Heavy flavor production and decay at colliders

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Outline

What are heavy flavors and why they are interesting

Discrete symmetries

Formalism for CP violation and unitarity triangle

Meson-antimeson oscillations

Flavor tagging

b-decay results from b-factories and LHCb

b-production results from ATLAS and CMS

Sources:

M. Bona’s PhD lectures

http://pprc.qmul.ac.uk/~bona/ulpg/cpv/

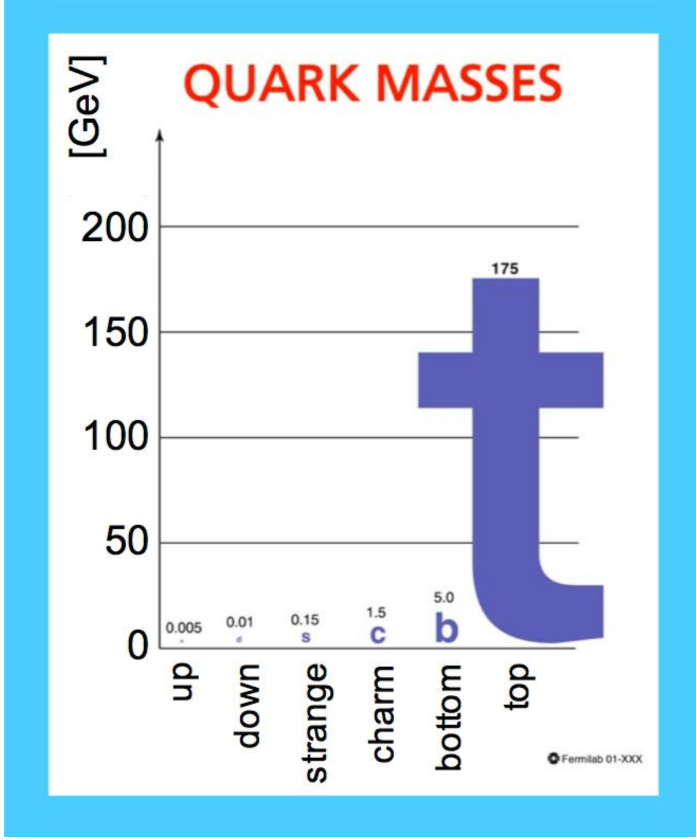
Talks at LHCP 2018

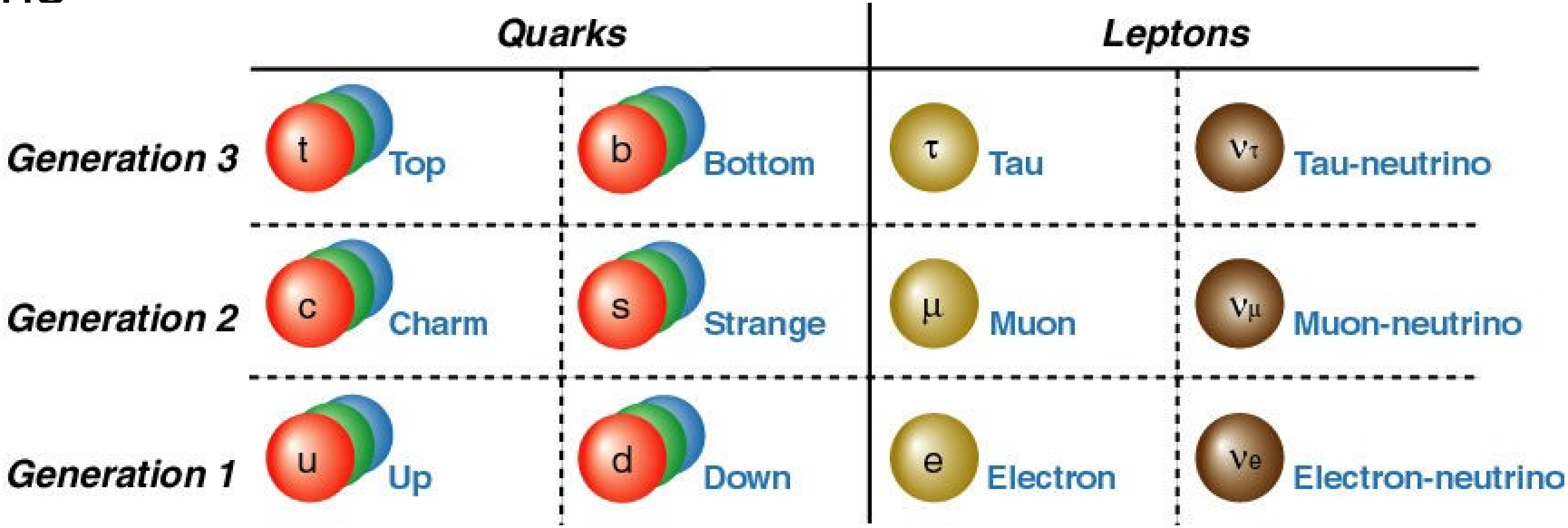
http://lhcp2018.bo.infn.it/programme.html#fh5co-agenda

What are heavy flavors?

Matter comes in three generations of quarks and three of leptons, that we order in mass. A quark (or lepton) type (for quarks: u,d,c,s,t,b) is called flavor, to distinguish it from color.

The heaviest quark is the top, so heavy that it decays before forming bound states. b and c are the heaviest to form mesons and baryons





	Quarks		Leptons	
Generation 3	t Top	b Bottom	τ Tau	ν_τ Tau-neutrino
Generation 2	c Charm	s Strange	μ Muon	ν_μ Muon-neutrino
Generation 1	u Up	d Down	e Electron	ν_e Electron-neutrino

Heavy Quark Effective Theory

Quantum ChromoDynamics has an intrinsic scale, Λ_{QCD} ~ 200 MeV, above which perturbative expansion can be applied, and below which (soft QCD) only empirical models can be used.

For quark masses $m_Q >> \Lambda_{QCD}$ Perturbative expansions can be used, and calculations easier

For states with two heavy quarks (J/Ψ, ϒ), Non-Relativistic QCD is used.

No time to describe HQET here; refer to e.g.

A.V. Manohar and M.B. Wise, Heavy Quark Physics, Cambridge University Press (2000)

Symmetries

An operator can be applied to a Lagrangian representing a physical system; if the Lagrangian is invariant under this transformation, the operator corresponds to a conserved quantity (Noether's theorem).

Ex. invariance of Lagrangian under translation

x → x+a leads to momentum conservation

If the Lagrangian is not conserved under an operator, the symmetry is broken, and the physics will be different. In some cases, symmetry breaking is subtle and can be treated as a perturbation

Discrete symmetries

Three discrete symmetries can be applied to a Lagrangian:

Parity

Charge conjugation

Time reversal

In classical physics, all these symmetries are conserved at microscopic level; macroscopically, the concept of entropy breaks T-symmetry.

Things are more complicated in quantum mechanics:

Parity: $\mathcal{P}$

- Reflection through a mirror, followed by a rotation of π around an axis defined by the mirror plane.
  - Space is isotropic, so we care if physics is invariant under a mirror reflection.

$\mathbf{r} \rightarrow -\mathbf{r}$

$\mathbf{p} \rightarrow -\mathbf{p}$

$\mathbf{L} \rightarrow \mathbf{L}$

- $\mathcal{P}$ is violated in weak interactions:

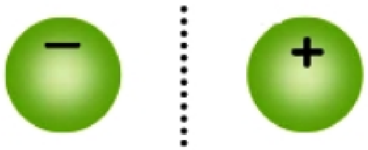
$$[\mathcal{P}, \mathcal{H}_W] \neq 0$$

- Vectors change sign under a $\mathcal{P}$ transformation, pseudo-vectors or axial-vectors do not.
- $\mathcal{P}$ is a unitary operator: $\mathcal{P}^2=1$.

T. D. Lee & G. C. Wick Phys. Rev. **148** p1385 (1966) showed that there is no operator $\mathcal{P}$ that adequately represents the parity operator in QM.

Charge Conjugation: $\mathcal{C}$

- Change a quantum field ϕ into $\phi^\dagger$, where $\phi^\dagger$ has opposite U(1) charges:
  - *baryon number, electric charge, lepton number, flavour quantum numbers like strangeness & beauty etc.*
- Change particle into antiparticle.
  - *the choice of particle and antiparticle is just a convention.*



$e^- \rightarrow e^+$

$\gamma \rightarrow \gamma$

- $\mathcal{C}$ is violated in weak interactions, so matter and antimatter behave differently, and:

$$[\mathcal{C}, \mathcal{H}_W] \neq 0$$

- $\mathcal{C}$ is a unitary operator: $\mathcal{C}^2 = 1$.

Parity and Charge Conjugation: $\mathcal{CP}$

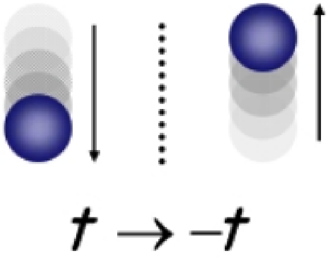
The fundamental point is that CP symmetry is broken in any theory that has complex coupling constants in the Lagrangian which cannot be removed by any choice of phase redefinition of the fields in the theory.

- ▣ Weak interactions are left-right asymmetric.
  - *It is not sufficient to consider $\mathcal{C}$ and $\mathcal{P}$ violation separately in order to distinguish between matter and antimatter.*
  - *i.e. if helicity is negative (left) or positive (right).*
- ▣ $\mathcal{CP}$ is a unitary operator: $\mathcal{CP}^2=1$

Time reversal: $\mathcal{T}$

Not to be confused with the
classical consideration of the
entropy of a macroscopic system.

- ‘Flips the arrow of time’
  - *Reverse all time dependent quantities of a particle (momentum/spin).*
  - *Complex scalars (couplings) transform to their complex conjugate.*
  - *It is believe that weak decays violate $\mathcal{T}$, but EM interactions do not.*



- $\mathcal{T}$ is an anti-unitary operator: $\mathcal{T}^2$=-1.

$\mathcal{CPT}$

- All locally invariant Quantum Field Theories conserve $\mathcal{CPT}$.[1]
- $\mathcal{CPT}$ is anti-unitary: $\mathcal{CPT}^2$=-1.
- $\mathcal{CPT}$ can be violated by non-local theories like quantum gravity. These are hard to construct.
  - *see work by Mavromatos, Ellis, Kostelecky etc. for more detail.*
- If $\mathcal{CPT}$ is conserved, a particle and its antiparticle will have
  - *The same mass and lifetime .*
  - *Symmetric electric charges.*
  - *Opposite magnetic dipole moments (or gyromagnetic ratio for point-like leptons).*

[1] See Weinberg volume I and references therein (Lueders 1954) for a proof of this.

Examples

$$\mathcal{CP}\,|\,u\,\rangle = |\,\bar{u}\,\rangle$$

The u quark has $J^P = \frac{1}{2}^+$, so the $\mathcal{P}$ operator acting on u has an eigenvalue of +1. The $\mathcal{C}$ operator changes particle to antiparticle.

$$\mathcal{CP}\,|\,\pi^0\,\rangle = -\,|\,\pi^0\,\rangle$$

The π^0 has $J^{PC} = 0^{-+}$, so the minus sign comes from the parity operator acting on the π^0 meson. The $\mathcal{C}$ operator changes particle to antiparticle. A π^0 is its own antiparticle.

$$\mathcal{CP}\,|\,\pi^\pm\,\rangle = -\,|\,\pi^\mp\,\rangle$$

The $\pi^\pm$ has $J^P = 0^-$, so the minus sign comes from the parity operator acting on the π meson. The $\mathcal{C}$ operator changes the particle to antiparticle.

CKM matrix in the Standard Model

The charged current interaction gets a flavour structure encoded in the Cabibbo Kobayashi Maskawa (CKM) matrix V.

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}}\left(\bar{\tilde{U}}_L \gamma^\mu W_\mu^+ V \tilde{D}_L + \bar{\tilde{D}}_L \gamma^\mu W_\mu^- V^\dagger \tilde{U}_L\right).$$

V_{ij} connects left-handed up-type quark of the ith gen. to left-handed down-type quark of jth gen. Intuitive labelling by flavour:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad V_{13} = V_{ub} \;\; etc$$

Via W exchange is the only way to change flavour in the SM.

Unitary matrix independent parameters

in general, an n × n unitary matrix has n^2 real and independent parameters:

- a n × n matrix would have $2n^2$ parameters
- the unitary condition imposes n normalization constraints
- n(n - 1) conditions from the orthogonality between each pair of columns:

thus $2n^2 - n - n(n - 1) = n^2$.

In the CKM matrix, not all of these parameters have a physical meaning:

- given n quark generations, 2n - 1 phases can be absorbed by the freedom to select the phases of the quark fields
  - Each u, c or t phase allows for multiplying a row of the CKM matrix by a phase, while each d, s or b phase allows for multiplying a column by a phase.

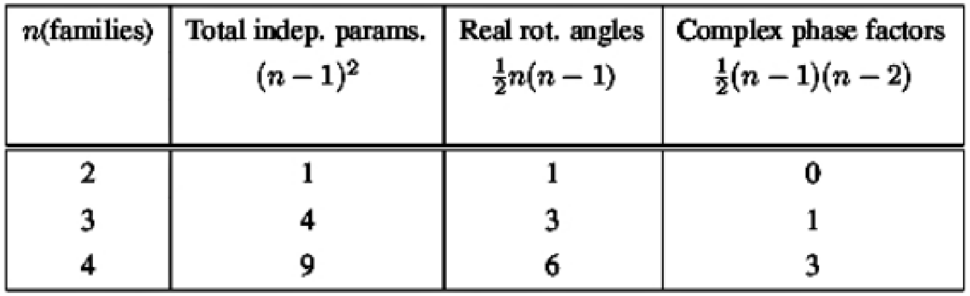
thus: $n^2 - (2n - 1) = (n - 1)^2$.

Among the n^2 real independent parameters of a generic unitary matrix:

- ½ n(n - 1) of these parameters can be associated to real rotation angles,

so the number of independent phases in the CKM matrix case is:

$n^2 - \frac{1}{2} n(n-1) - (2n - 1) = \frac{1}{2} (n - 1)(n - 2)$



n(families)	Total indep. params. $(n-1)^2$	Real rot. angles $\frac{1}{2}n(n-1)$	Complex phase factors $\frac{1}{2}(n-1)(n-2)$
2	1	1	0
3	4	3	1
4	9	6	3

CKM matrix parameterisations

"PDG" parametrization (exact, fully general)

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$s_{ij} \equiv \sin\Theta_{ij}$, $c_{ij} \equiv \cos\Theta_{ij}$. δ is the CP violating phase.

CKM matrix parameterisations

V in Nature is hierarchical $\Theta_{13} \ll \Theta_{23} \ll \Theta_{12} \ll 1$. Wolfenstein parametrization; expansion in $\lambda = \sin\Theta_C$, $A, \rho, \eta \sim \mathcal{O}(1)$

$$V = \begin{pmatrix} 1-\lambda^2/2 & +\lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & +A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

fits: $\lambda = 0.225, \quad A = 0.81, \quad \bar{\rho} = 0.14, \quad \bar{\eta} = 0.34$

we'll talk about the fit at the end

beyond lowest order $\bar{\rho} = \rho(1-\lambda^2/2)$ and $\bar{\eta} = \eta(1-\lambda^2/2)$

$\eta \neq 0$ signals CP violation; third gen. quarks decoupled at order λ^2.

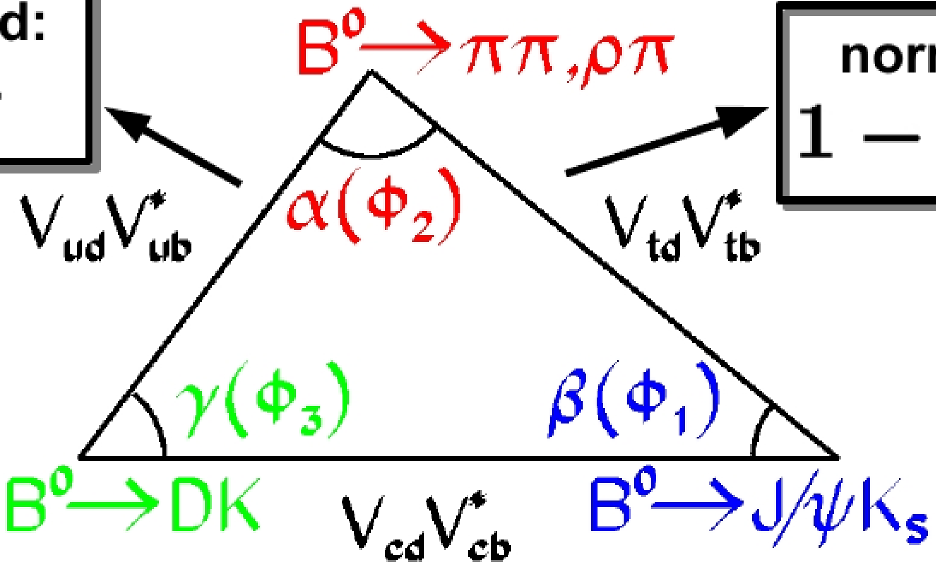
Unitarity triangle

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

many observables
functions of $\bar{\rho}$ and $\bar{\eta}$:
overconstraining

$$\alpha = \pi - \beta - \gamma$$

normalized:
$\bar{\rho} + i\bar{\eta}$



$B^0 \rightarrow \pi\pi, \rho\pi$

$\alpha(\phi_2)$

$V_{ud}V_{ub}^*$

$V_{td}V_{tb}^*$

$\gamma(\phi_3)$

$\beta(\phi_1)$

$B^0 \rightarrow DK$

$V_{cd}V_{cb}^*$

$B^0 \rightarrow J/\psi K_s$

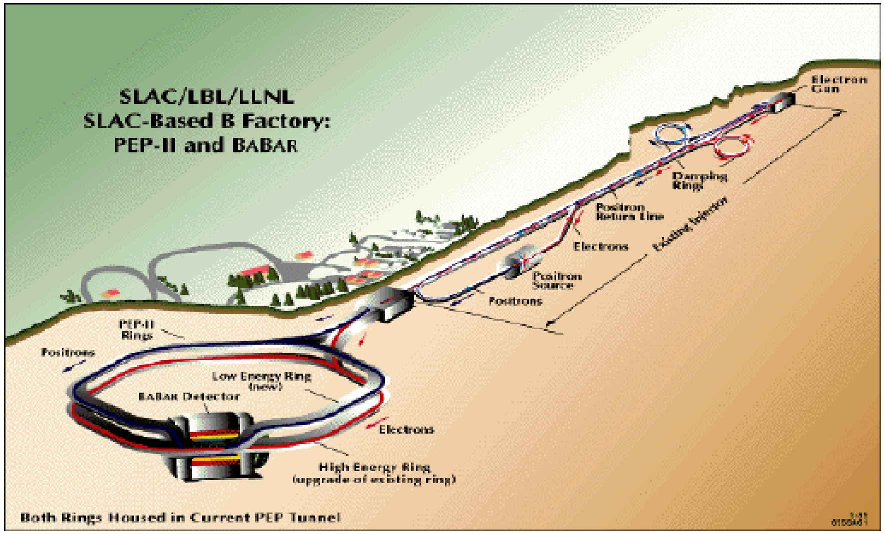
normalized:
$1 - \bar{\rho} - i\bar{\eta}$

$$\gamma = atan\left(\frac{\bar{\eta}}{\bar{\rho}}\right)$$

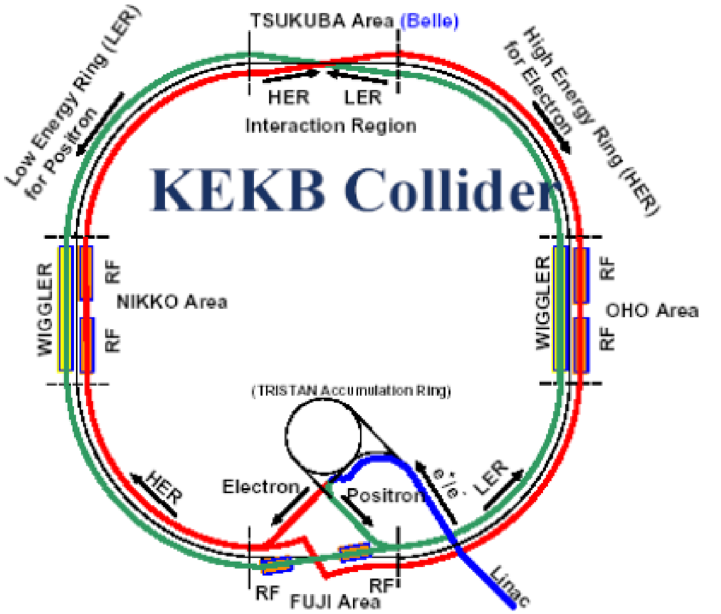
$$\beta = atan\left(\frac{\bar{\eta}}{(1-\bar{\rho})}\right)$$

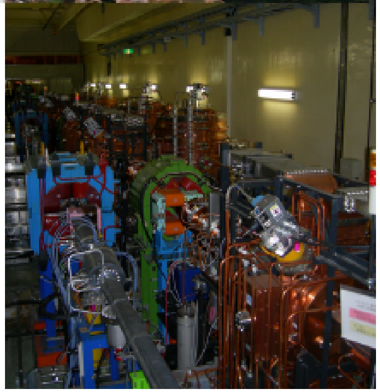
PEP-II and KEKB

PEP-II
- 9 GeV e^- on 3.1 GeV e^+
- $\Upsilon(4S)$ boost: $\beta\gamma = 0.56$



KEKB
- 8 GeV e^- on 3.5 GeV e^+
- $\Upsilon(4S)$ boost: $\beta\gamma = 0.425$

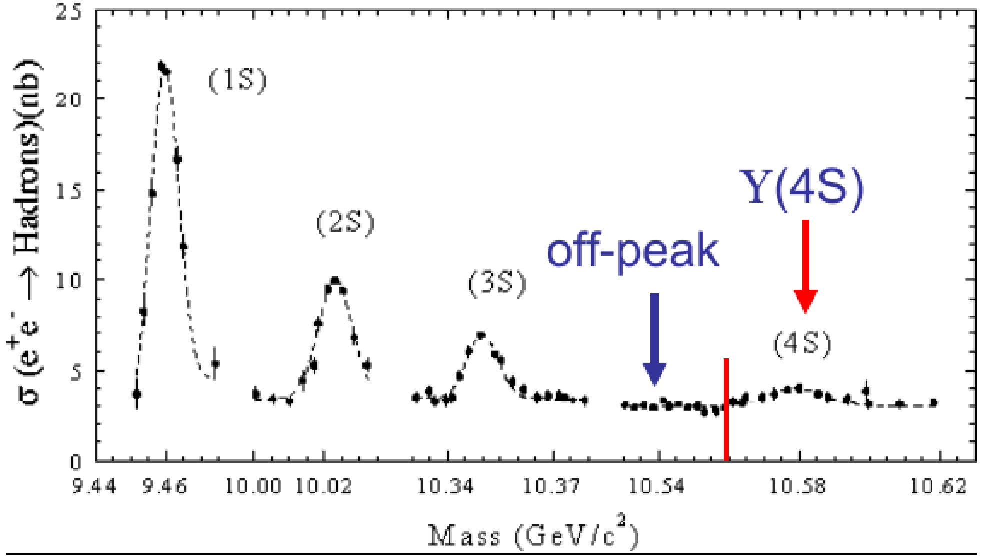




Producing B mesons

- **Collide electrons and positrons at center-of-mass energy √s = 10.58 GeV/c²**

$e^+e^- \to$	Cross-section (nb)
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$d\bar{d}$	0.35
$u\bar{u}$	1.39
$\tau^+\tau^-$	0.92
$\mu^+\mu^-$	1.16
e^+e^-	~ 40



many types of interaction occur.

- We're interested in **e^+e^- → Υ(4S) → $\bar{\textbf{B}}$B** (for B physics).
- where we have $$\frac{\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)}{\mathcal{B}(\Upsilon(4S) \to B^+B^-)} \simeq 1$$

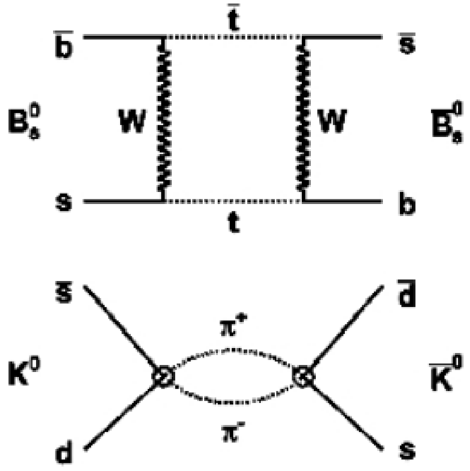
Neutral meson oscillation

- We have flavour eigenstates M^0 and $\overline{M}^0$:
  - M^0 can be K^0 (sd), D^0 (cu), B_d^0 (bd) or B_s^0 (bs)

flavour states ≠ H_{eff} eigenstates:
(defined flavour) (defined $m_{1,2}$ and $\Gamma_{1,2}$)

- if we consider only strong or electromagnetic interactions only, these flavour eigenstates would correspond to the physical ones
- However due to the weak interaction, the physical eigenstates are different from the flavour ones. This means that they can mix into each other:
  - via short-distance or long-distance processes
- and then the flavour superposition decays

$$M = p\,M^0 \pm q\,\overline{M}^0$$



Neutral meson oscillation (II)

- We have flavour eigenstates M^0 and $\overline{M}^0$:
  - M^0 can be K^0 (sd), D^0 (cu), B_d^0 (bd) or B_s^0 (bs)

flavour states	$\neq$	H_{eff} eigenstates:
(defined flavour)		(defined $m_{1,2}$ and $\Gamma_{1,2}$)

- Time-dependent Schrödinger eqn. describes the evolution of the system:

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = H\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix}$$

  - H is the hamiltonian; M and Γ are 2x2 hermitian matrices ($a_{ij} = \overline{a}_{ji}$)

$$M = \tfrac{1}{2}(H+H^\dagger) \text{ and } \Gamma = i(H-H^\dagger)$$

- CPT theorem: $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$
  - particle and antiparticle have equal masses and lifetimes

Solving the Schrödinger equation

- Physical states: eigenstates of effective Hamiltonian:

$$M_{S,L} \text{ (or } M_{L,H}) = p\, M^0 \pm q\, \overline{M}^0$$

label can be either S,L (short-, long-lived) or L,H (light, heavy) depending on values of Δm & $\Delta\Gamma$ (labels 1,2 usually reserved for CP eigenstates)

p & q complex coefficients that satisfy $|p|^2 + |q|^2 = 1$

  - CP conserved if physical states = CP eigenstates ($|q/p| = 1$)

- Eigenvalues (μ) and mass (Δm) and lifetime ($\Delta\Gamma$) differences can be derived with this formalism:

$$\mu_{L,H} = m_{L,H} - i/2\, \Gamma_{L,H} = (M_{11} - i/2\, \Gamma_{11}) \pm (q/p)\, (M_{12} - i/2\, \Gamma_{12})$$

$$\Delta m = m_H - m_L \text{ and } \Delta\Gamma = \Gamma_H - \Gamma_L$$

$$(\Delta m)^2 - \tfrac{1}{4} (\Delta\Gamma)^2 = 4\, (|M_{12}|^2 + \tfrac{1}{4} |\Gamma_{12}|^2)$$

$$\Delta m \Delta\Gamma = 4\, \mathcal{Re}\, (M_{12} \Gamma_{12}^*)$$

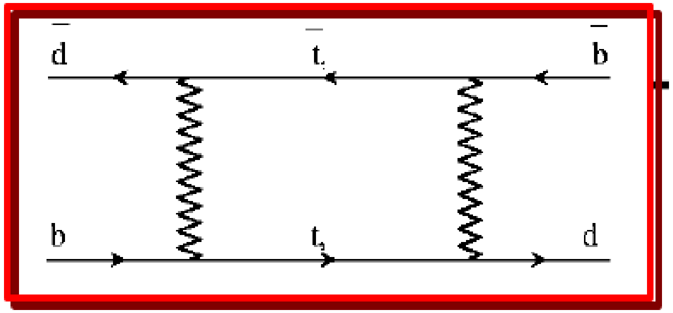
$$(q/p)^2 = (M_{12}^* - i/2\, \Gamma_{12}^*)/(M_{12} - i/2\, \Gamma_{12})$$

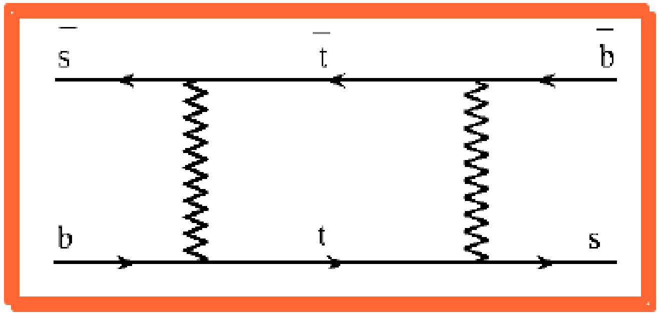
other useful definitions:

$x \equiv \Delta m/\Gamma$

$y \equiv \Delta\Gamma/2\Gamma$

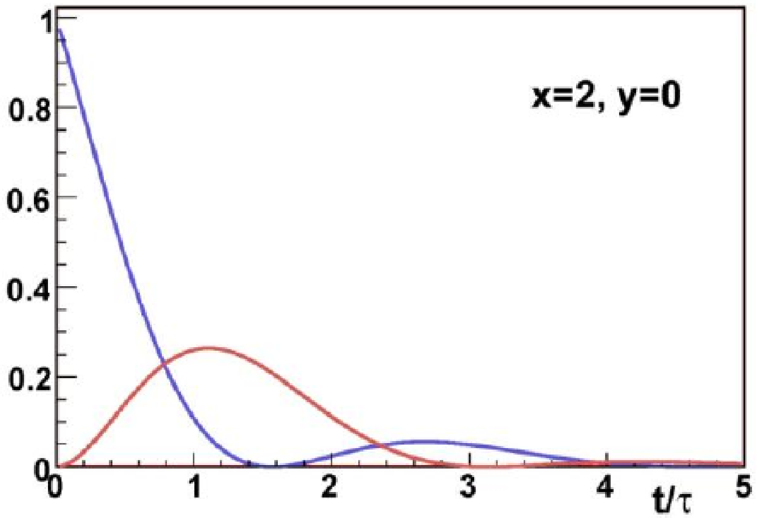
B oscillations

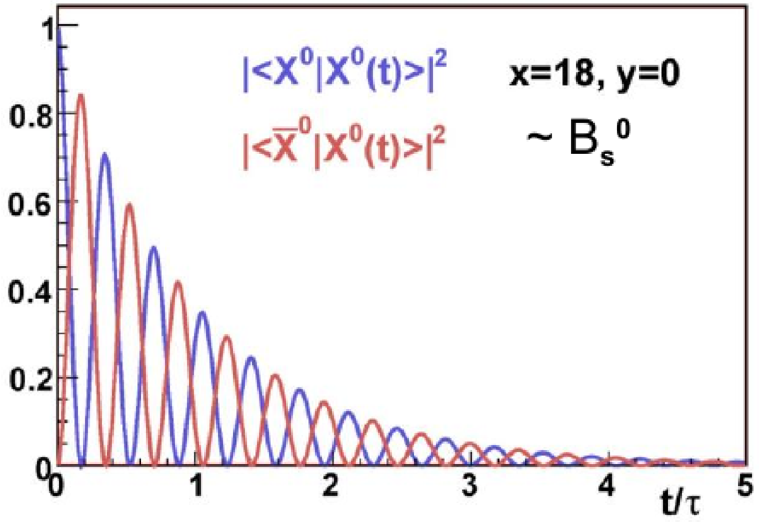




$\bar{B}^0$-B^0 transition →
box diagram at quark level

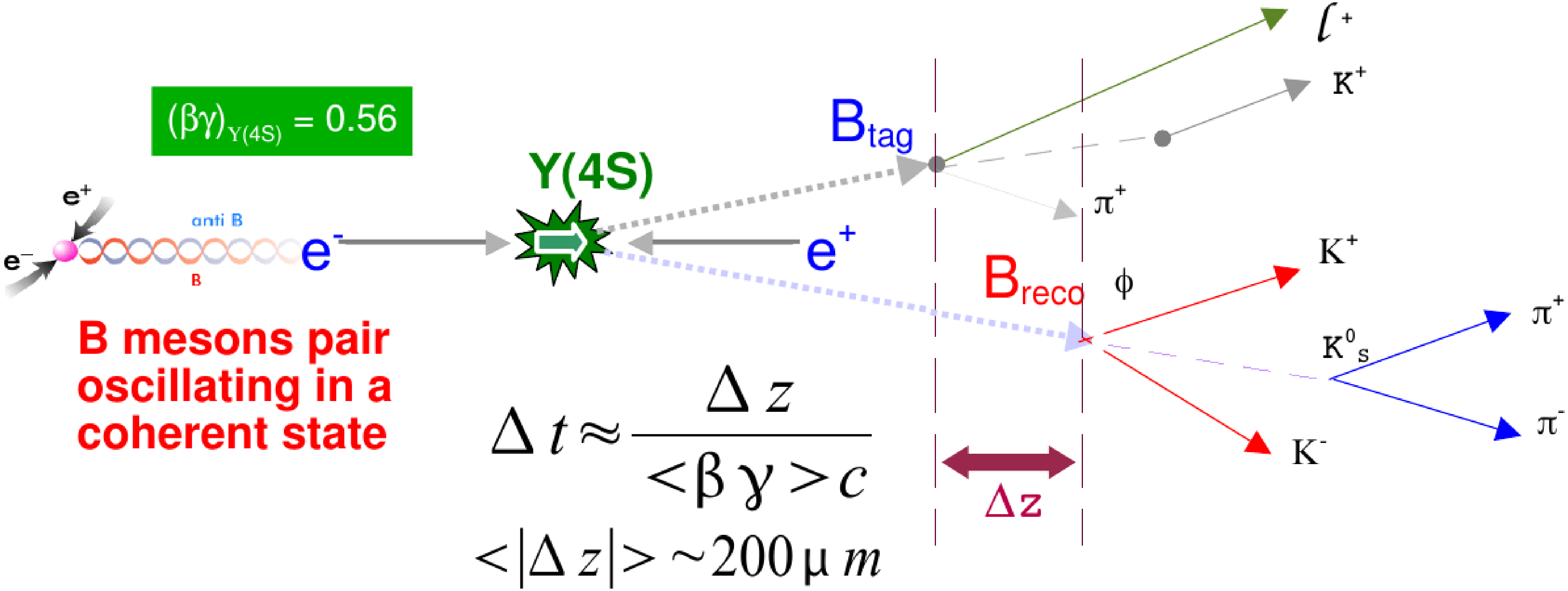
so same phenomenology also
in the B_s, except that
the oscillation frequency is very different





probab. to observe an initially produced X^0 as X^0 after time t
probab. to observe an initially produced X^0 as $\bar{X}^0$ after time t

Experimental technique



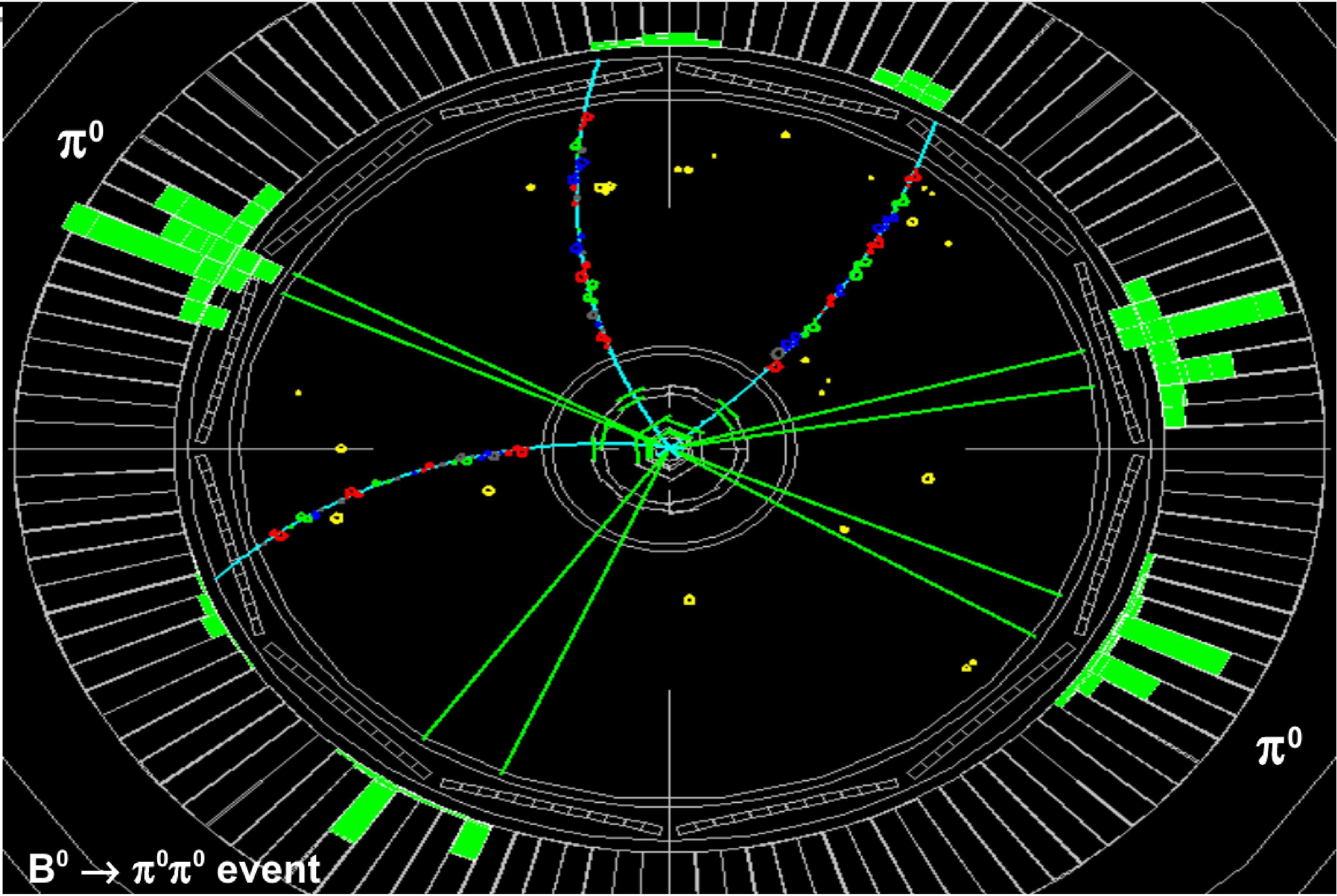
$(\beta\gamma)_{\Upsilon(4S)} = 0.56$

B mesons pair oscillating in a coherent state

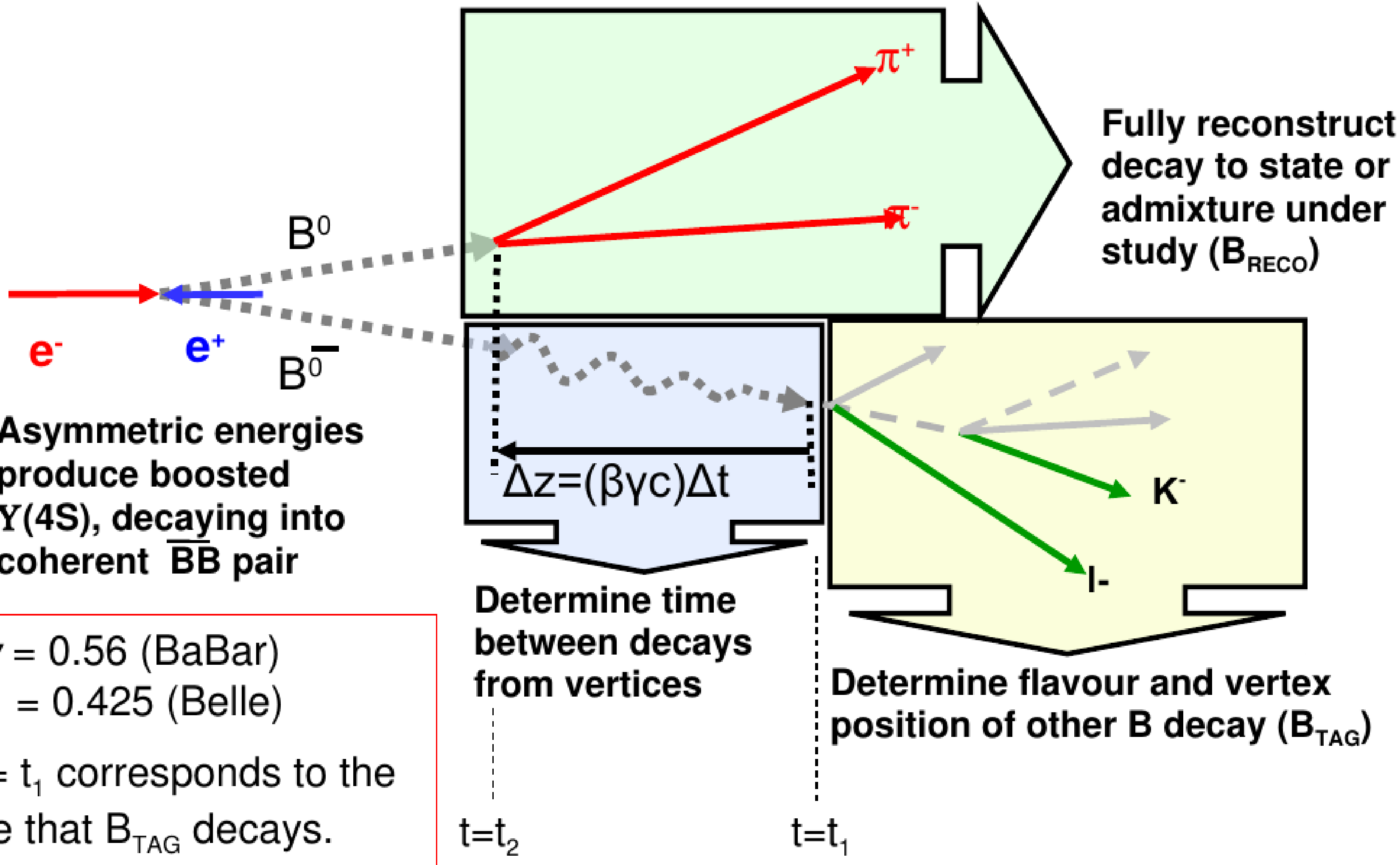
$$\Delta t \approx \frac{\Delta z}{<\beta\gamma>c}$$

$$<|\Delta z|> \sim 200\,\mu m$$

What does an event look like?



Measuring Δt



Asymmetric energies produce boosted $\Upsilon(4S)$, decaying into coherent $\overline{B}B$ pair

Fully reconstruct decay to state or admixture under study (B_{RECO})

Determine time between decays from vertices

Determine flavour and vertex position of other B decay (B_{TAG})

- $\beta\gamma = 0.56$ (BaBar)
  $= 0.425$ (Belle)
- $t = t_1$ corresponds to the time that B_{TAG} decays.
- $t_2 - t_1 = \Delta t$

⇨ Then fit the Δt distribution to obtain the amplitude of sine and cosine terms.

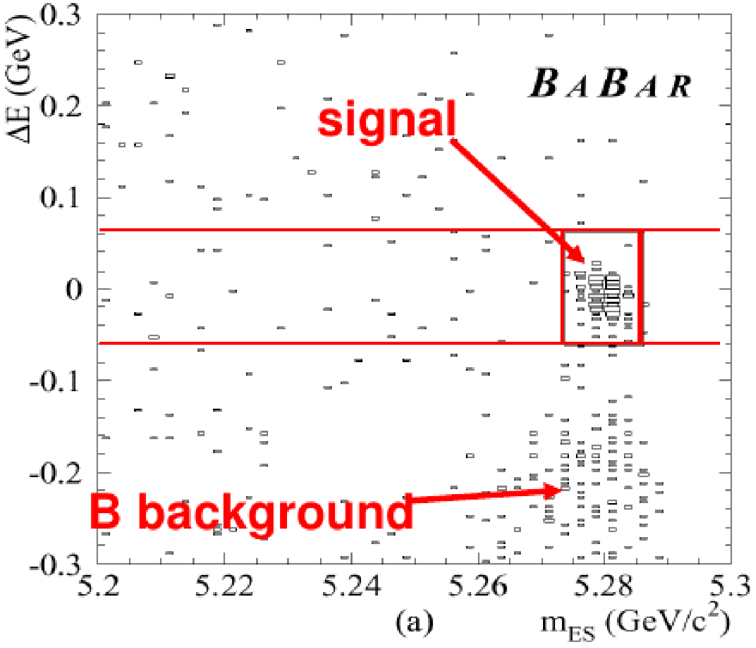
Isolating signal events

- Beam energy is known very well at an e^+e^- collider
  - use an energy difference and effective mass to select events:

$$\Delta E = E_B^* - \frac{\sqrt{s}}{2}$$

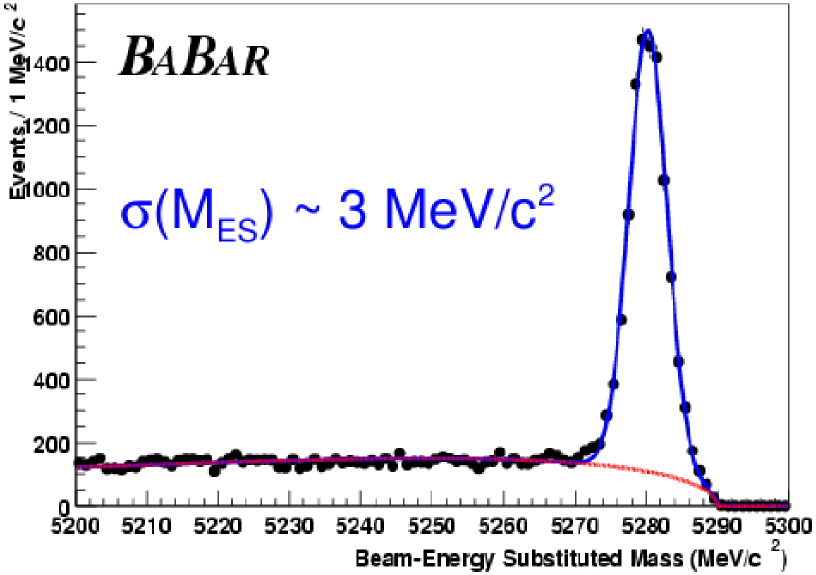
$$m_{ES} = \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$$

$\sigma(\Delta E)$ ~ 15-80 MeV (mode dependent)



signal

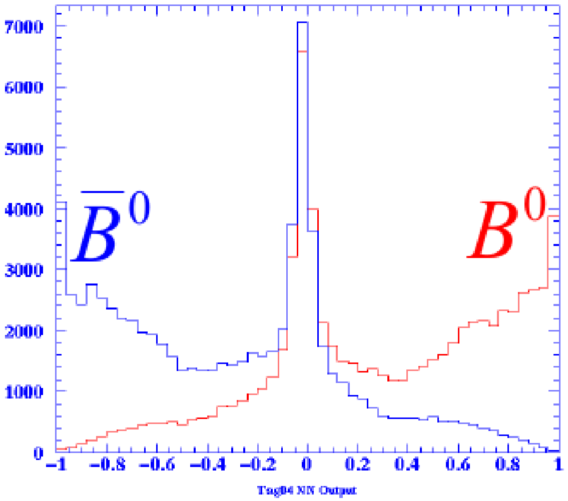
B background

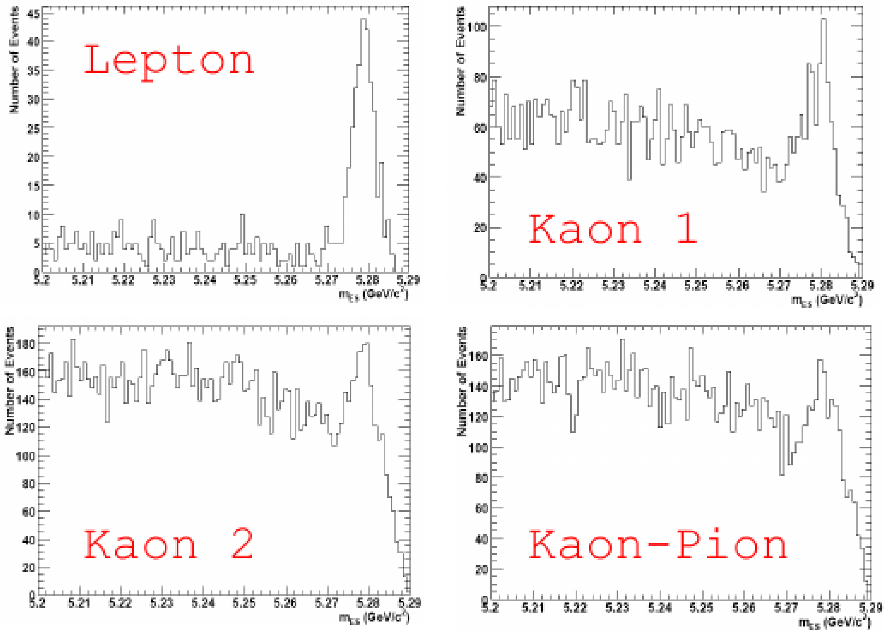


$\sigma(M_{ES})$ ~ 3 MeV/c^2

Flavour tagging

- Decay products of B_{TAG} are used to determine its flavour.
- At $\Delta t=0$, the flavour of B_{RECO} is opposite to that of other B_{TAG}.
- B_{RECO} continues to mix until it decays.
- Different B_{TAG} final states have different *purities* and different *mis-tag probabilities*.
- Can (bottom) split information by physical category or (top) use a continuous variable to distinguish particle and anti-particle.

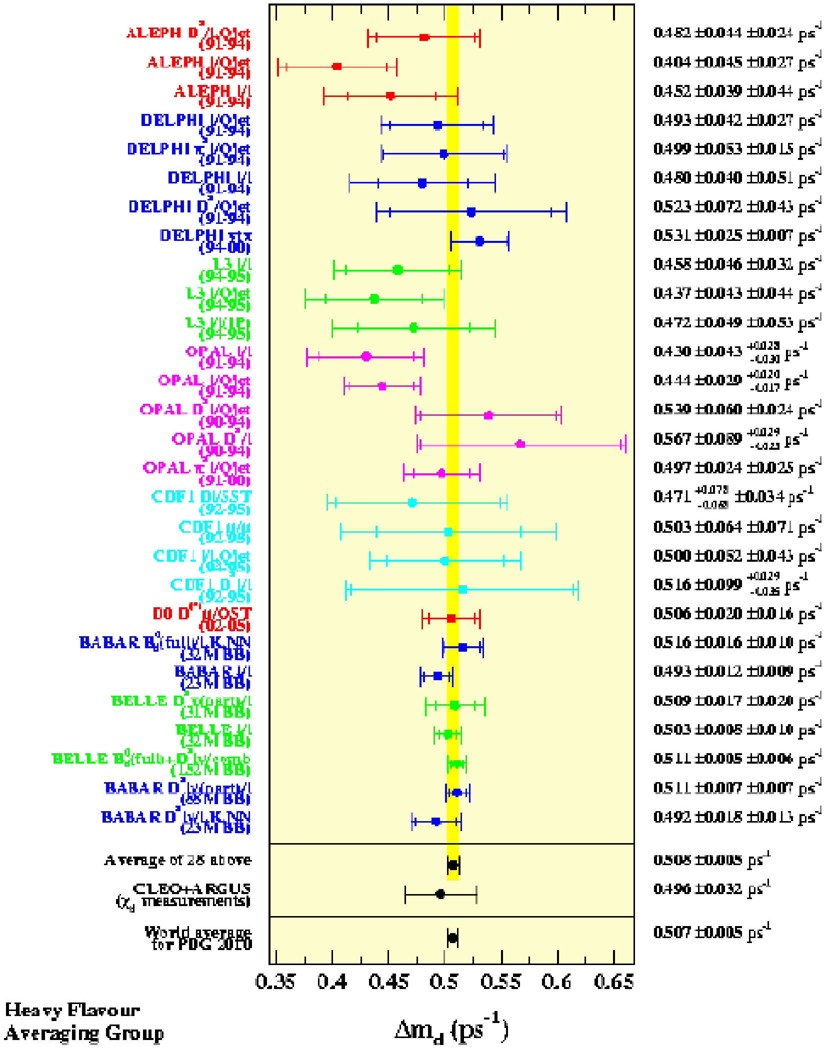




BaBar's flavour tagging algorithm splits events into mutually exclusive categories ranked by signal purity and mis-tag probability. Belle opts to use a continuous variable output.

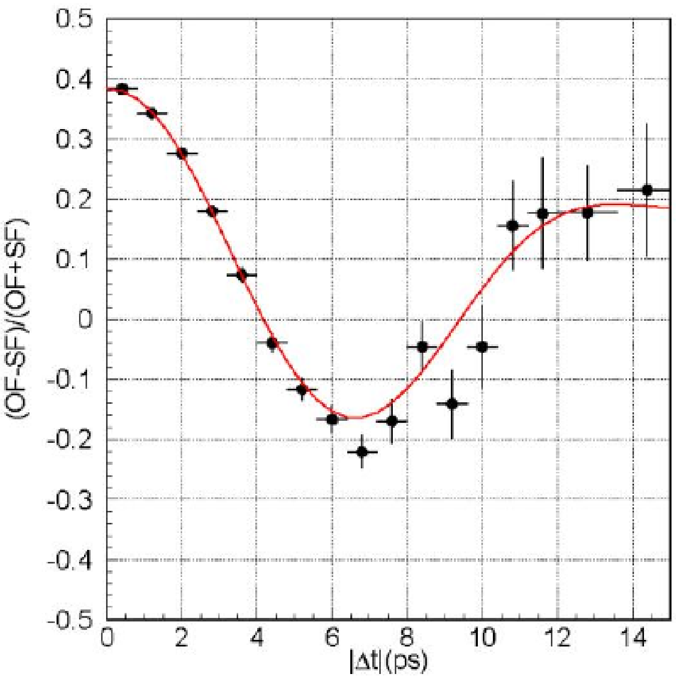
B_d oscillations

HFAG, http://www.slac.stanford.edu/xorg/hfag/



$$\frac{d\Gamma(B^0 \to f)/d\Delta t - d\Gamma(\overline{B} \to f)/d\Delta t}{d\Gamma(B^0 \to f)/d\Delta t + d\Gamma(\overline{B}^0 \to f)/d\Delta t} =$$

$$=(1-2w)\cos(x\Delta t) \otimes R(\Delta t)$$



$\Delta m_d = (0.507 \pm 0.005)\ \mathrm{ps}^{-1}$

$x = \Delta m_d \cdot \tau_{Bd} = 0.774 \pm 0.008$

B_s oscillations

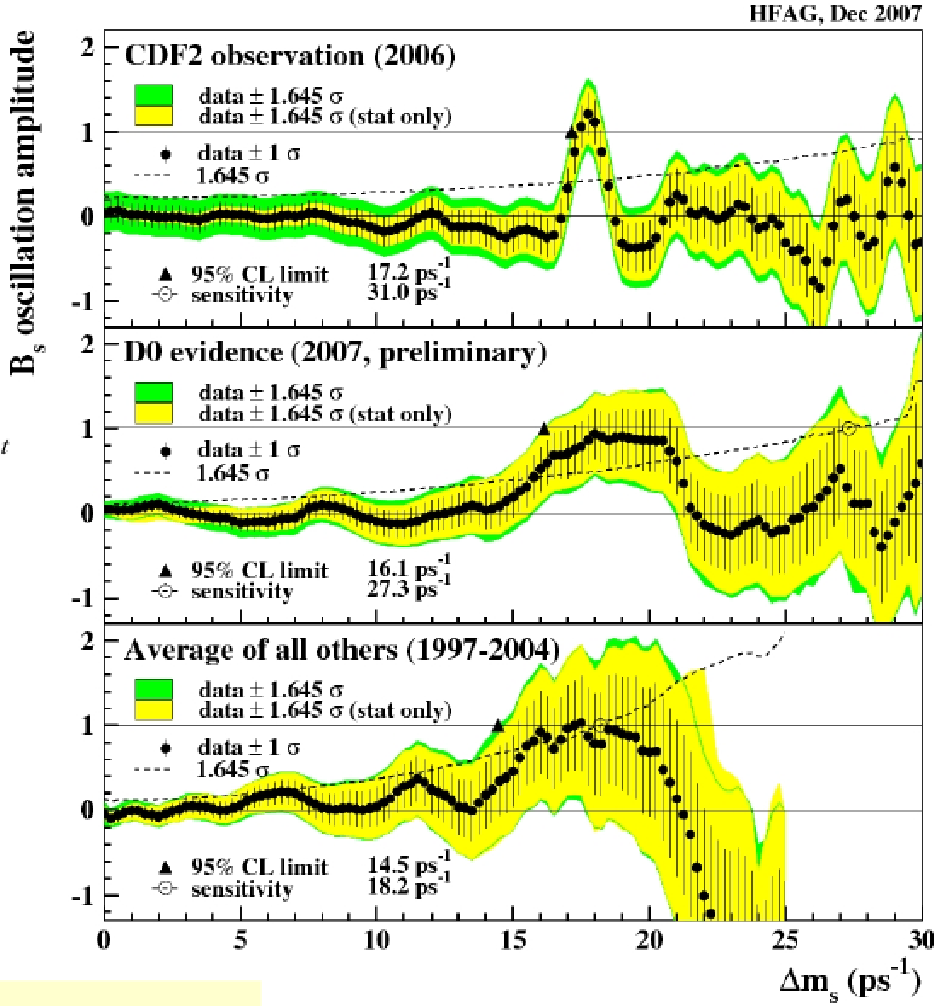
At the Tevatron on the B_s:

► amplitude method, instead of extracting directly Δm_s (*à la* LEP)

$$\frac{1}{|A_f|^2}\frac{d\Gamma(P^0(\overline{P}^0)\rightarrow f)}{d\Delta t} = [1 \pm A(1-2w)\cos(x\Delta t)]e^{-\Delta t}$$

► fit A at different values of Δm_s; if A=1

⇨ oscillations at this Δm_s value



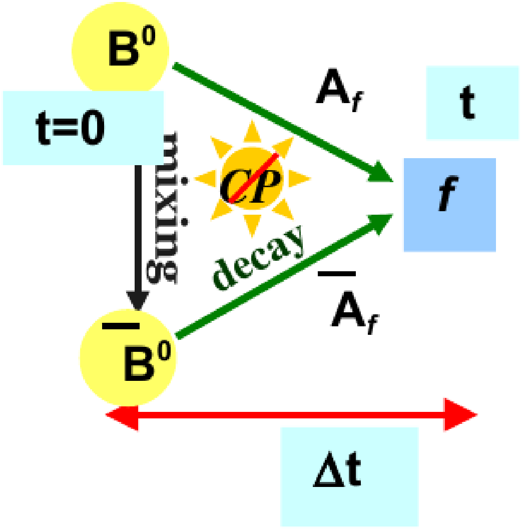
Very precise determination from the Tevatron:

Δm_s=(17.77±0.10±0.07) ps^{-1}

$x=\Delta m_s \cdot \tau_{Bs}$= 25.5±0.6

3 kinds of CP violation (recap)

Cartoon shows the decay of a B^0 or $\overline{B}^0$ into a CP eigenstate f_{CP}.



1. Direct CP violation.

$$P(B^0 \to f) \neq P(\overline{B}^0 \to \overline{f})$$

2. Indirect CP violation (CPV in mixing).

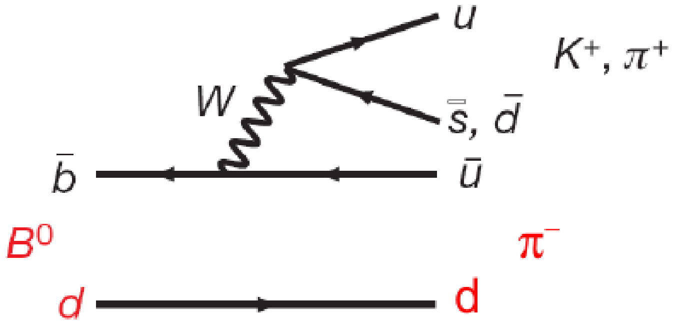
$$P(B^0 \to \overline{B}^0) \neq P(\overline{B}^0 \to B^0)$$

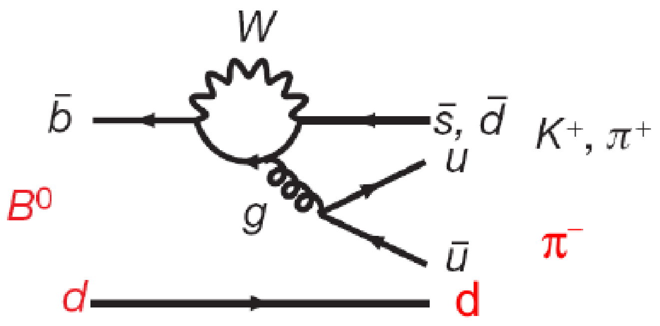
3. CPV in the interference between mixing and decay.

- Need more than one amplitude to have a non-zero CP violation: *interference*

Direct CP violation

- $B^0 \to K^{\pm}\pi^{\mp}$: Tree and gluonic penguin contributions

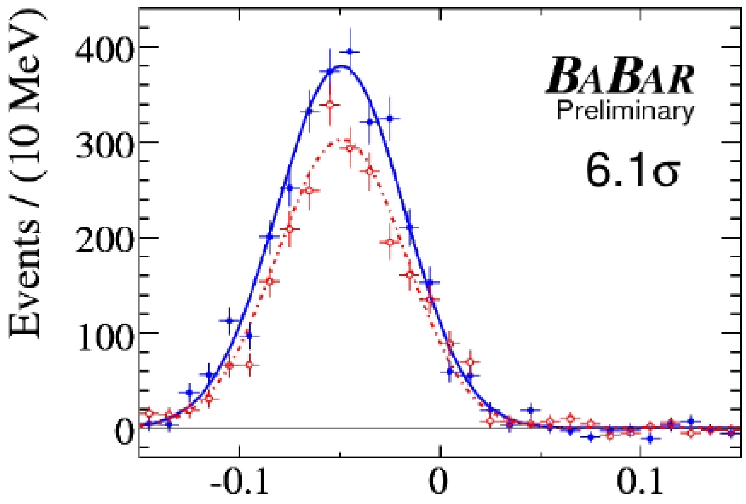




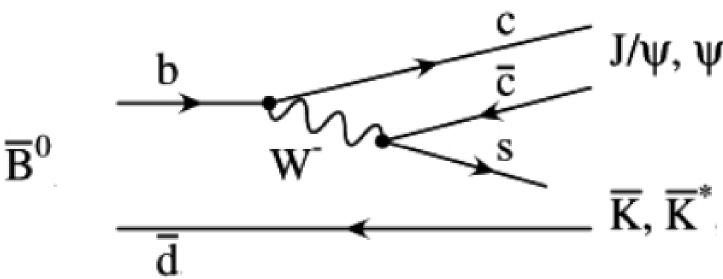
- Compute time integrated asymmetry

$$\mathcal{A}_{K^{\pm}\pi^{\mp}} \equiv \frac{N(\bar{B}^0 \to K^-\pi^+) - N(B^0 - K^+\pi^-)}{N(\bar{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.098 \pm 0.012$$

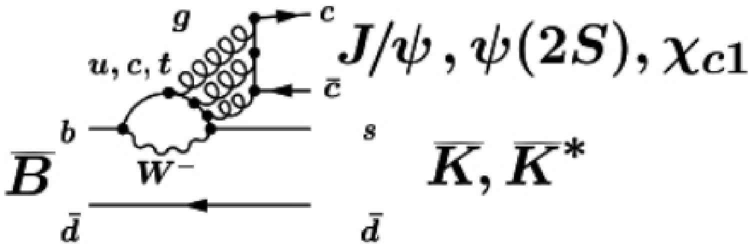
  - Experimental results from Belle, BaBar, and CDF have significant weight in the world average of this CP violation parameter.
  - Direct CP violation present in B decays.
  - Unknown strong phase differences between amplitudes, means we can't use this to measure weak phases!



sin2β in golden b → $\bar{c}$cs modes (recap)



$V^*_{cb}V_{cs}$



◎ branching fraction: $O(10^{-3})$
the colour-suppressed tree dominates and the t penguin has the same weak phase of the tree

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t)\to f_{CP}) - \Gamma(B^0(t)\to f_{CP})}{\Gamma(\bar{B}^0(t)\to f_{CP}) + \Gamma(B^0(t)\to f_{CP})}$$

S ~ sin2β

C ~ 0

◎ theoretical uncertainty:

- ◉ model-independent data-driven estimation from $J/\psi\pi^0$ data:

  $$\Delta S_{J/\psi K0} = S_{J/\psi K0} - \sin 2\beta = 0.000 \pm 0.012$$

- ◉ model-dependent estimates of the u- and c- penguin biases

  $$\Delta S_{J/\psi K0} = S_{J/\psi K0} - \sin 2\beta \sim O(10^{-3})$$

  $$\Delta S_{J/\psi K0} = S_{J/\psi K0} - \sin 2\beta \sim O(10^{-4})$$

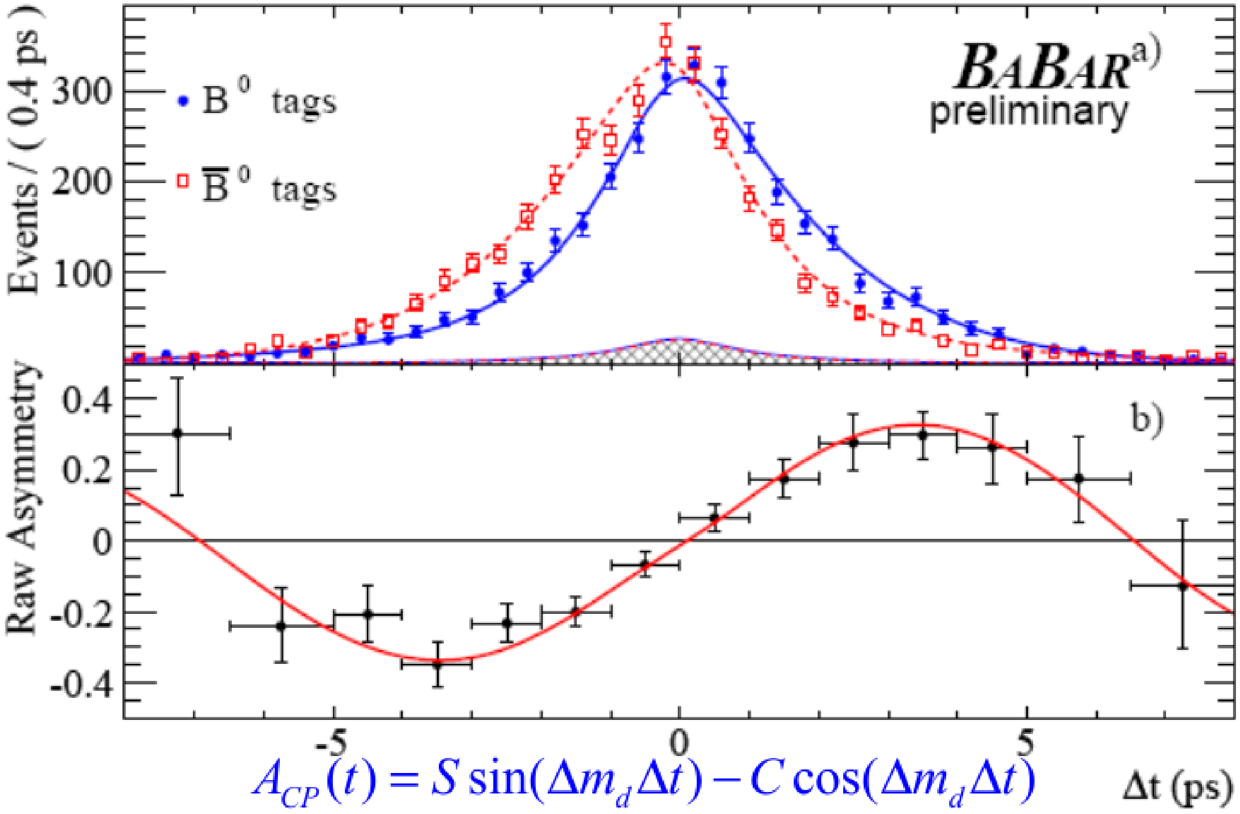
`H.Li, S.Mishima`
`JHEP 0703:009 (2007)`

`H.Boos et al.`
`Phys. Rev. D73, 036006 (2006)`

$\beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$

sin2β in golden b → $\bar{c}$cs modes

- The '*Golden Measurement*' of the B factories. The aims of this measurement were:
  - Measure an angle of the Unitarity Triangle.
  - Discover CP violation in B meson decays.



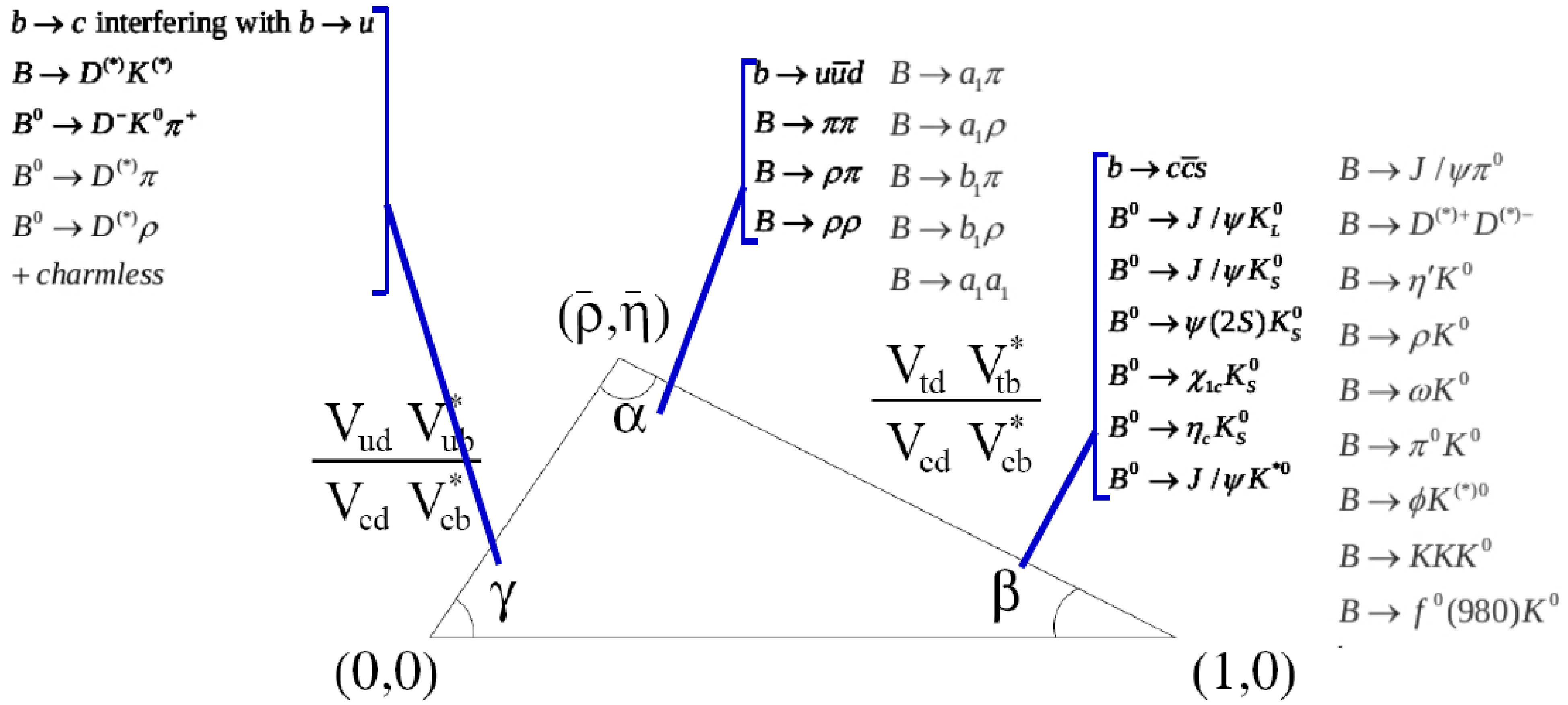
$A_{CP}(t) = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$

Sine term has a non-zero coefficient

$S = \sin 2\beta = 0.671 \pm 0.024$

This tells us that there is CP violation in the interference between mixing and decay amplitudes in $\bar{c}$cs decays.

There are many other measurements for the angles of the triangle



$b \to c$ interfering with $b \to u$
$B \to D^{(*)}K^{(*)}$
$B^0 \to D^- K^0 \pi^+$
$B^0 \to D^{(*)}\pi$
$B^0 \to D^{(*)}\rho$
+ *charmless*

$b \to u\bar{u}d$
$B \to \pi\pi$
$B \to \rho\pi$
$B \to \rho\rho$

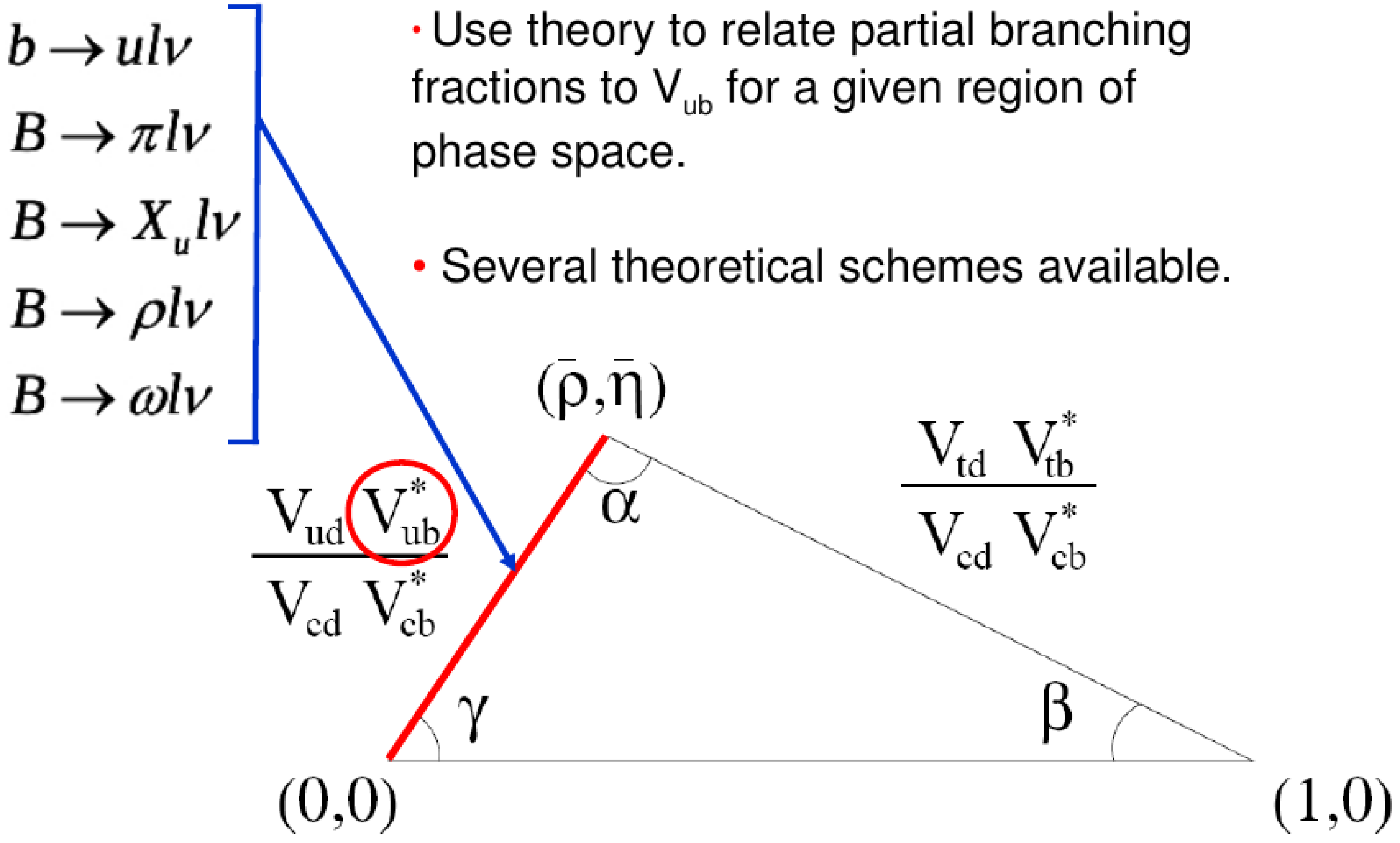
$B \to a_1\pi$
$B \to a_1\rho$
$B \to b_1\pi$
$B \to b_1\rho$
$B \to a_1 a_1$

$b \to c\bar{c}s$
$B^0 \to J/\psi K^0_L$
$B^0 \to J/\psi K^0_S$
$B^0 \to \psi(2S)K^0_S$
$B^0 \to \chi_{1c}K^0_S$
$B^0 \to \eta_c K^0_S$
$B^0 \to J/\psi K^{*0}$

$B \to J/\psi\pi^0$
$B \to D^{(*)+}D^{(*)-}$
$B \to \eta' K^0$
$B \to \rho K^0$
$B \to \omega K^0$
$B \to \pi^0 K^0$
$B \to \phi K^{(*)0}$
$B \to KKK^0$
$B \to f^0(980)K^0$

Sides of the Unitarity Triangle

- Use theory to relate partial branching fractions to V_{ub} for a given region of phase space.
- Several theoretical schemes available.



$b \to u l \nu$

$B \to \pi l \nu$

$B \to X_u l \nu$

$B \to \rho l \nu$

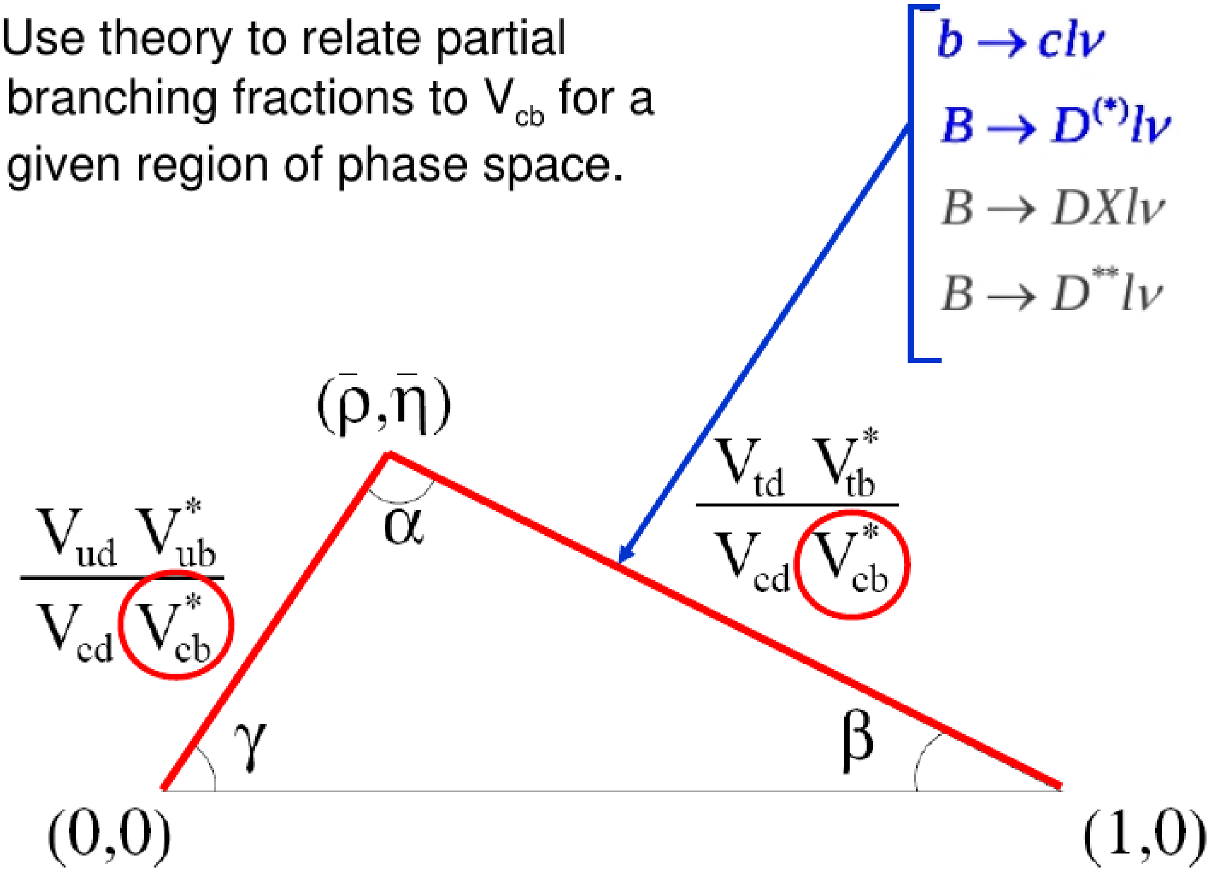
$B \to \omega l \nu$

$$\frac{V_{ud}\,\boxed{V_{ub}^*}}{V_{cd}\,V_{cb}^*}$$

$$\frac{V_{td}\,V_{tb}^*}{V_{cd}\,V_{cb}^*}$$

Sides of the Unitarity Triangle

- Use theory to relate partial branching fractions to V_{cb} for a given region of phase space.



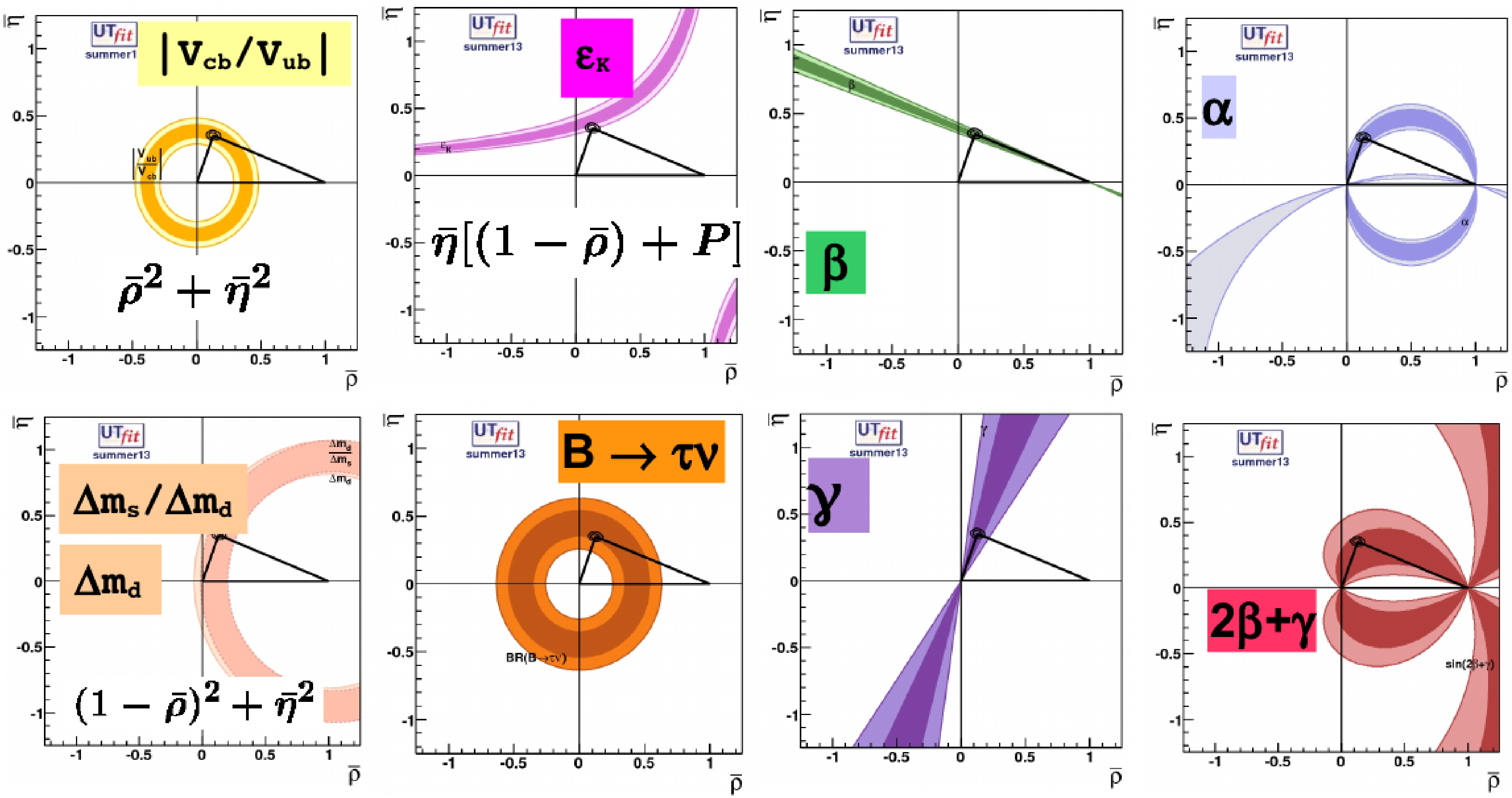
$b \to c l \nu$

$B \to D^{(*)} l \nu$

$B \to D X l \nu$

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

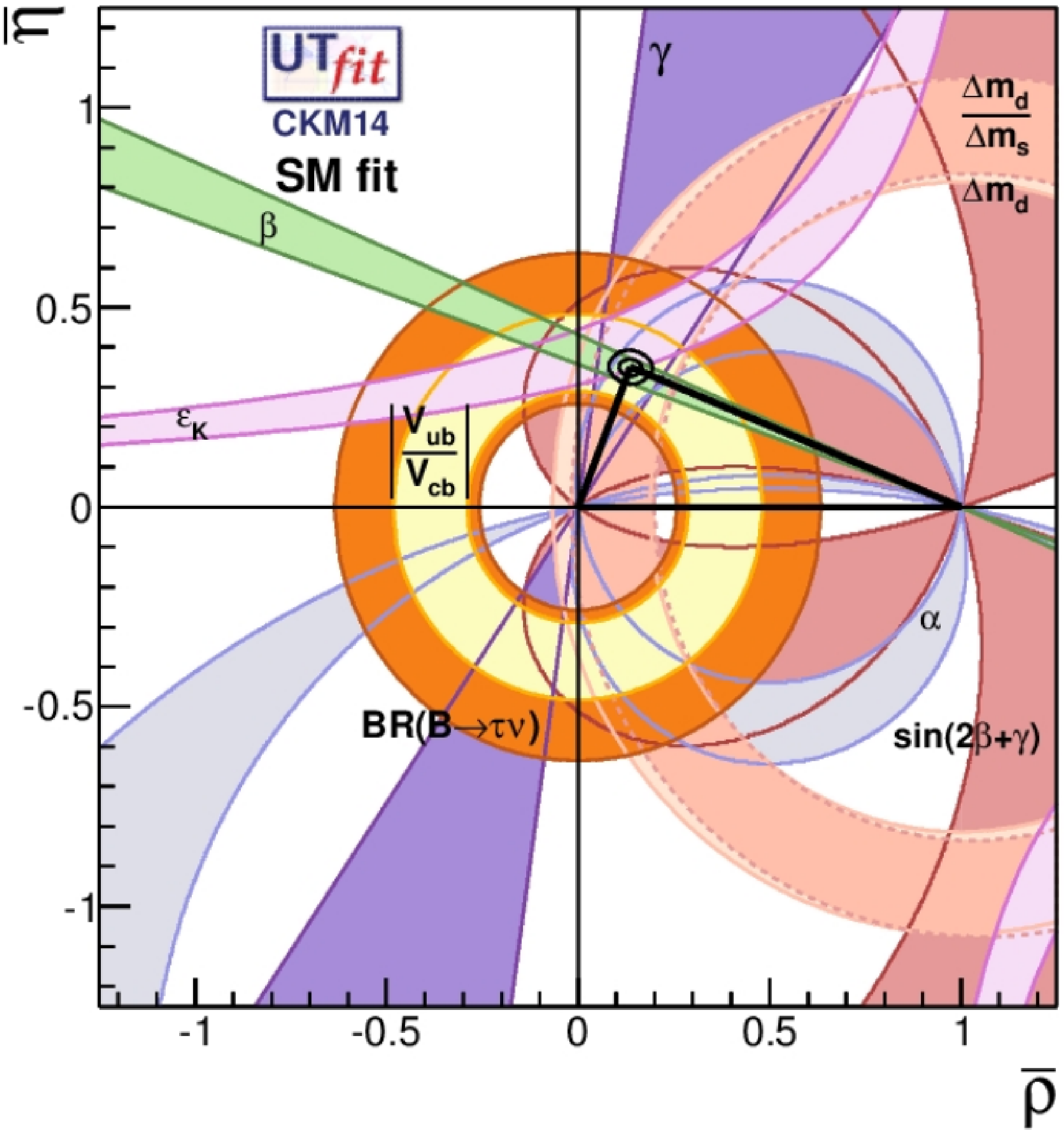
Unitarity Triangle analysis in the SM



Unitarity Triangle analysis in the SM

Observables	Accuracy
$\lvert V_{ub}/V_{cb} \rvert$	~ 13%
ε_K	~ 0.5%
Δm_d	~ 1%
$\lvert \Delta m_d/\Delta m_s \rvert$	~ 1%
sin2β	~ 3%
cos2β	~ 15%
α	~ 7%
γ	~ 11%
$BR(B \to \tau\nu)$	~ 19%

Unitarity Triangle analysis in the SM



levels @
95% Prob

$\bar{\rho} = 0.137 \pm 0.022$
$\bar{\eta} = 0.349 \pm 0.014$

analysis from

UTfit
www.utfit.org

M. Bona *et al.* (UTfit)
JHEP0507:028, 2005

B Physics Experiments at the LHC

- There are 3 B-physics experiments at the LHC:
  - LHCb is a dedicated forward arm spectrometer (a specialised detector with the aim of doing a fantastic job at studying B-physics from pp collisions).
    - The pp beams are defocused near the interaction point of LHCb, so the luminosity of collisions is a lot lower than at the GPDs.

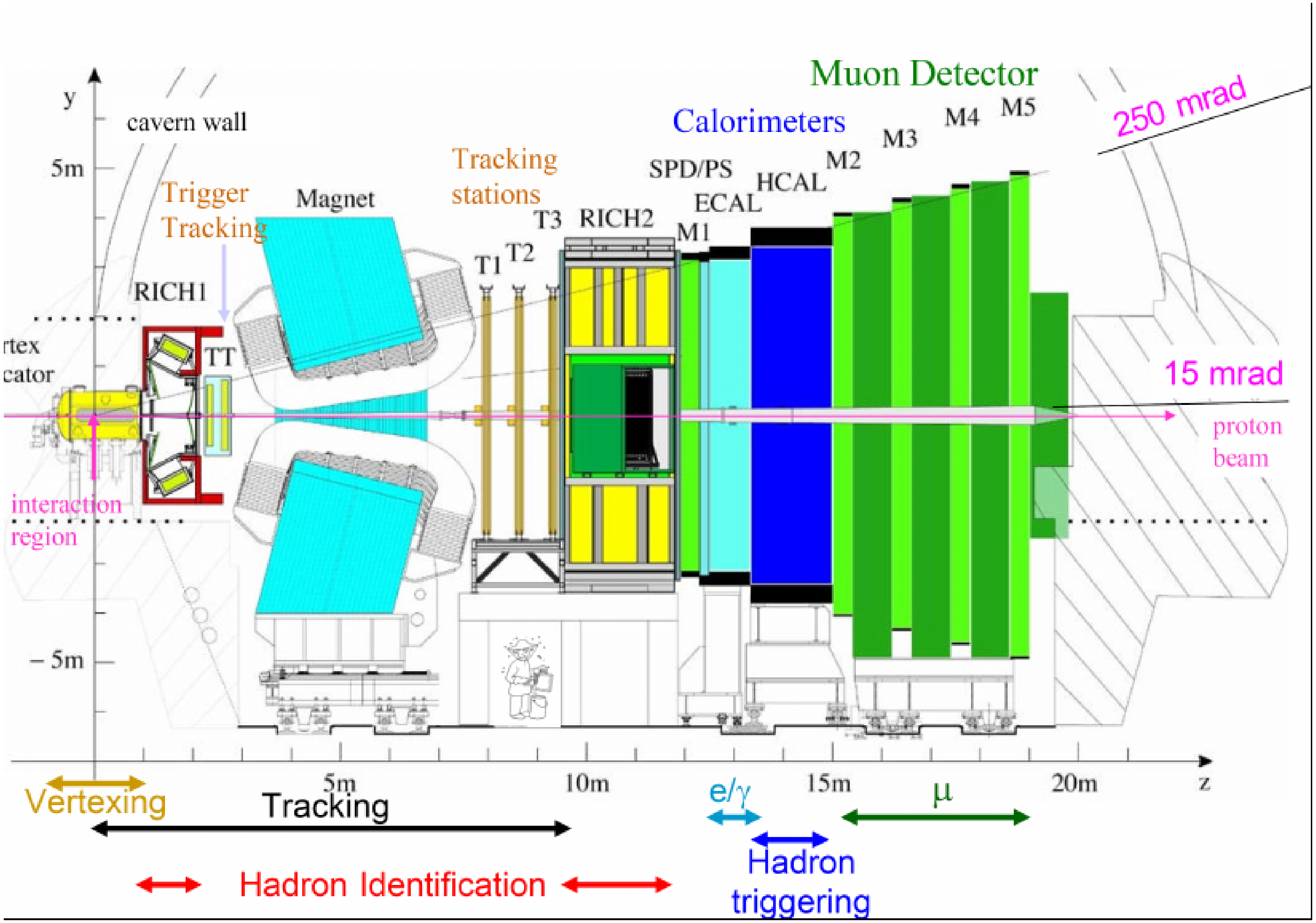
http://lhcb.web.cern.ch/lhcb/

  - ATLAS and CMS are general purpose detectors.
    - The cross-section for B hadron production is very large, and the luminosity of the pp collisions at these detectors is the same as for the rest of the GPD physics programme for these two experiments.

http://atlasexperiment.org/
http://cms.cern.ch/

LHCb Detector

- Single arm spectrometer design.



UK Groups:

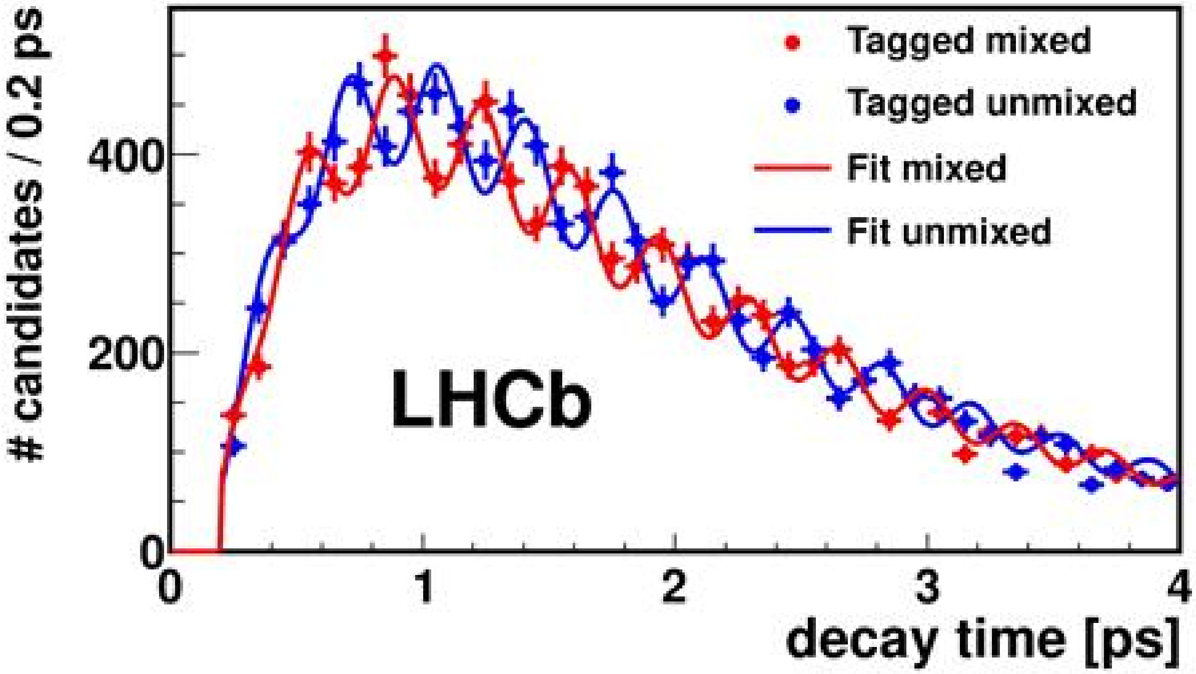
Bristol
Cambridge
Edinburgh
Imperial College
Liverpool
Glasgow
Oxford
RAL

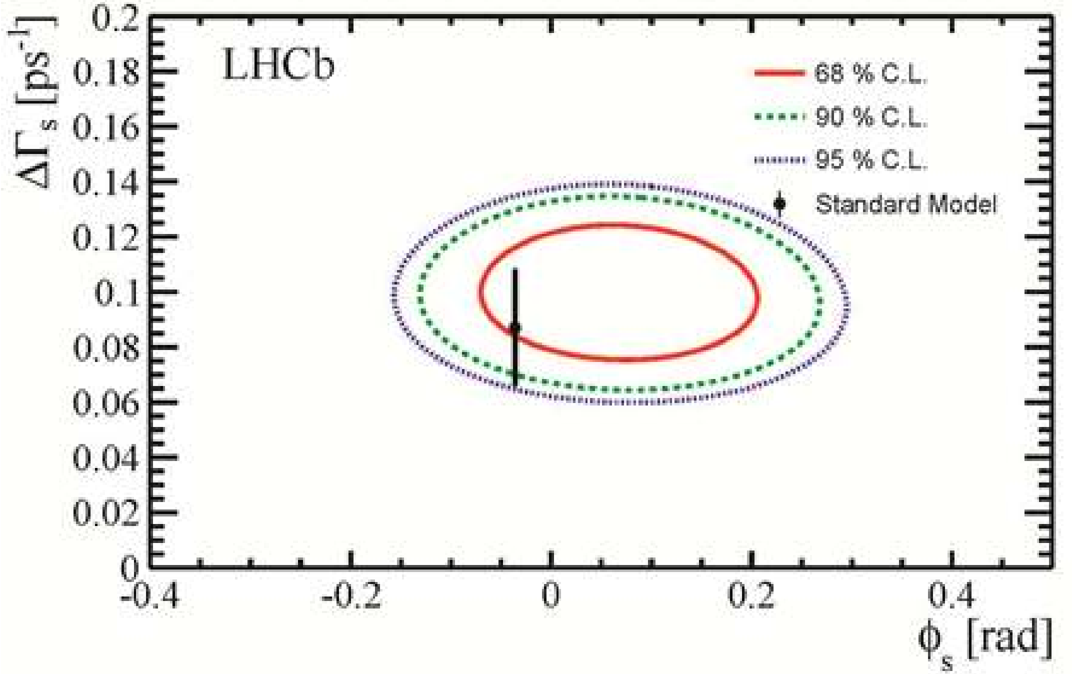
running at a reduced luminosity as the beams are locally defocused:

design luminosity (already reached)

$2\ 10^{32}\ cm^{-2}s^{-1}$

Example of LHCb physics: Bs oscillations





Only using 1/fb of 2011 data.

The B0s meson decays into D-sπ+ were used in this analysis with D-s decays into five different channels.

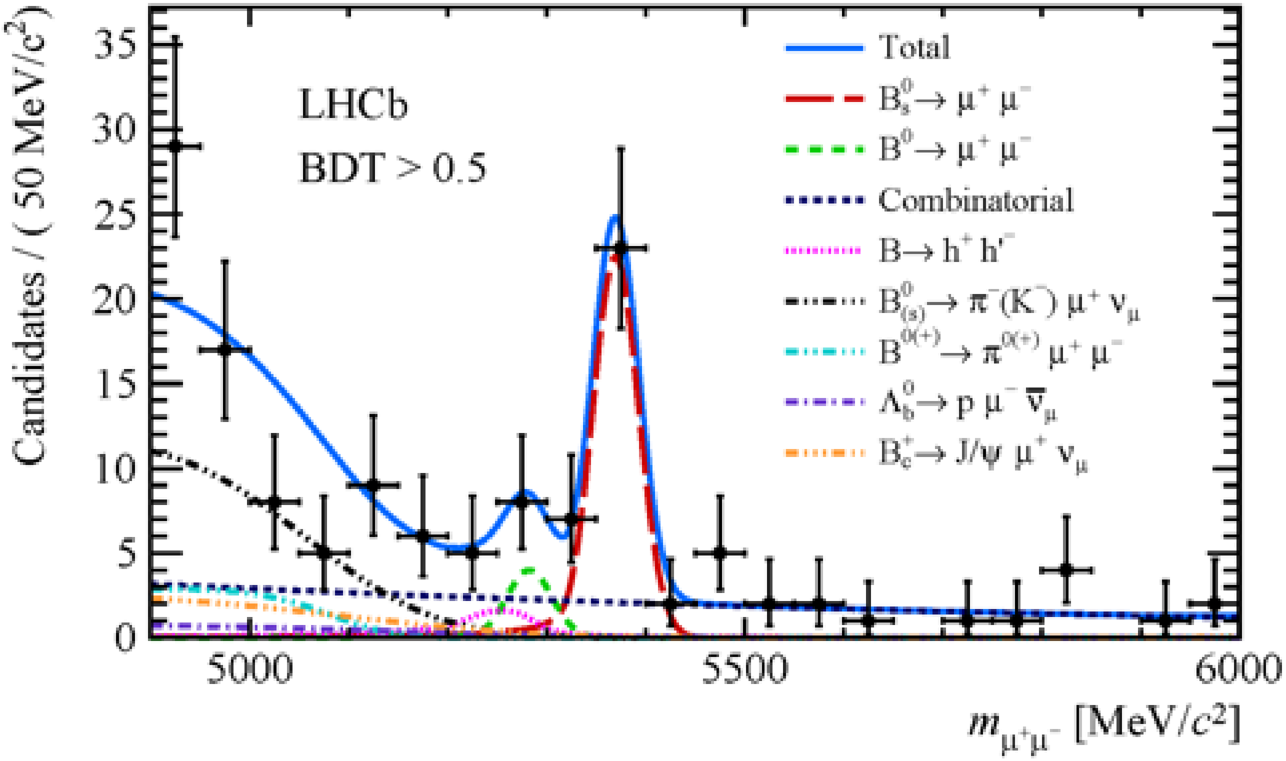
The parameter φs can be studied using B0s decays into a J/ψφ and a J/ψππ. Combination of oscillation amplitude and phase is in agreement with SM

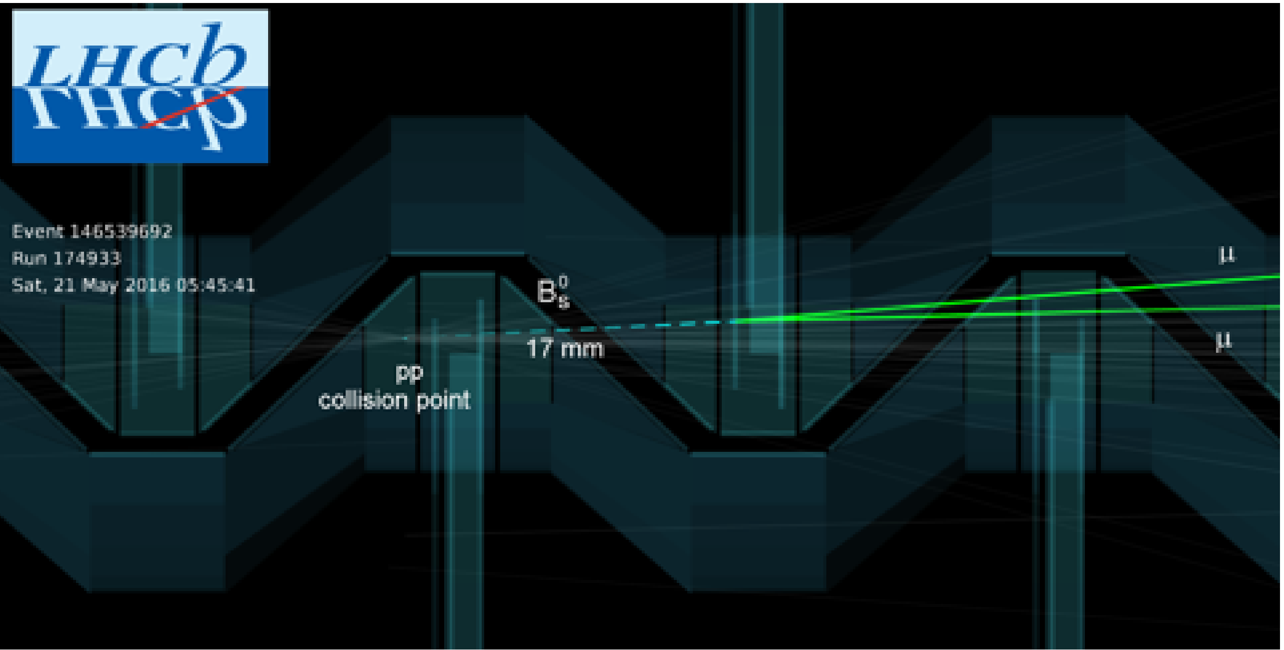
Δms = 17.768 ± 0.023 ± 0.006/ps

φs = 0.01 ± 0.07 ± 0.01 rad

ΔΓs = 0.106 ± 0.011 ± 0.007/ps

Search for super-rare decays





Decay of Bs into two muons is very rare in the SM : $(3.65 \pm 0.23) \times 10^{-9}$

New physics can enhance this ratio by large factors.

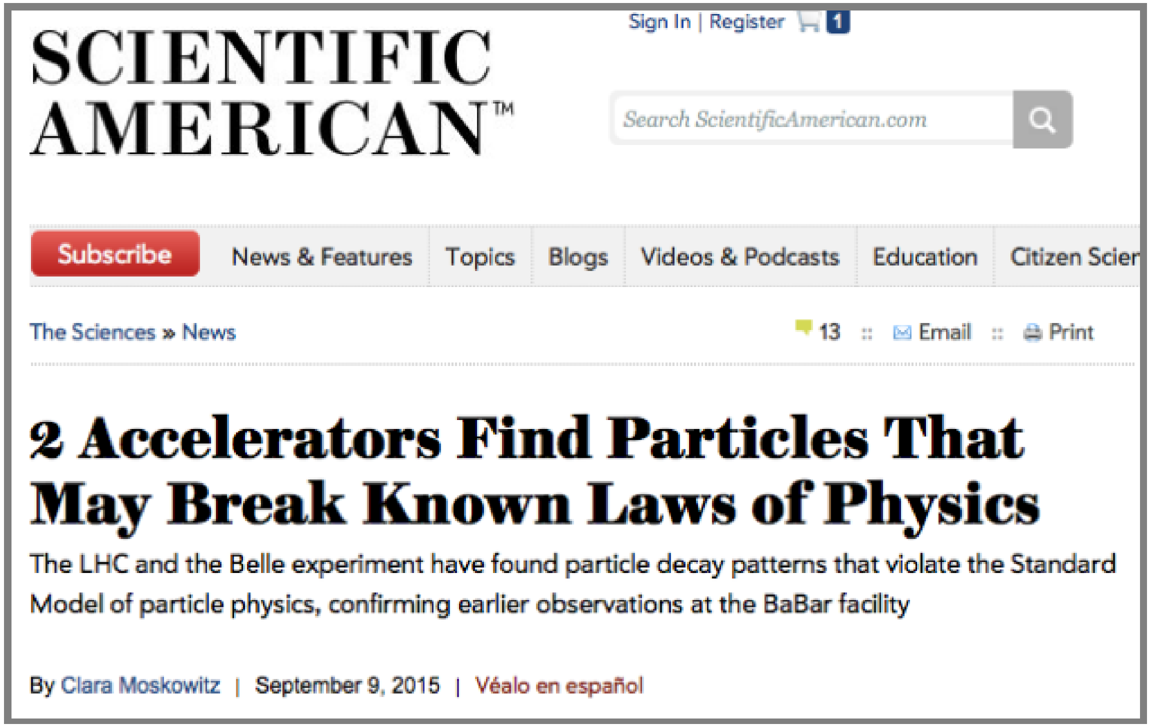
Branching fraction $B_s^0 \to \mu^+\mu^- = (3.0 \pm 0.6 + 0.3 - 0.2) \times 10^{-9}$

Compatible with SM prediction

Also search for even rarer decay of B0, but no evidence found so far:

$B^0 \to \mu^+\mu^- < 3.4 \times 10^{-10}$

Anomalies ?

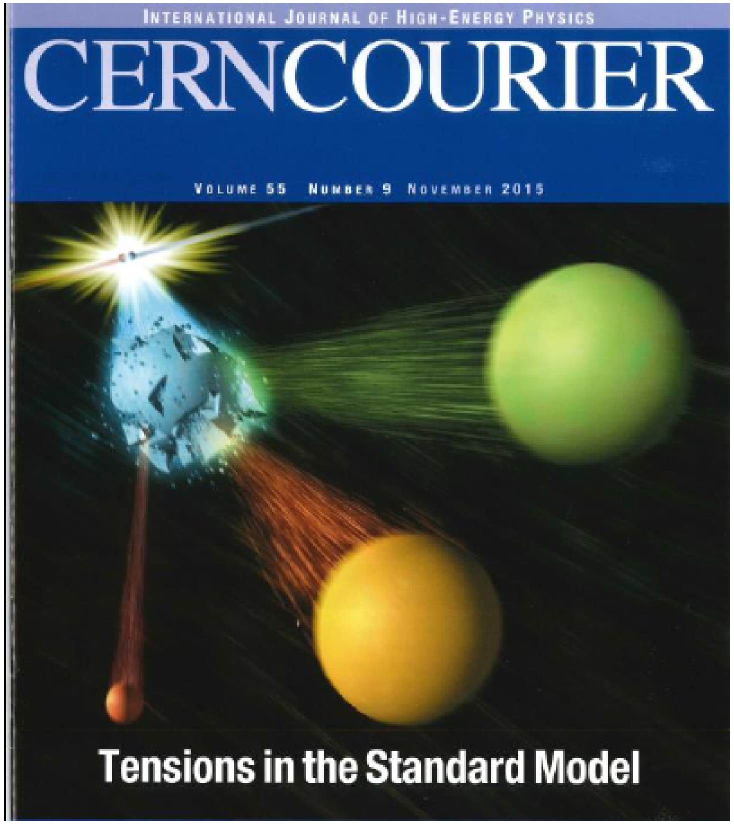


The Sciences » News

2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experiment have found particle decay patterns that violate the Standard Model of particle physics, confirming earlier observations at the BaBar facility

By Clara Moskowitz | September 9, 2015 | Véalo en español



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERNCOURIER

VOLUME 55 NUMBER 9 NOVEMBER 2015

Tensions in the Standard Model

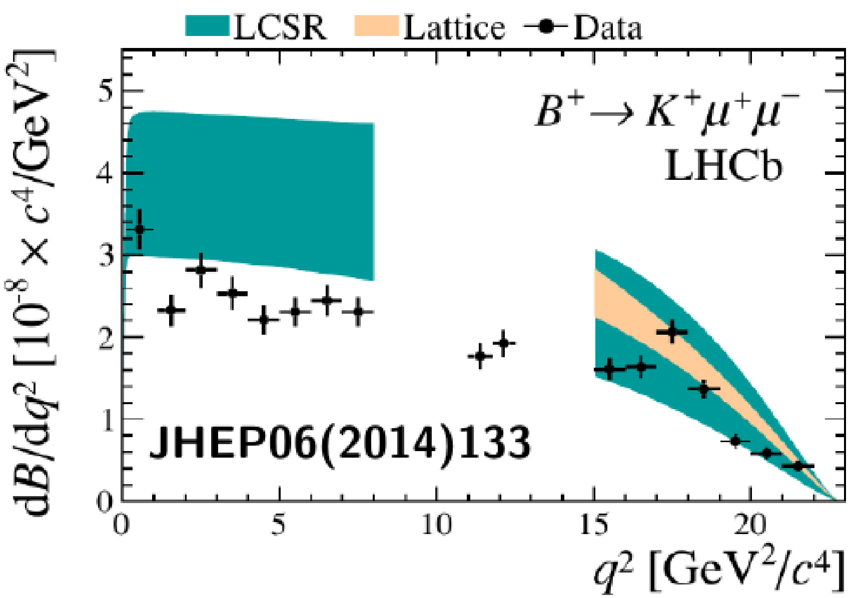
Democracy suffers a blow—in particle physics

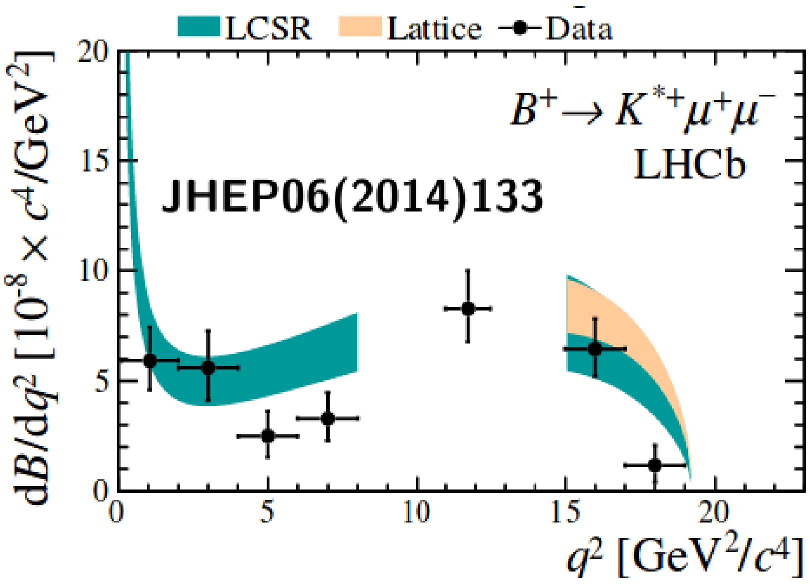
Three independent B-meson experiments suggest that the charged leptons may not be so equal after all.

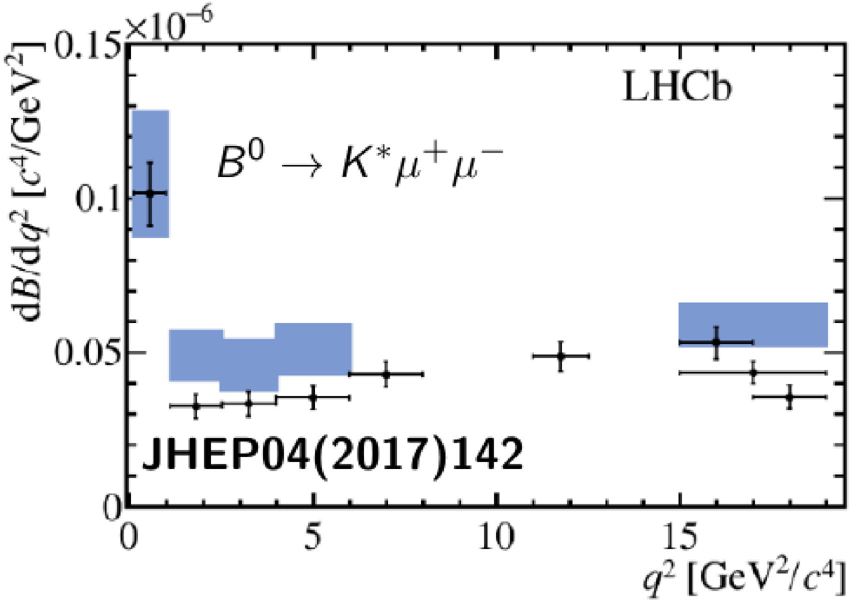
Steven K. Blau 17 September 2015

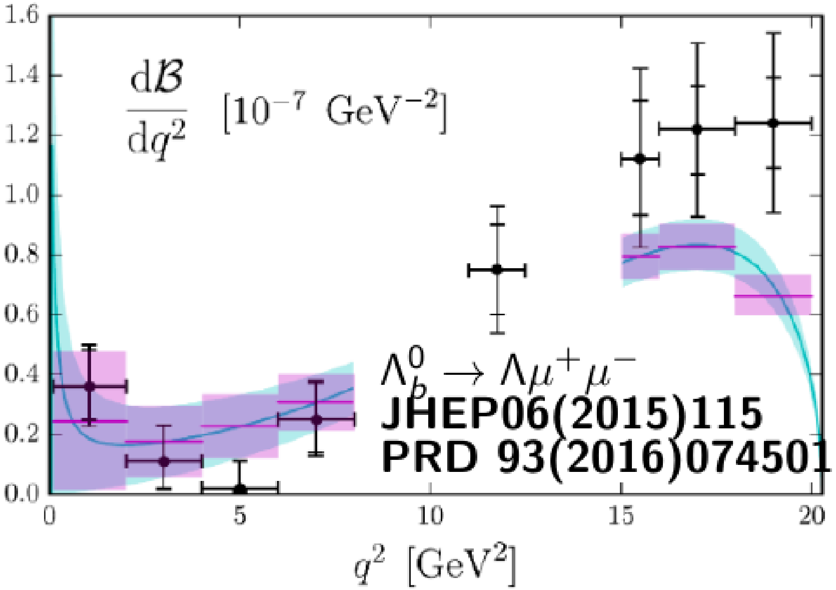
Hints for
New Physics
in flavour
observables

Branching ratios with muon final states



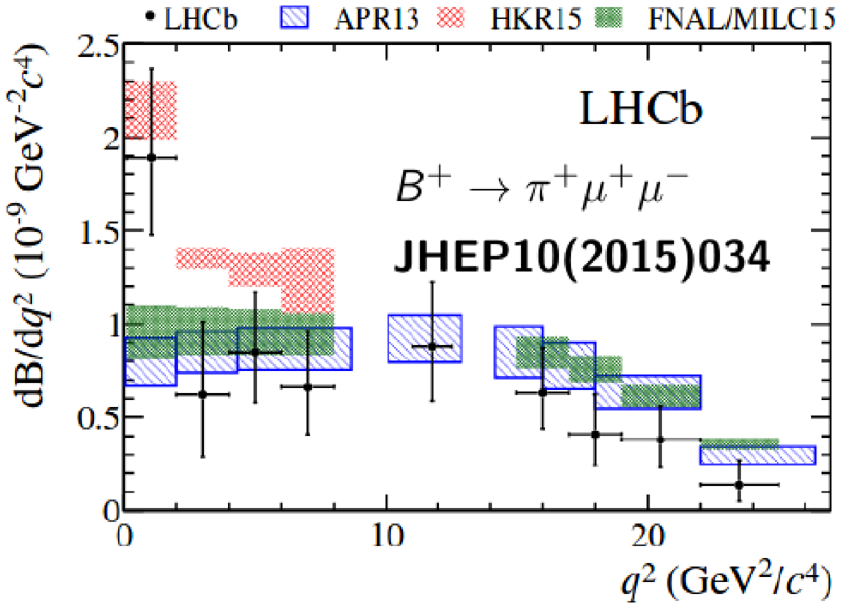




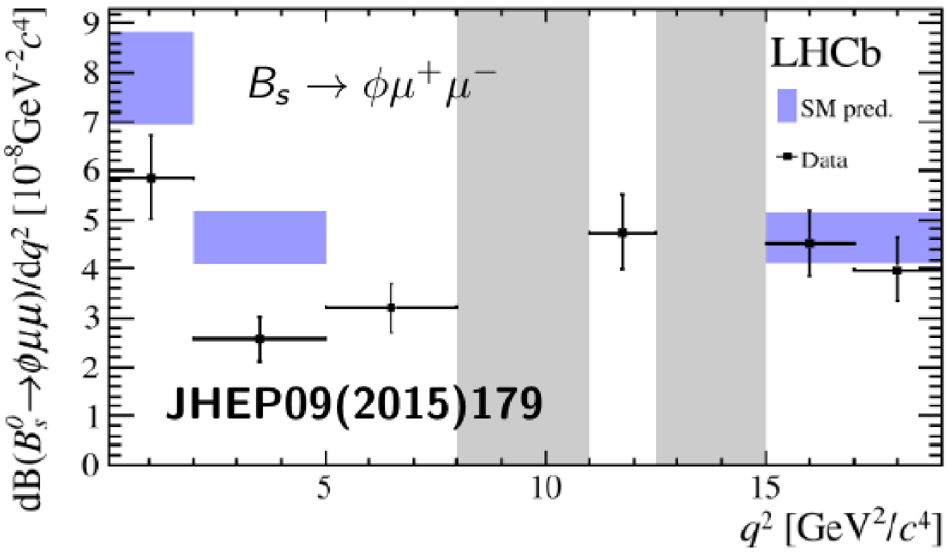


Branching ratios with muon final states

$\mathbf{b \to d\ell\ell}$



JHEP10(2015)034



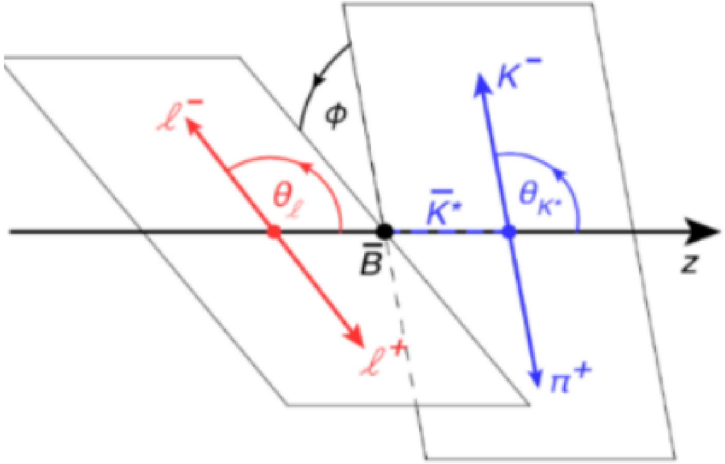
JHEP09(2015)179

- Measurements are consistently lower from the SM predictions for low (below ~ $\mathbf{6\ GeV^2/c^4}$) q^2.
- Largest deviation of the order of $\mathbf{3.3\sigma}$ is found in $\boldsymbol{B_s \to \phi\mu^+\mu^-}$.

Angular analysis of B → K μμ

- **Helicity** structure of $\mathcal{H}_{eff}$ can be accessed **using angles**.
- Dynamics described by **three** angles, i.e $\boldsymbol{\theta_l}$, $\boldsymbol{\theta_K}$ and $\boldsymbol{\phi}$.
- In $3fb^{-1}$ data sample is enough in order **not** fold on ϕ.
- Observables depend on q^2, $B^0 \rightarrow K^*$ form factors, long and short distance physics. Perform measurement in bins of q^2.

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$



$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$

$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$

$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$

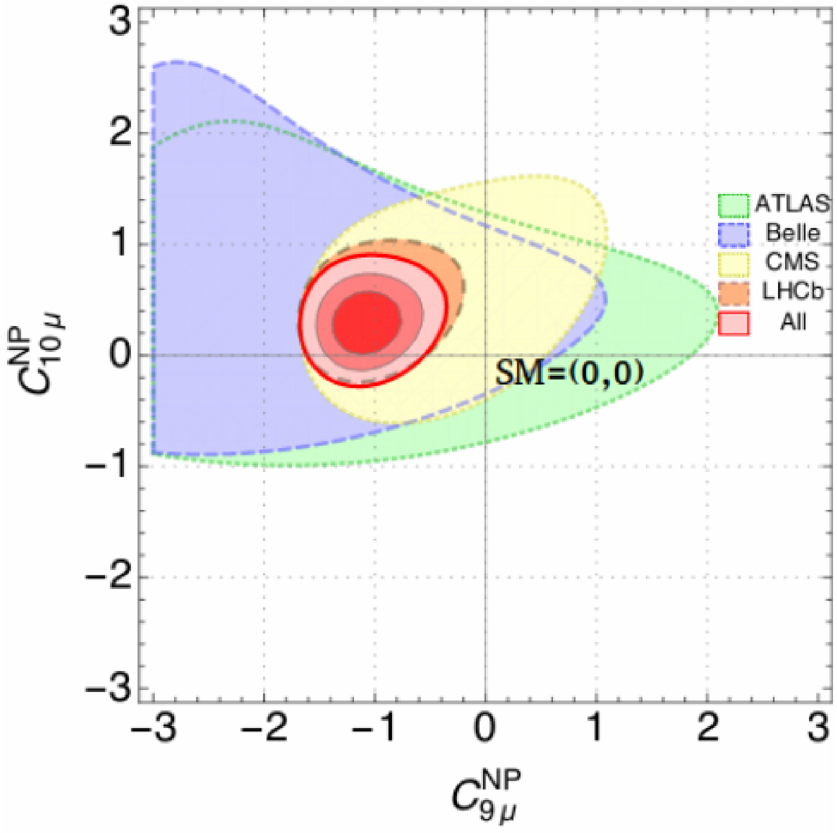
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$

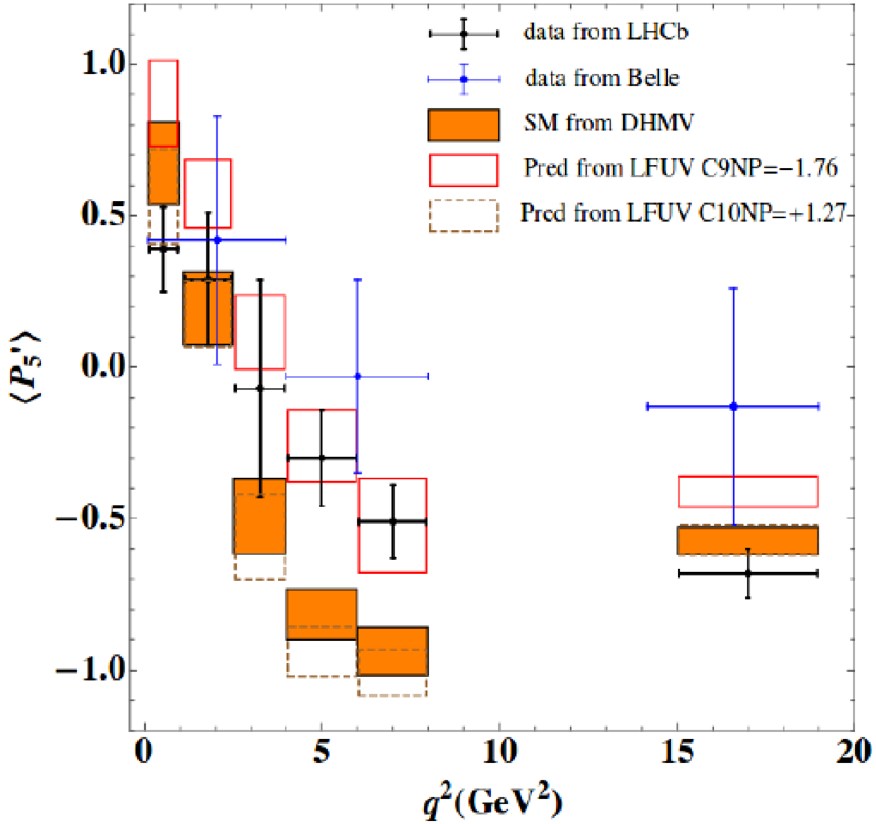
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

Fits for angular analysis to LHCb and Belle

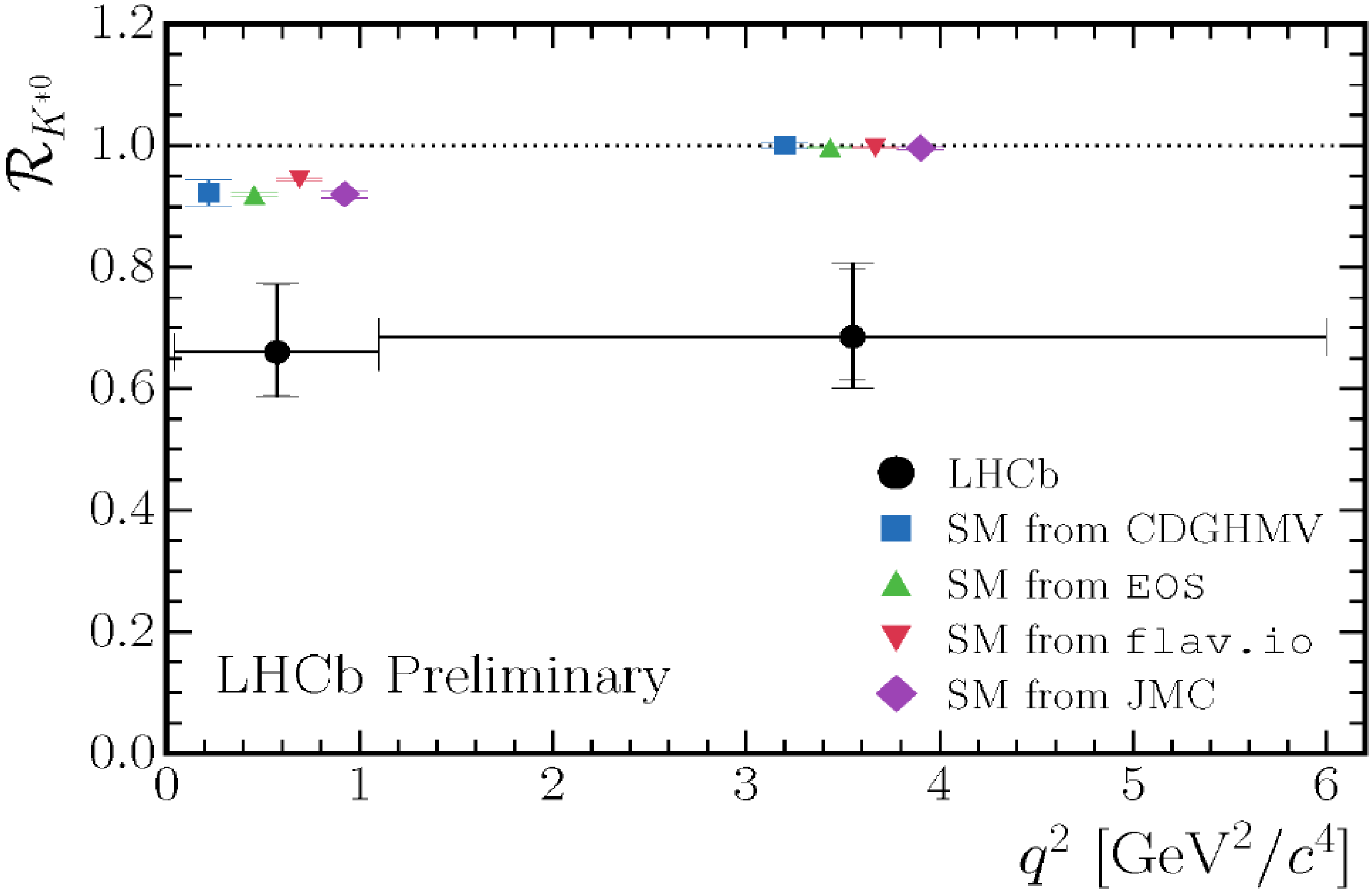
- Perform global fits to data to probe different NP scenarios.
- Deviations are explained most likely by shifts on C_9 or C_9 and C_{10}.

JHEP01(2018)093





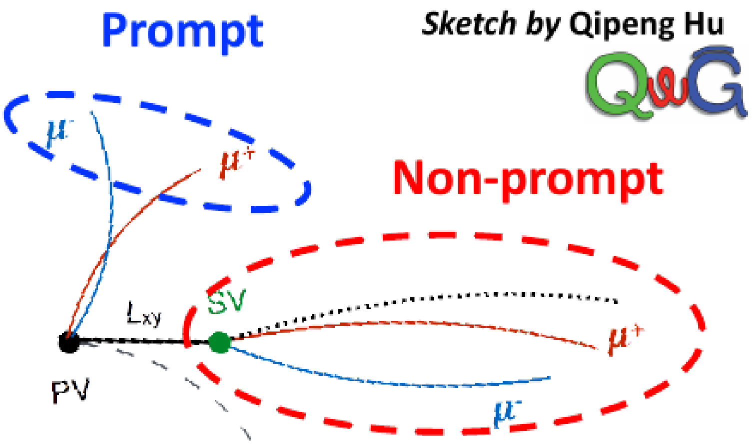
Lepton universality violation: R(K(*)) = B→K(*)μ+μ -/B→K(*)e+e-

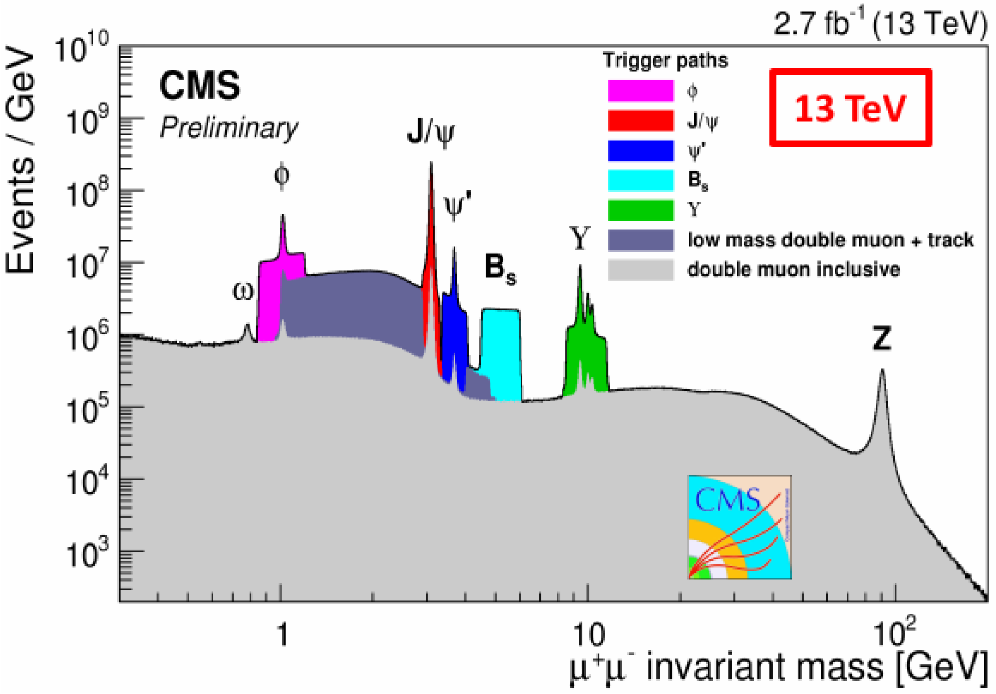


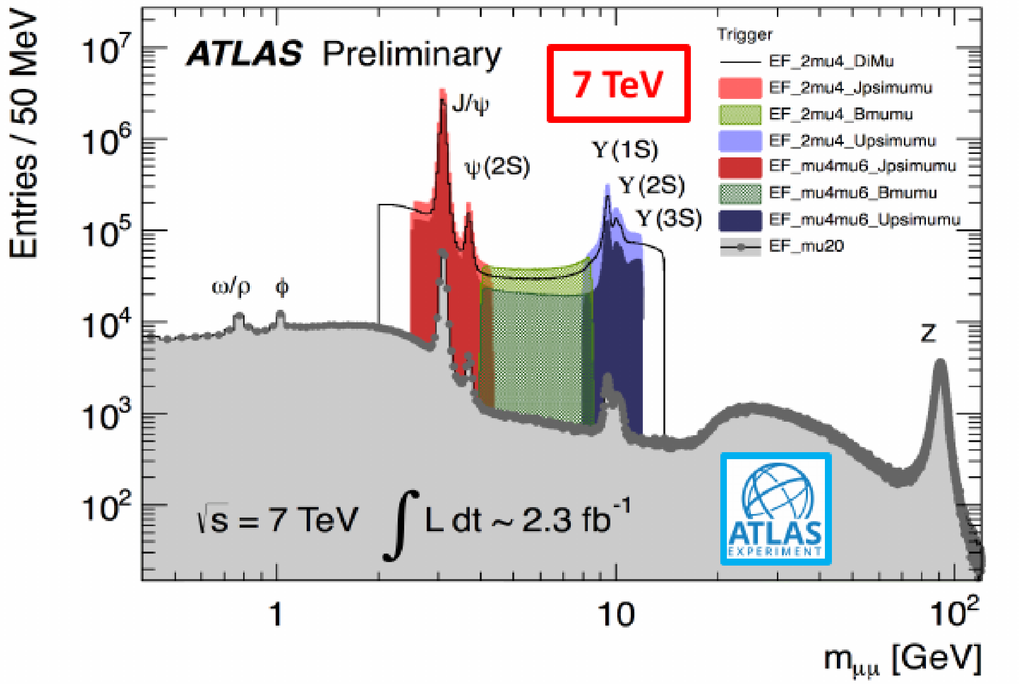
Combined ≈ 4σ evidence for LFUV

ATLAS and CMS: production of heavy quark-antiquark systems

- **For both ATLAS and CMS** experiments, **dimuon decays provide a particularly clean signature to trigger on** in order to reconstruct **quarkonium states**

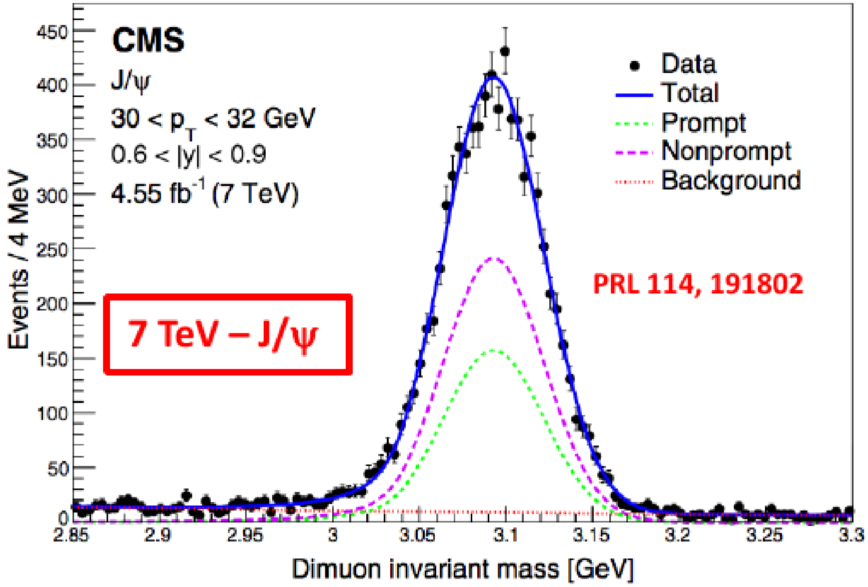






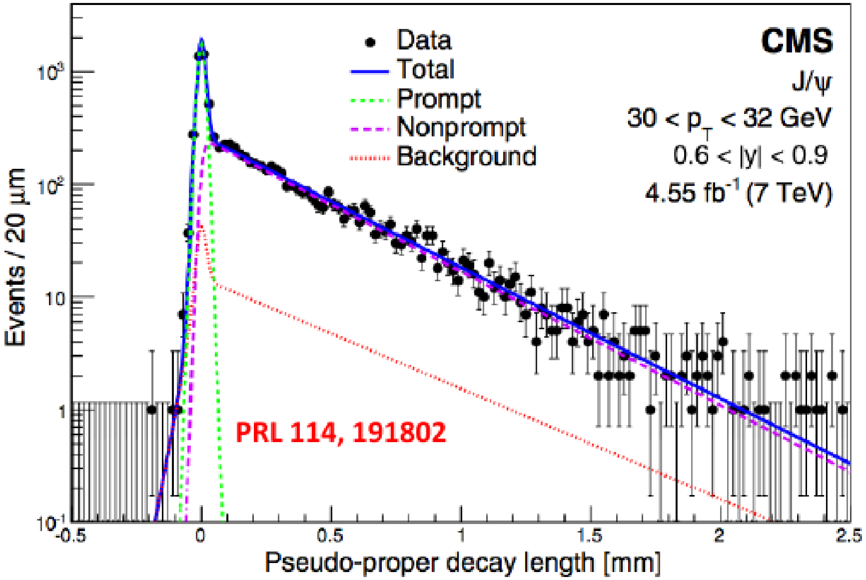
Prompt-non prompt quarkonia

- Also, to measure **prompt** and ***non-prompt*** yields simultaneously and disentangle the two contributions both **CMS** & **ATLAS** exploit a *2D* ***mass*** and ***pseudo-proper time fit***.

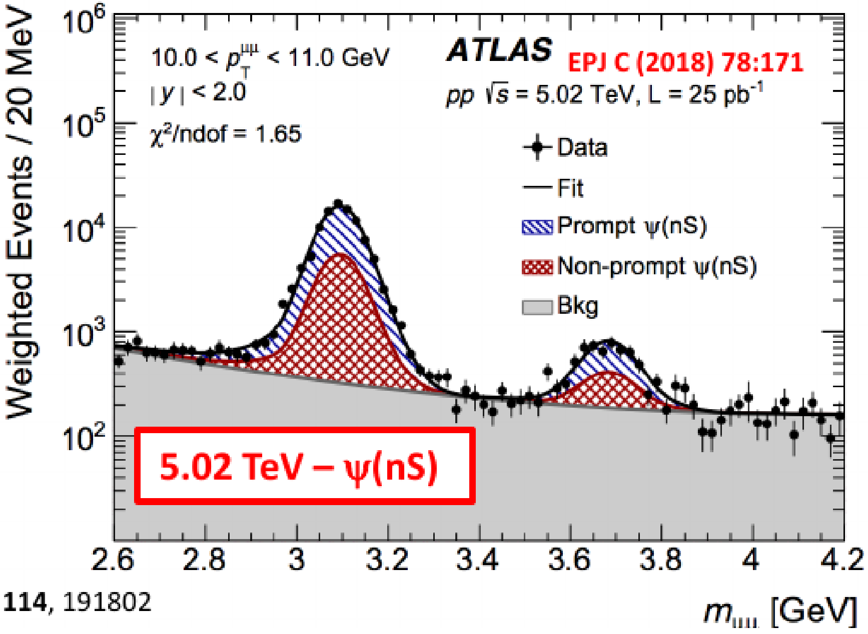


7 TeV – J/ψ

PRL 114, 191802

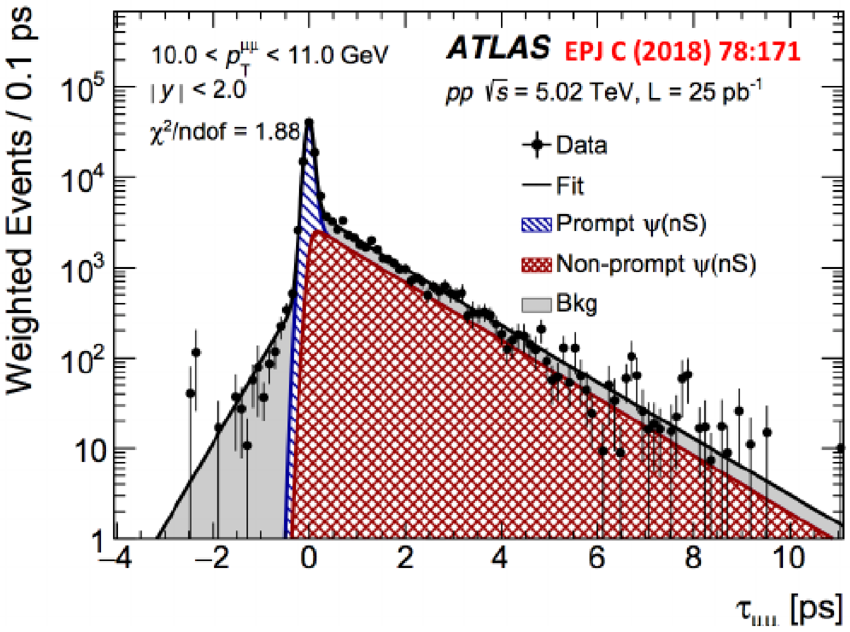


PRL 114, 191802



EPJ C (2018) 78:171

5.02 TeV – ψ(nS)

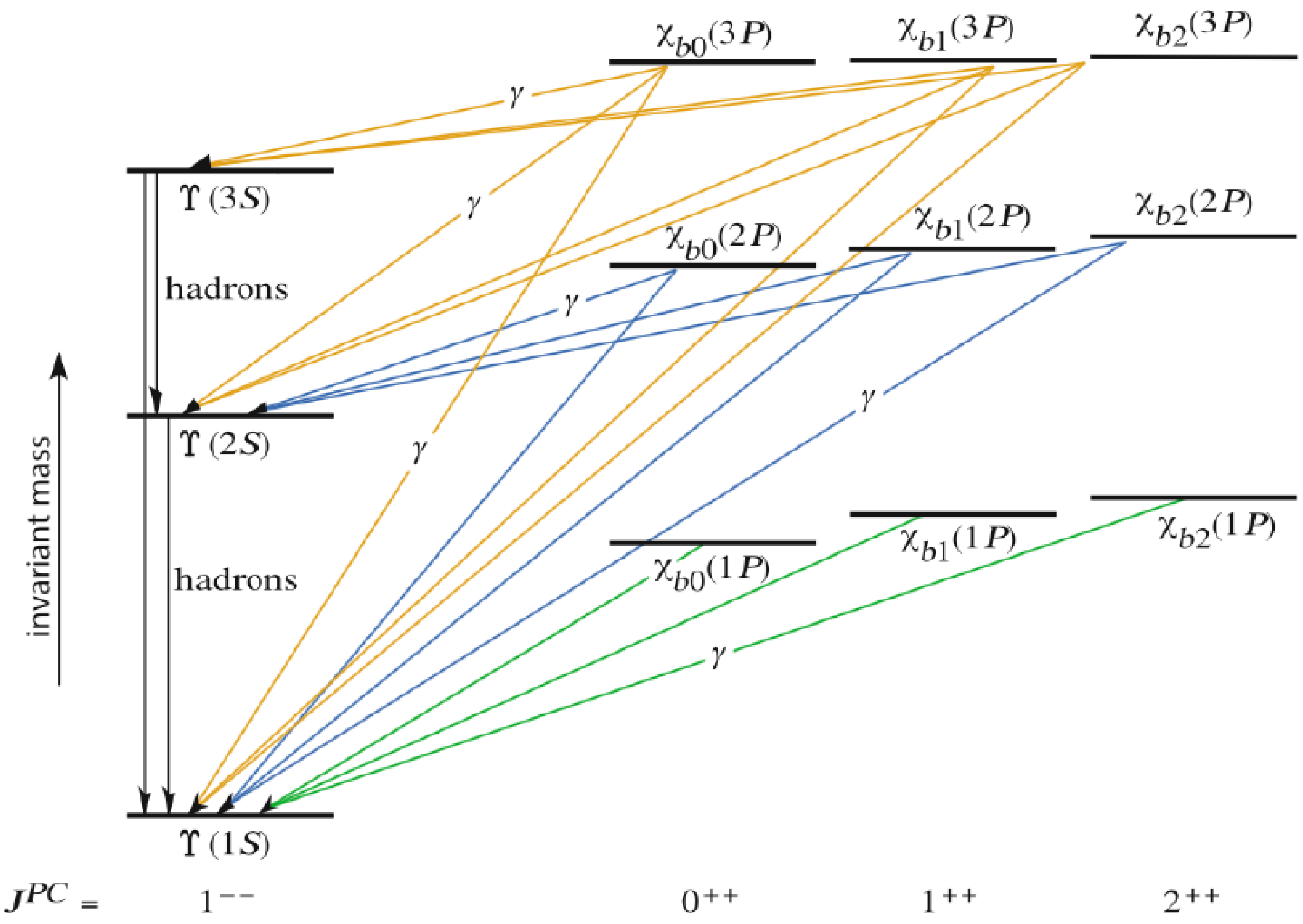


EPJ C (2018) 78:171

[1] PRL **114**, 191802

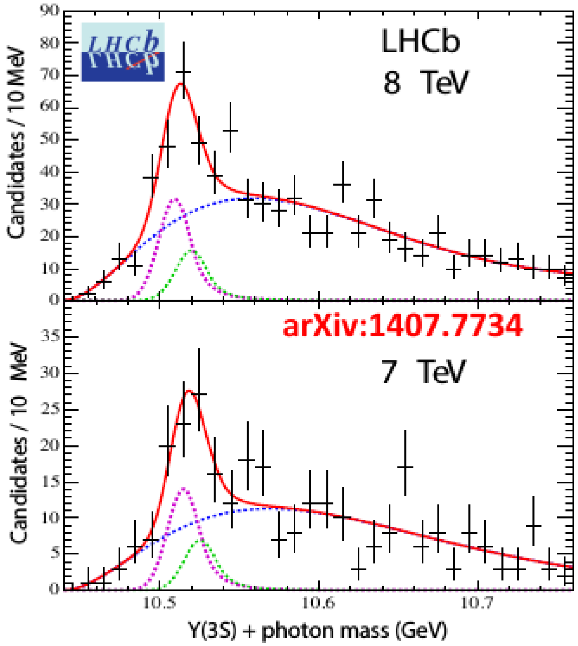
The bottomonium system

- The **bottomonium** family ($b\bar{b}$) plays a special role in understanding how the strong force binds quarks because, due to the high quark mass, allows **two important theoretical simplifications**. The measurements of the masses of the **χ_b(3P) triplet states** (J = 0, 1, and 2), is especially interesting to probe details of the bb interaction and test theoretical treatments of the influence of open-beauty states on the bottomonium spectrum.



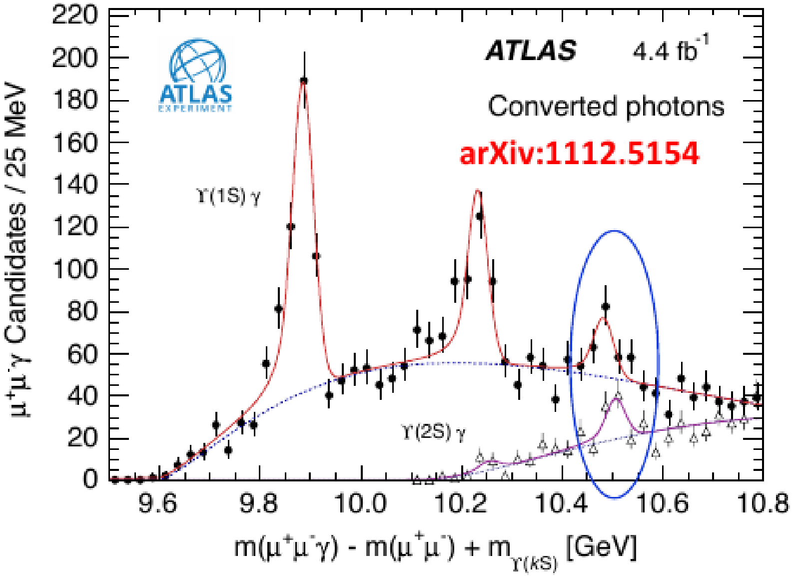
Picture from : V. Knünz, Measurement of Quarkonium Polarization to Probe QCD - *DOI 10.1007/978-3-319-49935-2_2*

The bottomonium system

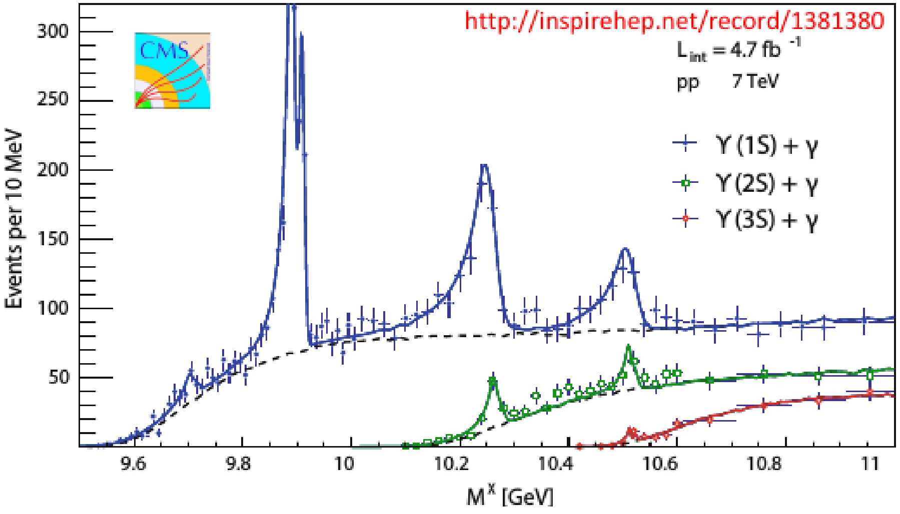


arXiv:1407.7734

- The $\chi_b(3P)$ was observed by **ATLAS** in **2011** as a new structure in the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decay modes.
- **LHCb** observed the $\chi_b(3P) \rightarrow \Upsilon(3S)\,\gamma$ decay channel.

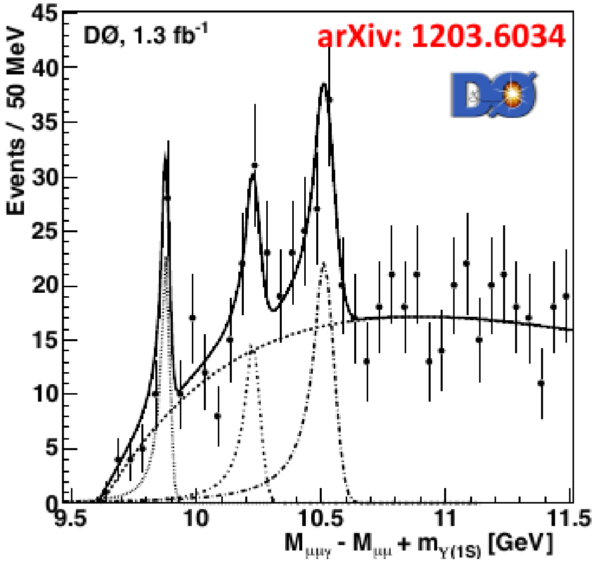


arXiv:1112.5154



http://inspirehep.net/record/1381380

- **DØ** saw the $\chi_b(3P)$ in the $\chi_b(3P) \rightarrow \Upsilon(1S)\,\gamma$ decay channel.
- **CMS** saw the $\chi_b(3P)$ in the Υ(1S), Υ(2S), and Υ(3S) radiative decays, in the 7 TeV data



arXiv: 1203.6034

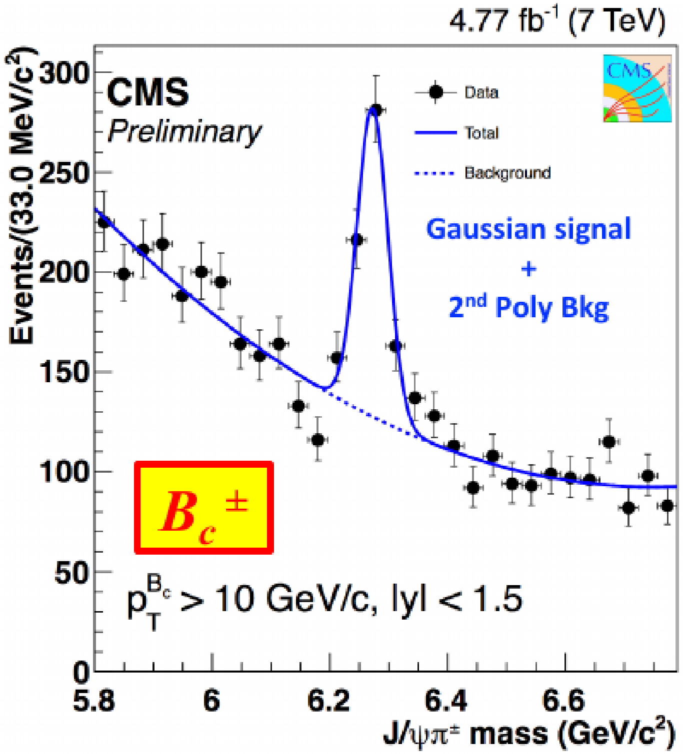
$B^\pm$ and Bc production

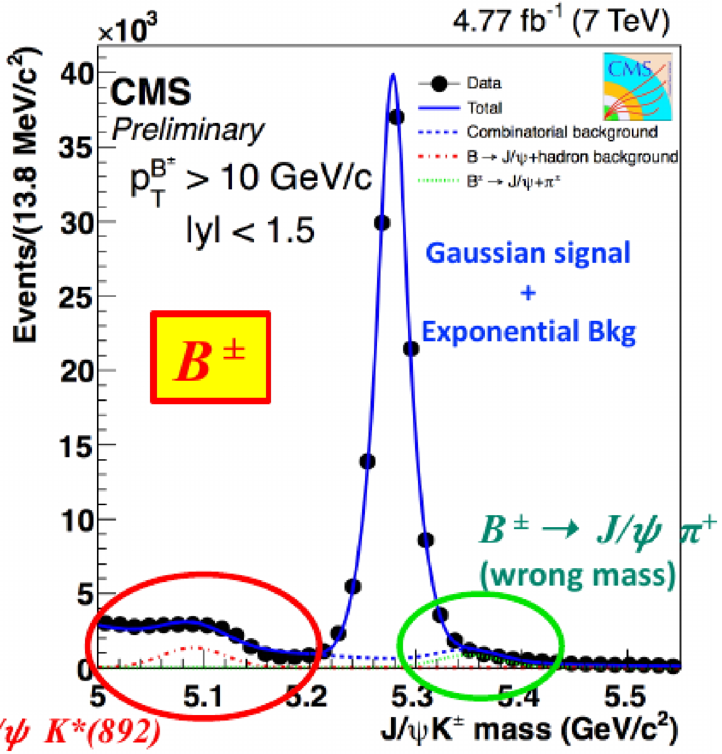
- **B^+ (B^-)** is the b-quark meson with the largest production rate composed of $u\bar{b}(\bar{u}b)$. **B_c^+ (B_c^-)** meson is a ground state of $\bar{b}c(b\bar{c})$ system and contains **two** heavy quarks of **different flavours** and its production **is then much rarer** $[\bar{b}b + \bar{c}c]$. **CMS** has reported the *inclusive* and *differential (y &p_T)* $\sigma \cdot \mathcal{B}$

$$B_c^\pm \rightarrow J/\psi\,(\rightarrow\mu\mu)\,\pi^\pm \qquad B^\pm \rightarrow J/\psi\,(\rightarrow\mu\mu) K^\pm$$

Theoretical prediction uncertainties up to 40%: renormalization, factorization scales and the m_b dependencies.

- Results from **4.77 fb^{-1}** Run I pp collisions @ **7 TeV** : event selection based on displaced dimuon triggers.





$B_0 \rightarrow J/\psi\ K^*(892)$
(partially reconstructed)

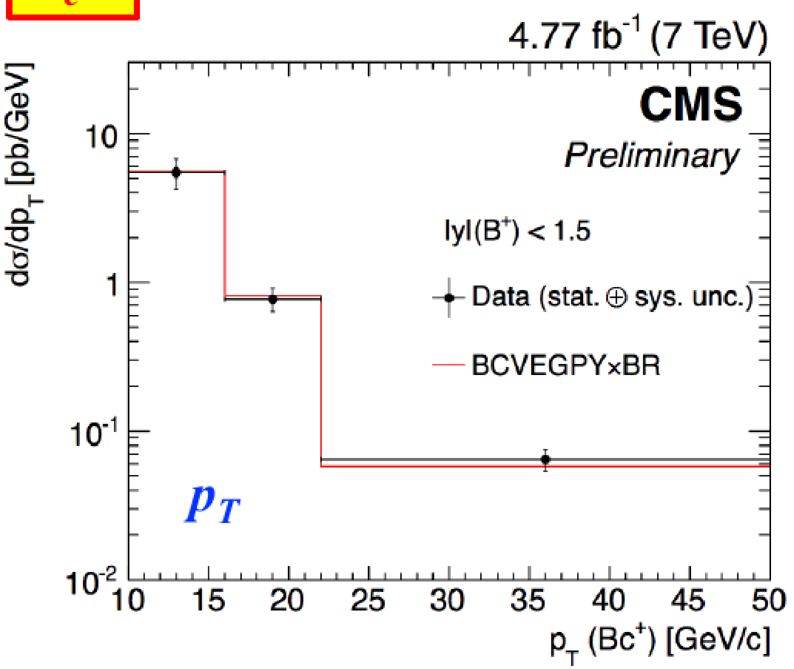
Kinematic region

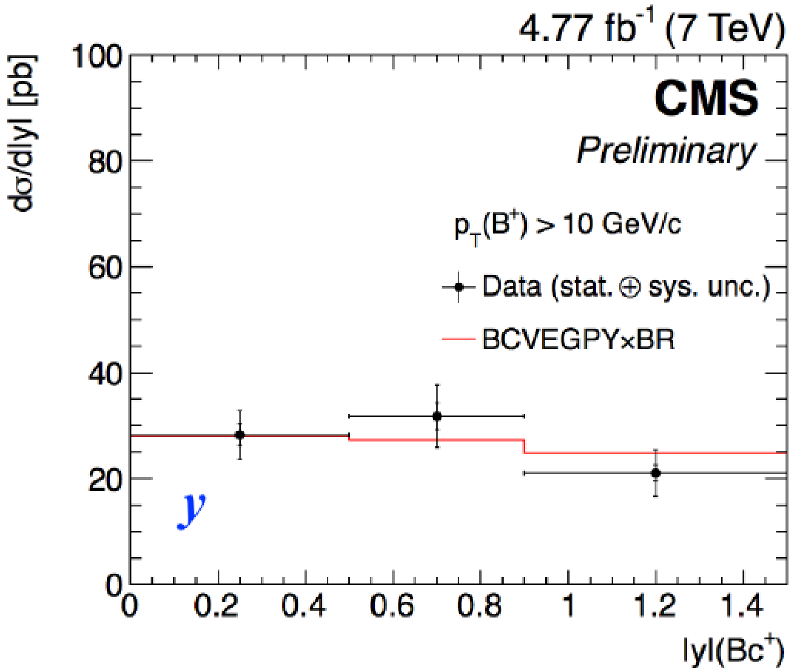
$p_T > 10$ GeV/c and $|y| < 1.5$ to maximize B_c^+ significance $[S/\sqrt{(S+B)}]$

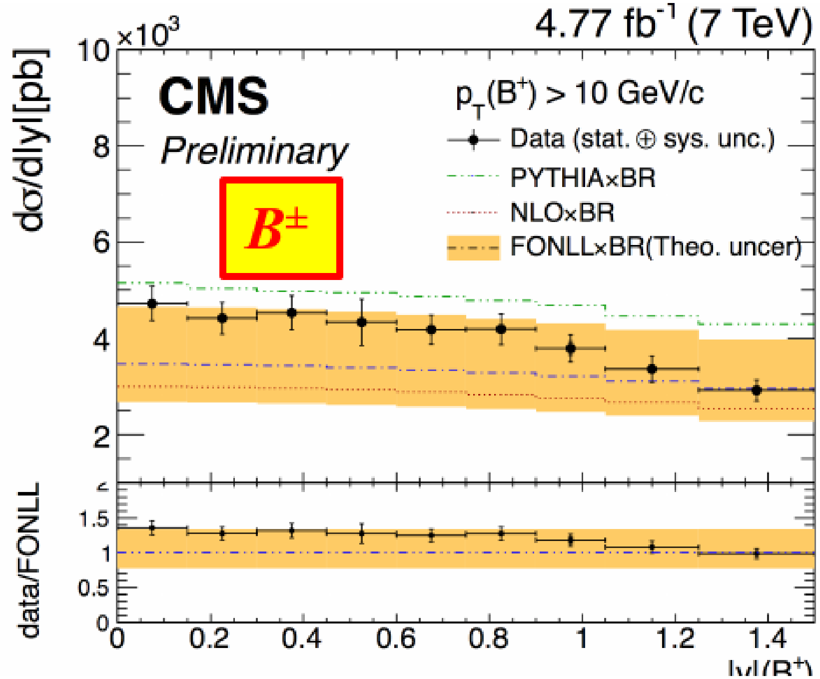
$\mathcal{S}$ from Gaussian fit to **MC**
[BCVEGPY $gg \rightarrow B_c + b + c$]
$\mathcal{B}$ from from $J/\psi\ \pi^+$ **sidebands in data**

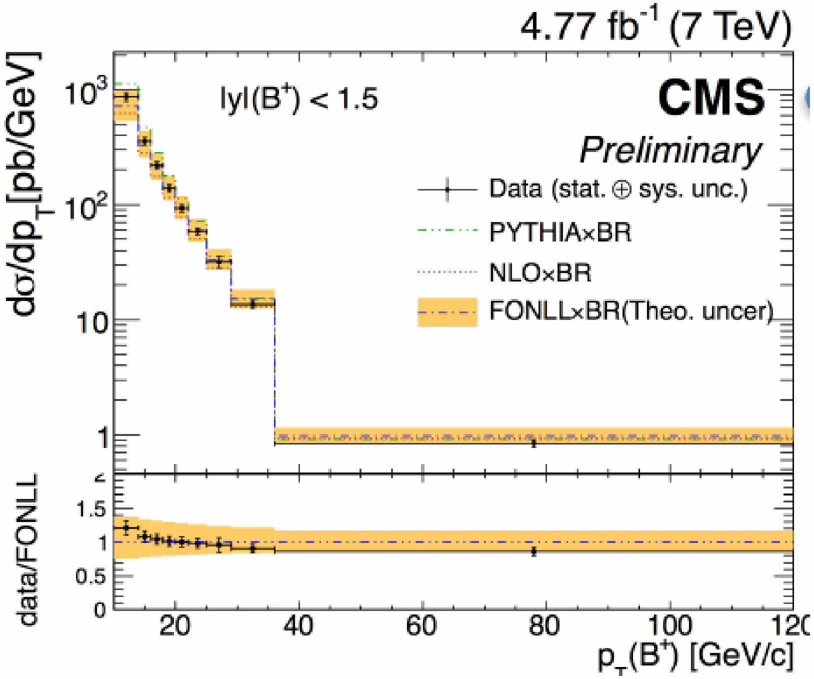
Cross-section results

$B_c^{\pm}$



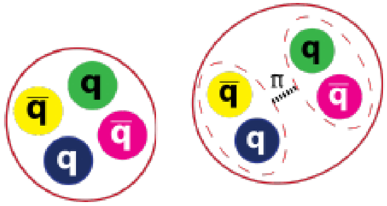






Beyond baryons and mesons: tetraquarks

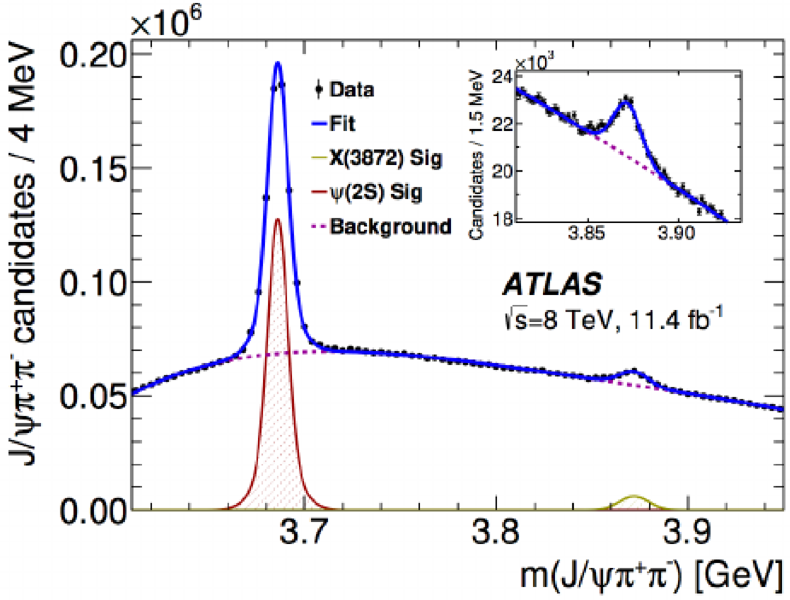
- The **X(3872) is the first exotic** state discovered by in the decays ***$B^+ \rightarrow K^+ X(3872) \rightarrow K^+$ (J/ψππ)*** and confirmed by CDF with $\bar{p}p$ collisions - **mainly prompt** production: only ~16% from mesons. Largely confirmed also by LHC experiments (***CMS,ATLAS,LHCb***):
  - X(3872) now measured as $J^{PC}=1^{++}$, **M=3871.69 ± 0.17 MeV**



LHCb PRL 110 (2013) 222001

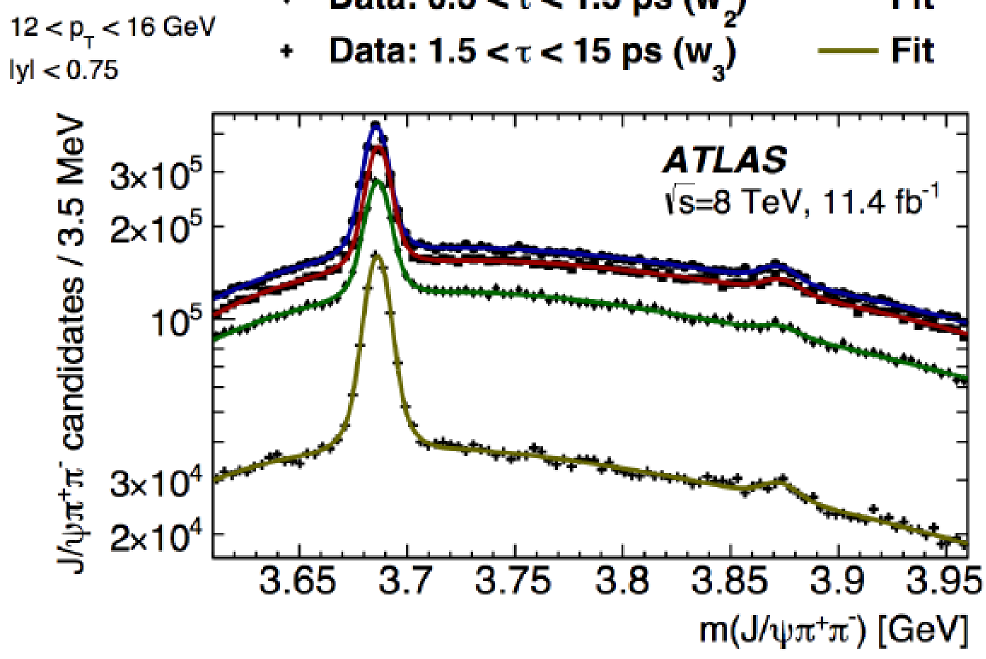
Very close to $D^0\overline{D}^{0*}$threshold; tetra-quark, molecule ($D^0\overline{D}^{0*}$ loose), mixed state ? **Still not clear (since 2003!)**

- **8TeV 11fb^{-1} pp data, ATLAS** has studied the ***J*** **ψ ππ** final state **comparing** X **and** ψ(2*S*) productions
  - |y| < 0.75 $\Delta R(J/\psi, \pi^{\pm}) < 0.5,$ $Q < 0.3\,\mathrm{GeV}$
  - use $\tau = \frac{L_{xy} m}{c p_T}$ **to select 4 pseudo-proper decay time bins**
  - 10 < pT < 70 GeV



4 τ bins

- **Data: -0.3 < τ < 0.025 ps (w_0)** **Fit**
- **Data: 0.025 < τ < 0.3 ps (w_1)** **Fit**
- **Data: 0.3 < τ < 1.5 ps (w_2)** **Fit**
- **Data: 1.5 < τ < 15 ps (w_3)** **Fit**



Conclusions

Particles with b and c quarks can be relatively easily identified, and perturbative models allow quite precise theory predictions

B meson decays, oscillations and interference allow over-constraining the CKM parameters and clarify our understanding for CP violation

So far multiple observations give a consistent picture for CP violation and mixing- the unitarity triangle closes!

However, some measurements of b→ s decays show very interesting deviations from the SM, being followed up very closely

Heavy flavor production in pp colliders used to search for QCD tests, PDF determination and search for rare decays

In the future LHCb will be upgraded, and a super-b factory is being built to upgrade Belle