Heavy flavour production and decays at colliders

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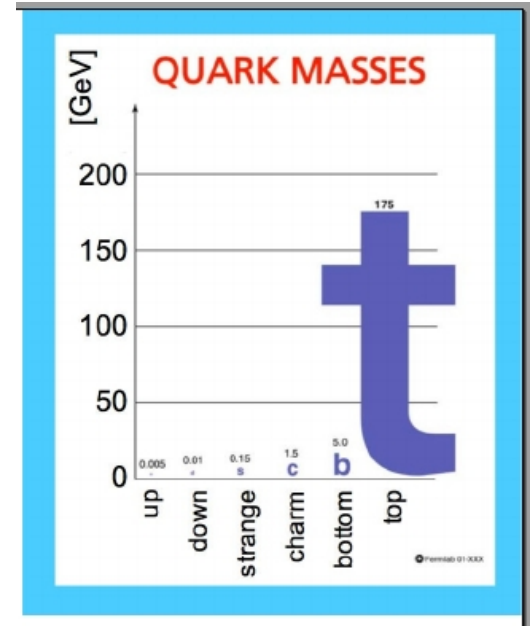University College London
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Physics and Applications
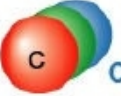
Outline

- What are heavy flavors and why they are interesting

- Discrete symmetries and CP violation

- CKM matrix and unitarity triangle

- Meson-antimeson oscillations

- b-production in ATLAS and CMS

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

Why interesting: Heavy Quark Effective Theory

- Quantum ChromoDynamics has an intrinsic scale, $\Lambda_{QCD} \sim 200$ 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, Y), 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 in Physics

- 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, thesymmetry 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

Partity: 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.

$$r \to -r$$

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

$$p \to -p$$

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

$$L \to L$$

- 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: 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.*

$$e^- \rightarrow e^+$$

$$\gamma \rightarrow \gamma$$
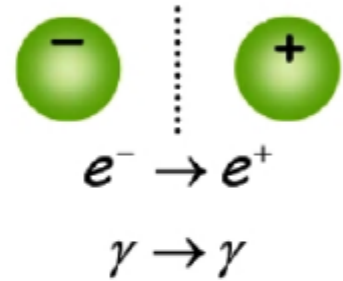
◈ C is violated in weak interactions, so matter and antimatter behave differently, and:

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

◈ C is a unitary operator: $C^2 = 1$.

Combining Charge and Parity: 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 C and P violation separately in order to distinguish between matter and antimatter.*
- *i.e. if helicity is negative (left) or positive (right).*

◨ CP is a unitary operator: $CP^2 = 1$

Time Reversal: 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.*

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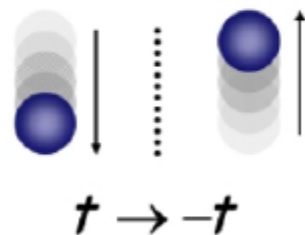
❑ $\mathcal{T}$ is an anti-unitary operator: $\mathcal{T}^2 = -1$.

Combining all symmetries: CPT

- All locally invariant Quantum Field Theories conserve CPT.[1]

- CPT is anti-unitary: $CPT^2=-1$.

- 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 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).*

Applying CP to physical states

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

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.

$$CP \,|\, \pi^0 \,\rangle = - \,|\, \pi^0 \,\rangle$$

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.

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

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.

Flavour interactions in the SM: the CKM matrix

- In the SM Lagrangian, charged-current interactions, mediated by the W boson, allow interactions between U-like and D-like quarks

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

- Where V is a non-diagonal mixing matrix

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

How many parameters in the matrix?

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

The matrix in terms of angles

- There are many ways of writing the matrix as a function of 4 parameters, but the most common (from PDG) uses 4 angles:

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

- Where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, with all angles real

- The only complex part of the matrix comes from the $e^{i\delta}$ terms, and that is responsible for CP violation!

- Indeed, the CP swapping on the Lagrangian gives a different result if the matrix has one or more complex terms
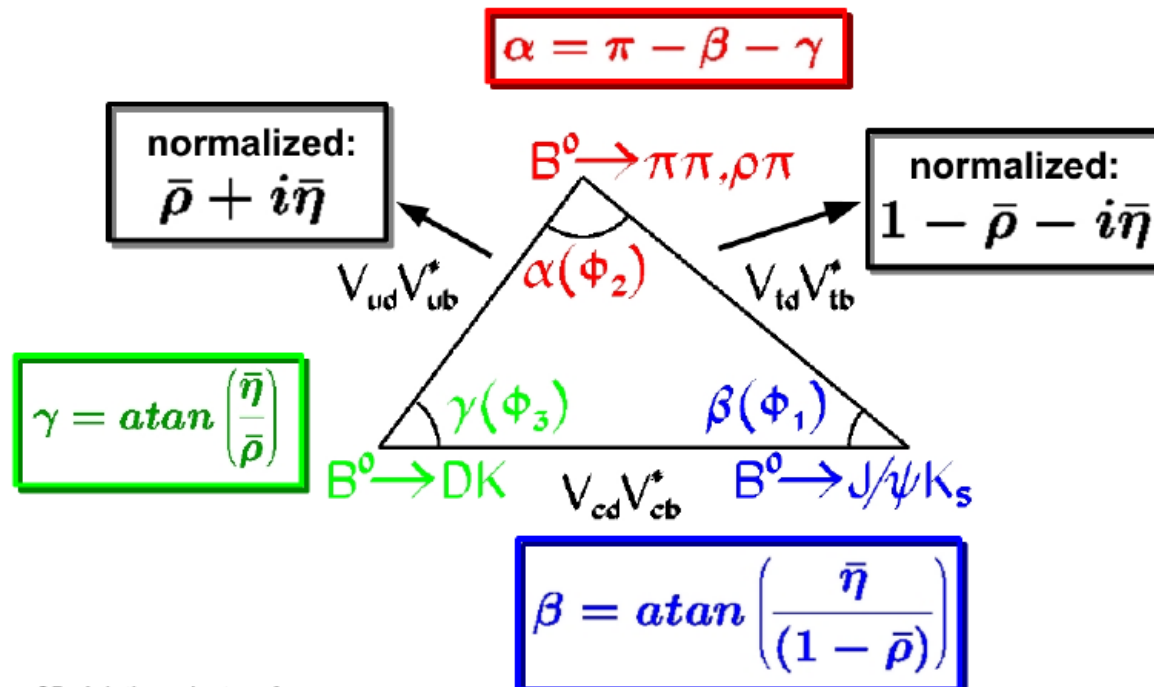
Approximate parametrisation

- Experimentally, mixing is larger for nearby generations, $1 \gg \theta_{12} \gg \theta_{23} \gg \theta_{13.}$ Wolfenstein expanded in $\lambda = \sin \theta_{12}$

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

- Diagonal terms ~1, $V_{12}, V_{21} \sim \lambda$, $V_{23}, V_{32} \sim \lambda^2$, $V_{13}, V_{31} \sim \lambda^3$

- At second order, use $\rho = \rho\,(1 - \lambda^2/2)$, $\eta = \eta\,(1 - \lambda^2/2)$

- Now the complex component is only in V_{13} and V_{31} (third family!)

The CKM triangle

- The Wolfenstein parametrisation is graphycally represented as a triangle with base at (0,0) and (1,0) and apex at (ρ, η).

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

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

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

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

$V_{ud}V_{ub}^*$ $\alpha(\Phi_2)$ $V_{td}V_{tb}^*$

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

$\gamma(\Phi_3)$ $\beta(\Phi_1)$

$B^0 \longrightarrow DK$ $V_{cd}V_{cb}^*$ $B^0 \longrightarrow J/\psi K_s$

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

Measuring triangle angles

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

$b \rightarrow u\bar{u}d$ $B \rightarrow a_1\pi$
$B \rightarrow \pi\pi$ $B \rightarrow a_1\rho$
$B \rightarrow \rho\pi$ $B \rightarrow b_1\pi$
$B \rightarrow \rho\rho$ $B \rightarrow b_1\rho$
$B \rightarrow a_1 a_1$

$b \rightarrow c\bar{c}s$ $B \rightarrow J/\psi\pi^0$
$B^0 \rightarrow J/\psi K_L^0$ $B \rightarrow D^{(*)+}D^{(*)-}$
$B^0 \rightarrow J/\psi K_S^0$ $B \rightarrow \eta'K^0$
$B^0 \rightarrow \psi(2S)K_S^0$ $B \rightarrow \rho K^0$
$B^0 \rightarrow \chi_{1c}K_S^0$ $B \rightarrow \omega K^0$
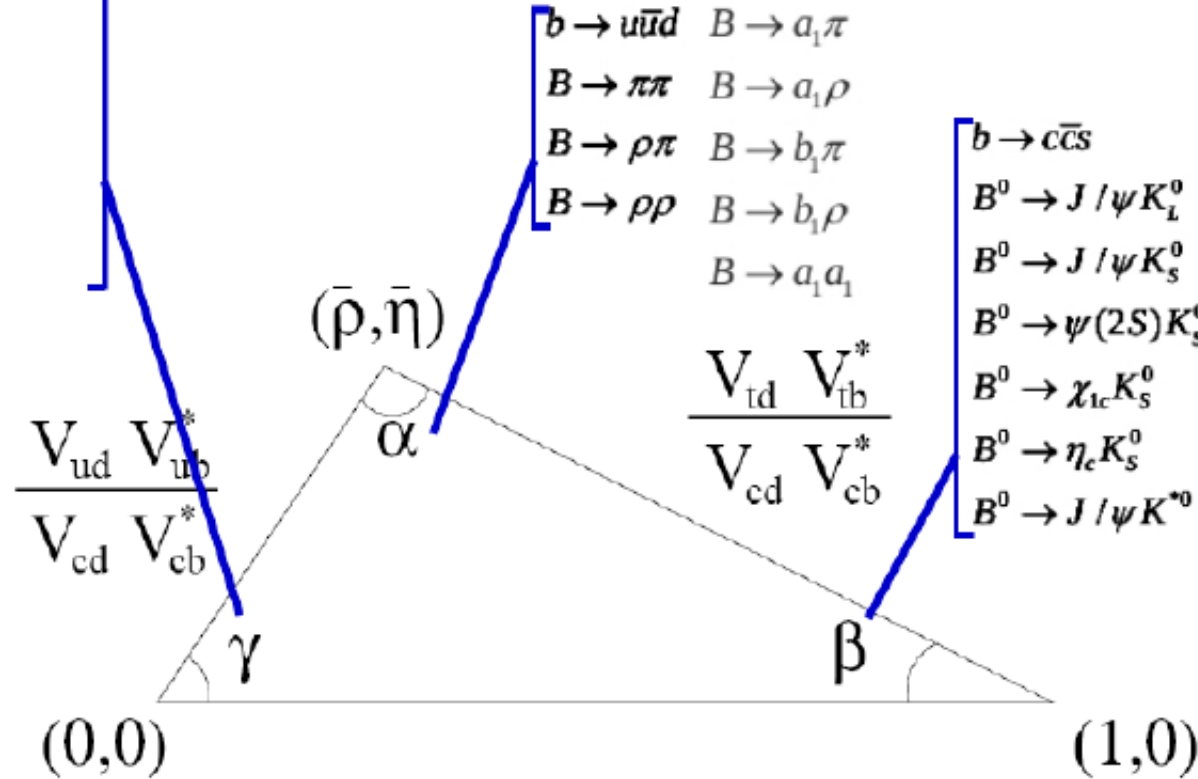$B^0 \rightarrow \eta_c K_S^0$ $B \rightarrow \pi^0 K^0$
$B^0 \rightarrow J/\psi K^{*0}$ $B \rightarrow \phi K^{(*)0}$
  $B \rightarrow KKK^0$
  $B \rightarrow f^0(980)K^0$

$(\bar{\rho},\bar{\eta})$

$\dfrac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}$

$\dfrac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*}$

α

γ β

$(0,0)$ $(1,0)$

Measuring triangle sides

Current constraints on triangle (from www.pdg.org)

Figure 12.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 99% CL.
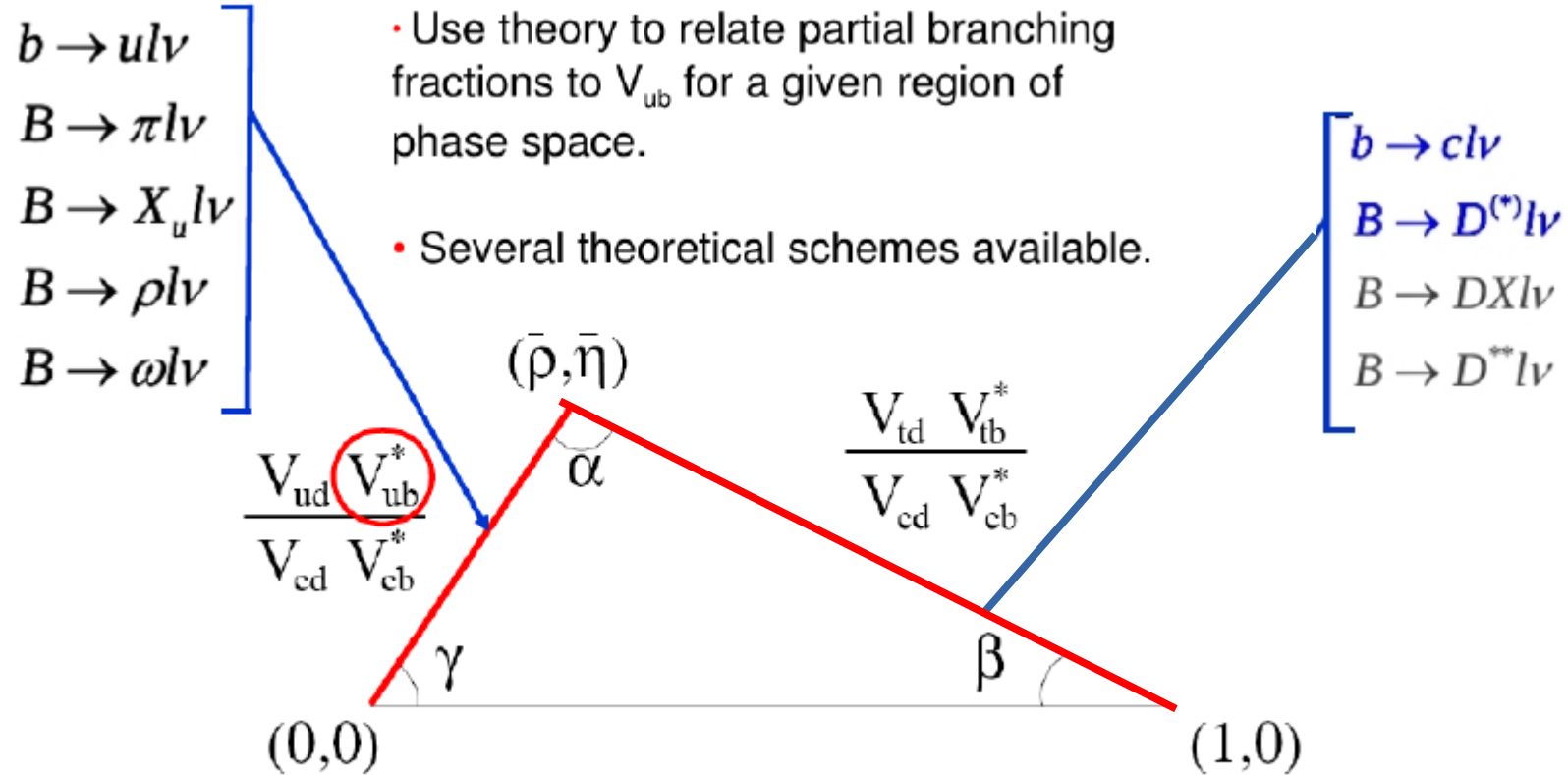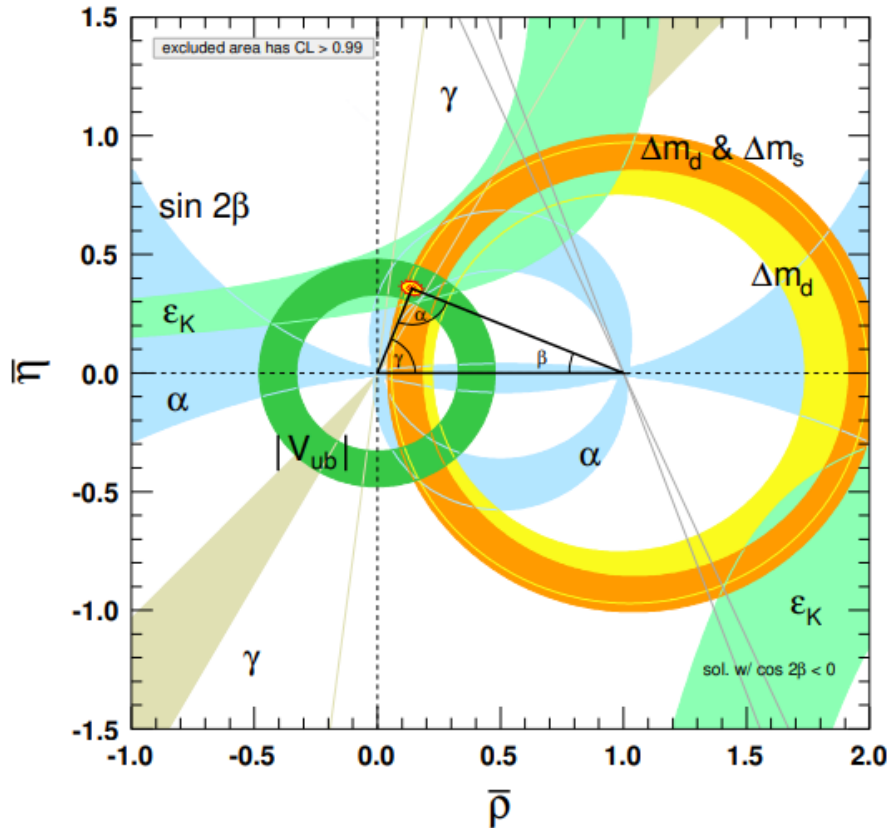
- Several ways to independently measure sides and angles

- All point to a coherent picture: CP violation well understood in the SM

Producing B mesons

- The "clean" way: e+e- collisions at the Υ(4S) peak, followed by decay into B^+B^- or B^0B^0 (Babar, BELLE)

- The "dirty" way: proton collisions followed by b-tagging (CDF, D0, LHCb, ATLAS, CMS)

 - Advantages: large rates, can produce Bs, Bc etc.

  - Disadvantages: large BG
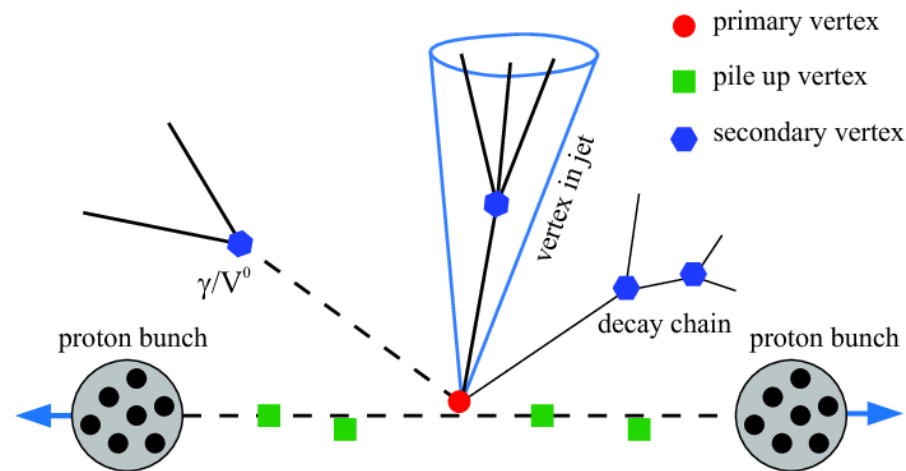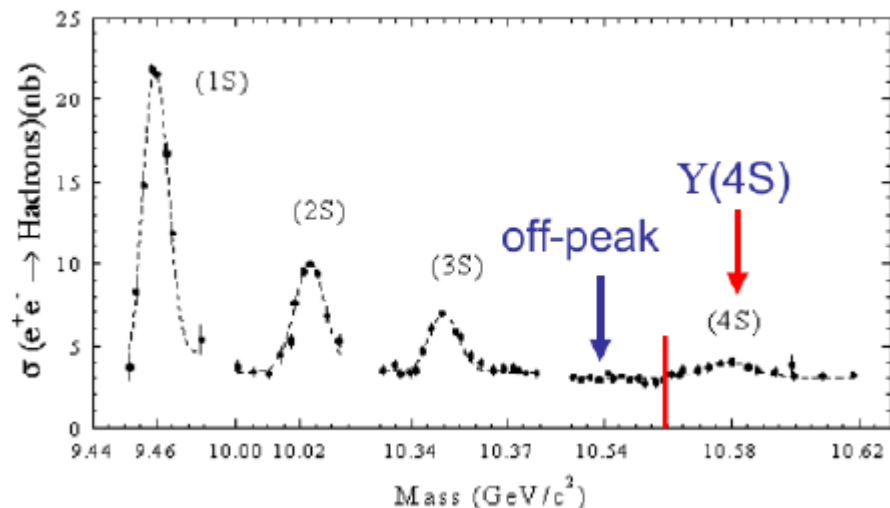
Oscillations of neutral mesons in QM

- 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 $\Gamma_{1,2}$)

- 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
$$M = p\, M^0 \pm q\, \overline{M}^0$$
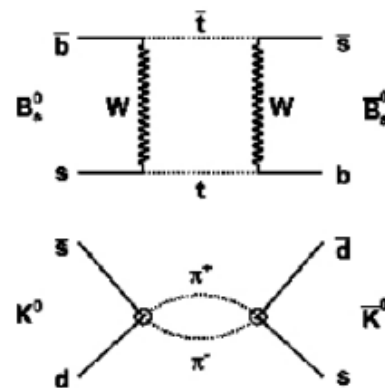
Schroedinger equation for oscillation

- 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 $\quad\neq\quad$ H_{eff} eigenstates:
  (defined flavour) $\qquad$ (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 ($a_{ij} = \overline{a}_{ji}$)

  $M = \frac{1}{2} (H+H^\dagger)$ 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

Solutions for physical states

◎ 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:

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

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

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

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

$$(q/p)^2 = (M_{12}{}^* - i/2 \, \Gamma_{12}{}^*)/(M_{12} - i/2 \, \Gamma_{12})$$
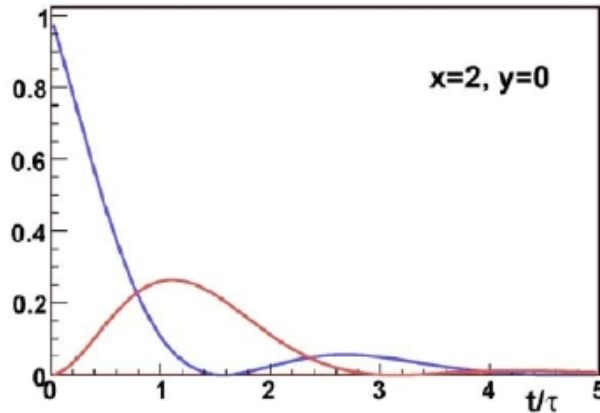
other useful
definitions:
$$x \equiv \Delta m/\Gamma$$
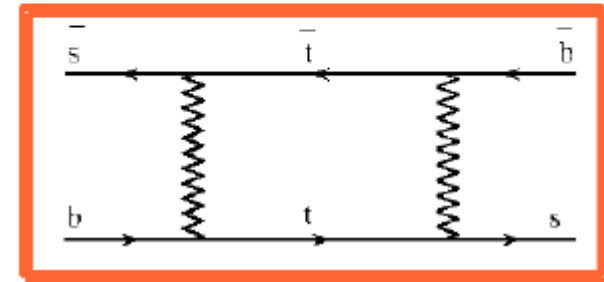$$y \equiv \Delta\Gamma/2\Gamma$$

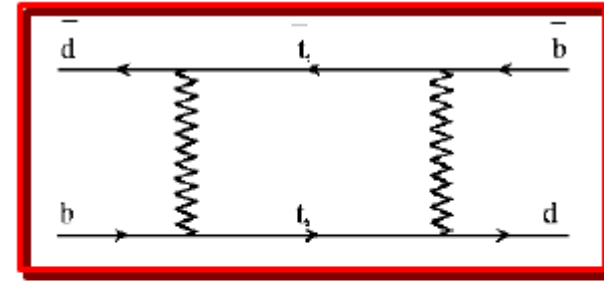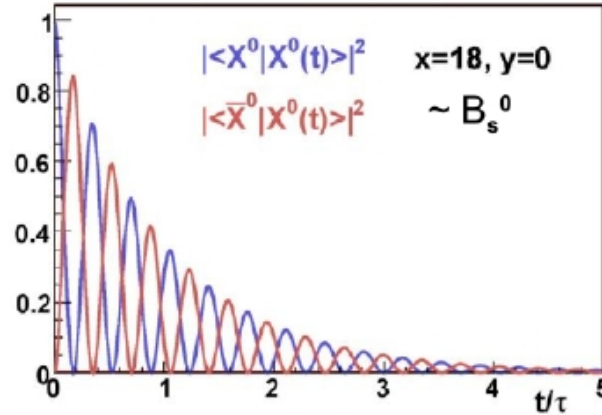# Oscillation probability

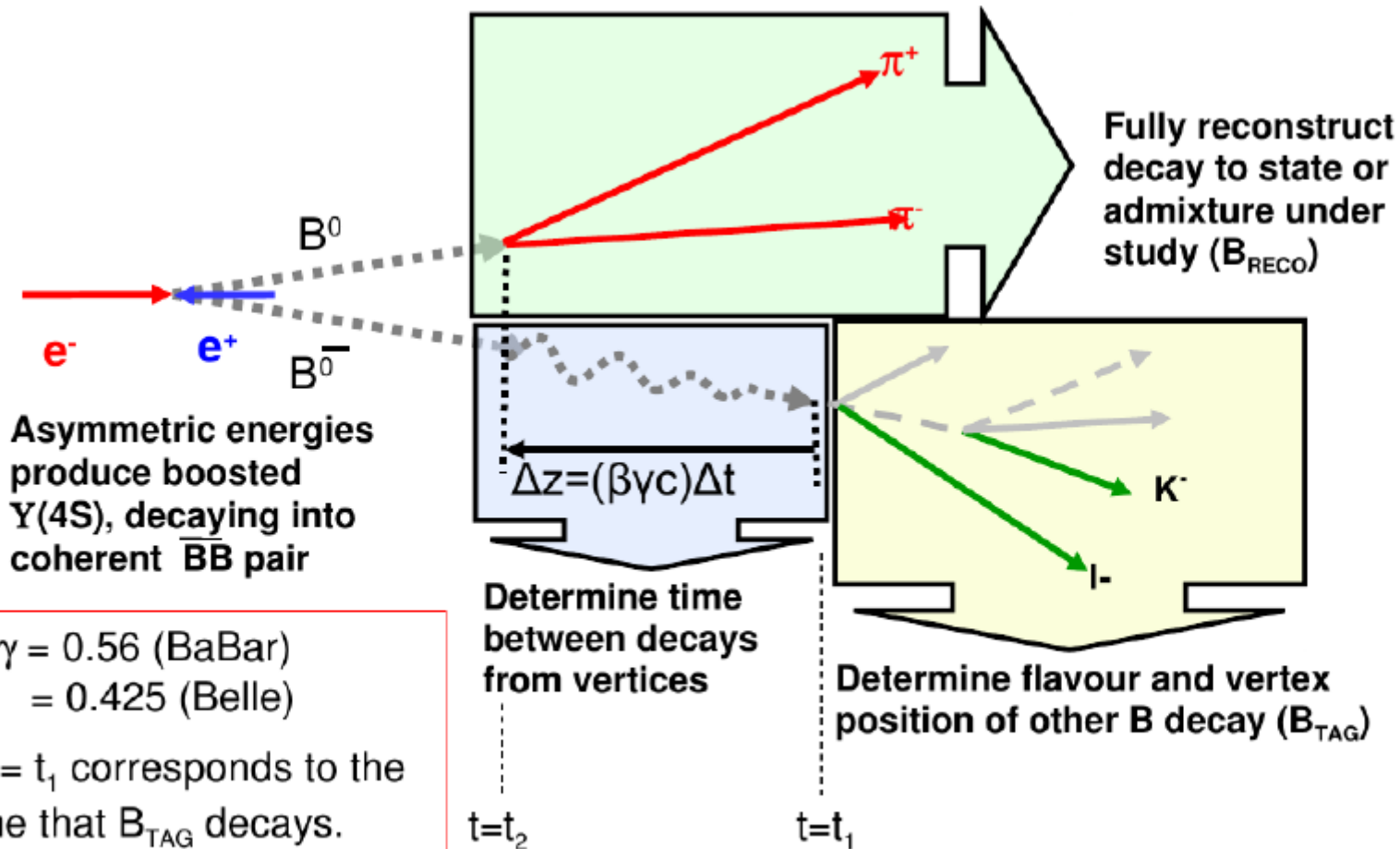- Bd and Bs oscillations formally identical, frequency very different

probab. to observe an initially produced X⁰ as X⁰ after time t
probab. to observe an initially produced X⁰ as X̄⁰ after time t

Oscillations in e⁺e⁻ collisions

B^0

π^+

π^-

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

$B^{\overline{0}}$

e^- e^+

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

$\Delta z = (\beta\gamma c)\Delta t$

K^-

l⁻

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)

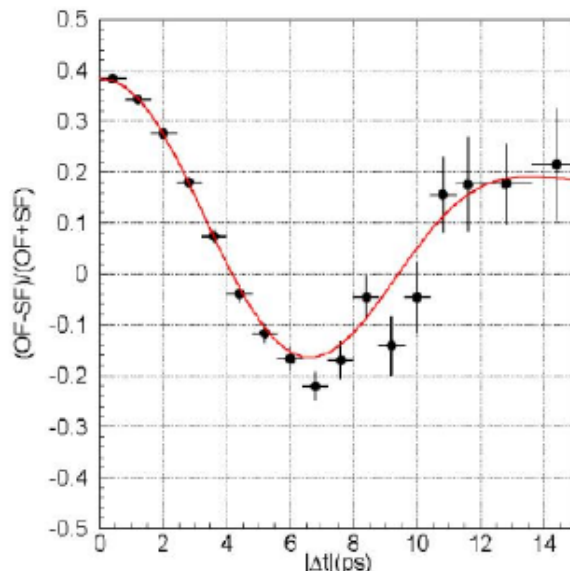- $t = t_1$ corresponds to the time that B_{TAG} decays.

- $t_2 - t_1 = \Delta t$

$t = t_2$

$t = t_1$

Bd oscillations

HFAG, http://www.slac.stanford.edu/xorg/hfag/
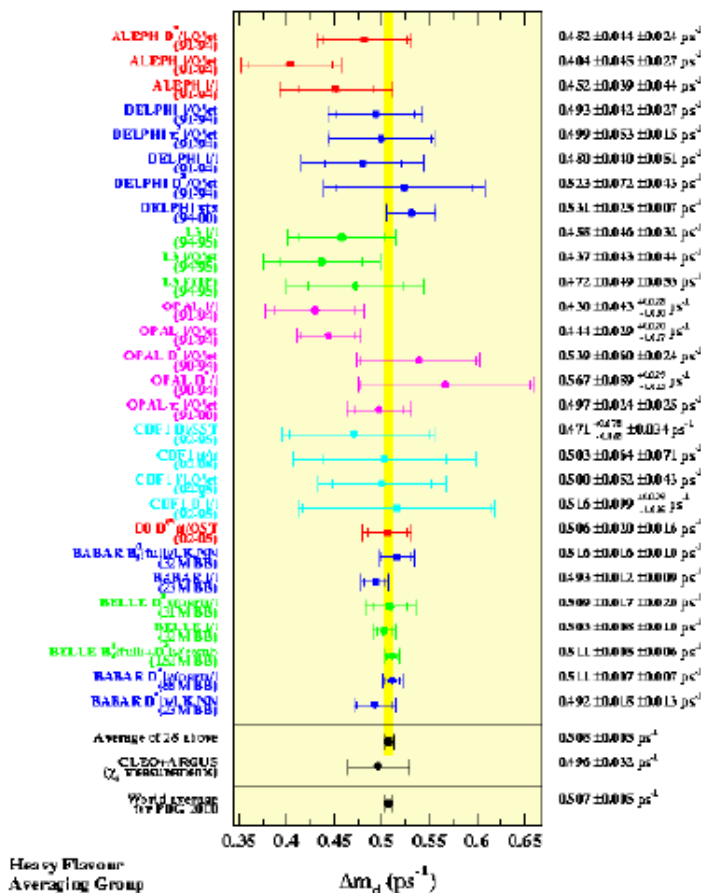
$$\frac{d\Gamma(B^0 \to f)/d\Delta t - d\Gamma(\overline{B} \to f)/d\Delta t}{d\Gamma(B^0 \to f)/d\Delta t + d\Gamma(\overline{B}^0 \to f)/d\Delta t} =$$

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

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

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

Bs oscillations

At the Tevatron on the B_s:

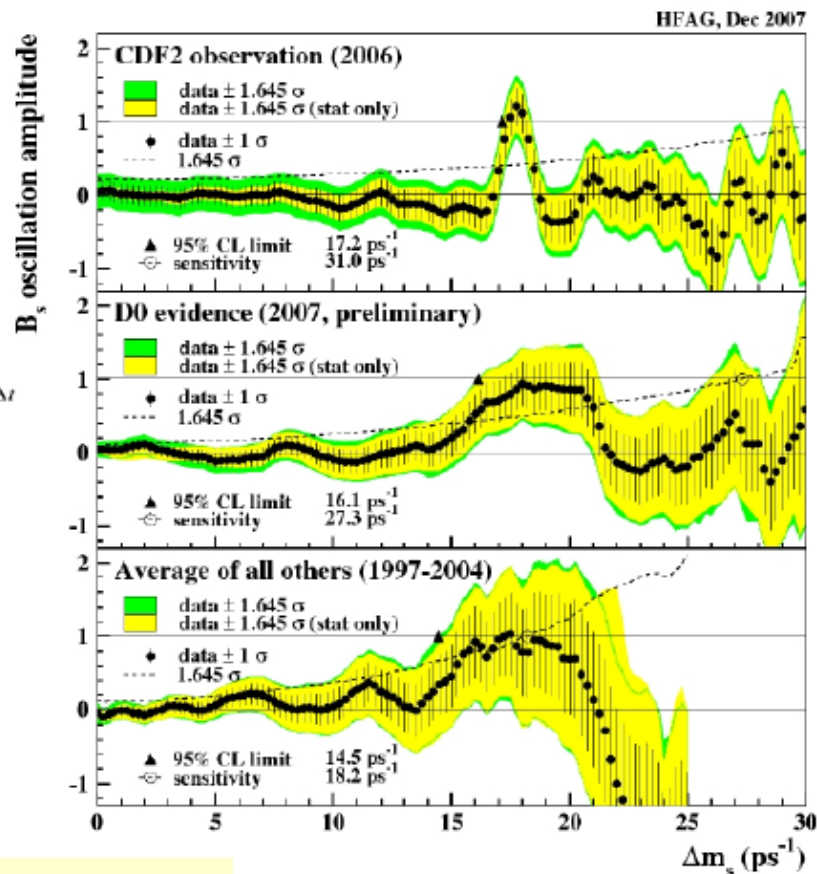► amplitude method, instead of extracting directly Δm_s (*à la* LEP)

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

► 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

HFAG, Dec 2007

B_s oscillation amplitude

CDF2 observation (2006)
- data ± 1.645 σ
- data ± 1.645 σ (stat only)
- ◆ data ± 1 σ
- ---- 1.645 σ
- ▲ 95% CL limit   17.2 ps^{-1}
- ⊕ sensitivity   31.0 ps^{-1}

D0 evidence (2007, preliminary)
- data ± 1.645 σ
- data ± 1.645 σ (stat only)
- ◆ data ± 1 σ
- ---- 1.645 σ
- ▲ 95% CL limit   16.1 ps^{-1}
- ⊕ sensitivity   27.3 ps^{-1}

Average of all others (1997-2004)
- data ± 1.645 σ
- data ± 1.645 σ (stat only)
- ◆ data ± 1 σ
- ---- 1.645 σ
- ▲ 95% CL limit   14.5 ps^{-1}
- ⊕ sensitivity   18.2 ps^{-1}

Δm_s (ps^{-1})

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**
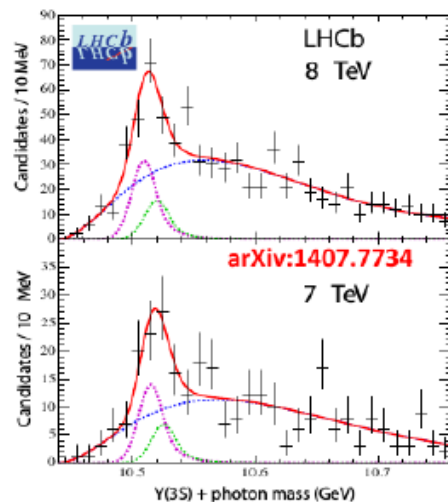

Sketch by Qipeng Hu
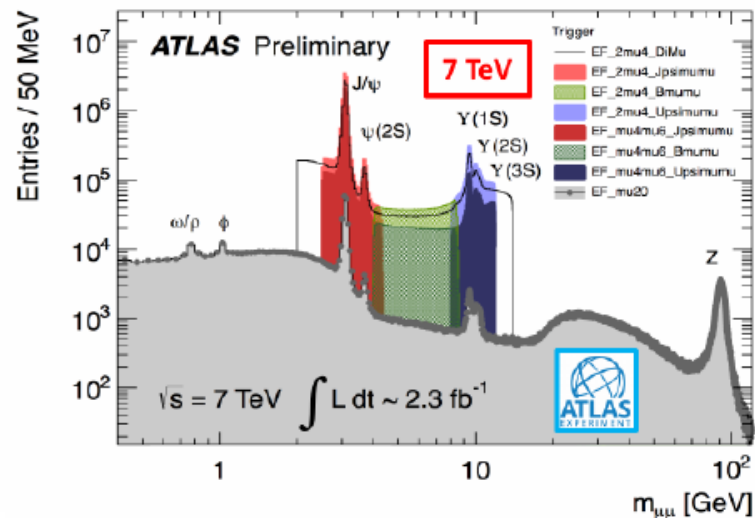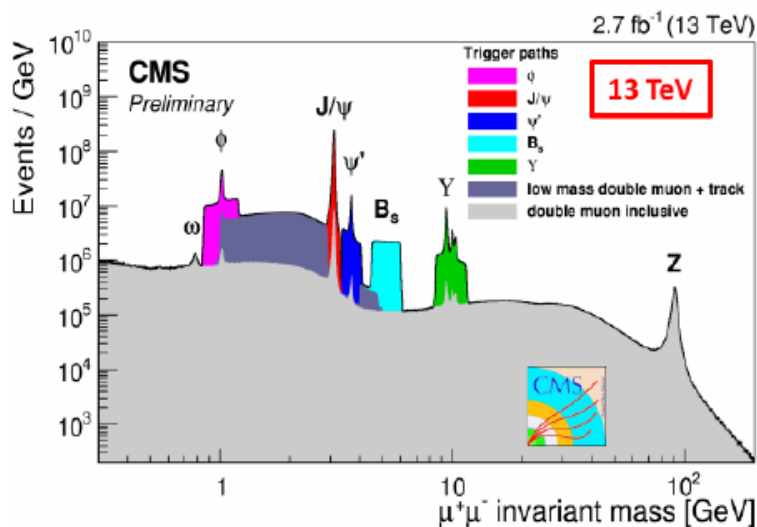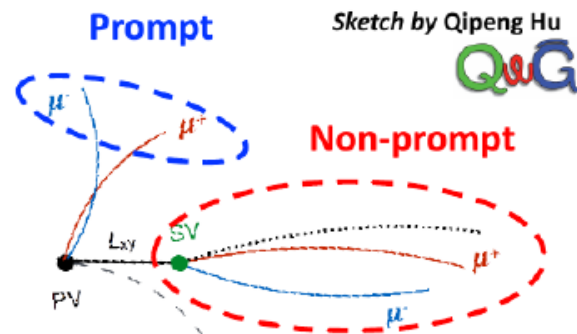
Prompt

Non-prompt

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*.
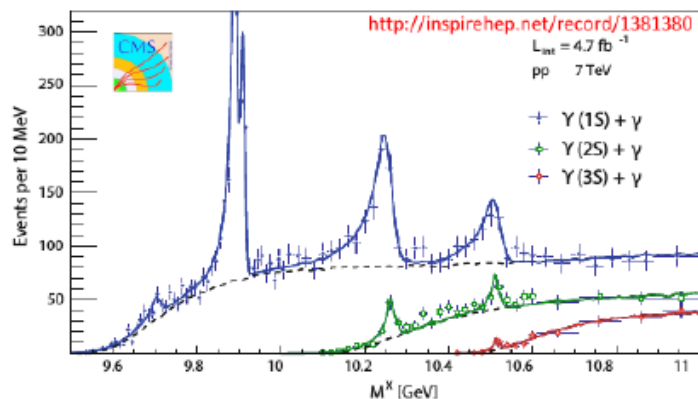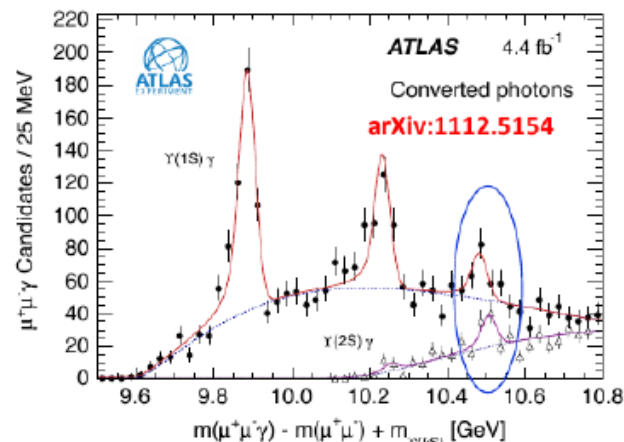

[1] PRL 114, 191802
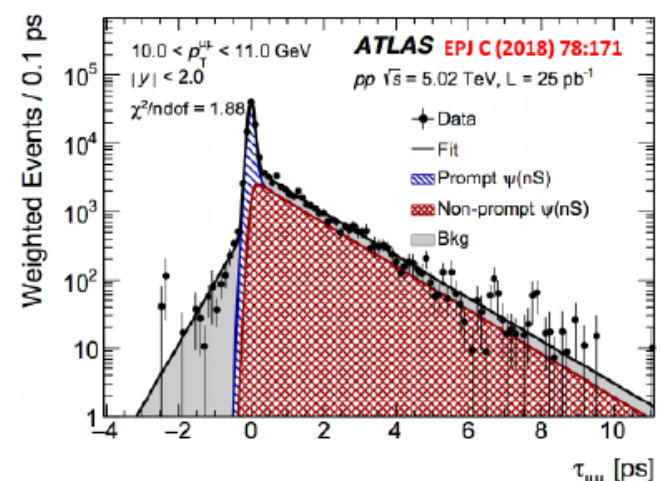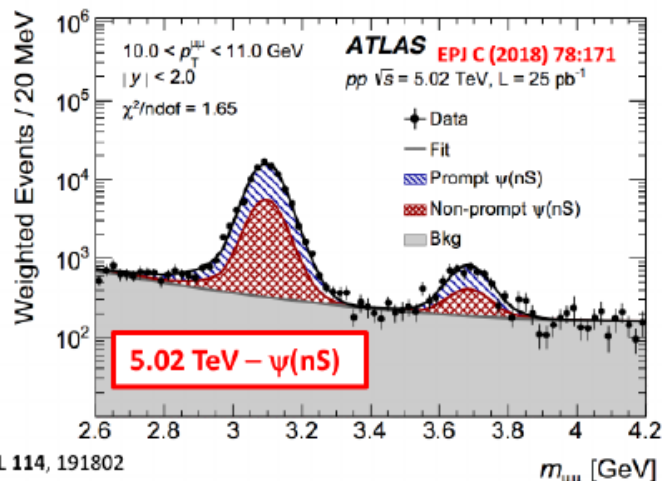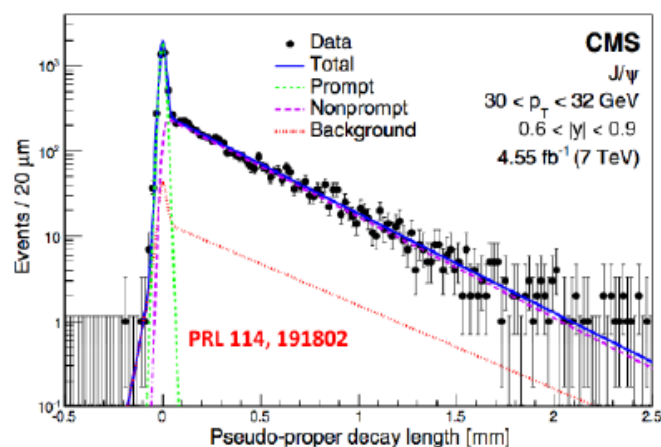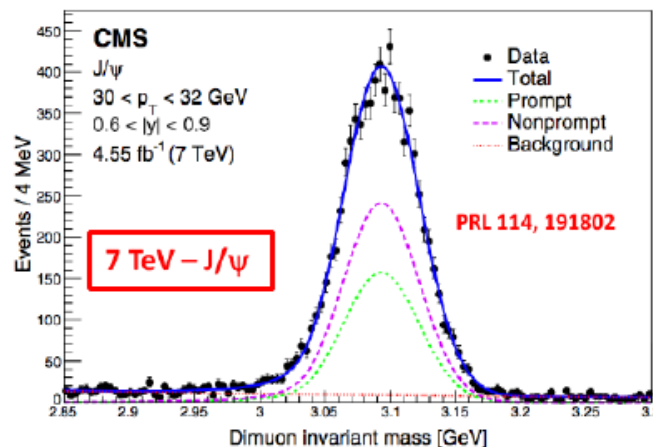
Observations of bottomium systems

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.

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 $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ radiative decays, in the 7 TeV data
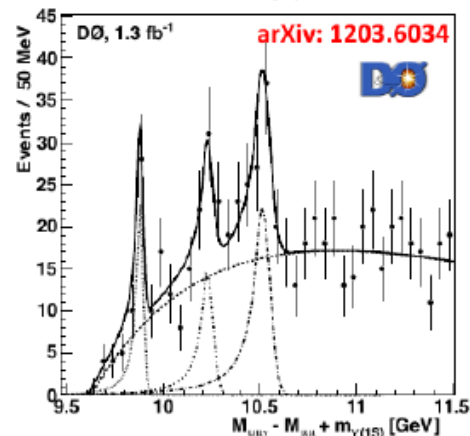
Mesons with beauty and charm: Bc

- $B^+ (B^-)$ 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.
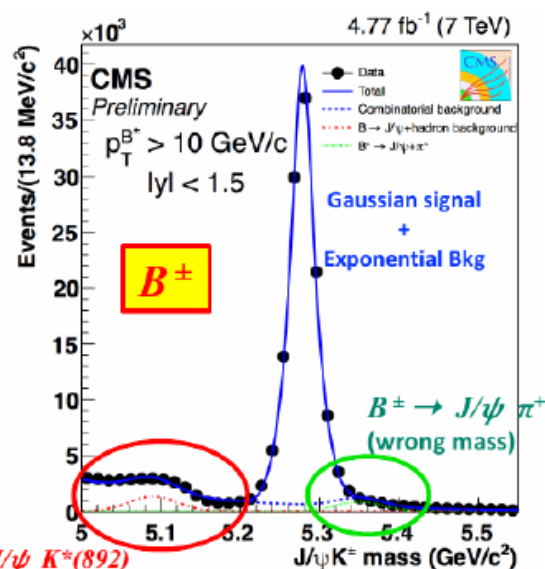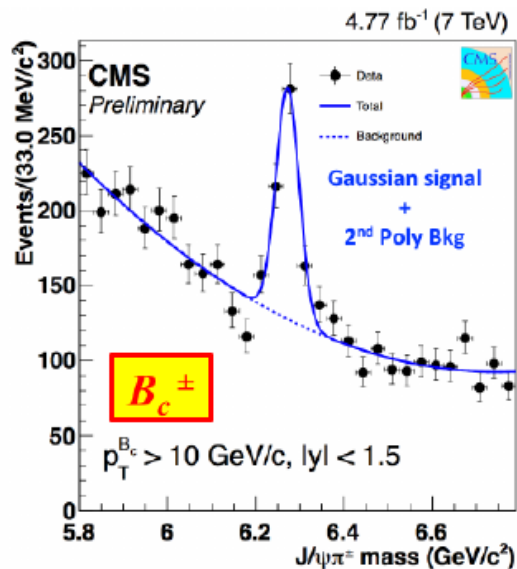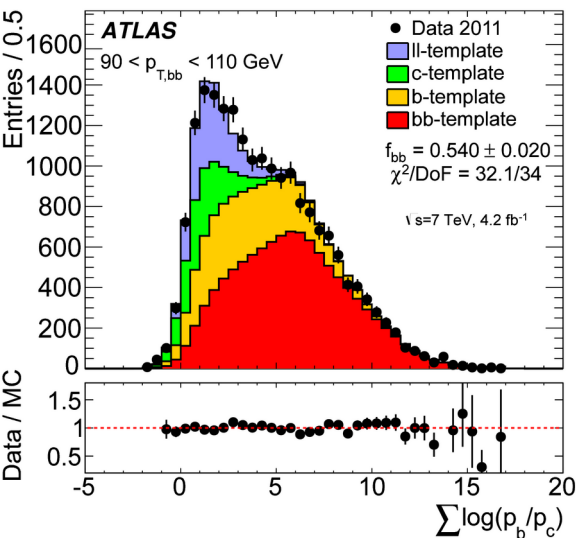

Kinematic region
$p_T > 10$ GeV/c and $|y| < 1.5$ to maximize B_c^+ significance $[S/\sqrt{(S + B)}]$

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

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

B jets at the LHC

ATLAS

$90 < p_{T,bb} < 110$ GeV

- Data 2011
- ll-template
- c-template
- b-template
- bb-template

$f_{bb} = 0.540 \pm 0.020$
$\chi^2/\text{DoF} = 32.1/34$

$\sqrt{s} = 7$ TeV, 4.2 fb^{-1}

Entries / 0.5

Data / MC

$\sum \log(p_b/p_c)$

4 main production mechanisms

(a) flavour creation (s-channel)

(b) flavour creation (t-channel)

(c) gluon splitting

(d) flavour excitation
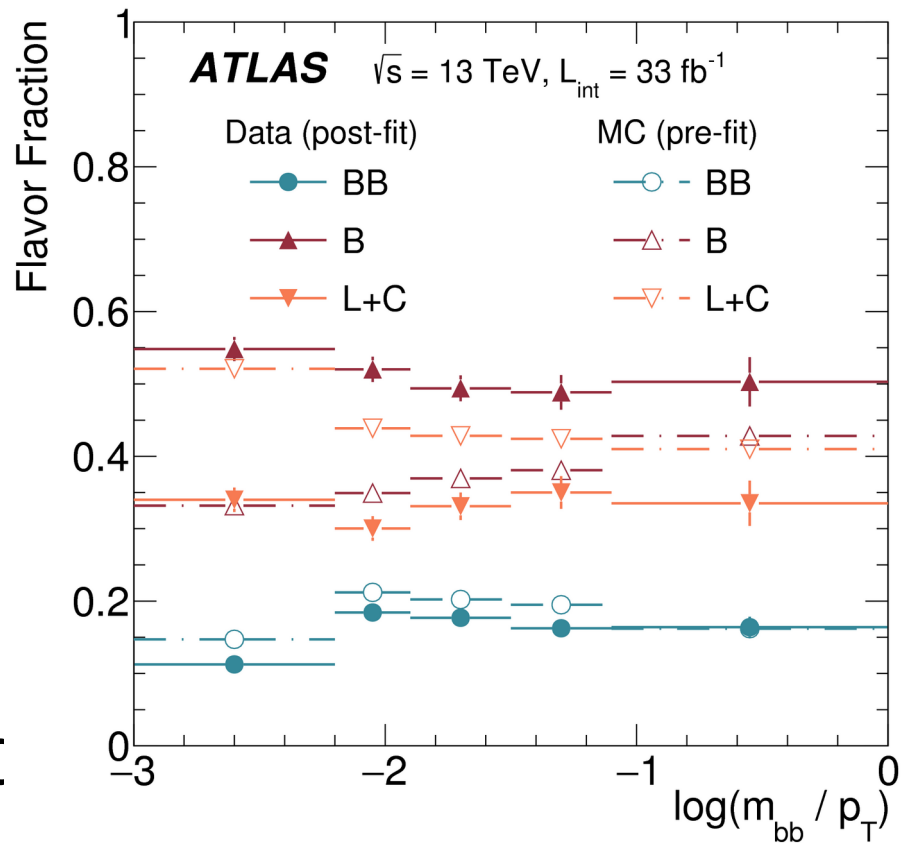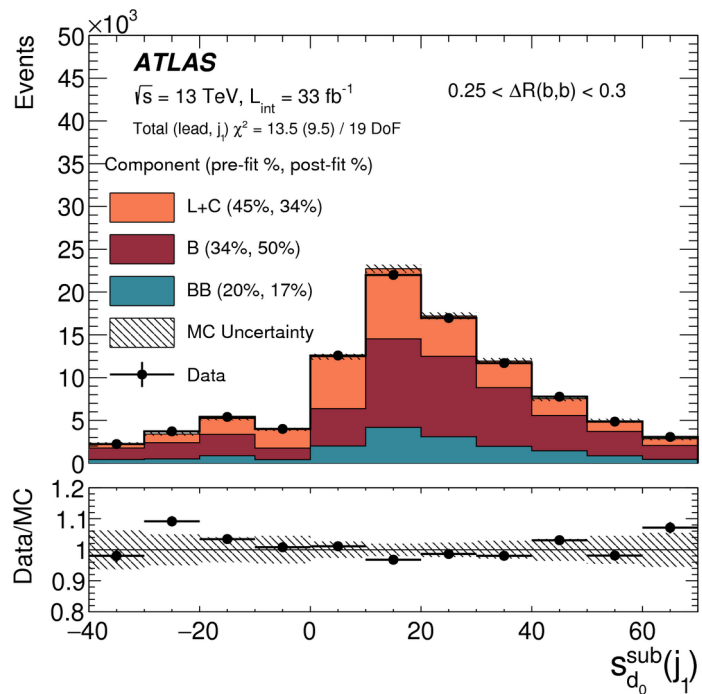
Use vertex mass and distance to distinguish bb, b, c and light quarks in jet

Invariant mass of two jets each identified as b

ATLAS

$\sqrt{s} = 7$ TeV, 4.2 fb^{-1}

- Data 2011
- Stat. + Syst.
- POWHEG+PYTHIA 6

$d\sigma(pp \rightarrow b\bar{b}+X)/dm_{bb}$ [pb/GeV]

NLO/ Data

- POWHEG+PYTHIA 6
- MC@NLO+HERWIG 6
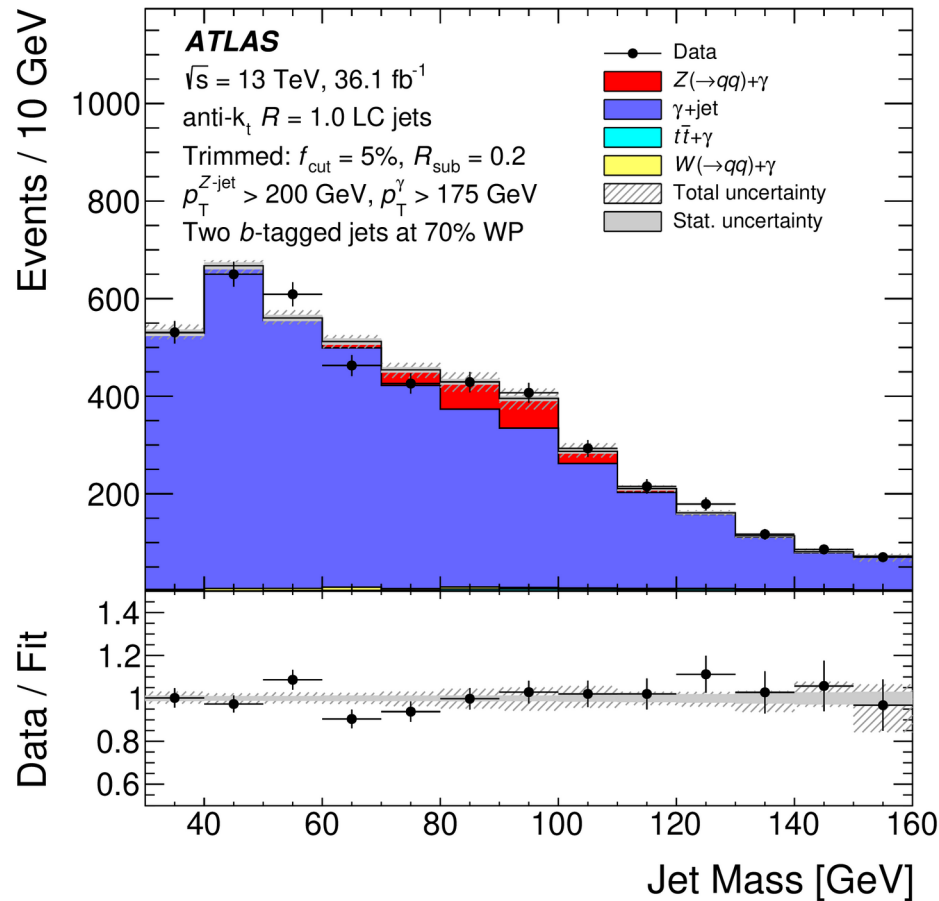
LO/Data

- PYTHIA 6 × 0.61
- SHERPA 1.43

m_{bb} [GeV]
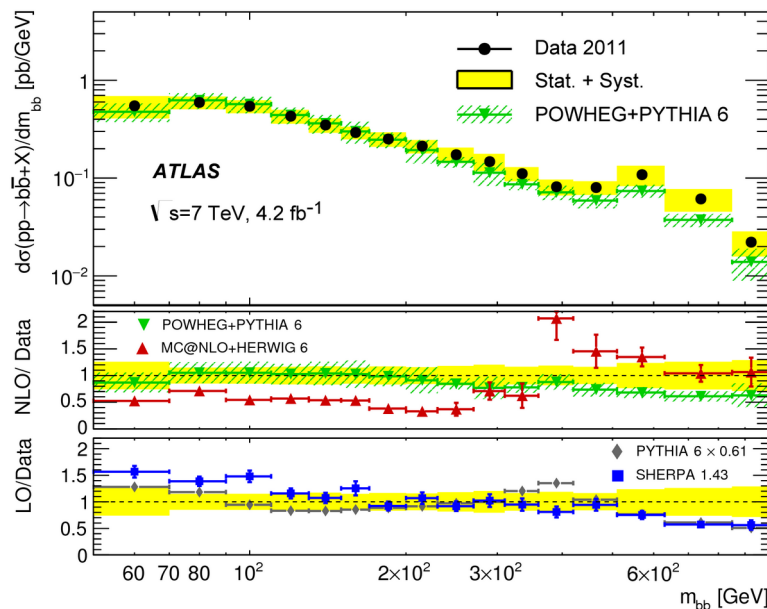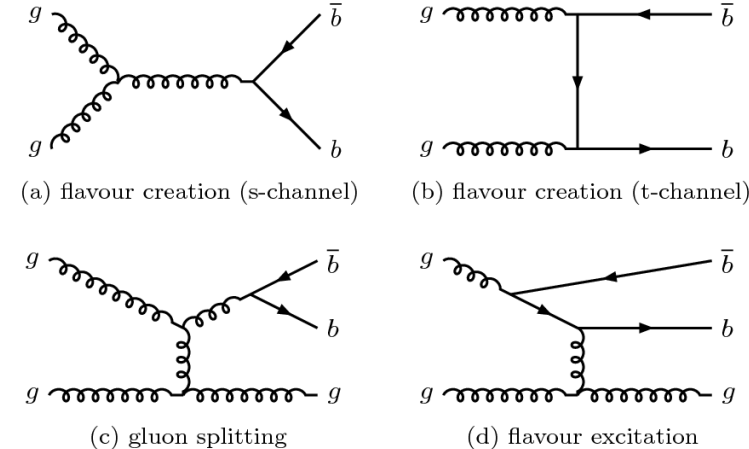
g → bb splitting with both b in a single jet

- Study composition of jets by fitting separately each bin and compare to theory

Finding Z → bb in a single jet

- Apply double b-tag photon + jet events

- Jet trimmed to remove piluep and underlying event

- Require two-prong structure

- Z peak visible in the jet mass despite huge background

Conclusions

- Heavy quarks a fundamental "laboratory" due to large mass (perturbative calculations) and long lifetime (reconstruction of secondary vertex)

- Also, CP-violating effects particularly relevant in third family

- Dedicated experiments (and accelerators!) built to extensively study the CKM matrix, all coherent with SM picture

- b and c production in jets studied in general-purpose LHC experiments

- More details on the dedicated experiment (LHCb) and its intriguing anomalies in Monica Pepe-Altarelli's talk next week!