QCD and heavy flavor physics at colliders

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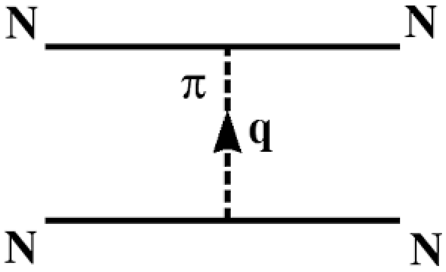
Outline

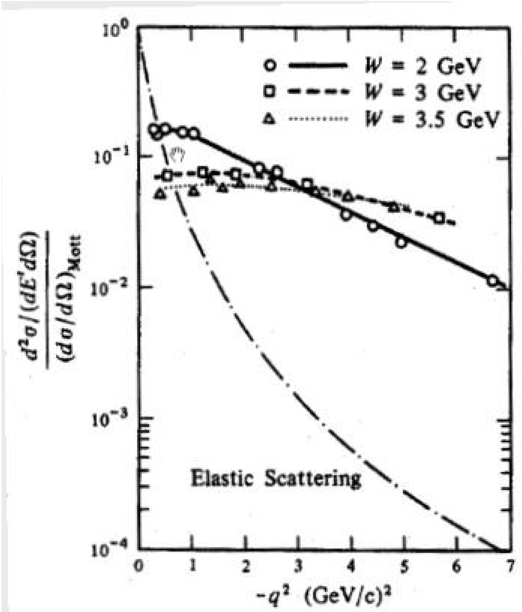
- Strong interactions and QCD
- Parton Distribution Functions
- Measuring jets at the LHC
- B-jet production
- Discrete symmetries and CP violation
- CKM matrix and unitarity triangle
- Meson-antimeson oscillations
- Exclusive final states

Strong interaction and QCD

Protons have equal positive charge, and would not be bound in nuclei without a strong, short-distance interaction.



Yukawa proposed that the exchange of particles with masses around 100 MeV could be responsible for these interactions.



Electron-proton Deep Inelastic Scattering has shown that (like Rutherford's experiment) cross-section has a very weak dependence on the momentum transfer.

Protons and neutrons are not elementary particles but made of smaller constituents (quarks, interacting through gluons)

QCD color charges

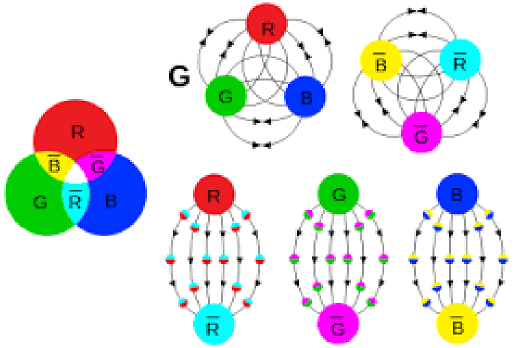
In the 70s, the current theory of strong interactions was formulated, based on gauge symmetries (like EW)

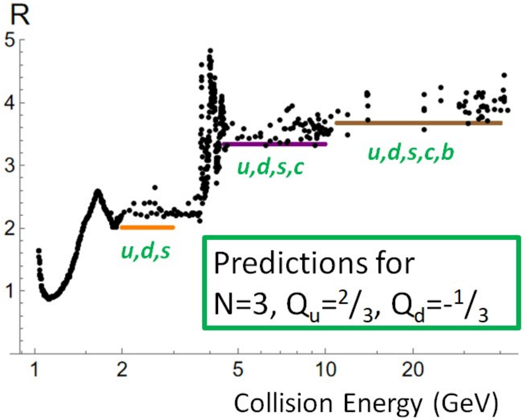
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i \gamma^\mu (D_\mu)_{ij} - m\, \delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Quarks interact through gluons that carry a charge called “color”.

Only 3-quark baryons of different colors,

or quark-antiquark mesons are stable.

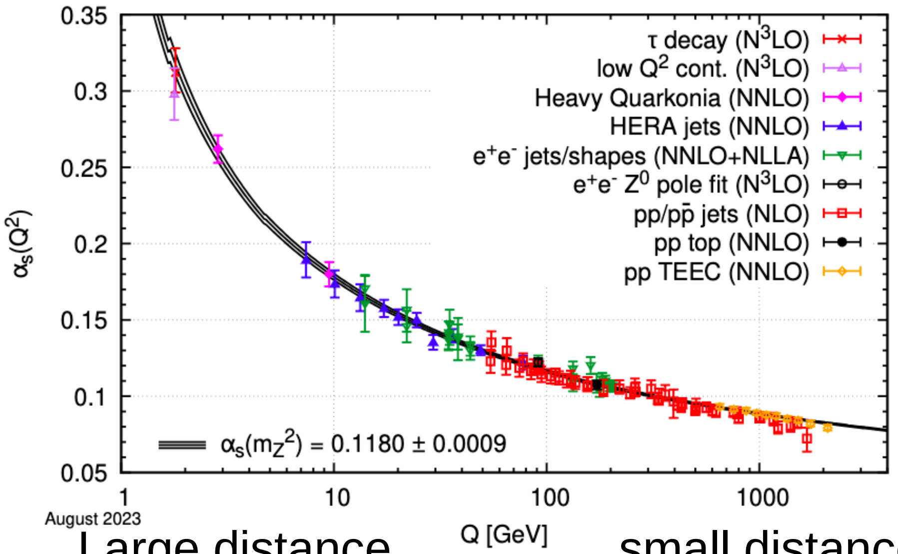




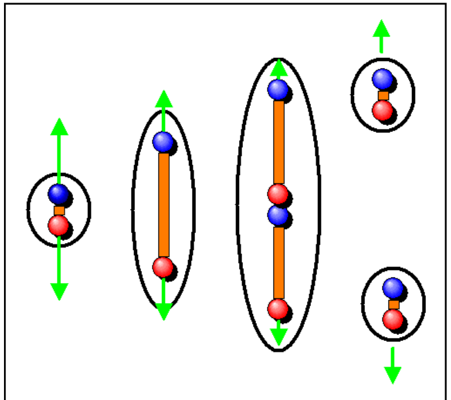
Evidence for reality of color comes from the fact that quark production is 3 times larger than what it would be without it!

α_s , confinement, asymptotic freedom

A beautiful property of QCD is that it only depends on one parameter, the coupling α_s. Its strength depends on the momentum transfer, so strong at low momenta- large distances



Large distance small distance

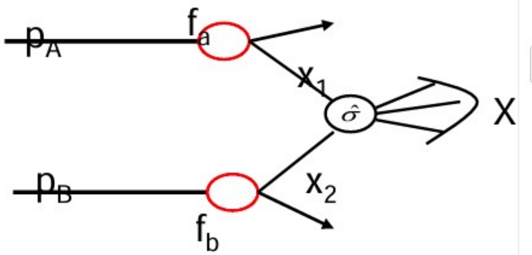


Quarks are almost free inside the hadrons (asymptotic freedom), but as they are separated in high energy collisions the binding energy between them increases until it can produce a new quark-antiquark pair, creating new hadrons

Parton Distribution Functions

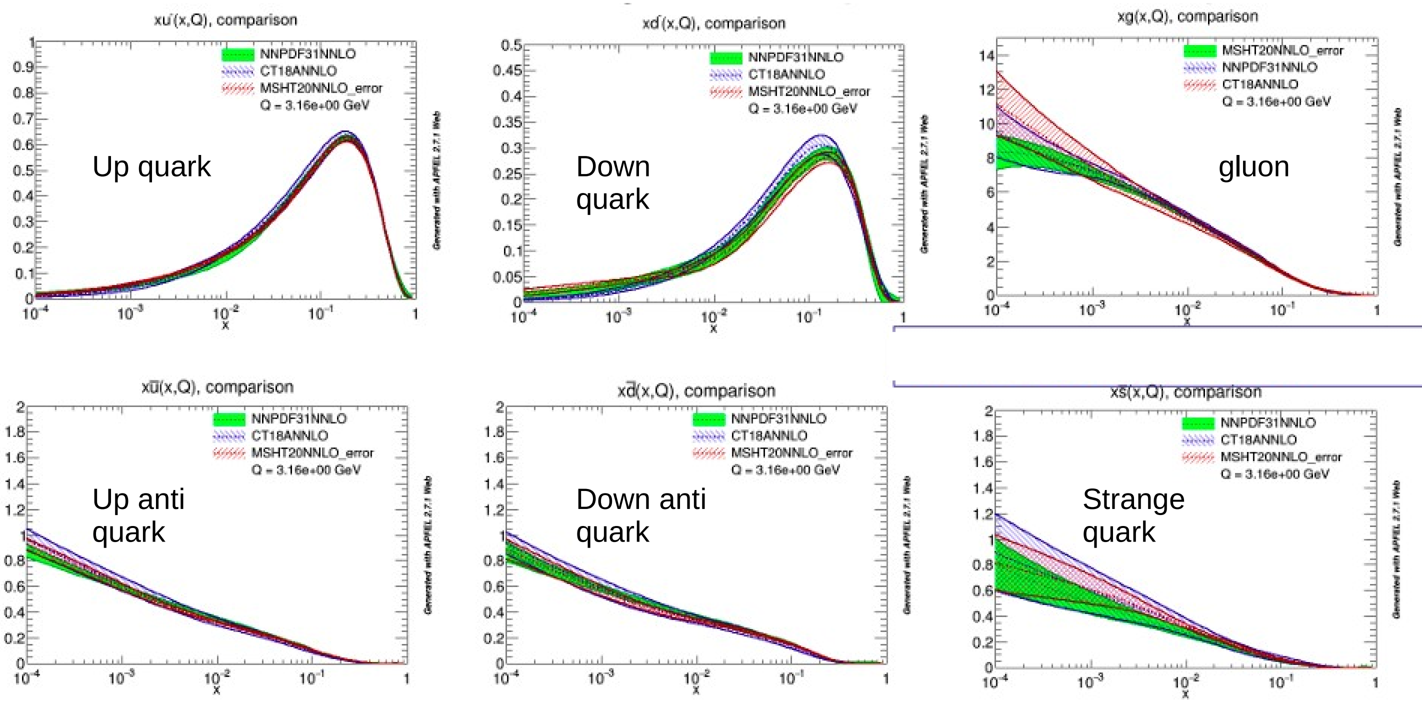
When we collide two protons, we really collide quarks and gluons (partons) within them. The cross-section is a convolution between the probability that the partons produce that final state, and the probability of having partons of that momentum fraction.

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) \, f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$



These probabilities are called Parton Distribution Functions, and are extracted from experimental data

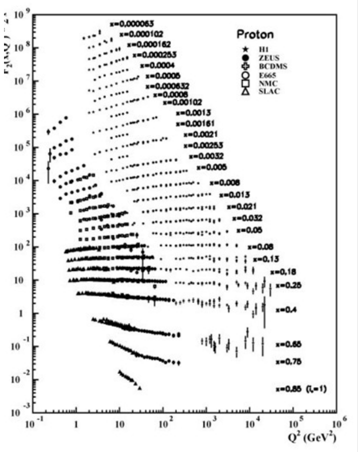
Most of LHC collisions come from low-momentum gluon interactions



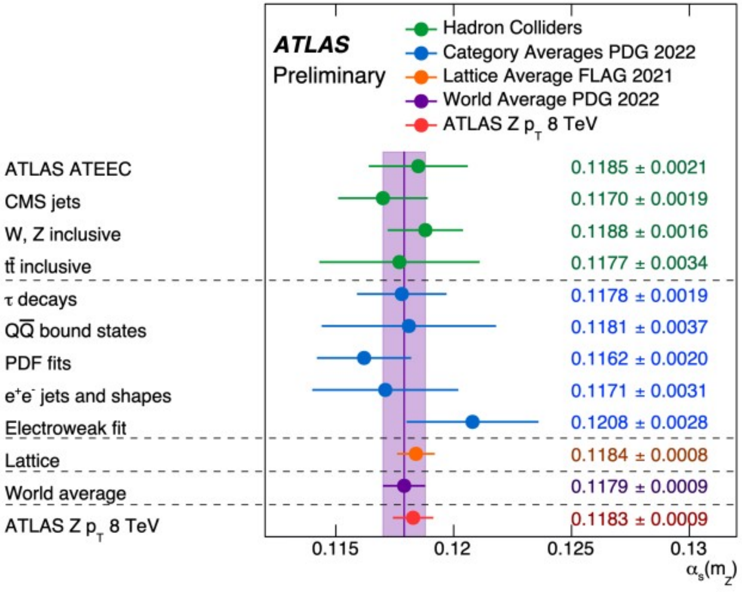
Measuring PDFs and α_s

We cannot predict PDFs from first principles, but symmetry considerations lead to an empiric formula whose parameters are fit from data

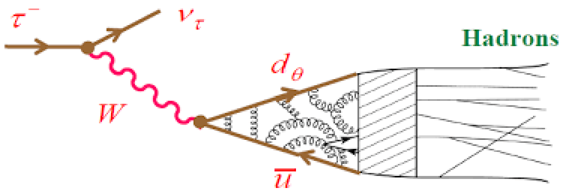
$$f(x) = x^{(a_1 - 1)}(1-x)^{a_2} e^{a_3 x}[1 + e^{a_4} x]^{a_5}$$

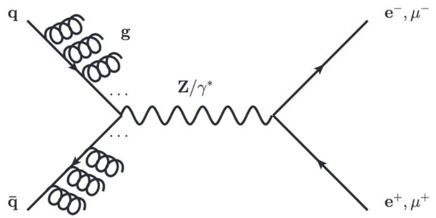


Data used range from ep Deep Inelastic Scattering (from HERA) to jet cross sections to angular distributions in W and Z production

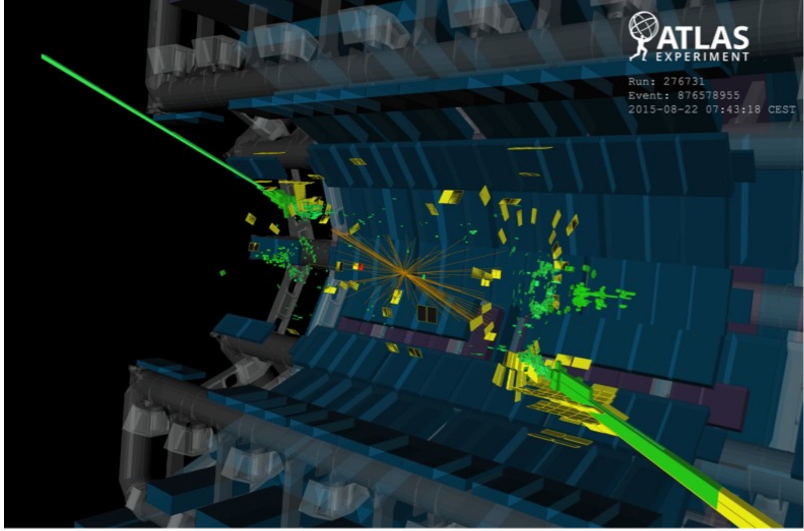


Similarly, the coupling constant of the strong force is measured fitting data taken at different energy scales, from hadronic tau decays to Z boson momenta, and accounting for the "running" of the parameter vs momentum transfer
Simultaneous fits of PDFs and αs are also performed

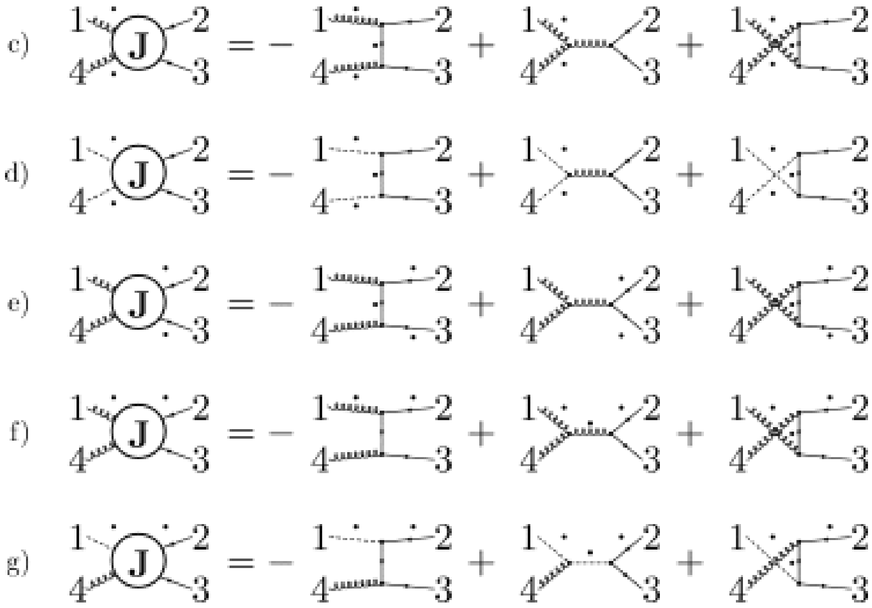




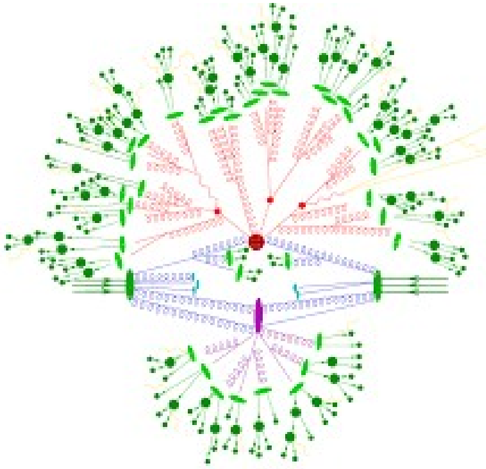
Jet production



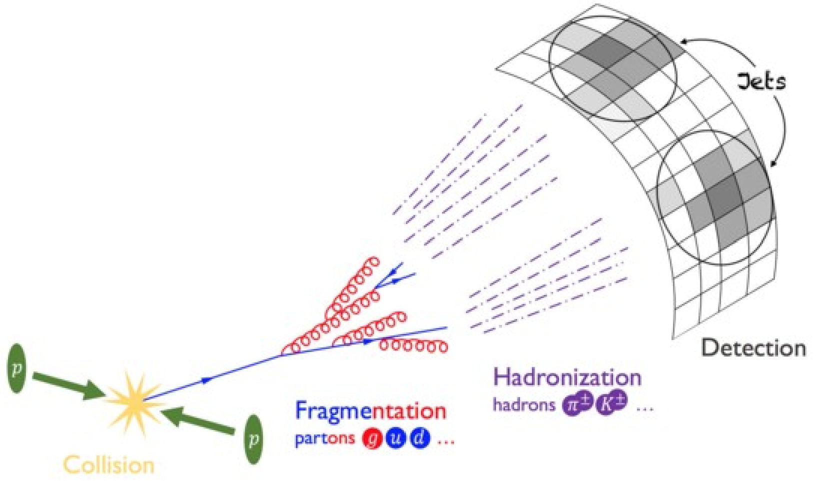
Most common process at the LHC is production of low-energy hadrons (MinBias), and at higher energies they are reconstructed into jets using dedicated clustering algorithms



Jet pairs can be produced in qq, qg or gg interactions, and additional gluon radiation can produce multijet events



Jet reconstruction and measurements



After hadronisation, particles are measured by tracker and calorimeter.

A particle-flow algorithm combines tracking and calorimeter in an optimal way to produce particle candidates.

Particles are clustered using an iterative procedure merging those close in terms of metric

constituent pT — angular separation

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \qquad d_{iB} = k_{ti}^{2p}$$

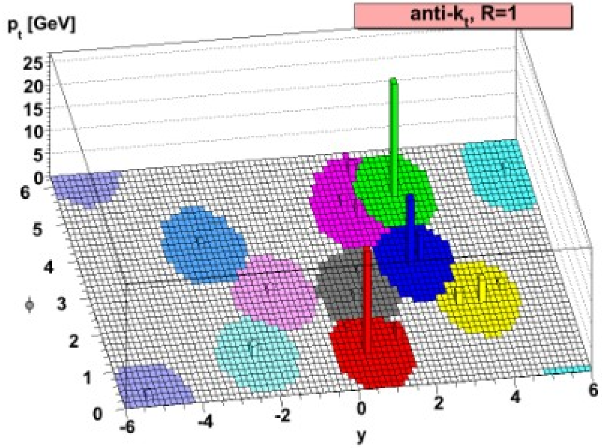
Radius parameter — "Beam distance"

indices *i* and *j* run over all candidate jet constituents

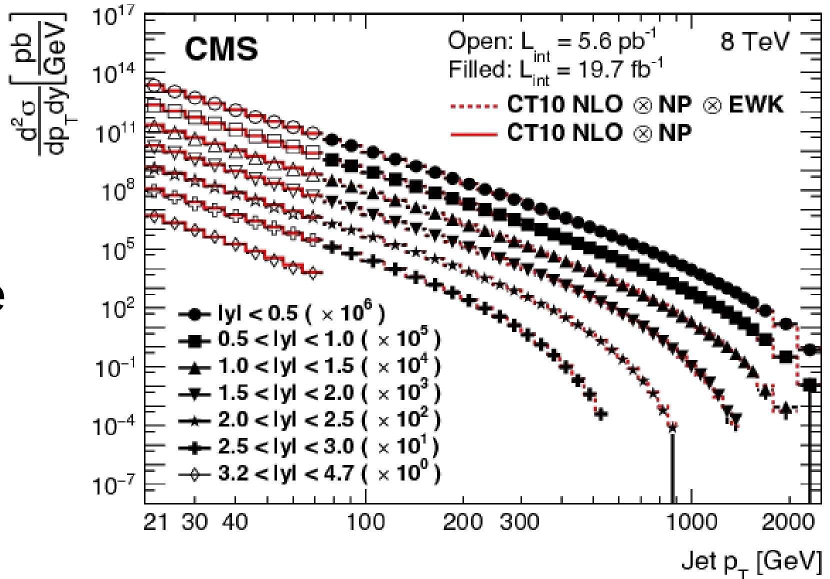
p = 1 : k_t algorithm

p = 0 : Cambridge/Aachen algorithm

p = -1: anti-k_t algorithm



Inclusive jets: cross-section: each jet in the event in a given pT and y range



Jet tagging

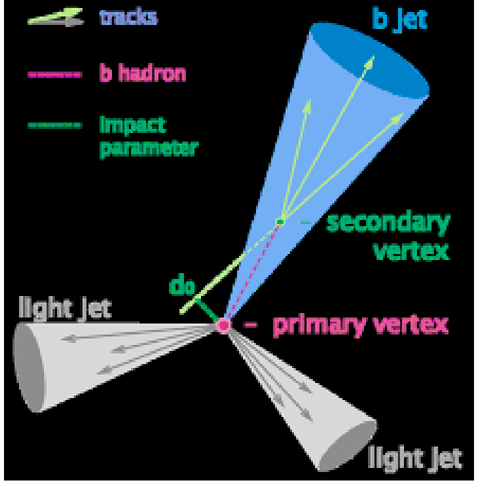
Not all jets come from light quarks or gluons.

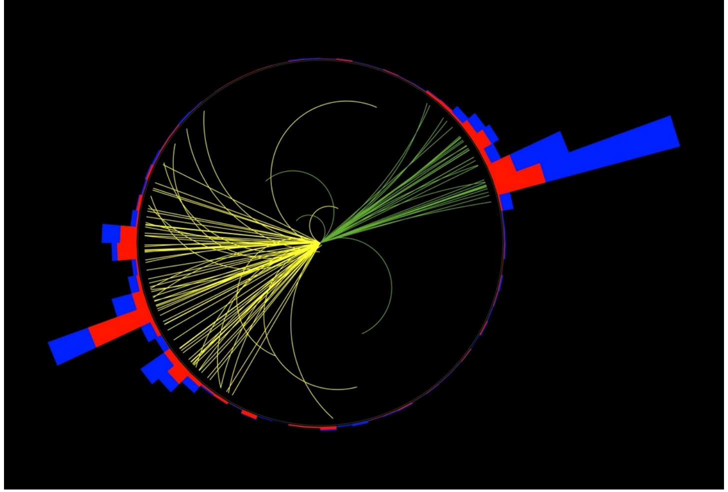
B-quarks have a lifetime of a few ps and can travel a few mm before decaying, producing a secondary vertex.

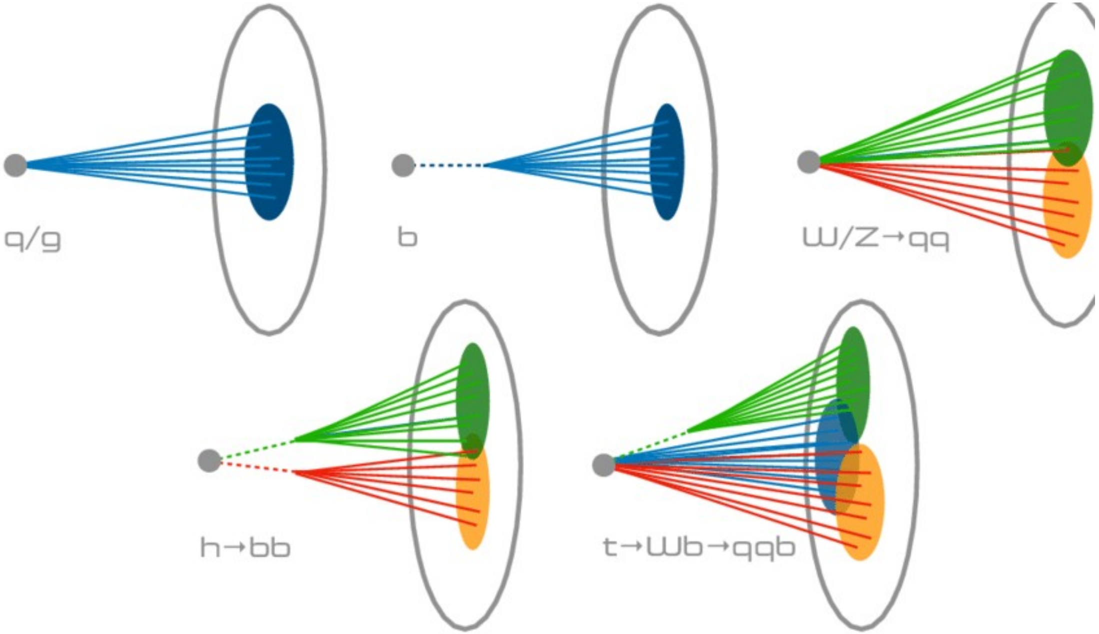
Energetic W bosons can decay into 2 nearby jets, reconstructed as a single jet with 2 prongs

Energetic top quarks decay into a b and a W, with 3 prongs

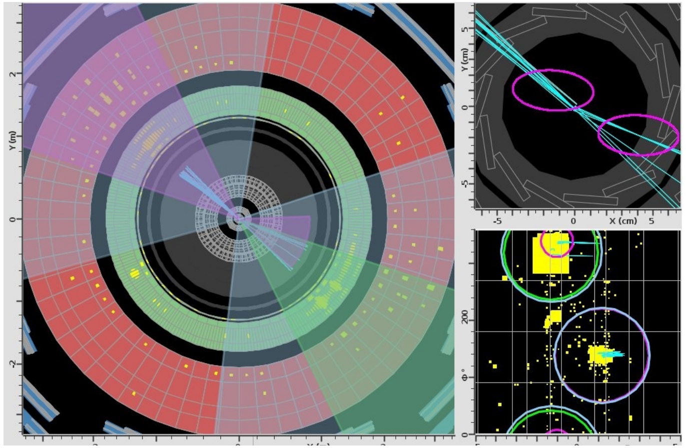
Looking at secondary vertices and at the jet internal structure can help distinguish these cases

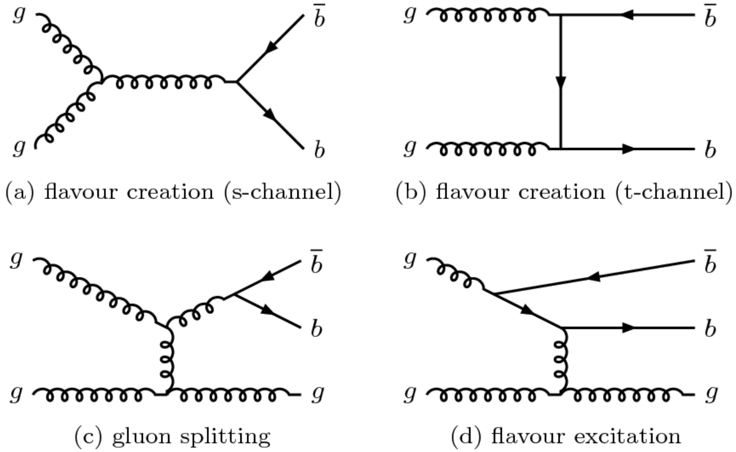




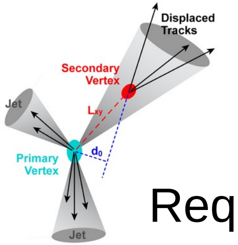


B jet production at the LHC

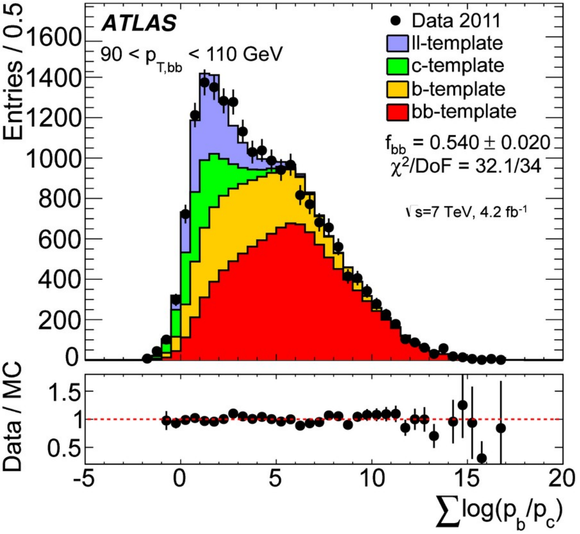




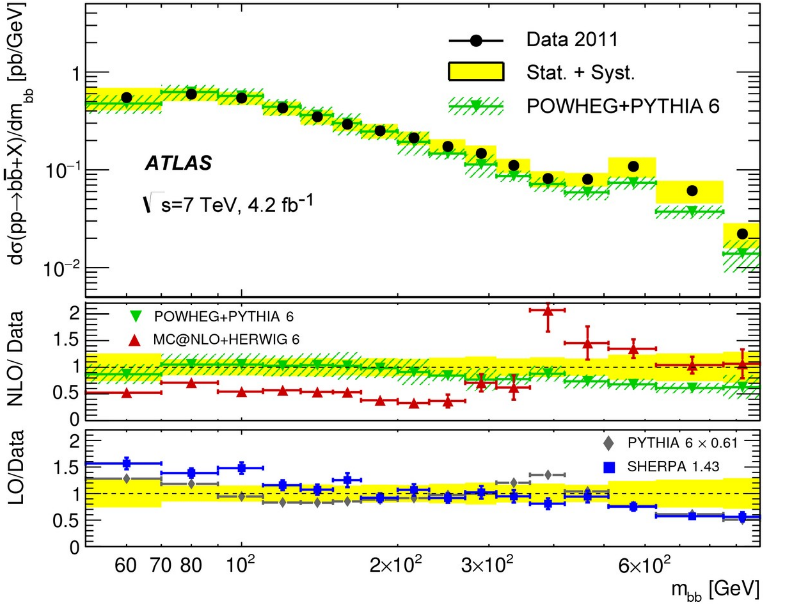
4 main production mechanisms



Request b-tagging

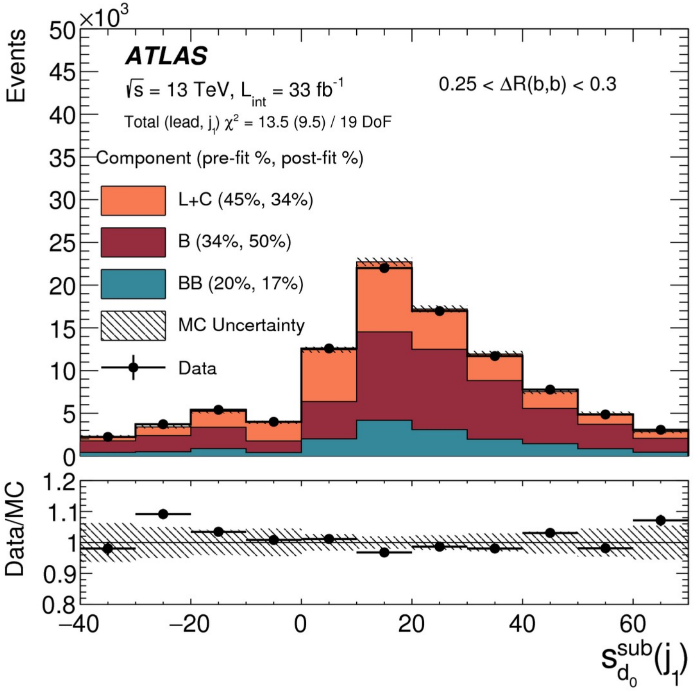


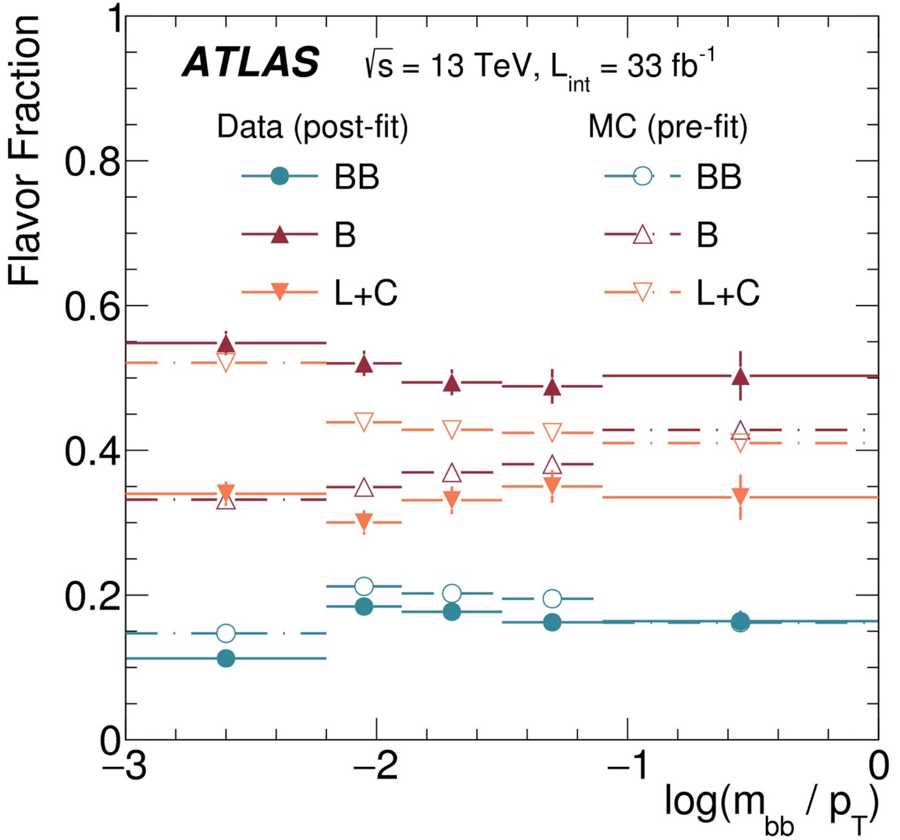
Use vertex mass and distance to distinguish bb, b, c and light quarks in jet



Invariant mass of two jets each identified as b

$g \rightarrow bb$ splitting with both b in a single jet

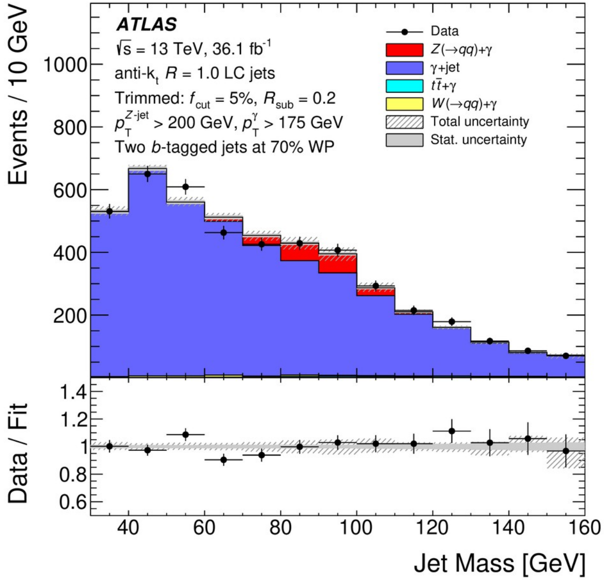


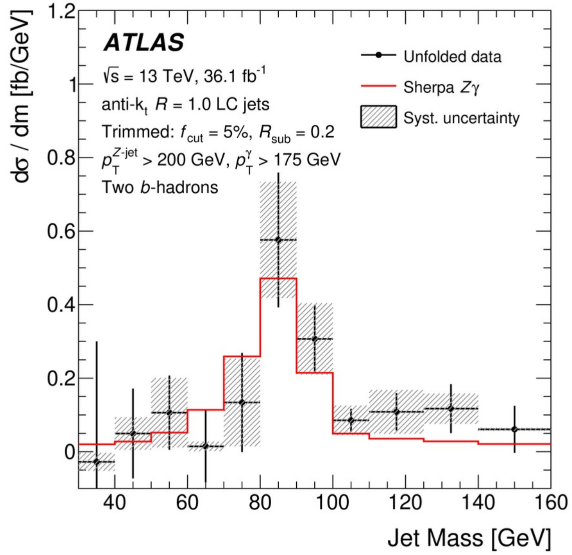


Study composition of jets by fitting separately each bin and compare to theory

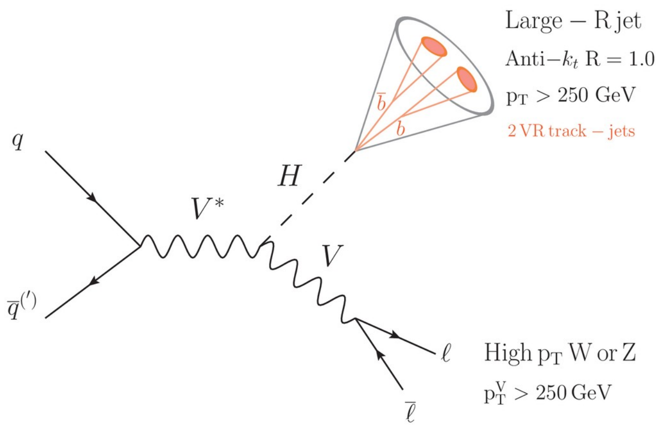
Boosted Z → bb in a single jet

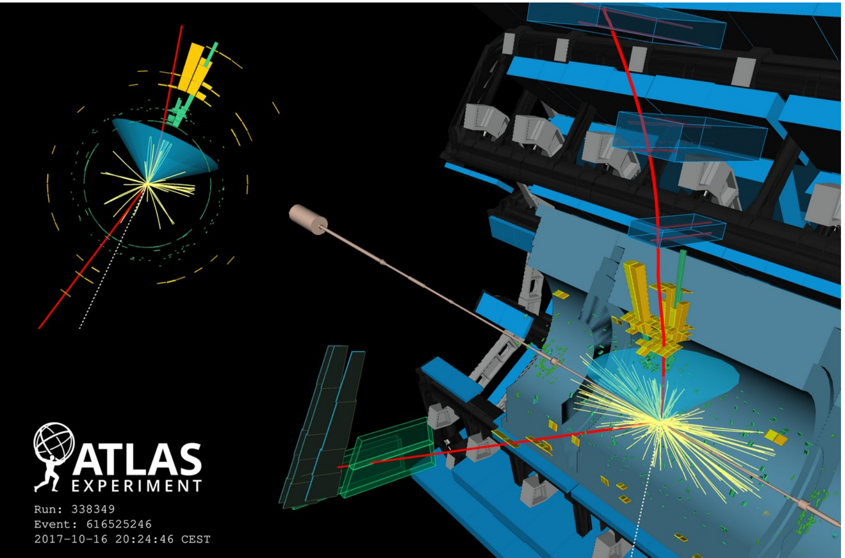
- To reduce BG, require production of a photon and a very energetic Z decaying into bb
- Being very energetic, the Z->bb is reconstructed as a single jet
- The jet must have:
  - a two-prong structure
  - two displaced vertices
- Z peak visible in the jet mass despite huge background





Boosted Higgs->bb





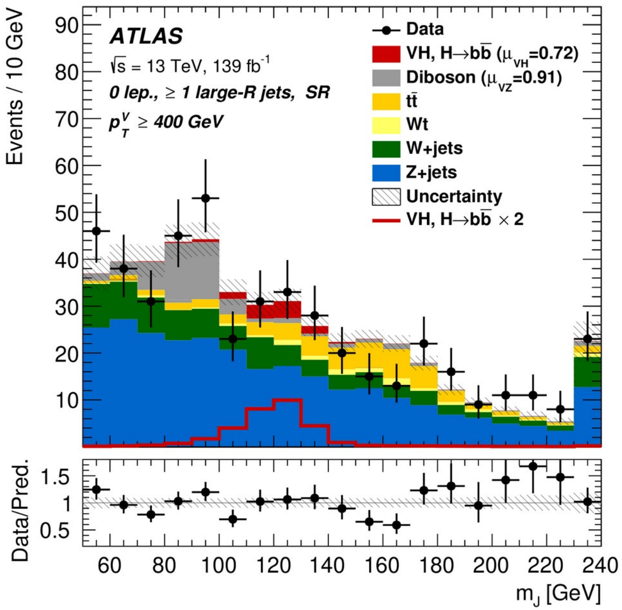
The Higgs coupling is proportional to the mass squared, so the largest decay probability is in 2 b-quarks final states

This decay mode suffers from large BG from b quarks produced in normal strong interactions (see above)

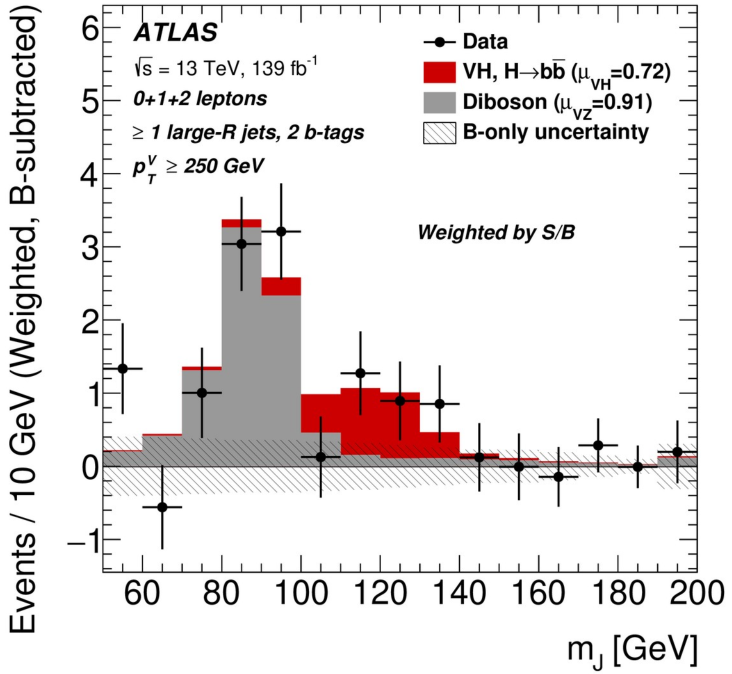
To reduce BG, search for b-jets produced in association with a W or Z boson (associate production)

Since signal/BG ratio improves with Higgs pT, we only look at cases where the Higgs is boosted: its decay products are reconstructed in a single jet with a 2-prong sub-structure

Results for H->bb



- Events divided in 6 categories:
  - 0, 1 or two leptons
  - Medium- or high jet pT



Background estimated from data and subtracted.
Then the various categories are combined in an optimised way.
First observation of the main decay mode of the Higgs boson!

Heavy Quark decays: 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 $m_Q \gg \Lambda_{QCD}$ 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 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:

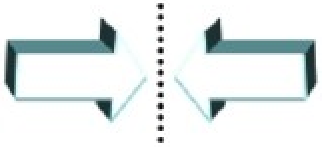
- Parity
- Charge conjugation
- Time reversal

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.



$$\mathbf{r} \to -\mathbf{r}$$

$$\mathbf{p} \to -\mathbf{p}$$

$$\mathbf{L} \to \mathbf{L}$$

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

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

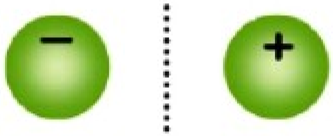
- Vectors change sign under a $\mathcal{P}$ transformation, pseudo-vectors or axial-vectors do not.

- $\mathcal{P}$ 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: 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.*



$e^- \to e^+$

$\gamma \to \gamma$

- Change particle into antiparticle.
  - *the choice of particle and antiparticle is just a convention.*
- $\mathcal{C}$ 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: $\mathcal{C}^2=1$.

Combining Charge and Parity: CP

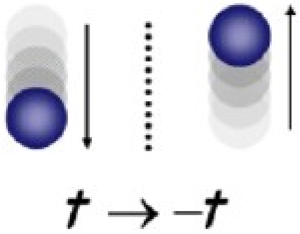
The fundamental point is that CP symmetry is broken in any theory that has complex coupling constants in the Lagrangian which cannot be removed by any choice of phase redefinition of the fields in the theory.

- Weak interactions are left-right asymmetric.
  - *It is not sufficient to consider $\mathcal{C}$ 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: 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.



Combining all symmetries: 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).*

Applying CP to physical states

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

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.

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

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

- 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 × 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

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

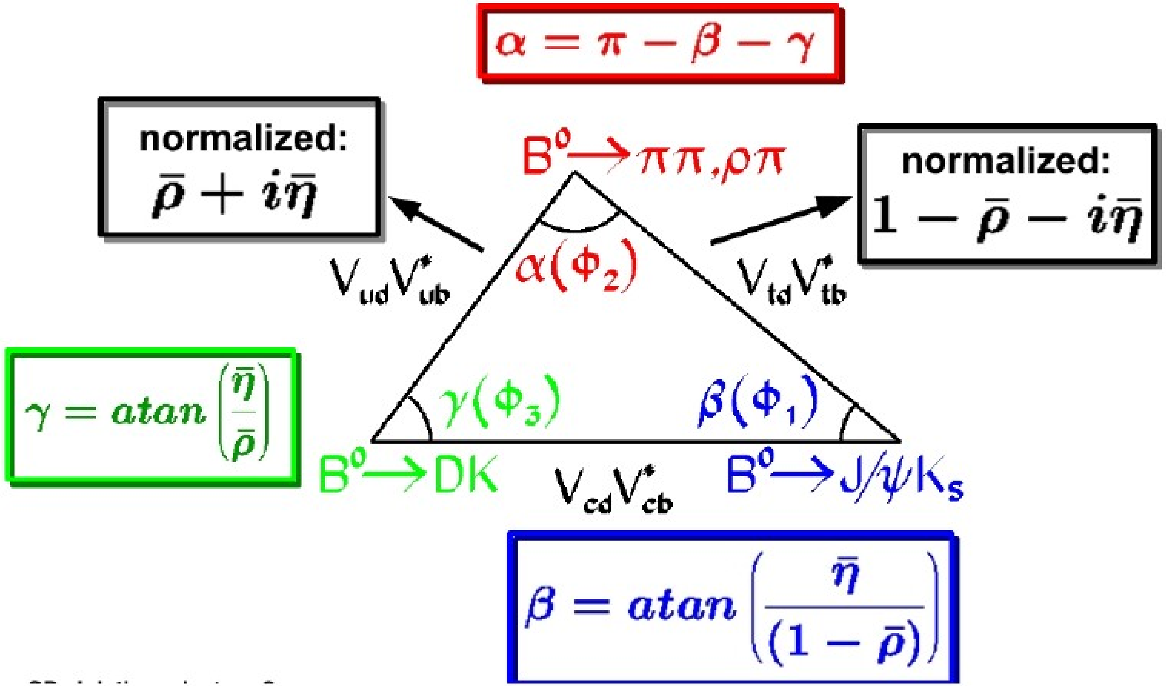
- Experimentally, mixing is larger for nearby generations, $1 \gg q_{12} \gg q_{23} \gg q_{13}$. Wolfenstein expanded in $l = \sin q_{12}$

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

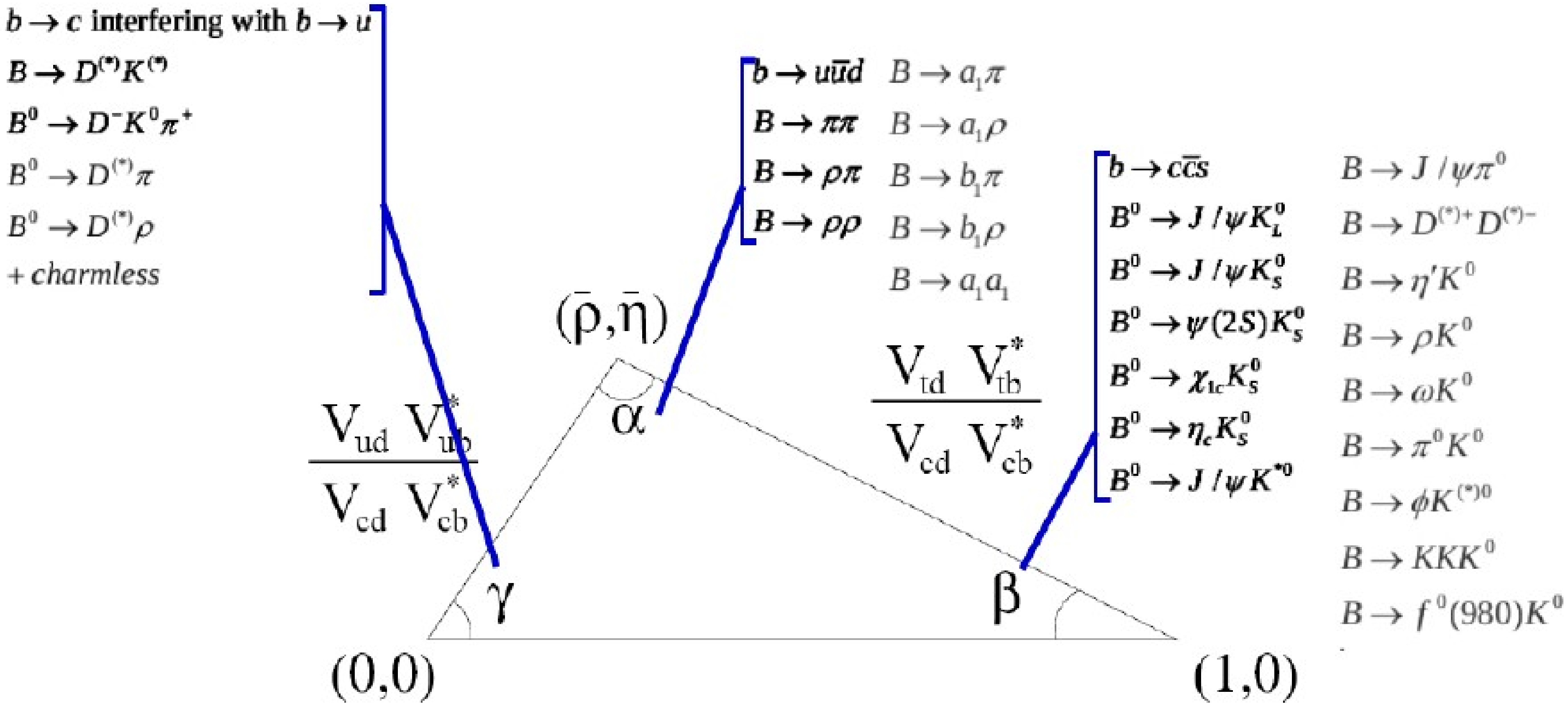
- Diagonal terms ~1, $V_{12}, V_{21} \sim l$, $V_{23}, V_{32} \sim l^2$, $V_{13}, V_{31} \sim l^3$
- At second order, use $r = r\,(1 - l^2/2)$, $\eta = \eta\,(1 - l^2/2)$
- Now the complex component is only in V_{13} and V_{31} (third family!)

The CKM triangle

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

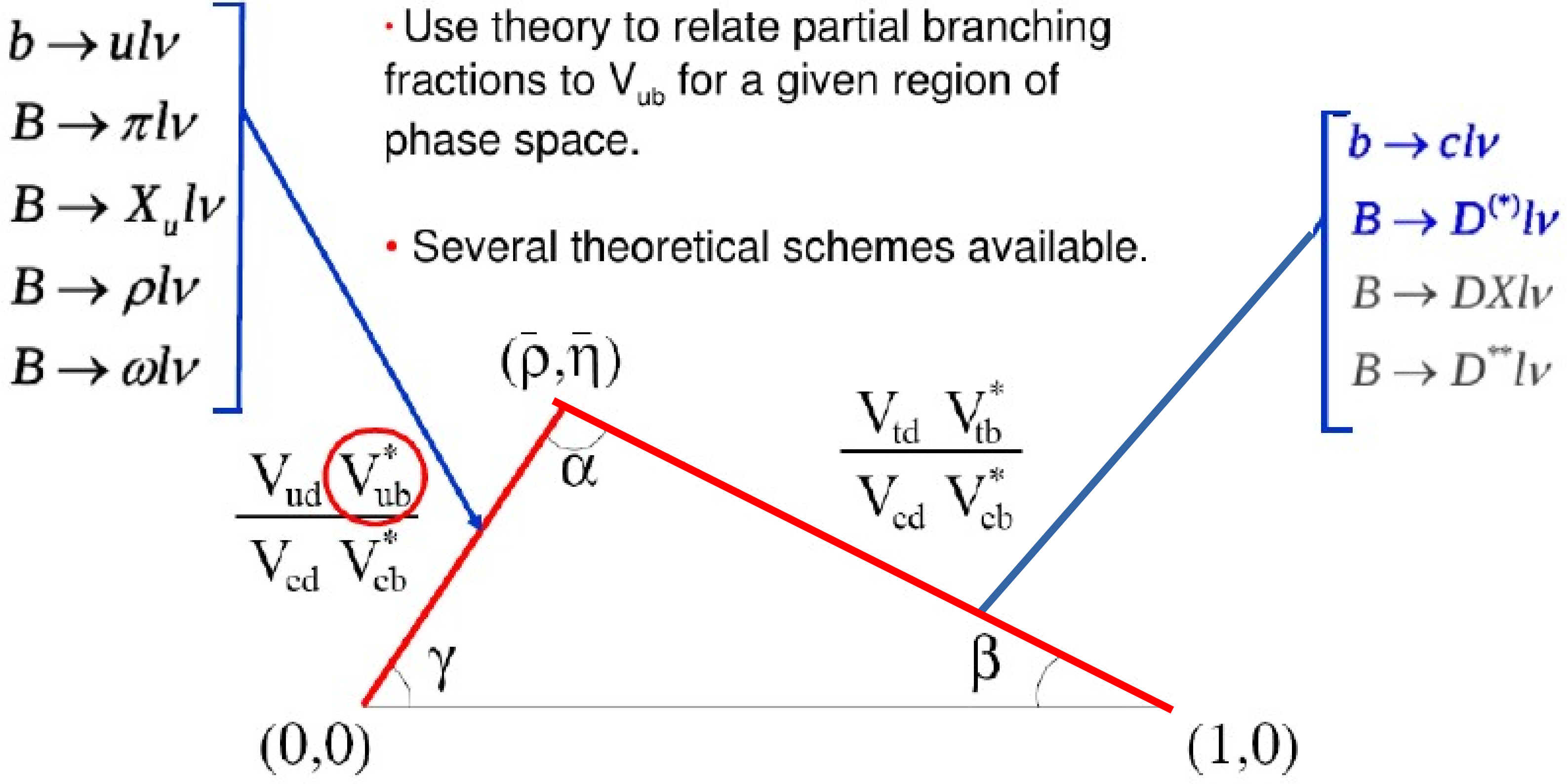


Measuring triangle angles

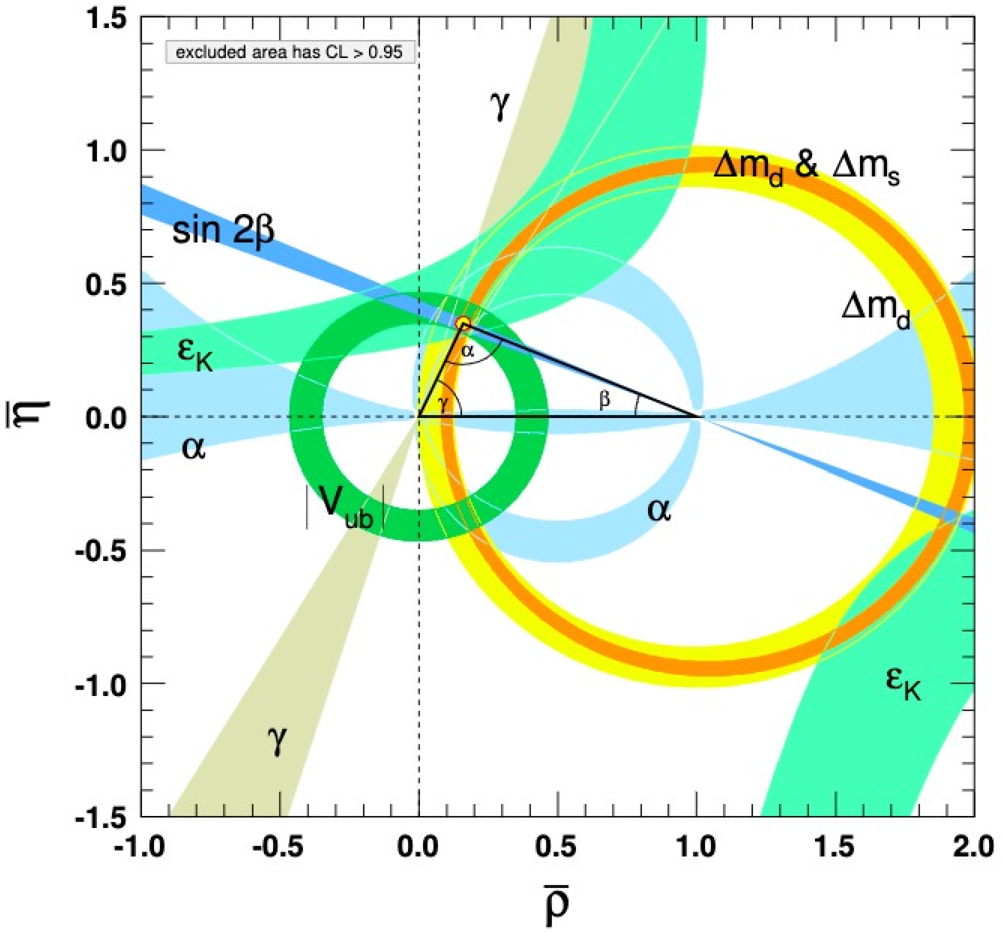


Measuring triangle sides

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



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



Several ways to independently measure sides and angles

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

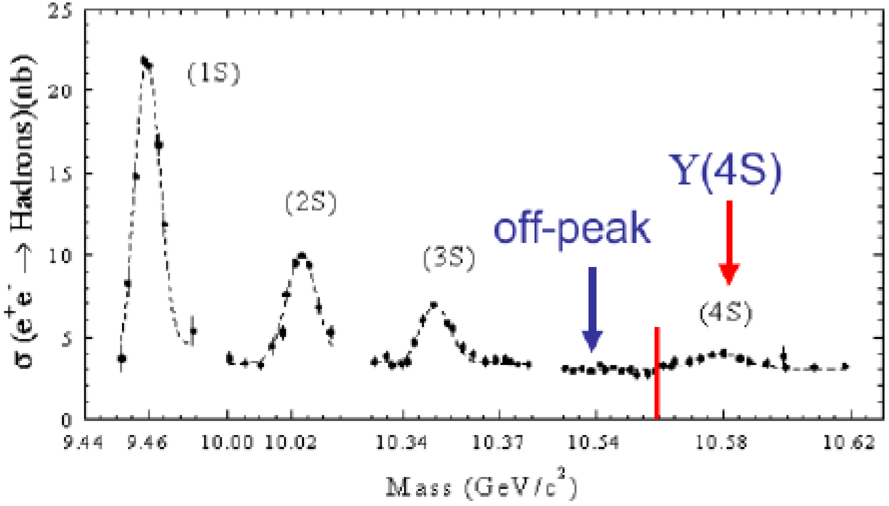
$$|V_{\rm CKM}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix},$$

$$\sin\theta_{12} = 0.22500 \pm 0.00067\,, \qquad \sin\theta_{13} = 0.00369 \pm 0.00011\,,$$
$$\sin\theta_{23} = 0.04182^{+0.00085}_{-0.00074}\,, \qquad \delta = 1.144 \pm 0.027\,.$$

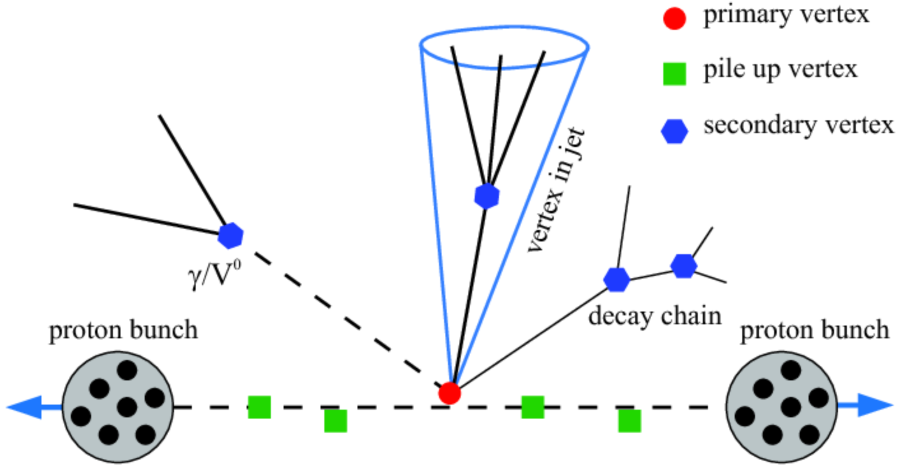
$$\lambda = 0.22500 \pm 0.00067\,, \qquad A = 0.826^{+0.018}_{-0.015}\,,$$
$$\bar\rho = 0.159 \pm 0.010\,, \qquad \bar\eta = 0.348 \pm 0.010\,.$$

Full reconstruction of B mesons

- The “clean” way: e+e- collisions a the Y(4S) peak, followed by decay into B^+B^- or B^0B^0 (Babar, BELLE)



- The “dirty” way: proton collisions followed by b-tagging and invariar mass of final state combinations (LHCb, ATLAS, CMS)
  - Advantages: large rates, can produce Bs, Bc etc.
  - Disadvantages: large BG



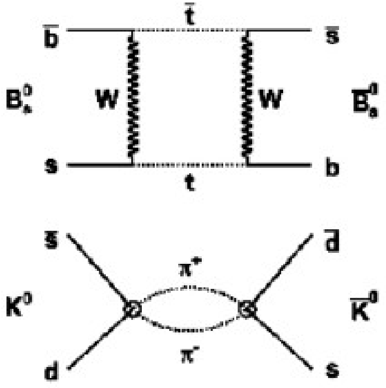
Oscillations of neutral mesons in QM

- 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 ≠ 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	$\neq$	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

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:

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

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

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

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

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

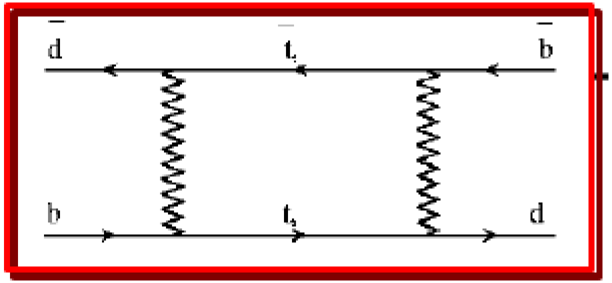
other useful definitions:

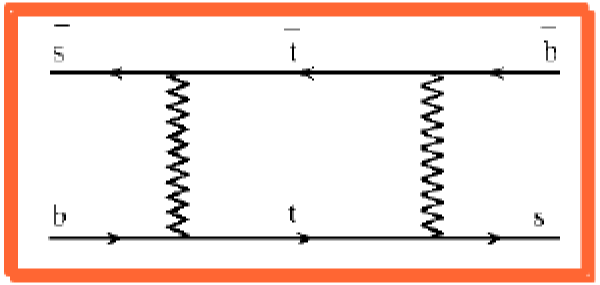
$x \equiv \Delta m/\Gamma$

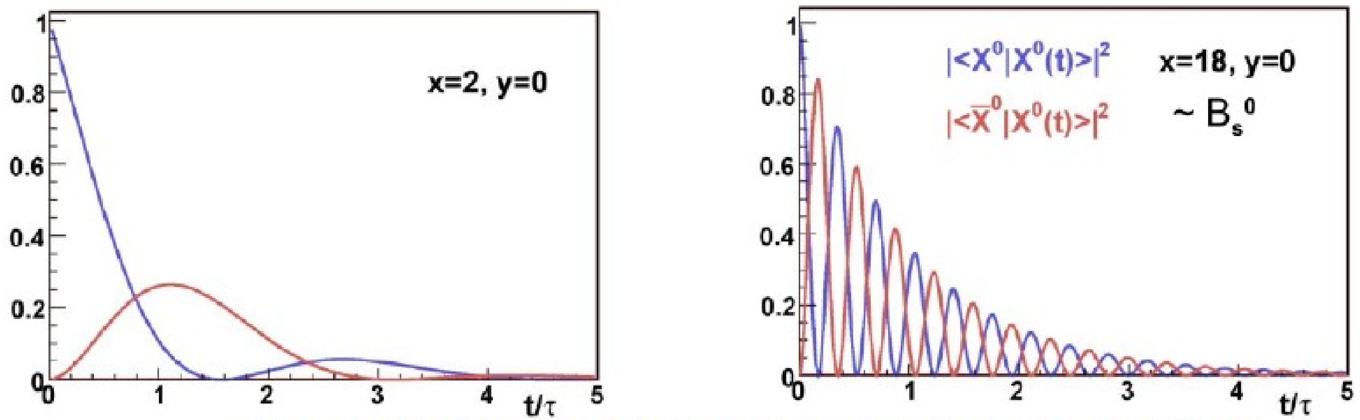
$y \equiv \Delta\Gamma/2\Gamma$

Oscillation probability

- Bd and Bs oscillations formally identical, frequency very different

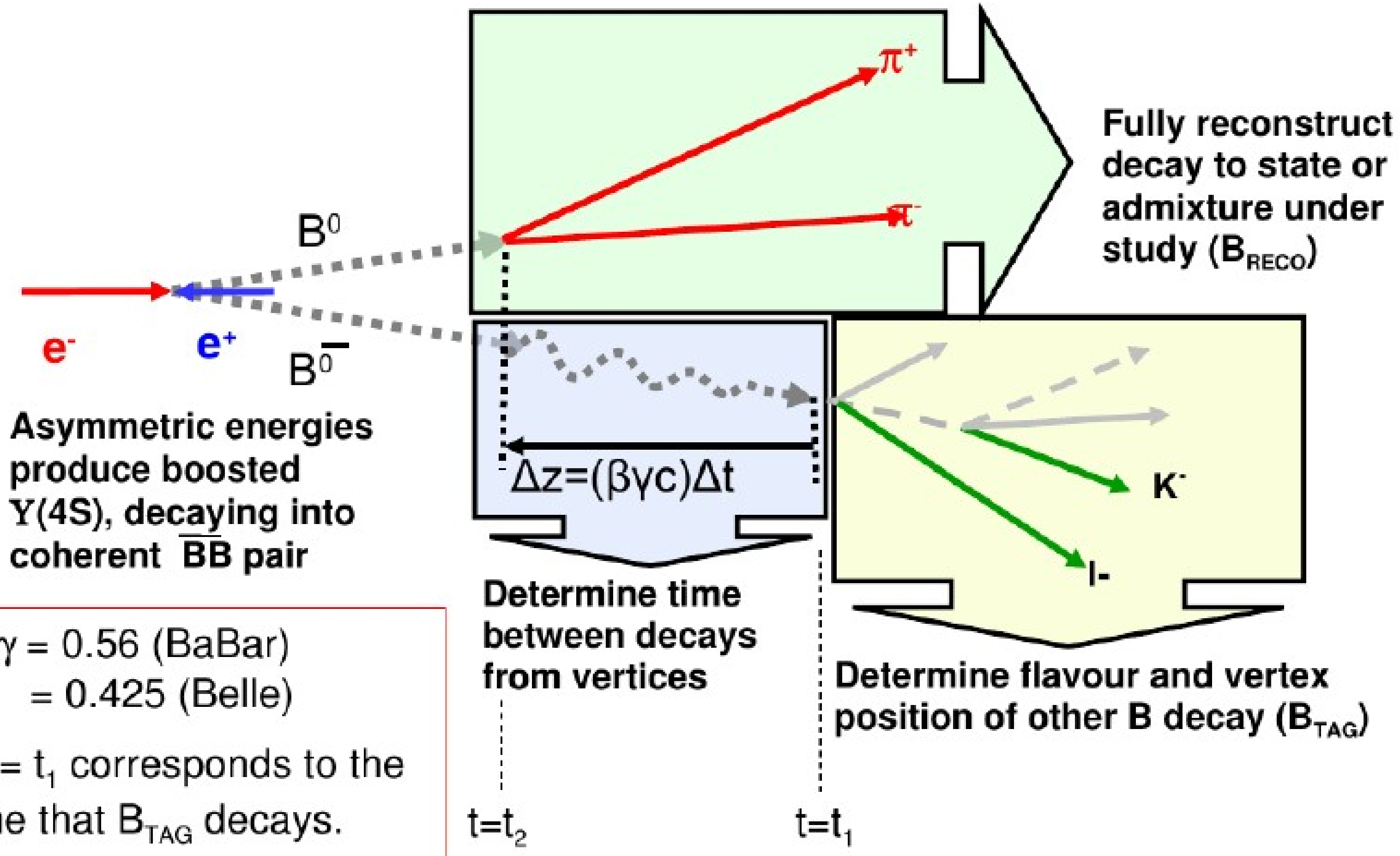






probab. to observe an initially produced X^0 as X^0 after time t
probab. to observe an initially produced X^0 as $\overline{X}^0$ after time t

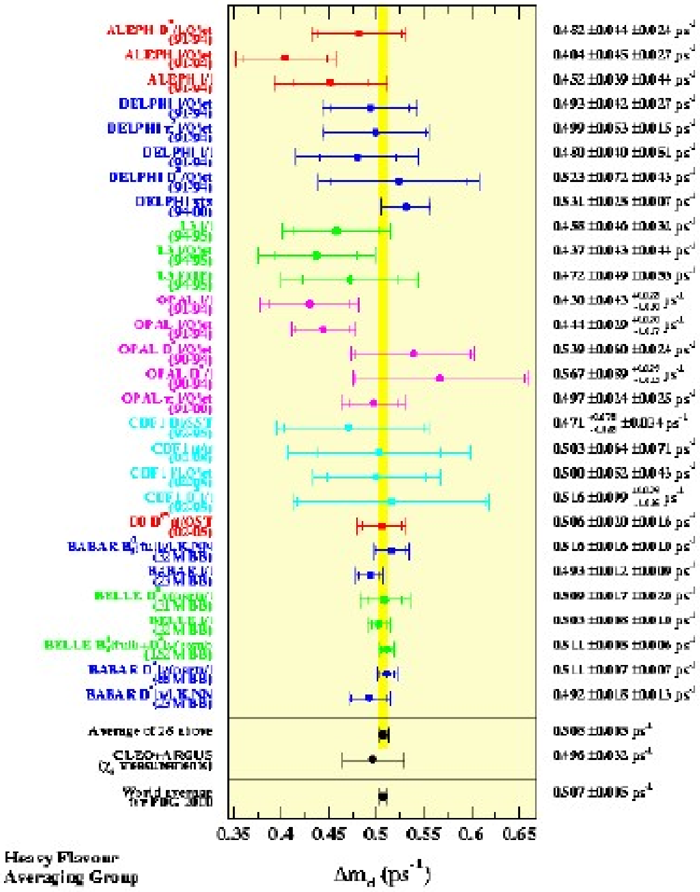
Oscillations in e^+e^- collisions



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

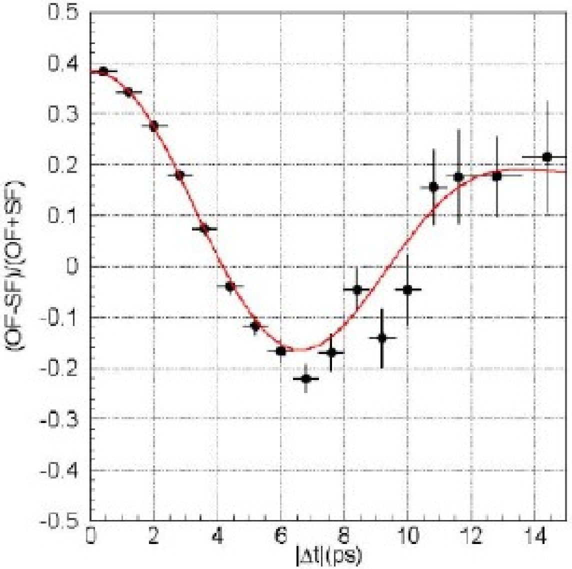
Bd oscillations

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



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

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



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

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

Bs oscillations

At the Tevatron on the B_s:

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

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

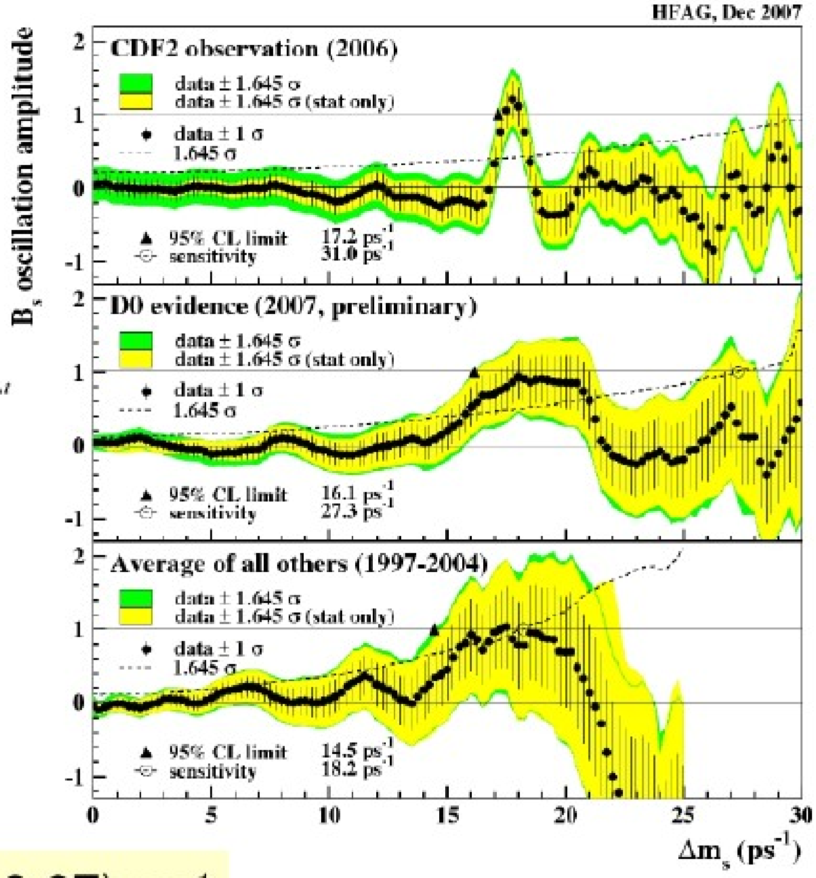
► fit A at different values of Δm_s; if A=1

⇨ oscillations at this Δm_s value

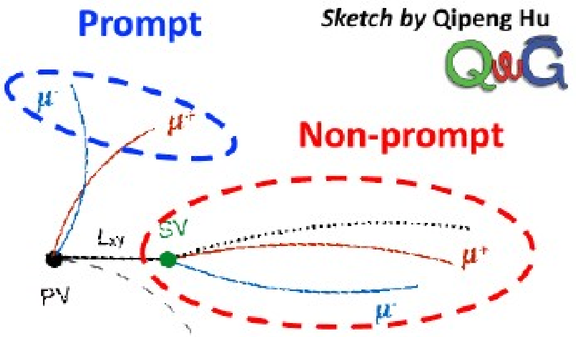
Very precise determination from the Tevatron:

$\Delta m_s=(17.77\pm0.10\pm0.07)\ ps^{-1}$

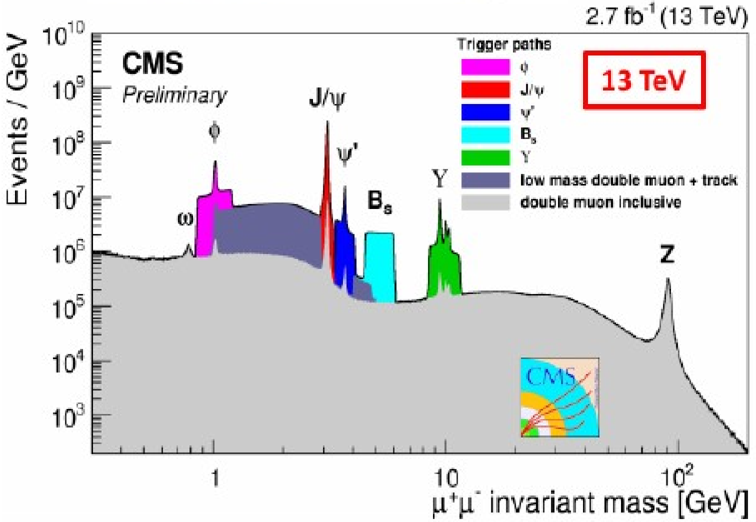
$x=\Delta m_s\cdot\tau_{Bs}= 25.5\pm0.6$

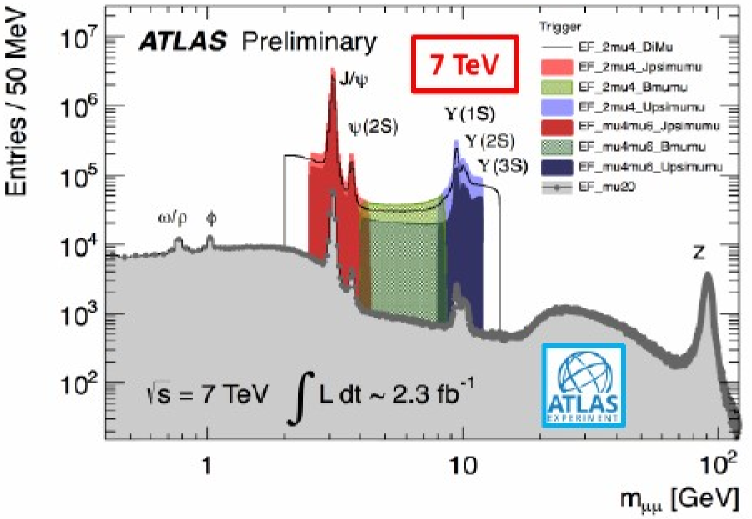


ATLAS and CMS: production of heavy quark-antiquark systems



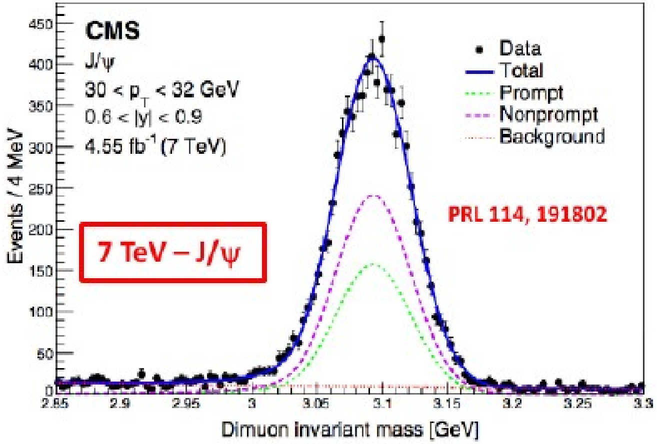
- **For both ATLAS and CMS** experiments, **dimuon decays provide a particularly clean signature to trigger on** in order to reconstruct **quarkonium states**

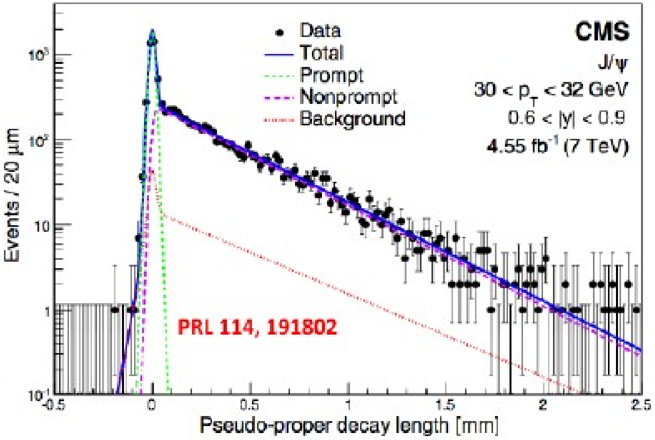


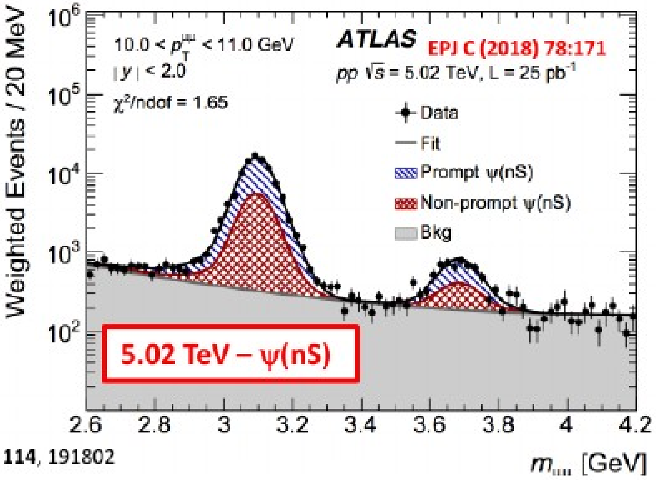


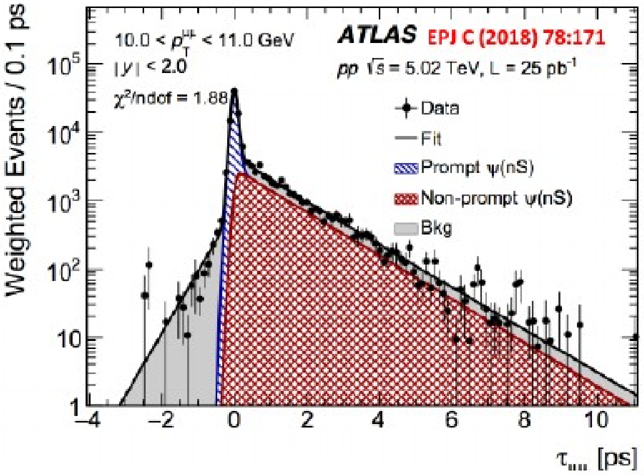
Prompt-non prompt quarkonia

- 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***.



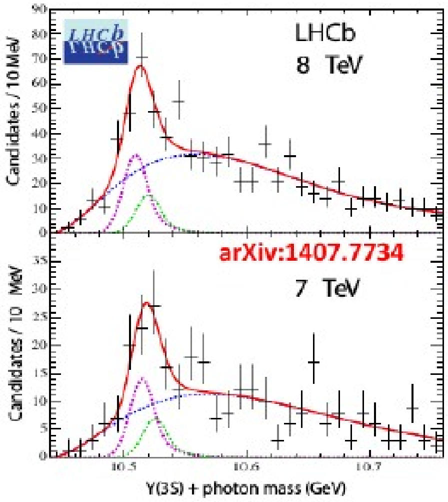




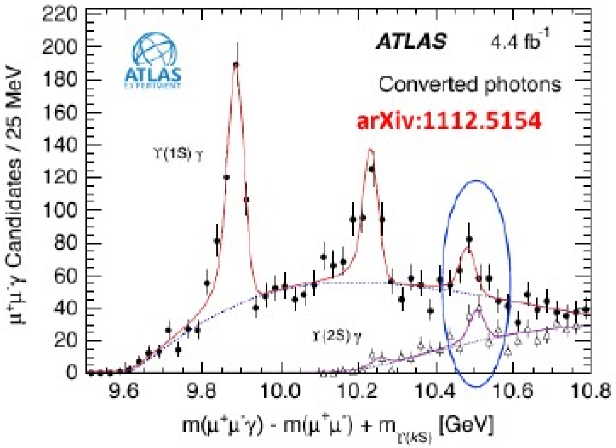


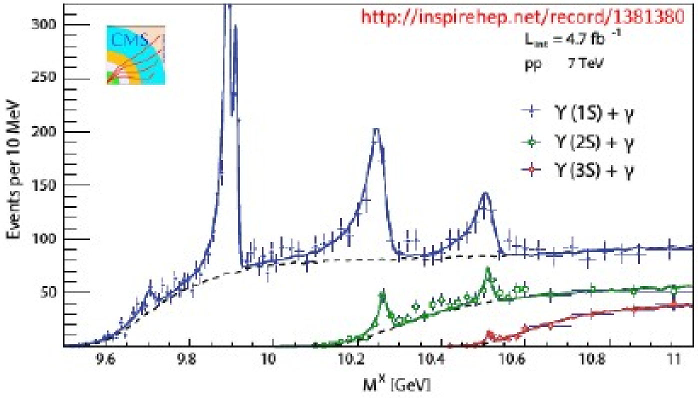
[1] PRL **114**, 191802

Observations of bottomium systems

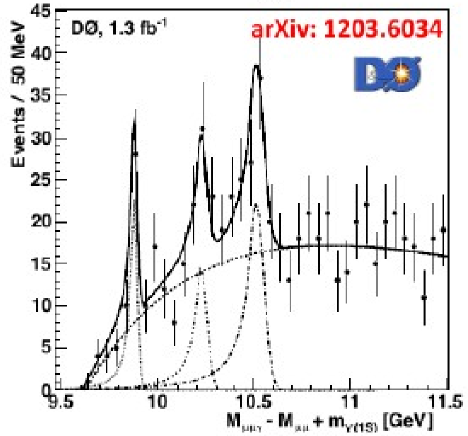


- The $\chi_b(3P)$ was observed by **ATLAS** in **2011** as a new structure in the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decay modes.
- **LHCb** observed the $\chi_b(3P) \rightarrow \Upsilon(3S)\ \gamma$ decay channel.





- **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 Υ(1S), Υ(2S), and Υ(3S) radiative decays, in the 7 TeV data



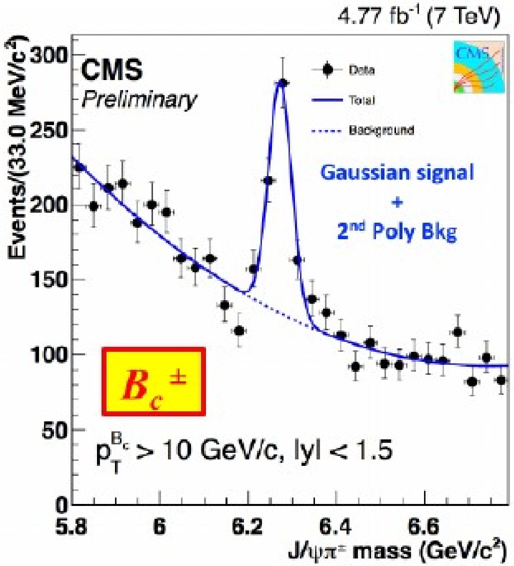
Mesons with beauty and charm: Bc

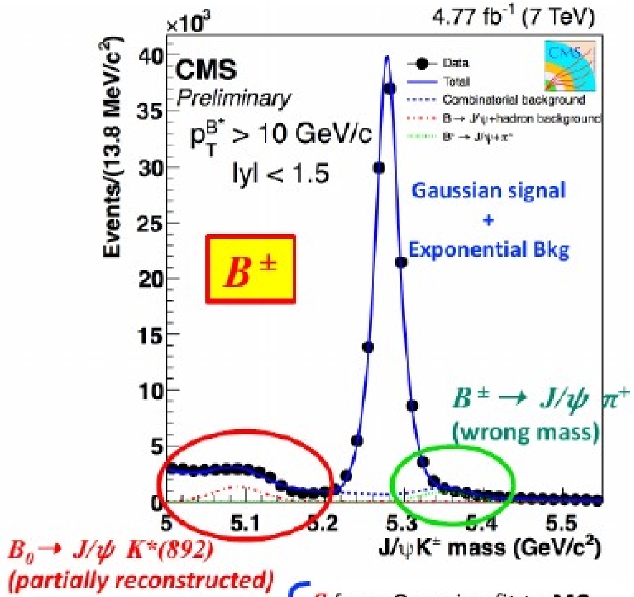
- **B^+ (B^-)** is the b-quark meson with the largest production rate composed of $u\bar{b}(\bar{u}b)$. **B_C^+ (B_C^-)** meson is a ground state of $\bar{b}c(b\bar{c})$ system and contains **two** heavy quarks of **different flavours** and its production **is then much rarer** $[\bar{b}b + \bar{c}c]$.
  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 $[S/\sqrt{(S+B)}]$

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

Conclusions

Proton collisions are really collisions between quarks and gluons, so Parton Distribution Functions fundamental to interpret the results

Strong interactions are everywhere at the LHC, and jets are produced either alone on in association with many other objects

Using secondary vertices and/or jet substructure it is possible to measure jets from b-quarks, t-quarks or bosons (even Higgs)

Heavy quarks a fundamental “laboratory” due to large mass (perturbative calculations) and long lifetime

CP-violating effects particularly relevant in third family

Dedicated experiments (and accelerators!) built to extensively study quark mixing, all coherent with SM picture