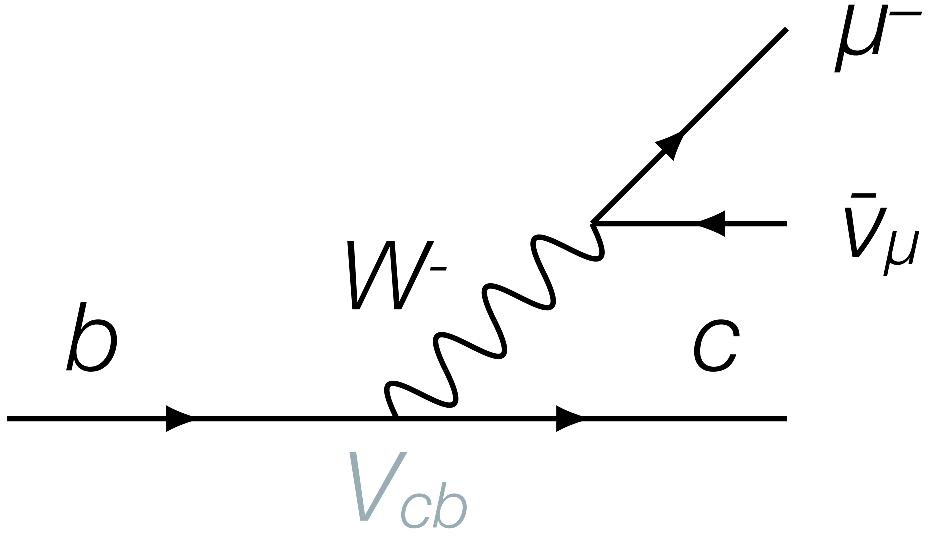
$$V \approx \begin{array}{cccc} d & s & b & \\ V_{ud} & V_{us} & V_{ub} & u \\ V_{cd} & V_{cs} & V_{cb} & c \\ V_{td} & V_{ts} & V_{tb} & t \end{array}$$

Each Vij element expresses the “intensity” of the interaction between quark i and quark j. They are free parameters of the SM that need to be determined experimentally

How do we measure these?

The *b*-quark decay is simple…

Most straightforward approach — identify a process that is directly sensitive to a single Vij element and measure its relative frequency ("rate")



Observed

$$\text{Rate} = |\text{Amplitude}|^2 \propto G_F\,|V_{cb}|^2\,m_b^5$$

Effective weak-interaction constant: known

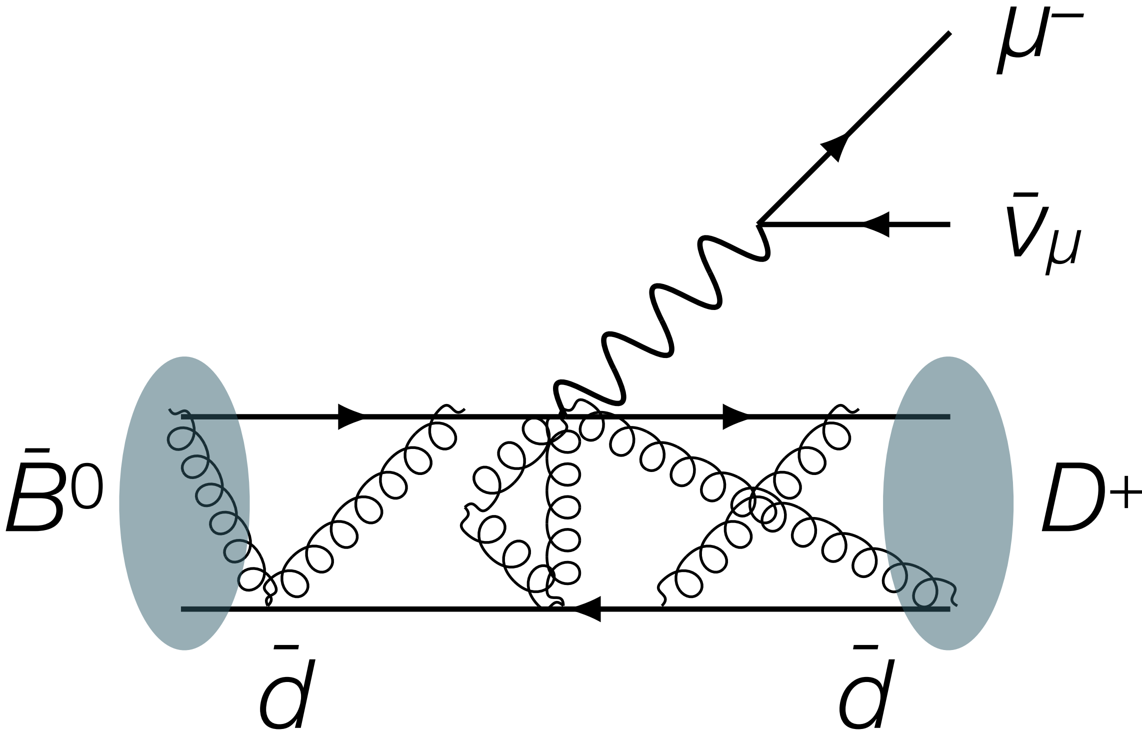
b-quark mass: known

A measurement of rate allows extracting $|V_{cb}|$

The *B*-hadron decay is not

We cannot observe the weak interactions of quarks in isolation: quarks are bound into hadrons by the strong nuclear force, which contributes to the transition amplitude.

Exchange of low-energy gluons renders expressing the amplitude a much harder task.



QCD at low energy is strongly coupled, invalidating the perturbative expansion we use to calculate transition amplitudes. (The expansion series diverges, each element is bigger than the previous one…)

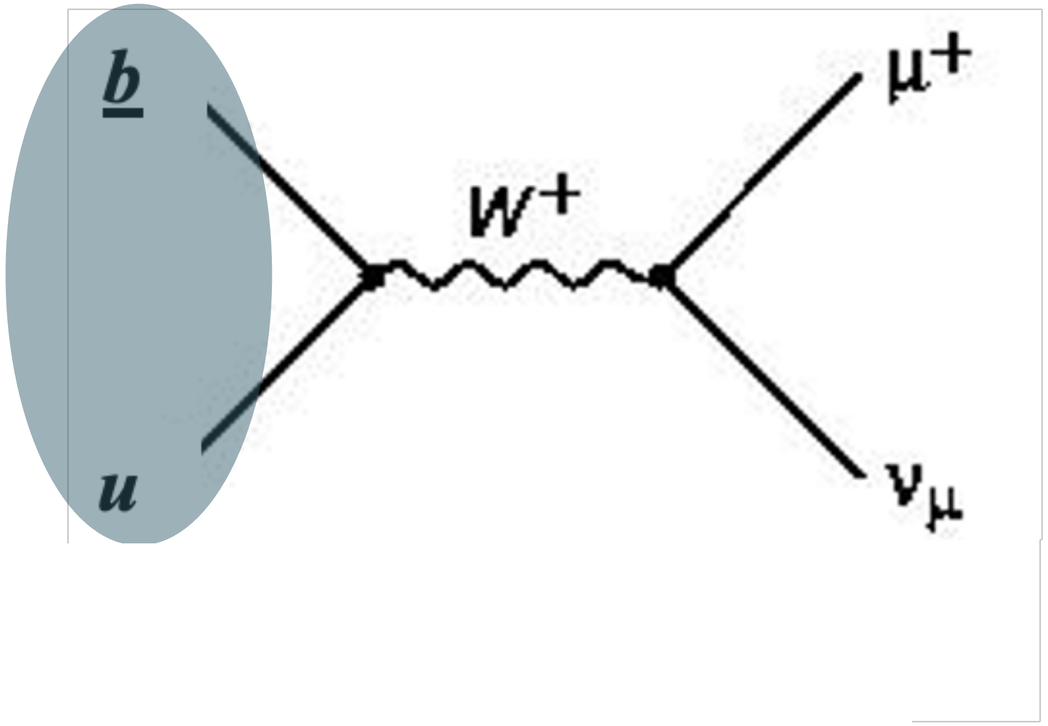
Rate is $|\text{Amplitude}|^2 \propto G_F |V_{cb}|^2 m_b^5 \times$[hadronic unknowns]

The more the final-state hadrons, the harder are calculations..

Difficulties associated with hadronic unknowns are probably the single most severe limiting factor in our understanding of flavor dynamics

Leptonic decays are easier to calculate…

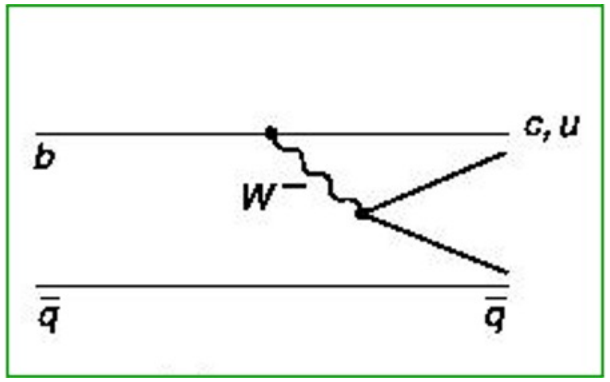
$$\mathcal{B}(B^+ \to l^+\nu) = \frac{G_F^2 |V_{ub}|^2}{8\pi} f_B^2 \tau_B m_B m_l^2 \left[1 - \frac{m_l^2}{m_B^2}\right]^2$$

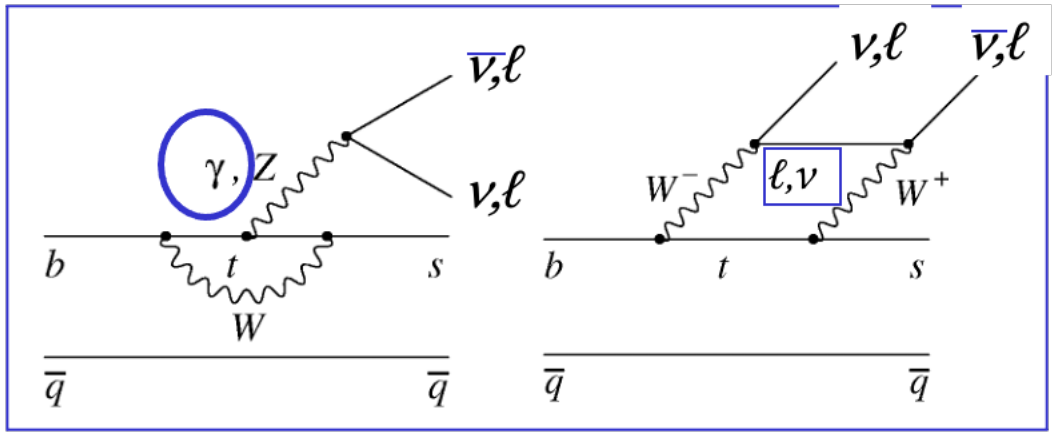


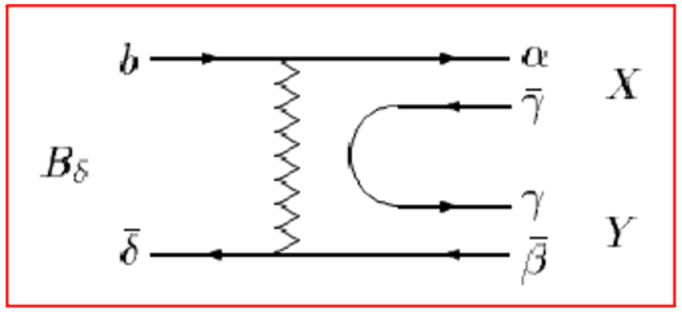
But much harder to observe as they are rarer (one every ten million or less because they are helicity suppressed, just as π → eν)

Additional difficulties

Typically more than one amplitude contribute. Hence observed quantities end up depending on additional and unwanted quark-couplings and hard-to-calculate QCD factors making the extraction of the target quark coupling harder.







A restricted set of “privileged” processes exists whose rate is dominated by a simple combination of quark-couplings and minimally spoiled by hadronic unknowns — the so-called “golden channels”

In most other cases, opportune combinations (ratios/differences) of quantities from processes connected by symmetries allow suppressing the unknowns.

In addition, not all KM matrix elements are accessible via decays.

How to measure V_{td} and V_{ts}?

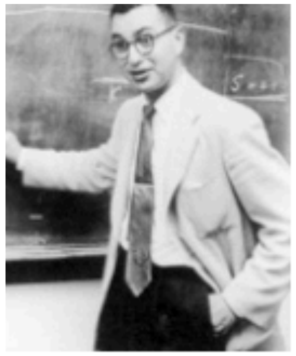
In principle one could look at top-quark decay rates into d and s quarks.

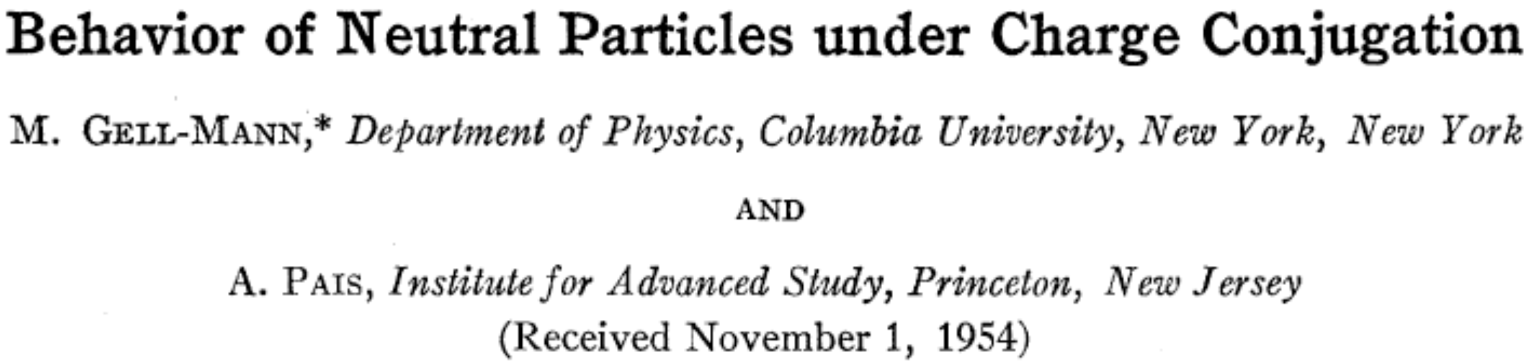
In practice the top quark decays ~always into a bottom quark and no sufficiently large samples of top-quark decays are available for a reliable direct measurement.

Use neutral bottom mixing instead

The flavor of (flavored) neutral mesons evolving in time oscillates — an exquisitely quantum-mechanical phenomenon that happens because flavor eigenstates are not eigenstates of the full Hamiltonian.

Postulated by Gell-Mann and Pais in 1954





Behavior of Neutral Particles under Charge Conjugation

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AND

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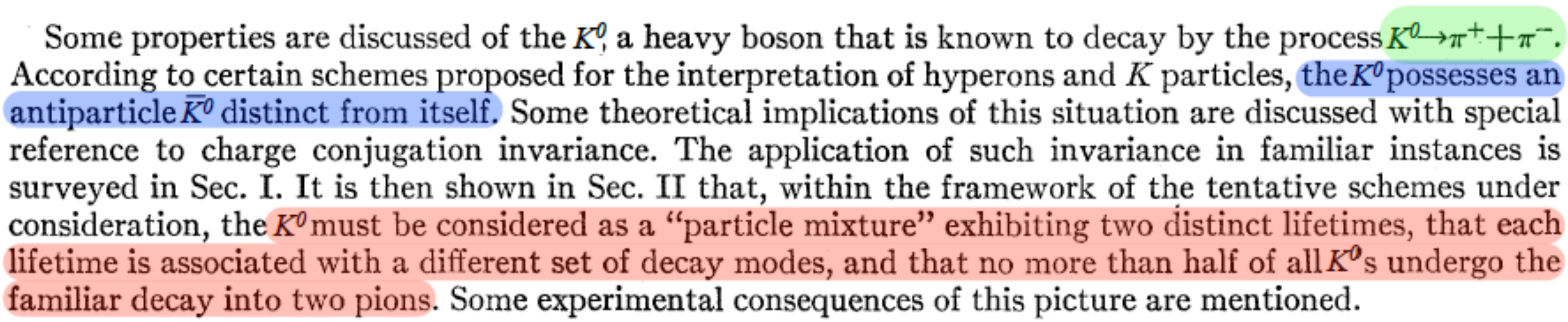
(Received November 1, 1954)



Some properties are discussed of the K^0, a heavy boson that is known to decay by the process $K^0 \to \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the K^0 possesses an antiparticle $\overline{K}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the K^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all K^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

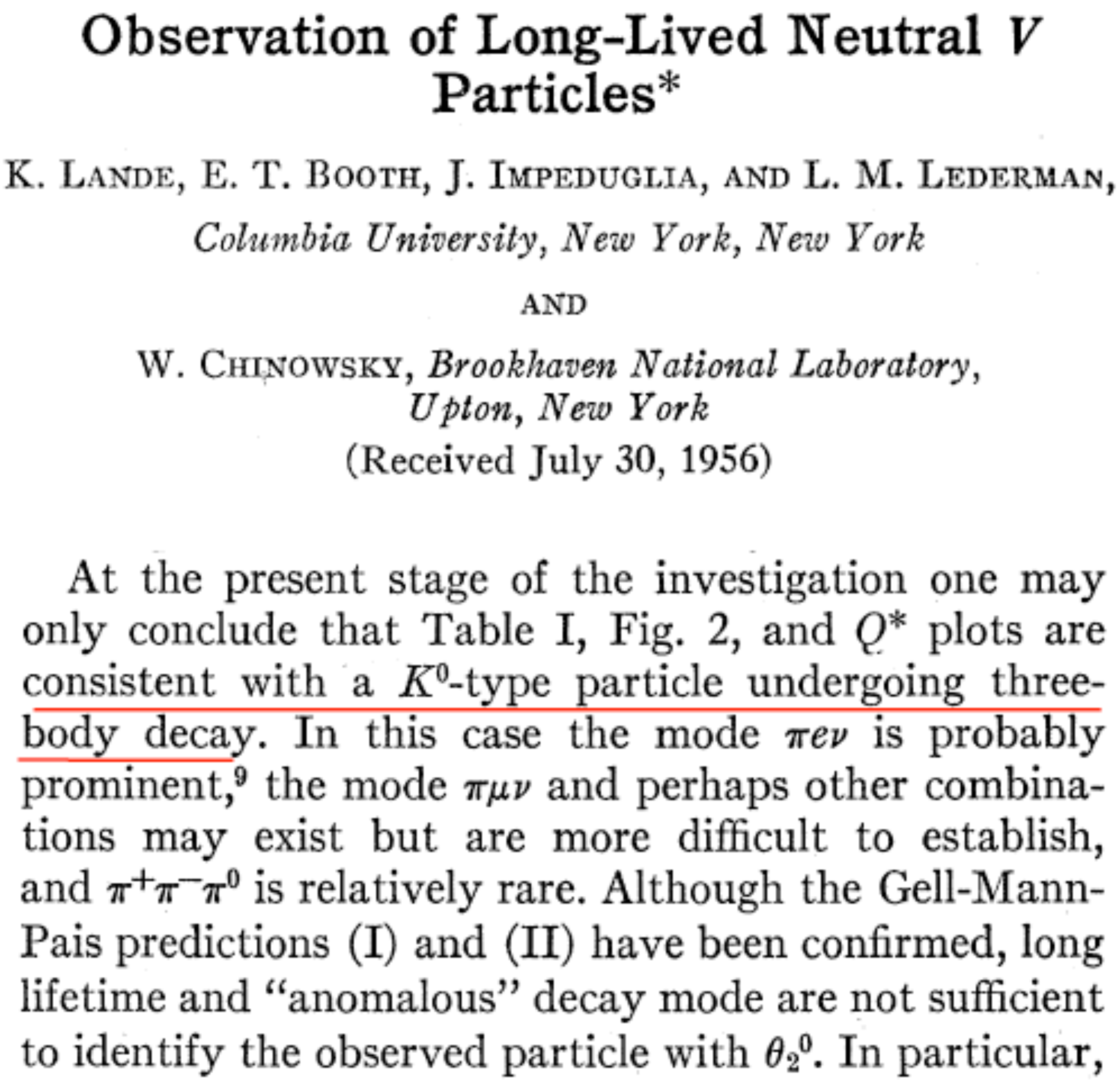
Since strangeness isn't conserved, K^0 and anti-K^0 can mix.

Known:
- $K^0 \to \pi^+\pi^-$

Hypothesis:
- $\overline{K}^0$ is *not* equal to K^0

Use C (actually, CP) to deduce:
1. K^0 ($\overline{K^0}$) is an 'admixture' with two distinct lifetimes
2. Each lifetime associated to a distinct set of decay modes
3. No more than 50% of K^0 will decay to two pions...

Observed by Lederman et al. in 1956



Observation of Long-Lived Neutral V Particles*

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(Received July 30, 1956)

At the present stage of the investigation one may only conclude that Table I, Fig. 2, and Q^* plots are consistent with a K^0-type particle undergoing three-body decay. In this case the mode $\pi e \nu$ is probably prominent,[9] the mode $\pi \mu \nu$ and perhaps other combinations may exist but are more difficult to establish, and $\pi^+\pi^-\pi^0$ is relatively rare. Although the Gell-Mann-Pais predictions (I) and (II) have been confirmed, long lifetime and "anomalous" decay mode are not sufficient to identify the observed particle with $\theta_2{}^0$. In particular,

Neutral flavored meson mixing

Weak interactions do not conserve flavor. Flavor eigenstates (i.e., states with definite quark composition/flavor content such as B^0 ($\bar{b}d$) or $\bar{B}^0$ ($b\bar{d}$)) are only eigenstates of the strong interaction, not of the full Hamiltonian, which includes weak interactions.

Hence, neutral flavored mesons produced (e.g, through a strong process) as flavor eigenstates B^0 ($\bar{b}d$) or $\bar{B}^0$ ($b\bar{d}$)) gets mixed into Hamiltonian eigenstates B_H and B_L, which are the physically observable states with definite lifetime and mass (but not flavor) as soon as time evolution kicks-in.

$$i\frac{\partial}{\partial t}\Psi = H\Psi \qquad\qquad \Psi(t) = a(t)\left|B^0\right\rangle + b(t)\left|\overline{B}^0\right\rangle$$

Eigenvectors:

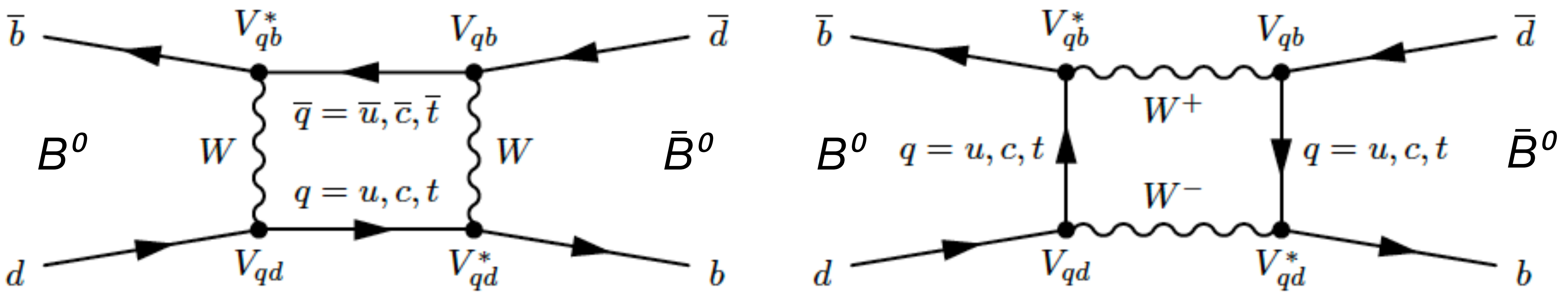
$$\left|B_H\right\rangle = p\left|B\right\rangle + q\left|\overline{B}\right\rangle$$
$$\left|B_L\right\rangle = p\left|B\right\rangle - q\left|\overline{B}\right\rangle$$

Evolution of eigenvectors:

$$|B_H(t)\rangle \;=\; |B_H\rangle\, e^{-i\left(M+\frac{1}{2}\Delta m-\frac{i}{2}(\Gamma-\Delta\Gamma)\right)t}$$
$$|B_L(t)\rangle \;=\; |B_L\rangle\, e^{-i\left(M-\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma+\Delta\Gamma)\right)t}$$

The particle-antiparticle oscillatory pattern as a function of time is driven by two parameters: the mass difference Δm and the width difference $\Delta\Gamma$ between physical eigenstates

But what has this got to do with V_{td}?



Quark in the loop	Contribution to rate	
$t-\bar{t}:$	$\propto m_t^2 \lvert V_{tb} V_{td}^* \rvert^2$	$\propto m_t^2 \lambda^6$
$c-\bar{c}:$	$\propto m_c^2 \lvert V_{cb} V_{cd}^* \rvert^2$	$\propto m_c^2 \lambda^6$
$c-\bar{t}, \bar{c}-t:$	$\propto m_c m_t V_{tb} V_{td}^* V_{cb} V_{cd}^*$	$\propto m_c m_t \lambda^6$

Dominated by top contribution as m_t = 175 GeV and m_c = 1.5 GeV

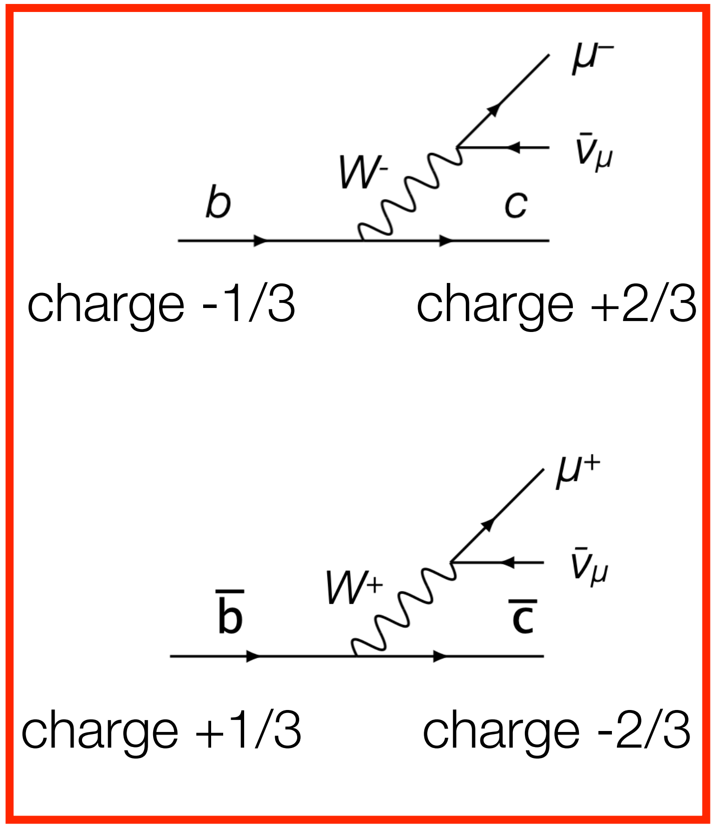
Mixing frequency $$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_B S_0(m_t^2 / m_W^2) m_{B_d} \lvert V_{td} \rvert^2 B_{B_d} f_{B_d}^2$$

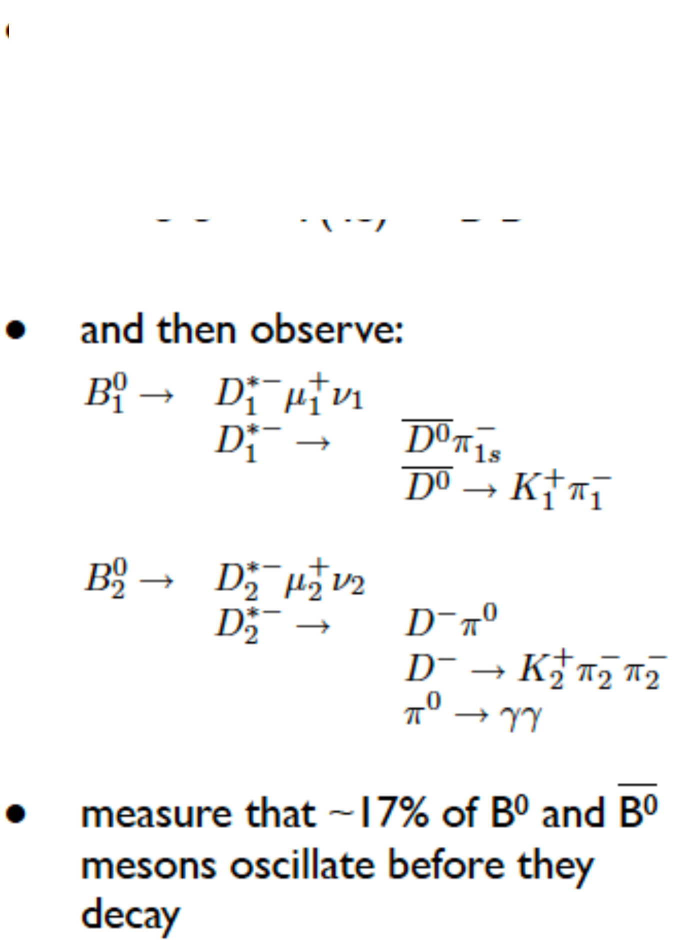
Measuring mixing frequency offers a measurement of mass difference, which is in turn sensitive to the magnitude of the quark-mixing matrix element Vtd

B^0 mixing — ARGUS 1987

Produce $B^0\bar{B}^0$ pairs in $e^+e^- \to \Upsilon(4S)$ collisions. Look at semimuonic decays $b \to c\ \mu\ \nu$.

b-quark charge imposes that *positive* μ can only come from B^0, which contains a $\bar{b}$ quark, and *negative* μ from $\bar{B}^0$, which contains a b quark.



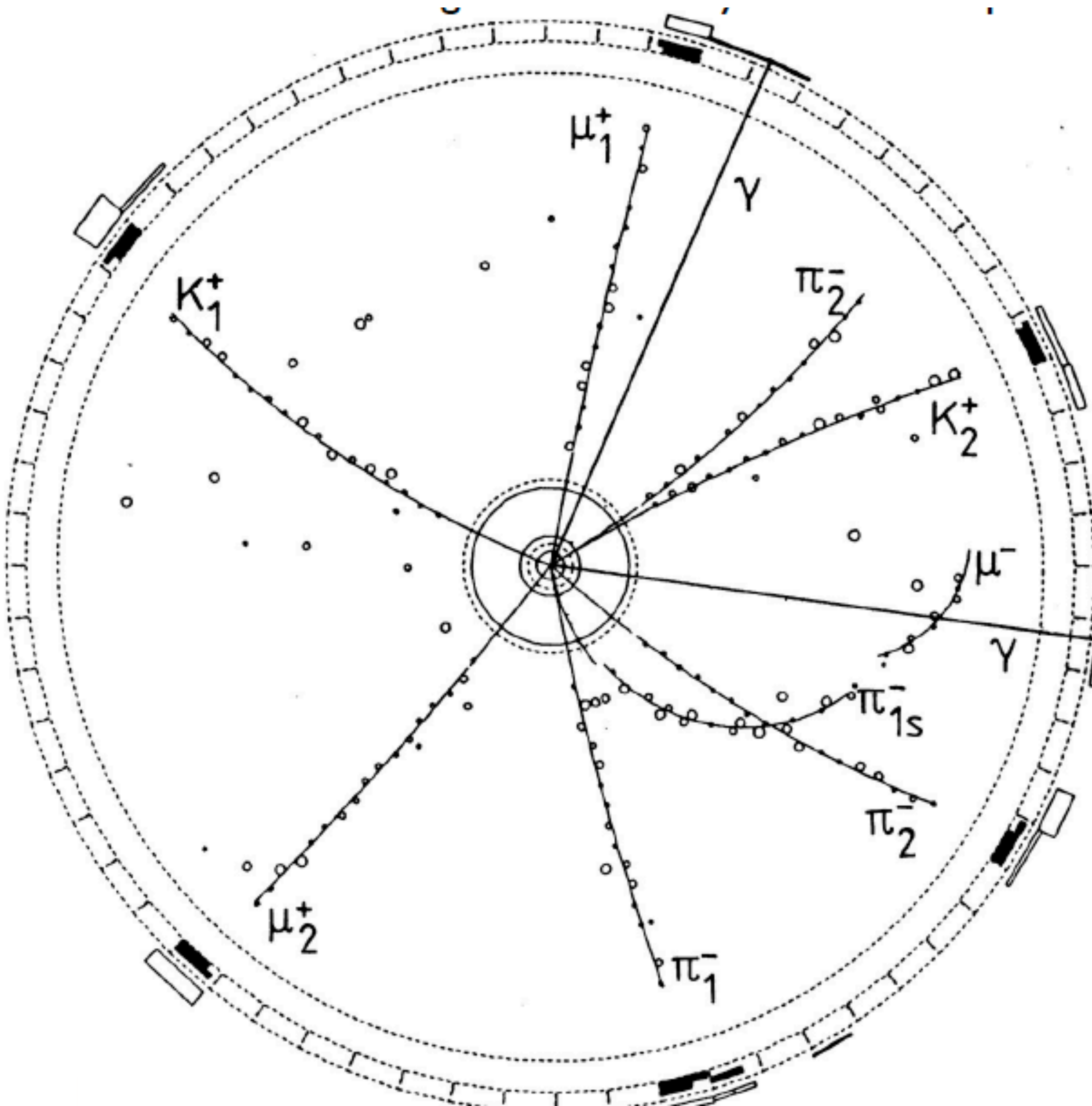


- and then observe:

$B_1^0 \to D_1^{*-}\mu_1^+\nu_1$
$D_1^{*-} \to \overline{D^0}\pi_{1s}^-$
$\overline{D^0} \to K_1^+\pi_1^-$

$B_2^0 \to D_2^{*-}\mu_2^+\nu_2$
$D_2^{*-} \to D^-\pi^0$
$D^- \to K_2^+\pi_2^-\pi_2^-$
$\pi^0 \to \gamma\gamma$

- measure that ~17% of B⁰ and $\overline{\text{B}^0}$ mesons oscillate before they decay

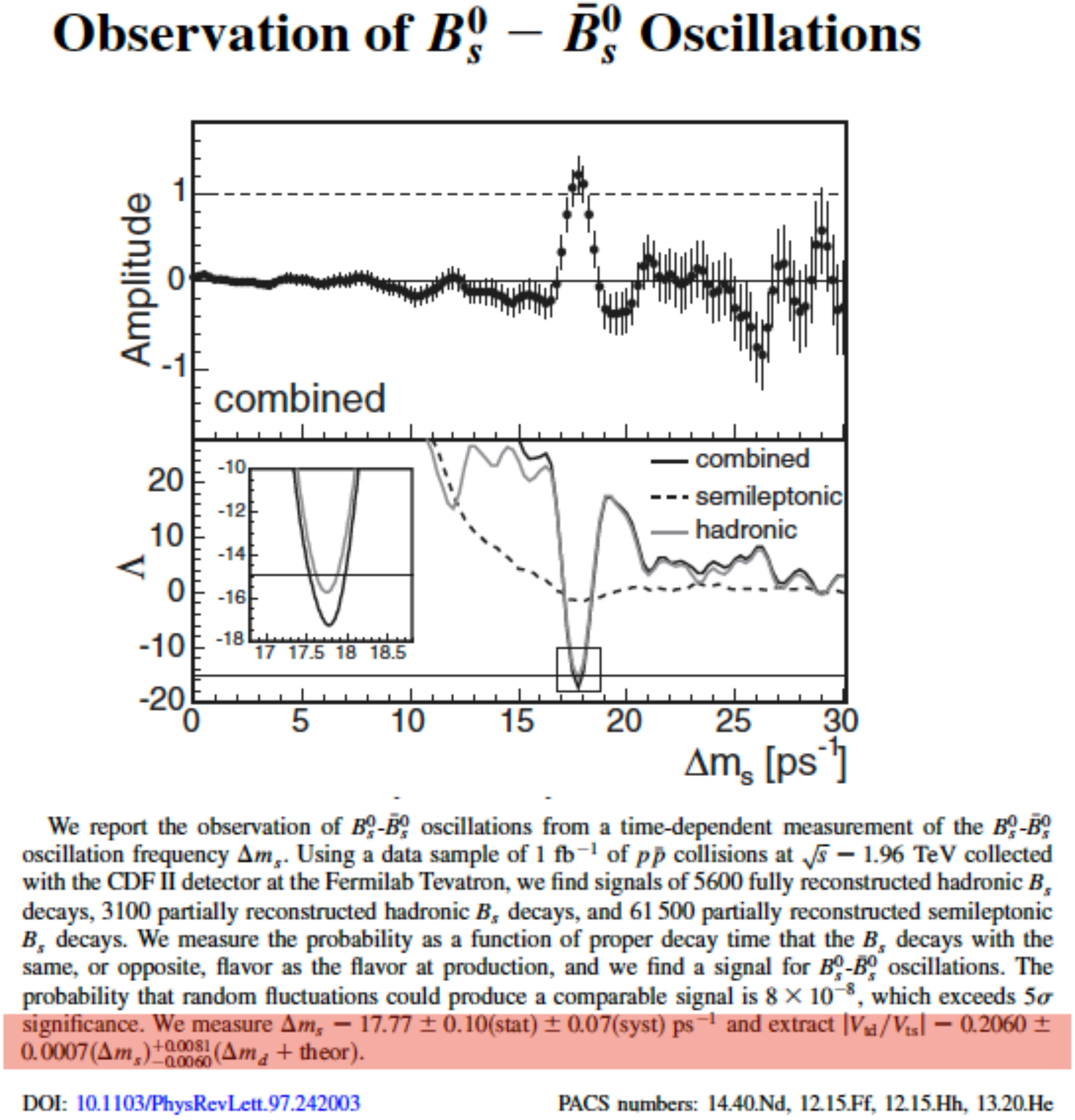


Observation of two μ⁺ in the event meant that the $\bar{B}^0$ had oscillated into B^0

B^0_s mixing, which determines V_{ts} — CDF 2006

Higher oscillation frequency and various other B^0_s features make this measurement much more involved than ARGUS' — which explains the 20 years lapse.

Details are beyond scope of lectures.



Observation of $B^0_s - \bar{B}^0_s$ Oscillations

We report the observation of B^0_s-$\bar{B}^0_s$ oscillations from a time-dependent measurement of the B^0_s-$\bar{B}^0_s$ oscillation frequency Δm_s. Using a data sample of 1 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector at the Fermilab Tevatron, we find signals of 5600 fully reconstructed hadronic B_s decays, 3100 partially reconstructed hadronic B_s decays, and 61 500 partially reconstructed semileptonic B_s decays. We measure the probability as a function of proper decay time that the B_s decays with the same, or opposite, flavor as the flavor at production, and we find a signal for B^0_s-$\bar{B}^0_s$ oscillations. The probability that random fluctuations could produce a comparable signal is 8×10^{-8}, which exceeds 5σ significance. We measure $\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$ ps^{-1} and extract $|V_{td}/V_{ts}| = 0.2060 \pm 0.0007(\Delta m_s)^{+0.0081}_{-0.0060}(\Delta m_d + \text{theor})$.

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PACS numbers: 14.40.Nd, 12.15.Ff, 12.15.Hh, 13.20.He

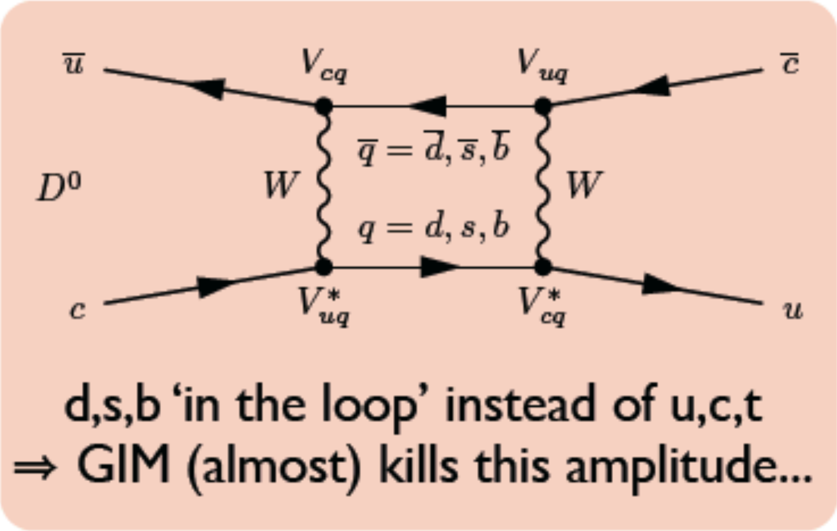
D mixing — Belle/Babar 2007

Unrelated to Vts or Vtd but still important.

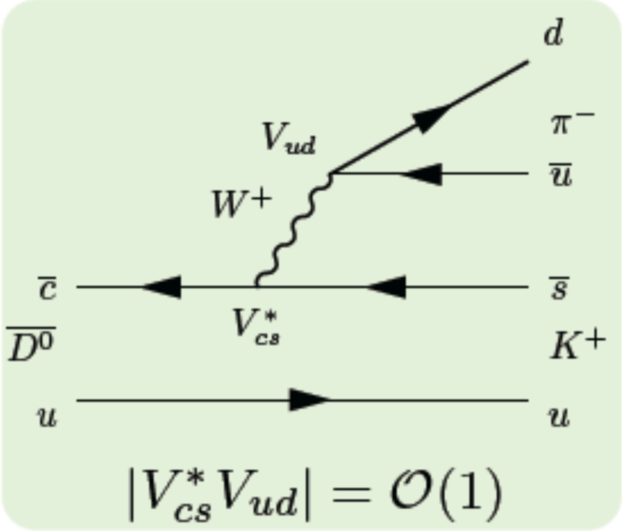
Measurement concept similar to ARGUS — but using Kπ final states rather than semimuonic:

Look for a decay-time dependence in the rate of “wrong-sign” $D^0 \to K^+\pi^-$ decays, which signals $D^0 \to \bar{D}^0 \to K^+\pi^-$

Difficulty here is to collect a sufficient number of decays to see the <u>*very low*</u> oscillation frequency.



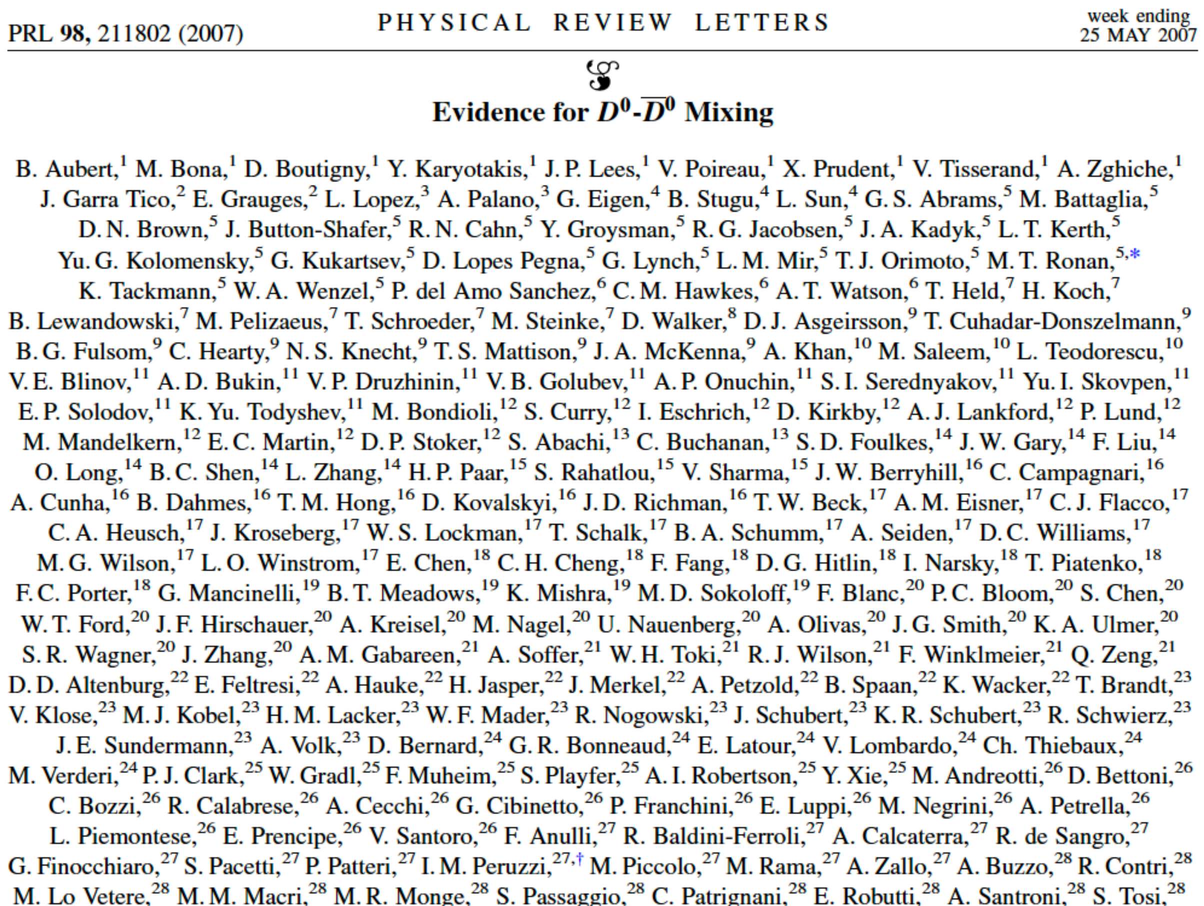
d,s,b ‘in the loop’ instead of u,c,t
⇒ GIM (almost) kills this amplitude...



$|V^*_{cs}V_{ud}| = \mathcal{O}(1)$

Look for ‘wrong sign’ D^0 decays

$$D^0 \longrightarrow \overline{D^0} \Rightarrow K^+\pi^-$$



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Evidence for D^0-$\overline{D}^0$ Mixing

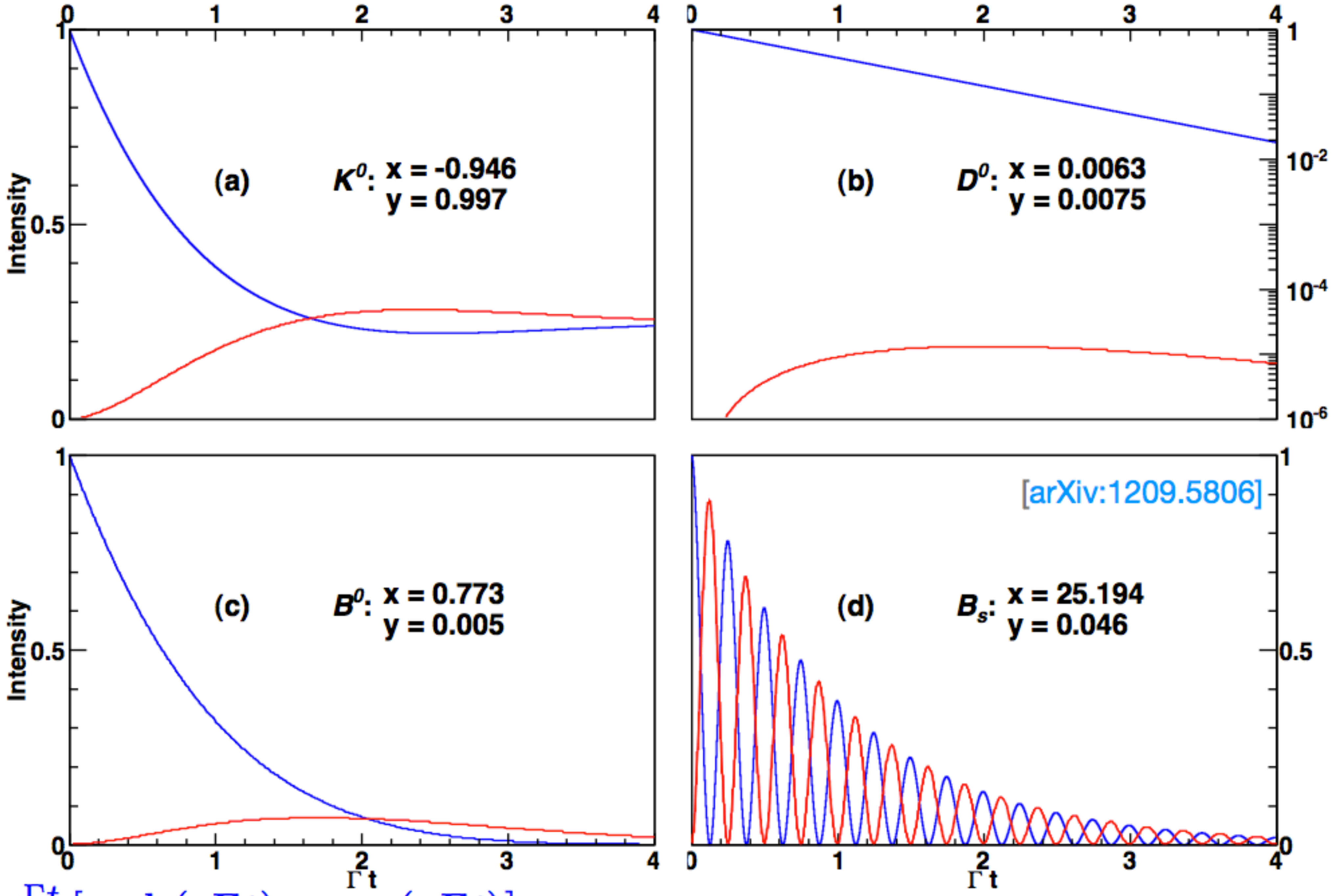
B. Aubert,[1] M. Bona,[1] D. Boutigny,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] X. Prudent,[1] V. Tisserand,[1] A. Zghiche,[1] J. Garra Tico,[2] E. Grauges,[2] L. Lopez,[3] A. Palano,[3] G. Eigen,[4] B. Stugu,[4] L. Sun,[4] G. S. Abrams,[5] M. Battaglia,[5] D. N. Brown,[5] J. Button-Shafer,[5] R. N. Cahn,[5] Y. Groysman,[5] R. G. Jacobsen,[5] J. A. Kadyk,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Kukartsev,[5] D. Lopes Pegna,[5] G. Lynch,[5] L. M. Mir,[5] T. J. Orimoto,[5] M. T. Ronan,[5,*] K. Tackmann,[5] W. A. Wenzel,[5] P. del Amo Sanchez,[6] C. M. Hawkes,[6] A. T. Watson,[6] T. Held,[7] H. Koch,[7] B. Lewandowski,[7] M. Pelizaeus,[7] T. Schroeder,[7] M. Steinke,[7] D. Walker,[8] D. J. Asgeirsson,[9] T. Cuhadar-Donszelmann,[9] B. G. Fulsom,[9] C. Hearty,[9] N. S. Knecht,[9] T. S. Mattison,[9] J. A. McKenna,[9] A. Khan,[10] M. Saleem,[10] L. Teodorescu,[10] V. E. Blinov,[11] A. D. Bukin,[11] V. P. Druzhinin,[11] V. B. Golubev,[11] A. P. Onuchin,[11] S. I. Serednyakov,[11] Yu. I. Skovpen,[11] E. P. Solodov,[11] K. Yu. Todyshev,[11] M. Bondioli,[12] S. Curry,[12] I. Eschrich,[12] D. Kirkby,[12] A. J. Lankford,[12] P. Lund,[12] M. Mandelkern,[12] E. C. Martin,[12] D. P. Stoker,[12] S. Abachi,[13] C. Buchanan,[13] S. D. Foulkes,[14] J. W. Gary,[14] F. Liu,[14] O. Long,[14] B. C. Shen,[14] L. Zhang,[14] H. P. Paar,[15] S. Rahatlou,[15] V. Sharma,[15] J. W. Berryhill,[16] C. Campagnari,[16] A. Cunha,[16] B. Dahmes,[16] T. M. Hong,[16] D. Kovalskyi,[16] J. D. Richman,[16] T. W. Beck,[17] A. M. Eisner,[17] C. J. Flacco,[17] C. A. Heusch,[17] J. Kroseberg,[17] W. S. Lockman,[17] T. Schalk,[17] B. A. Schumm,[17] A. Seiden,[17] D. C. Williams,[17] M. G. Wilson,[17] L. O. Winstrom,[17] E. Chen,[18] C. H. Cheng,[18] F. Fang,[18] D. G. Hitlin,[18] I. Narsky,[18] T. Piatenko,[18] F. C. Porter,[18] G. Mancinelli,[19] B. T. Meadows,[19] K. Mishra,[19] M. D. Sokoloff,[19] F. Blanc,[20] P. C. Bloom,[20] S. Chen,[20] W. T. Ford,[20] J. F. Hirschauer,[20] A. Kreisel,[20] M. Nagel,[20] U. Nauenberg,[20] A. Olivas,[20] J. G. Smith,[20] K. A. Ulmer,[20] S. R. Wagner,[20] J. Zhang,[20] A. M. Gabareen,[21] A. Soffer,[21] W. H. Toki,[21] R. J. Wilson,[21] F. Winklmeier,[21] Q. Zeng,[21] D. D. Altenburg,[22] E. Feltresi,[22] A. Hauke,[22] H. Jasper,[22] J. Merkel,[22] A. Petzold,[22] B. Spaan,[22] K. Wacker,[22] T. Brandt,[23] V. Klose,[23] M. J. Kobel,[23] H. M. Lacker,[23] W. F. Mader,[23] R. Nogowski,[23] J. Schubert,[23] K. R. Schubert,[23] R. Schwierz,[23] J. E. Sundermann,[23] A. Volk,[23] D. Bernard,[24] G. R. Bonneaud,[24] E. Latour,[24] V. Lombardo,[24] Ch. Thiebaux,[24] M. Verderi,[24] P. J. Clark,[25] W. Gradl,[25] F. Muheim,[25] S. Playfer,[25] A. I. Robertson,[25] Y. Xie,[25] M. Andreotti,[26] D. Bettoni,[26] C. Bozzi,[26] R. Calabrese,[26] A. Cecchi,[26] G. Cibinetto,[26] P. Franchini,[26] E. Luppi,[26] M. Negrini,[26] A. Petrella,[26] L. Piemontese,[26] E. Prencipe,[26] V. Santoro,[26] F. Anulli,[27] R. Baldini-Ferroli,[27] A. Calcaterra,[27] R. de Sangro,[27] G. Finocchiaro,[27] S. Pacetti,[27] P. Patteri,[27] I. M. Peruzzi,[27,†] M. Piccolo,[27] M. Rama,[27] A. Zallo,[27] A. Buzzo,[28] R. Contri,[28] M. Lo Vetere,[28] M. M. Macri,[28] M. R. Monge,[28] S. Passaggio,[28] C. Patrignani,[28] E. Robutti,[28] A. Santroni,[28] S. Tosi,[28]

Mixing summary

x = Δm/Γ
y = ΔΓ/2Γ

Blue line:
given a P^0, at t=0, the probability of finding a P^0 at t

Red Line:
given a P^0, at t=0, the probability of finding a $\overline{P}^0$ at t

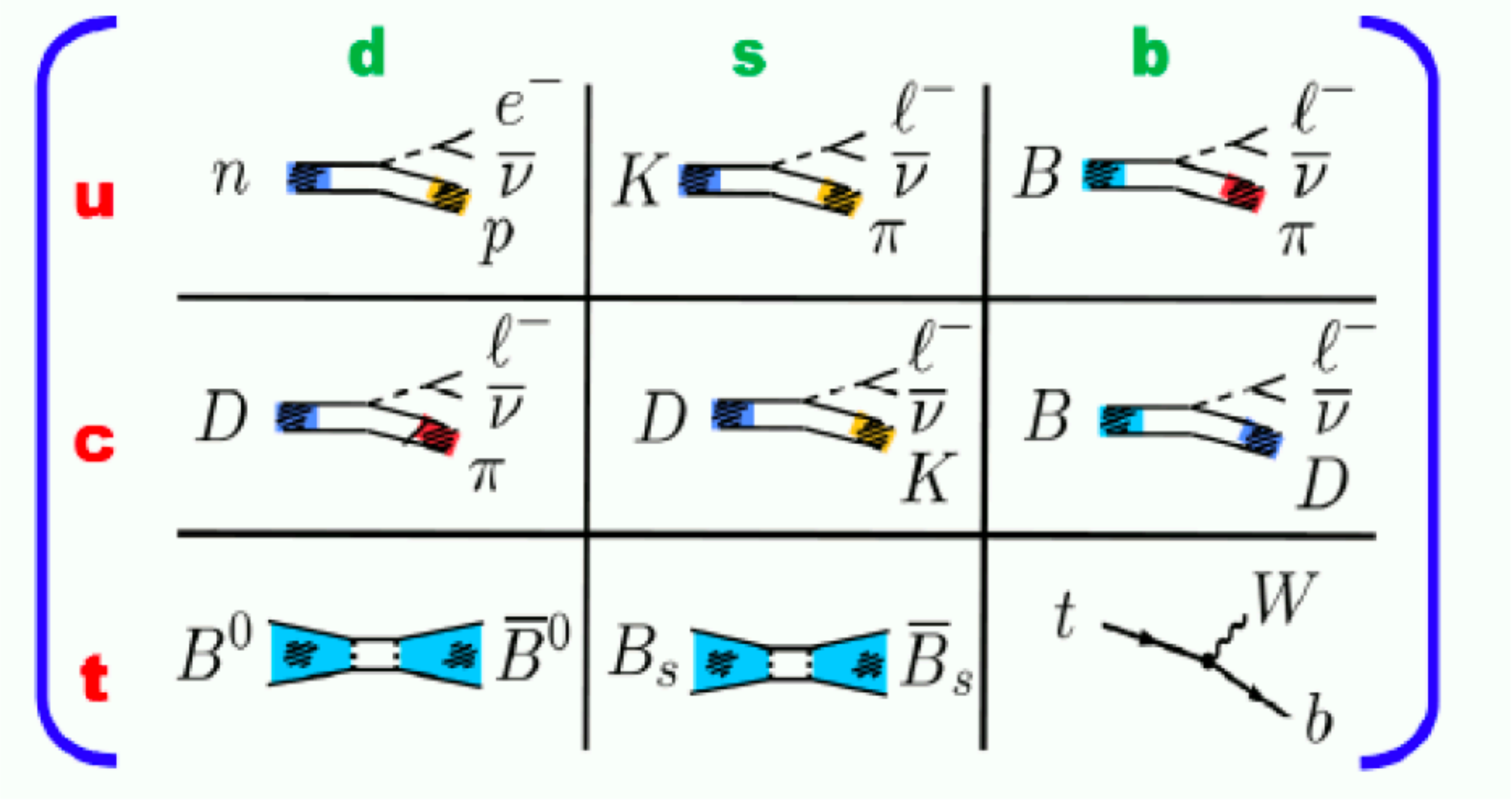


[arXiv:1209.5806]

$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

$$|\langle P^0(0)|\overline{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

Quark-mixing magnitude determination summary



Parameter redundancy

The CKM matrix has 9 complex parameters, but dynamical relationships/symmetrie reduce the number of independent free parameters to just 4

- complex NxN matrix: $2N^2$ parameters
- must be unitary:
  - eg. t must decay to either b, s or d, so $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$
  - in general: $V^{*T} V = I \rightarrow N^2$ constraints
- freedom to change phase of quark fields $|q_j\rangle \rightarrow e^{i\phi_j} |q_j\rangle$
  - 2N-1 phases are irrelevant:

$$\langle q_i | V_{ij} | q_j \rangle \rightarrow \langle q_i | e^{-i\phi_i} V_{ij} e^{i\phi_j} | q_j \rangle$$

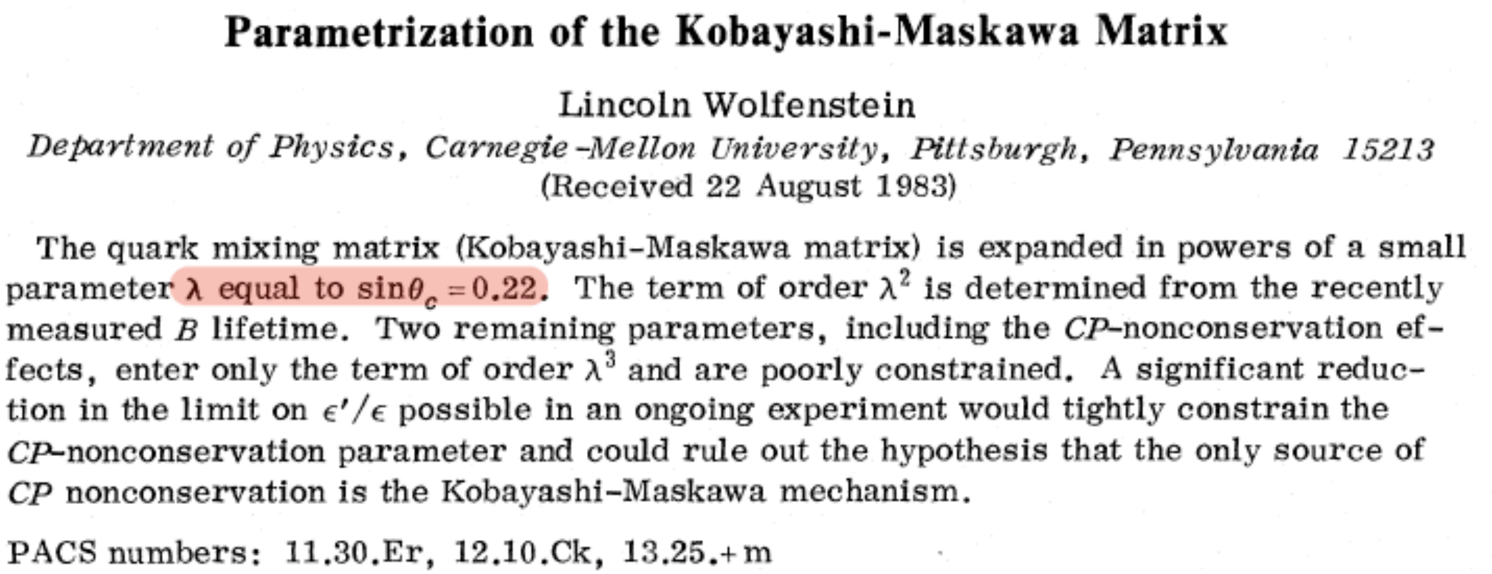
$$V_{ij} \rightarrow e^{i(\phi_j - \phi_i)} V_{ij}$$

- number of 'physical' parameters = N^2-2N+1
- how many can be rotation angles? $N(N-1)/2$
- For N=2 : 1 parameter, with 1 rotation angle (Cabbibo!)
- For N=3: 4 parameters = 3 rotations + 1 *irreducible* complex phase!

Parameter hierarchy

A hierarchy emerges from the measurements of quark-mixing parameters: the CKM matrix is a perturbation of the identity matrix.

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$



Parametrization of the Kobayashi-Maskawa Matrix

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(Received 22 August 1983)

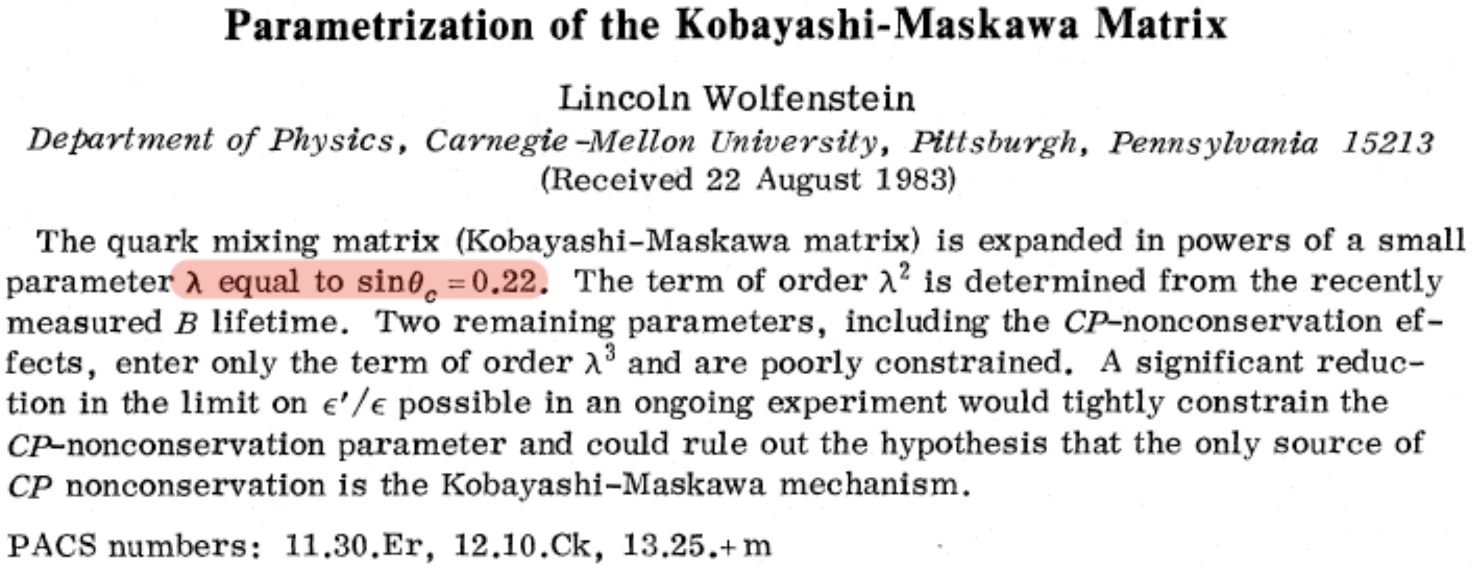
The quark mixing matrix (Kobayashi-Maskawa matrix) is expanded in powers of a small parameter λ equal to $\sin\theta_c = 0.22$. The term of order λ^2 is determined from the recently measured *B* lifetime. Two remaining parameters, including the *CP*-nonconservation effects, enter only the term of order λ^3 and are poorly constrained. A significant reduction in the limit on ϵ'/ϵ possible in an ongoing experiment would tightly constrain the *CP*-nonconservation parameter and could rule out the hypothesis that the only source of *CP* nonconservation is the Kobayashi-Maskawa mechanism.

PACS numbers: 11.30.Er, 12.10.Ck, 13.25.+m

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\lambda)$$

Hirerarchy, order λ

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \equiv \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$



Parametrization of the Kobayashi-Maskawa Matrix

Lincoln Wolfenstein

Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

(Received 22 August 1983)

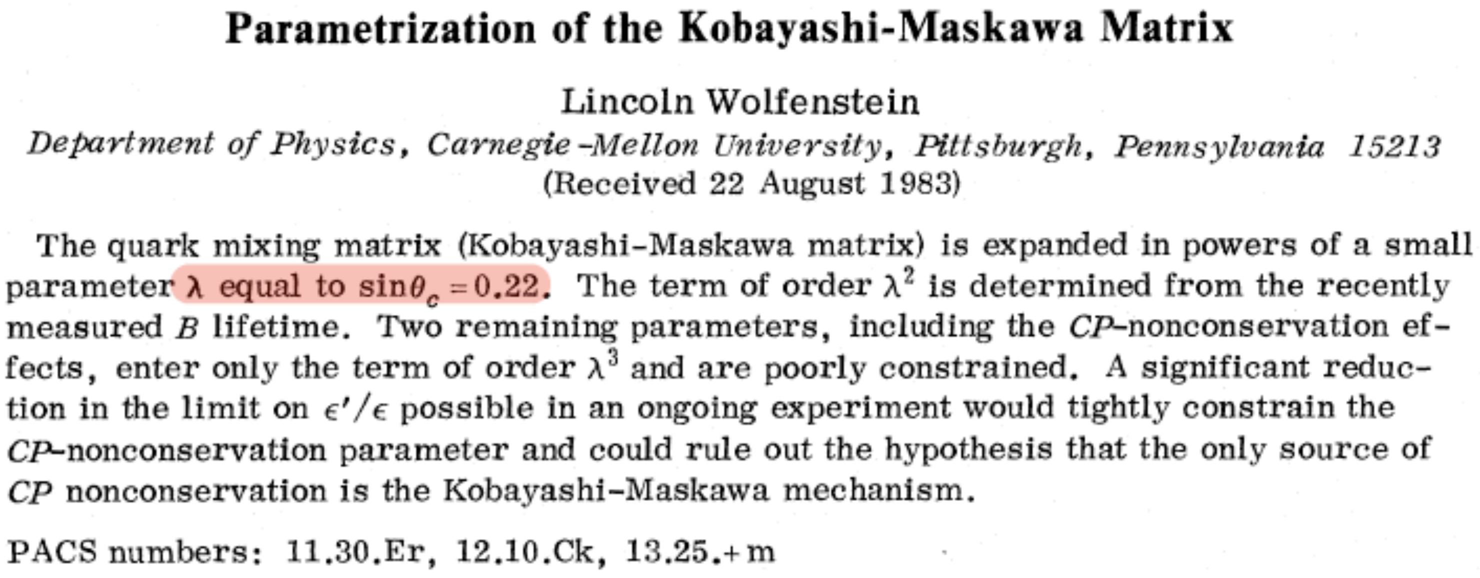
The quark mixing matrix (Kobayashi-Maskawa matrix) is expanded in powers of a small parameter λ equal to $\sin\theta_c = 0.22$. The term of order λ^2 is determined from the recently measured B lifetime. Two remaining parameters, including the CP-nonconservation effects, enter only the term of order λ^3 and are poorly constrained. A significant reduction in the limit on ϵ'/ϵ possible in an ongoing experiment would tightly constrain the CP-nonconservation parameter and could rule out the hypothesis that the only source of CP nonconservation is the Kobayashi-Maskawa mechanism.

PACS numbers: 11.30.Er, 12.10.Ck, 13.25.+m

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\lambda^2)$$

Hirerarchy, order λ²

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$



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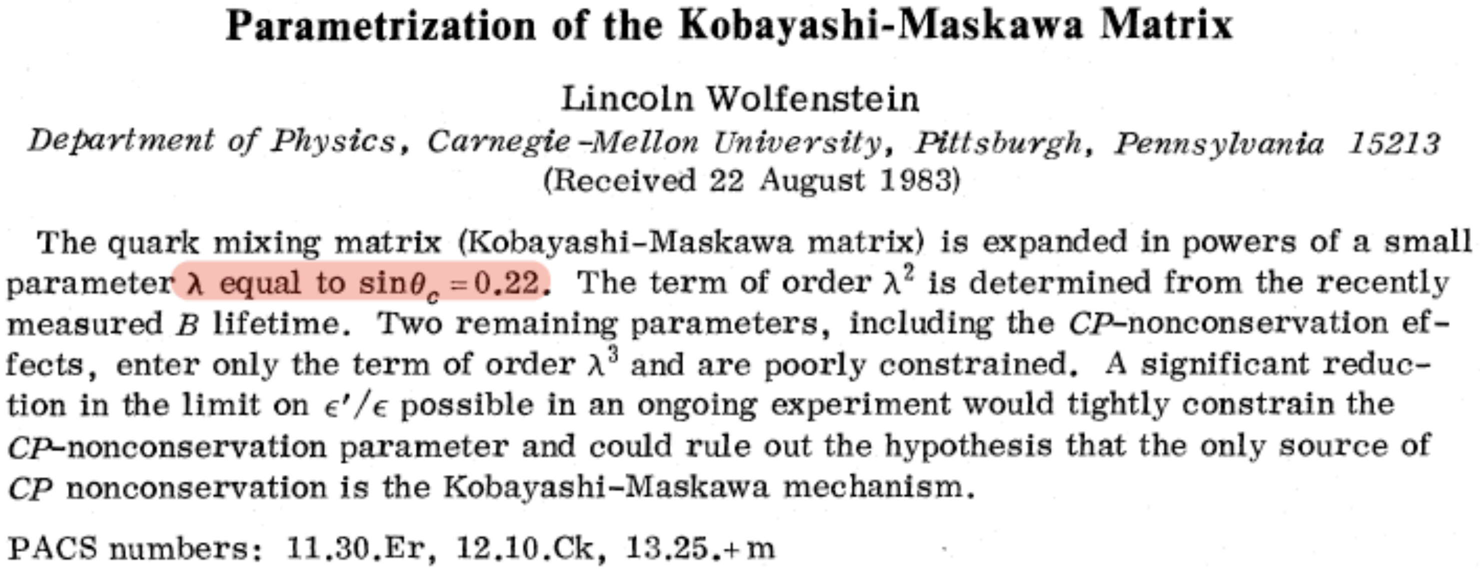
Hirerarchy, order λ^3

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$



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Kobayashi-Maskawa mechanism at work

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ V \approx & \left(\begin{array}{ccc} 1 & \lambda & \lambda^3 e^{i\varphi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 \end{array}\right) \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

$$\lambda \approx 0.22$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

About 150 pages of PDG-booklet listings explained by 4 parameters only: A, λ, ρ, and η (the only one parameter to account for all CPV phenomena!)

Many many possible observables — plenty of redundancy to test the KM picture with very high precision and look for discrepancies!

Checking KM consistency

Putting everything together

- Many measurements, but in the end, V_{CKM} has only four parameters
- ...and only *one* of them is actually responsible for CP violation
- How to make a coherent/powerful/... test of the model?
- How to integrate CP measurements in this?

- V_{CKM} has *many* relations amongst its elements....

Use the unitarity constraints

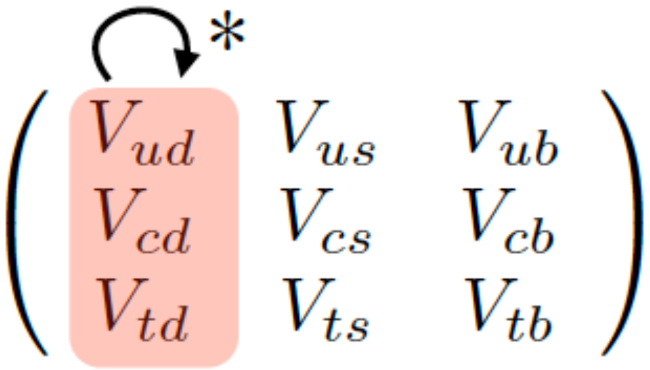
The 9 unitarity conditions of the 3×3 generations CKM matrix:

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

Use the unitarity constraints

The 9 unitarity conditions of the 3×3 generations CKM matrix:

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$$



$$\left(\begin{array}{ccc} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{array}\right)$$

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$$\begin{pmatrix} V_{ud} & \overset{\curvearrowright *}{V_{us}} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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The 6 complex "**Unitarity Triangles**" involve different physics processes

Use the unitarity constraints

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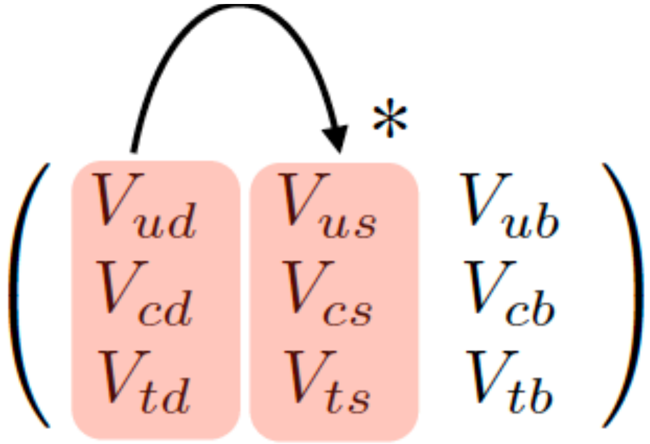

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The 6 complex "**Unitarity Triangles**" involve different physics processes

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0 \qquad \mathcal{O}(\lambda) + \mathcal{O}(\lambda) + \mathcal{O}(\lambda^5) = 0$$

'sd' triangle: K^0

Use the unitarity constraints

The 9 unitarity conditions of the 3×3 generations CKM matrix:

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$$
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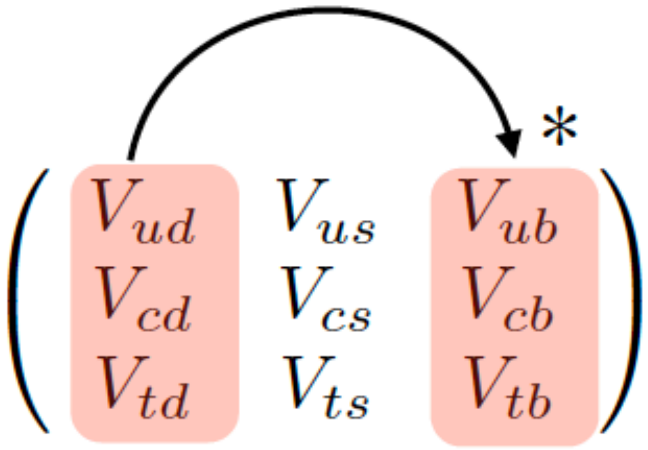

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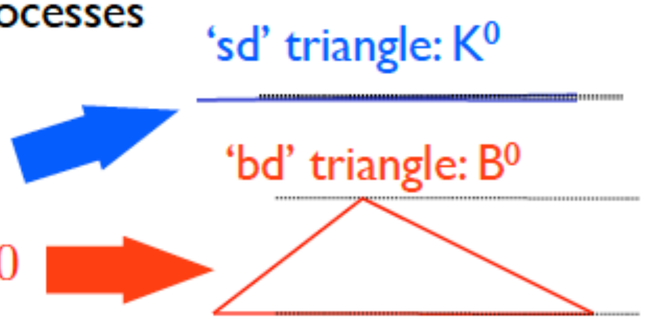

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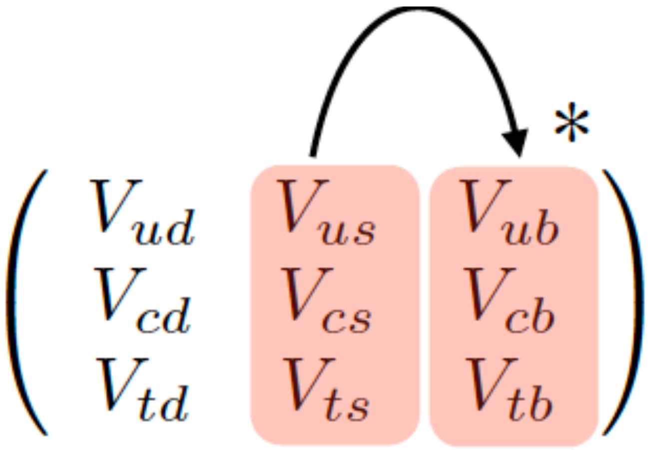

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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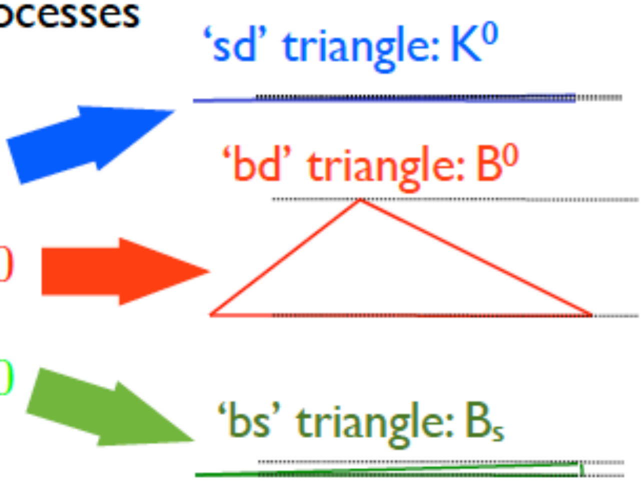
$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0 \qquad \mathcal{O}(\lambda^4) + \mathcal{O}(\lambda^2) + \mathcal{O}(\lambda^2) = 0$$



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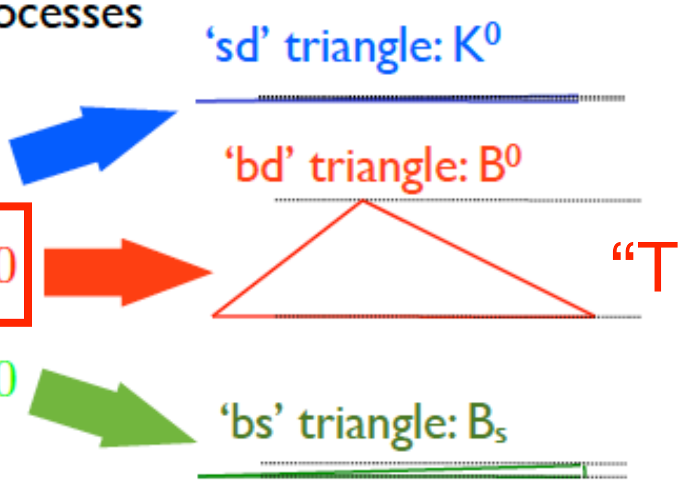


"The" unitarity triangle

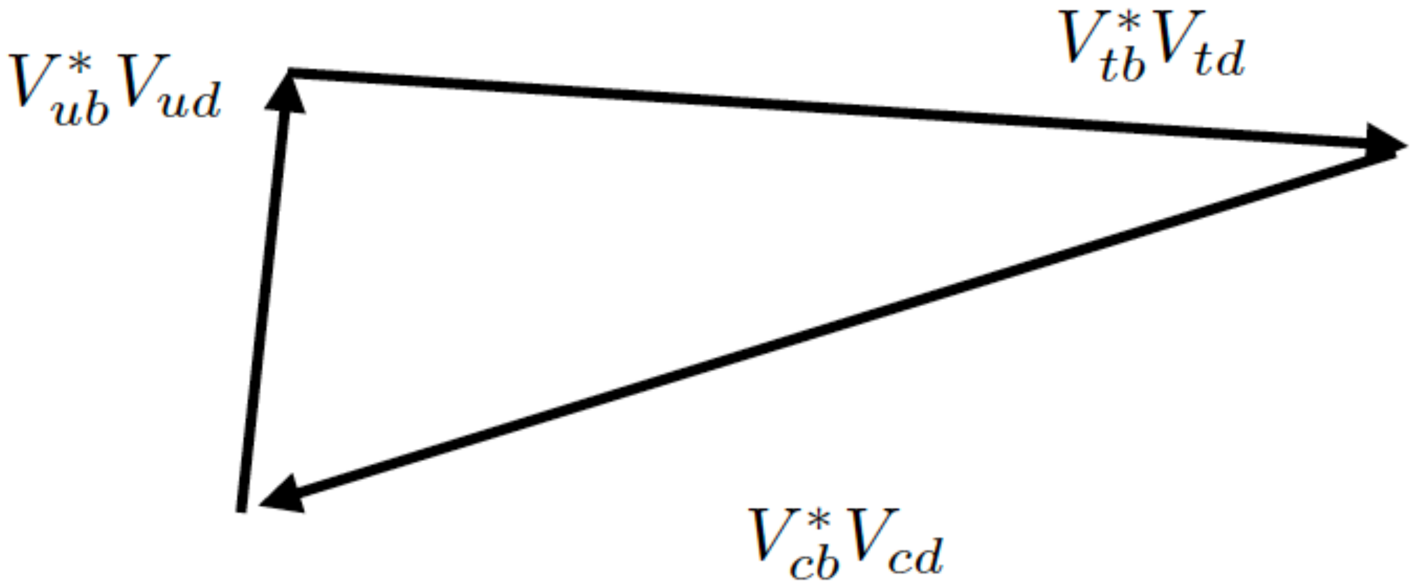
$$V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0$$

$$V_{ud} V_{td}^* + V_{us} V_{ts}^* + V_{ub} V_{tb}^* = 0$$

$$V_{cd} V_{td}^* + V_{cs} V_{ts}^* + V_{cb} V_{tb}^* = 0$$

“The” Unitarity Triangle

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



“The” Unitarity Triangle

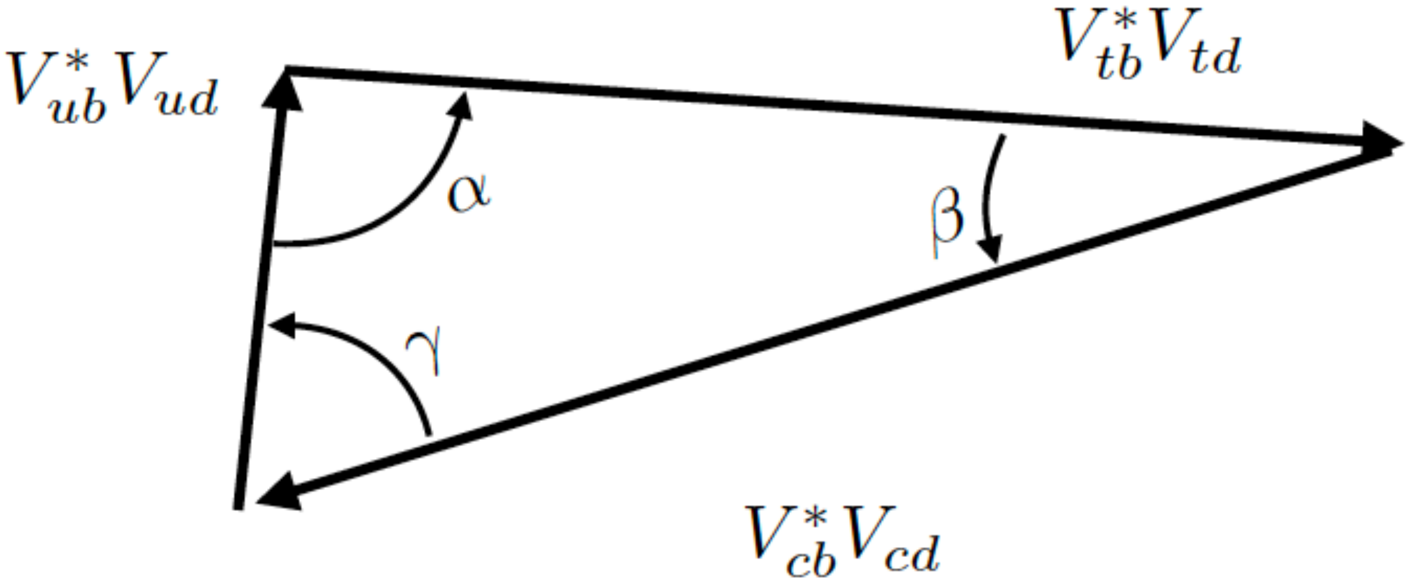
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- The internal angles are quark rephasing *independent* and *observable*

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$



“The” Unitarity Triangle

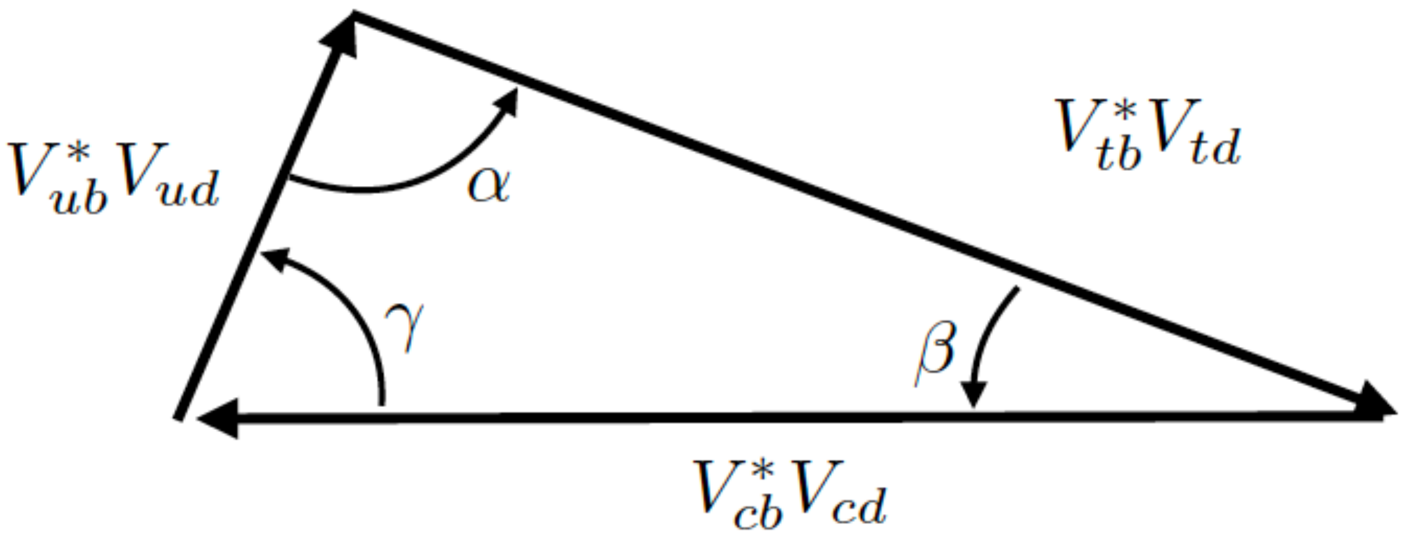
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- pick a quark phase convention such that $V_{cb}^* V_{cd}$ is real

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$



“The” Unitarity Triangle

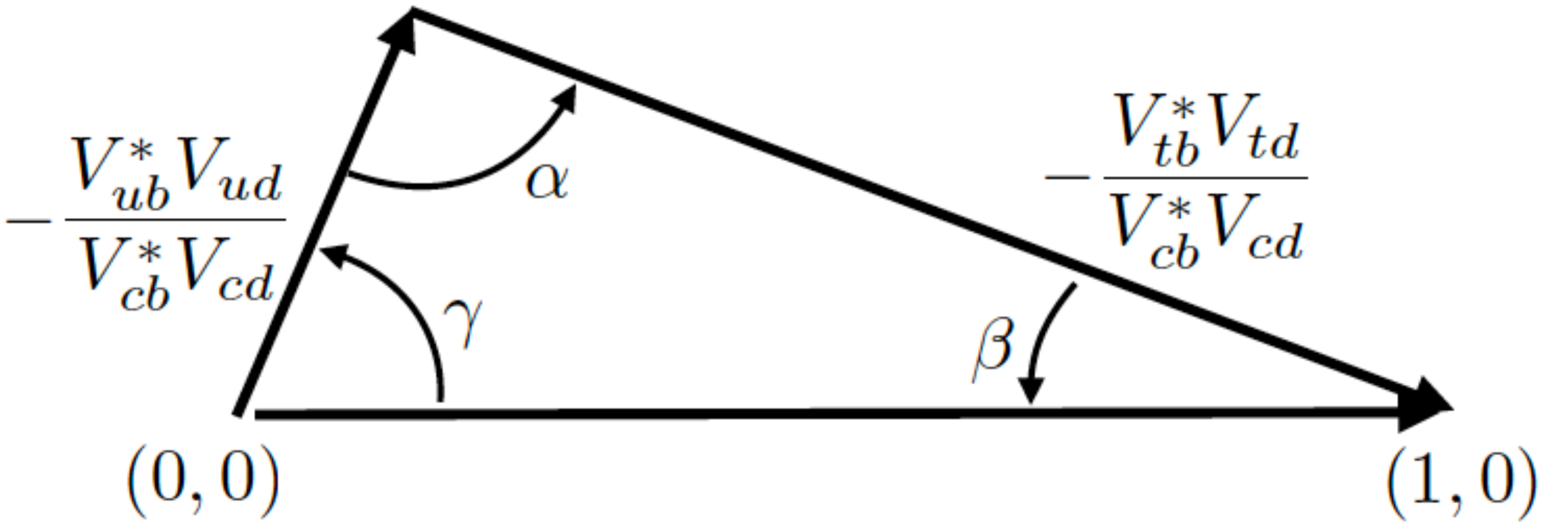
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- Normalize all sides by $-V_{cb}^* V_{cd}$

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$



this become of unit length

“The” Unitarity Triangle

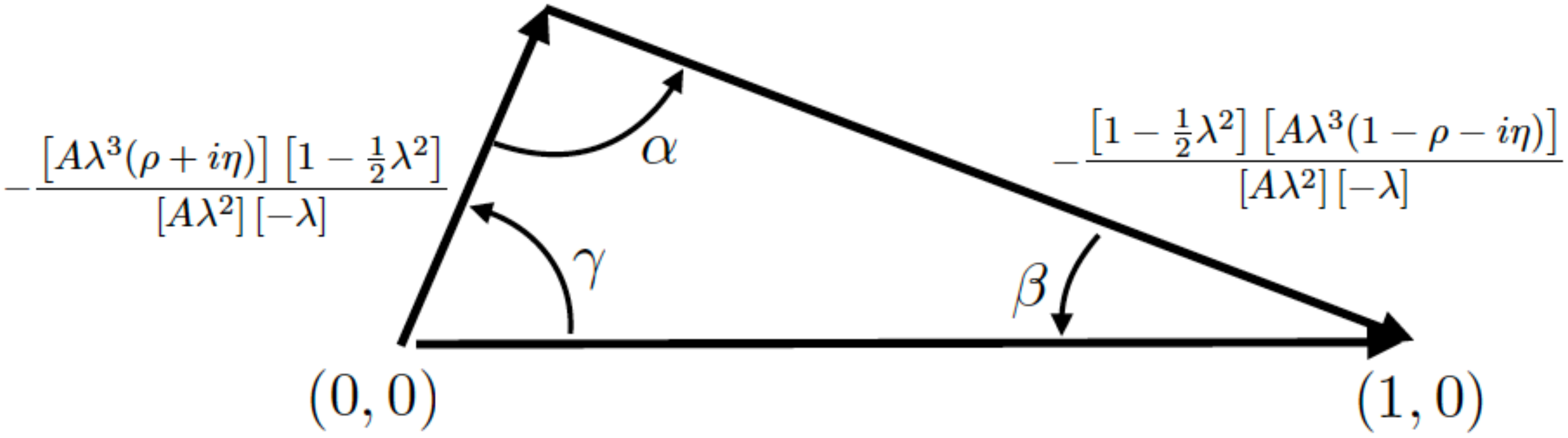
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- Put in the Wolfenstein parameterization of the V_{CKM} elements

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$



“The” Unitarity Triangle

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

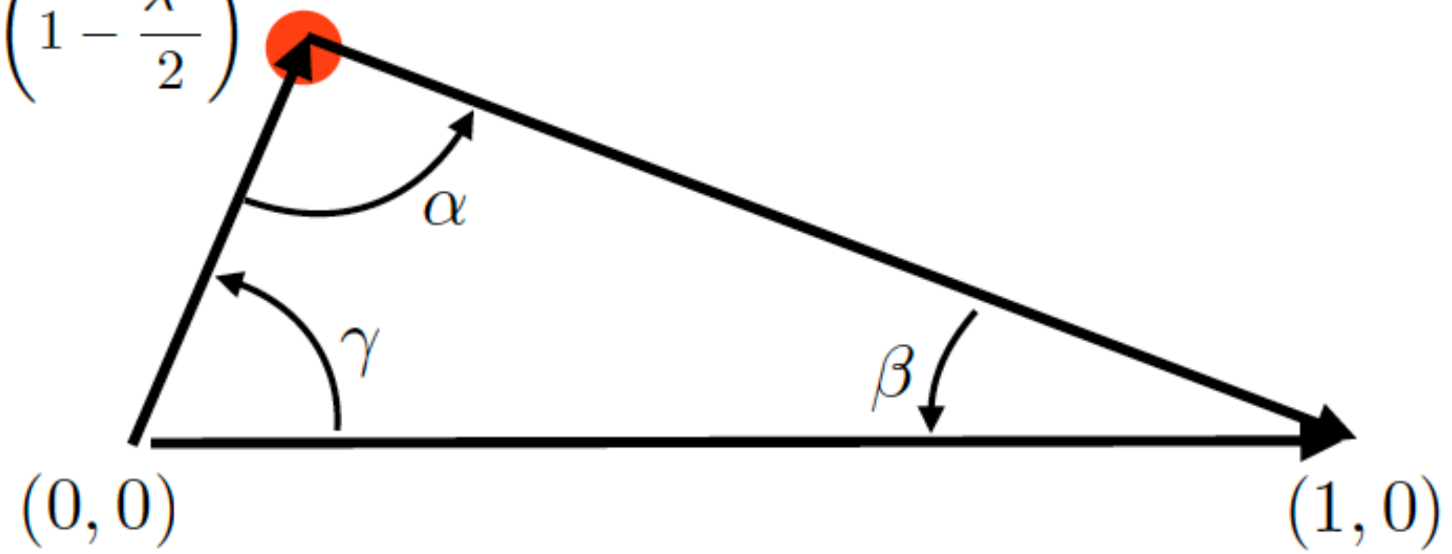
- And simplify…

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

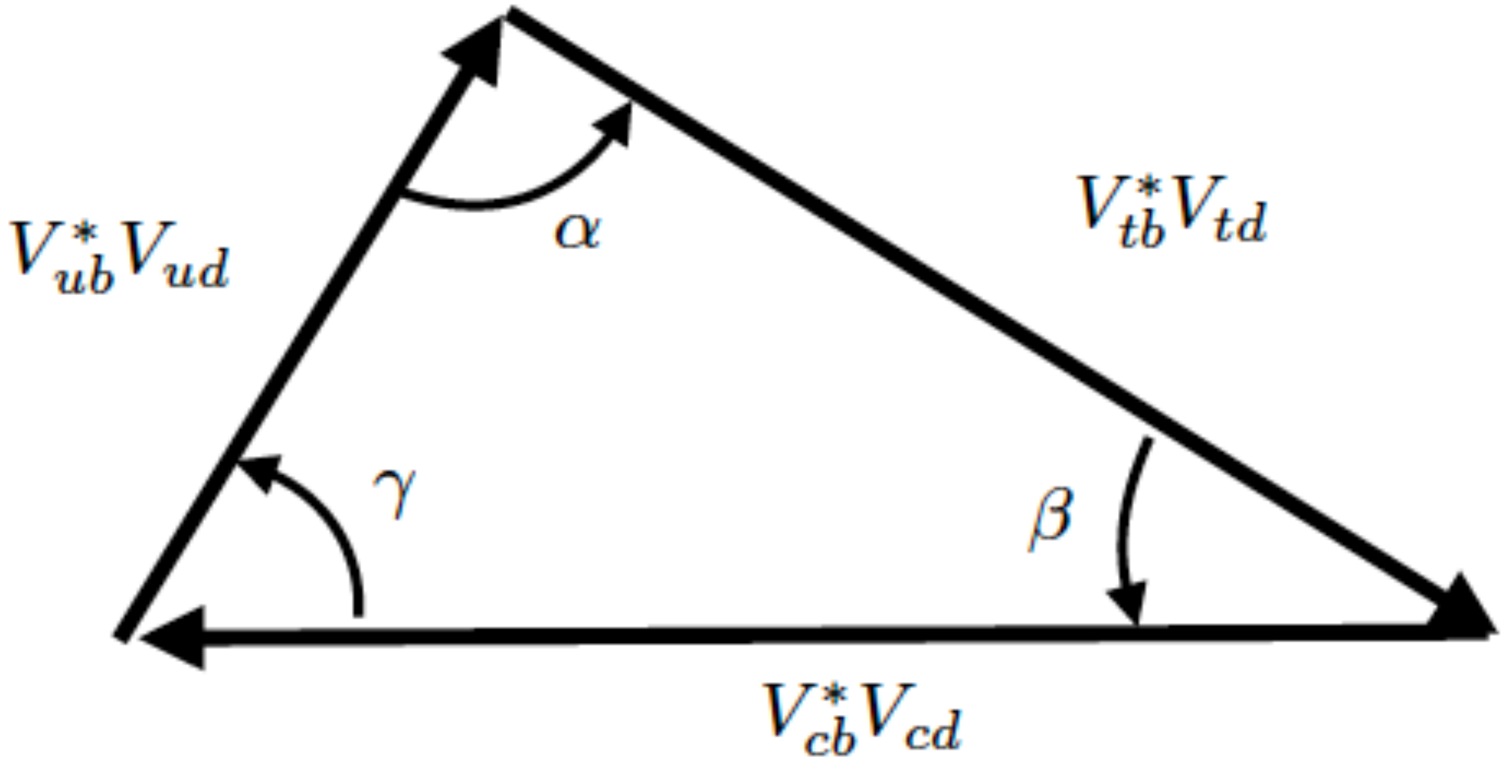
$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$

$$\overline{\rho} + i\overline{\eta} \equiv (\rho + i\eta)\left(1 - \frac{\lambda^2}{2}\right)$$

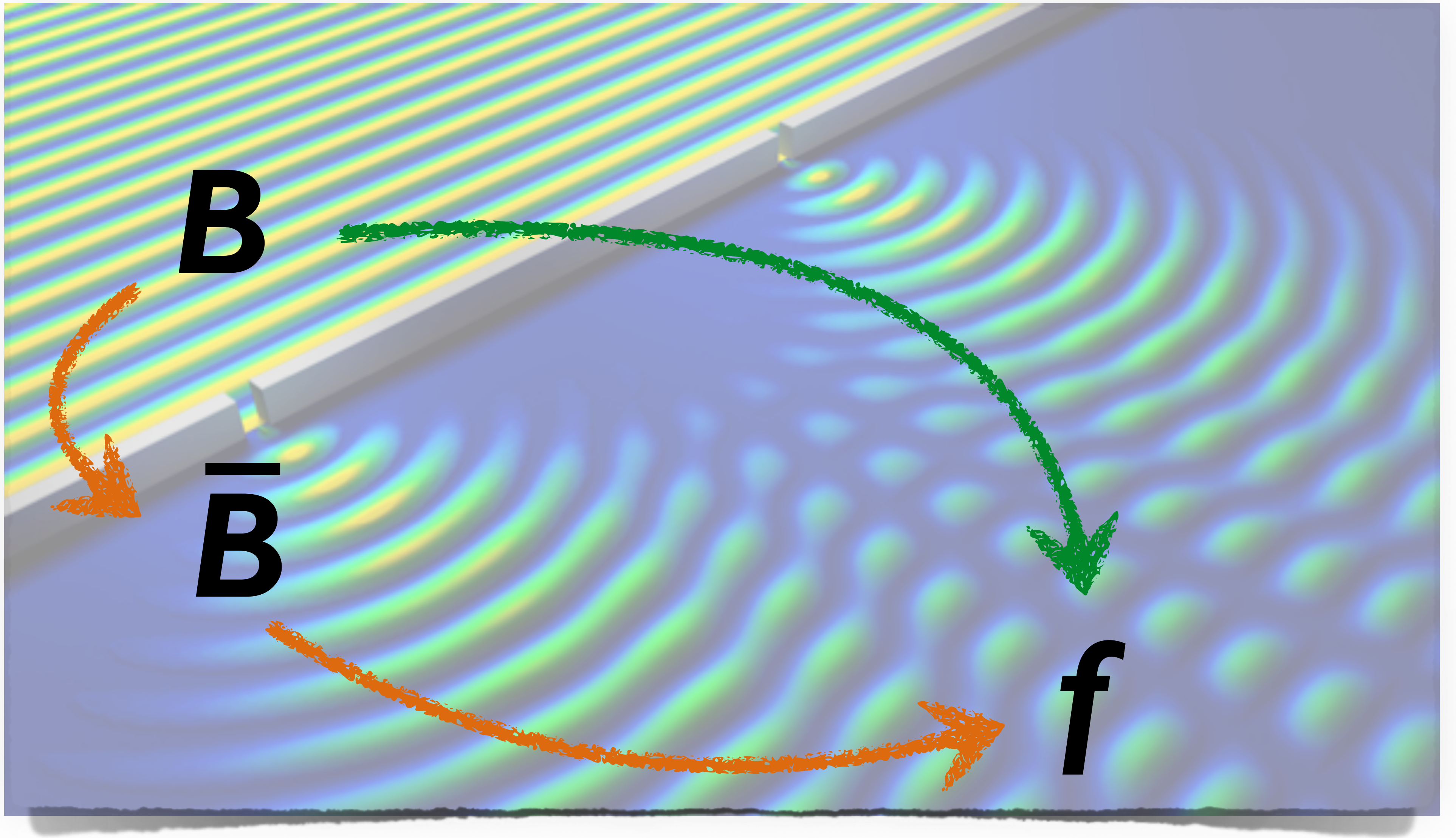


What about the angles?



- We've measured the sides, and have predictions for the angles,
- But how to measure the angles, i.e. phases?

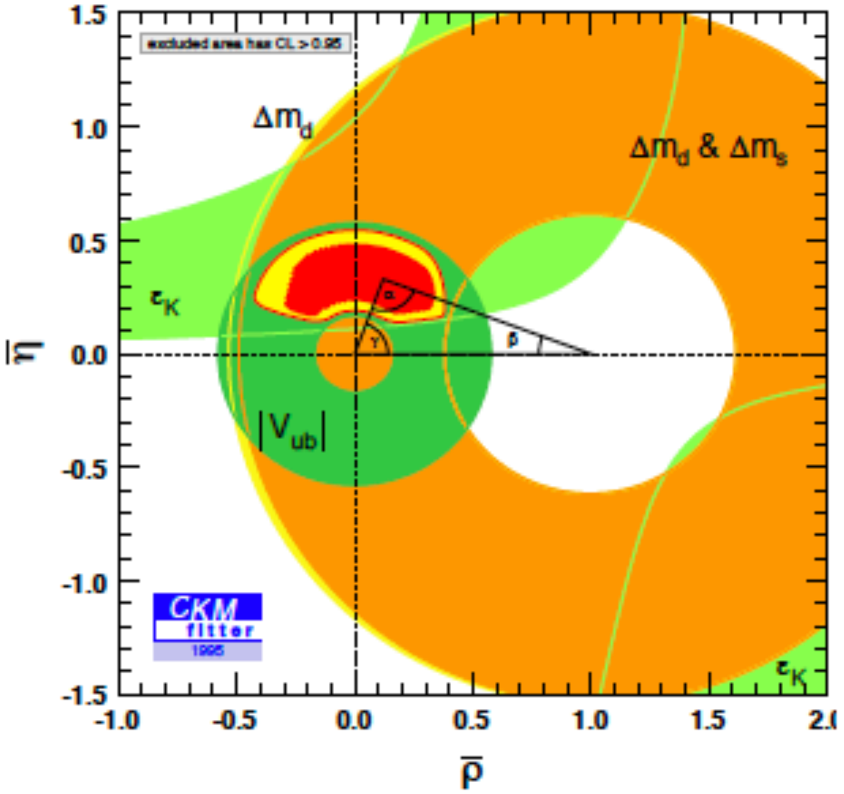
Interference



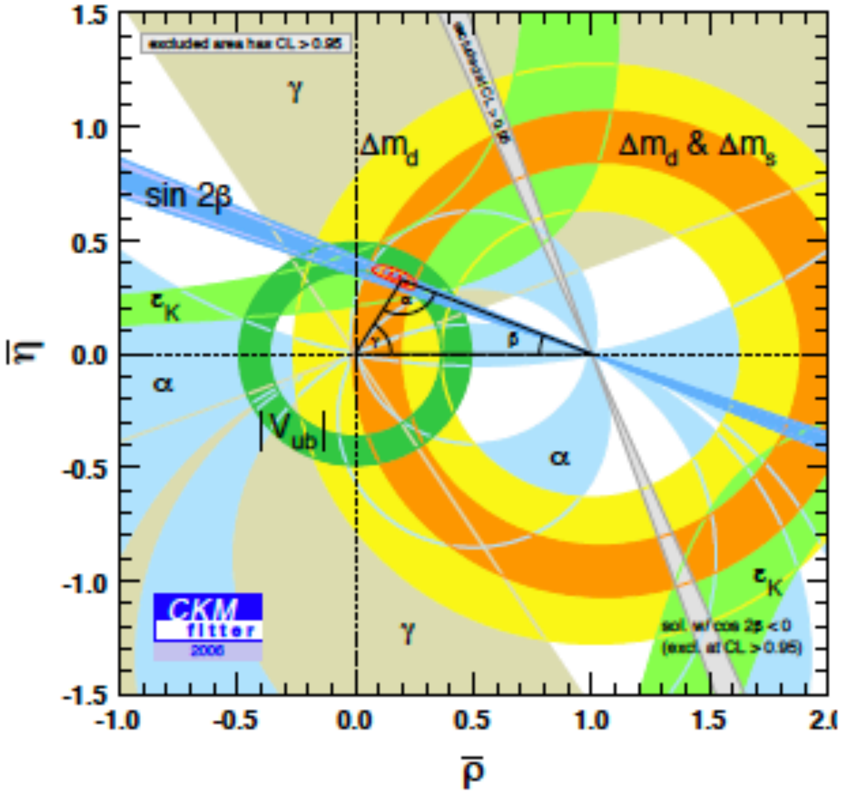
Won’t discuss phenomenological details of how measurements of interference probe each of the UT angles. Concept mirrors the Vij measurements: find processes where interference renders the measured quantity a simple function of the target UT angle. Implementation is more beautiful although a bit more technical/intricate (see PhD lectures linked at the end if interested)

A 25-year endeavor

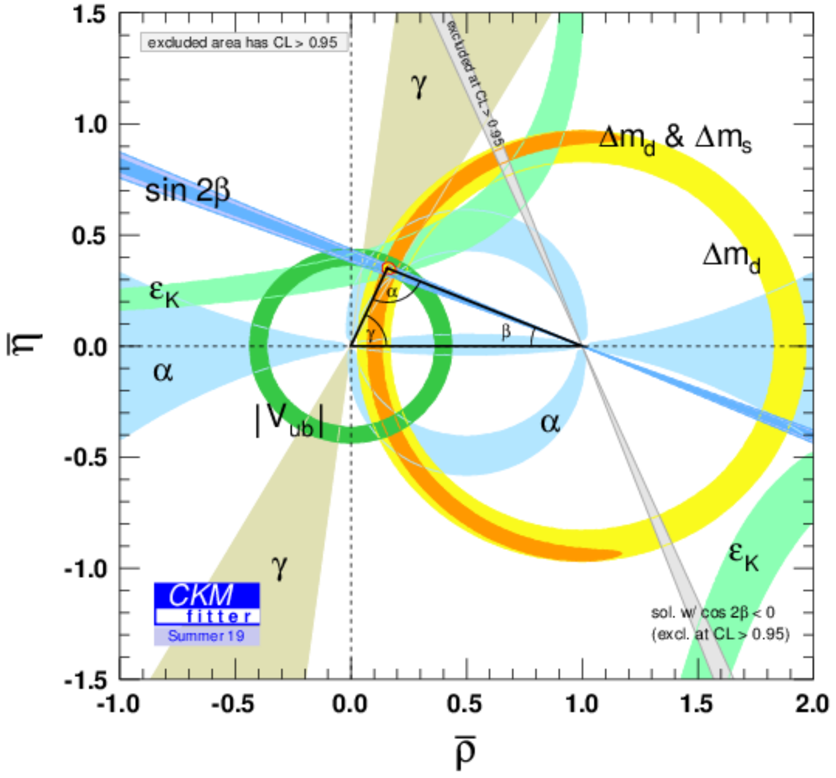
1995



2006



2019



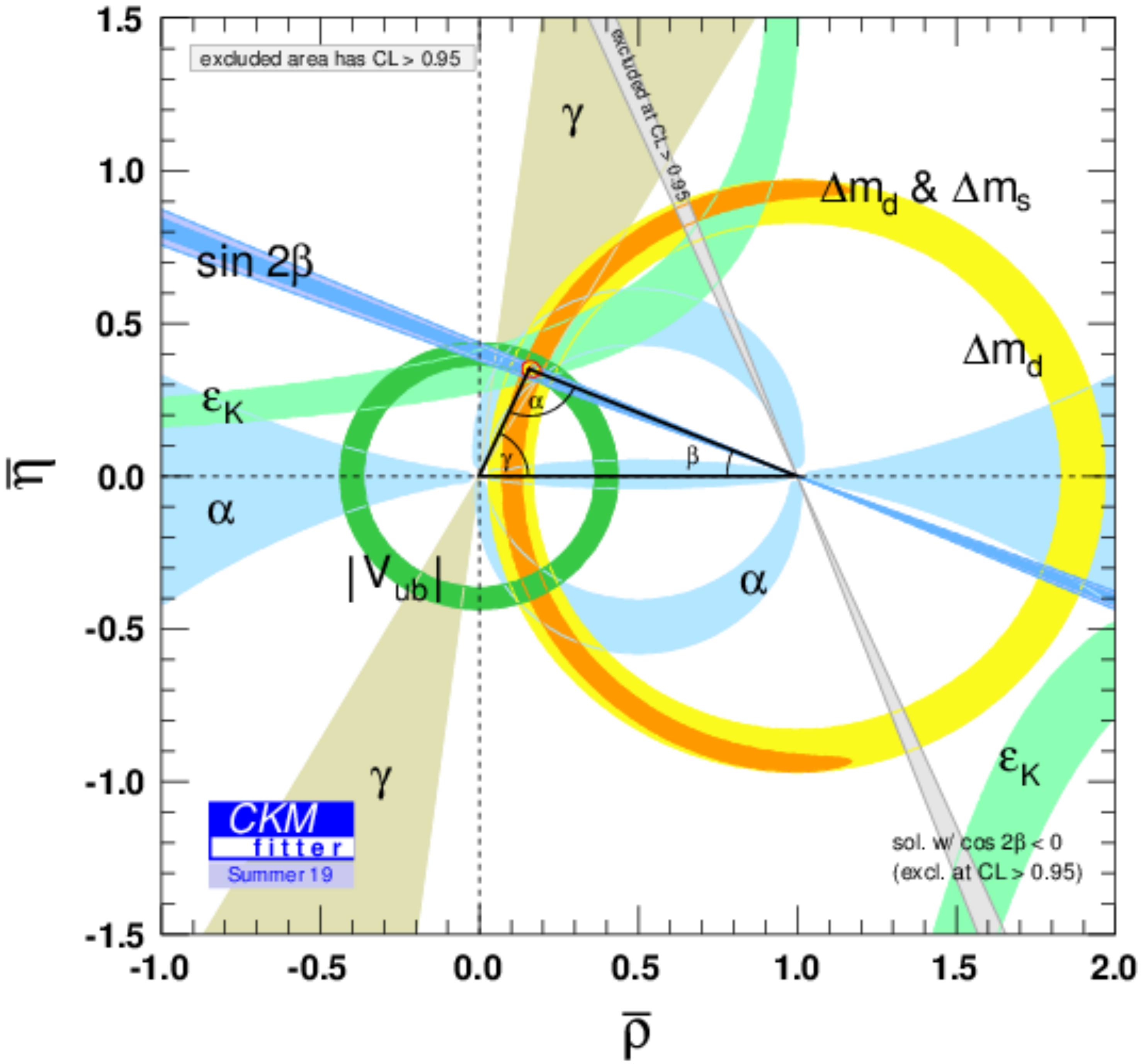
Exploitation of the data, plus plus theory advances, plus lattice-based calculations

Mission accomplished. Is it?

CKM is the leading source of CP violation in the standard model.

But this spectacular agreement still leaves 10-15% wiggle-room for non-SM contributions due to existing uncertainties.

The exciting thing is that these uncertainties are dominated by the experimental component — more work for us



Getting your hands dirty

At a glance…

Particles containing heavy quarks have 2–5 GeV masses and decay in 0.5–1.5 ps, which — combined with typical momenta (few GeV or more)— results in measurable (hundreds of microns) flight distances before decay.

Produce as many as possible in a controlled environment (typically 0.01–10 TeV particle collisions) surrounded by particle detectors — giant cameras sensitive shooting thousand to million times per second.

Produced particles evolve in time until decaying in lighter products that interact with the detector exciting electric signals. Reconstruction software processes these by combining them with geometric and kinematic constraints to reconstruct each *candidate* particle's trajectory, energy, etc.

Resulting 4-vectors are combined in kinematic fits to form decay-*candidates* of the channels more directly connected to the specific quantities we are targeting. Such candidates include background events, that are suppressed in downstream analysis.

You want (experimental requirements)

For a fruitful program in B and D physics — need to

- ☐ Produce large and low-background samples of B and D hadrons
- ☐ Reconstruct precisely many B and D decays with good S/B
- ☐ Reconstruct precisely B and D decay time
- ☐ Identify if a particle (B, D) or antiparticle (anti-B, anti-D) was produced
- ☐ Control precisely instrumental charge asymmetries

Large samples — production

After 40+ years of experiments with various facilities and techniques, the flavor community converged on two synergic approaches considered optimal in producing large samples of B and D hadrons:

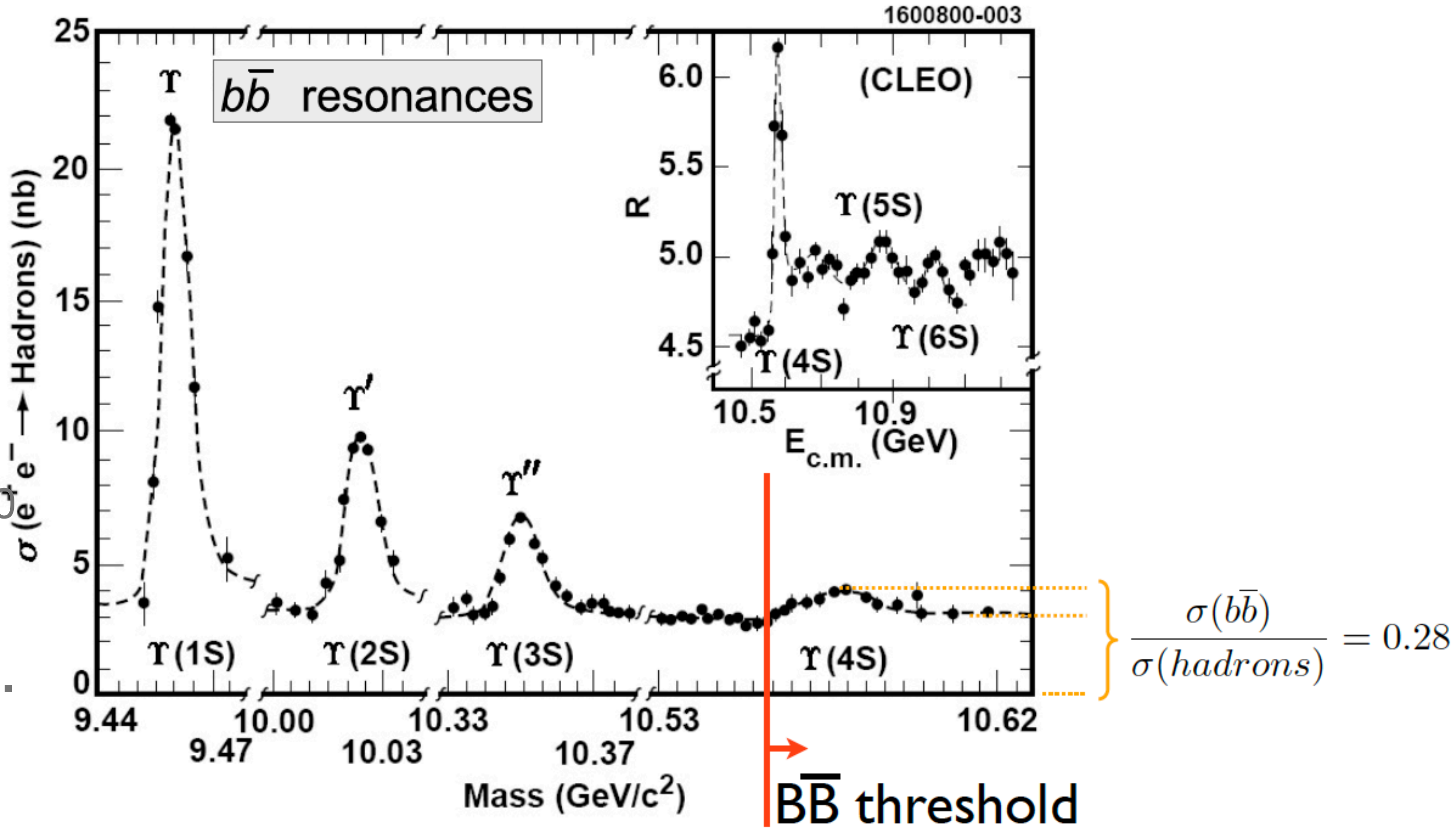
☐ Quantum-coherent pair-production of B mesons decayed from Y(4S) produced at threshold in energy-asymmetric electron-positron colliders.

☐ Incoherent QCD production of b-bbar pairs in high-energy hadron collisions (ppbar or pp)

Large samples — production at B factories

At~1 nb,Y(4S) makes up 30% of the x-section.

Y(4S) mass lies just above the B-Bbar kinematic threshold: 96% of Y(4S) decay strongly into B^0anti-B^0 or B^+B^- pairs (and nothing else — can't locate the production vertex).

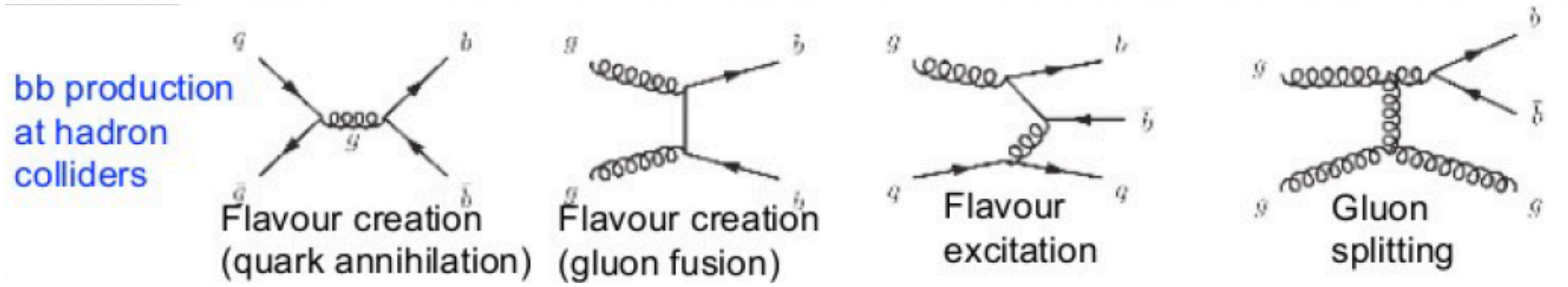


Coherence: Y(4S) is spin-1. B mesons are spin-0, hence L=1 (antisymmetric two-particle state) to conserve angular momentum. Simultaneous presence of two B or two Bbar forbidden as two identical bosons in an antisymmetric state violate Bose statistics. B and Bbar evolve as a particle-antiparticle pair until one decays.

Low-background production of 10-1000 BBbar pairs per second, which evolve coherently as particle-antiparticle until one decays. Production of B^0_s mesons and b-baryons is energetically forbidden

Large samples — production at hadron colliders

High-energy *pp* or $p\bar{p}$ collisions produce bottom (charm) hadrons with O(1-100) μb cross sections: 1000×–100000× higher than at $Y(4S)$. Cross-section enhanced in the “forward region” close to the beams.



Total inelastic *pp* or $p\bar{p}$ cross sections are O(1000) times higher, so production S/B is quite low, 1/1000, due to lots of light-quark background.

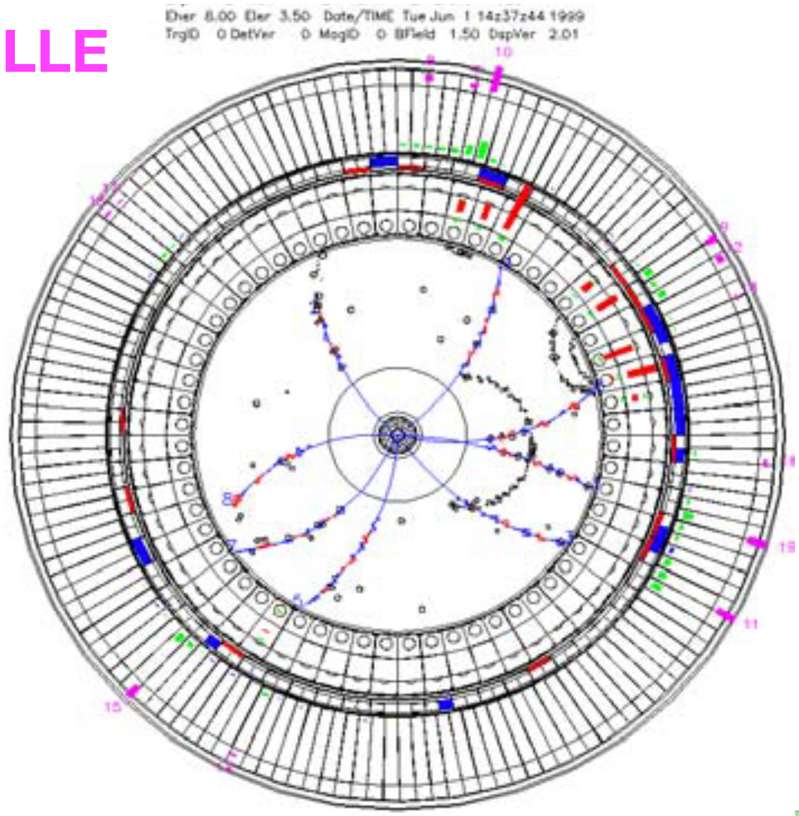
In addition, the composite nature of the colliding hadrons and the large extra energy available after the collision yields many particles that complicate signal identification and reconstruction (but allow locating the production vertex)

All kind of bottom hadrons (B^0_s, B^+_c, *b*-baryons) are produced.

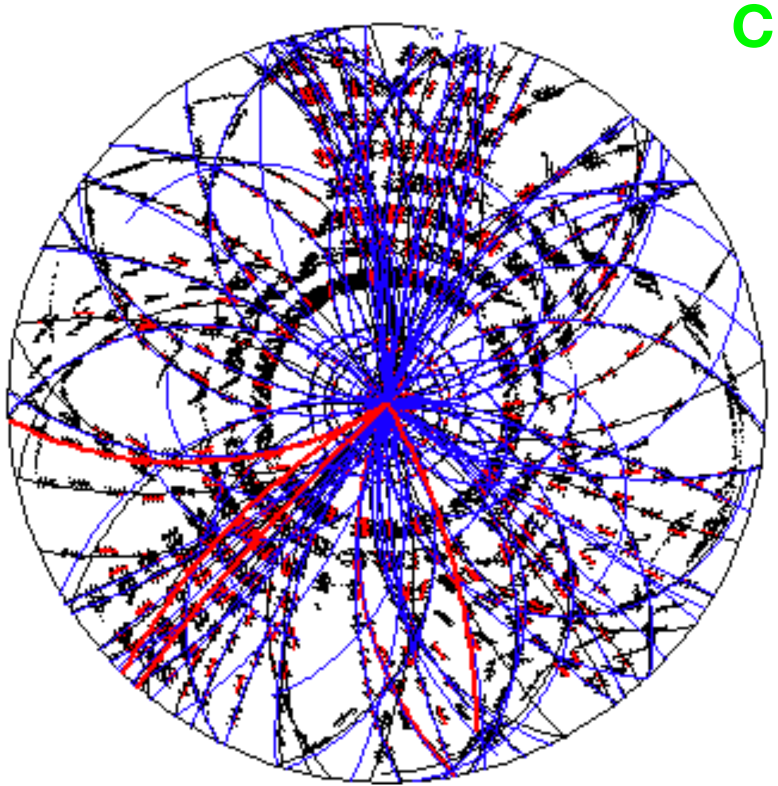
High-background, incoherent production of 10^5-10^6 *b*-hadrons (of any species) per second.

At a glance

BELLE



CDF



	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$ **PEP-II, KEK-B**	$p\bar{p} \to b\bar{b}X \quad (\sqrt{s} = 2\ \text{TeV})$ **TeVatron**	$pp \to b\bar{b}X \quad (\sqrt{s} = 14\ \text{TeV})$ **LHC**
prod	1 nb	~100 μb	~500 μb
typ. $b\bar{b}$ rate	10 Hz	~100 kHz	~500 kHz
purity	~1/4	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.2\%$	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.6\%$
pile-up	0	1.7	0.5-20
B content	$B^+B^-(50\%), B^0\bar{B}^0(50\%)$	$B^+(40\%), B^0(40\%), B_s(10\%), B_c(<1\%),\ \text{b}-\text{baryons}(10\%)$	
B boost	small, βγ~0.56	large, decay vertices are displaced	
event structure	BB pair alone	many particles non-associated to $b\bar{b}$	
prod. vertex	Not reconstructed	reconstructed with many tracks	
$B^0\bar{B}^0$ mixing	coherent	incoherent→ flavour tagging dilution	

You want (experimental requirements)

☑ Produce large and low-background samples of *B* and *D* hadrons

☐ Reconstruct precisely many *B* and *D* decays with good S/B

☐ Reconstruct precisely *B* and *D* decay time

☐ Identify if a particle (*B*, *D*) or antiparticle ($\bar{B}$, $\bar{D}$) was produced

☐ Control tightly instrumental charge asymmetries

Reconstruction — what exactly?

To design my detector, I first need to identify the leading final states.
Crude estimate of *B* decay rates (akin to *μ* decay corrected for |V$_{cb}$| and QCD)

Tree level only

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \underbrace{N_c f_{QCD}}_{\text{QCD}} \underbrace{f_{ps}}_{\text{phase space}}$$

Mode	N_c	f_{QCD}	f_{ps}	V_{xb}	$\mathcal{B}$
$c\bar{u}d'$	3	1.3	0.52	0.041	48.3%
$c\bar{c}s'$	3	1.3	0.25	0.041	23.2%
$ce\bar{\nu}_e$	1	1.0	0.52	0.041	12.1%
$c\mu\bar{\nu}_\mu$	1	1.0	0.52	0.041	12.1%
$c\tau\bar{\nu}_\tau$	1	1.0	0.13	0.041	3.0%

color favored

color suppressed

Reconstruction — what exactly?

To design my detector, I first need to identify the leading final states.
Crude estimate of *B* decay rates (akin to *μ* decay corrected for $|V_{cb}|$ and QCD).

Tree level only

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \underbrace{N_c f_{QCD}}_{\text{QCD}} \underbrace{f_{ps}}_{\text{phase space}}$$

	Mode	N_c	f_{QCD}	f_{ps}	V_{xb}	$\mathcal{B}$	
✓	$c\bar{u}d'$	3	1.3	0.52	0.041	48.3%	**E.g., $B^0 \to D^-(\to K\pi\pi)\pi^+$, fully reconstructable in all tracks**
✓ ✓	$c\bar{c}s'$	3	1.3	0.25	0.041	23.2%	**E.g, $B^0 \to \psi(\to\mu\mu)K^0(\to\pi\pi)$ fully reconstructable in tracks and μ or e**
✓	$ce\bar{\nu}_e$	1	1.0	0.52	0.041	12.1%	**E.g, $B^0 \to D^-(\to K\pi\pi)e^+\nu$ partially reconstructable with e**
✓ ✓	$c\mu\bar{\nu}_\mu$	1	1.0	0.52	0.041	12.1%	**E.g, $B^0 \to D^-(\to K\pi\pi)\mu^+\nu$ partially reconstructable with μ**
✓	$c\tau\bar{\nu}_\tau$	1	1.0	0.13	0.041	3.0%	**E.g, $B^0 \to D^-(\to K\pi\pi)\tau^+\nu$ partially reconstructable with τ**

Reconstruction — what exactly?

To design my detector, I first need to identify the leading final states.
Crude estimate of *B* decay rates (akin to *μ* decay corrected for $|V_{cb}|$ and QCD)

Tree level only

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 N_c f_{QCD} f_{ps}$$

QCD

phase space

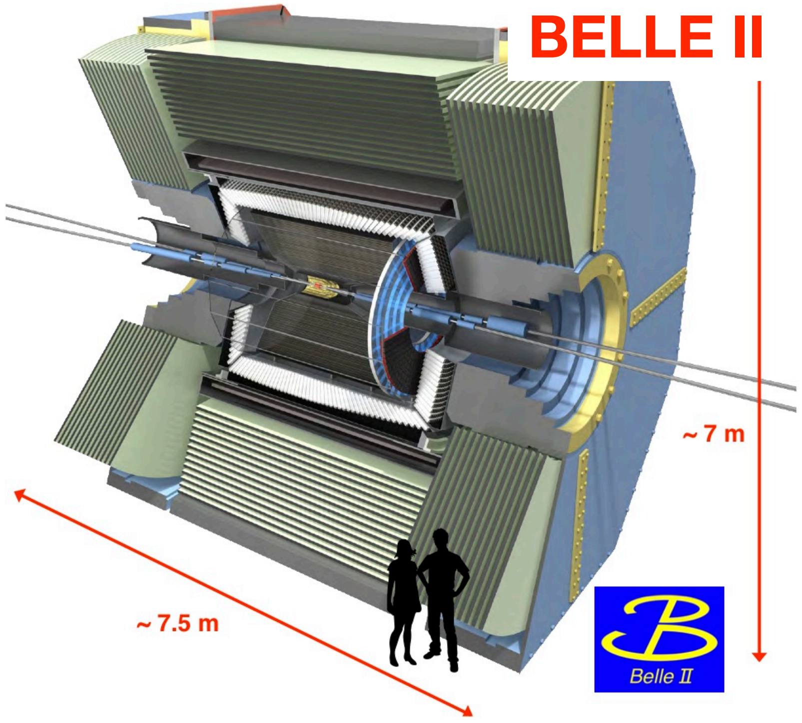
	Mode	N_c	f_{QCD}	f_{ps}	V_{xb}	$\mathcal{B}$	
✓	$c\bar{u}d'$	3	1.3	0.52	0.041	48.3%	**E.g., $B^0\to D^-(\to K\pi\pi)\pi^+$, fully reconstructable in all tracks**
✓ ✓	$c\bar{c}s'$	3	1.3	0.25	0.041	23.2%	**E.g, $B^0\to \psi(\to\mu\mu)K^0(\to\pi\pi)$ fully reconstructable in tracks and μ or e**
✓	$ce\bar{\nu}_e$	1	1.0	0.52	0.041	12.1%	**E.g, $B^0\to D^-(\to K\pi\pi)e^+\nu$ partially reconstructable with e**
✓ ✓	$c\mu\bar{\nu}_\mu$	1	1.0	0.52	0.041	12.1%	**E.g, $B^0\to D^-(\to K\pi\pi)\mu^+\nu$ partially reconstructable with μ**
✓	$c\tau\bar{\nu}_\tau$	1	1.0	0.13	0.041	3.0%	**E.g, $B^0\to D^-(\to K\pi\pi)\tau^+\nu$ partially reconstructable with τ**

Second, identify the discriminating signatures. b quark is heavy and long lived: hence, tracks and leptons are stiffer than from light-quarks and displaced from the production vertex. Need for strong tracking.

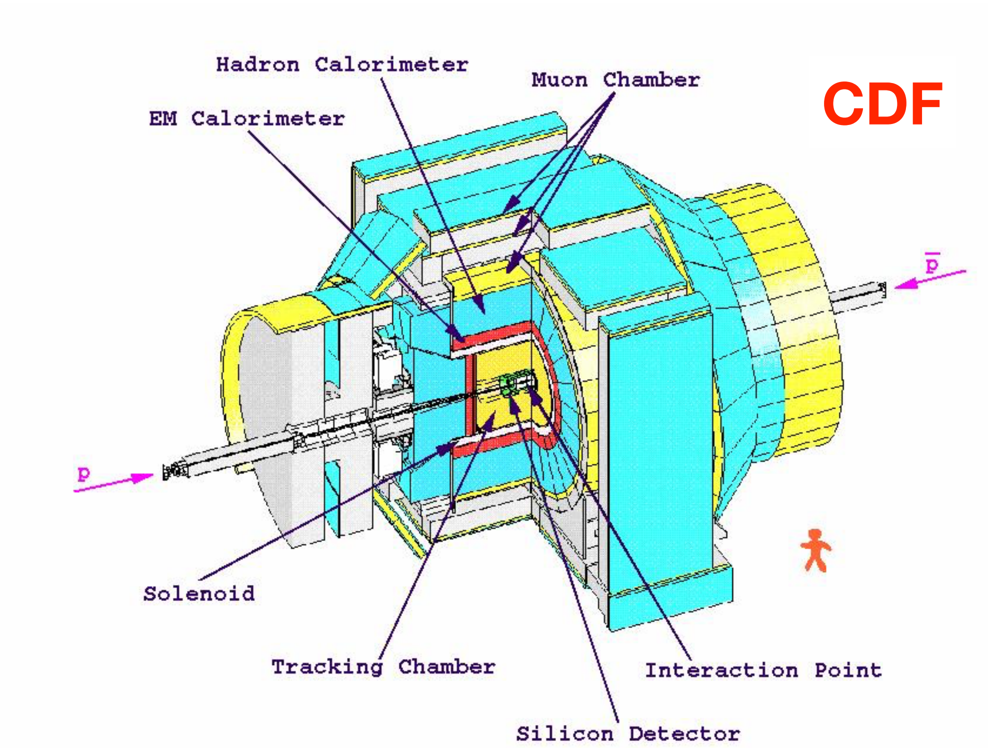
Many different particles in final states — need some PID.

Reconstruction — detector coverage

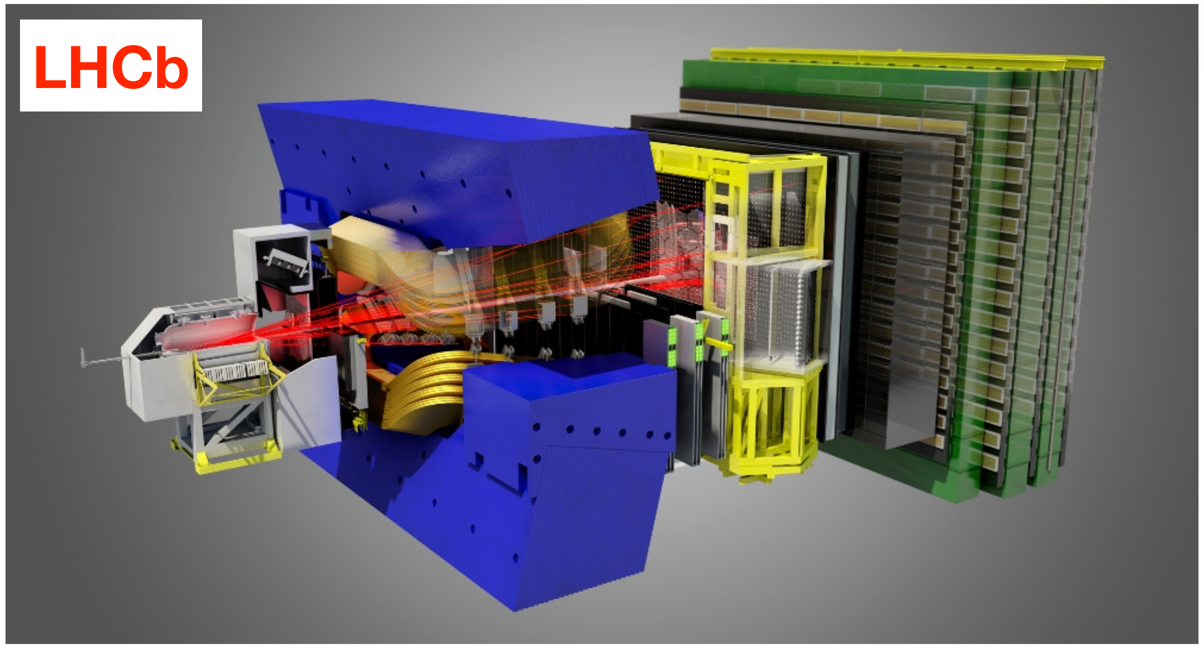
First requirement is obviously to instrument the volume surrounding the interaction region where *B/D* hadrons fly and decay and so do their decay products



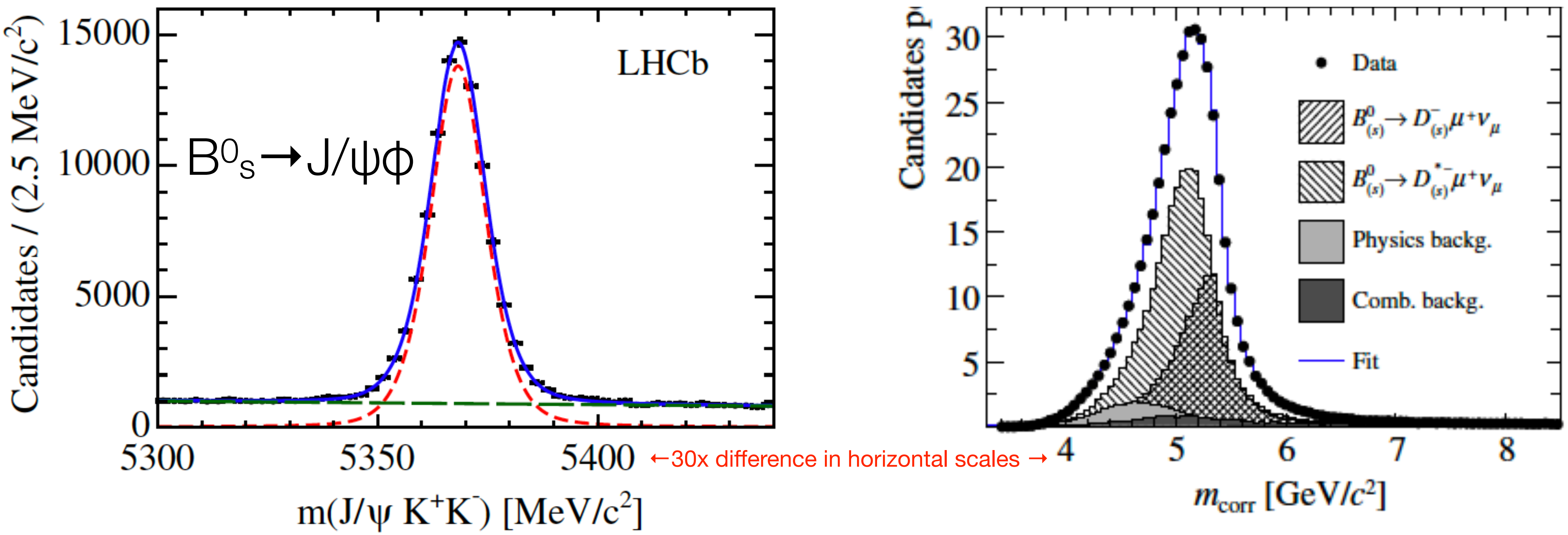
Classic: barrel-shaped solenoidal magnetic spectrometers



Novel concept: single-arm forward spectrometer. Exploits larger forward HF cross section, but gives up to all HF produced “on the other side”



Partially vs fully reconstructed



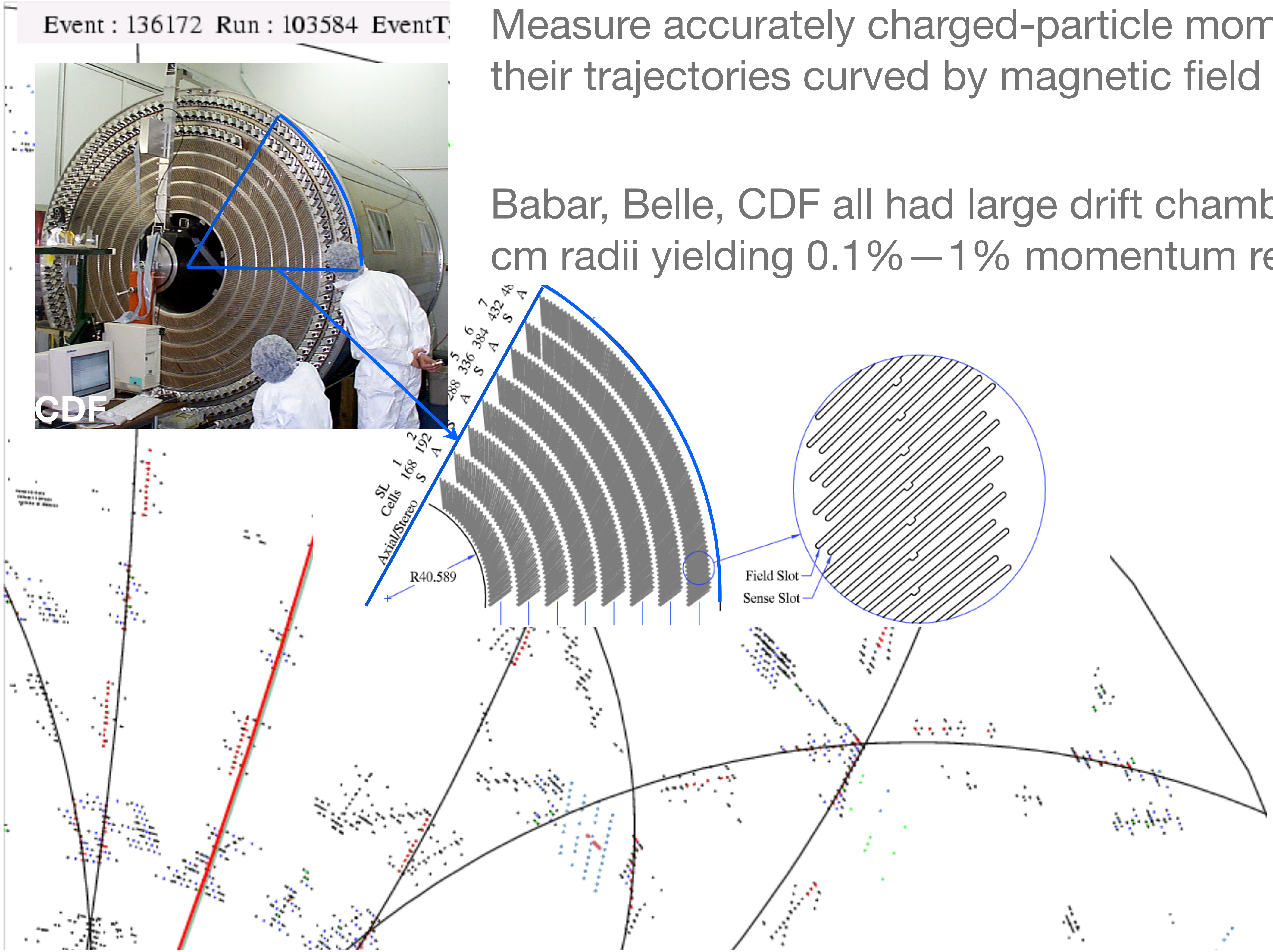
Fully reconstructed *B⁰ₛ*. Narrow prominent peak over a smooth background.

Partially reco'd *B⁰ₛ*. Open kinematics due to ν broadens peak (40x), which overlaps backgrounds. Incomplete *B⁰ₛ* momentum prevents from unbiased reconstruction of decay time. At *B* factories, beam-energy constraints partially mitigate these shortcomings

Tracking

Measure accurately charged-particle momenta by sampling their trajectories curved by magnetic field along large radii.

Babar, Belle, CDF all had large drift chambers at 50 —150 cm radii yielding 0.1%—1% momentum resolutions.

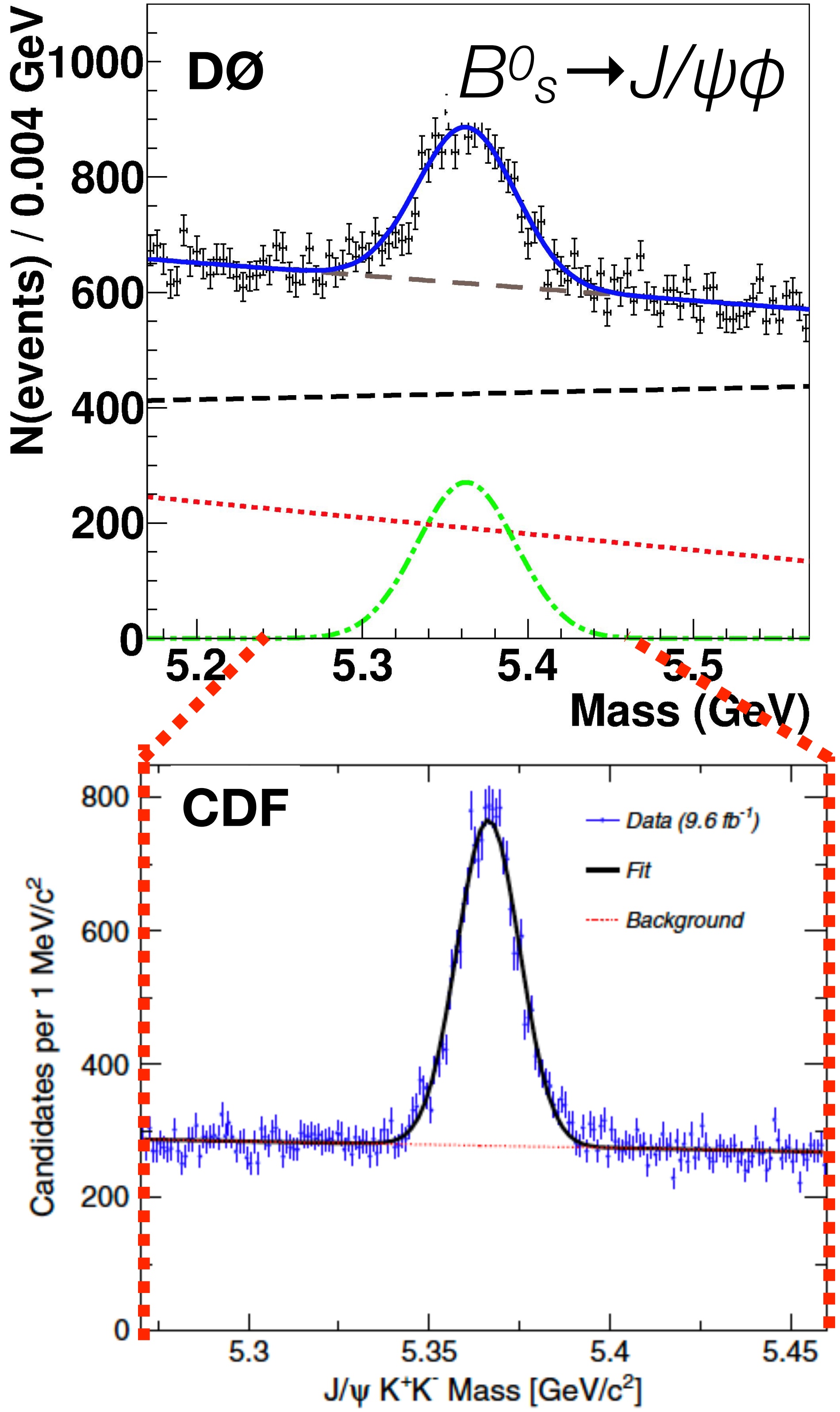


The difference good tracking makes

Strong tracking yields narrower fully reconstructed signals resulting in better S/B.

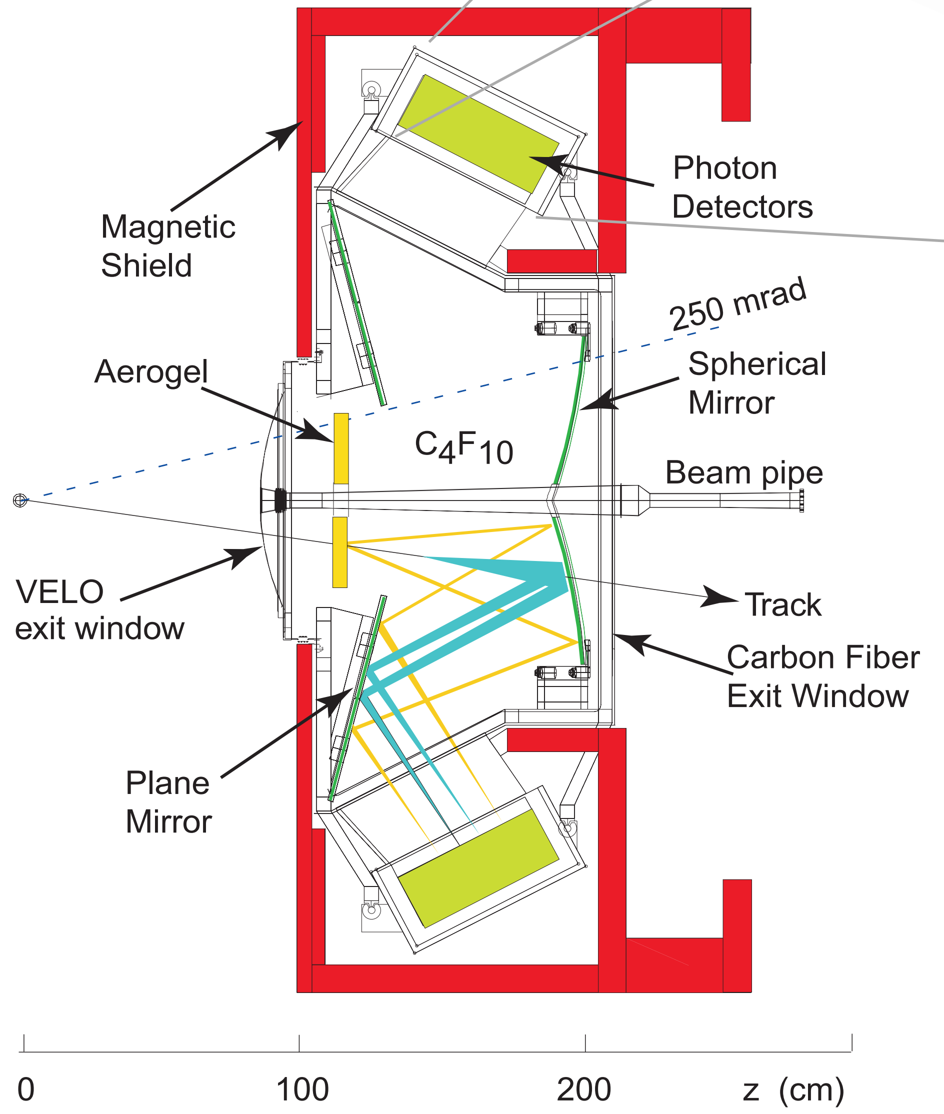
What is lost in tracking performance is hard to recover down the line using other detector or data analysis performances.

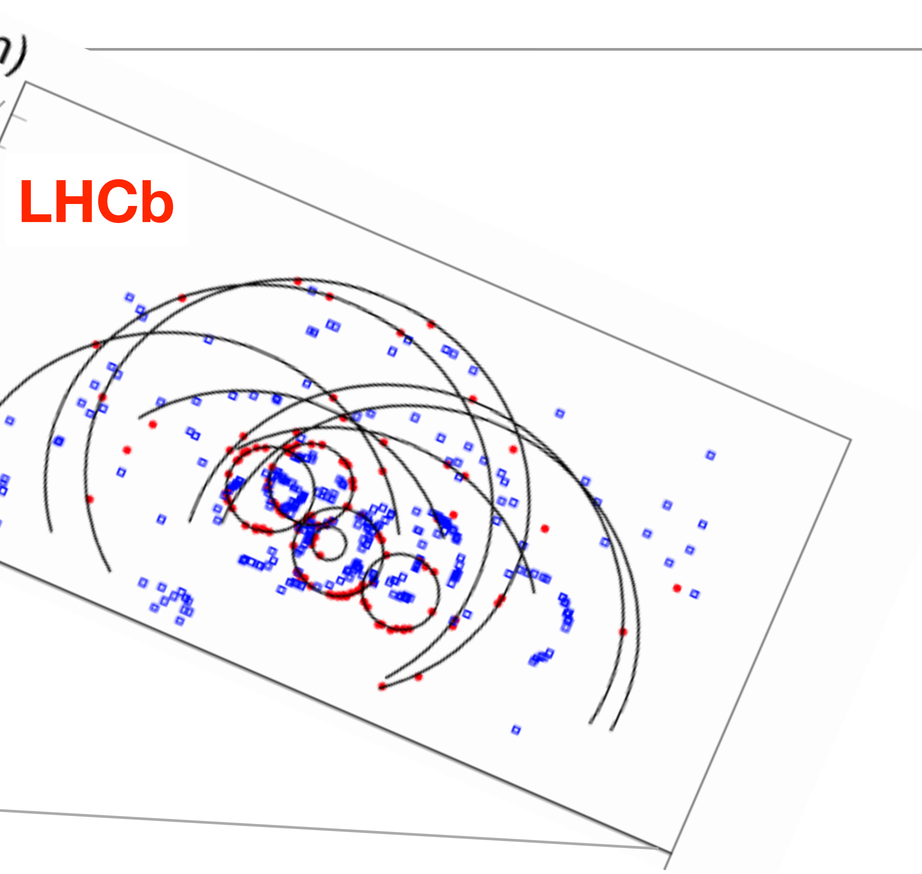
That is why DØ flavor has typically been second to CDF, and — similarly — ATLAS Run I flavor is less competitive than CMS's.



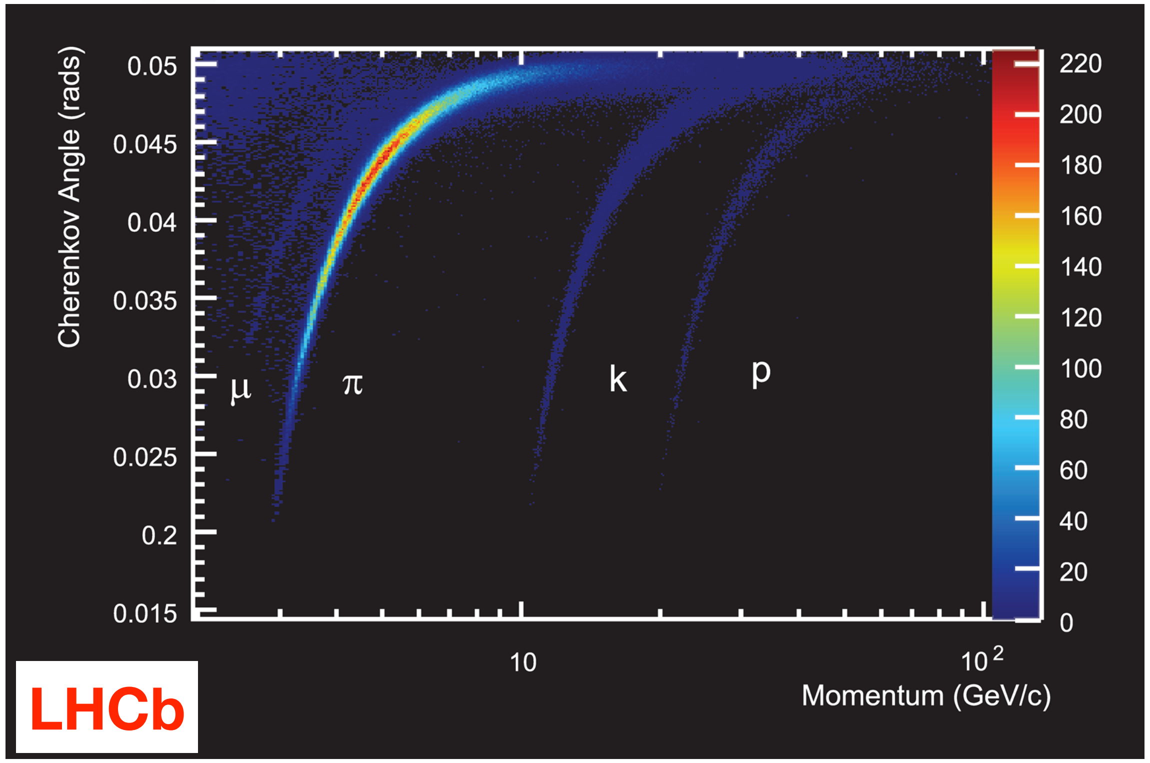
Hadron identification

Charged hadrons require dedicated systems

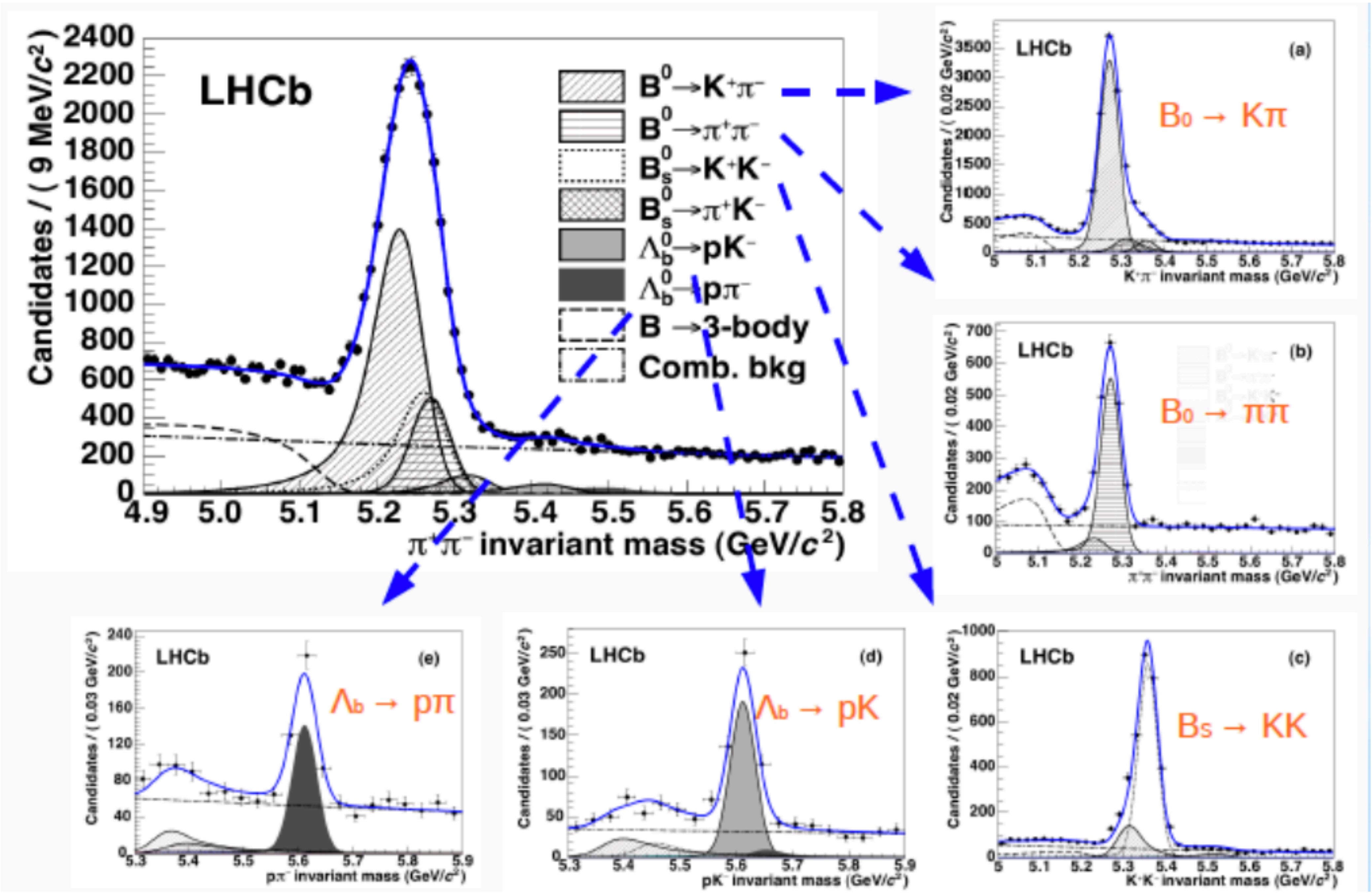




Systems based on Cherenkov radiation (BaBar, Belle, LHCb) offer best performance *K/π* separation > 5σ over a wide range in momentum



The difference good PID makes



Dedicated hadron PID can be a key performance driver in many channels where multiple similar signals overlap to each other.

You want (experimental requirements)

- ☑ Produce large and low-background samples of B and D hadrons
- ☑ Reconstruct precisely many B and D decays with good S/B
- ☐ Reconstruct precisely B and D decay time
- ☐ Identify if a particle (B, D) or antiparticle ($\bar{B}$, $\bar{D}$) was produced
- ☐ Control tightly instrumental charge asymmetries

You want (experimental requirements)

- ☑ Produce large and low-background samples of *B* and *D* hadrons
- ☑ Reconstruct precisely many *B* and *D* decays with good S/B
  - ☐ Do it online!
- ☐ Reconstruct precisely *B* and *D* decay time
- ☐ Identify if a particle (*B*, *D*) or antiparticle ($\bar{B}$, $\bar{D}$) was produced
- ☐ Control tightly instrumental charge asymmetries

Online event selection

Depending on digitized-event size and complexity, current DAQ systems cannot write kB/MB-sized events at more than O(10) kHz

Not critical at *B*-factories — crossing rate is very high (MHz to GHz), but the interesting interactions are a small, and very distinctive fraction of the total collisions. In addition, detector activity following an interaction is also low (10 tracks/event), which makes it easier to process it fast by trigger algorithms. Typically, requiring a few tracks and energy deposits in a collision is sufficent to trigger flavor physics with >95% efficiency.

Effective triggering is absolutely essential in hadron collisions: MHz crossing rate with multiple interactions per crossing, each yielding O(10-100) tracks. High rates and massive combinatorial problem call for maximally parallel fast processing.

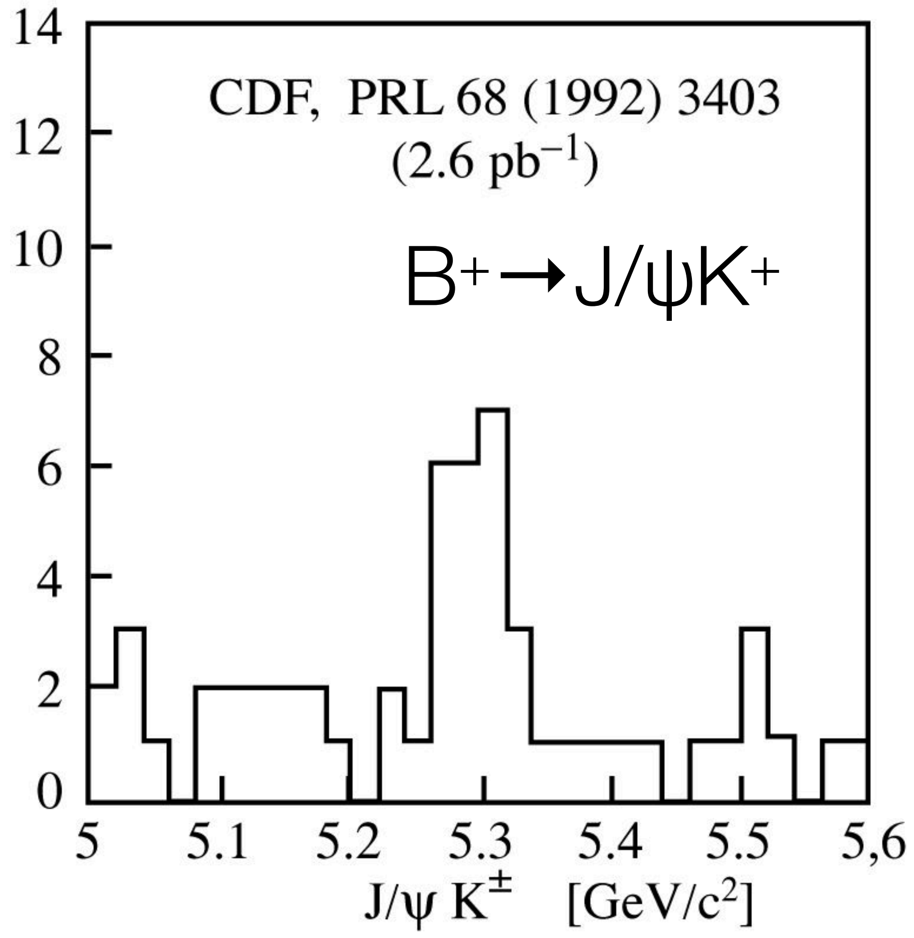
Online selection — good ole muons..

Muons have a striking signature: charged particles that penetrate thick absorbers offering distinctive features wrt generic (mostly π) track backgrounds.

Thicker absorber reduces π punch-through but impacts kinematic acceptance: the purer the μ, the fewer.

Dimuons (from $B \rightarrow \psi X$) are best: low trigger rate, double discriminating information, and $\mu\mu$-mass restrictions around ψ further suppress background.

Electrons also distinctive, but radiate a lot.

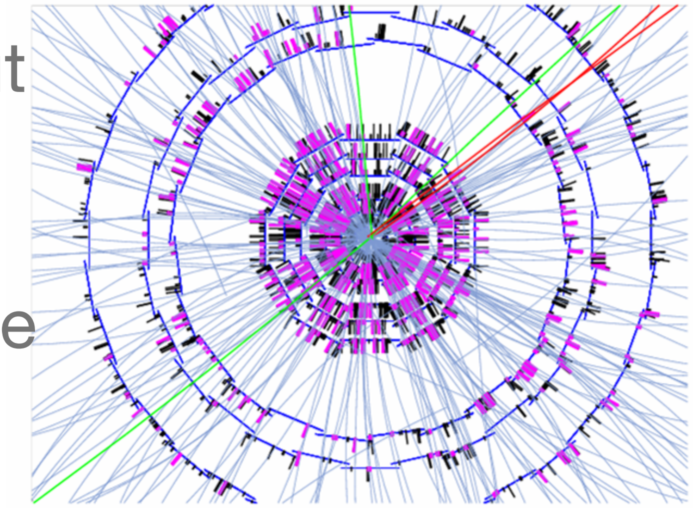


1992: first fully reconstructed *B* decay in hadron collisions — largest sample at the time: competitive *B* physics at hadron colliders is possible!

Muon triggers have been the traditional triggering workhorse for flavor physics at hadron colliders (CDF, D0, LHCb, CMS, ATLAS…). Cannot do hadronic decays.

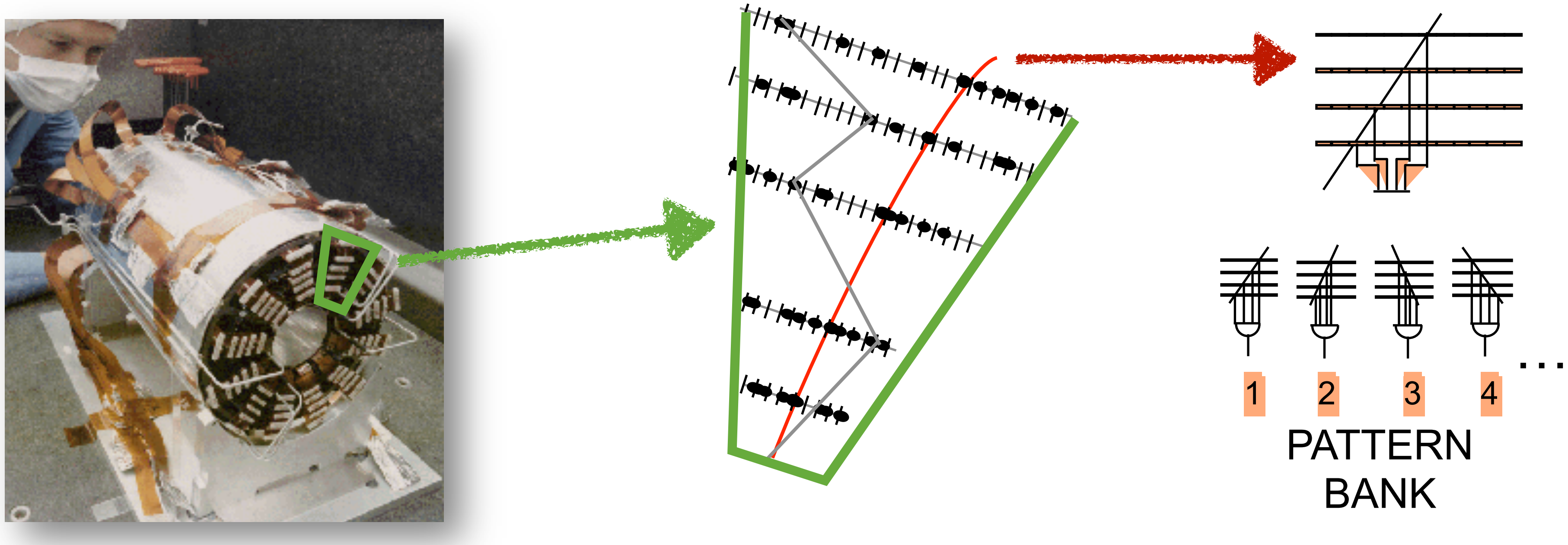
Triggering on displaced tracks

Displaced tracks allow widening significantly the breadth of triggered channels.



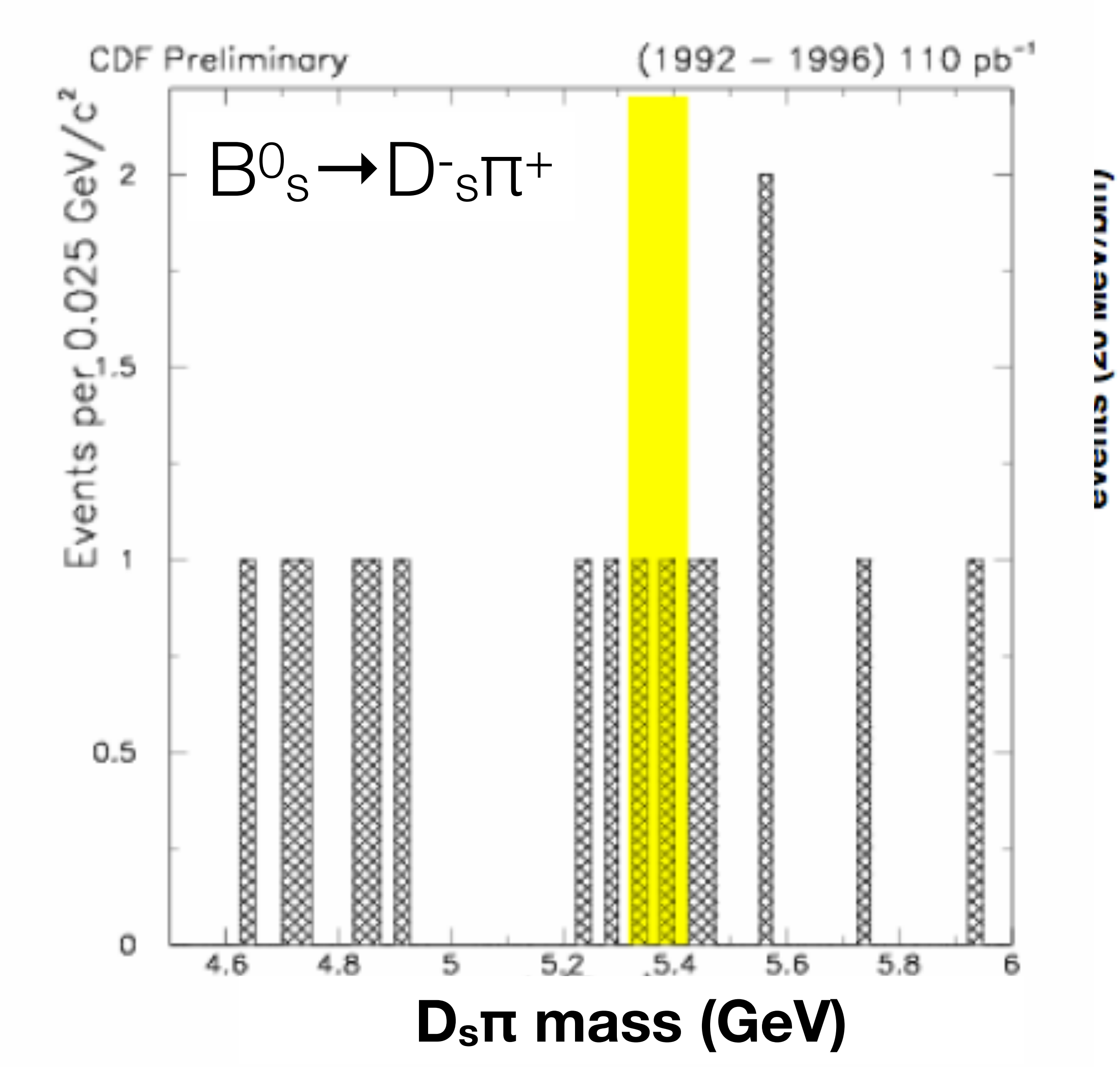
But online tracking poses a formidable challenge: read-out O(10k-1M) silicon channels to reconstruct in real time O(10-100) tracks, each leaving 5-20 hits. A daunting combinatorial task — need smart algorithms that maximize parallelism in fast electronics.

Pattern-matching implemented on custom chip: compare silicon hit coordinates in parallel with a previously stored set of possible sequences of hits corresponding to genuine tracks — the revolutionary associative memory.

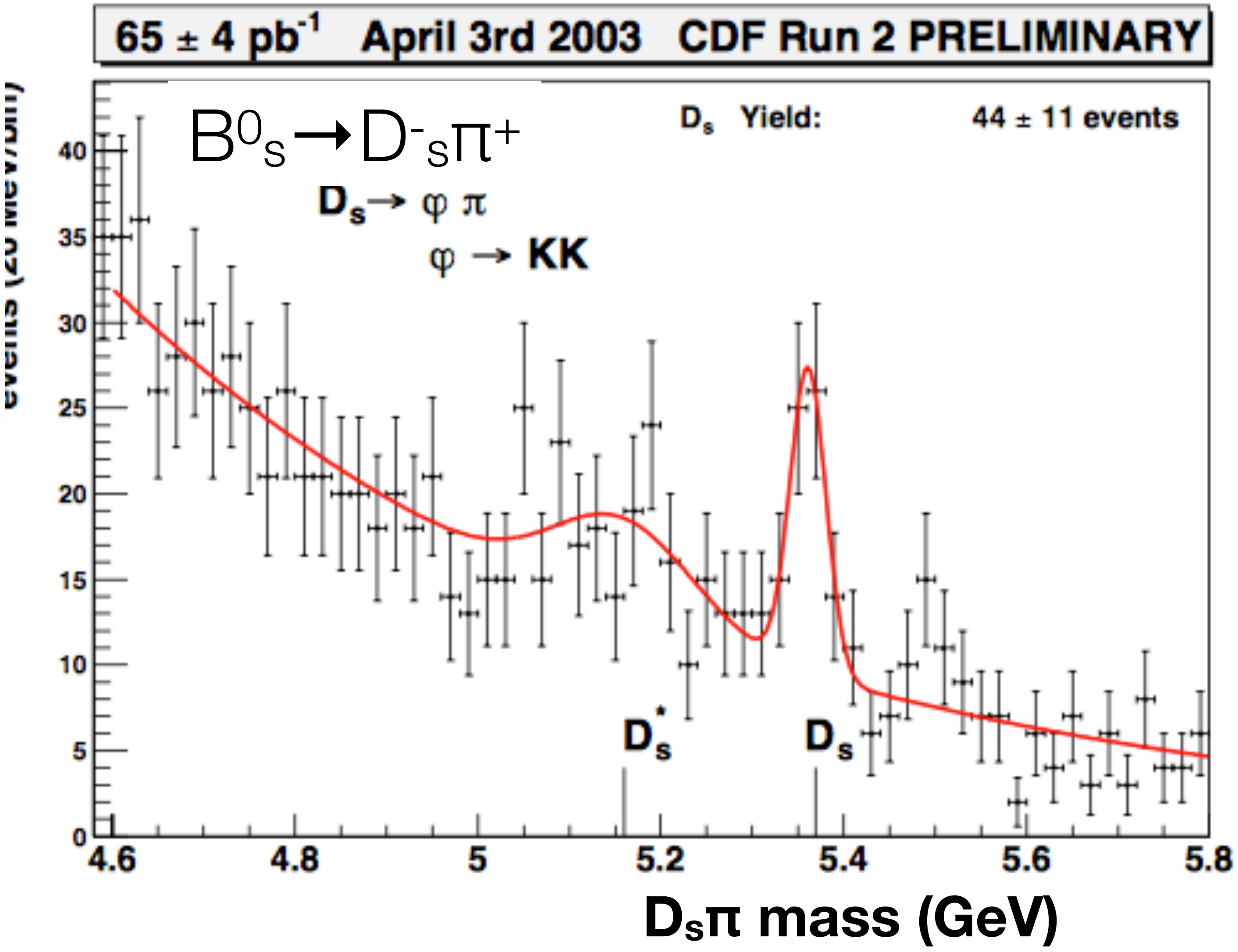


The difference track-triggers make

Without track trigger



With track trigger (and half the data!)



CDF is the only experiment to successfully operate a track trigger for *B* physics: key enabler of the B^0_s mixing result and a major fraction of CDF's *B* program

You want (experimental requirements)

☑ Produce large and low-background samples of *B* and *D* hadrons

☑ Reconstruct precisely many *B* and *D* decays with good S/B

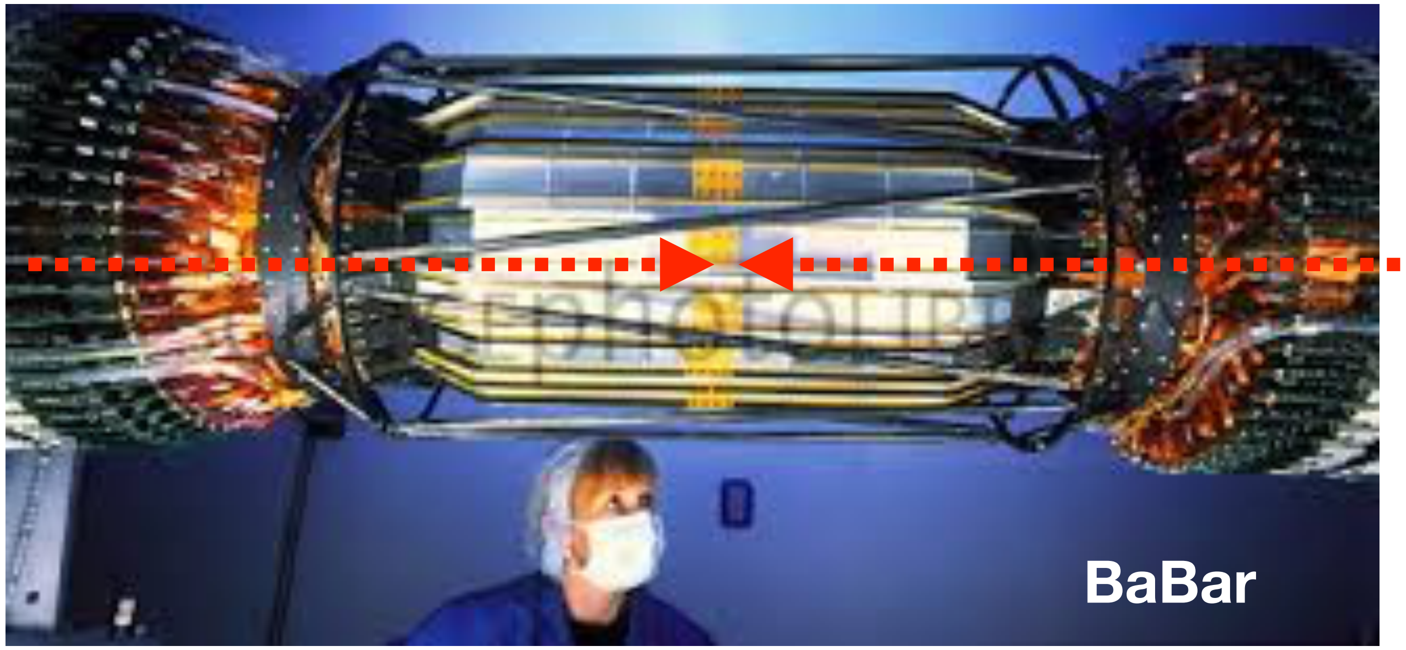
  ☑ Do it online!

☐ Reconstruct precisely *B* and *D* decay time

☐ Identify if a particle (*B*, *D*) or antiparticle ($\bar{\text{B}}$, $\bar{\text{D}}$) was produced

☐ Control tightly instrumental charge asymmetries

Decay time — vertexing



With $c\tau \approx 0.5$ mm, *B* hadrons fly 0.2 to 50 mm depending on momentum. Measure the decay position by sampling precisely the trajectories of charged decay products as close to the beam as possible

Double-sided microstrip (or pixel) silicon sensors 1-5 cm from the beam reach vertex position resolutions of 10-30 μm in the transverse plane and 50-100 μm along the beam.

Material from supporting infrastructure increases multiple scattering of low-momentum charged particles and radiation from electrons and γ, degrading efficiencies and mass resolutions.

You want (experimental requirements)

- ☑ Produce large and low-background samples of *B* and *D* hadrons
- ☑ Reconstruct precisely many *B* and *D* decays with good S/B
  - ☑ Do it online!
- ☑ Reconstruct precisely *B* and *D* decay time
- ☐ Identify if a particle (*B*, *D*) or antiparticle ($\bar{B}$, $\bar{D}$) was produced
- ☐ Control tightly instrumental charge asymmetries

Was it a particle or an antiparticle at production?

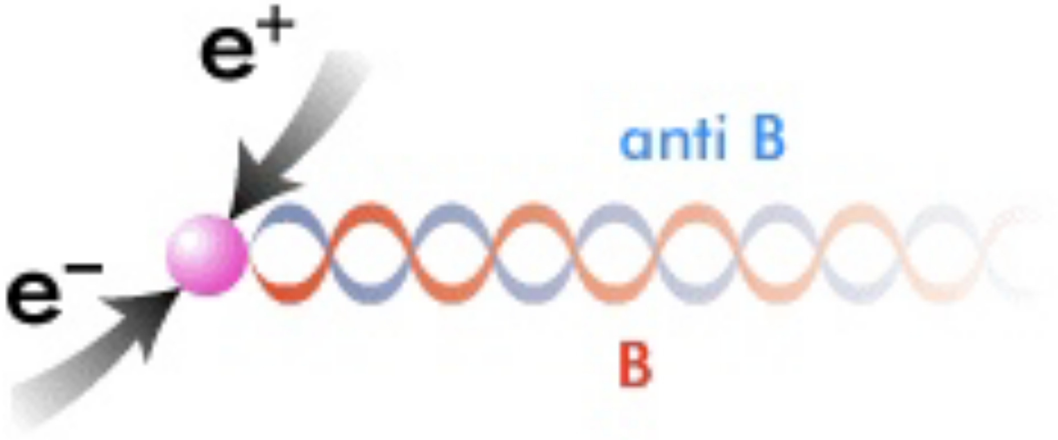
In measurements involving flavor oscillations, need to know whether oscillations occurred or not for the signal *B* meson.

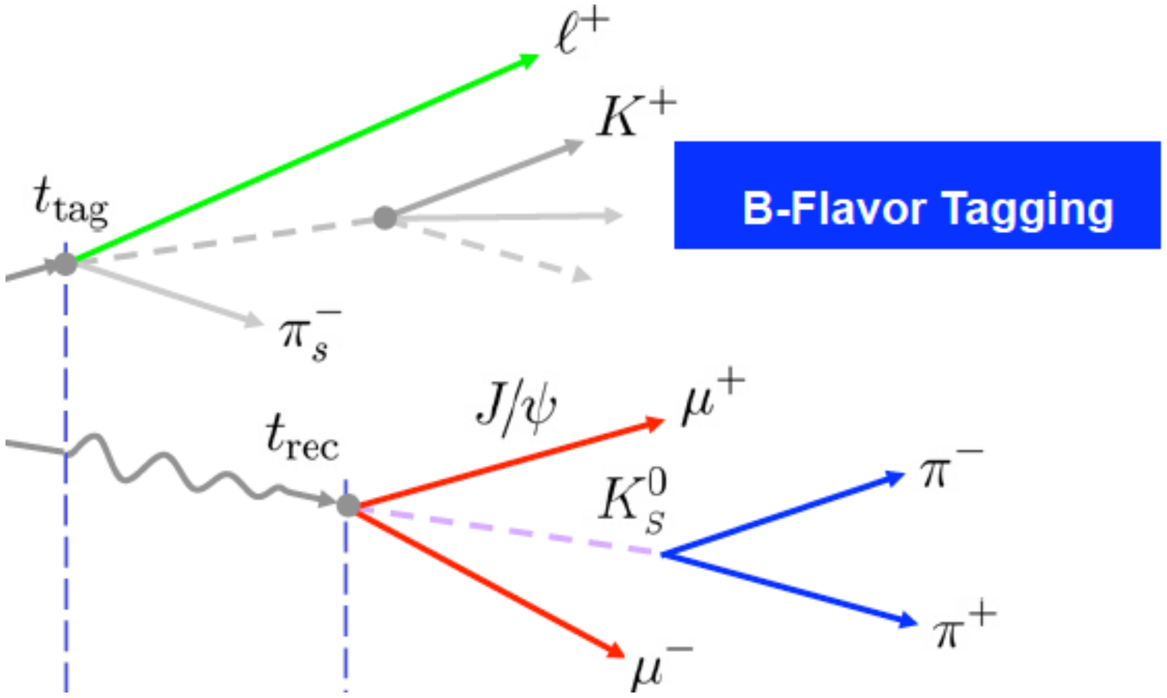
Compare the flavor at time of decay with flavor at t = 0 to see if an oscillation occurred.

If it was a particle when I started measuring the time and it was an antiparticle when it decayed (or viceversa) then it oscillated

Flavor tagging at B factories

B factories, exploit coherent flavor anticorrelation ofthe $B\ \bar{B}$ pair.



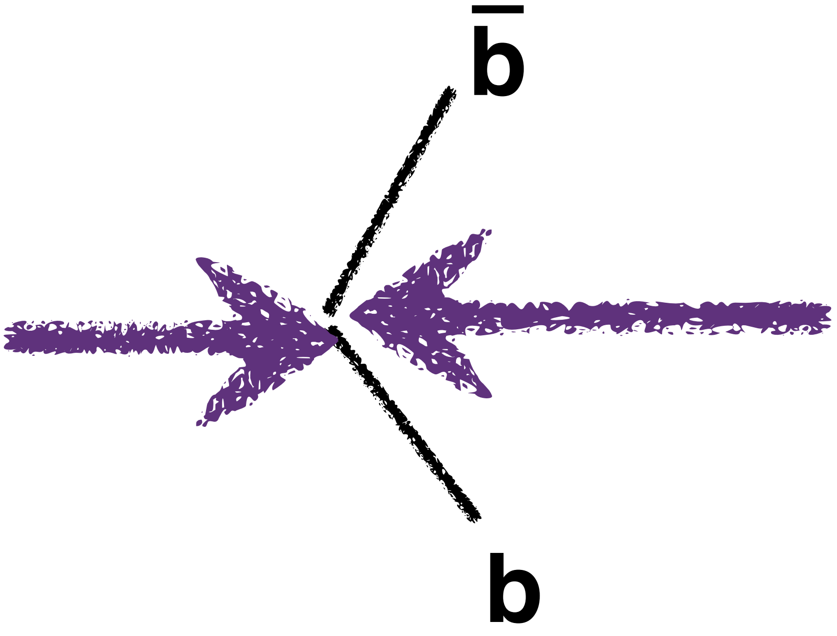


Two mesons evolve with opposite flavors until the first decays (which sets t = 0) and the signal *B* meson continues its evolution incoherently.

If the decay is in a final state only accessible by either particle or antiparticle, then the flavor of the decaying meson "tags" the flavor of the signal one at t = 0.

The flavor is correctly determined for 1/3 of signal *B* mesons

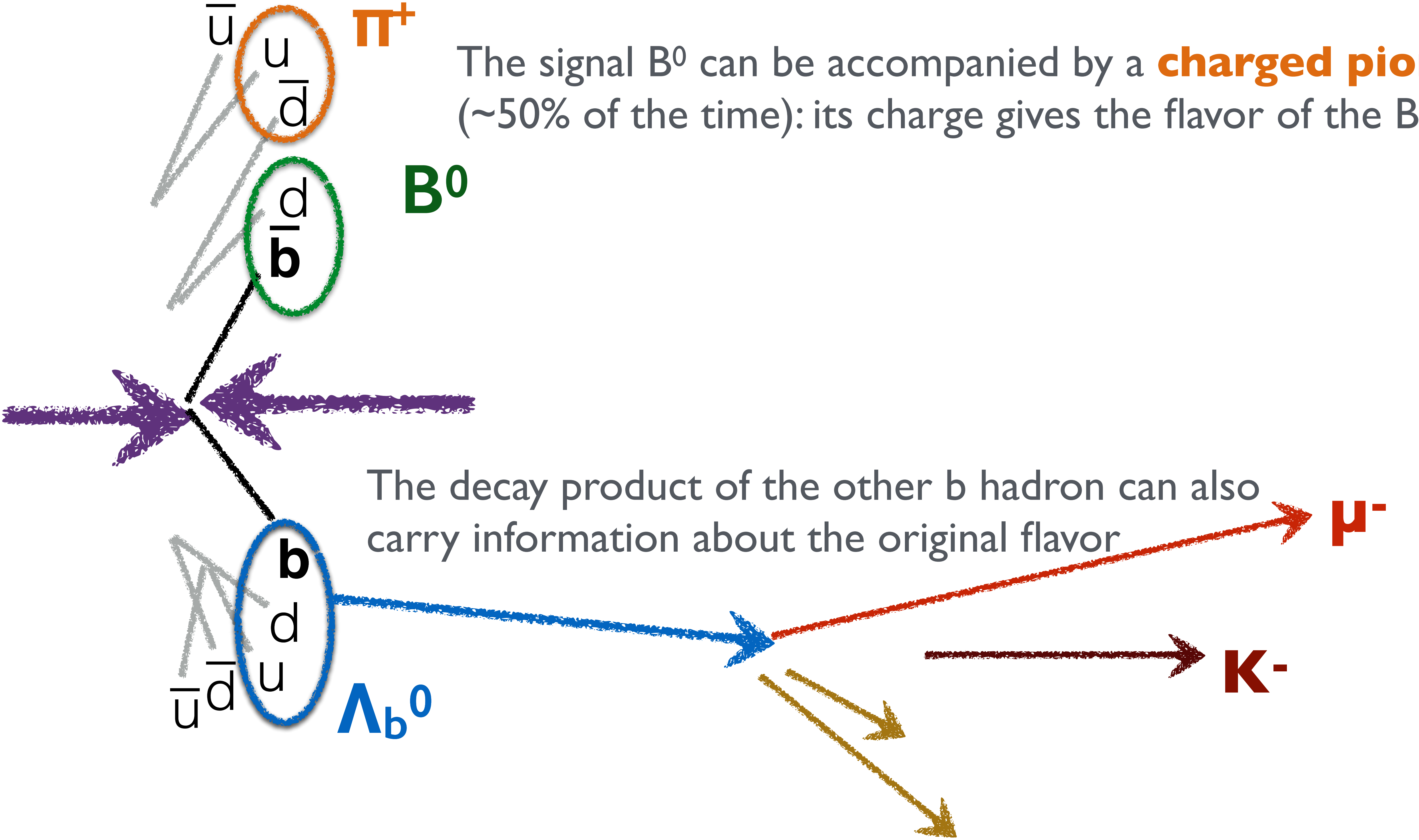
Flavor tagging in hadron collisions



Main production mechanism of b quark at hadron collider: b anti-b pair production

The two b quarks hadronise independently into two b hadron (incoherent production)

Flavor tagging in hadron collisions



The signal B^0 can be accompanied by a **charged pion** (~50% of the time): its charge gives the flavor of the B!

The decay product of the other b hadron can also carry information about the original flavor

The flavor is correctly determined only in 1/20 to 1/50 of signal *B* mesons

You want (experimental requirements)

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- ☑ Reconstruct precisely *B* and *D* decay time
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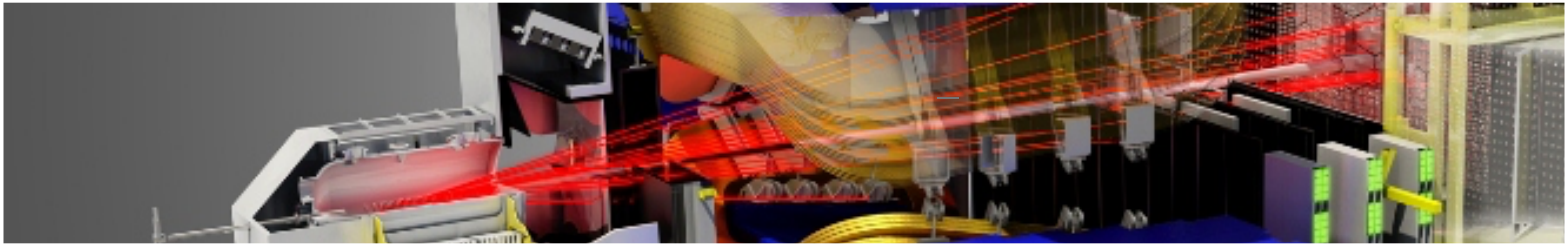
- ☐ Control tightly instrumental charge asymmetries

Production asymmetries

While measuring asymmetries in decay rates, any particle-antiparticle asymmetry in production rates is a potential source of bias.

Production asymmetries not an issue in *B*-factories and $p\bar{p}$ collisions recorded with detectors symmetric around the collision point.

A concern at LHCb: *pp* collisions with geometrically asymmetric detector. Null net *b* flavor is conserved in the strong *pp* interaction, but this holds for the whole phase space, not necessarily to the subspace covered by detectors.

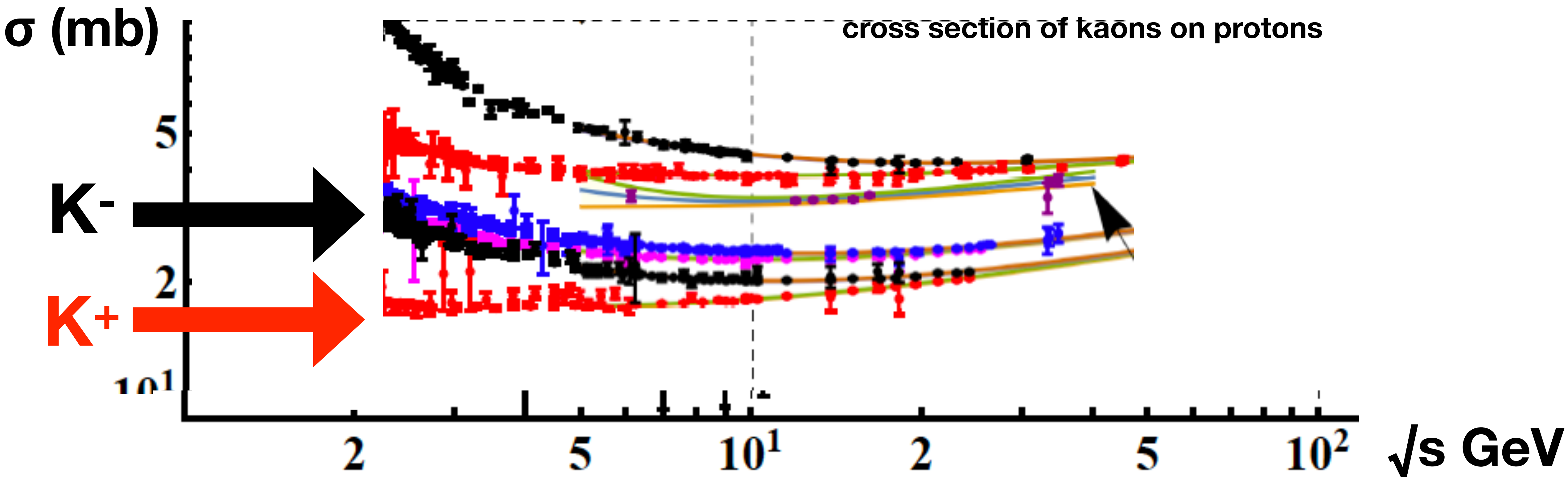


When relevant, correct the measured asymmetries with factors extracted from independent production asymmetry measurements in data.

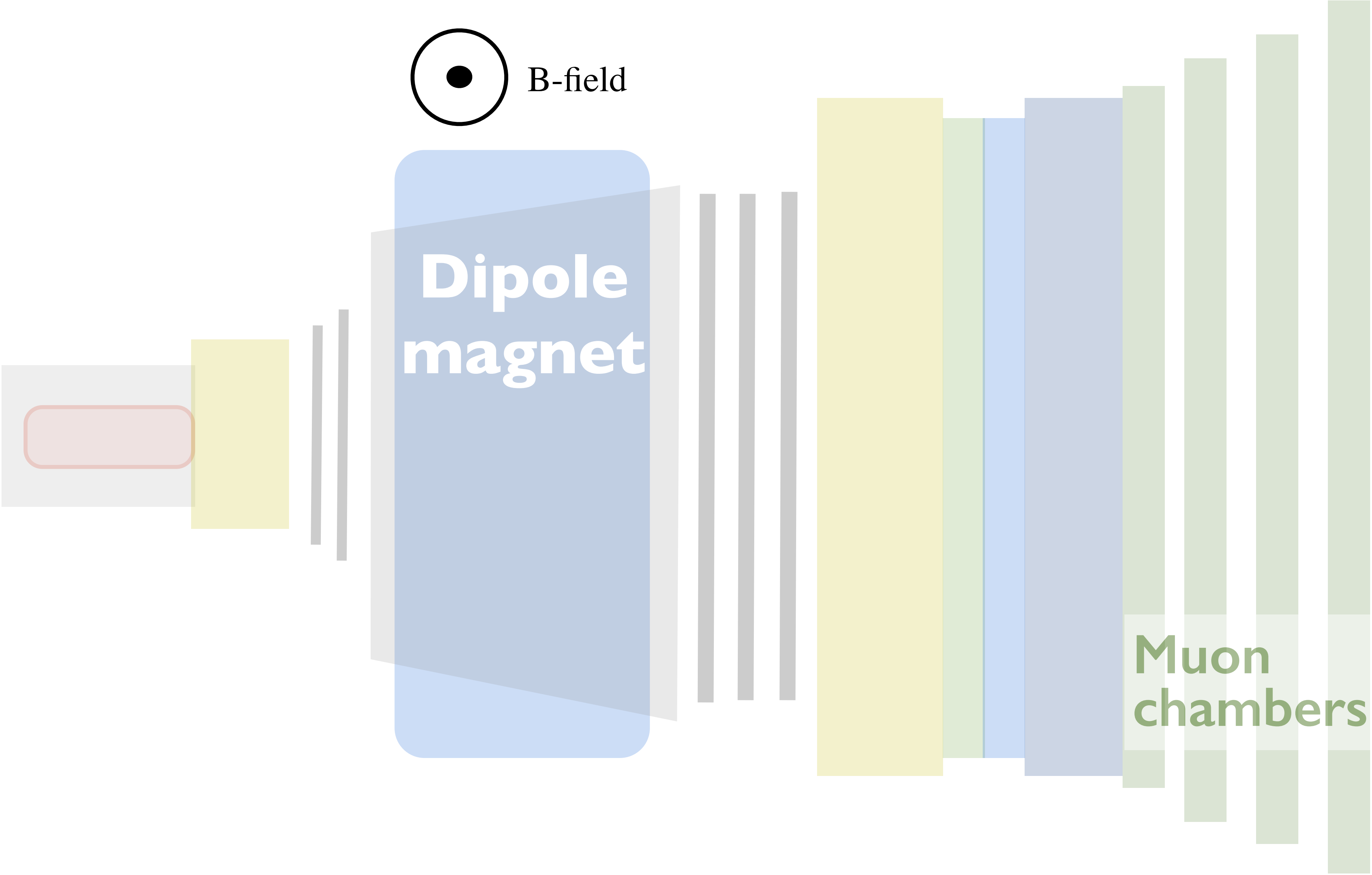
Instrumental asymmetries

While measuring asymmetries in decay rates, any particle-antiparticle asymmetry in reconstruction efficiency is a potential source of bias.

Even assuming detectors ideally symmetric in geometry and material, detectors are made of matter (not antimatter): some instrumental asymmetries are unavoidable, like the difference between K^- and K^+ interaction cross sections.

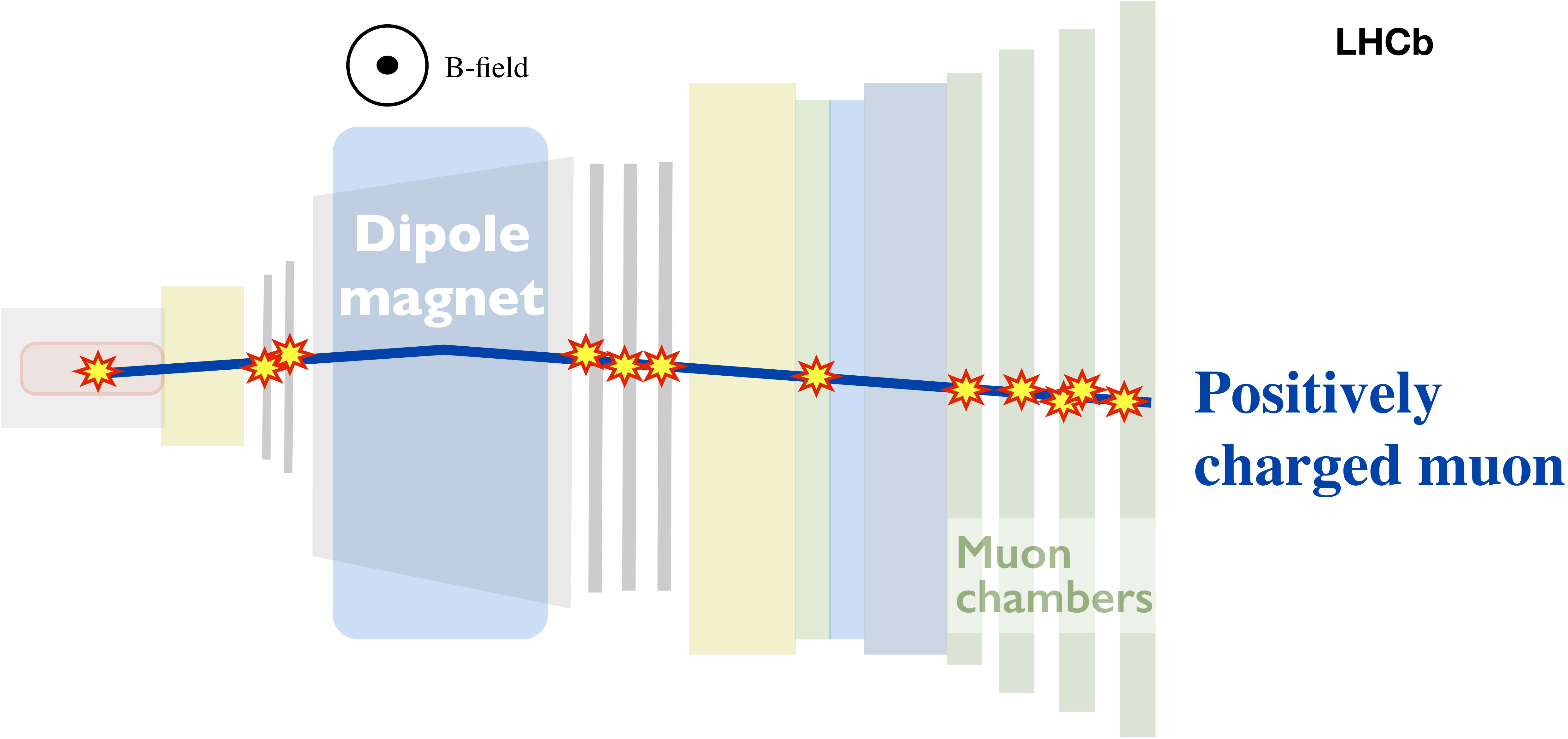


Instrumental asymmetries

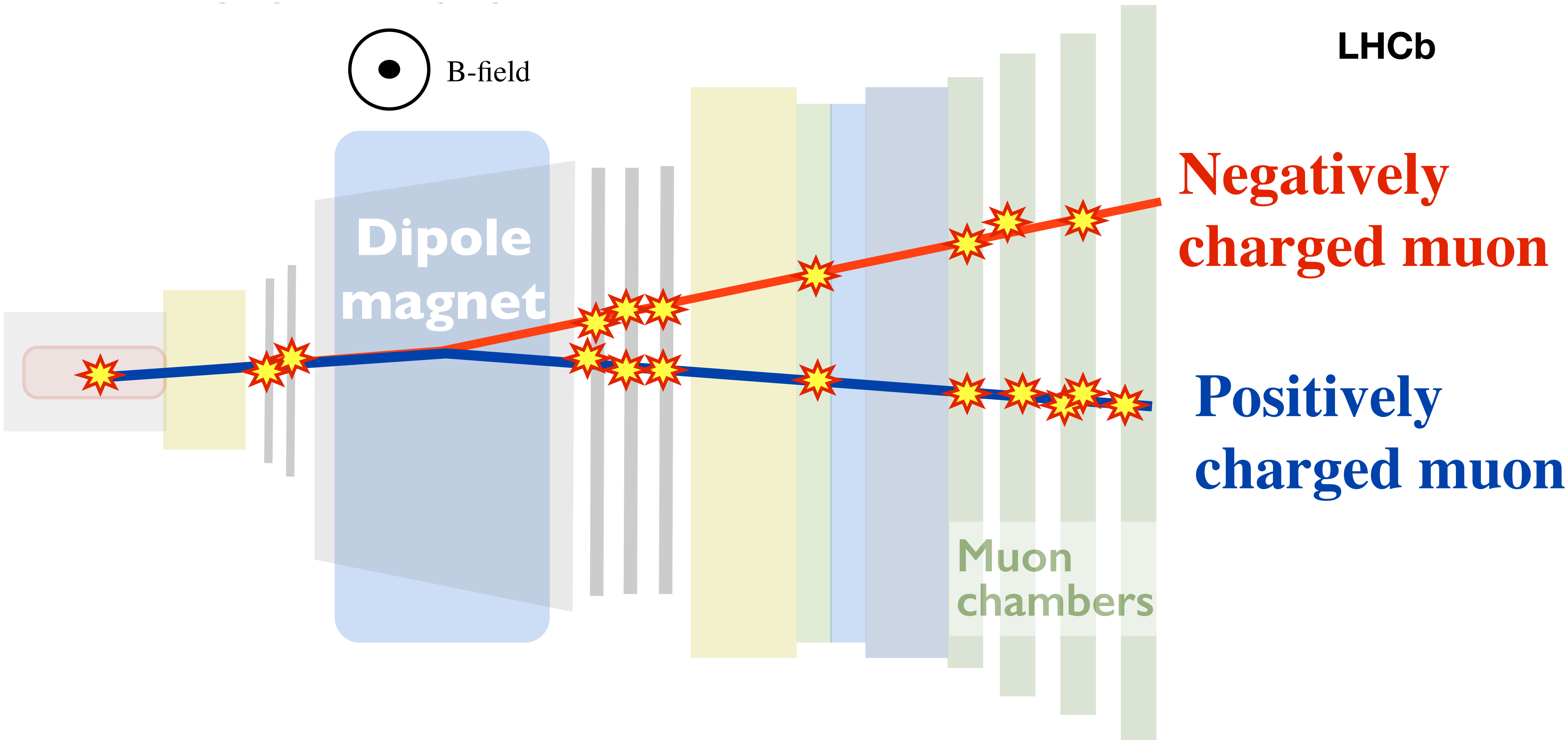


LHCb

Instrumental asymmetries

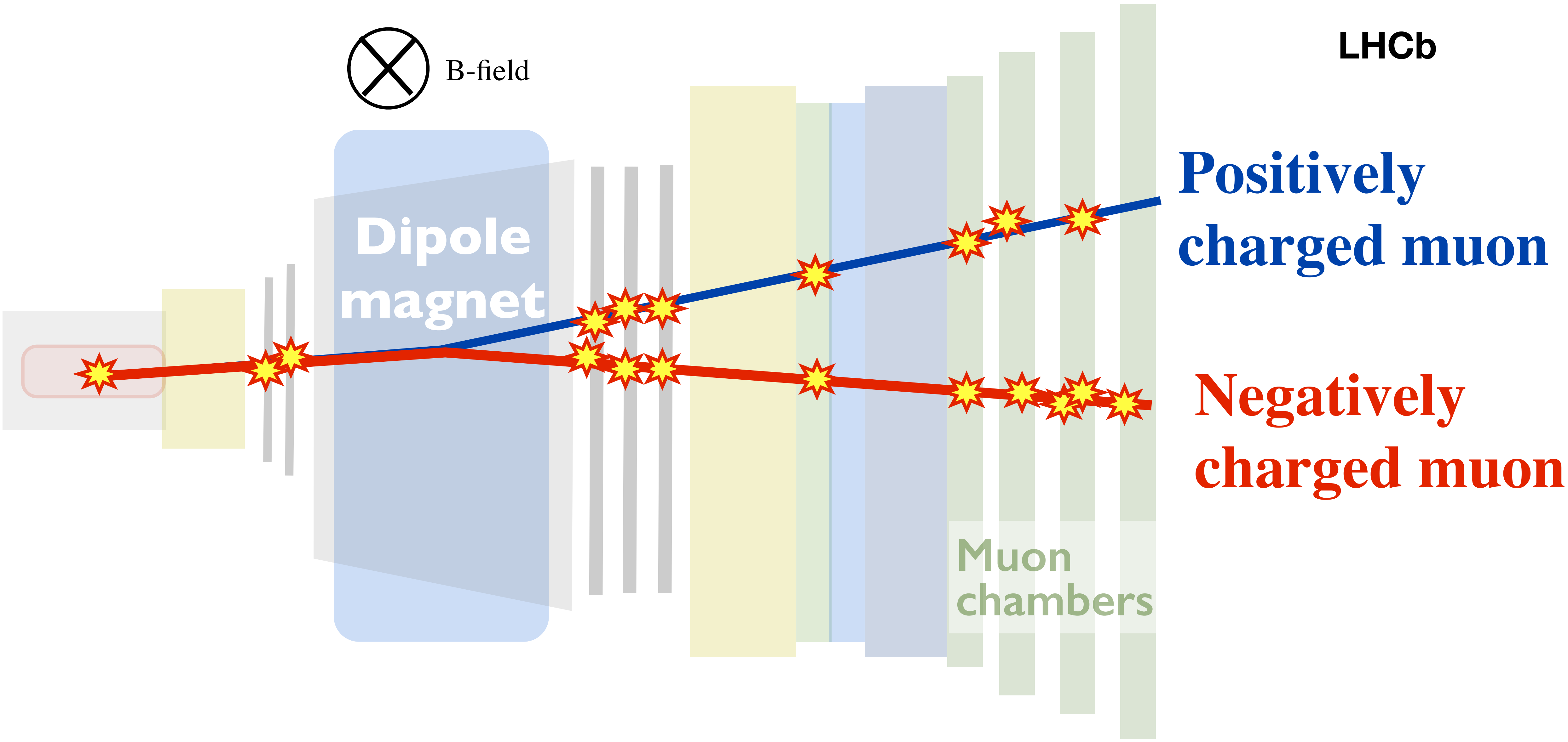


Instrumental asymmetries



Any left-right asymmetry in the material of the detector may potentially induce asymmetries in detection efficiency between positive and negative charged particles

Instrumental asymmetries



Periodic inversion of magnet polarity and average of measurements based on data sets at opposite polarities reduces instrumental asymmetries. Correct for residual effects using control samples of data

You want (experimental requirements)

☑ Produce large and low-background samples of *B* and *D* hadrons

☑ Reconstruct precisely many *B* and *D* decays with good S/B

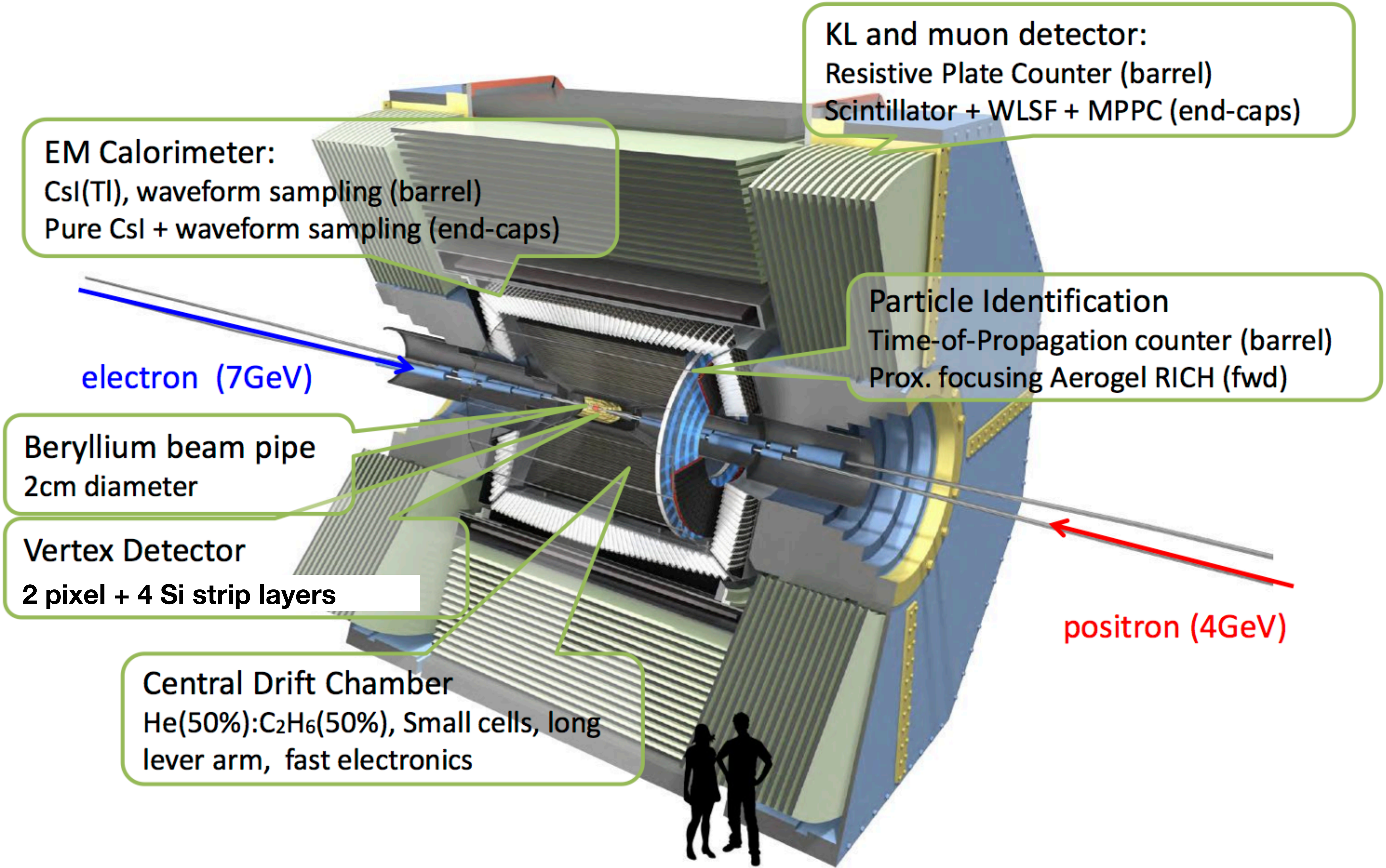
- ☑ Do it online!

☑ Reconstruct precisely *B* and *D* decay time

☑ Identify if a particle (*B*, *D*) or antiparticle ($\bar{B}$, $\bar{D}$) was produced

☑ Control tightly instrumental charge asymmetries

Belle II: a state-of-art B-factory detector



KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electron (7GeV)

Beryllium beam pipe
2cm diameter

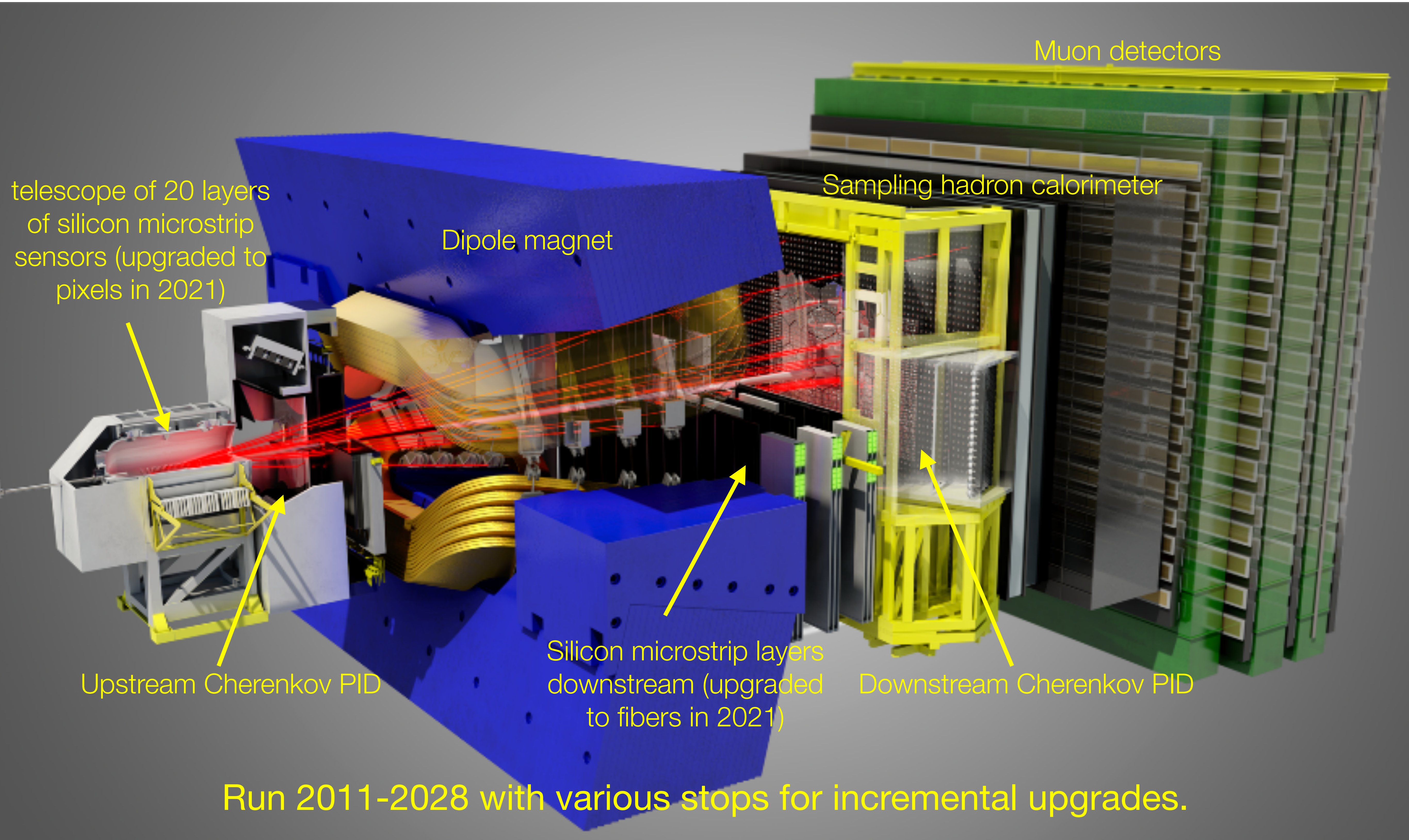
Vertex Detector
2 pixel + 4 Si strip layers

positron (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

Run 2018—2025 to collect 50x data collected by previous *B*-factory experiments

LHCb: a state-of-art hadron-collision detector



Muon detectors

telescope of 20 layers of silicon microstrip sensors (upgraded to pixels in 2021)

Dipole magnet

Sampling hadron calorimeter

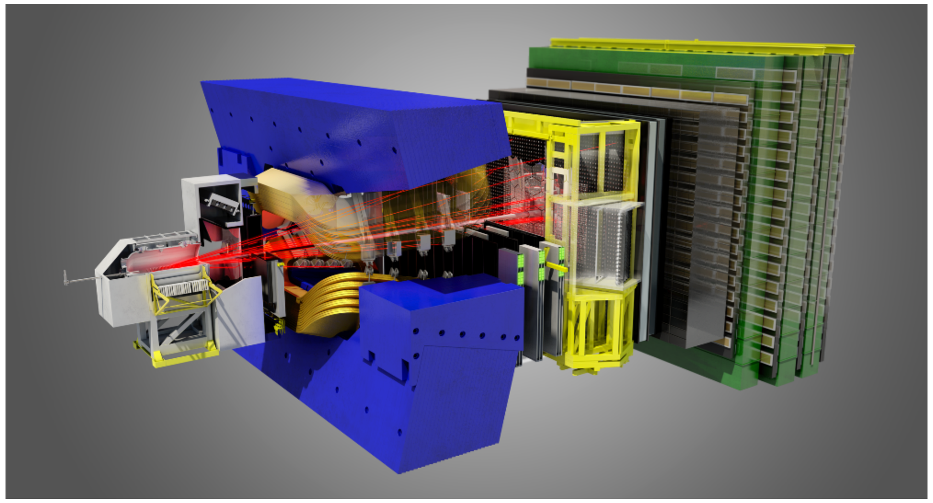
Upstream Cherenkov PID

Silicon microstrip layers downstream (upgraded to fibers in 2021)

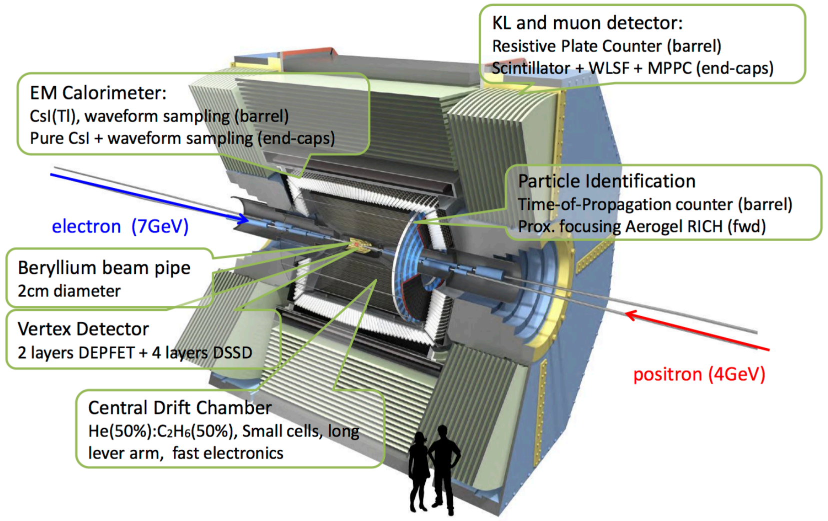
Downstream Cherenkov PID

Run 2011-2028 with various stops for incremental upgrades.

Performances



- ☐ Superb signal yield for *all types* of b hadrons
- ☐ Outstanding reach on final states with only tracks



- ☐ Superior or unique on B^0, B^+, and D decays into multiple neutrals
- ☐ Superior for partially reconstructable final states thanks to beam-energy constraints (superb semileptonics and τ physics)
- ☐ Competitive for all-tracks channels when flavor tagging is needed

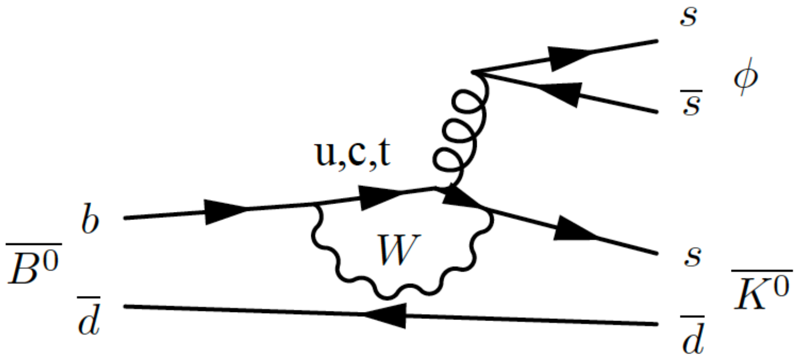
Synergic and complementary performances to sharpen up the quark-flavor picture for decades to come. Probably the last experiments dedicated to quark-flavor

Flavor beyond the SM

The loop approach — couplings strengths

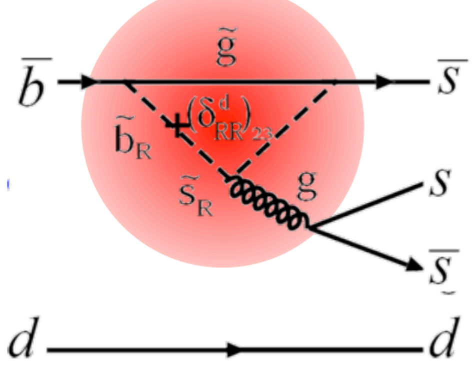
Any internal quark line is replaceable with non-SM particles (with compatible quantum numbers) without affecting the decay’s initial or final states .

SM amplitude



+

non-SM amplitude



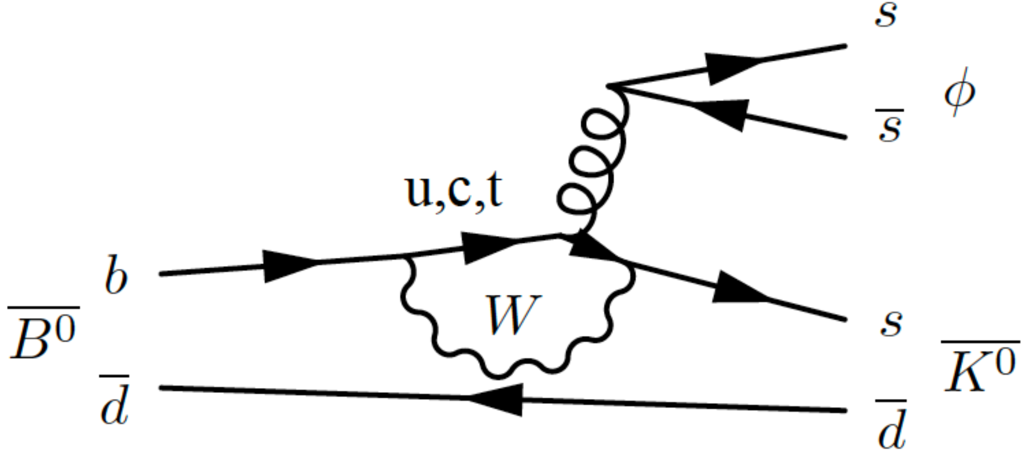
Momentum flowing through the loop gets integrated to infinity: amplitude not suppressed by the possibly high masses of the non-SM particles contributing.

Access non-SM coupling strength through processes where “loop” amplitudes dominate the SM contributions: flavor-changing neutral currents are sharp probes for non-SM dynamics. SM transitions between same-charge quarks are suppressed unlike in many SM extensions. Observing flavor-changing neutral current interactions at rates incompatible with the SM is unambiguous sign of non-SM dynamics.

The loop approach — coupling phases too

Indirect searches for non-SM in loops access not only coupling strengths but also coupling phases. Intereference of different quantum paths opens access to the phase of non-SM couplings, notably through measurements of CP violation.

SM amplitude



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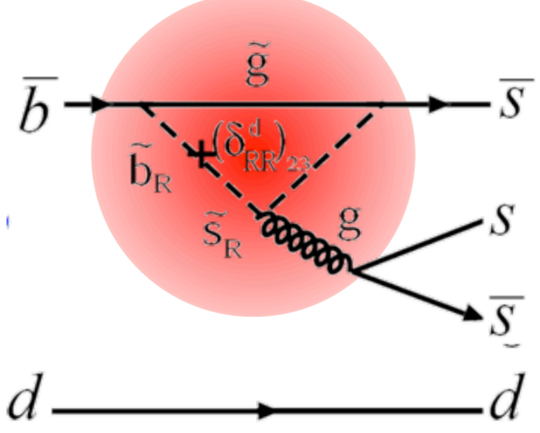
non-SM amplitude



Will it work? Why should I bother with flavor while all my friends are on the verge of great discoveries at CMS and ATLAS?

Noone knows. But track-record is encouraging — many fundamental discoveries happened away from the “energy frontier” of their time.

- 1927: neutrino existence (Ellis and Woster missing energy experiment)
- 1932: discovery of the neutron (could have been seen years earlier)
- 1933 proton’s magnetic moment (indicated proton substructure)
- 1934 neutron-induced radioactivity and consequences (bomb, medical isotopes, nuclear reactors)
- 1944 Conversi-Pancini-Piccioni difference between π and μ
- 1956 parity violation and K^0-K^0 mixing
- 1964 CP violation
- Late 60’s: solar neutrino deficit
- 1974 J/ψ (ISR was the energy frontier since 1971 and missed that out)
- 1976 τ lepton and 1977 bottom quark
- 1983 long B-meson lifetime
- 1987 B mixing (indicating heavy top quark)
- 1998 atmospheric neutrino mixing

Mantra

Precision measurements of FCNC can reveal non-SM particles of masses way greater than current (TeV) and future (~10 TeV) direct collider reach and/or provide key information on their coupling and phases.

If nothing is found, results still essential to guide and inform future scientific choices for collider priorities and refine knowledge of fundamental SM parameters. For this vision to work, need to restrict to processes:

☐ that are experimentally accessible

☐ for which reliable SM predictions exist

☐ in which the precisions of both are similar

Predicting quark flavor dynamics

(I am out of my element here, just want to suggest the subtending conceptual idea, since that’s very powerful and physics-rich)

Key idea— scale separation and effective field theory

Dynamics at a certain energy depend negligibly on the details of the dynamics at higher energies. For many systems, low-energy dynamics is *effectively* decoupled from high-energy dynamics. E.g., engineers need no knowledge of strong interactions to build a good bridge: design depends on macroscopic parameters at the 1m scale; short distance properties of nature are irrelevant.

Hence, a simpler, *effective* Lagrangian that has a number of degrees of freedom (fields, that is, particles) reduced and restricted to those particles that are relevant at the energy of the investigate process can describes dynamics satisfactorily.

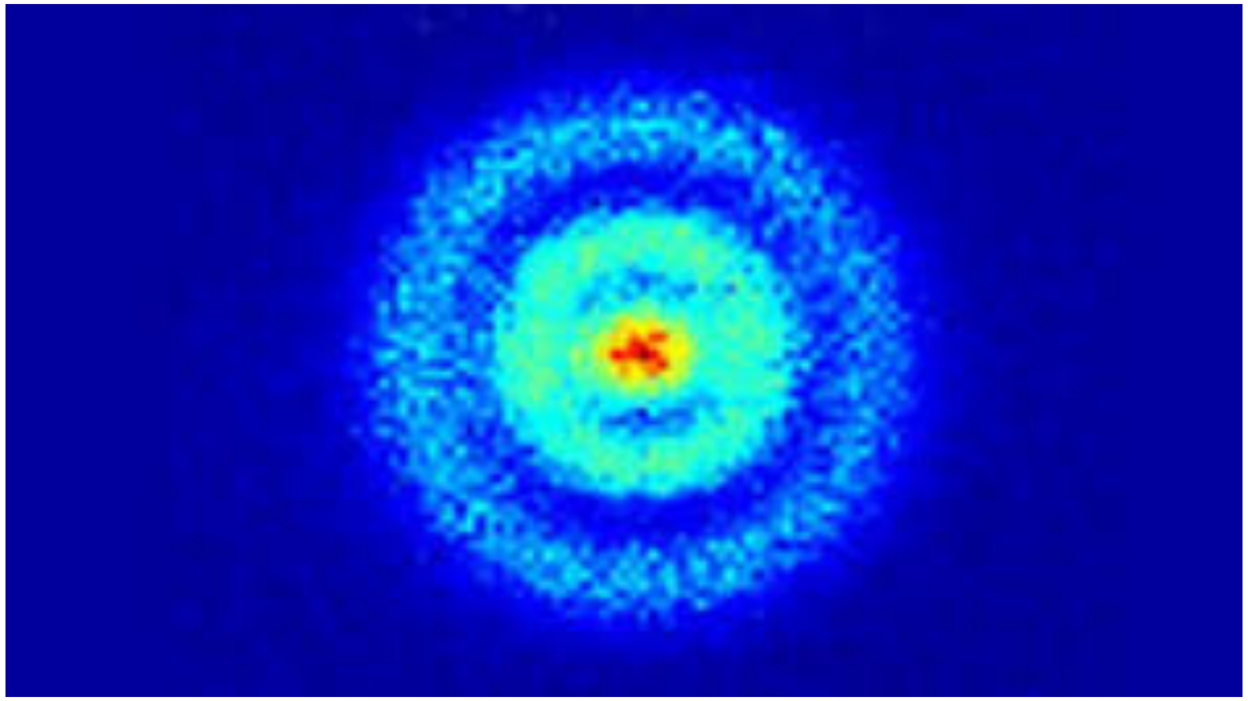
EFT is a quantum field theory where heavy particles that cannot be produced directly in experiment have been integrated out, and their effects are encoded into contact interactions of the lighter particles that are relevant at the probed energies

Very useful to (i) calculate predictions in the presence of uncertainties from soft QCD interactions (ii) parametrize the dynamical effects of generic extensions of the SM as functions of observable quantities in a model independent way.

An example — hydrogen atom

The Coulomb-potential Hamiltonian

$$\mathscr{H} = \frac{\mathbf{p}^2}{2m_e} - \frac{\alpha}{r}\,.$$



suffices to calculate binding energies and EM transition rates with no knowledge of quarks, weak force and no detailed QED or QCD inputs.

The only needed information is knowing that the proton has charge +1: can be measured from long distance (i.e., at low energy) via Coulomb interaction.

Finer corrections can enter systematically in a perturbation series.

Example — hydrogen atom

☐ proton recoil: $m_e \to m_e m_p/(m_e + m_p)$, thus introducing a first QCD parameter m_p

☐ fine-structure relativistic corrections $O(\alpha^2)$ include spin-spin interactions, which depend on the e and p magnetic moments: enters a 2nd QCD parameter μ_p

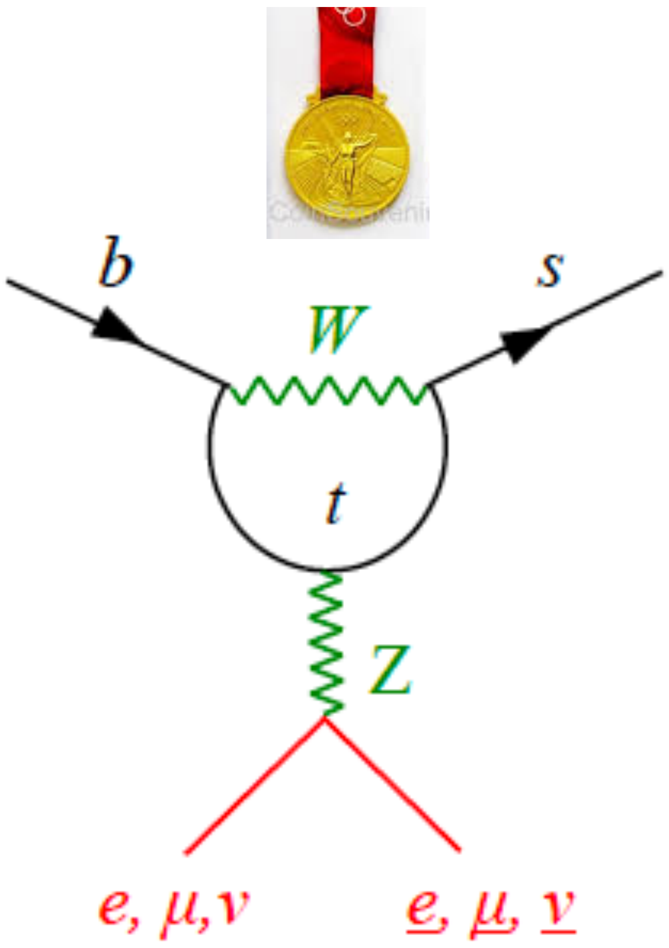
☐ more accurate calculations require to include additional parameters and QED corrections (electron g-2, proton charge radius, QED radiative Lamb shift correction etc.)

☐ weak interactions introduce tiny corrections to the energy levels but are the leading contributions to atomic parity violation effects: the ranking and priority of the corrections to include depends on what one wants to calculate. Corrections that are irrelevant for energy levels are maximally relevant for P-violating effects,

Example shows that for a relatively simple system like an H atom, the dynamics depends on multiple expansion parameters: $m_e/m_p,$ α, m_p/m_W

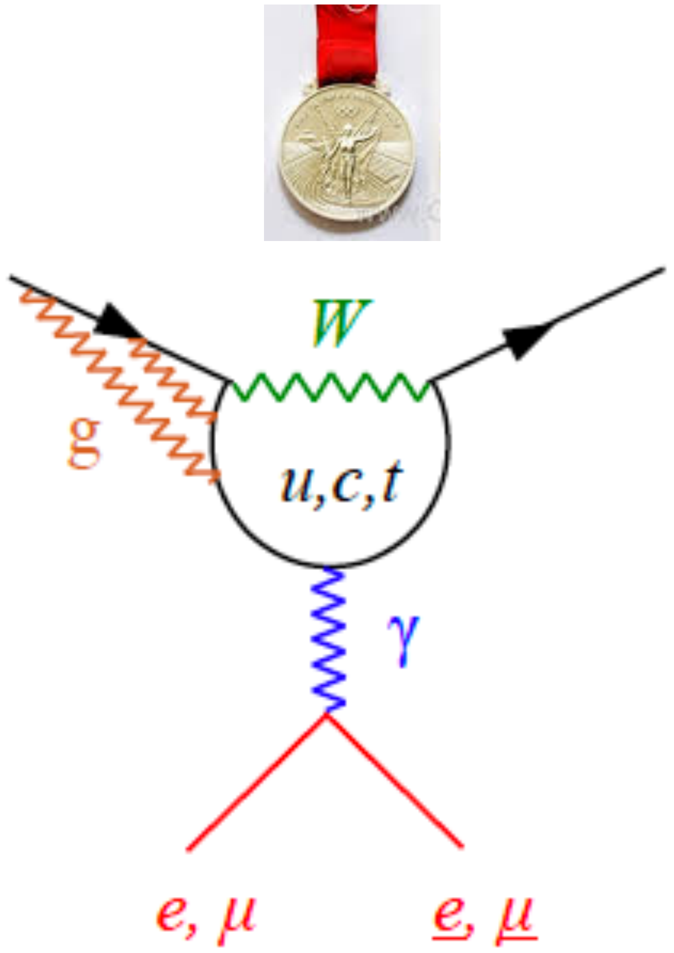
What to expect

Not all FCNC are equal



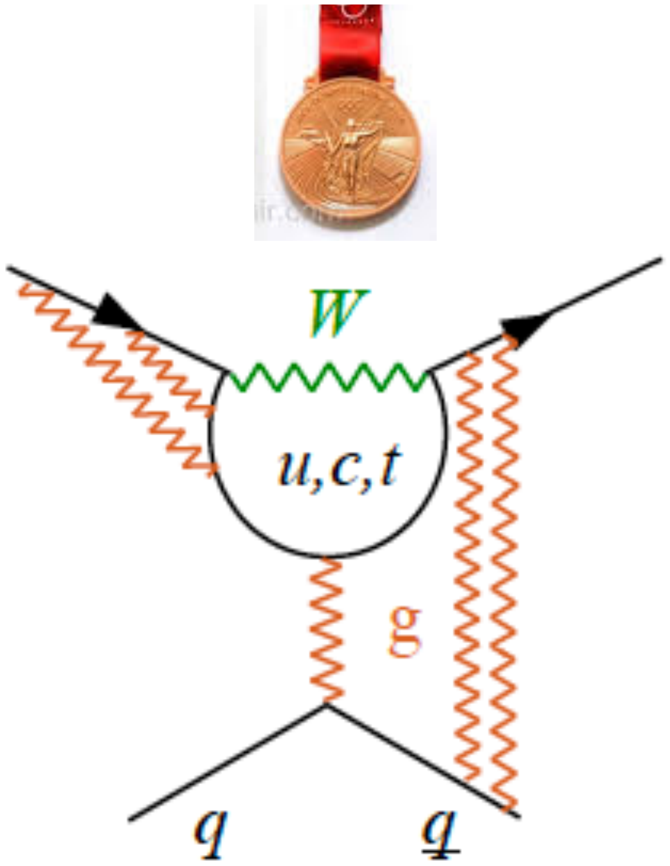
Very reliable SM prediction with O(1%) th. uncertainty

$B \to \mu\mu$, $B \to K\nu\nu$
$K \to \pi\nu\nu$



Less reliable SM prediction with O(10%) th. uncertainty

$B \to K\ell\ell$, $B \to K^*\ell\ell$



Unreliable SM prediction with O(100%) th. uncertainty

$B \to K\pi$, KK, $\pi\pi$ and many more

Golden channel luxury is (almost) over

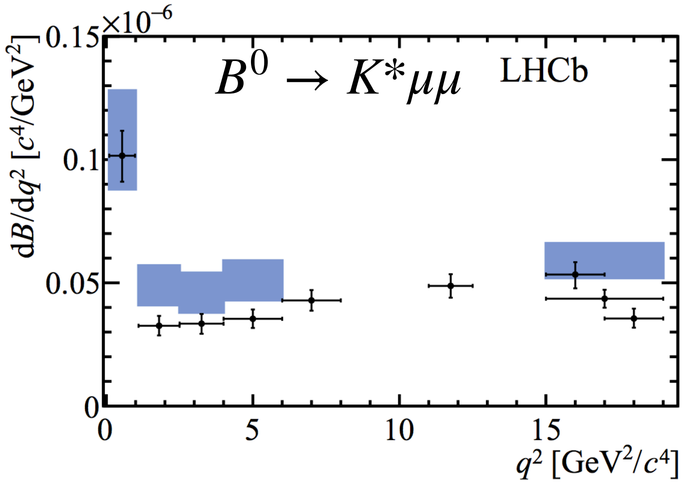
Most of the classic golden channels already explored in the past two decades — with SM-like outcomes.

Exploration of others is ongoing or about to be started, with the upgraded LHCb and Belle II detector, which will collect factors 50—100 more data than available now, supplemented by a few dedicated experiments to kaon physics and the upgraded ATLAS and CMS. In addition, advancements in the phenomenological prediction tools and lattice calculations will further sharpen the reach.

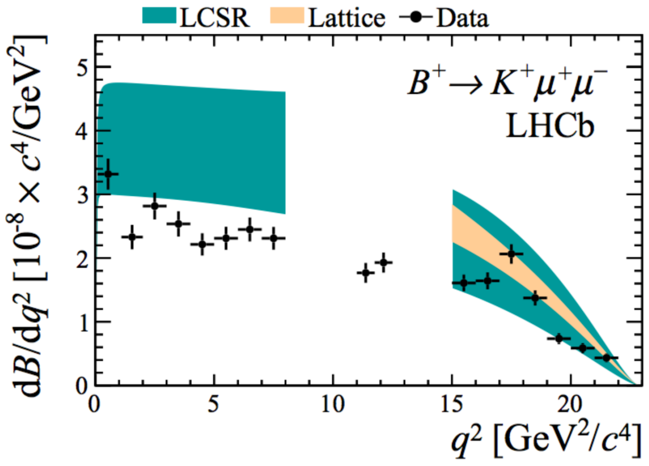
This is not empty advertising: in recent years various anomalous patterns have attracted to flavor physics an attention that is probably unprecedented…

Not a problem…we have anomalies..

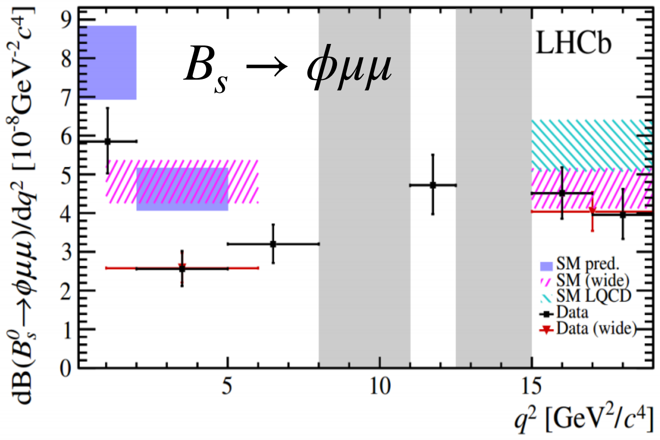
JHEP 11 (2016) 047



JHEP 06 (2014) 133



JHEP 09 (2015) 179



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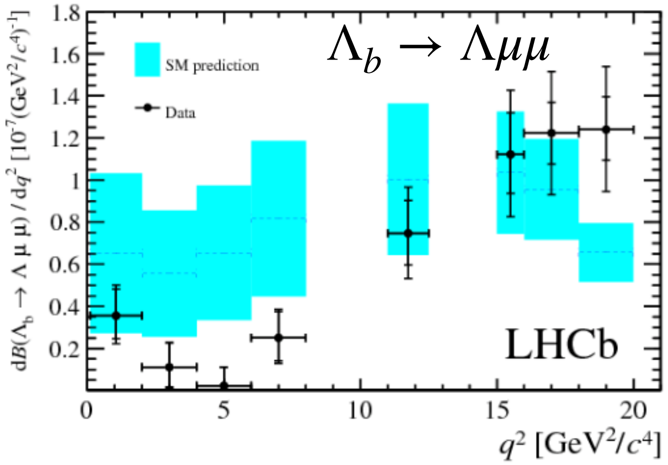

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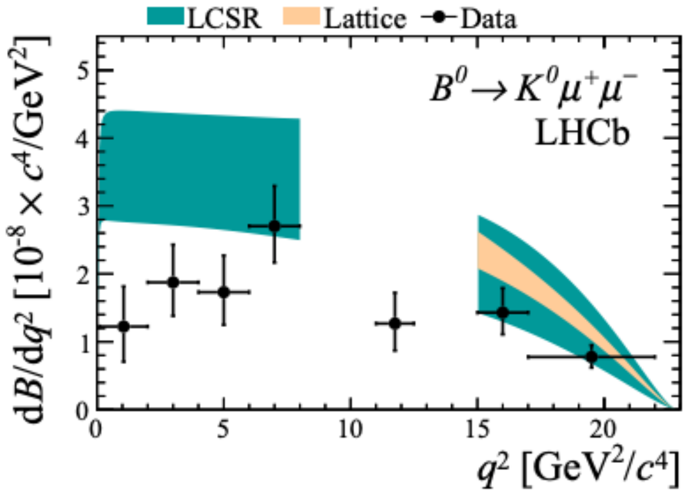

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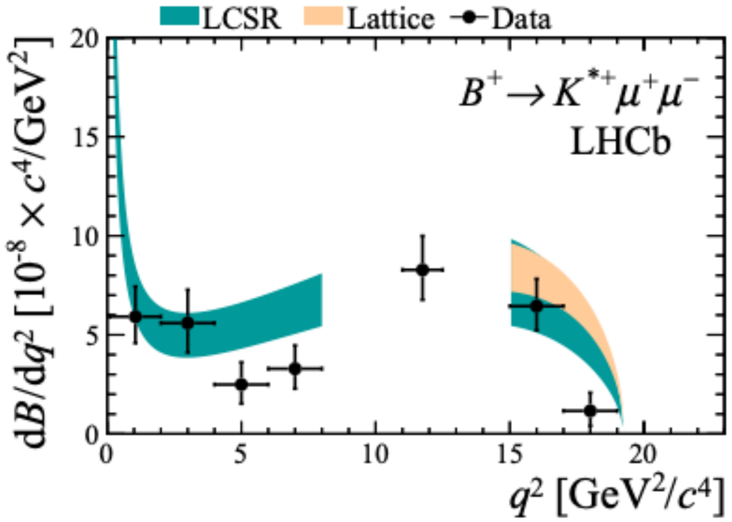
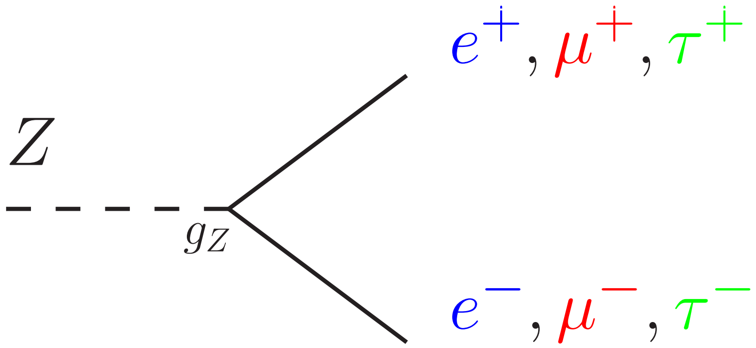
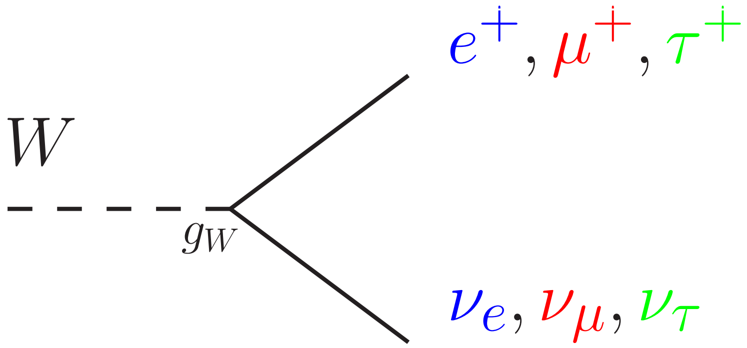


$b \to s\mu^+\mu^-$ transitions show a consistent pattern of deviations of measurements of decay rates vs dimuon mass squared (points with error bars) from predictions (colored bands), which however suffer from large hadronic uncertainties

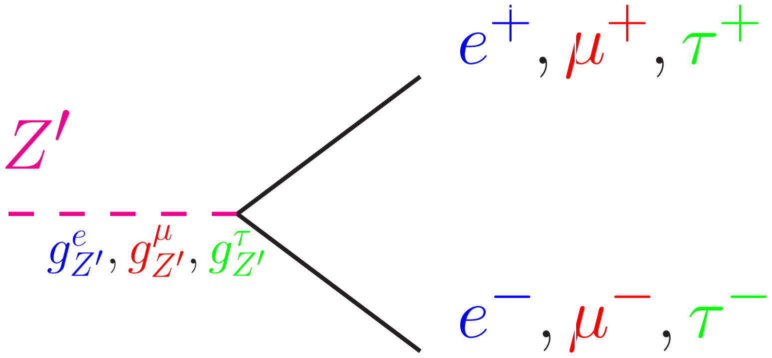
WTF?

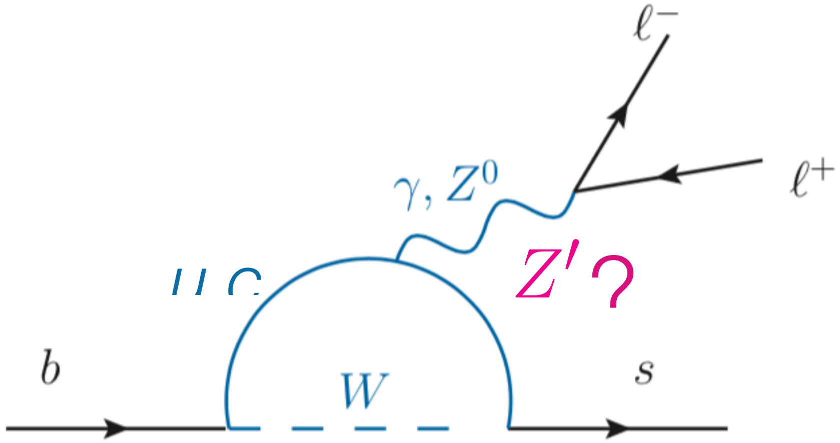
Unlike in quarks, couplings of the electroweak force to charged leptons are the same (“universal”). BF of Z and W into e, mu, or tau only differ because of lepton masses.





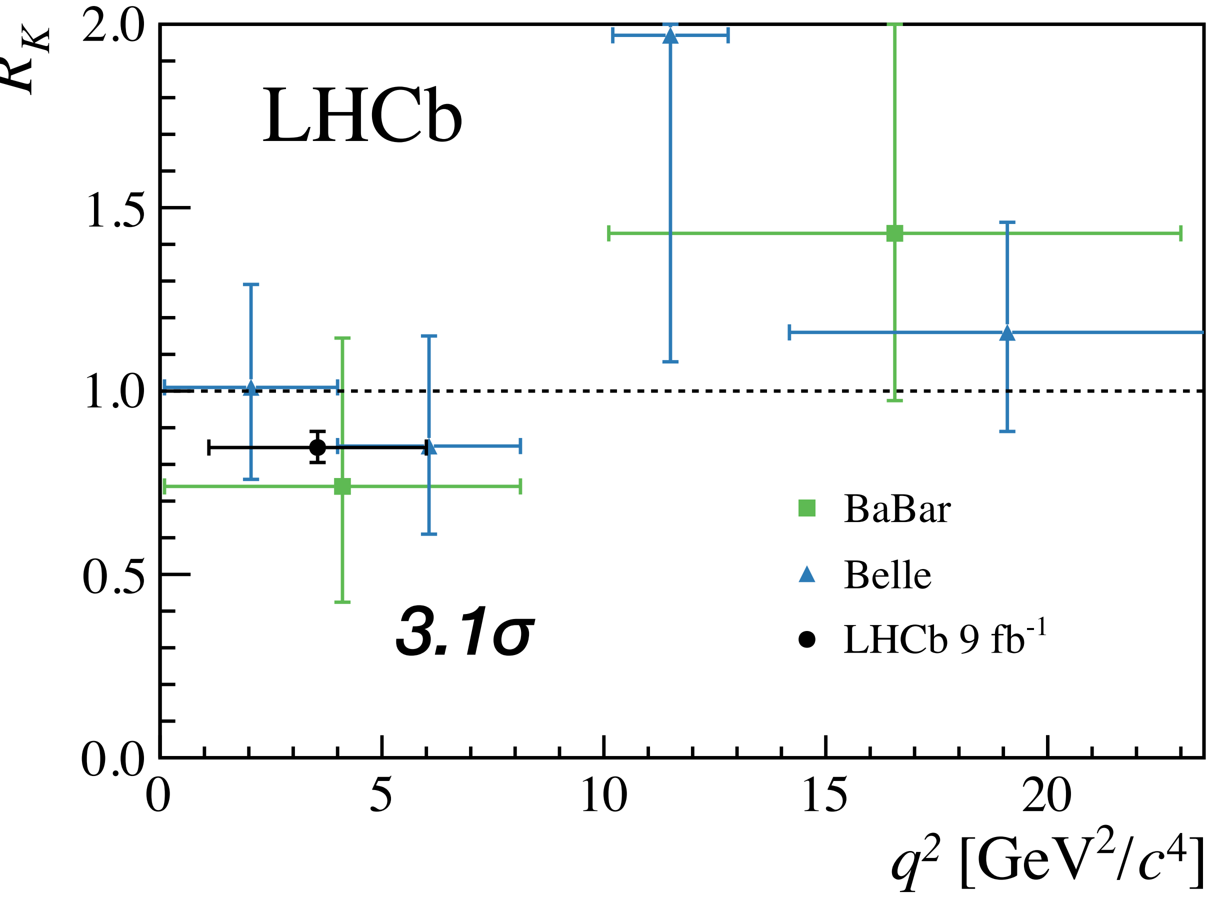
Couplings of non-SM particles, like a Z’, could instead be non-universal. Violation of lepton flavor universality would unambiguously signal non-SM physics



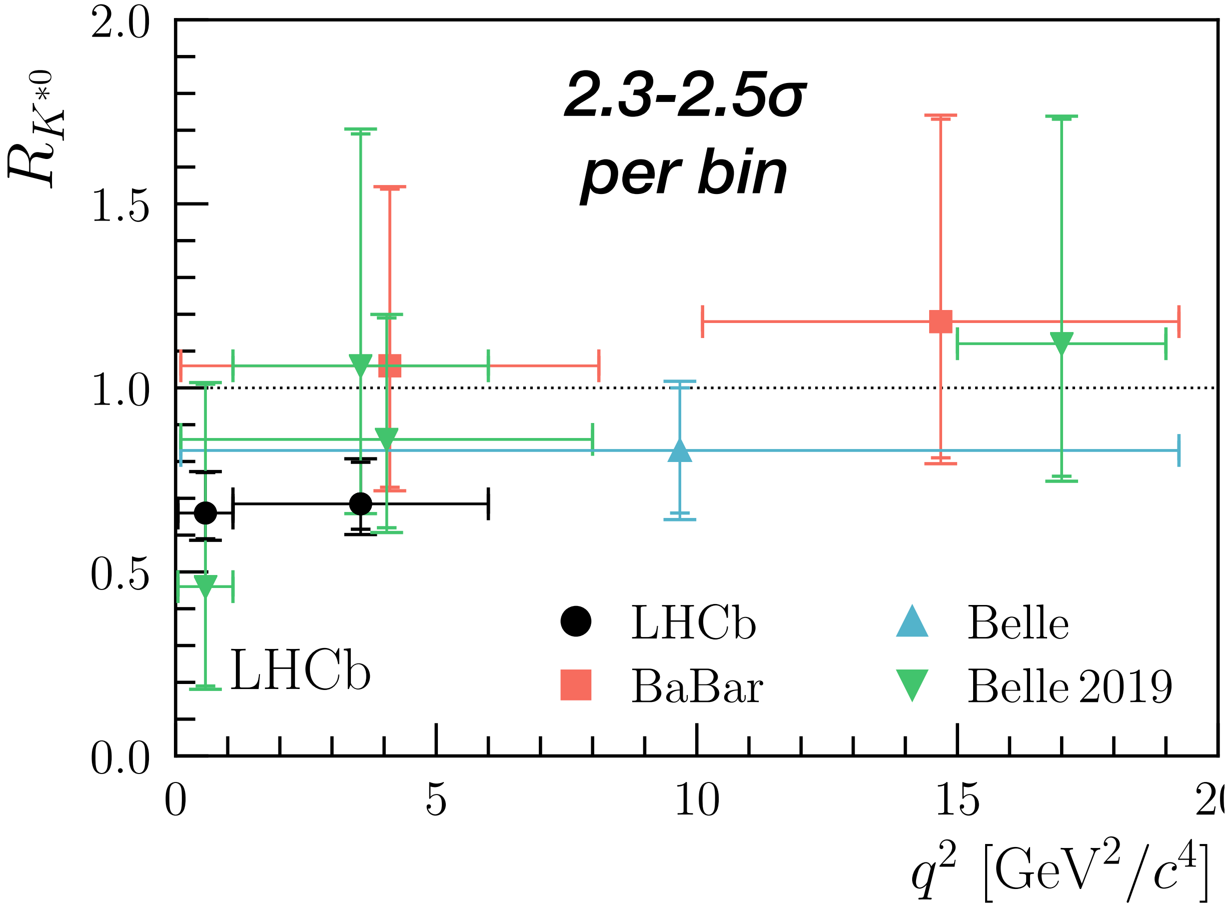


WTF?

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$



3.1σ



2.3-2.5σ per bin

Lepton flavor universality would align all data points over the dashed horizontal lines at R = 1.

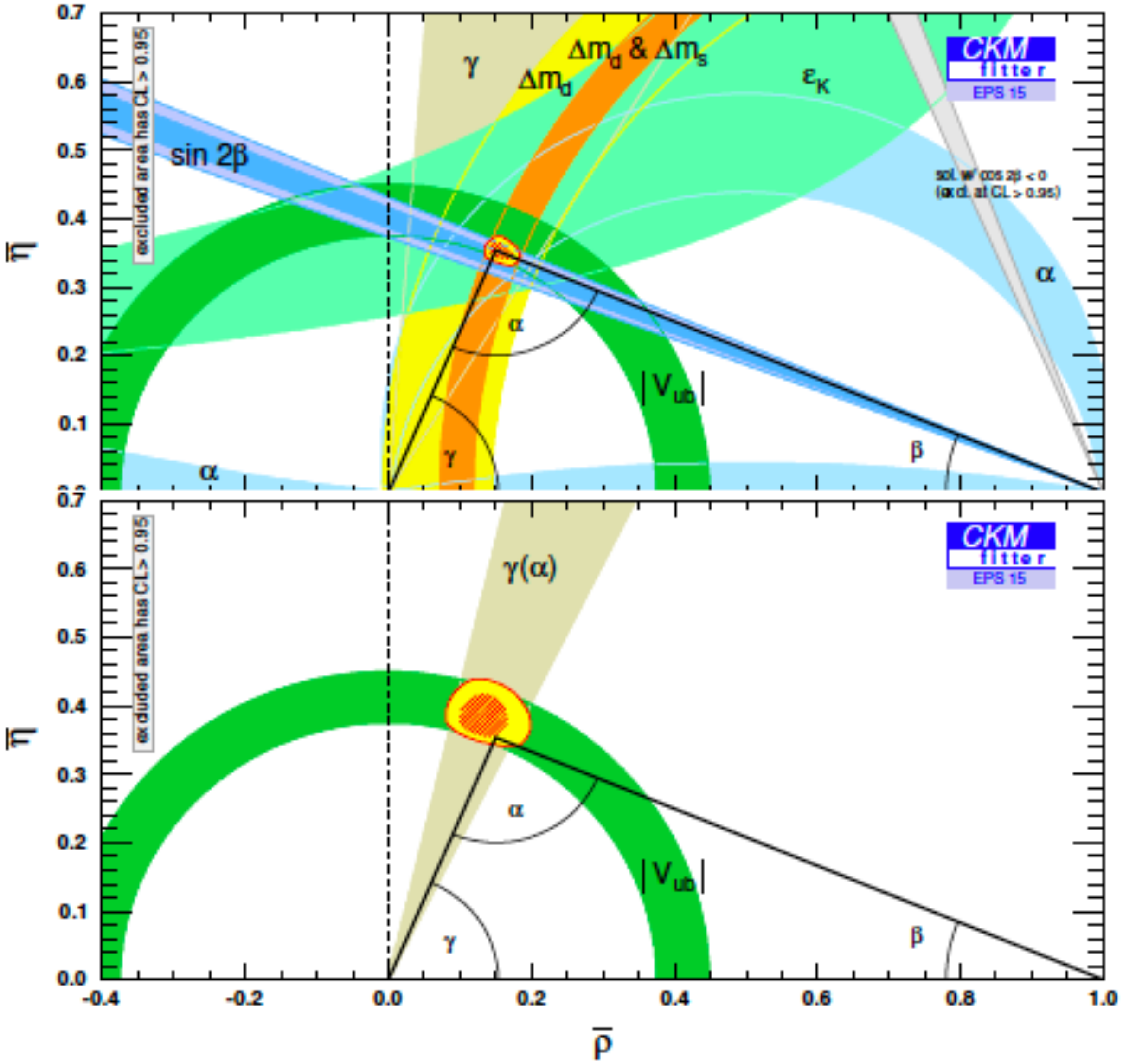
Not just fancy FCNC — need a reliable SM reference too

Angle γ

Despite the consistency of the KM picture — the allowed region for the triangle vertex blows up if SM isn't assumed.

This is driven by the 5-degree uncertainty on the CKM angle γ, the least well determined angle of the triangle.

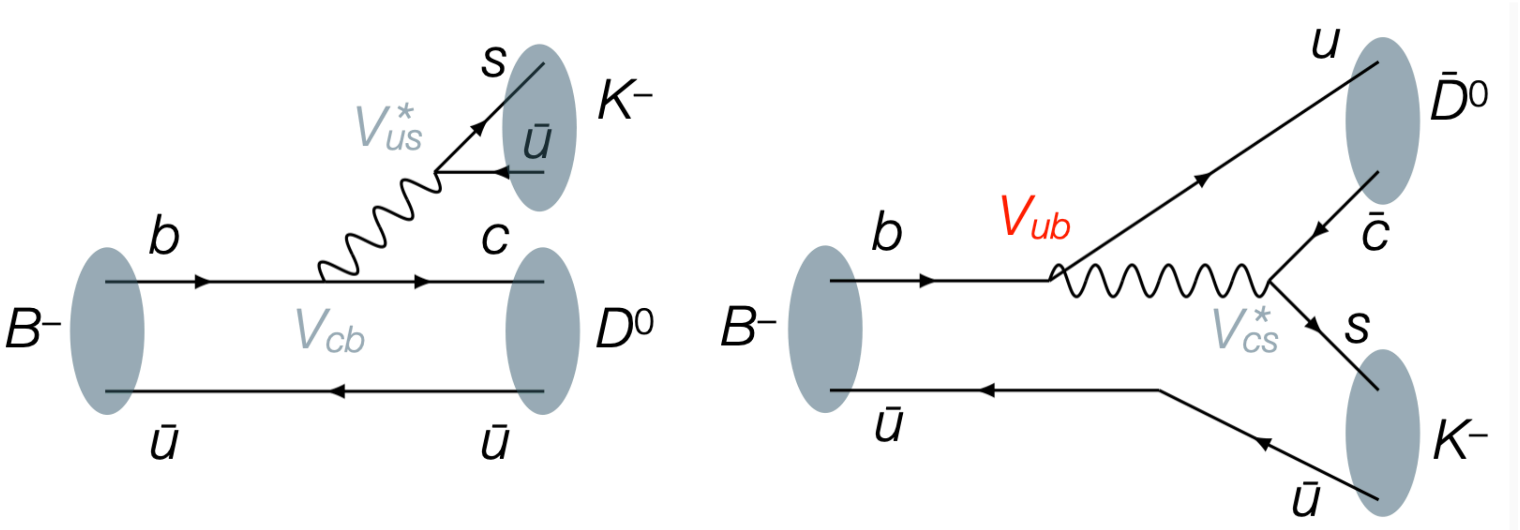
γ uncertainty totally statistical because γ is accessed through interference of various rare tree-level decays of the type *B —> D h*



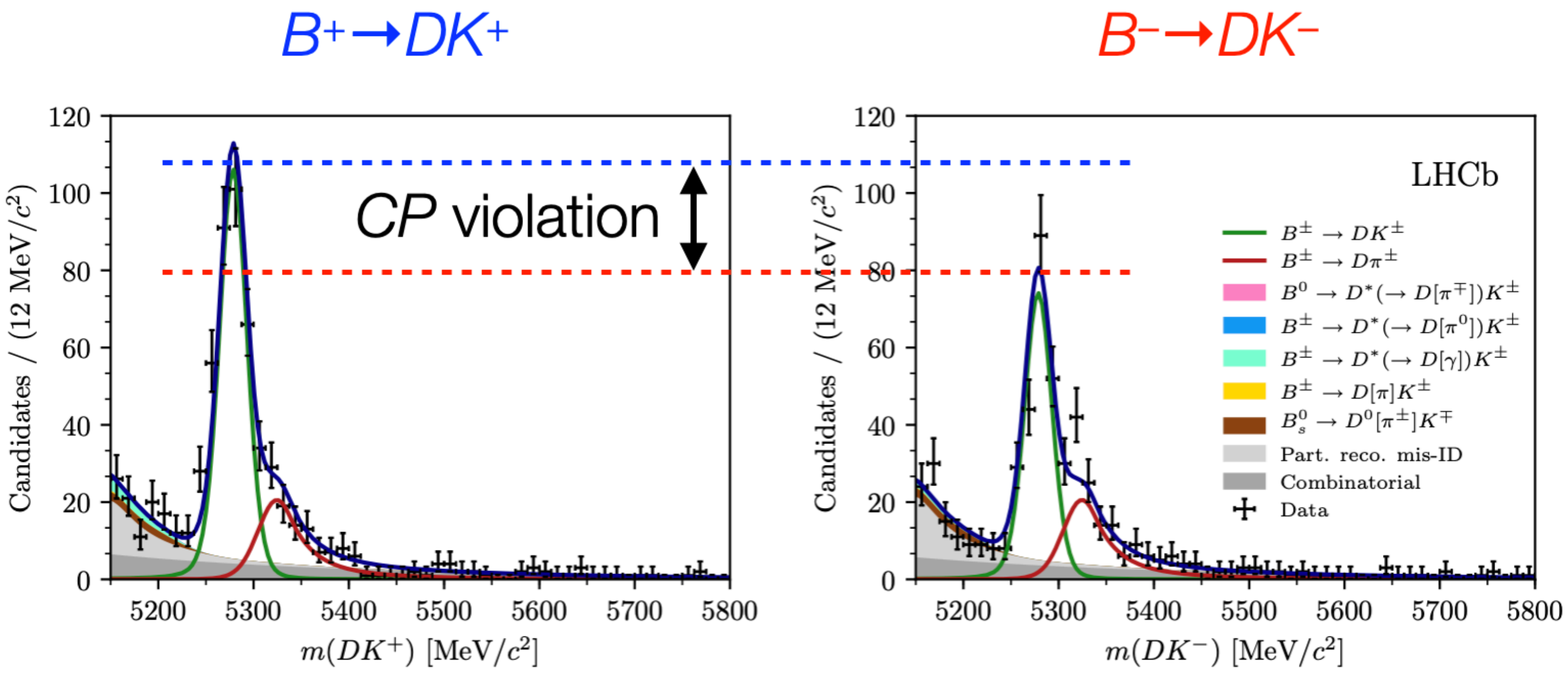
Zeroing-in on γ is a key goal of current CKM physics.

Expect γ uncertainty to shrink to 1-3 degrees with full LHCb and Belle II data sets

Angle γ



The two amplitudes interefere if D0 and D0bar reconstructed in the same final state such as Ks pipi. The measurement of the interference allows determining gamma.



$D \to K_S^0 \pi^+ \pi^-$

Expect γ uncertainty to shrink to 1-3 degrees with full LHCb and Belle II data sets

Take-home

The standard model is incomplete but technically stable up to 10^{10} GeV

High-energy direct searches are coming empty handed — more powerful colliders do not seem to come anytime soon.

Exploiting the power of quantum interference in quark-flavor transitions by measuring precisely low-energy processes may well be our best (only?) resort to uncover the ultraviolet completion of the SM (or to learn where not to search).

LHCb, Belle II, and dedicated K experiments will be driving such program at full steam in the next decade. Important contributions expected from ATLAS/CMS too.

Over the next decade we will zero-in on quark flavor. If any sizable anomaly is lurking there we will nail it. If not, we will anyhow exclude a plethora of SM extensions, informing and guiding the searches in the future.

Whatever the outcome, the result would lead to a significantly more accurate understanding of the physics of matter at its most fundamental level. And it will be much fun…

The end

Credits

Thanks to I. Mannelli, G. Punzi, L. Ristori, M. Rescigno, B. Wicklund, J. Kroll, F. Bedeschi, P. Giromini. G. Isidori, I. Bigi, S. Gori, W. Altmannshofer, U. Nierste, M. Dorigo, A. Di Canto.

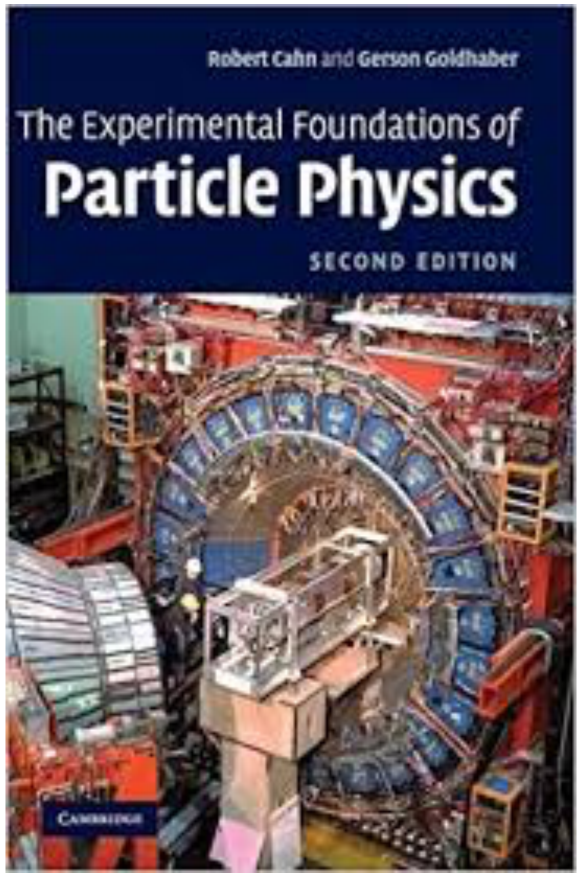
for enlightning many of the notions discussed here in formal lectures, discussions, etc…

Thanks to G. Raven, T. Gershon, K. Trabelsi, V. Sharma, F. Wuerthwein, G. Isidori, A. Manowar, M. Sozzi

for making your slides/notes publicly available so that I could steal from them.

Further sources

An extended/expanded version of these slides: https://wwwusers.ts.infn.it/~dtonelli/FlavorPhysics/ (PhD level)



Robert Cahn and Gerson Goldhaber

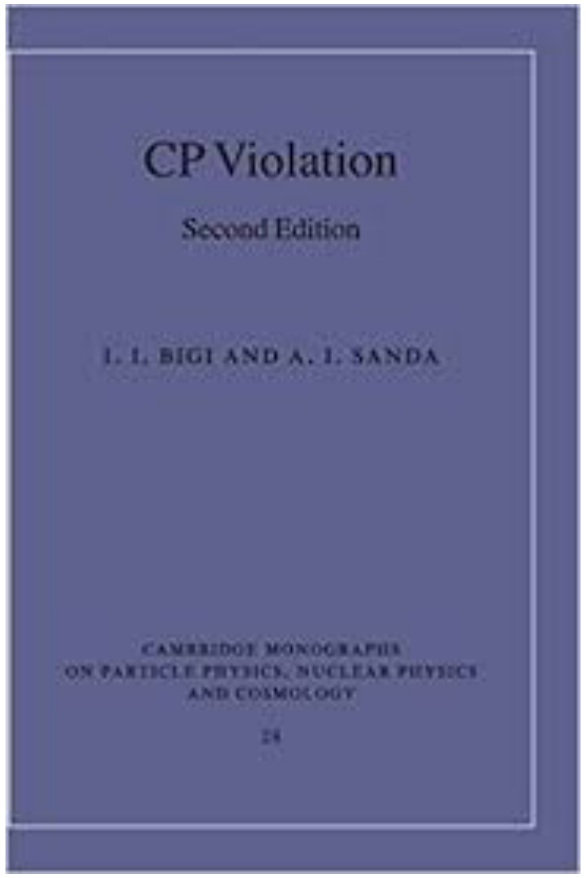
The Experimental Foundations of

Particle Physics

SECOND EDITION

CAMBRIDGE

Great book at large, independently of this course



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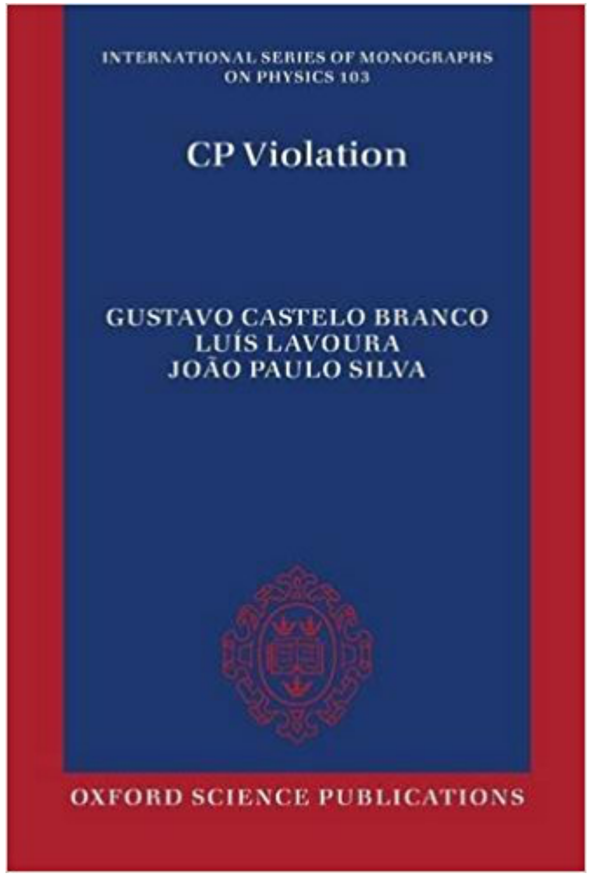

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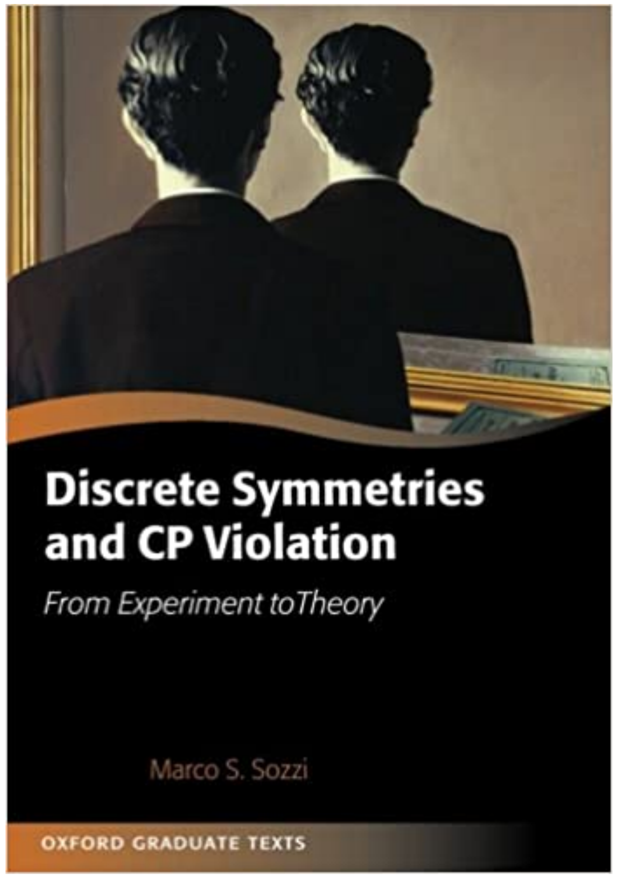

Discrete Symmetries and CP Violation

From Experiment toTheory

Marco S. Sozzi

OXFORD GRADUATE TEXTS

Rich experimental descriptions

In addtion, google "flavo(u)r physics lectures" — lots of nice material from various HEP schools: Karim Trabelsi at Jennifer and Jennifer2 schools, Tim Gershon/Gerhard Raven at the CERN-Fermilab schools etc

Thank you

https://en.wikipedia.org/wiki/Flavor_Flav