Heavy flavor production and decay at colliders

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THE THIRD BIENNIAL AFRICAN SCHOOL OF FUNDAMENTAL PHYSICS AND ITS APPLICATIONS

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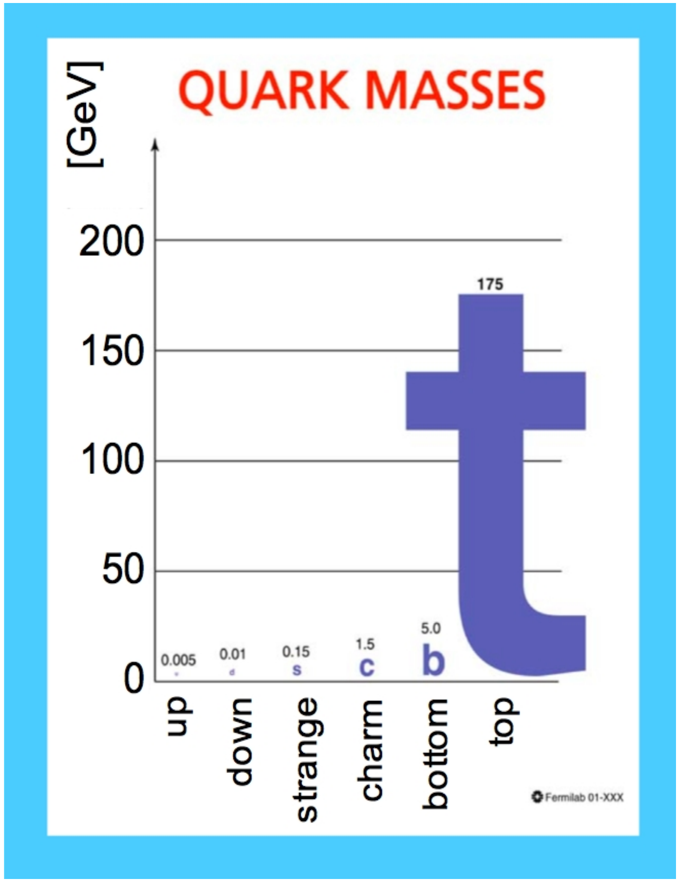
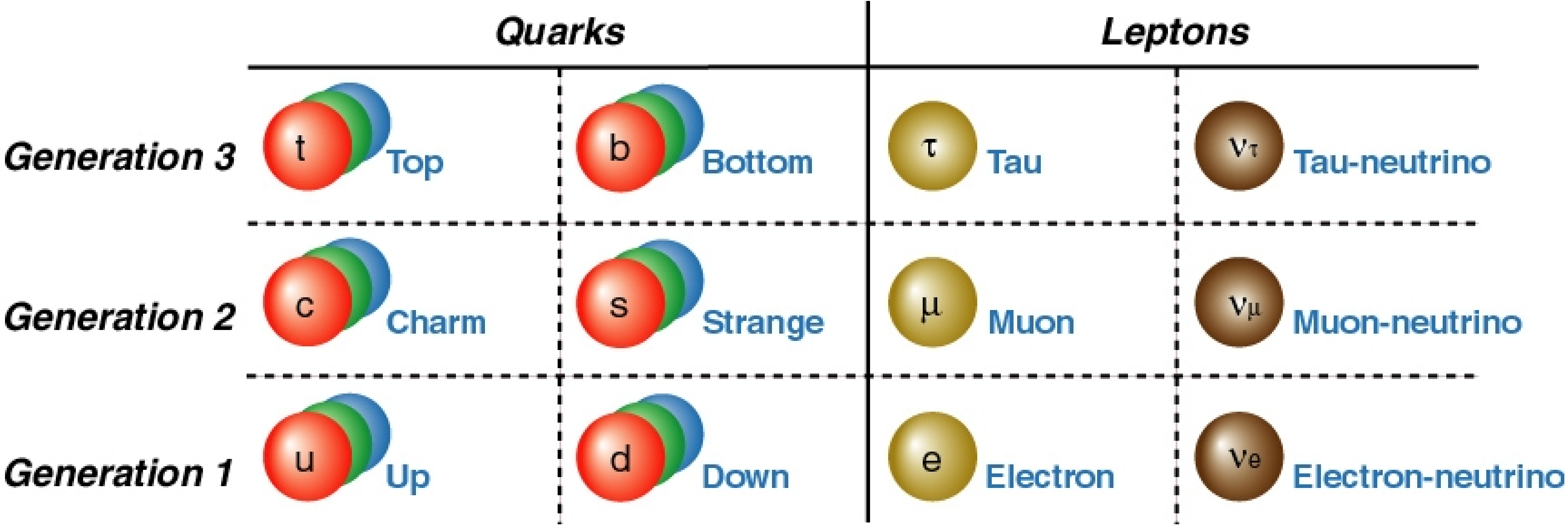
Outline

- 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
- Heavy flavors in ep collisions

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
    $x \rightarrow x+a$ 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:

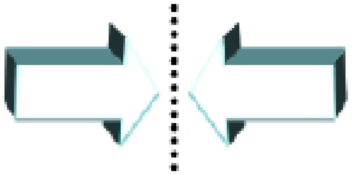
- Parity
- Charge conjugation
- Time reversal

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:

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

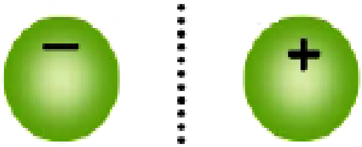
- Vectors change sign under a $\mathcal{P}$ transformation, pseudo-vectors or axial-vectors do not.

- $\mathcal{P}$ 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: $\mathcal{CP}$

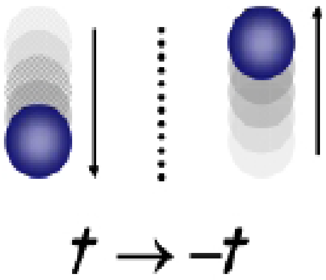
The fundamental point is that CP symmetry is broken in any theory that has complex coupling constants in the Lagrangian which cannot be removed by any choice of phase redefinition of the fields in the theory.

- 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.*
- We need to consider $\mathcal{CP}$ to remove the convention dependence of what is ***left*** or ***right*** in nature
  - *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

$$\mathcal{CP}\,|\,\mathrm{u}\,\rangle = |\,\overline{\mathrm{u}}\,\rangle$$

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 flavor structure, encoded in the Cabibbo Kobayashi Maskawa (CKM) matrix V.

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

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

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

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

Unitary matrix independent parameters

in general, an $n \times n$ unitary matrix has n^2 real and independent parameters:

- a $n \times n$ 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.

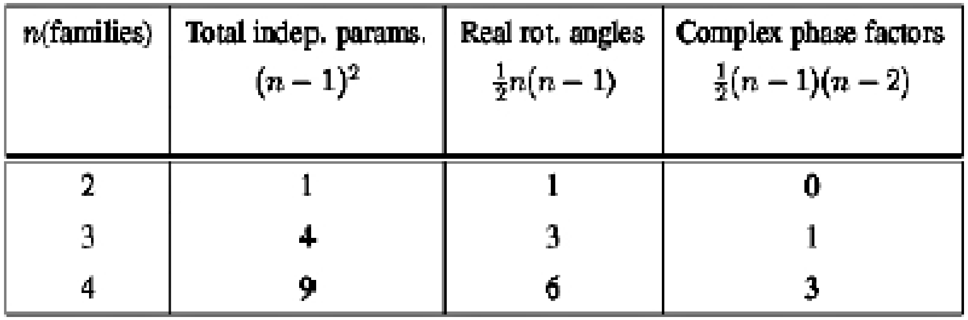
thus: $n^2 - (2n - 1) = (n - 1)^2$.

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

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

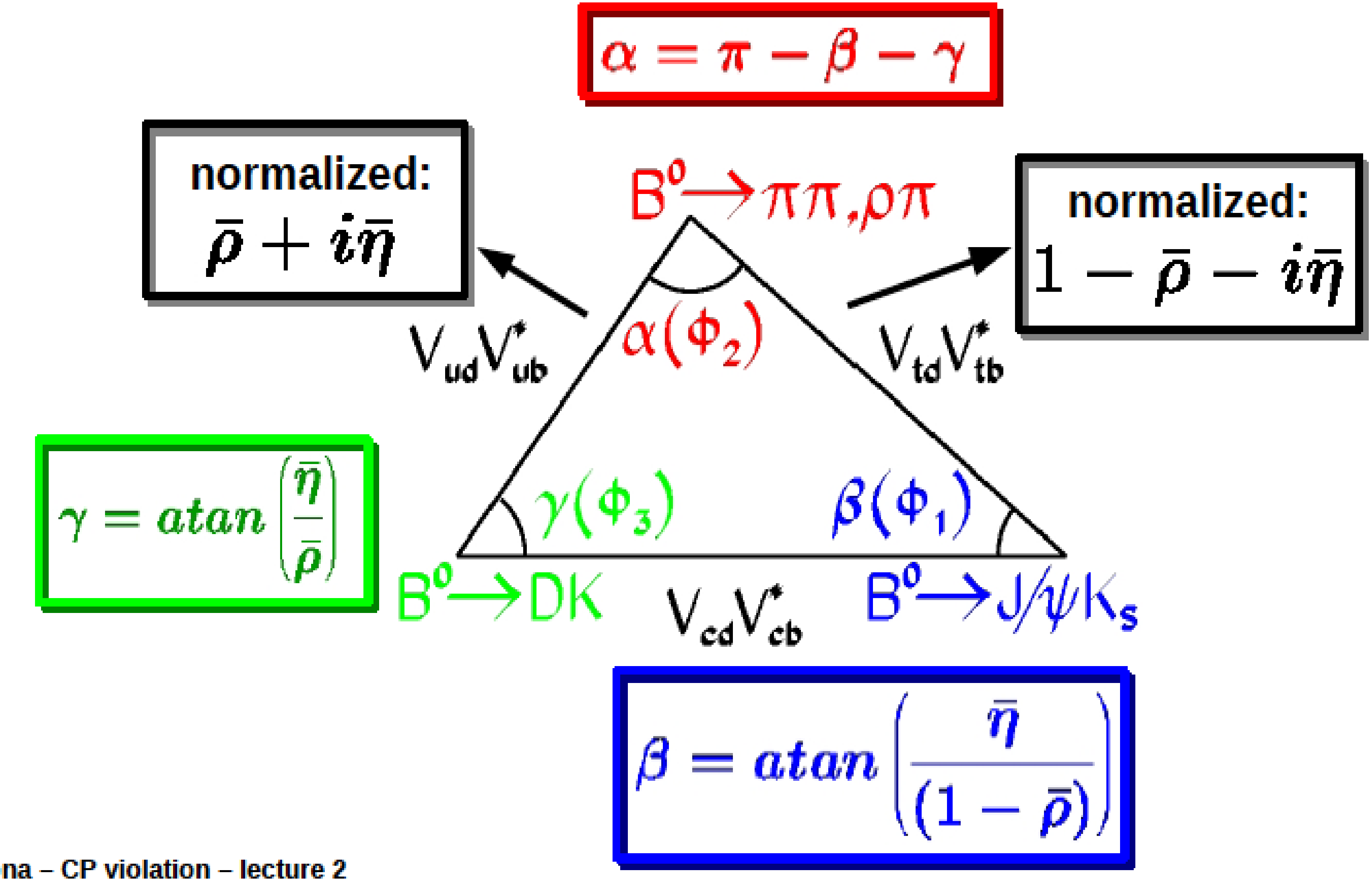
beyond lowest order $\bar{\rho} = \rho(1-\lambda^2/2)$ and $\bar{\eta} = \eta(1-\lambda^2/2)$

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

Unitarity triangle

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

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



$$\boxed{\alpha = \pi - \beta - \gamma}$$

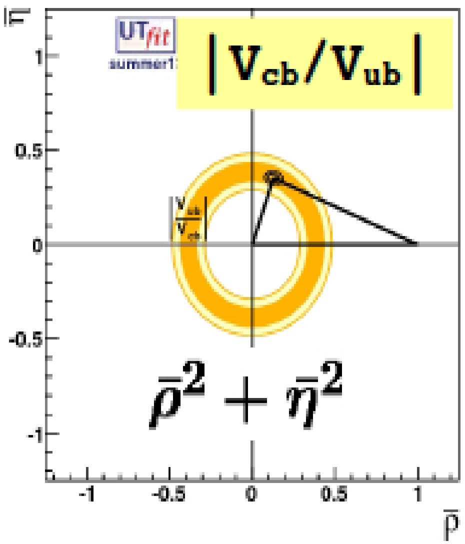
normalized: $\bar{\rho} + i\bar{\eta}$

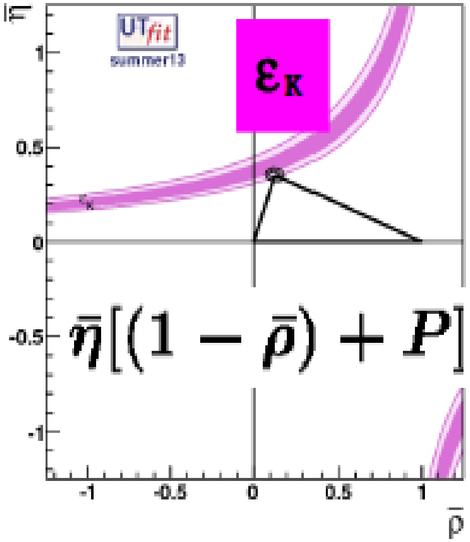
normalized: $1 - \bar{\rho} - i\bar{\eta}$

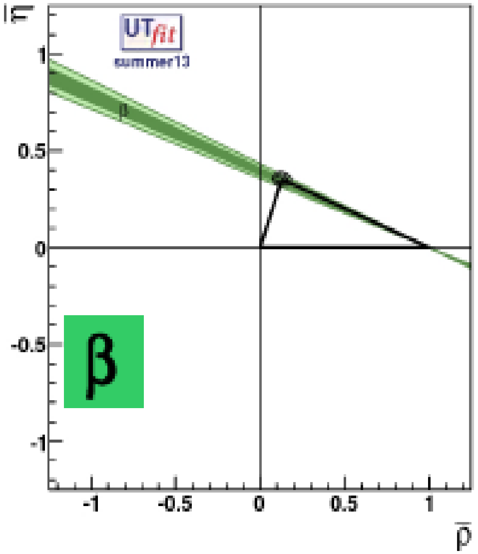
$$\boxed{\gamma = atan\left(\frac{\bar{\eta}}{\bar{\rho}}\right)}$$

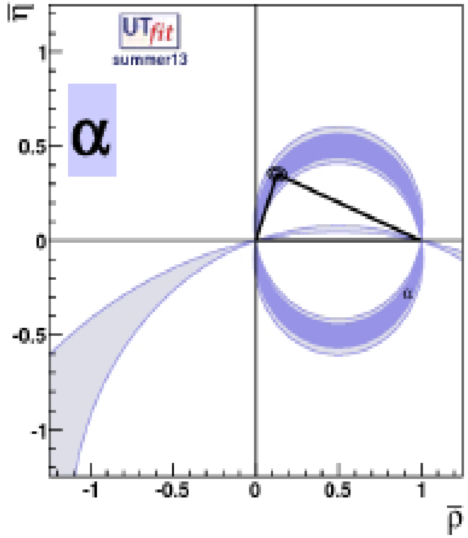
$$\boxed{\beta = atan\left(\frac{\bar{\eta}}{(1-\bar{\rho})}\right)}$$

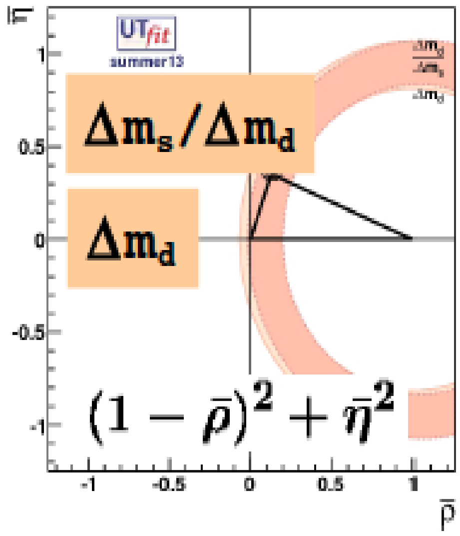
Unitarity Triangle analysis in the SM

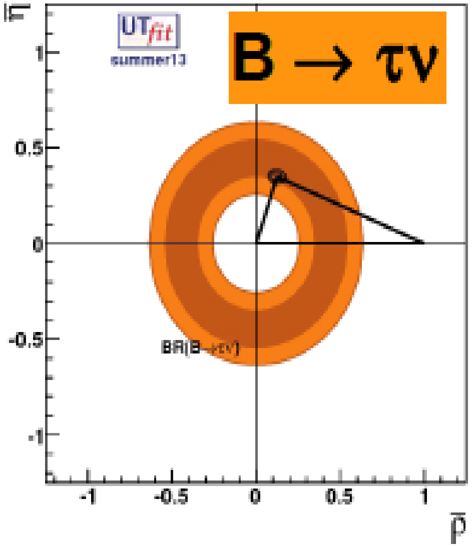


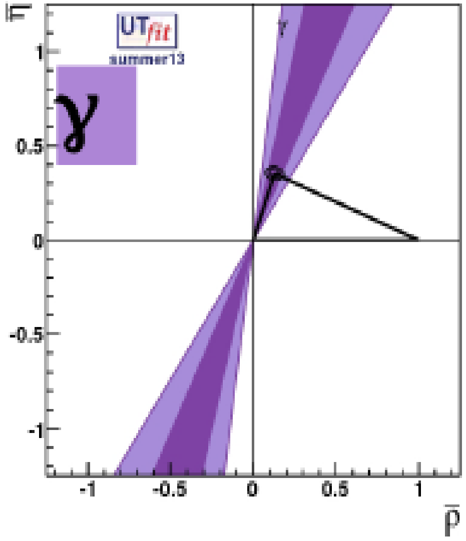


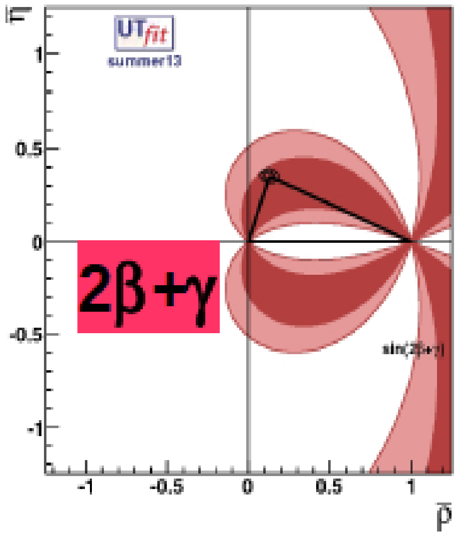








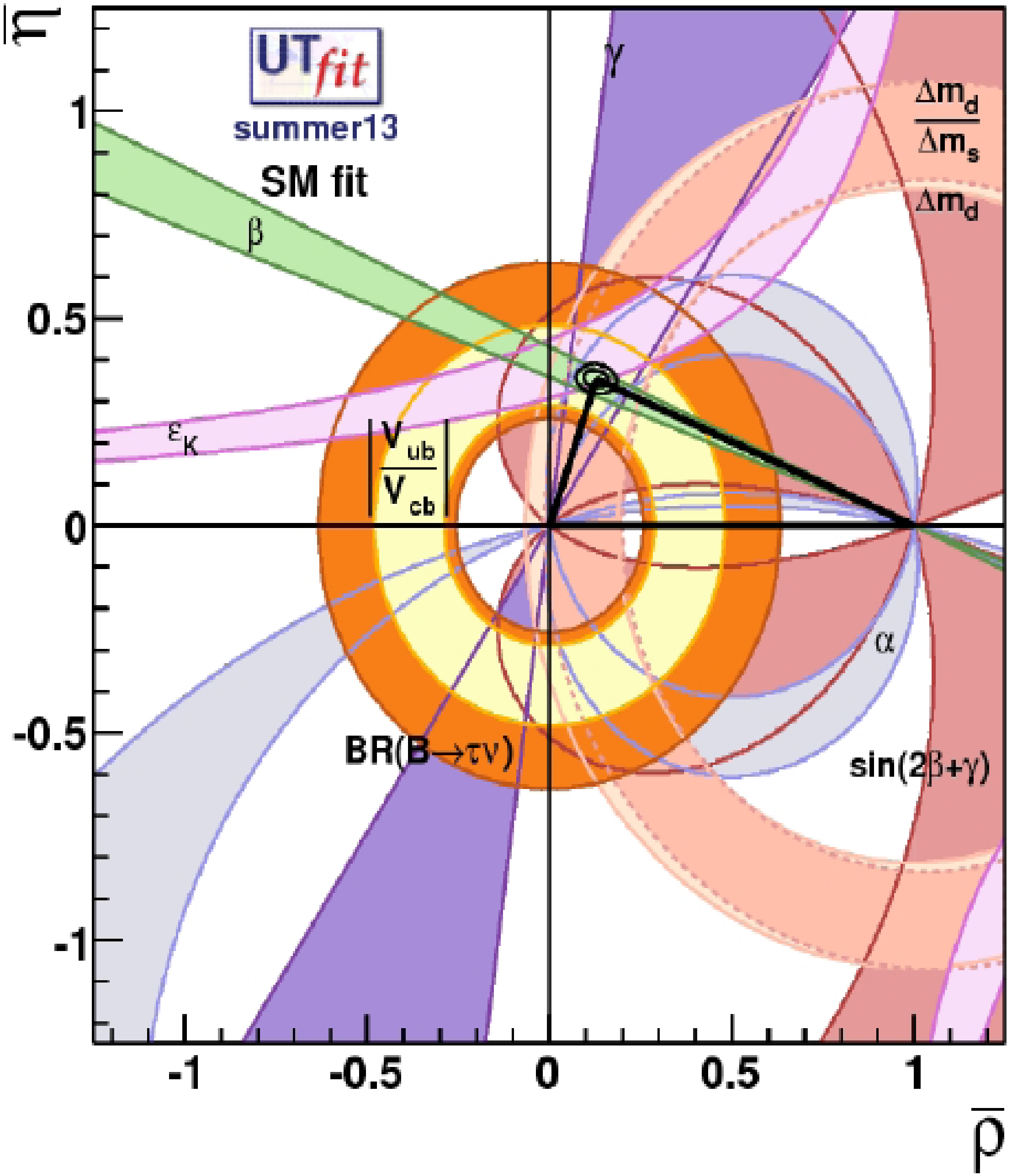




Unitarity Triangle analysis in the SM

Observables	Accuracy
$\|V_{ub}/V_{cb}\|$	~ 13%
ε_K	~ 0.5%
Δm_d	~ 1%
$\|\Delta m_d/\Delta m_s\|$	~ 1%
$\sin 2\beta$	~ 3%
α	~ 8%
γ	~ 10%
$BR(B \rightarrow \tau\nu)$	~ 19%

Unitarity Triangle analysis in the SM



levels @
95% Prob

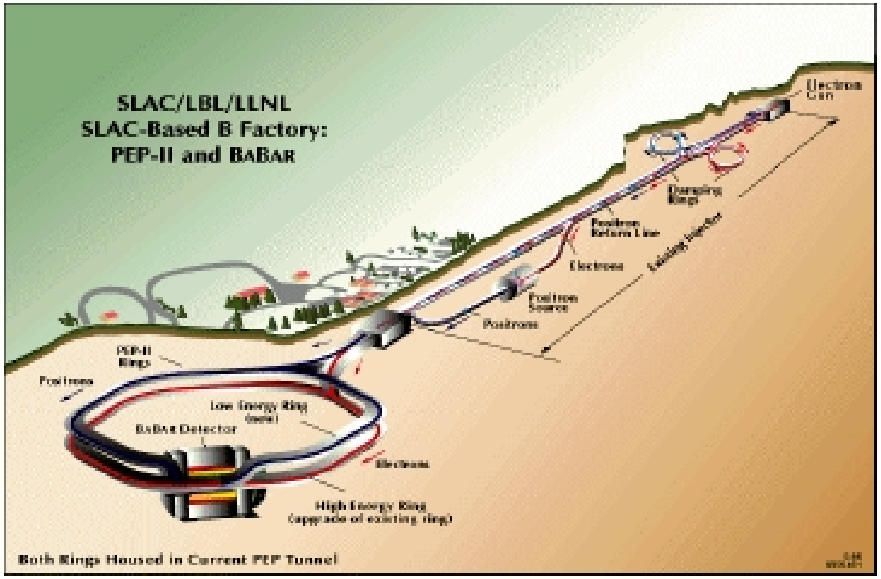
$$\bar\rho = 0.129 \pm 0.024$$
$$\bar\eta = 0.353 \pm 0.016$$

analysis from

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

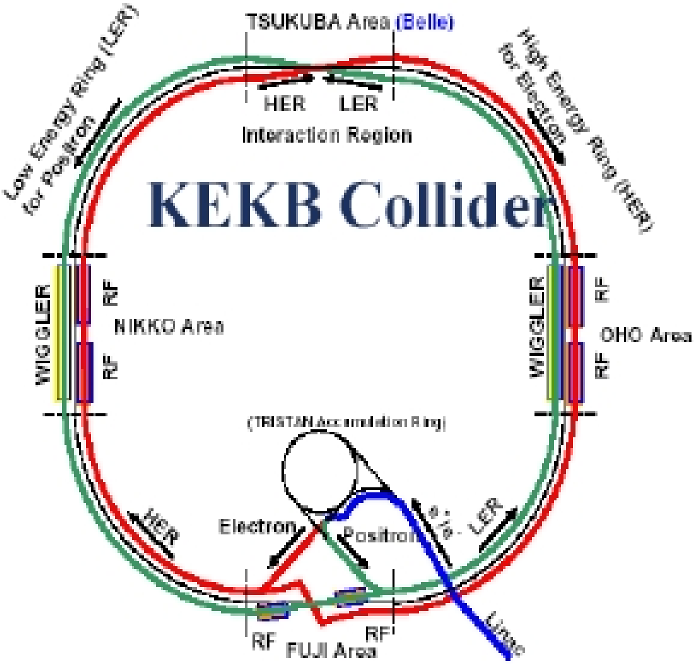
www.utfit.org

PEP-II and KEKB



PEP-II

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

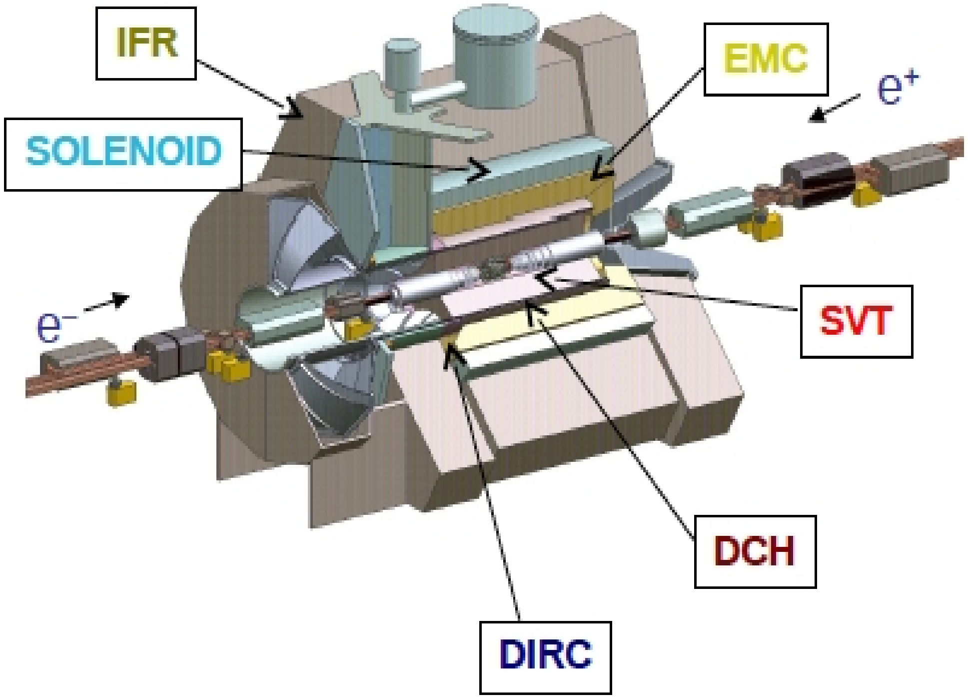


KEKB

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

BaBar and Belle

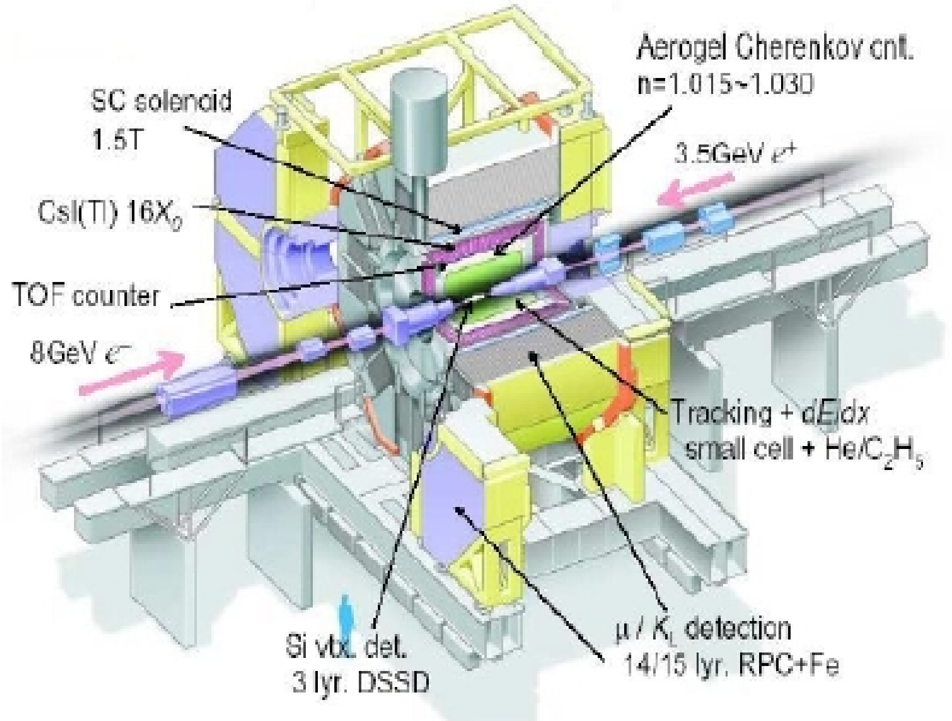
BABAR



The differences between the two detectors are small. Both have:

- **Asymmetric design.**
- **Central tracking system**
- **Particle Identification System**
- **Electromagnetic Calorimeter**
- **Solenoid Magnet**
- **Muon/K^0_L Detection System**
- **High operation efficiency**

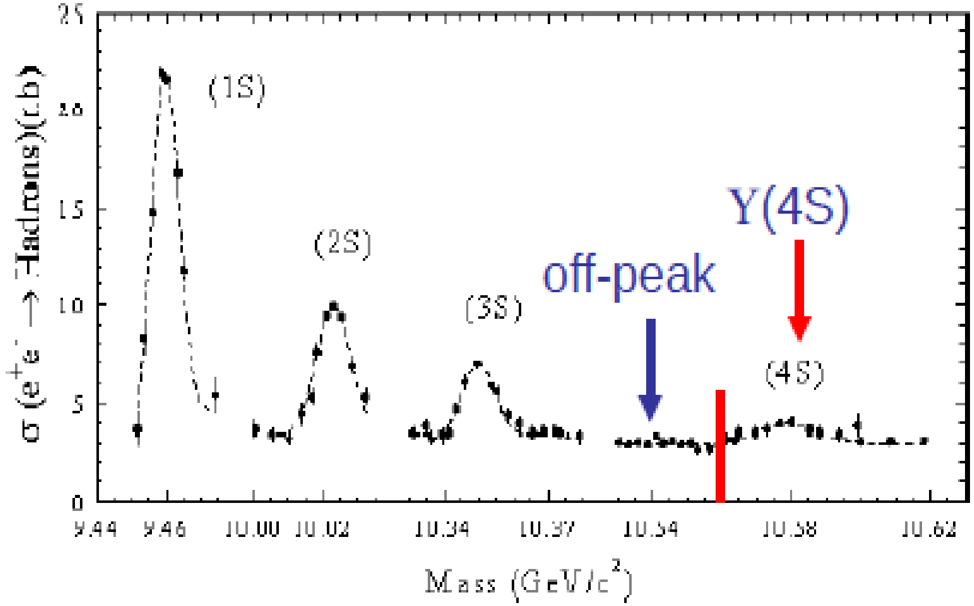
BELLE



Producing B mesons

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

$e^+e^- \rightarrow$	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)** → **$\overline{\text{B}}$B** (for B physics).
- where we have $\dfrac{\mathcal{B}(\Upsilon(4S) \rightarrow B^0\overline{B}^0)}{\mathcal{B}(\Upsilon(4S) \rightarrow B^+B^-)} \simeq 1$

Neutral meson oscillation

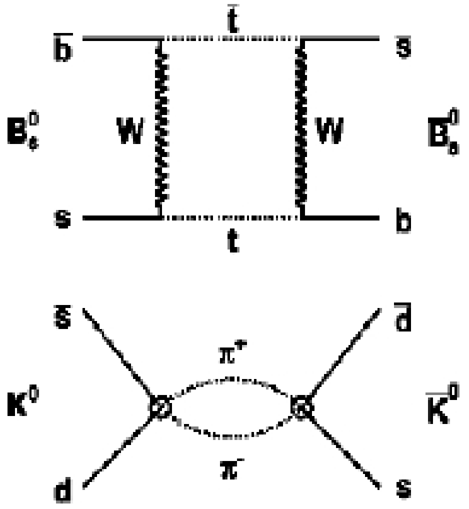
- We have flavour eigenstates M^0 and $\overline{M}^0$:
  - M^0 can be K^0 (sd), D^0 (cu), B_d^0 (bd) or B_s^0 (bs)

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 $m_{\mathbf{1,2}}$ and $\Gamma_{\mathbf{1,2}}$)

- 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 ($a_{ij} = \overline{a}_{ji}$)

$$M = ½\,(H+H^\dagger) \text{ and } \Gamma = i(H-H^\dagger)$$

- 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:

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

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

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

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

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

other useful definitions:

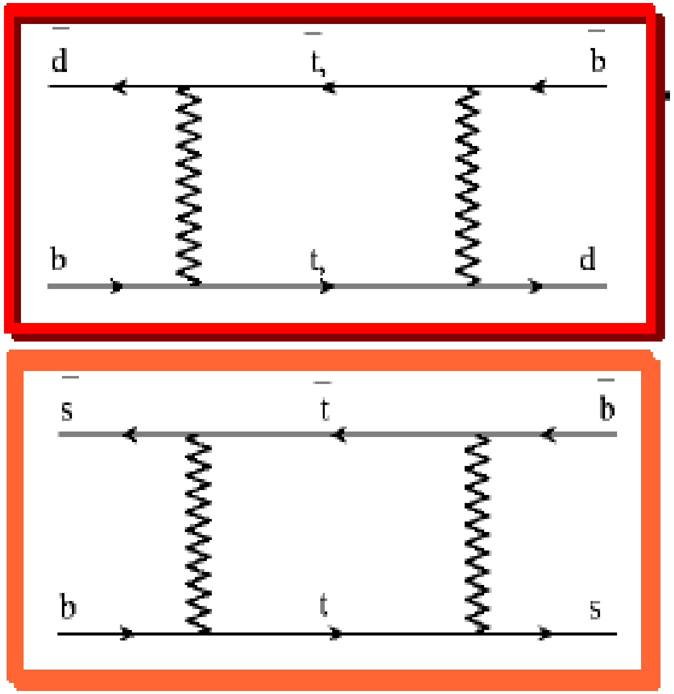
$x \equiv \Delta m/\Gamma$

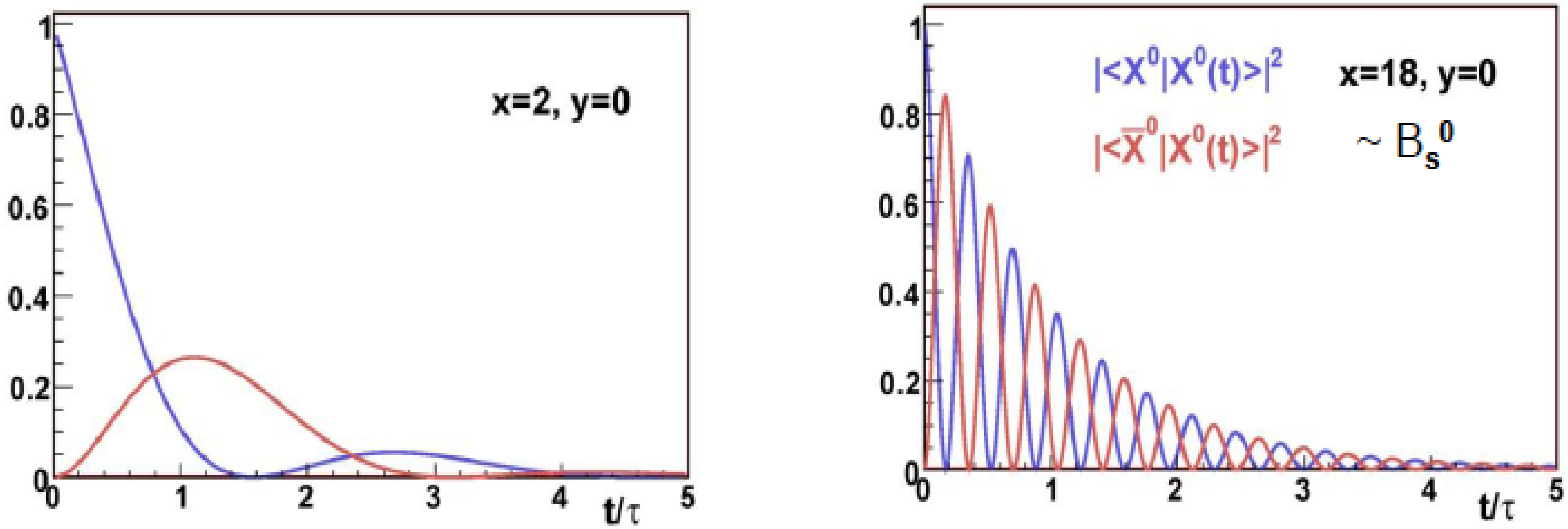
$y \equiv \Delta\Gamma/2\Gamma$

B oscillations

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

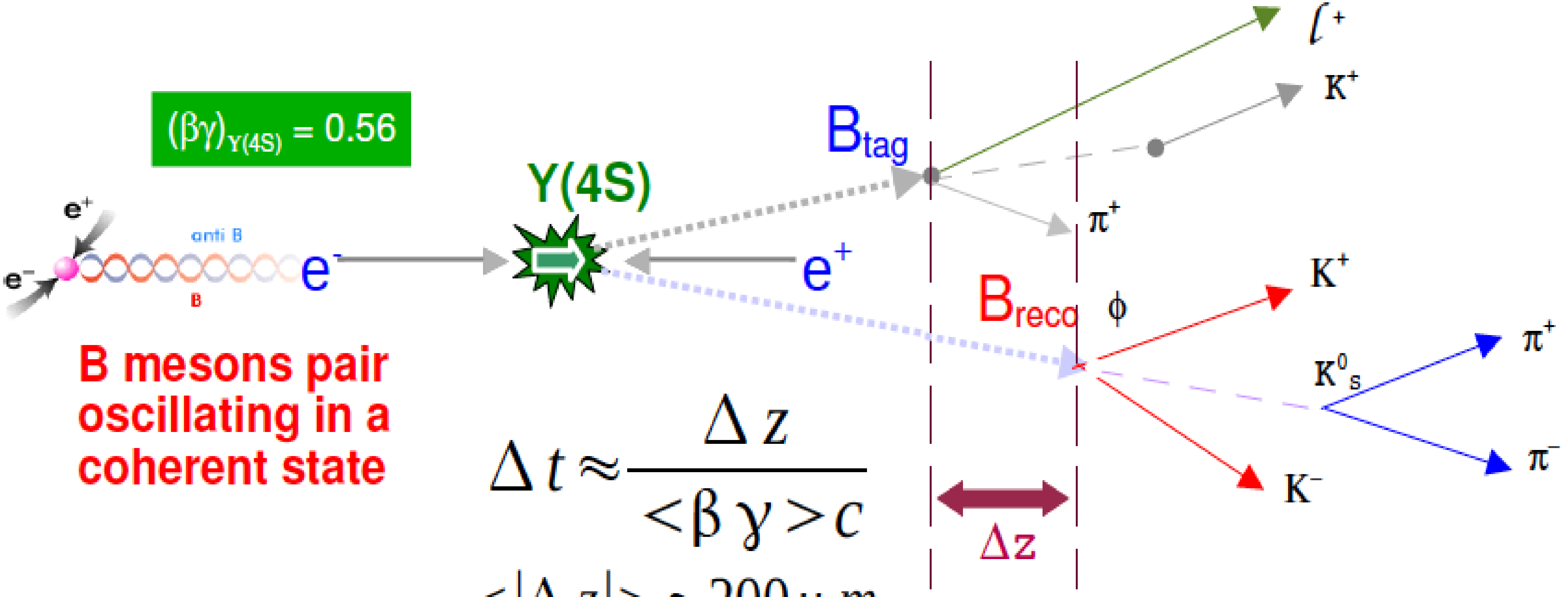
so same phenomenology also
in the B_s, except that
the oscillation frequency is very different





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

Experimental technique

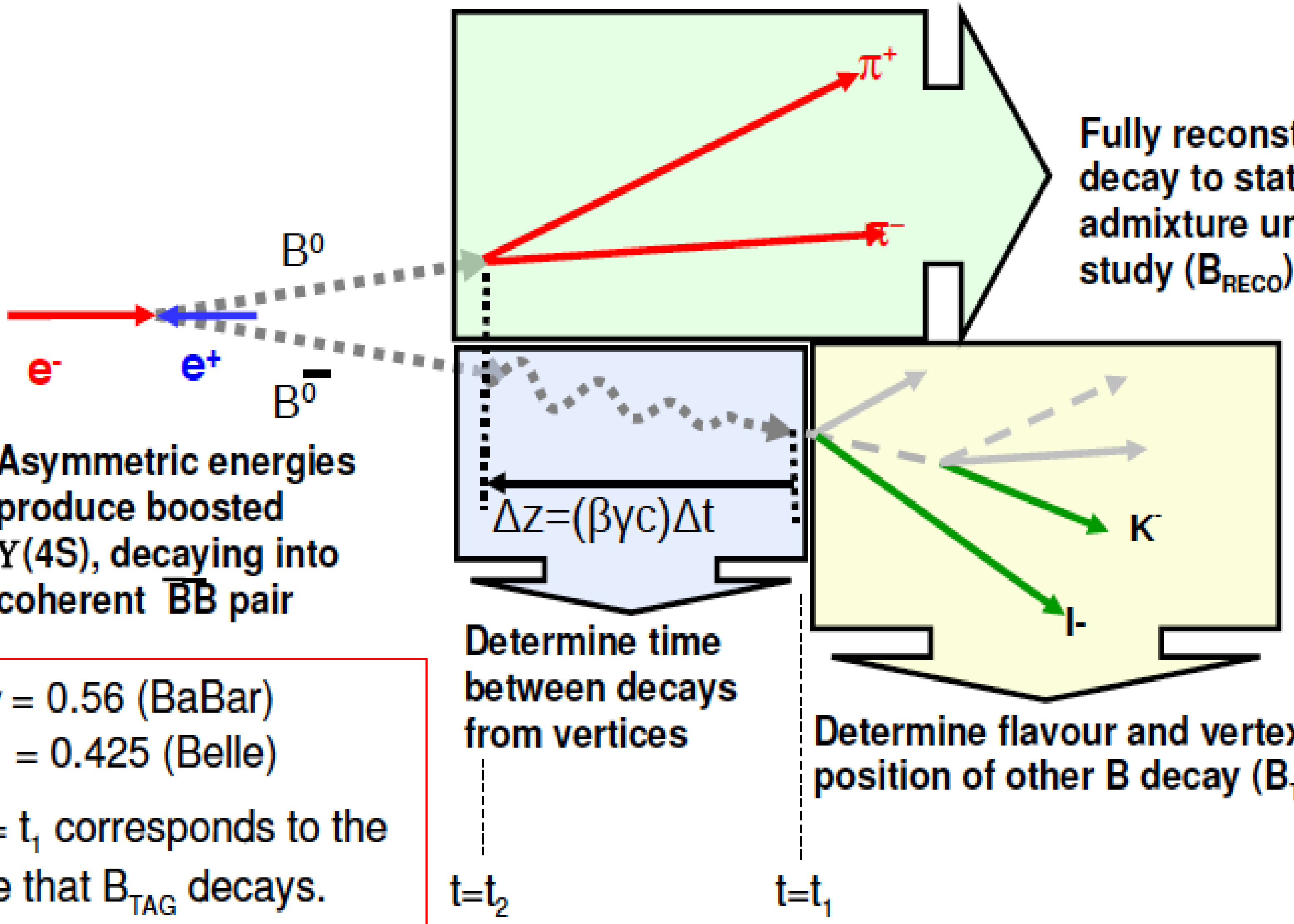


B mesons pair oscillating in a coherent state

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

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

Measuring Δt



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

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

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.

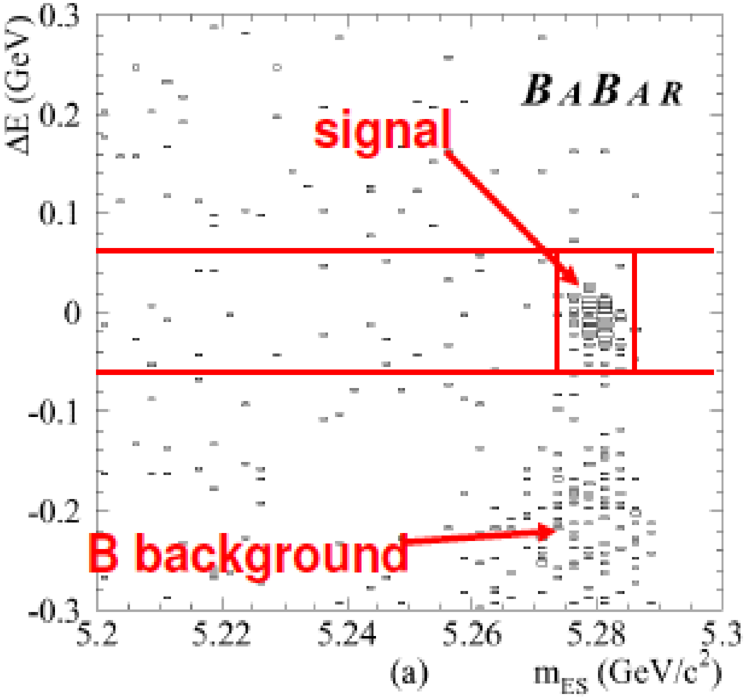
Isolating signal events

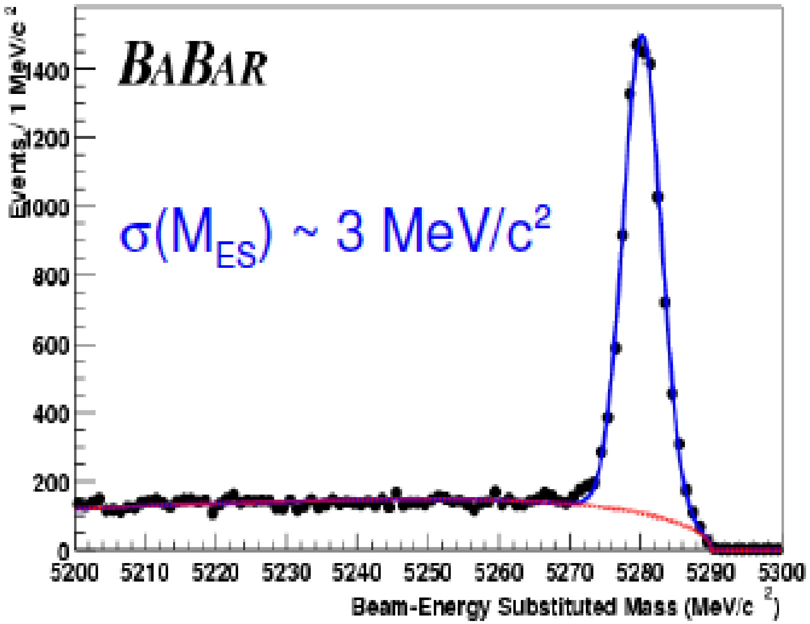
- Beam energy is known very well at an e^+e^- collider
  - use an energy difference and effective mass to select events:

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

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

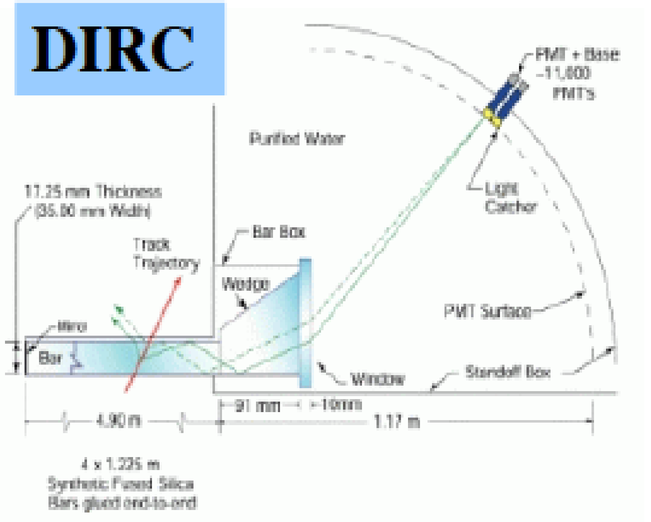
$\sigma(\Delta E)$ ~ 15-80 MeV (mode dependent)

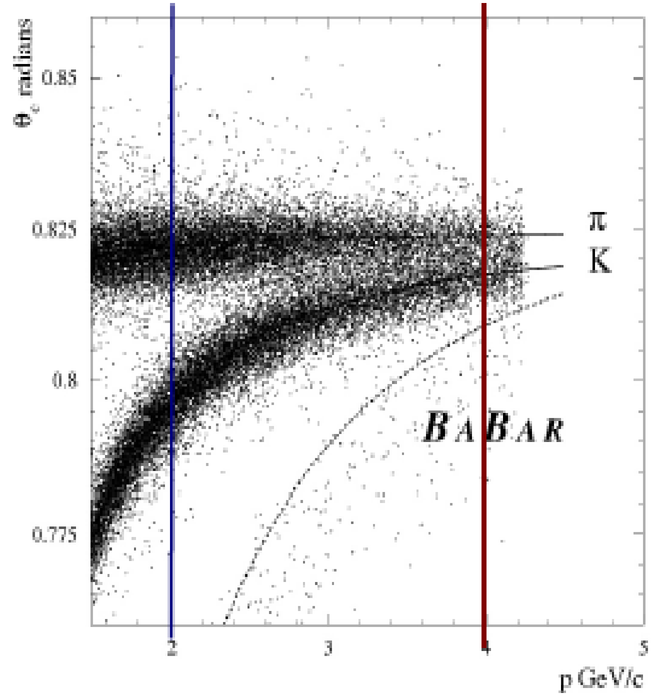


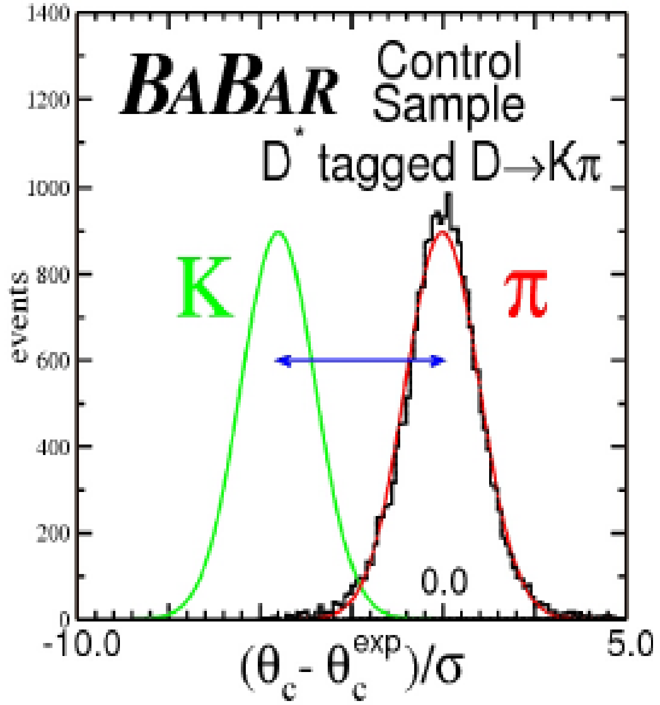


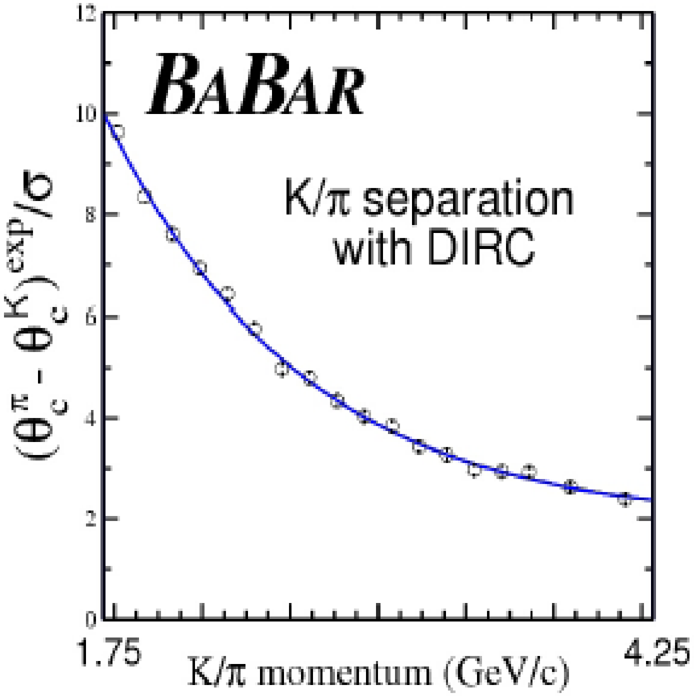
$\sigma(M_{ES})$ ~ 3 MeV/c^2

Particle identification





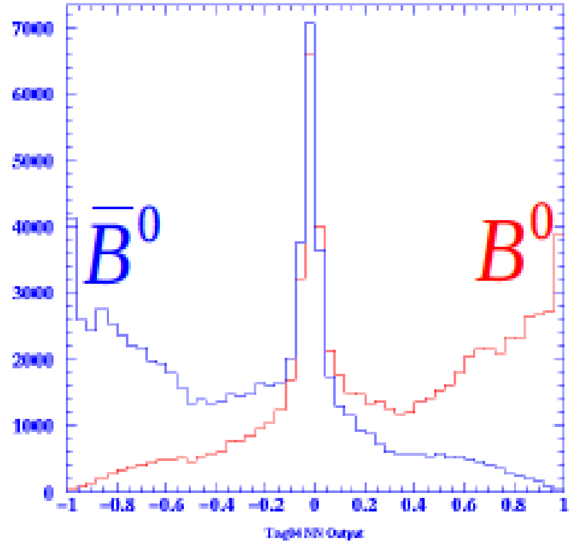


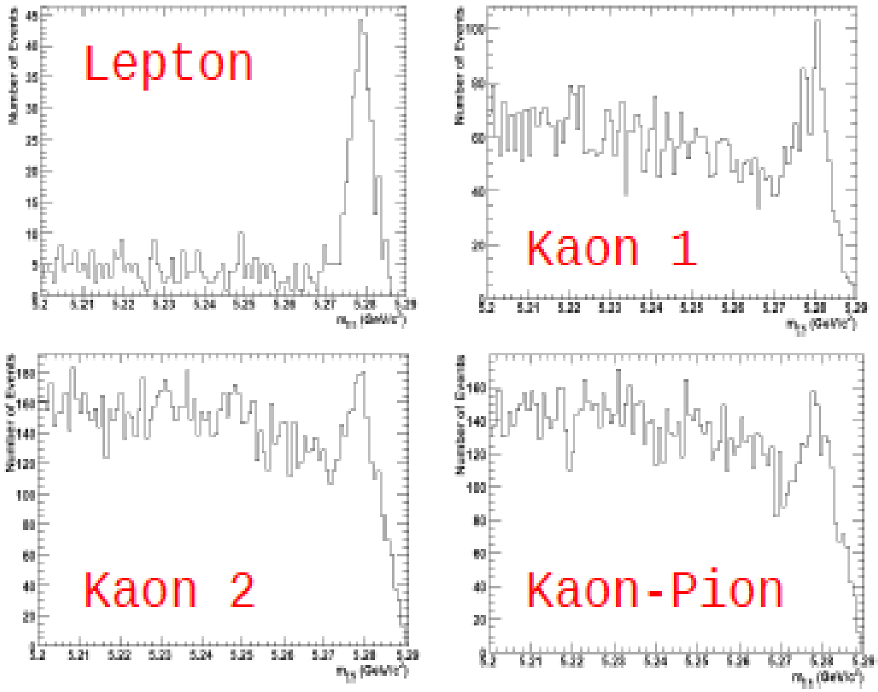


- ◎ measurement of the Cherenkov angle
  - ◉ K/π separation:
    8σ @ 2 GeV/c and 2.5σ @ 4 GeV/c
  - ◉ dE/dx from SVT and DCH
    up to 0.7 GeV/c
  - ◉ Kaon selection:
    efficiency ~90%, π mis-id <10%

Flavour tagging

- Decay products of B_{TAG} are used to determine its flavour.
- At Δt=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.

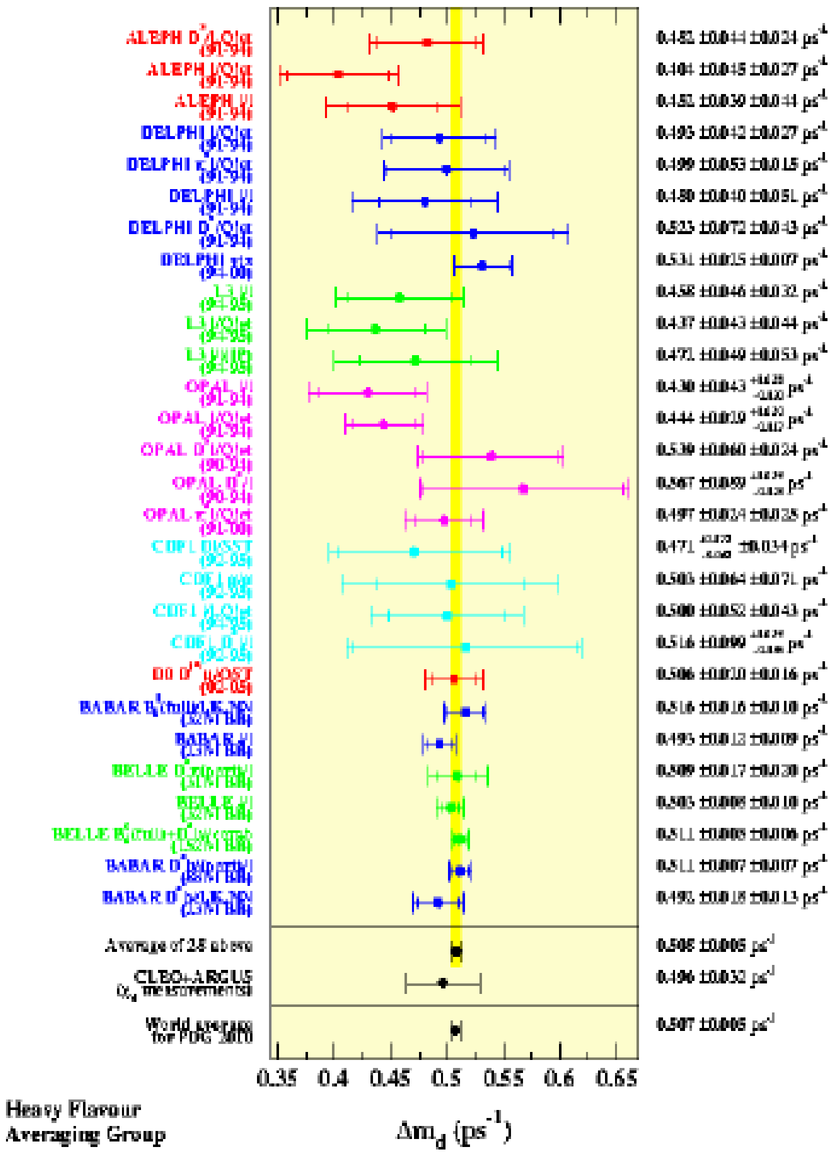




BaBar's flavour tagging algorithm splits events into mutually exclusive categories ranked by signal purity and mis-tag probability. Belle opts to use a continuous variable output.

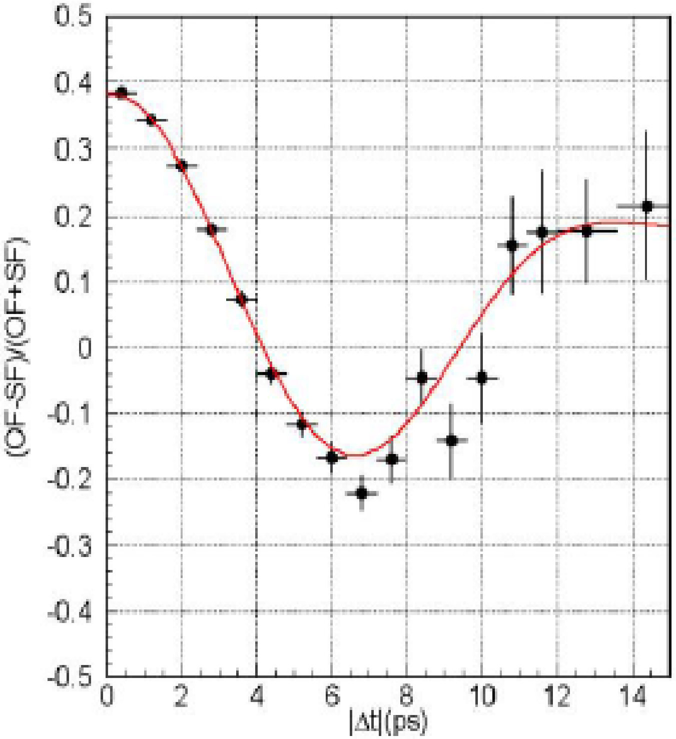
B_d oscillations

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



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

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



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

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

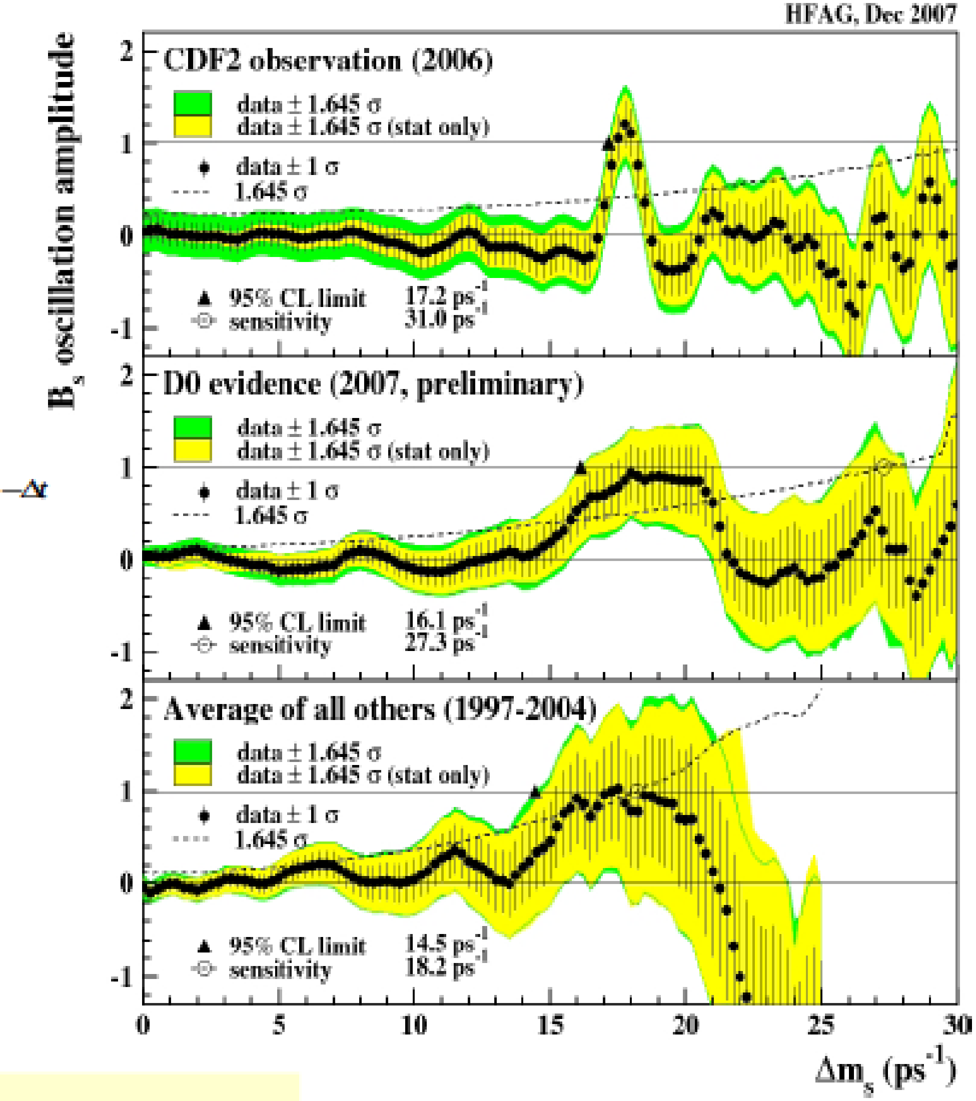
B_s oscillations

At the Tevatron on the B_s:

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

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

- ► fit A at different values of Δm_s;
  if A=1
  ⇨ oscillations at this Δm_s value

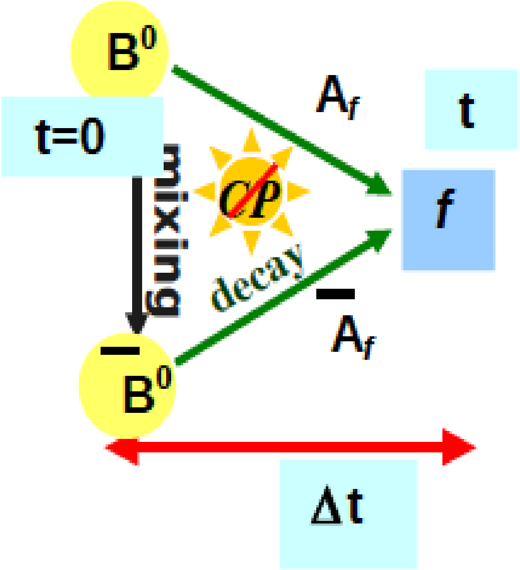


Very precise determination from the Tevatron:

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 $\bar{B}^0$ into a CP eigenstate f_{CP}.

1. Direct CP violation.

$$P(\ B^0 \rightarrow f\ ) \neq P(\ \bar{B}^0 \rightarrow \bar{f}\ )$$

2. Indirect CP violation (CPV in mixing).

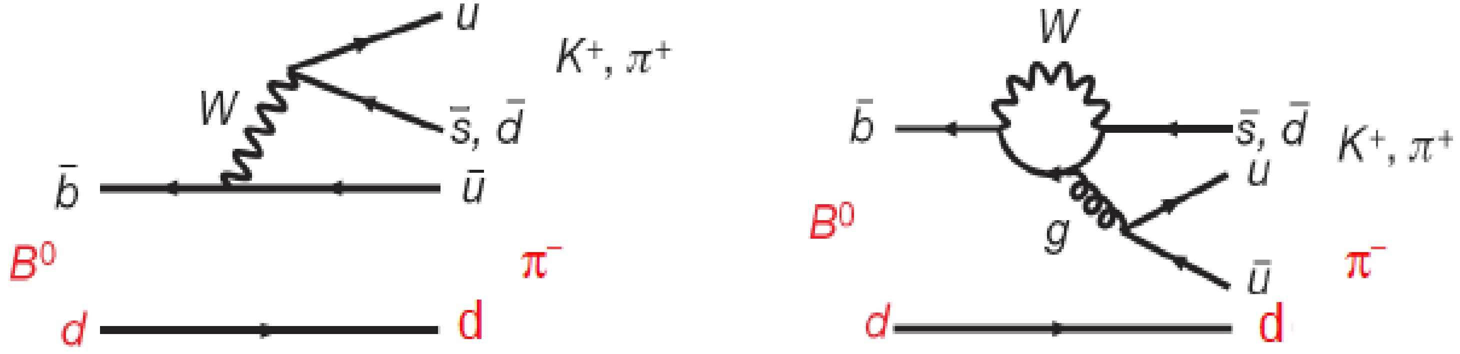
$$P(\ B^0 \rightarrow \bar{B}^0\ ) \neq P(\ \bar{B}^0 \rightarrow B^0\ )$$

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

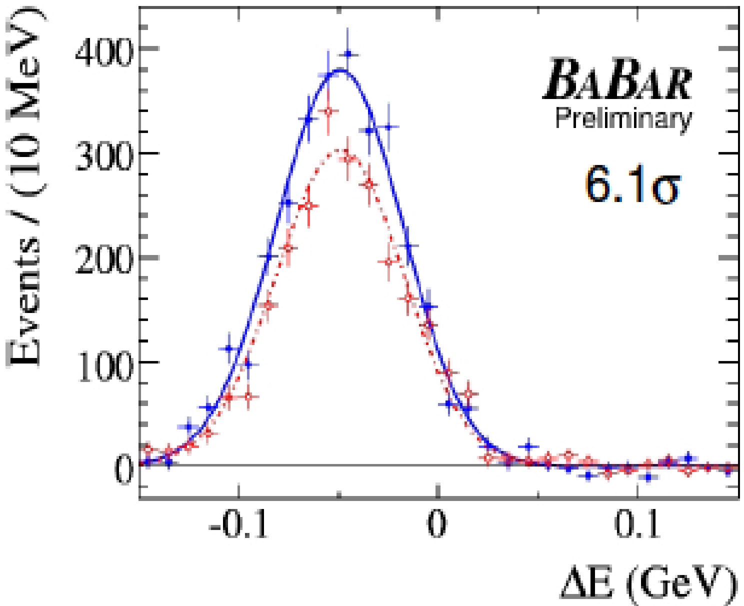
- $B^0 \to K^{\pm}\pi^{\mp}$: Tree and gluonic penguin contributions



- Compute time integrated asymmetry

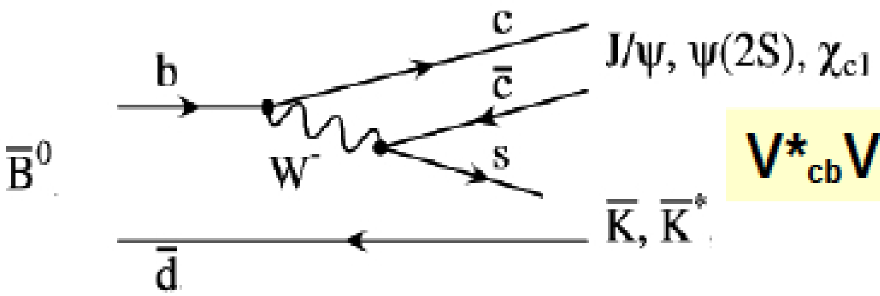
$$\mathcal{A}_{K^{\pm}\pi^{\mp}} \equiv \frac{N(\bar{B}^0 \to K^-\pi^+) - N(B^0 - K^+\pi^-)}{N(\bar{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.098 \pm 0.012$$

- 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!

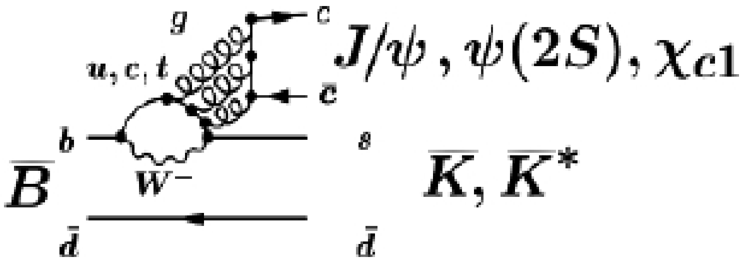


$\beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$

sin2β in golden b → $\bar{c}$cs modes



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



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

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

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

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

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

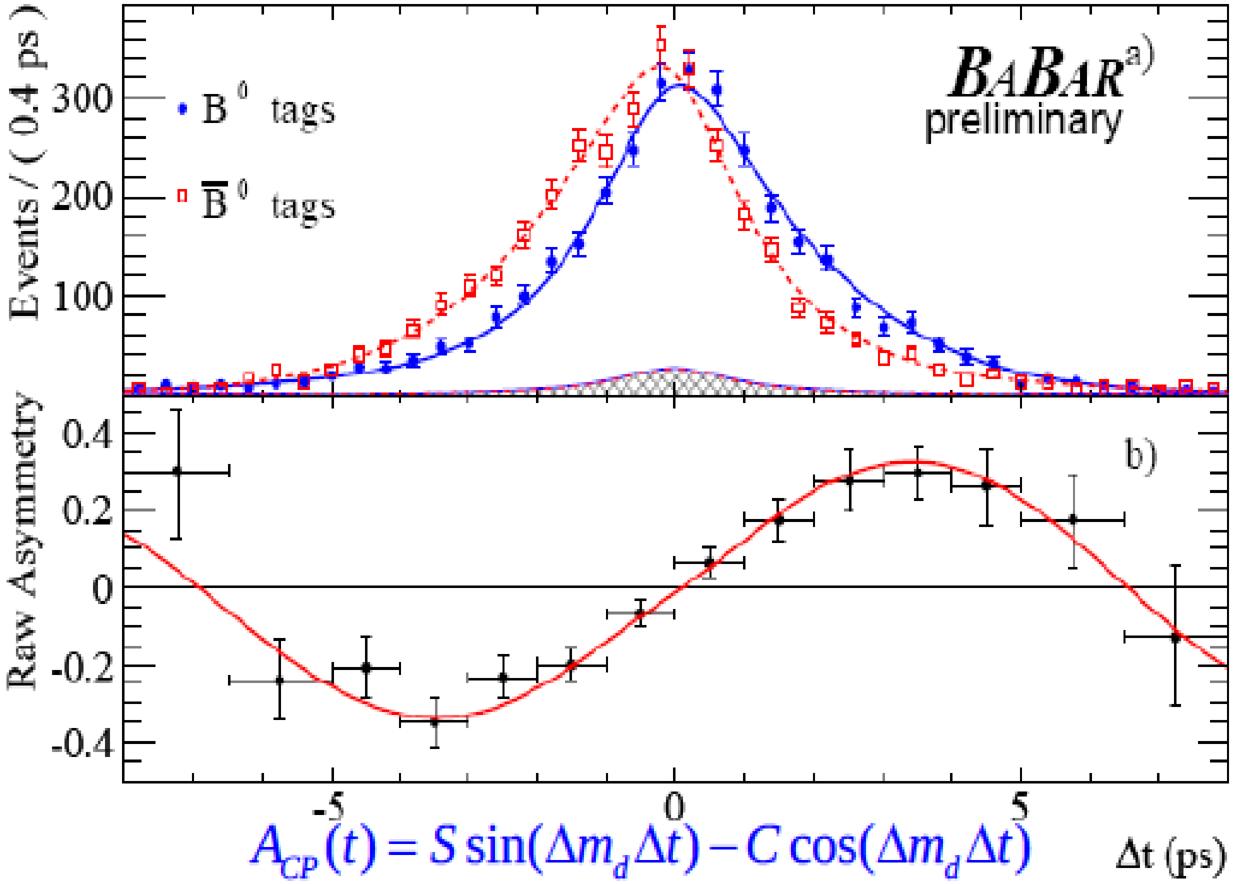
H.Li, S.Mishima
JHEP 0703:009 (2007)

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 $b \rightarrow \bar{c}cs$ 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

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

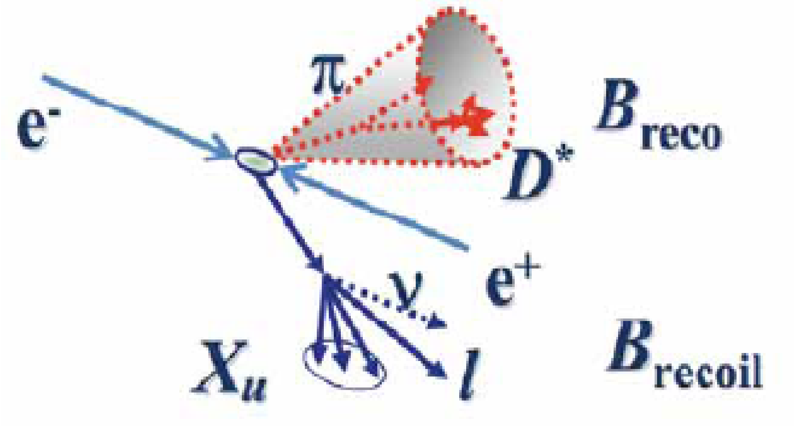
This tells us that there is CP violation in the interference between mixing and decay amplitudes in $\bar{c}cs$ decays.

Side measurements: V_{ub}

- $|V_{ub}| \propto BR(B \to X_u l\nu)$ in a limited region of phase space.
- Reconstruct both B mesons in an event.
  - Study the B_{recoil} to measure V_{ub}.
  - Measure BR as a function of

    $q^2_{l\nu}$, m_X, m_{MISS} or E_l

    and use theory to convert these results into $|V_{ub}|$.



- Can study modes exclusively or inclusively.
- Several models available to estimate $|V_{ub}|$
  - The resulting values of V_{ub} have a significant model uncertainty.

Exclusively reconstructed b → ulν

- If we fully reconstruct one B meson in an event, then …
- … with a single ν in the event, we can infer P^μ and 'reconstruct' the ν.
- Clean signals
- but low efficiency

- Study B decays to:

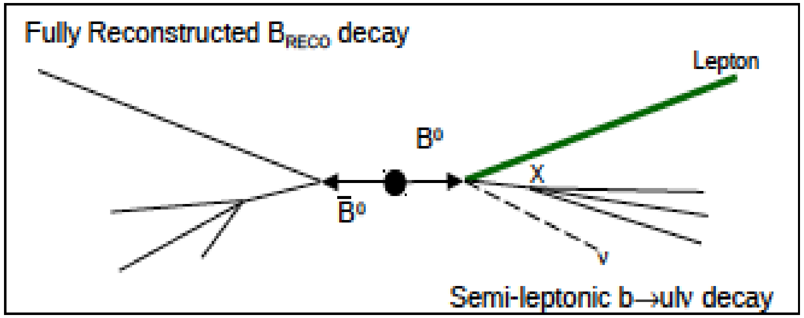
$$B^0 \to \pi^- l^+ \nu$$
$$B^0 \to \rho^- l^+ \nu$$
$$B^+ \to \pi^0 l^+ \nu$$
$$B^+ \to \rho^0 l^+ \nu$$
$$B^+ \to \omega l^+ \nu$$

- Fully reconstruct B_{RECO}
- Extract yields from m^2_{MISS}

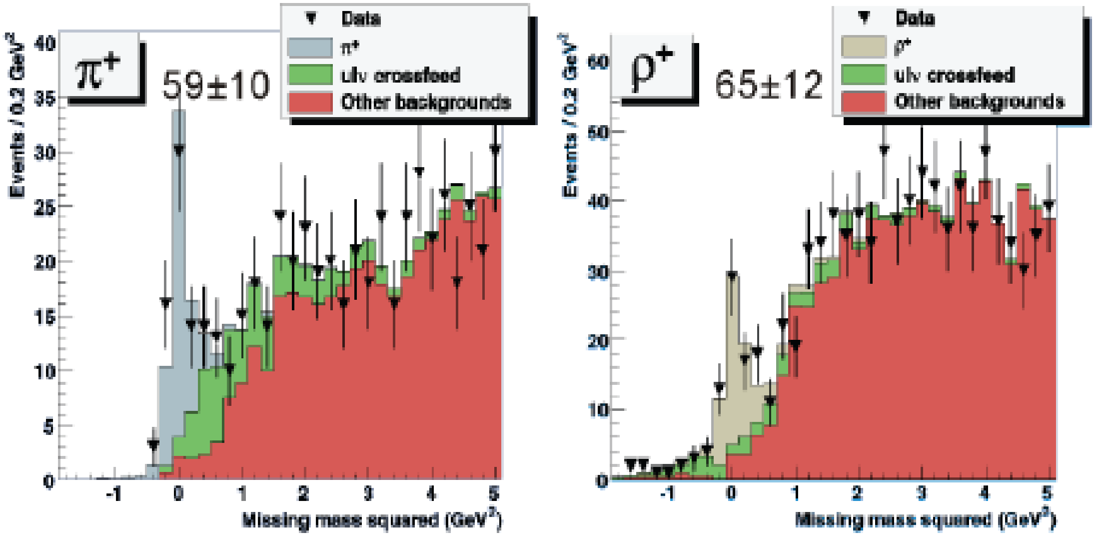
$$q^2 < 8 (GeV)^2$$
$$8 < q^2 < 16 (GeV)^2$$
$$q^2 > 16 (GeV)^2$$

(reduces form factor dependence)

- Then compute $|V_{ub}|$.



Use the beam energy to constrain P^μ to effectively 'reconstruct' ν from the missing energy-momentum: $m_{MISS} = m_\nu = 0$.



Side measurements: V_{cb}

- Use the differential decay rates of $B \to D^* l\nu$ to determine $|V_{cb}|$:

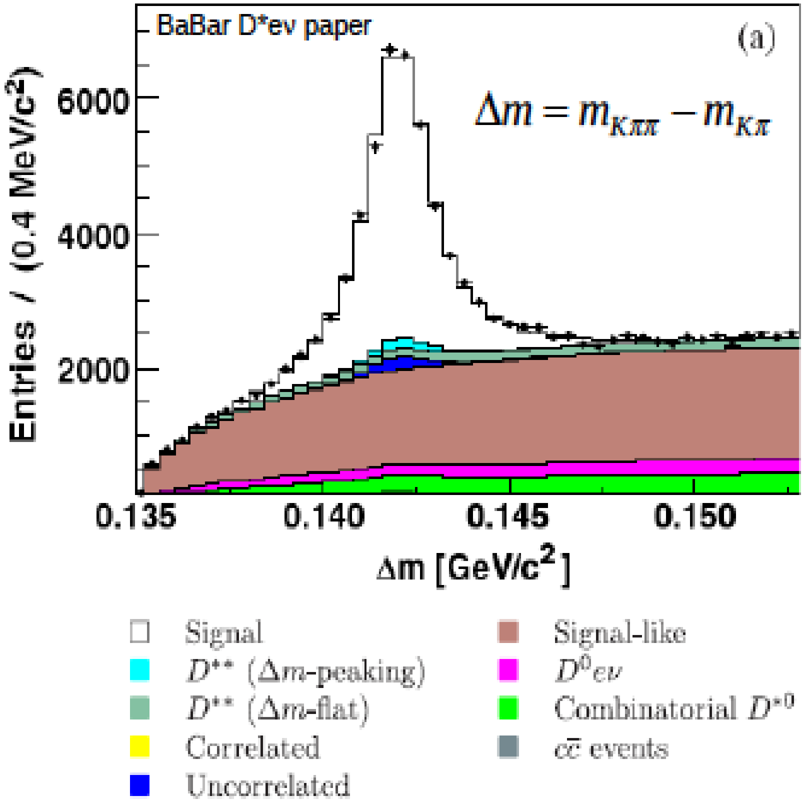
$$\frac{d\Gamma(\bar{B} \to D^* l^- \bar{\nu})}{d\omega d\cos\theta_l d\cos\theta_V d\chi} \propto F^2(\omega,\theta_l,\theta_V,\chi)|V_{cb}|^2$$

- F is a form factor.
- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.

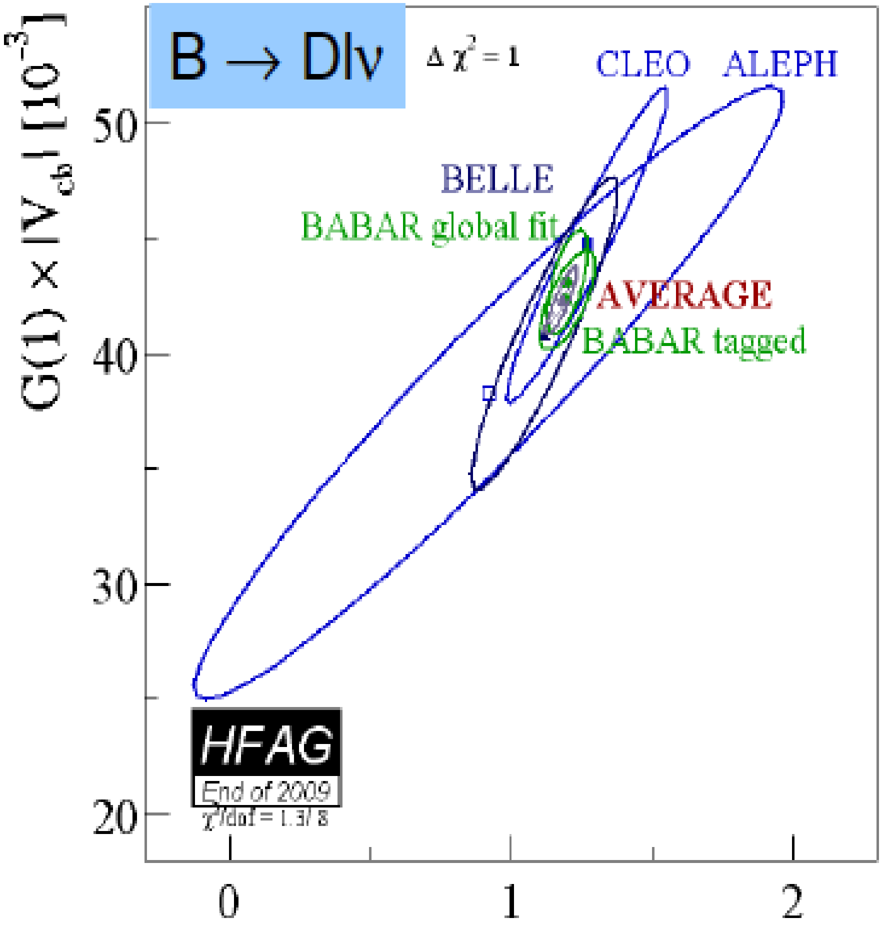
- Reconstruct

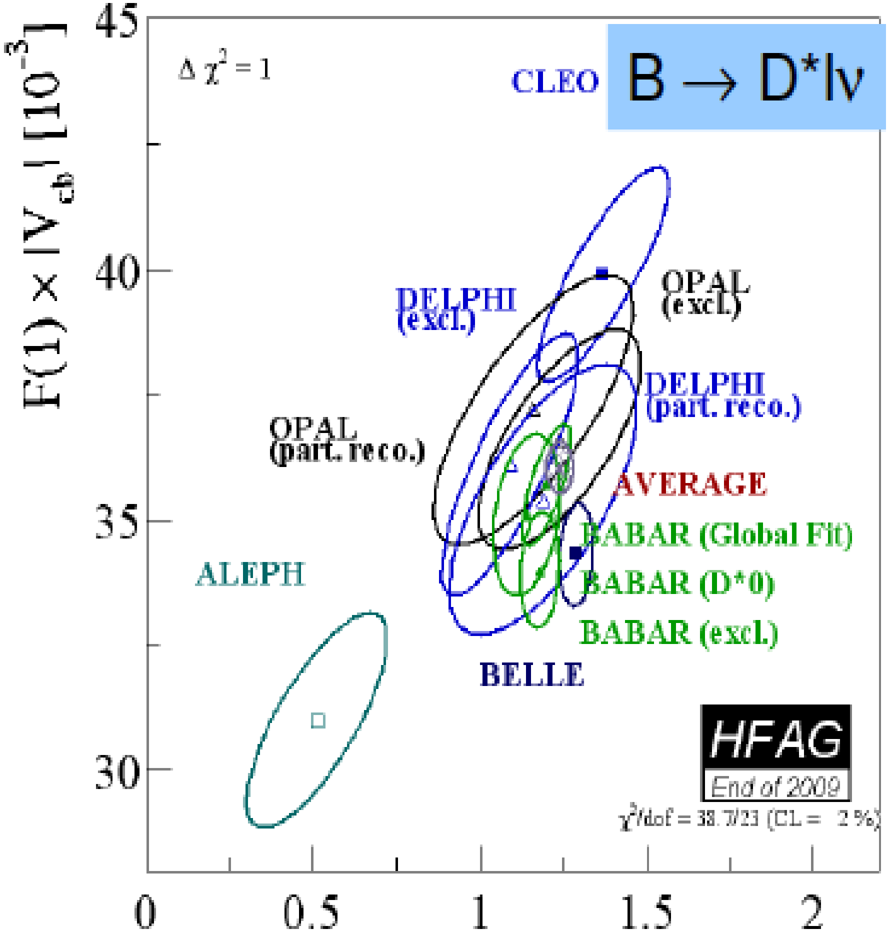
$$\begin{tikzcd} B^- \arrow[r] & D^{*0}e^-\bar{\nu}_e \arrow[d] & & \\ & D^{*0} \arrow[r] & D\pi \arrow[d] & \\ & & D \arrow[r] & K^+\pi^- \end{tikzcd}$$

- Measurement is not statistically limited, so use clean signal mode for $D \to K\pi$ decay only.
- Extract signal yield, $F(1)|V_{cb}|$ and ρ from 3D binned fit to data.



$|V_{cb}|$





$G(1)|V_{cb}| = (42.3 \pm 1.5)\ 10^{-3}$ ρ^2

$|V_{cb}| = (39.4 \pm 1.7)\ 10^{-3}$

- Using $G(1)=1.074\pm0.018\pm0.016$ from Okamoto et al., NPPS **140**, 461 (2005).

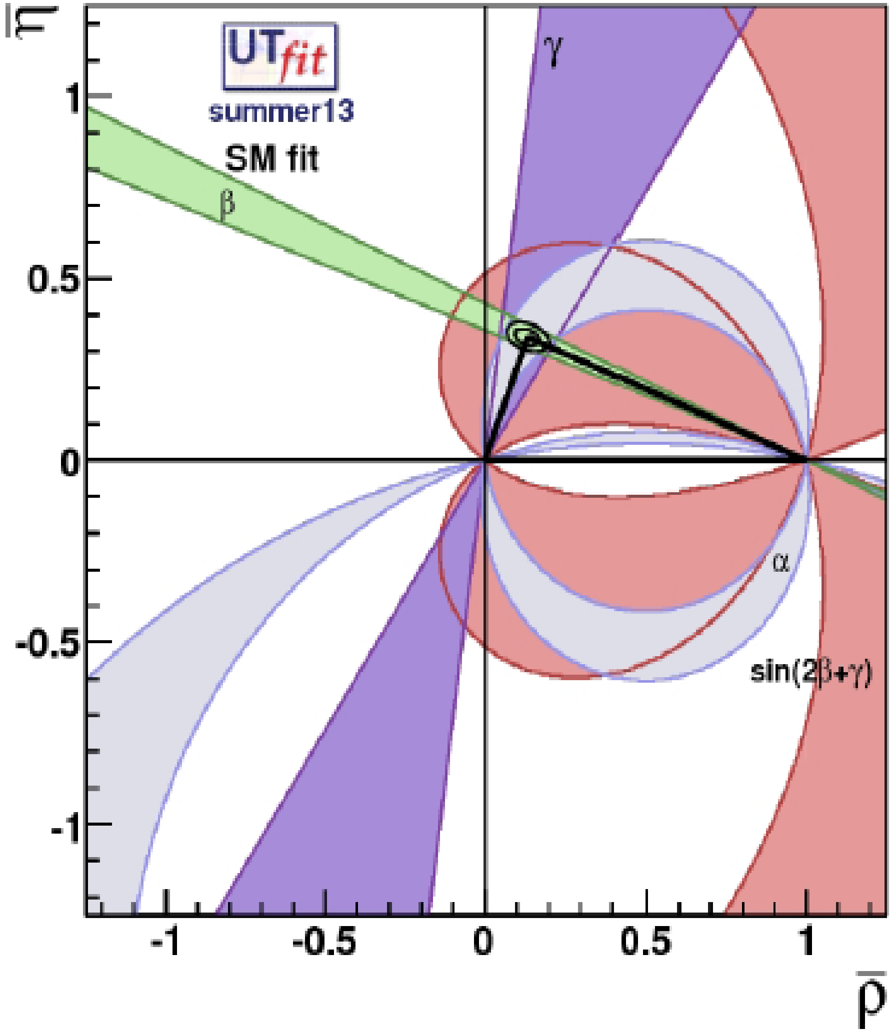
$F(1)|V_{cb}| = (36.0 \pm 0.5)\ 10^{-3}$ ρ^2

$|V_{cb}| = (39.0 \pm 1.1)\ 10^{-3}$

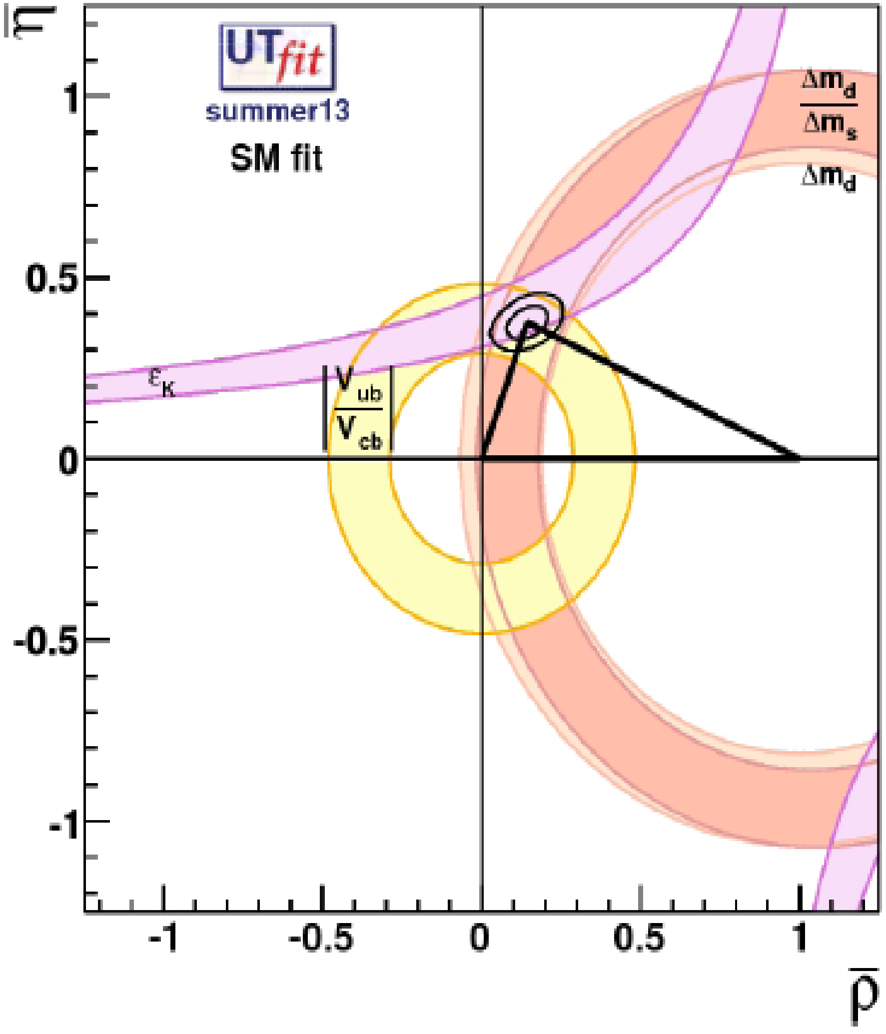
- Using $F(1)=0.924\pm0.012\pm0.019$ from Laiho, arXiv:0710.1111 [hep-lat].

Angles vs the others

levels @
95% Prob



$\bar{\rho} = 0.134 \pm 0.029$
$\bar{\eta} = 0.339 \pm 0.017$

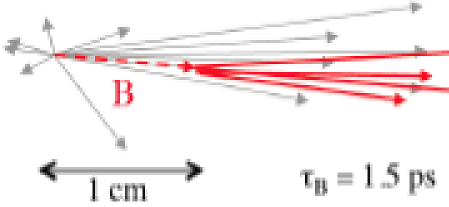


$\bar{\rho} = 0.144 \pm 0.046$
$\bar{\eta} = 0.376 \pm 0.030$

The LHCb detector

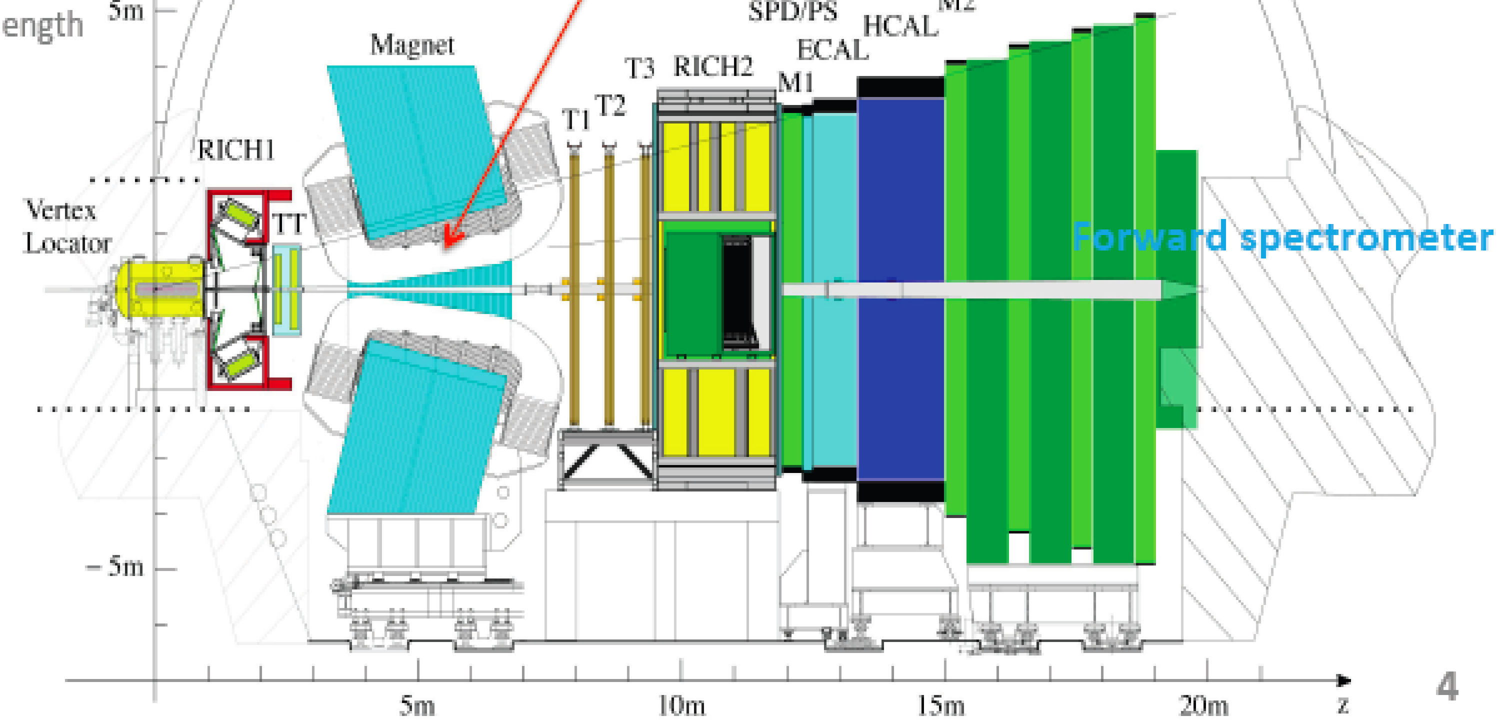
Experiment optimized for B physics requires:
- Precision tracking and vertexing (mass, proper time).
- Excellent particle identification: e, γ, μ, **π**, K, p
- Efficient trigger for hadronic and leptonic modes.

LHCb performance:
- Decay time resolution **Δ**t: 30-50 fs
- **Δ**p/p = 0.35-0.55%, 1 < p < 100 Gev/c
- **Δ**m = 10-20 MeV/c^2
- MUON ID:
  ε(μ/μ) = 95%, mis-ID **ε**(**π**/μ) ~ 1%
- RICH ID **π**/K:
  ε(K/K) = 95%, mis-ID **ε**(**π**/K) ~ 10%



average decay length

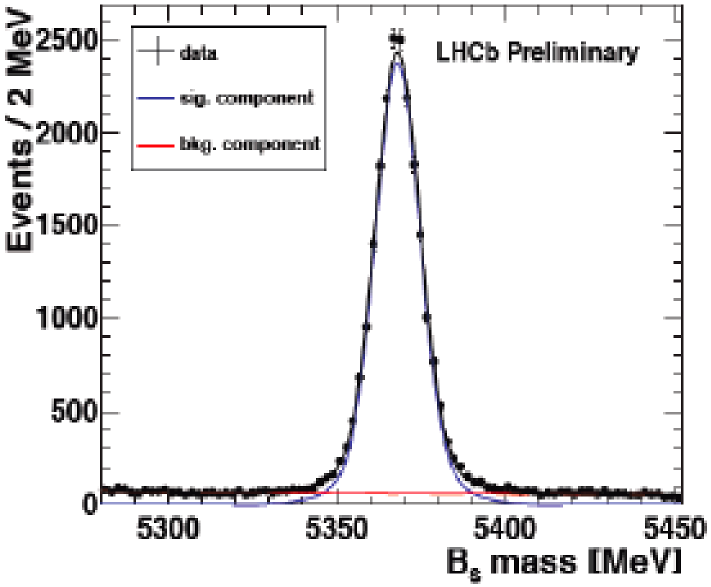
B field polarity regularly reversed



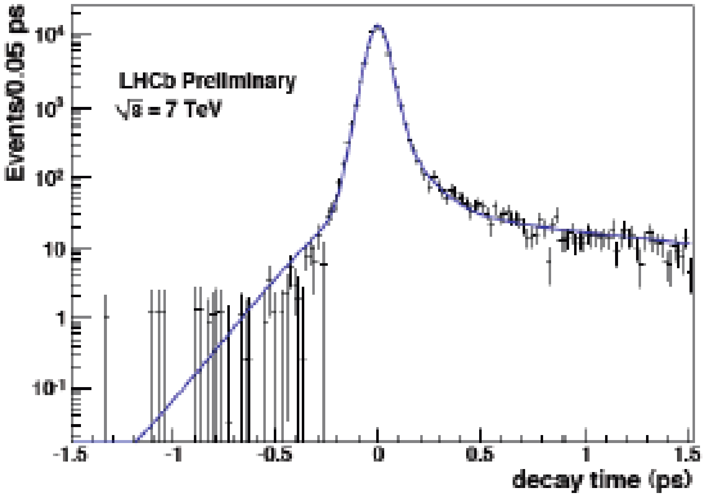
Forward spectrometer

$B_S \rightarrow J/\psi\phi$ signals and resolutions

$B_S \rightarrow J/\psi\phi$ mass resolution



Proper time resolution



$B_S \rightarrow J/\psi\phi$ candidates:

- Require t > 0.3 ps
- 8 MeV/c^2 mass resolution.
- 21200 signal events (1 fb^{-1}).

Time resolution

- Apply selection without decay length or impact parameter cuts (trigger + offline)
- Calibrate per-event estimate of proper time error from fit to prompt peak.
- **45 fs time resolution.**

$B_S \rightarrow J/\psi\phi$ fits $(1.0\ \mathrm{fb}^{-1})$

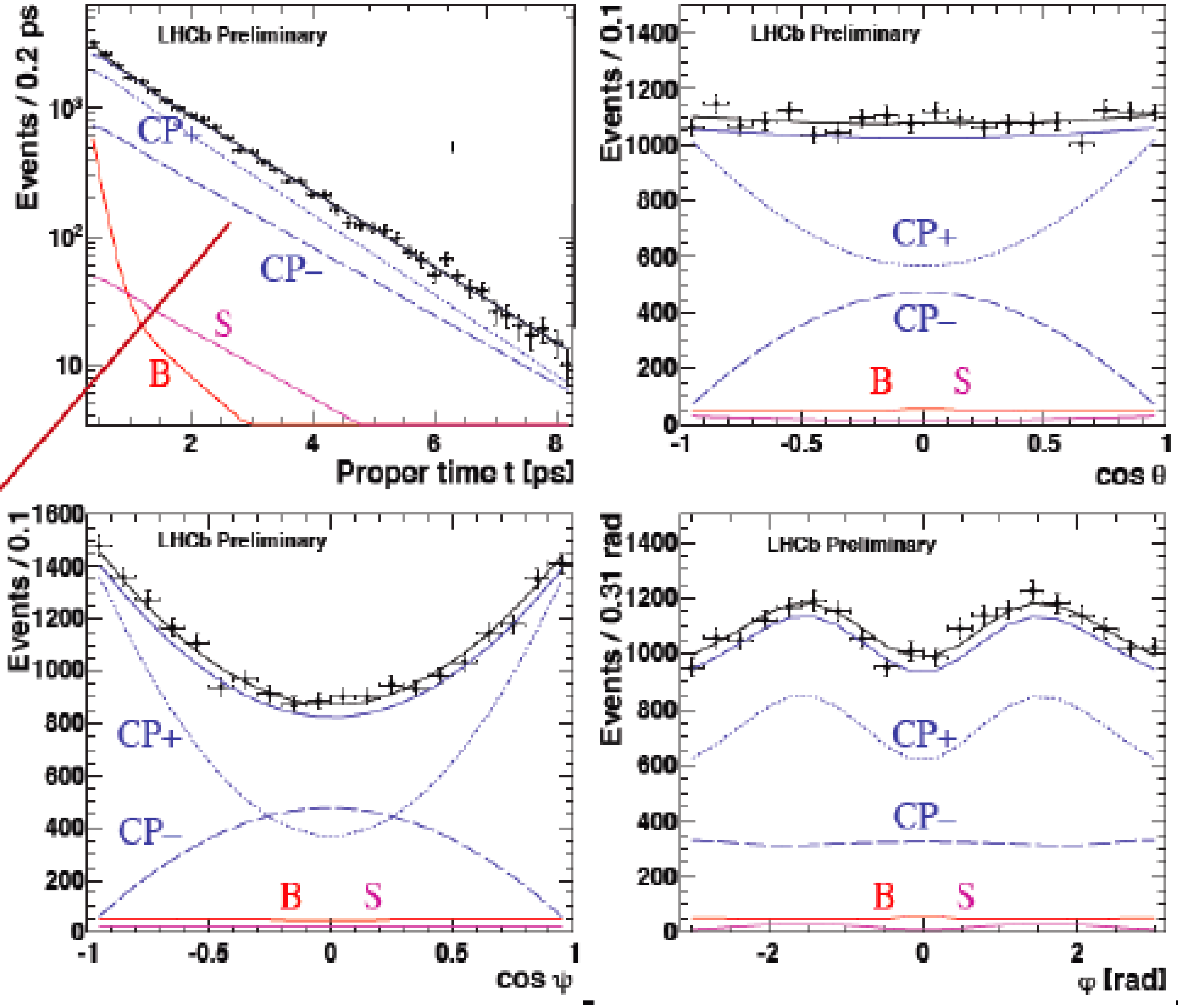
LHCb-CONF-2012-002

CP = +1: CP-even final state

CP = -1: CP-odd final state

S : J_{KK} =0, S-wave CP-odd

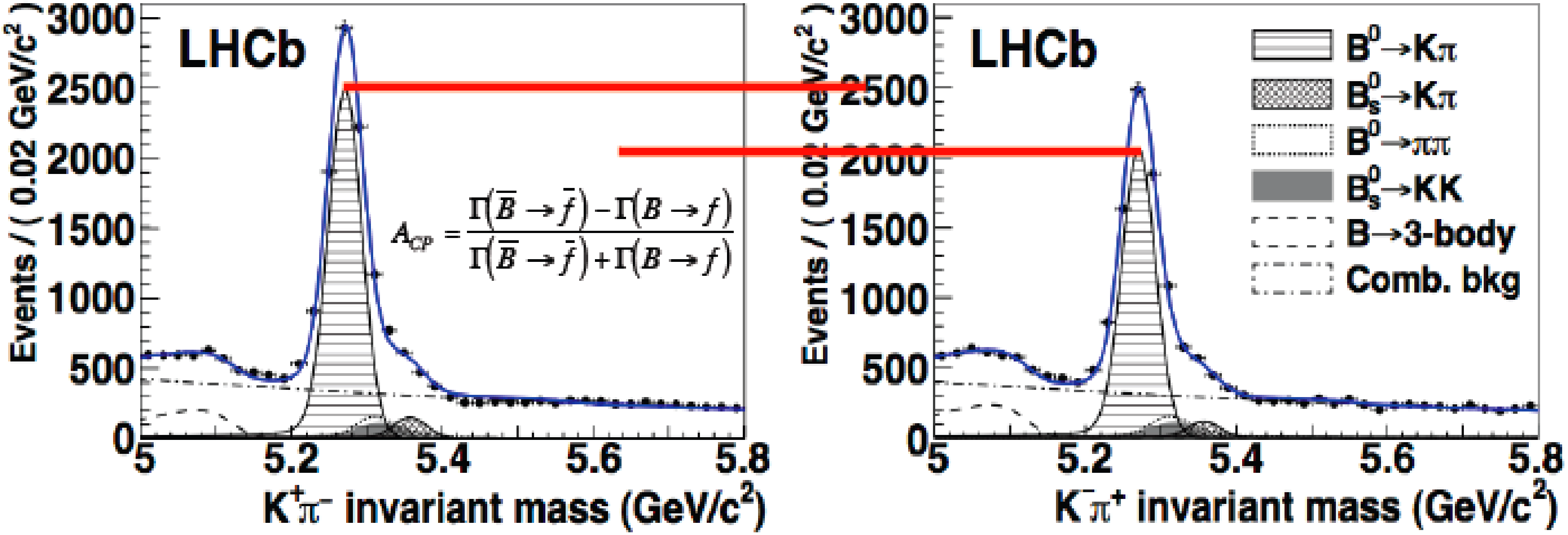
B : combinatorial background



Similar to the K_s K_L case.
First >5σ observation of non zero $\Delta\Gamma_S$
CP=-1 state lives longer than CP=+1 state.

Direct CPV in $B^0 \rightarrow K\pi$ ($0.32\ \mathrm{fb}^{-1}$)

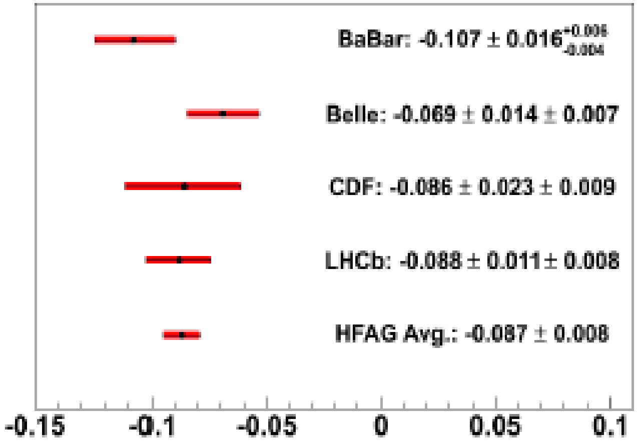
arXiv:1202.6251 (accepted by PRL)   13250 ± 150 $B^0 \rightarrow K\pi$



$$A_{CP} = \frac{\Gamma(\overline{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \bar{f}) + \Gamma(B \to f)}$$

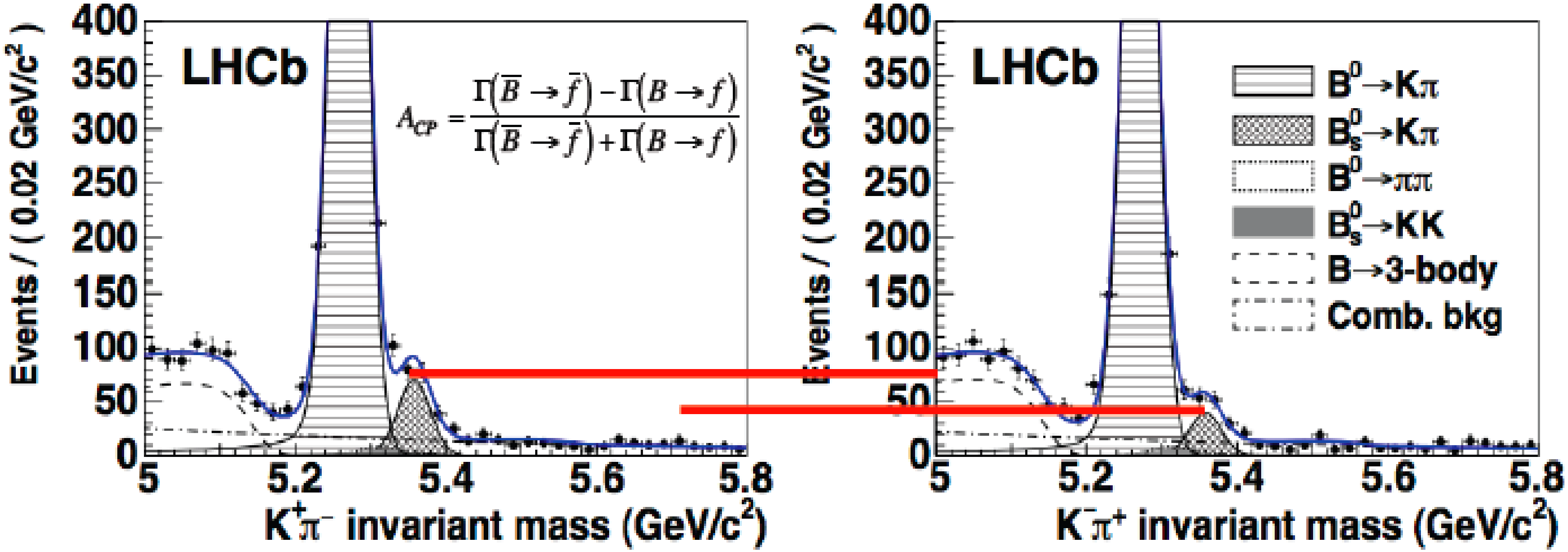
$$\boxed{A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})}$$

- First observation of CP violation at an hadron collider (> 6σ)



Direct CPV in $B_S \to \pi K$ (0.32 fb^{-1})

arXiv:1202.6251 (accepted by PRL) 314 ± 27 $B_s \to \pi K$



$$A_{CP}(B^0_s \to K\pi) = 0.27 \pm 0.08\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$$

First evidence of CP violation in B_s decays (3.3σ)

$A_{CP}(B_s \to \pi K) = 0.39 \pm 0.15 \pm 0.08$ CDF [Phys. Rev. Lett. 106 (2011) 181802]

$$A_{CP}(B_s \to \pi K) \approx A^{\pi\pi}_{dir} = \begin{cases} 0.25 \pm 0.08 \pm 0.02 & \text{BaBar [arXiv:0807.4226]} \\ 0.55 \pm 0.08 \pm 0.05 & \text{Belle [PRL 98 (2007) 211801]} \end{cases}$$

Assuming U-spin symmetry

Bs Oscillations

$$B_s^0 \to D_s^- \pi^+ \quad - \quad D_s^- \to KK\pi, K\pi\pi, \pi\pi\pi$$

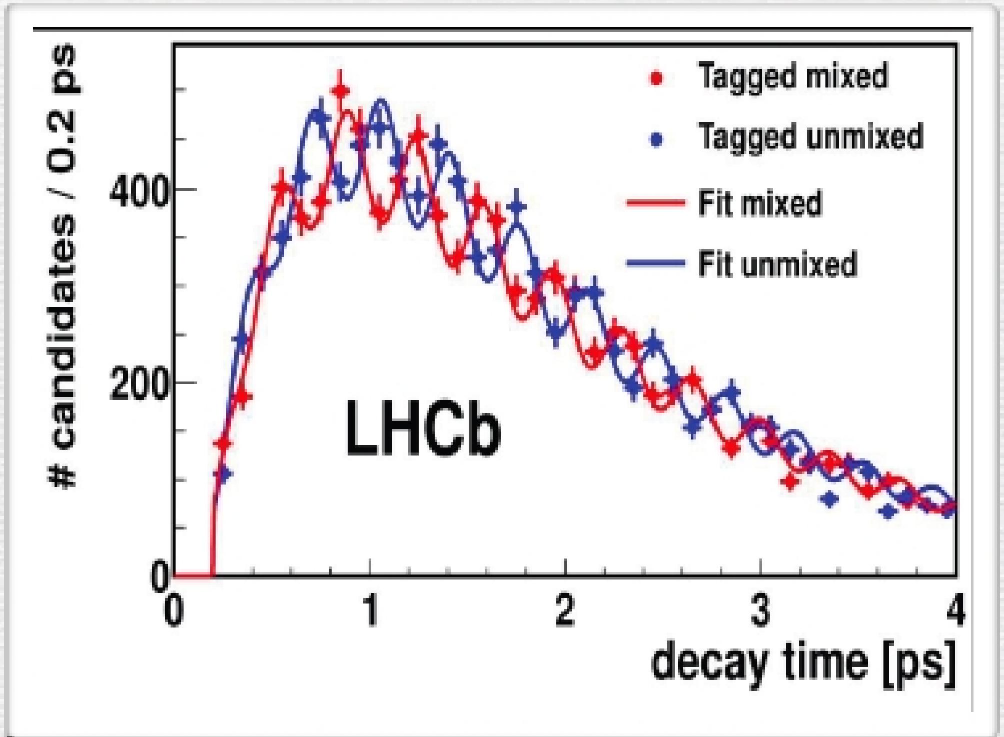
resonant and non-resonant

LHCb time resolution: 45 fs

1 fb

Flavour tagged at production
same side and opposite side

New J. Phys. Vol 15, (2013) 053012

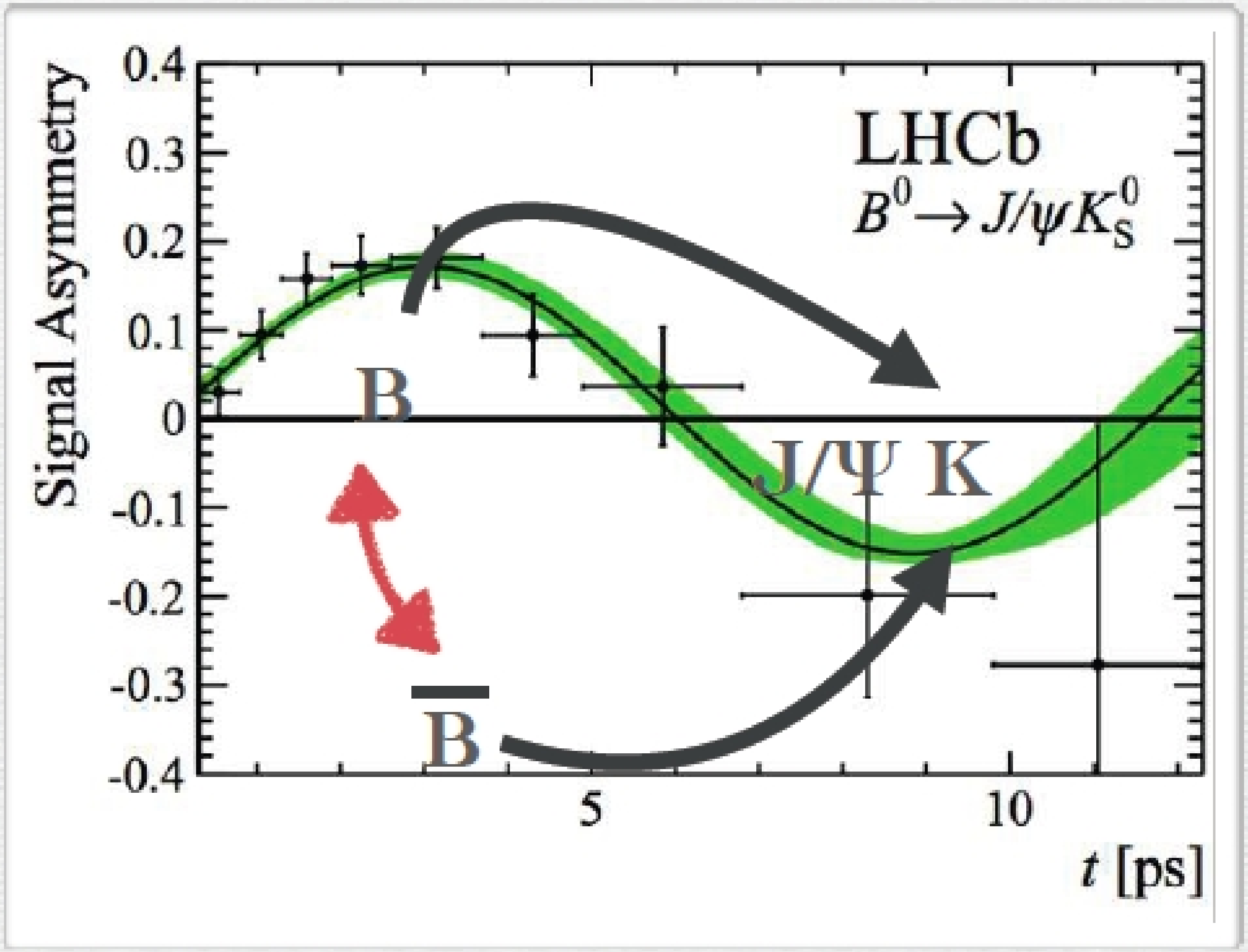


$$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \ ps^{-1}$$

$$PDF \propto (e^{-\Gamma t} \cdot \cosh \Delta\Gamma t \pm D \cdot \cos \Delta m t) \otimes R\sigma_t$$

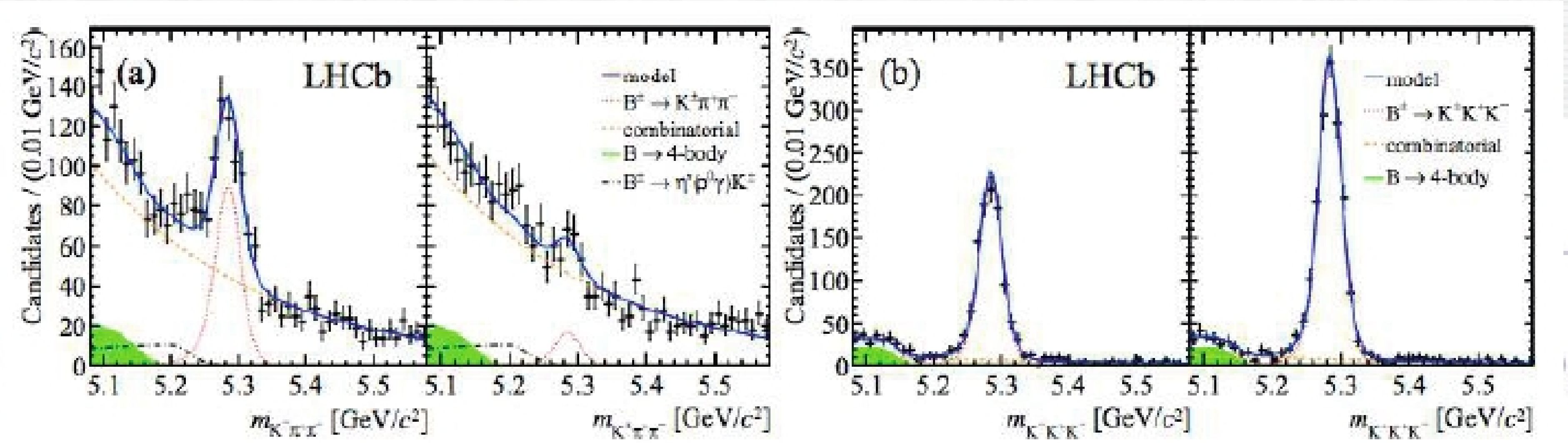
$sin\,2\beta$ — $B^0 \to J/\Psi K_s^0$

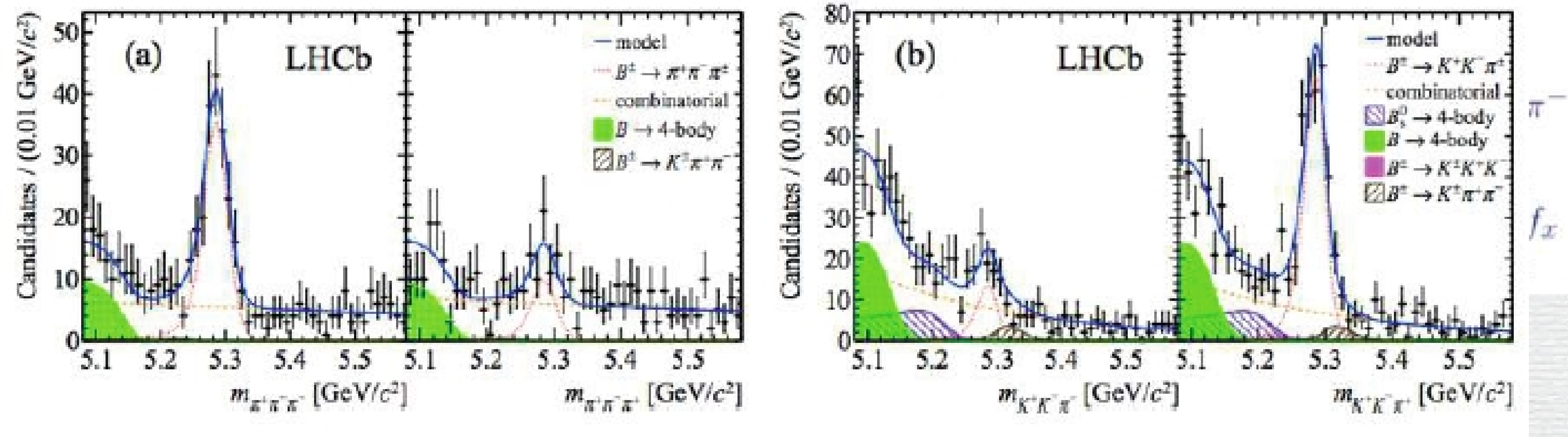
- 2011 data
- Phys. Lett. B721 (2013) 24
- J/Ψ
- first measurement @ hadron collider
- consistent with SM expectation



$$S_{J/\Psi K_s^0} = 0.73 \pm 0.07 \pm 0.04$$

CPV in B


(a)
LHCb
Candidates / (0.01 GeV/c^2)
model
$B^\pm \to K^\pm\pi^+\pi^-$
combinatorial
$B \to$ 4-body
$B^\pm \to \eta'(\rho^0\gamma)K^\pm$
$m_{K^-\pi^+\pi^-}$ [GeV/c^2]
$m_{K^+\pi^+\pi^-}$ [GeV/c^2]
(b)
LHCb
model
$B^\pm \to K^\pm K^+K^-$
combinatorial
$B \to$ 4-body
$m_{K^-K^+K^-}$ [GeV/c^2]
$m_{K^+K^+K^-}$ [GeV/c^2]


(a)
LHCb
Candidates / (0.01 GeV/c^2)
model
$B^\pm \to \pi^\pm\pi^+\pi^-$
combinatorial
$B \to$ 4-body
$B^\pm \to K^\pm\pi^+\pi^-$
$m_{\pi^+\pi^-\pi^-}$ [GeV/c^2]
$m_{\pi^+\pi^-\pi^+}$ [GeV/c^2]
(b)
LHCb
model
$B^\pm \to K^+K^-\pi^\pm$
combinatorial
$B_s^0 \to$ 4-body
$B \to$ 4-body
$B^\pm \to K^\pm K^+K^-$
$B^\pm \to K^\pm\pi^+\pi^-$
$m_{K^+K^-\pi^-}$ [GeV/c^2]
$m_{K^+K^-\pi^+}$ [GeV/c^2]

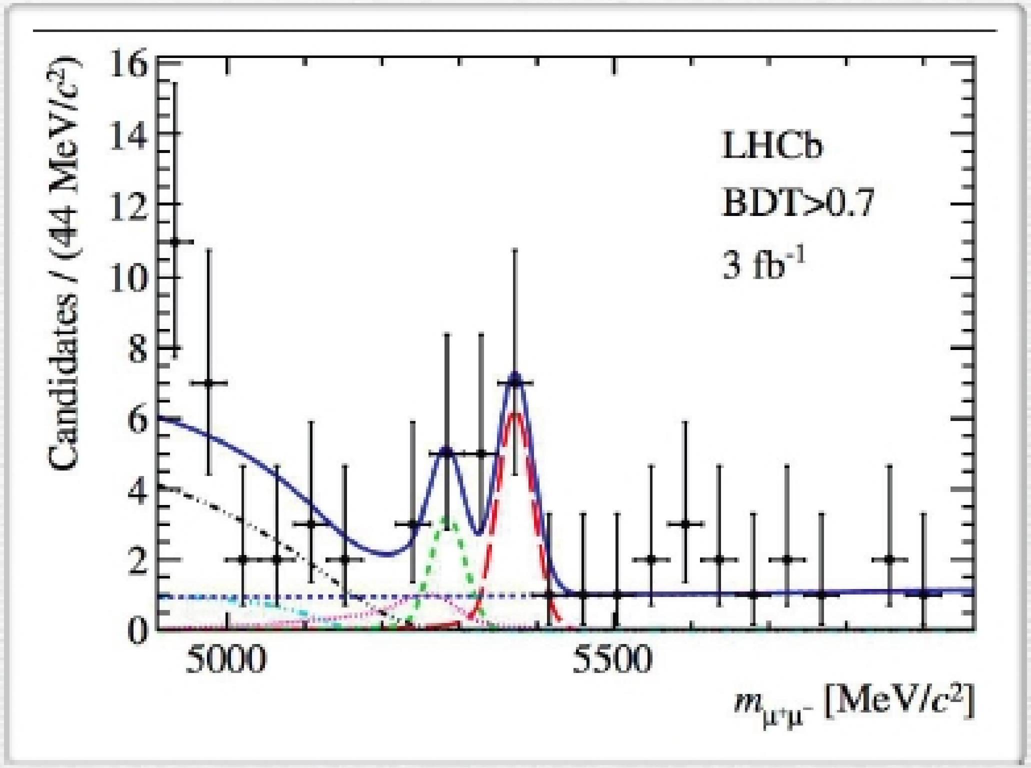
$B^0_{(s)} \to \mu^+\mu^-$

- 2011 and 2012 data

- Normalization channels:

  $B^+ \to J/\Psi K^+$
  $B^0 \to K^+\pi^-$

- LHCb: 1fb
- CMS: 5 fb



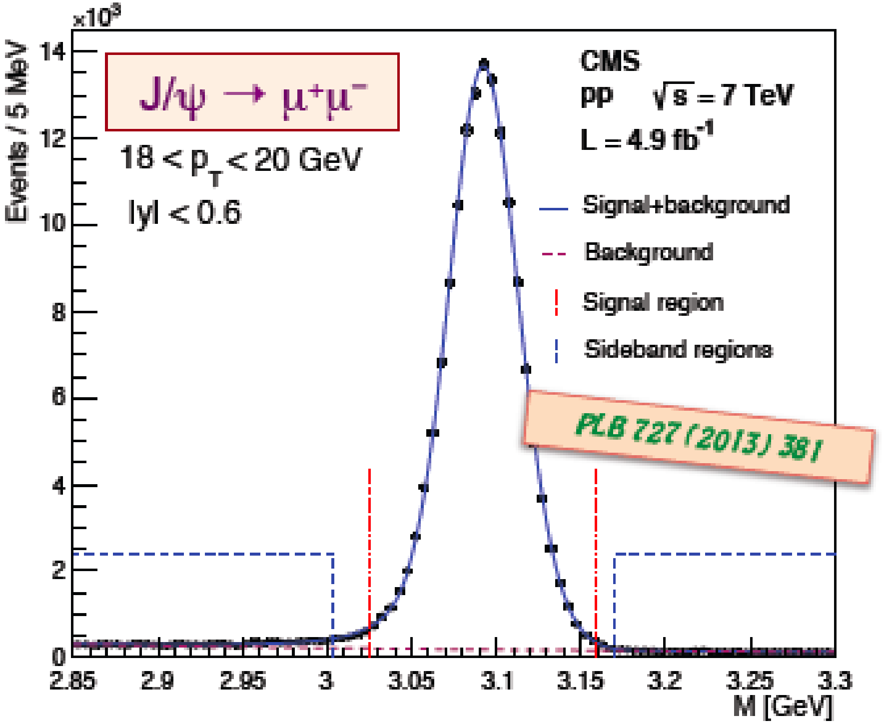
	$\mathcal{B}(B^0_s \to \mu\mu) \times 10^{-9}$	$\mathcal{B}(B^0 \to \mu\mu) \times 10^{-10}$	
LHCb	$2.9^{+1.1}_{-1.0}$	$3.7^{+2.4}_{-2.1}$	PRL 111 (2013) 101805
CMS	$3.0^{+1.0}_{-0.9}$	$3.5^{+2.1}_{-1.8}$	PRL 111 (2013) 101804
Combined	2.9 ± 0.7	$3.6^{+1.6}_{-1.4}$	LHCb-CONF-2013-012
SM	3.56 ± 0.18	1.07 ± 0.1	

Charmonia in ATLAS and CMS

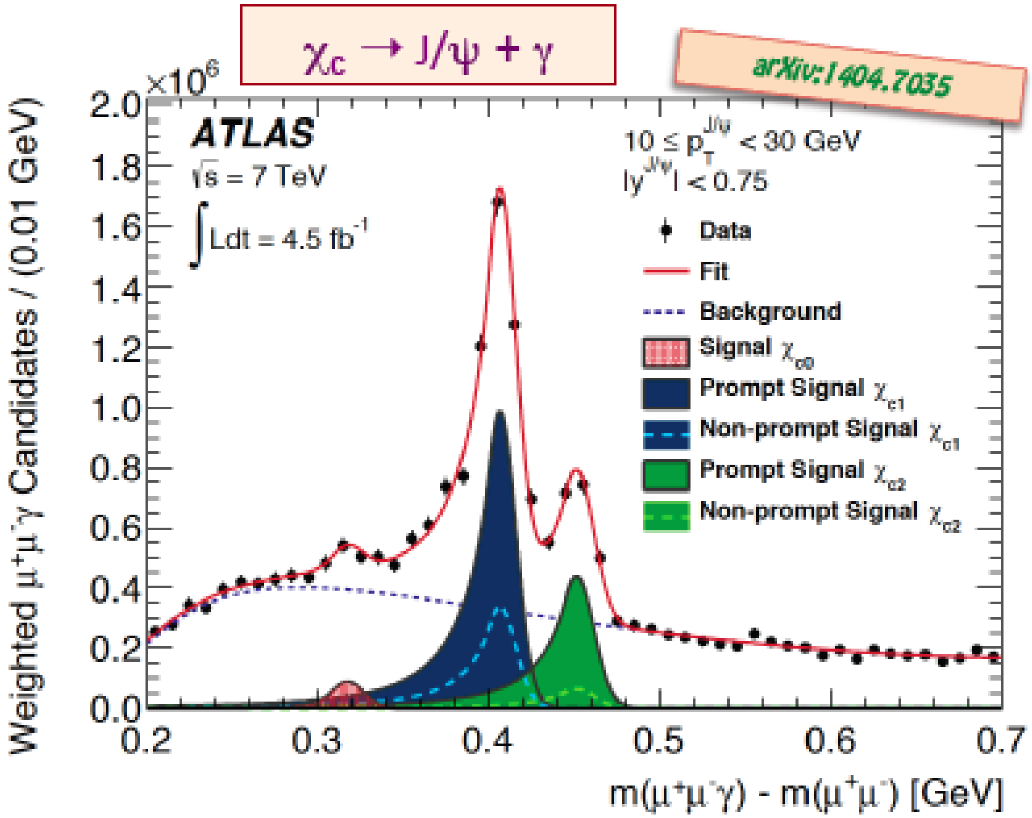
Very good dimuon mass resolution

Accurate reconstruction of low-energy photon conversions in e^+e^- pairs; crucial to detect radiative decays of P-wave states

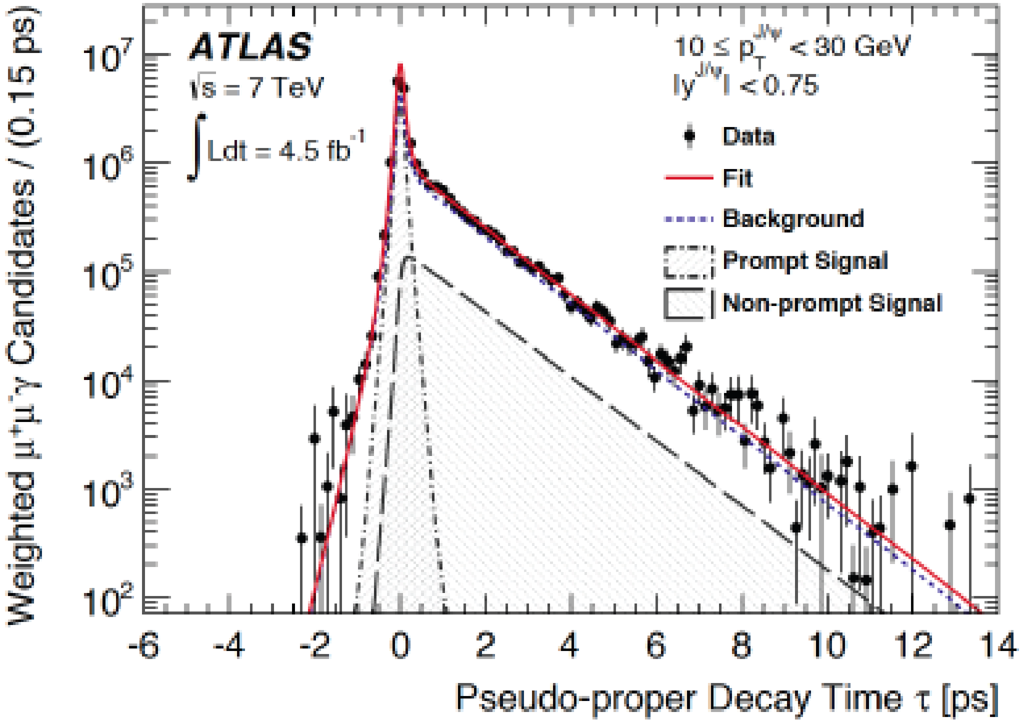
Excellent secondary vertexing; crucial to remove non-prompt charmonia


$J/\psi \rightarrow \mu^+\mu^-$

PLB 727 (2013) 381


$\chi_c \rightarrow J/\psi + \gamma$

arXiv:1404.7035



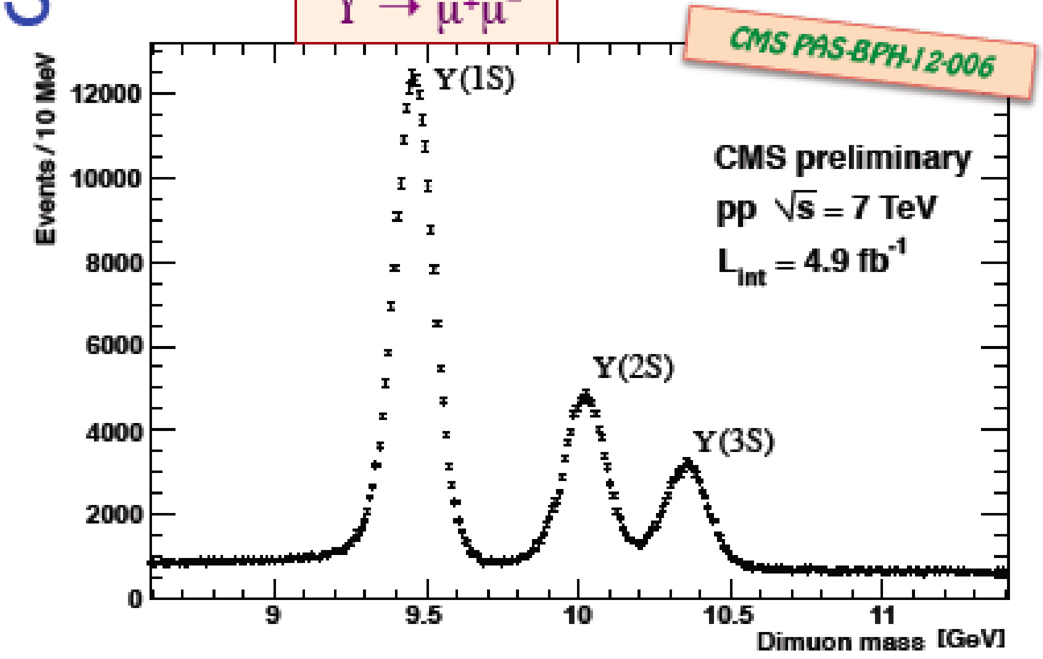
Bottomonia in ATLAS and CMS

CMS detects χ states with ≈5 MeV resolution

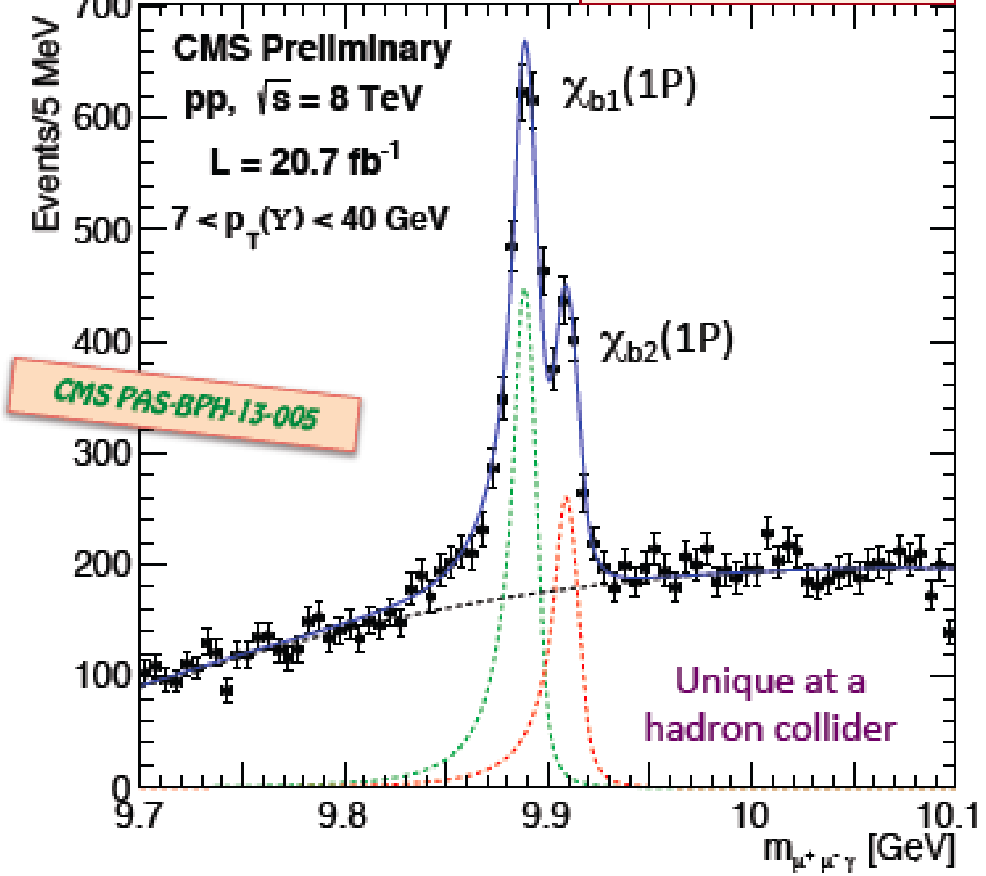
Crucial to resolve the $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ states (ΔM = 19 MeV)

ATLAS discovered a new quarkonium state: χ_b (3P)

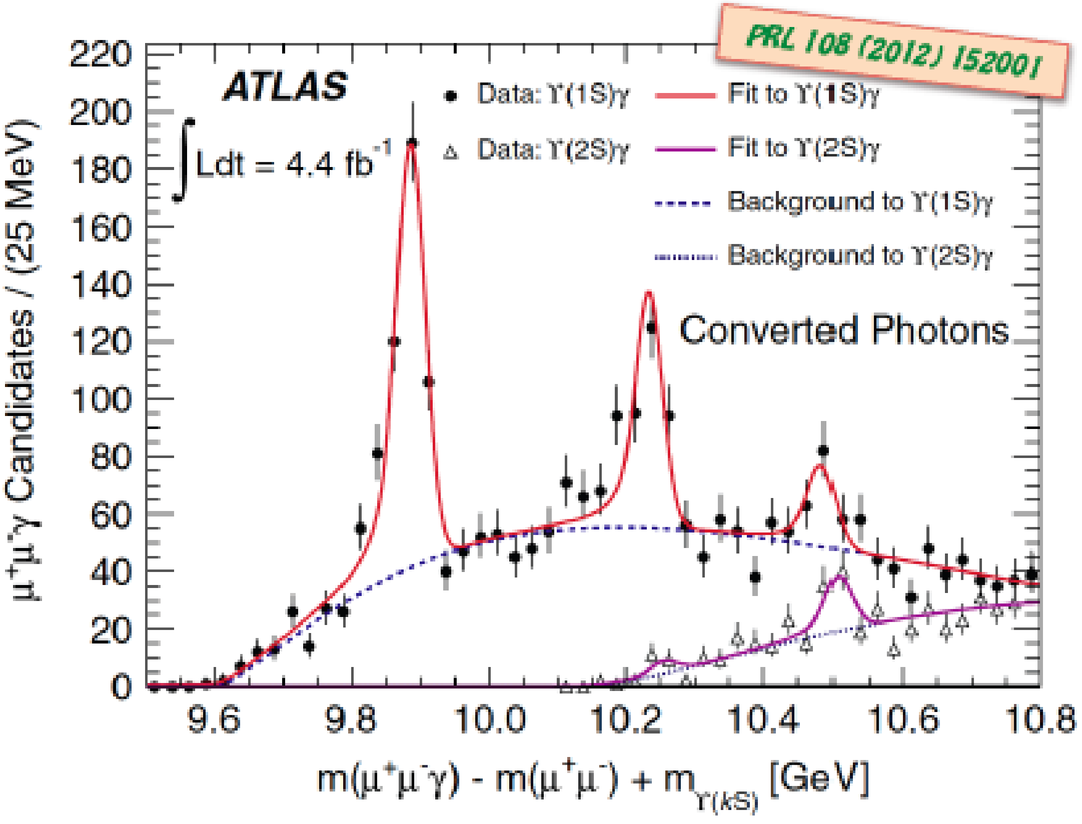
$\Upsilon \to \mu^+\mu^-$



$\chi_b \to \Upsilon(1S) + \gamma$



Unique at a hadron collider



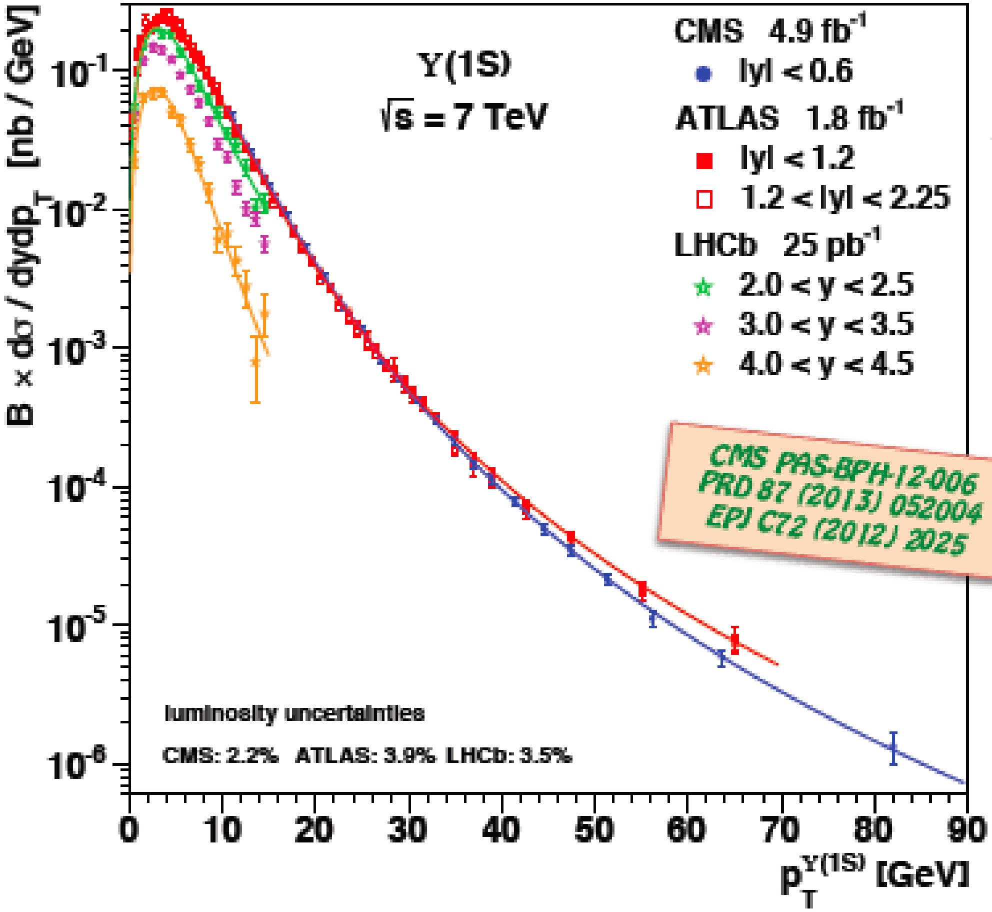
S-wave quarkonium cross sections

ATLAS and CMS measurements will reach beyond p_T = 100 GeV once 2012 data will be analysed

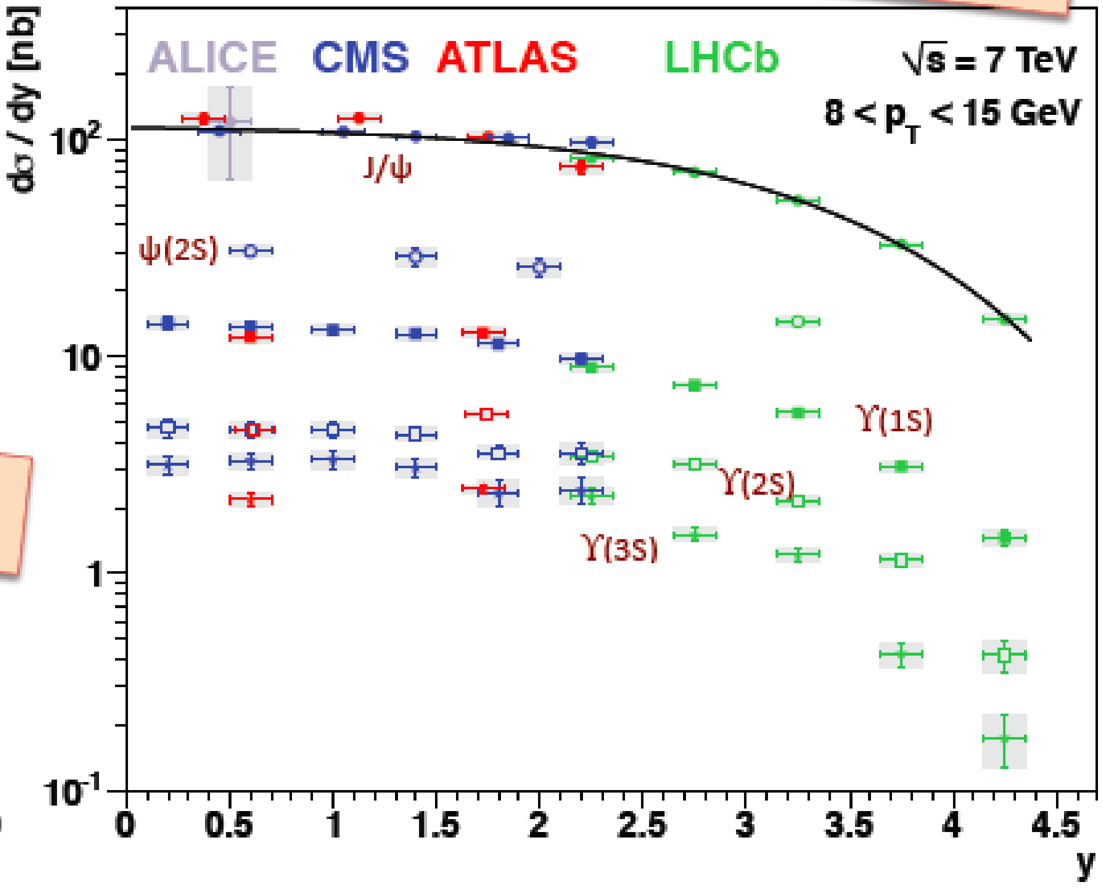
LHCb data limited to p_T < 15 GeV

Having results from several experiments allows us to evaluate their reliability

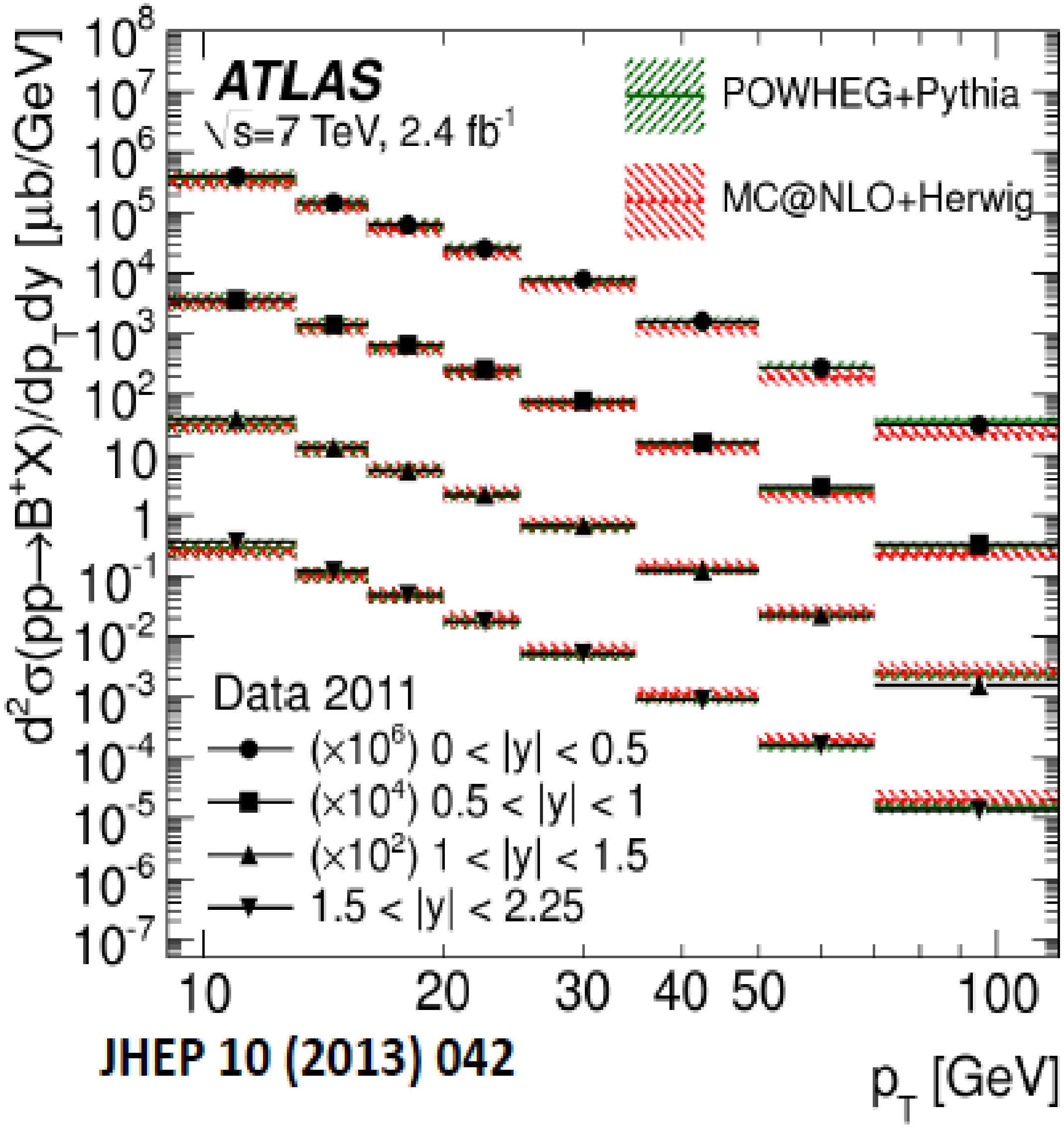
JHEP 11 (2012) 065
EPJC 71 (2011) 1645
NPB 850 (2011) 387
JHEP 02 (2012) 011
EPJC 72 (2012) 2100
PLB 727 (2013) 101
PRD 87 (2013) 052004
EPJC 72 (2012) 2025



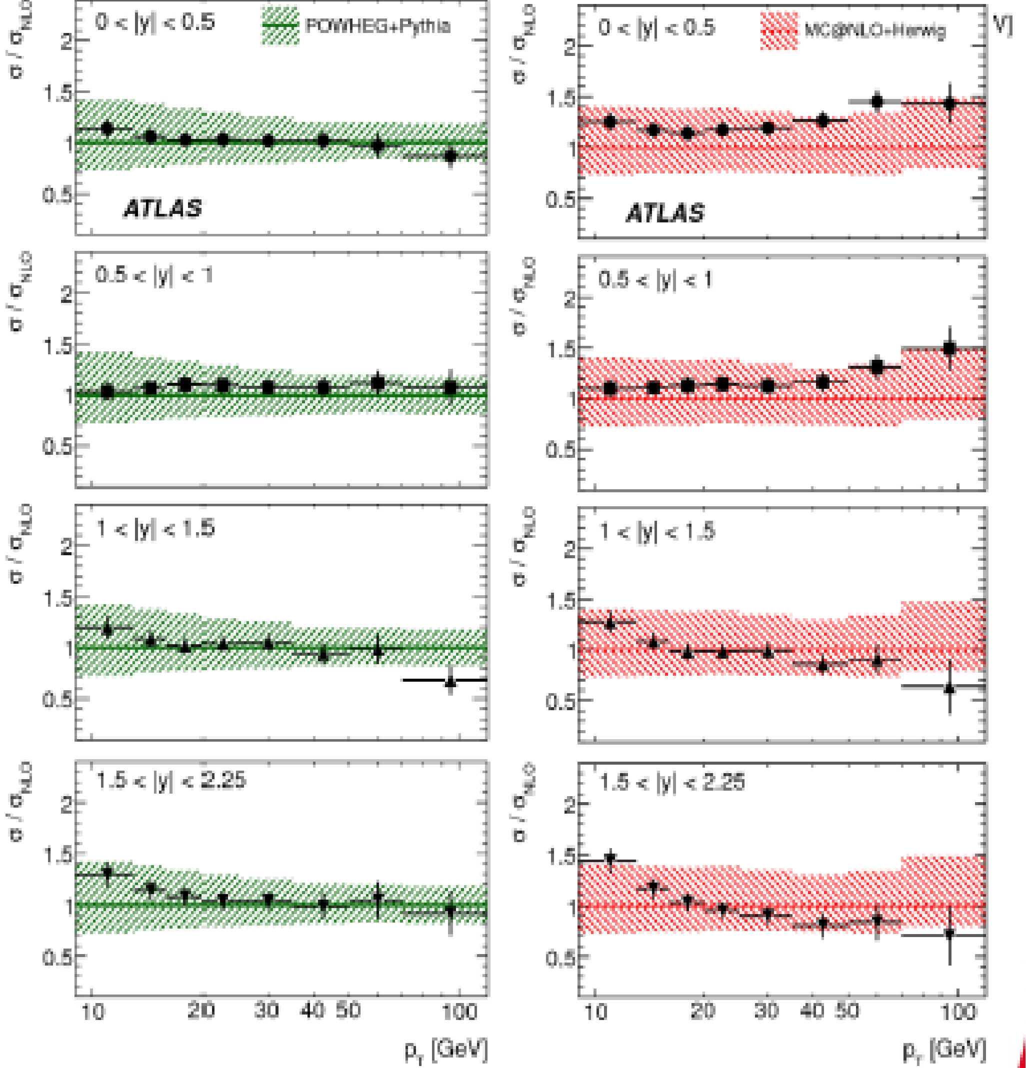
CMS PAS-BPH-12-006
PRD 87 (2013) 052004
EPJ C72 (2012) 2025

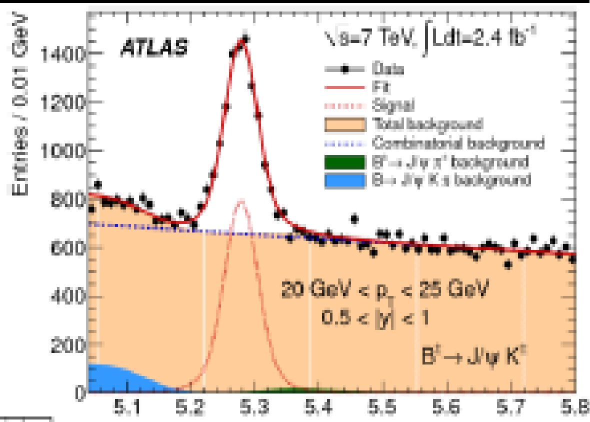


B+ Meson Production - ATLAS



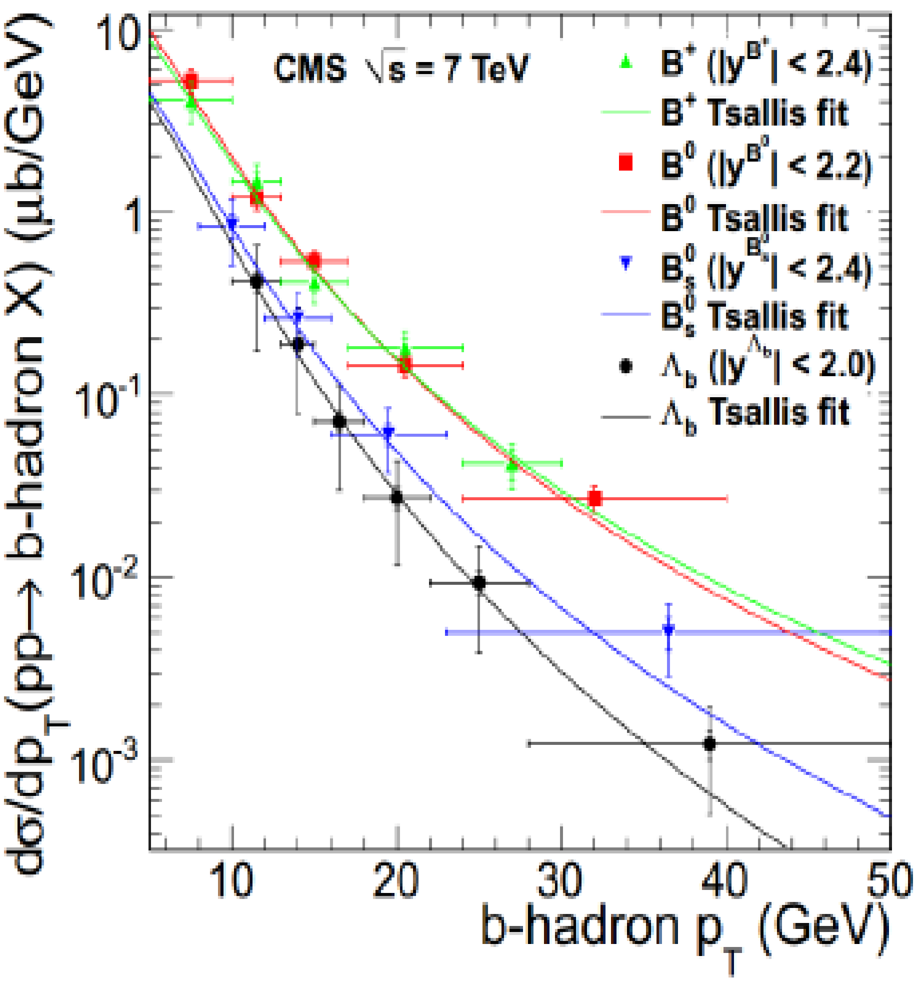
JHEP 10 (2013) 042

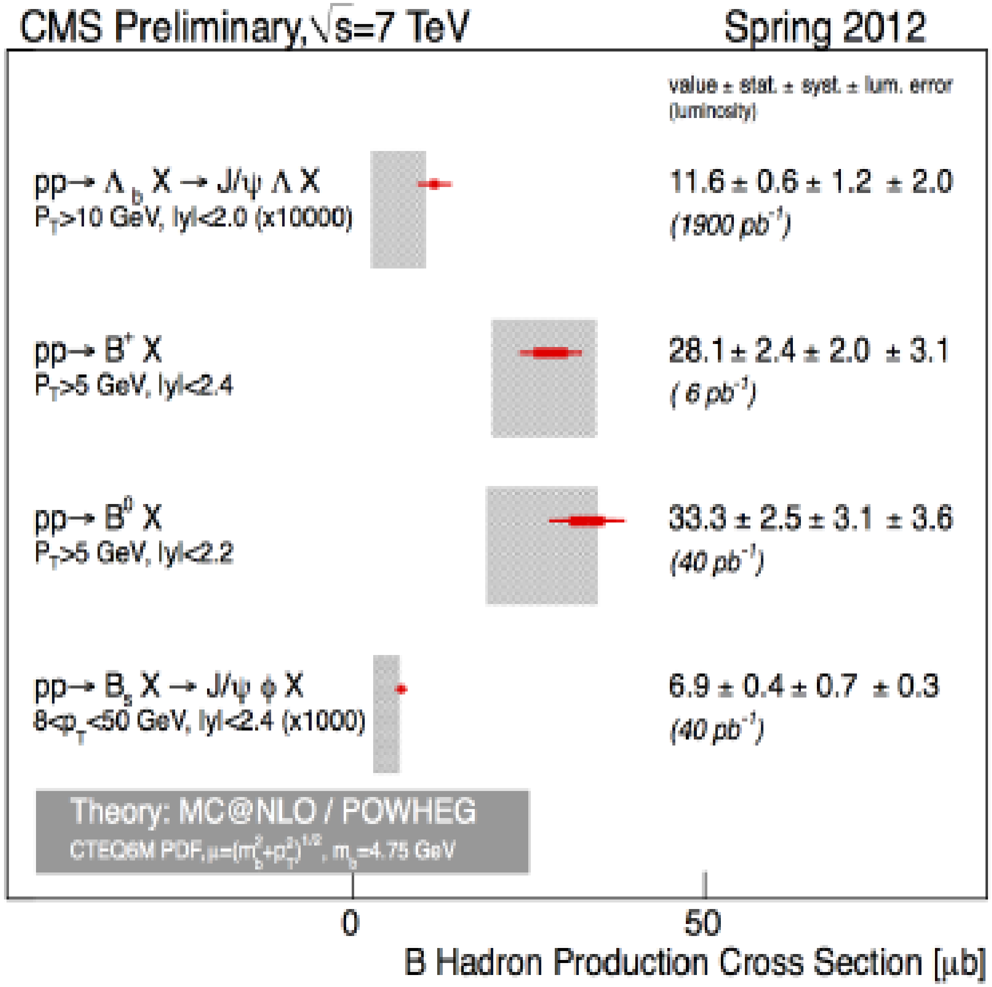




Double-differential cross-section of B^+ production as a function of p_T and y, averaged over each (p_T,y) interval

B Hadron Production - CMS

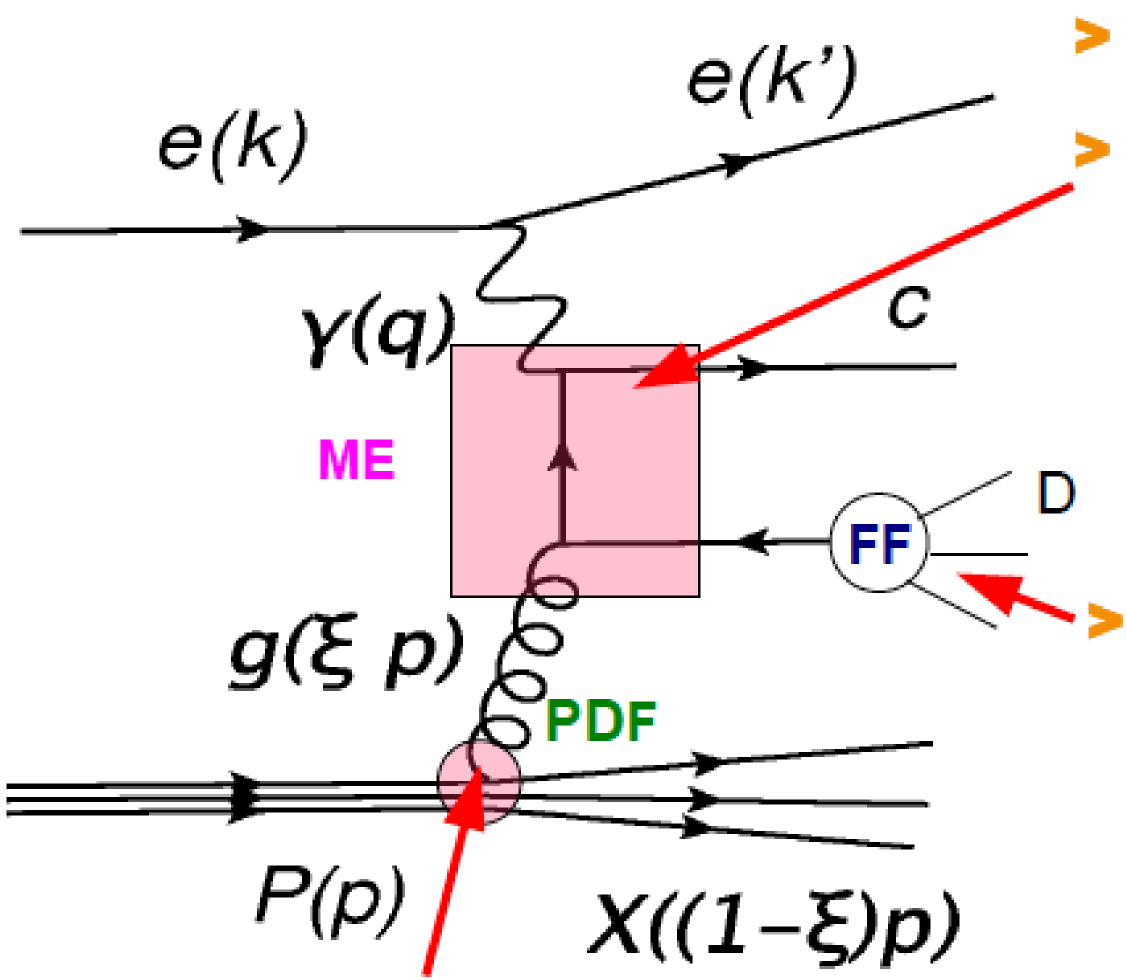




Theory describes data well, tends to be on the low side

The heavier the hadron, the steeper the pT spectrum

Introduction to HQ production @ HERA.

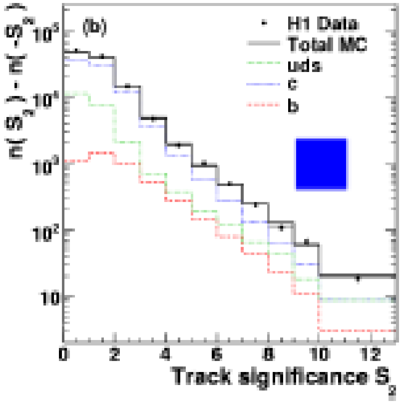


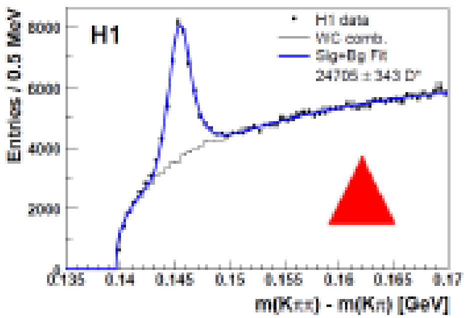
- Important test of QCD
- Multiple scales (Q^2, $m_{c,b}$, $p_T(c,b)$): a challenge for pQCD. Massive/fixed-order pQCD calculations: heavy flavours are produced perturbatively
- Fragmentation model c,b → D,B
- Direct probe of the gluon in the proton: predominantly boson-gluon fusion.

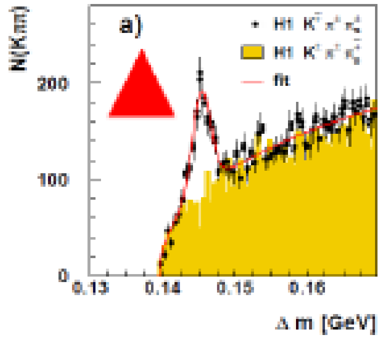
$$\sigma^{HQ} = \text{PDF} \otimes \text{ME} \otimes \text{FF}$$

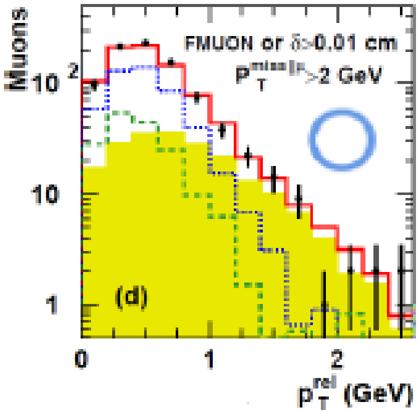
Charm combination.

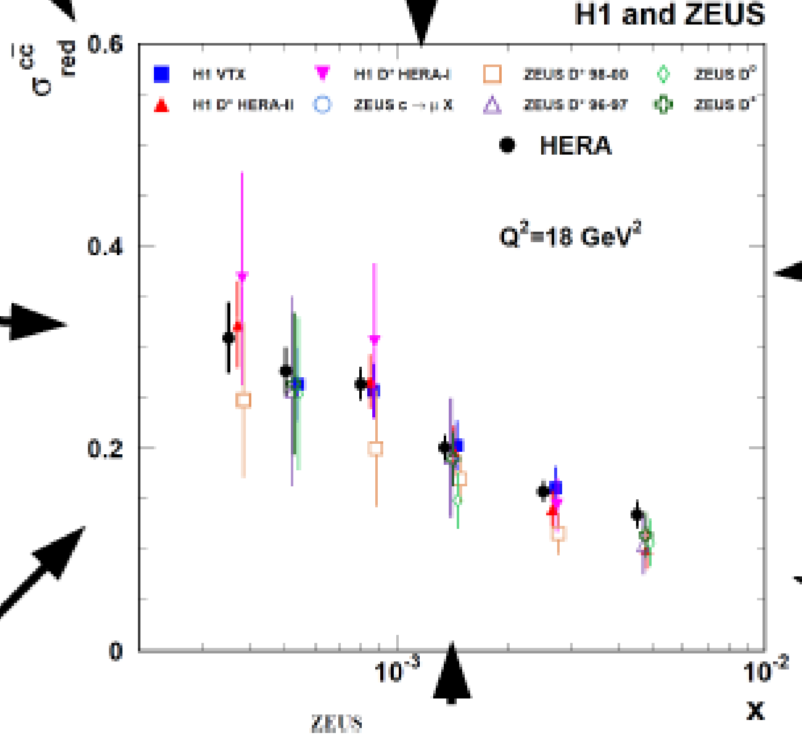
EPJ C73 (2013) 2311

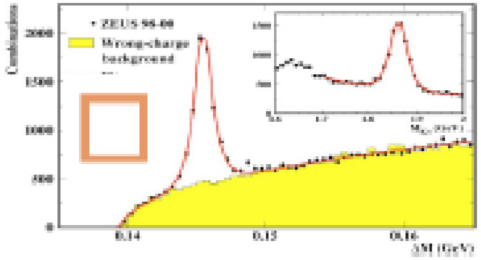


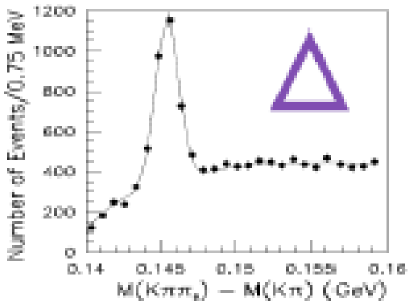


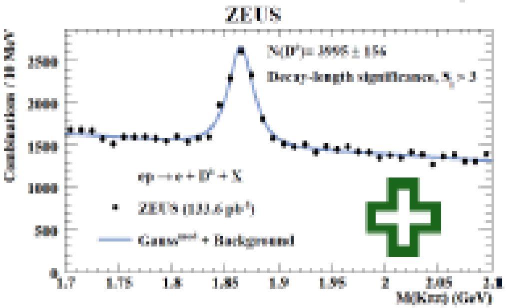


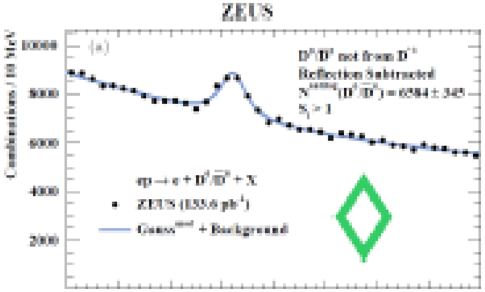








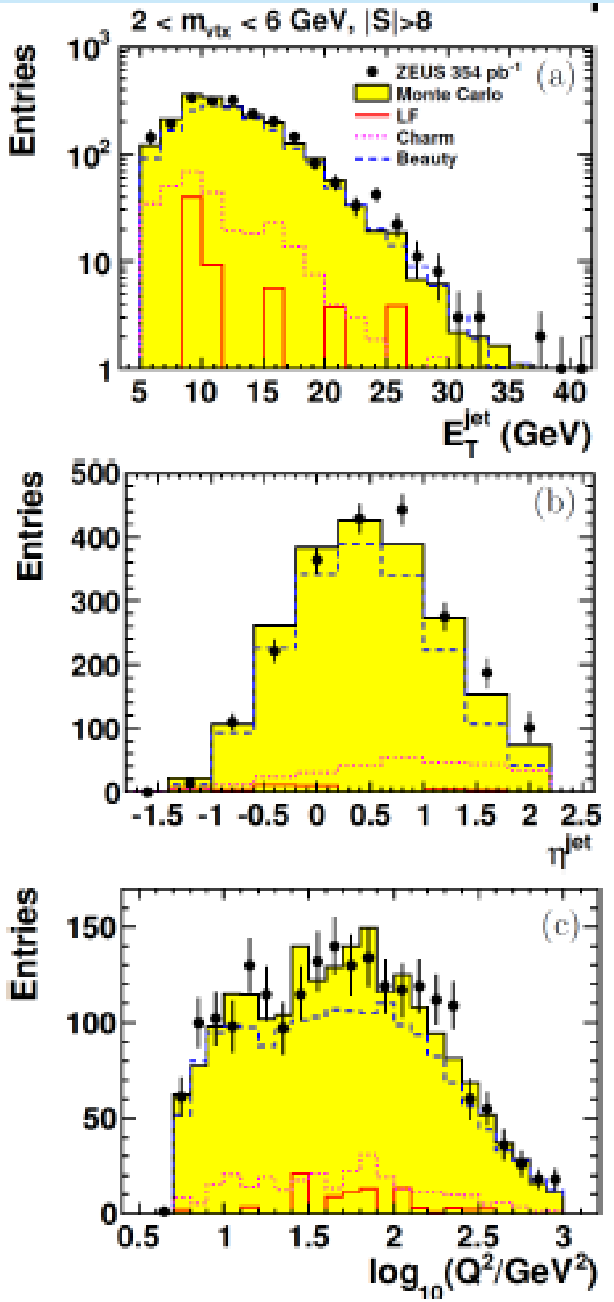




- 55 data points -> 52 combined points.
- χ^2/ndf=62/103.

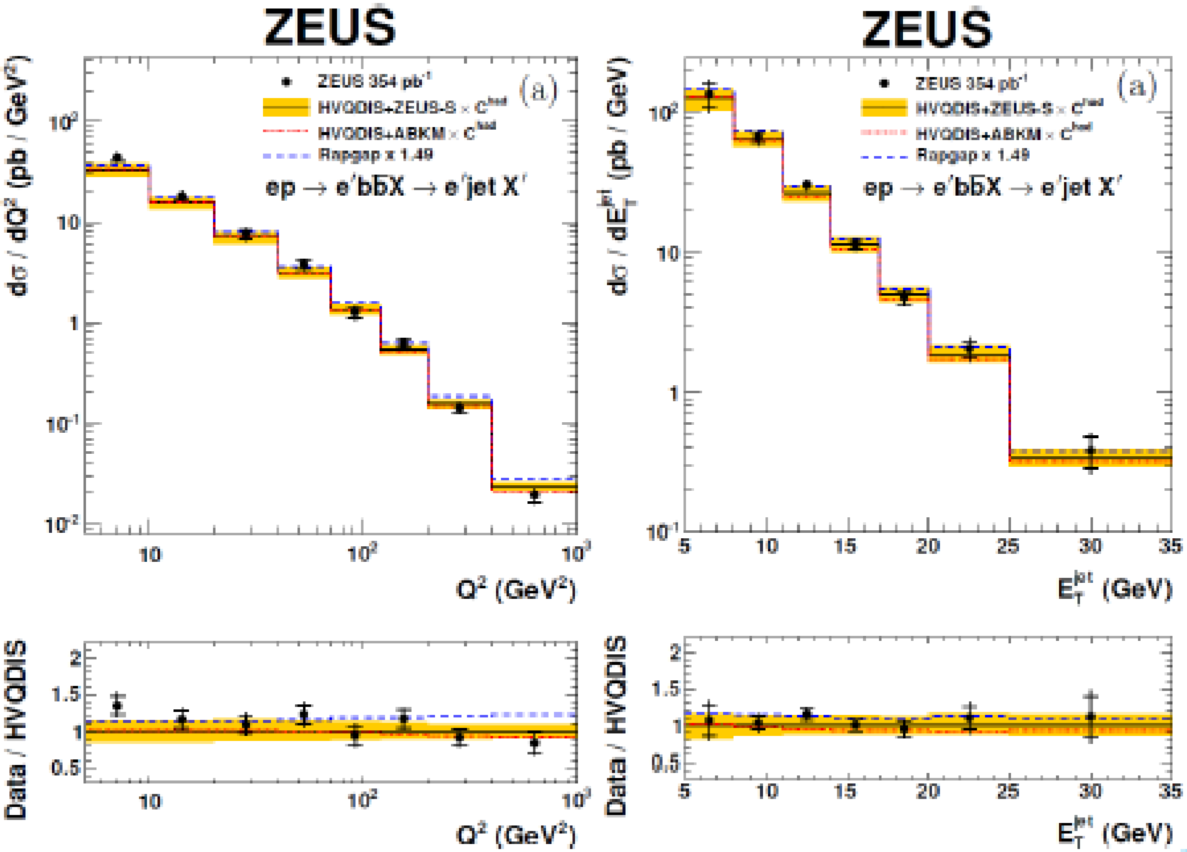
New beauty measurement: sec.vtx.

arXiv:1405.6915



Beauty-enriched sample

- Measurement of HF jets using secondary vertices + lifetime tag (simultaneous and b measurement).
- Good description of the data by the massive NLO QCD predictions.



New beauty measurement: sec.vtx.

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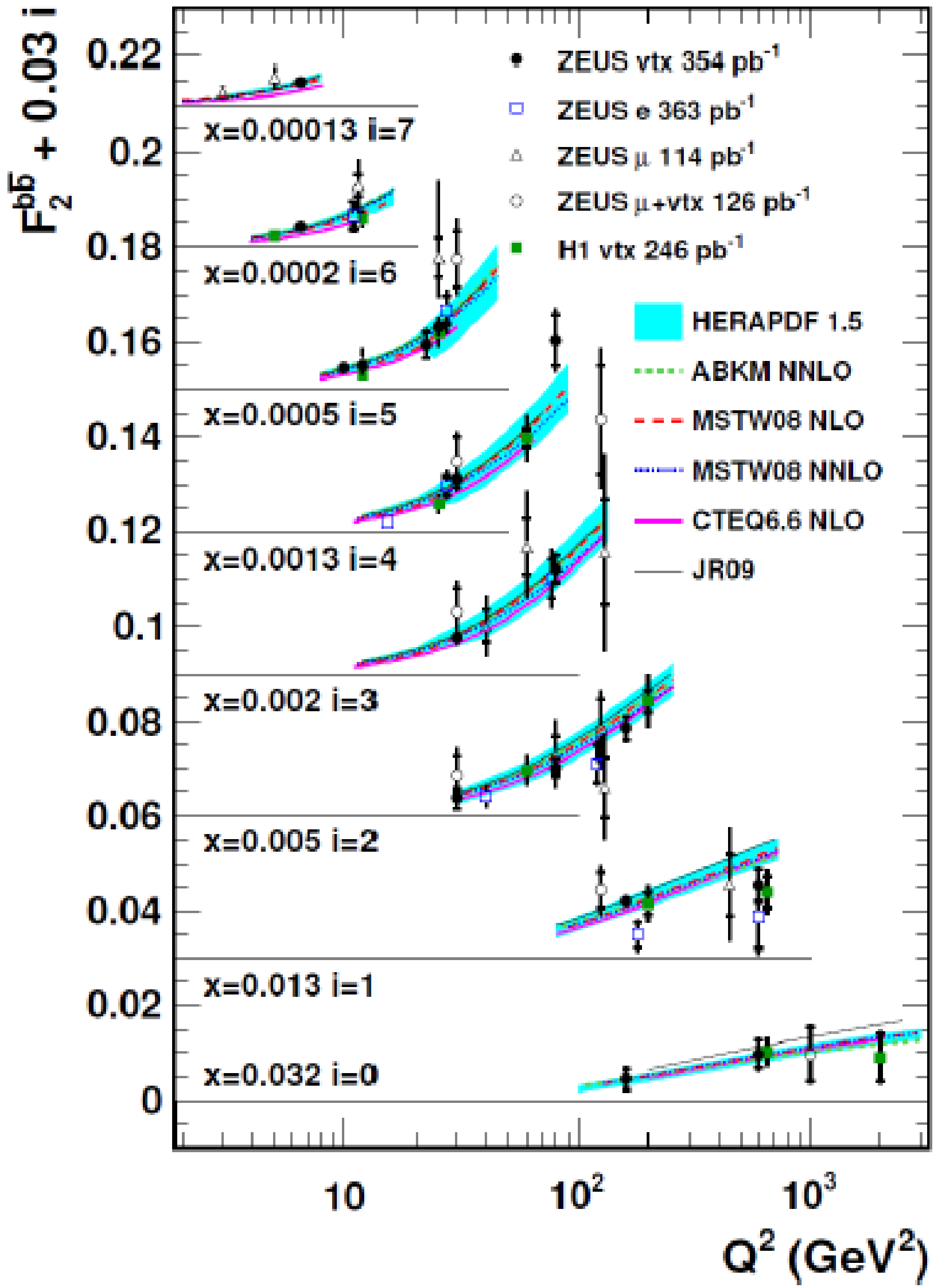

$$\frac{d\sigma^{b\bar b}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\cdot\left[\left(1+(1-y)^2\right)\cdot F_2^{b\bar b} - y^2\cdot F_L^{b\bar b}\right]$$

- In a wide range of Q^2, the new measurement is the most precise determination of F_2^b at HERA.
- All beauty data are in good agreement and well described by fixed-order (massive) and variable-flavour (mixed) NLO and NNLO QCD calculations.

Conclusions

- Particles with b and c quarks could 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- no need to invoke new physics
- Heavy flavor production in pp and ep 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