Lecture on
heavy flavor physics
& rare decay searches

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N. Leonardo’s introduction

- **Under-graduate: LEFT/IST**
- **Graduate: MSc Cambridge, PhD MIT**
  - CDF experiment @ Fermilab’s Tevatron
    ➠ the most powerful collider then
  - discovery of $B_s$ particle-antiparticle oscillations
    (doctoral thesis)
- **Post-graduate: CERN, Purdue**
  - CMS experiment @ CERN’s LHC
    ➠ the most powerful collider now (and next decades’)
  - discovery of sequential meson melting in QGP
  - discovery of $B_s \rightarrow \mu\mu$ rare decay
  - CMS Trigger Performance and Validation coordinator
- **PI Researcher, LIP**
  - CMS heavy Flavor physics group coordinator
LHC goal: find **New Physics** beyond the SM

**Path A**

BSM particles directly produced in collision (provided NP scale ~ few TeV)

**the direct way**

search for

- $Z'$
- SUSY
- extra dimensions
- other Exotica objects

**Path B**

BSM particles modify SM processes via Quantum mechanical effects

**the indirect way**

measure

- Higgs
- electroweak
- top quark
- $b$ hadron properties

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constraining the theory

Standard Model

\[ SU(3) \times SU(2) \times U(1) \times \ldots \]

Strong sector

Electroweak sector

New sector

HF production & suppression

HF decay (mixing, cpv, ...)

Rare decays

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rare and not-so-rare decays
LHC: measurements & searches

Impressive amount of sophisticated measurements exploring fantastic and unique data.
LHC discovery flagships

a 4-decade search effort... ended in 2012: **Higgs** by ATLAS & CMS

a 3-decade search effort... ended in 2015: **B_s → μμ** by CMS & LHCb
Contents

1. LHC: status & highlights

2. motivation

3. detection

4. production

5. suppression

6. lifetime

7. tagging & mixing

8. CP violation

9. rare decays

Selected highlights.

NP scale, puzzles, CKM, unitarity, global fits

displaced topology, LHC as a HF factory

cross section, polarization, spectroscopy

melting and energy loss in QGP

proper time bias and resolution

flavor tagging techniques, dilution factors, oscillation frequency

in decay, mixing, and interference

as New Physics probes, FCNC, LFV
the role of flavor physics

- in searching for **New Physics**
  - discovery potential beyond energy frontier e.g. via searches for rare processes
- in understanding why the **SM** appears so fundamental
  - in that no phenomena beyond the SM has (yet) been detected at LHC
- in learning about standing mysteries of the **flavor structure** of SM (and BSM)
- in connecting **CP violation** to the matter-antimatter asymmetry in the observable universe
- in understanding **QCD**, and probing the properties of **deconfined** matter at high temperature and density
- extra: as an experimental tool & probe
  - serve as probe or a **dominant background** in SM measurements and BSM searches
  - used for **detector calibration** (e.g. material budget, magnetic field, detector performance)
indirect discovery via precision

- new physics can show up at precision frontier before energy frontier
  - kaon (1947), $\Lambda^0$ (1950) led to discovery of strangeness
  - neutral current (1973) before discovery of $Z$ (1983)
  - precision W and t mass meas. constrained Higgs mass, etc!

1970
GIM mechanism
(Glashow–Iliopoulos–Maiani)
required the fourth quark: Charm
e.g. $K^+ \rightarrow \mu^+\nu_\mu$ so why not $K^0 \rightarrow \mu^+\mu^-$?

1974
$J/\psi$ meson discovery
(SPEAR+AGS)

1977
$\Upsilon$ meson discovery
(E288)

1973
3rd quark generation predicted
bottom and top
by Kobayachi and Maskawa
to explain observed CP violation
(discovered in 1964 in the kaon system)

bottom line: historically, precision measurements at lower energies predicted the existence of new, heavier states
«flavor» physics?

- the SM flavor sector arises from interplay of fermion-weak–gauge and fermion-Higgs couplings

Out of the 19 parameters of the SM (excluding neutrino masses/mixing), 14 arise from the flavor sector.
flavor «puzzle»

• there are standing mysteries intrinsic to the SM flavor sector
  ‣ why are there so many free parameters
    ‣ why do these parameters exhibit strong hierarchical structure spanning several orders of magnitude
  ‣ why are there so many fermions
  ‣ what is responsible for their organization into generations
    ‣ and why are there 3 such generations each of leptons and quarks
  ‣ why wide range of fermion couplings and masses
    ‣ for example: $O(10^{-5}) \cdot m_t \sim m_u \sim m_v \cdot O(10^{+6})$, $|V_{ub}| \sim O(10^{-3}) \cdot |V_{td}|$
  ‣ why are there flavor symmetries
    ‣ and what breaks them
  ‣ why is $\theta_{QCD} < 10^{-9}$
  ‣ what is the origin of CP violation

• various solutions to this puzzle have been proposed (but not established), inevitably leading to beyond-the-SM scenarios
  ‣ for within the SM these parameters can only be accommodated, not explained
another, related «puzzle»: BAU
(baryon asymmetry in the universe)

- Sakharov conditions (1967), necessary for dynamical evolution of matter dominated universe from symmetric initial state:
  1. baryon number violation
  2. C & CP violation
  3. thermal inequilibrium
- no significant amounts of antimatter observed
  \[ \Delta N_B/N_\gamma \equiv \frac{[N(\text{baryon})-N(\text{antibaryon})]}{N_\gamma} \sim 10^{-10} \]
- amount of CP violation in SM not sufficient to explain BAU
  \[ \text{CPV in quark sector (CKM) would yield an asymmetry of } O(10^{-17}) \ll 10^{-10} \]
- more CPV is needed!
  - to create a larger asymmetry, require: new sources of CP violation ... that occur at higher energies
- where might it be found?
  - lepton sector: CPV in neutrino oscillations
  - quark sector: discrepancies with KM predictions
  - gauge/higgs sector; extra dimensions or other new physics?
  - precision measurements of flavor observables sensitive to additions to SM
«heavy» flavor?

light quarks: \( m \ll \Lambda_{QCD} \)
- u, d: realm of nuclear physics
- s: rare kaon decays test SM

light charged leptons
- e.g. electric and magnetic dipole moments test SM
- \( \tau \rightarrow \mu\mu\mu \)

neutrinos
- have their own phenomenology, not detected (directly) at LHC

top (not that heavy!)
- the top quark has its own phenomenology (since it does not hadronize)

Study Beauty and Charm quarks
- hidden flavor aka quarkonia: \( \psi \) (cc), \( \Upsilon(bb) \), \( X_{c,b} \); plus exotic \( X,Y,Z \) states
- open charm: D mesons
- open beauty, B mesons (\( B_u, B_d, B_s, B_c \)) and b-baryons (\( \Lambda_b, \Xi_b, \Omega_b \), ...)

note:
- «B physics» refers to study of flavor-changing interactions of b-quark mesons
- some extra focus placed today on \( \Upsilon \) and \( B(s) \) – particularly interesting at LHC
quark masses [higgs]

- A Lagrangian mass term \( m \bar{\psi} \psi \) would break chiral gauge symmetry \( \rightarrow \) not allowed
- Introducing Yukawa interactions with a scalar field, fermion mass terms get generated

\[ -Y \bar{\psi} \psi \phi \quad \longrightarrow \quad \text{spontaneous symmetry breaking} \quad -Y \bar{\psi} \psi (v + \phi') \]

- The mass terms for up- and down-type quarks have the form

\[ \mathcal{L}_M = -\bar{u}^T_R m_u u_L - \bar{d}^T_R m_d d_L + \text{h.c.} \]

- The mass matrices - \( m_u, m_d \) - are not diagonal; may be diagonalized (w/ unitary matrices \( L, R \))

\[ L_u m_u R^T_u = \hat{m}_u \]
\[ L_d m_d R^T_d = \hat{m}_d \]

- Flavor changing interactions in the SM (charged currents) through couplings to \( W^\pm \) bosons

\[ \mathcal{L}_W = \frac{g}{\sqrt{2}} \bar{u}^T_L \gamma^\mu \bar{d}_L W^+_{\mu} + \text{h.c.} = \frac{g}{2\sqrt{2}} \bar{u}^T \gamma^\mu (1 - \gamma^5) V d W^+_{\mu} + \text{h.c.} \]

- The unitary quark-mixing matrix \( V \) is the Cabibbo-Kobayashi-Maskawa matrix

\[ V \equiv L_u L^T_d \]

- Describing quark-flavor mixing

\[ d' = V d \quad \leftrightarrow \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \]
quark mixing [CKM]

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

• CKM: a unitary 3x3 matrix
  † has 9 parameters: 3 rotation (Euler angles) + 6 phases
  † 5 of these phases can be absorbed by making phase rotations of quark fields
  † we are left with 4 independent parameters: 3 angles & 1 (complex) phase
  † in a standard parameterization (Wolfenstein) these are: A, \lambda, \rho & \eta

• one irreducible phase \(\uparrow\) the source of CP violation in the SM

Exercise:
* show that in case of \(N\) generations, unitarity implies \((N-1)^2\) independent parameters, with \(N(N-1)/2\) rotation angles and \((N-1)(N-2)/2\) complex phases
* show that at least three quark generations are required for CP violation
• unitarity of the CKM matrix
  \[ \sum_i V_{ij} V_{ik}^* = \delta_{jk} = \sum_i V_{ji} V_{ki}^* \]
  • e.g. multiplying 1st & 3rd columns
    \[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]
  • may be represented as a triangle in the (\rho, \eta) plane
  • CPV is proportional to triangles’ area

Exercise: show that CKM unitarity yields six triangles
(note: the bs triangle is much squeezed wrt to the bd one, with small area; a large, \beta_{bs}, angle would indicate BSM contributions)
constraining the unitarity triangle

• is the CKM matrix unitary (as expected in the SM)?
  ‣ 4th generation of quarks? New forces? E.g. SUSY?
• over-constrain the UT: measure each side and each angle
  ‣ do all measurements cross at one single point?

![Graph showing constraints on the unitarity triangle with various decay processes]

- **semileptonic B decays**
  \[ B \rightarrow X_{ul}l\nu, D(\ast)l\nu \]

- **CPV in neutral kaons**
  \[ K \rightarrow \pi\pi \]

- **CPV in B → D\*K, D\pi, K\pi**
  angle: gamma (the least well known)

- **Bd,s mixing**
  \[ B_s \rightarrow D_s\pi(\pi\pi), D_s\ell X \]
  \[ B_d \rightarrow D\pi, D(\ast)l\nu \]

- **CPV in B → \pi\pi, \rho\pi**
  angle: alpha

- **CPV in Bd**
  \[ Bd \rightarrow \psi K, D'D' \]
  angle: sin(2β)
example: B meson mixing

→ neutral B mesons undergo spontaneous flavor oscillations between particle and antiparticle!
example: B meson mixing

- the mixing process (and oscillation frequency, $\Delta m_q$) is proportional to the involved CKM matrix elements

$$\Delta m_q = C_q |V_{tb}^* V_{tq}|^2, \quad (q = d, s)$$

- i.e., the ratio of $B_d$ and $B_s$ oscillation frequencies yields a circle centered at the point $(\rho=1, \eta=0)$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{C_d}{C_s} \frac{|V_{td}|^2}{|V_{ts}|^2} = \frac{m_{B_0}}{m_{B_s}} \frac{\xi_{\Delta}^2 |V_{td}|^2}{|V_{ts}|^2}$$

$$\frac{\Delta m_s}{\Delta m_d} = \xi_{\Delta}^2 \frac{m_{B_s}}{m_{B_0}} \left( \frac{1 - \frac{1}{2} \lambda^2}{\lambda} \right)^2 \frac{1}{(1 - \rho)^2 + \eta^2}$$

$$(1 - \rho)^2 + \eta^2 = c$$

⇒ a measured value of $\Delta m_s$ away from $\sim 17.5 \text{ps}^{-1}$ would have been incompatible with the SM
UT fit

\[(1 - \bar{\rho})^2 + \bar{\eta}^2 = c\]

- if \(c\) would be exactly known, the constraint would indeed be a circle
  \[f(\bar{\rho}, \bar{\eta}|c) = \delta((1 - \bar{\rho})^2 + \bar{\eta}^2 - c)\]
- but... there are uncertainties, both theoretical and experimental

- thus \(c\) is described by a probability density function (PDF): \(f(c)\)
- upon employing Bayes’ theorem
  \[\mathcal{L}(\bar{\rho}, \bar{\eta}, c, x|\bar{c}) \propto f(\bar{c}|\bar{\rho}, \bar{\eta}, c, x) \cdot f(c, x, \bar{\rho}, \bar{\eta})\]
- we obtain the PDF for \(\rho, \eta\) as
  \[\mathcal{L}(\bar{\rho}, \bar{\eta}, x) \propto \prod_{j=1,M} f(\bar{c}_j|c_j(\bar{\rho}, \bar{\eta}, x)) \times \prod_{i=1,N} f_i(x_i)\]
  posterior PDF
  constraints
  prior PDF

- integration requires use of numerical and statistical sampling techniques, e.g. Monte Carlo

Exercise: which factor limits the CKM-constraining power of \(B\) mixing; may it be constrained experimentally
UT fit

• as seen, experimental and theoretical inputs with corresponding uncertainties are combined in global inference frameworks
  ‣ imposing SM relations -- or testing alternative BSM flavor scenarios
  ‣ using frequentist or Bayesian statistical fit approaches, e.g.
UT fit evolution over 20 years
constraining NP

- allowing for New Physics contributions, via generic parameterizations
- e.g. NP contribution to off-diagonal B mass mixing matrix $M_{12}$
  - $M_{12}^{SM,q} = M_{12}^{SM,q} \cdot \Delta_q$, with $\Delta_q = |\Delta_q| \cdot \exp(i\Phi_{\Delta_q})$ and $q=s,d$
  - SM point corresponds to: $\Delta_s=1=\Delta_d$
  - NP phases, $\Phi_{\Delta}$, shift CP phases from mixing-induced CP asymmetries
    - $2\beta_s \leftrightarrow 2\beta_s - \Phi_{\Delta s} (B_s \to J/\psi \phi)$ and $2\beta_d \leftrightarrow 2\beta_d + \Phi_{\Delta d} (B_d \to J/\psi K)$
detection
a distinctive experimental signature

• bottom and charm hadrons live longer than the other unstable particles
  ‣ $\tau(D) \sim 0.5-1\text{ps}$, $\tau(B) \sim 1.5\text{ ps}$
  ‣ they travel macroscopic (i.e. measurable) distances in the detector before decaying, producing a displaced vertex topology

• extensively explored
  ‣ in heavy-flavor analyses themselves
  ‣ b-jet tagging: discriminate b-jets from the lighter quark jets
  ‣ in SM measurements and BSM searches: to detect signal HF components (e.g. $t \rightarrow Wb$, $H \rightarrow bb,...$) or control HF backgrounds (e.g. $bb$ dijets,...)

Exercise: determine how far a $B^0$ meson with typical momentum $P_{B^0} = 100\text{GeV}$ is expected to fly at the center of a LHC detector

N. Leonardo flavor physics & rare decays
heavy flavor “factories”

**PEP II at SLAC (US)**
9 GeV e⁻ on 3.1 GeV e⁺

**KEKB at KEK (Japan)**
8 GeV e⁻ on 3.5 GeV e⁺

**Asymmetric e⁺e⁻ colliders**
at Y(4S) resonance (10.58 GeV)
aka “B factories”

**Tevatron at FNAL (US)**
pp at 2 TeV

**General purpose hadron colliders**

**LHC at CERN**
pp at 14 TeV

**note:** currently only LHC is operational

**flavor physics & rare decays**
colliders (comparison)

- **lepton collider (at $\Upsilon$ resonance)**
  - **pros**: clean events, high purity
  - **cons**: produces only $B_u$ and $B_d$ mesons
- **hadron collider**
  - **pros**: high cross sections ($O(10^3)$ larger), all b-hadron species produced
  - **contra**: trigger, bandwidth, dilution, pileup, ...

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^-\rightarrow\Upsilon(4s)\rightarrow B\bar{B}$</th>
<th>$p\bar{p}\rightarrow b\bar{b}X \left(\sqrt{s} = 2\text{ TeV}\right)$</th>
<th>$p\bar{p}\rightarrow b\bar{b}X \left(\sqrt{s} = 14\text{ TeV}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>prod</td>
<td>1 nb</td>
<td>$\sim 100$ $\mu$b</td>
<td>$\sim 500$ $\mu$b</td>
</tr>
<tr>
<td>typ. $b\bar{b}$ rate</td>
<td>10 Hz</td>
<td>$\sim 100$ kHz</td>
<td>$\sim 500$ kHz</td>
</tr>
<tr>
<td>purity</td>
<td>$\sim 1/4$</td>
<td>$\sigma_{b\bar{b}}/\sigma_{inel} = 0.2%$</td>
<td>$\sigma_{b\bar{b}}/\sigma_{inel} = 0.6%$</td>
</tr>
<tr>
<td>pile-up</td>
<td>0</td>
<td>1.7</td>
<td>0.5-20</td>
</tr>
<tr>
<td>B content</td>
<td>$B^+B^-(50%), B^0\bar{B}^0(50%)$</td>
<td>$B^+(40%), B^0(40%), B(10%), B_c (&lt;1%), b$-baryons$10%$</td>
<td></td>
</tr>
<tr>
<td>B boost</td>
<td>small, $\beta\gamma \sim 0.56$</td>
<td>large, decay vertices are displaced</td>
<td></td>
</tr>
<tr>
<td>event structure</td>
<td>$BB$ pair alone</td>
<td>many particles non-associated to $b\bar{b}$</td>
<td></td>
</tr>
<tr>
<td>prod. vertex</td>
<td>Not reconstructed</td>
<td>reconstructed with many tracks</td>
<td></td>
</tr>
<tr>
<td>$B^0\bar{B}^0$ mixing</td>
<td>coherent</td>
<td>incoherent $\rightarrow$ flavour tagging dilution</td>
<td></td>
</tr>
</tbody>
</table>
detectors

General purpose

**ATLAS (LHC)**

**CMS (LHC)**

Specialized

**LHCb (LHC)**

**Belle (KEK)**

**BaBar (PEPII)**

**DO (Tevatron)**

**CDF (Tevatron)**

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flavor physics & rare decays
detector capability

- main requirements
  - ability to detect secondary, displaced decay vertices
    - precise silicon tracker
  - ability to select displaced topologies online, in real time
    - flexible trigger system
  - robust and precise event and particle reconstruction
    - momentum resolution
  - particle identification: leptons (distinguish muons from kaons, with low fake rates), hadrons (separate protons from kaons from pions)
the ideal heavy flavor detector?

Disclaimer: this (combined detector layout) doesn’t actually exist
production
HF production

- high HF production rates at the LHC
  - very large production cross section \((\sigma)\)
  - large accumulated luminosity \((L)\)
- LHC: HF ‘factory’ \((N=L\cdot\sigma)\)
  - allow to perform precision measurements, as well as to search for very rare processes
- HF production is ubiquitous
  - forming backgrounds for many physics processes explored at the LHC
  - need to be thoroughly understood
hadron production

- different mechanisms contribute to HF production
  - produced quarks evolve into hadrons: known as fragmentation
    - involving short-distance/perturbative vs long-distance processes
  - heavy quarkonia \( Q\bar{Q} = (b\bar{b}, c\bar{c}) \) are an ideal laboratory in which to study the strong force and the mechanisms of hadron formation
    - non-perturbative evolution of \( Q\bar{Q} \) pair into a quarkonium state
    - employ effective theories: e.g. non-relativistic QCD (NRQCD; CSM, CEM...)

need to carry out detailed studies of HF production, including cross sections, polarizations, etc
the ‘rediscovery’ of the SM plot
CMS, √s = 7 TeV
L = 36 pb⁻¹, lyy1 < 0.4

LHCB Preliminary
√s = 7 TeV

Mass (1S) = 9449.2 ± 0.4 MeV/c²
a (1S) = 52.4 ± 0.4 MeV/c²
N_{signal} (1S) = 34429 ± 261
N_{signal} (2S) = 8800 ± 181
N_{signal} (3S) = 4419 ± 147

ATLAS
√s = 7 TeV
L = 1.8 fb⁻¹

ALICE PERFORMANCE
3/05/2013

Pb-Pb | √s_NN = 2.76 TeV
2.5yc4

0%-90%

RUN6PP
South Arm

PHENIX Preliminary

CDF II Preliminary, 2.9 fb⁻¹

Data
Total Fit
Bkg only
Y (1S)
Y (2S)
Y (3S)

D0, 1.3 fb⁻¹

Events / 50 MeV/c²

Events / 0.33 GeV

ZEUS (prelim) / (410 pb⁻¹)

Bethe-Heitler

H + H

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s-wave quarkonia

charmonia (cc) ➔

bottomonia (bb) ➔
cross section

\[ \frac{d^2\sigma(Q\bar{Q})}{dp_Tdy} B(Q\bar{Q} \rightarrow \mu^+\mu^-) = \frac{N_{\text{fit}}(Q\bar{Q})}{\mathcal{L} \cdot A \cdot \varepsilon \cdot \Delta p_T \cdot \Delta y} \]

“\( N = L \sigma \)”

- **N**: fitted signal yield
- **A**: detector acceptance from simulation
  - dependent on unknown production polarization
- **\( \varepsilon \)**: track, muon reconstruction and trigger efficiencies, from data-driven (T&P) methods
- **L**: integrated sample luminosity
  - Acceptance and efficiency corrections applied event-per-event or as bin averages \( 1/A, \varepsilon \)

![Graph showing CMS data for J/\( \psi \) and \( \psi'(2S) \) events](image1)

![Graph showing CMS data for \( \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \) events](image2)
cross section

\( \frac{d^2 \sigma(Q\bar{Q})}{dp_T dy} B(Q\bar{Q} \rightarrow \mu^+ \mu^-) = \frac{N_{\text{fit}}(Q\bar{Q})}{\mathcal{L} \cdot A \cdot \varepsilon \cdot \Delta p_T \cdot \Delta y} \)

\( N = L \sigma \)

\begin{align*}
\text{Acceptance} & \quad \text{[simulation]} \\
\text{Efficiency} & \quad \text{[data-driven]} \\
\end{align*}

\( \varepsilon \)

\( \frac{\text{Events}}{(0.1 \text{GeV/c}^2)} \)

1. CMS, \( \sqrt{s} = 7 \text{ TeV}, L = 3 \text{ pb}^{-1} \)
2. \( (0 < p_T^\mu < 1) \text{ GeV/c} \)
3. \( (1 < p_T^\mu < 2) \text{ GeV/c} \)
4. \( (2 < p_T^\mu < 3) \text{ GeV/c} \)
5. \( (3 < p_T^\mu < 4) \text{ GeV/c} \)
6. \( (4 < p_T^\mu < 5) \text{ GeV/c} \)
7. \( (5 < p_T^\mu < 6) \text{ GeV/c} \)
8. \( (6 < p_T^\mu < 7) \text{ GeV/c} \)
9. \( (7 < p_T^\mu < 8) \text{ GeV/c} \)
10. \( (8 < p_T^\mu < 9) \text{ GeV/c} \)
11. \( (9 < p_T^\mu < 10) \text{ GeV/c} \)
12. \( (10 < p_T^\mu < 11) \text{ GeV/c} \)
13. \( (11 < p_T^\mu < 12) \text{ GeV/c} \)
14. \( (12 < p_T^\mu < 13) \text{ GeV/c} \)
15. \( (13 < p_T^\mu < 14) \text{ GeV/c} \)
16. \( (14 < p_T^\mu < 15) \text{ GeV/c} \)
17. \( (15 < p_T^\mu < 16) \text{ GeV/c} \)
18. \( (16 < p_T^\mu < 17) \text{ GeV/c} \)
19. \( (17 < p_T^\mu < 18) \text{ GeV/c} \)
20. \( (18 < p_T^\mu < 19) \text{ GeV/c} \)

\( \mu^+ \mu^- \text{ mass (GeV/c}^2) \)

N. Leonardo  flavor physics & rare decays
quarkonia production \( [\text{in pp}] \)

- precision measurements of quarkonium production
- LHC allows to probe higher \( p_T \) region for the first time

(Note: see polarization details in lecture: ‘polarization in LHC physics’)

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flavor physics & rare decays
b–hadron production

- integrated cross sections and NLO predictions in agreement
- baryon spectrum falls faster than meson spectra
- analysis of larger datasets will much improve precision of differential measurements
**$B_c$**

- meson with different heavy flavors -- unique in SM
  - sometimes also referred to as ‘quarkonium’: similar non-relativist potential techniques used to predict properties
  - formed of $b+c$ quarks: the heaviest quark flavors expected to form mesons
  - $b$ and $c$ may both decay weakly
    - much shorter lifetime than other $B$ mesons
- state by now observed in several modes
  - no excited states observed yet (many expected)
Before 2006, only one b baryon had been seen: $\Lambda_b$

CDF and D0 contributed several such discoveries:
- $\Sigma_b^-$ (2006)
- $\Xi_b^-$ (2007)
- $\Omega_b$ (2008)

LHC:
- $\chi_b(3P)$ (ATLAS’ 2011)
- $\Xi_b^{*0}$ (CMS’ 2012)
- $B_c(2S)$ (ATLAS’ 2014)
- $\Xi_b^{*+}$ $\Xi_b^-$ (LHCb’ 2014)

Several other composite particles awaiting to be discovered!...
the first new particles found at the LHC

- first new particle discovered by ATLAS
- reconstruct the radiative bottomonium decay by exploring photon conversions in tracker material
  \[
  \chi_b \rightarrow \Upsilon \gamma \quad \begin{array}{l}
  \downarrow \\
  e^+e^- \\
  \mu^+\mu^-
  \end{array}
  \]

- first new particle discovered by CMS
- first new b baryon observed at LHC
- complex cascade decay topology
  - 4 displaced vertices
  - 6 final state tracks

\[\Xi^*_b \quad \text{baryon} \]

\[\chi_b(3P) \quad \text{meson} \]

\[\text{note: these (orthogonal capabilities) further illustrate the ability of general purpose detectors to make flavor discoveries} \]
and couple more recent discoveries

[ATLAS’2014]  
$B_c(2S) \rightarrow \mu \mu \pi \pi$

[ATLAS]  
$Q_{B_c,\pi} = 288 \pm 5$ MeV  
$\sigma_{B_c,\pi} = 18 \pm 4$ MeV  
$N_{B_c,\pi} = 22 \pm 6$

[ATLAS’2014]  
$\Xi_b^-, \Xi_b^* \rightarrow p \kappa \pi \pi$

[LHCb’2014]  
$\Omega_{c}^{0} \rightarrow \Xi_{c}^{+}K^{-}$

[LHCb’2017]  
$\Omega_{c}^{0} \rightarrow 5$ new $\Omega_{c}^{0}$ excited states!
exotic spectroscopy

• while not all of the predicted states have been observed yet... many unexpected ones already have
• referred to as XYZ states
• all started with the discovery of the X(3872) state by Belle in 2003
  ‣ quickly confirmed by Babar, CDF, D0
  ‣ other unconventional states popped up

Many theoretical interpretations in discussion:

- conventional quarkonia;
- tetra-quarks states;
- meson-molecules;
- hybrid mesons;
- threshold effects;

→ properties do not well fit the quarkonia picture

XYZ states

\( X(3872) \to J/\psi \pi \pi \)

\( \Upsilon(4140) \) in \( B_u \to X[J/\psi \phi]K \) decays

N. Leonardo

flavor physics & rare decays

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heavy flavor (suppression) in heavy ion collisions
at large energy densities, QCD predicts the existence of a deconfined state of quarks and gluons -- the quark gluon plasma (QGP)

- studied in heavy ion collisions
- the goal is to characterize and quantify the properties of the dense and hot medium produced at the unprecedented LHC energies

- heavy-flavor states are ideal “hard probes” for studying the properties of the created medium

note: topic presented in dedicated lecture: ‘matter at high density and temperature’
quarkonium suppression

• first (quantitative) measurements of the Y(nS) states in HI collisions
• unprecedented resolutions, allowing to separate the three states
  ‣ experimentally and theoretically robust
• excited states observed (>5σ) to be more suppressed than ground state
• spectacular indication of formation of Quark Gluon Plasma in heavy ion coll.

“the LHC heavy-ion text book result”

Exercise: the excited states being suppressed, what may be expected also of the observed ground state (hint: nS→1S feed-down)
quarkonium sequential suppression

quarkonia suppression pattern experimentally established:
less tightly bound states are more suppressed in the medium
in medium hadron suppression

- measure of suppression, $R_{AA}$ (nuclear modification factor)
  - cross section ration in PbPb vs pp, scaled by number of binary collisions
- different particle species undergo different energy loss in the medium
  - colorless probes ($W, Z, \gamma$) are not suppressed ($R_{AA} \sim 1$)
  - study flavor dependence of energy loss
b−hadron detection

- prior to LHC, b−hadron detection was pursued mostly through inclusive-lepton ($B \rightarrow lX$) and inclusive-charmonia ($B \rightarrow J/\psi X$) studies
- with LHC, moved to a new class of more reliable and precise new measurements
  - through non-prompt charmonia: remove prompt contribution through lifetime analysis [see next section]
  - through exclusive state reconstruction [see next slide]
    ➡ both achieved for the first time at the LHC
**B\textsubscript{u}, B\textsubscript{d}, B\textsubscript{s} [in p-Pb]**

- first B meson peaks reconstructed in collisions involving heavy ions (2014/5)

> these systems constitute precise handles that will facilitate a much improved understanding of the mechanisms of energy loss of hadrons in the deconfined (‘hot’) and nuclear (‘cold’) media -- and of its flavor dependence
Heavy flavor studies at the LHC are opening up new research lines in nuclear physics, benefiting from the exquisite capability of the detectors and unprecedented collision energies at the LHC.

Several ground-breaking results already delivered, many more to come.

<table>
<thead>
<tr>
<th>Energy (TeV)</th>
<th>Proton-Proton</th>
<th>Heavy-Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (Run II)</td>
<td>1.96</td>
<td>0.2</td>
</tr>
<tr>
<td>LHC Run I</td>
<td>7(8)</td>
<td>2.76</td>
</tr>
<tr>
<td>LHC Run II</td>
<td>13(14)</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Very large datasets are being accumulated at the LHC.

- Large HF production cross section + precision HF detection capability
lifetime
quantum mechanics (i)

- an unstable particle may be described by an effective Hamiltonian
- through the non-relativistic Schrödinger equation
- the solution reproduces the law of radioactive decay
  \[ \mathcal{P}(t) \sim \frac{1}{\tau} e^{-t/\tau} \]
  \( \tau \) is the lifetime
- \( t \) is the proper decay time, experimentally it is measured from the decay length \( L \) and momentum \( p \) (or their projections on the transverse plane)
  \[ t = \frac{L}{\beta \gamma} = L \frac{M}{p} = L_{xy} \frac{M}{p_T} \]
  Lorentz boost factor

\[ \mathcal{H} = m - \frac{i}{2} \Gamma \]
\[ i \partial_t \psi = \mathcal{H} \psi \]
\[ |\psi_t\rangle = e^{-imt} e^{-\frac{1}{2} \Gamma t} |\psi_0\rangle \]
\[ |\langle \psi_0 | \psi_t \rangle|^2 = e^{-\Gamma t} \]
\[ \tau \equiv 1/\Gamma \]
lifetime modeling

\[ L(t|\sigma_t, \tau) = \frac{1}{N} \cdot \left[ \frac{1}{\tau} e^{-\frac{t}{\tau}} \theta(t) \otimes G(t; \sigma_t) \right] \cdot \mathcal{E}(t) \]

- **t-resolution**
  - use per-event uncertainties \( \sigma_t \)
    (more precisely reco’d B’s get larger weight)
  - calibrate using data (high stat. modes)
    \[ \sigma_t \rightarrow S_t \cdot \sigma_t \]

- **trigger/selection bias**
  - vertex detachment requirements
    used in selection bias t-distribution,
    requires acceptance correction, \( \mathcal{E}(t) \)

- **backgrounds**
  - prompt, \( \delta(t) \) (\( \rightarrow \) resolution)
  - long-lived (from decay products of other b-hadrons)

PDF normalization
theory model
t-resolution function
t-acceptance function

example \( \Downarrow \) lifetime fit
\[ \text{[t-resolution, } \sigma_t \text{]} \]

- \( \sigma_t \) may be taken per-event from the vertex kinematic fit
- should be calibrated, using data
- a possible strategy (CDF, also used for example by LHCb)
  - if dataset is t-unbiased: fit prompt peak with scale factor, \( e^{-\Gamma \cdot t} \otimes R(t, S_t, \sigma_t) \); else:
  - construct a prompt sample of B-like vertices, closely mimicking kinematics and topology of the signal; fit this sample as above, allowing for scale factor
  - to further facilitate transfer to signal sample, parameterize \( S_t(\Delta R, l, \eta, z, X^2) \)

**CDF**

signals:
\[ B \rightarrow D \pi, D X \]
triggered by SVT

calibration sample:
SVT-displaced \( D \) + prompt tracks

**LHCb**

signal:
\[ B \rightarrow J/\psi \pi \pi \pi \]
displaced

calibration sample:
prompt \( J/\psi \) + prompt pion pair

(PLB 713 (2012) 378)
[t–acceptance, $\varepsilon(t)$]

- **if** dataset is not biased, $\varepsilon(t)=1$
- **if** bias corresponds to a threshold (global or per-event) on $L_{xy}$ or $t$, then the efficiency is given by a threshold function $\varepsilon(t)=\theta(t-t_0)$
- **if** a more general bias, $\varepsilon(t)$ can be estimated from MC or data

MC driven:

$$\varepsilon(t) = \frac{t\text{–distribution after selection}}{\sum \{ \sigma_t \} \frac{1}{\tau} e^{-t/\tau} \otimes G(t; \sigma_t)}$$

Data driven: PRD 83 (2011) 032008
b–hadron lifetimes

\[ \tau(B^0) = 1.508 \pm 0.025 \pm 0.043 \text{ ps} \]
\[ \tau(\Lambda_b) = 1.303 \pm 0.075 \pm 0.035 \text{ ps} \]

PRD 85 (2012) 112003

\[ \tau(B^0) = 1.639 \pm 0.009 \pm 0.009 \text{ ps} \]
\[ \tau(B^+) = 1.507 \pm 0.010 \pm 0.008 \text{ ps} \]
\[ \tau(\Lambda_b) = 1.537 \pm 0.045 \pm 0.014 \text{ ps} \]
\[ \tau(B^+)/\tau(B^0) = 1.088 \pm 0.009 \pm 0.004 \]
\[ \tau(\Lambda_b)/\tau(B^0) = 1.020 \pm 0.030 \pm 0.008 \]

PRL 106 (2011) 121804

\[ \tau(B^0) = 1.519 \pm 0.007 \text{ ps} \]
\[ \tau(B^+) = 1.641 \pm 0.008 \text{ ps} \]
\[ \tau(B_s) = 1.516 \pm 0.011 \text{ ps} \]
\[ \tau(B_c) = 0.452 \pm 0.033 \text{ ps} \]
\[ \tau(\Lambda_b) = 1.429 \pm 0.024 \text{ ps} \]

PDG 2013

\[ \tau(\Lambda_b) = 1.503 \pm 0.052 \pm 0.031 \text{ ps} \]

JHEP 07 (2013) 163

\[ \tau(\Lambda_b) = 1.449 \pm 0.036 \pm 0.017 \text{ ps} \]

PRD 87 (2013) 032002

\[ \tau(B^0) = 1.508 \pm 0.025 \pm 0.043 \text{ ps} \]
\[ \tau(B^+) = 1.639 \pm 0.009 \pm 0.009 \text{ ps} \]
\[ \tau(B^0) = 1.507 \pm 0.010 \pm 0.008 \text{ ps} \]
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PRD 85 (2012) 112003
flavor oscillations
&
flavor tagging
quantum mechanics (ii)

- allowing for a flavor-changing perturbation ($\Delta F$) in the Hamiltonian

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{\Delta F}$$

$$i \frac{d}{dt} \psi = \mathcal{H} \psi \quad \quad i \frac{d}{dt} \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} m - \frac{i}{2} \Gamma & M_{12} - \frac{i}{2} \Gamma_{12} \\ M_{12}^* - \frac{i}{2} \Gamma_{12}^* & m + \frac{i}{2} \Gamma \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

- a pure flavor eigenstate at $t=0$ will evolve to an admixture
  - non-diagonal elements in $\mathcal{H} \Rightarrow$ flavor eigenstates differ from mass eigenstates

- flavor eigenstates

$$|P_L\rangle = p |P^0\rangle + q |\bar{P}^0\rangle$$

$$|P_H\rangle = p |P^0\rangle - q |\bar{P}^0\rangle$$

with $|p|^2 + |q|^2 = 1$

- time evolution of flavor eigenstates (after finding $\mathcal{H}$ eigenvalues $\lambda_{H,L}$)

$$|P_{L,H}\rangle_t = e^{-i \lambda_{L,H} t} |P_{L,H}\rangle = e^{-i m_{L,H} t - \frac{1}{2} \Gamma_{L,H} t} |P_{L,H}\rangle$$

- probability for particle-antiparticle transition

$$|\langle P^0 | \mathcal{H} | \bar{P}^0 \rangle|^2 = \left| \frac{p}{q} \right|^4 |\langle \bar{P}^0 | \mathcal{H} | P^0 \rangle|^2 = \left| \frac{p}{q} \right|^2 \frac{1}{2} e^{-\Gamma t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) \cdot \cos (\Delta m t) \right]$$

with $\Delta \Gamma \equiv \Gamma_L - \Gamma_H$ and $\Delta m \equiv m_H - m_L$

- neglecting CPV in mixing (i.e. $p/q=1$) and $\Delta \Gamma$, the mixing probability is:

$$\mathcal{P}_{B_q^0 \to \bar{B}_q^0} (t) = \mathcal{P}_{\bar{B}_q^0 \to B_q^0} (t) = \frac{\Gamma}{2} e^{-\Gamma t} \left[ 1 - \cos (\Delta m t) \right]$$
flavor oscillations

\[
p(B \rightarrow B) = \frac{e^{-t/\tau}}{2\tau} (1 + \cos \Delta m t)
\]

\[
p(B \rightarrow \bar{B}) = \frac{e^{-t/\tau}}{2\tau} (1 - \cos \Delta m t)
\]

- oscillation frequency given by mass difference between heavy and light H eigenstates

- but... one critical ingredient still missing: need to known whether or not a given B candidate in the data has mixed flavor tagging

Exercise: show that a proper time cut \( t > t_0 \) induces undershootings besides the peak in the Fourier transform of the oscillation signal
particle or antiparticle

- (let ‘flavor’ here refer to the particle and antiparticle state)

- flavor at decay time:
  - trivially given by the charge of the decay products, if using flavor specific final states
  - (e.g. final flavor given by pion charge in $B_s \rightarrow D_s^- \pi^+ \text{ vs } \overline{B_s} \rightarrow D_s^+ \pi^-$)

- flavor at production time: ...

how may it be determined ??

Exercise: think about it before resuming discussion in next 2 slides
how to tag?

• attempt #1: use $B_s$ mesons from the decay of heavier particles

  the initial $B$ flavor ($b$ or $\bar{b}$) could be inferred from the decay products of the heavier, parent state, eg from the charge of the pion in the examples

• attempt #2: make use of the other $b$ quark (from the originally produced $b\bar{b}$ pair), by reconstructing the other $b$-hadron in the event, say $B^\pm \rightarrow J/\psi K^\pm$ (flavor given by the kaon charge)

  these possibilities are quite interesting! but given reconstruction inefficiencies (of parent or other $B$), very high signal statistics would/will be required...

⇒ catch: infer flavor without full decay reconstruction
flavor tagging methods

- opposite-side tagging
  - lepton (e, μ)
  - jet-charge
  - kaon

- same-side tagging

**Exercise:**
1. Explain how $B$ flavor oscillations cause an intrinsic dilution of the OST methods performance.
2. Show how the lepton tagger, based on semileptonic $B$ decays ($B \rightarrow l$), is affected by sequential decays such as $B \rightarrow D \rightarrow l$.

**Exercise:** Explain why the performance of SST (OST) should (not) depend on the species of $B$ meson being tagged.
**dilution factors**

- various effects decrease the amplitude of an oscillation signal

\[
\left( \frac{\text{mixing significance}}{} \right)^2 \sim \frac{\varepsilon D^2 S}{2 \cdot \frac{S}{S+B}} \cdot e^{-\sigma^2 w^2}
\]

- tagging power \( \varepsilon D^2 \) is given by the algorithm efficiency \( \varepsilon \) and dilution \( D=(1-2w)^2 \) where \( w \) is the wrong-tag fraction (i.e. probability algorithm gives wrong decision)

- it determines the effective statistical reduction of the sample size: \( S \rightarrow S \cdot \varepsilon_{\text{tag}} D^2 \)

**Exercise:** explain why the t-resolution is even more determining for \( B_s \) than \( B_d \) mixing

<table>
<thead>
<tr>
<th>tagger ( \varepsilon D^2 ) for decay ( B_s \rightarrow J/\psi \Phi )</th>
<th>CDF</th>
<th>D0</th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>for decay ( B_s \rightarrow J/\psi \Phi )</td>
<td>1.39±0.05% [OST]</td>
<td>3.5±1.4% [SST]</td>
<td>4.68±0.54% [OST+SST]</td>
<td>1.45±0.05% [OST]</td>
<td>2.43±0.08±0.26% [OST]</td>
</tr>
<tr>
<td>~4.9%</td>
<td></td>
<td>~4.7%</td>
<td></td>
<td>~1.5%</td>
<td>0.89±0.06% [SST]</td>
</tr>
</tbody>
</table>
mixing model

\[ L = L_{\text{mass}} \cdot L_t \cdot L_{\sigma_t} \cdot L_D \]  
[for each sample component & event]

- ingredients: mass, proper time, proper time resolution, t-acceptance function, kinematic factor (for partially reco’d decays), and... flavor tagging

\[
L_t = \frac{1}{N} \kappa \frac{e^{-\frac{\kappa t'}{\tau}}}{\tau} \left( 1 \pm A S_D D \cos(\Delta m_s \kappa t') \right) \frac{R(t - t'; S_{\sigma_t} \sigma_t) \cdot E(t) \otimes F(\kappa)}{2}
\]

analytical computation

(if need be)

Frequency $\Delta m_s$

or

Amplitude $(A, \sigma_A)$ for fixed $\Delta m_s$
$B_d$ mixing

CDF Run II Preliminary

L = 355 pb$^{-1}$

JVX Jet Charge Tagger

CDF Run II Preliminary

L = 355 pb$^{-1}$

Soft Muon Tagger

CDF Run II Preliminary

L = 355 pb$^{-1}$

Soft Muon Tagger

LHCb

$B^0 \rightarrow D^- \pi^+$

combined

LHCb

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

combined

$\Delta m_d = 0.5156 \pm 0.0051 \text{ (stat.)} \pm 0.0033 \text{ (syst.) ps}^{-1}$

(most precise measurement)
**B_s mixing**

observation by CDF (2006)

- $p$-value = $8 \times 10^{-8}$ corresponding to $5.4\sigma$
- $\Delta m_s = 17.77 \pm 0.10\text{(stat)} \pm 0.07\text{(syst)} \text{ps}^{-1}$

LHCb confirmed (improved precision)

- $\Delta m_s = 17.768 \pm 0.023\text{ (stat)} \pm 0.006\text{ (syst)} \text{ps}^{-1}$

In agreement with SM expectation $\Delta m_s = 17.3 \pm 2.6 \text{ ps}^{-1}$ [arXiv:1102.4274]

note: experimental precision $O(10^2)$ times better than theory calculation
CP violation
quantum mechanics (iii)

- discrete symmetries
  - Charge conjugation: particle $\rightarrow$ antiparticle
  - Parity: $x \rightarrow -x$
  - Time reversal: $t \rightarrow -t$
- C and P are maximally violated in weak interactions
  - no right handed neutrinos, no left-handed antineutrinos)
- CPT is conserved in any Lorentz invariant gauge field theory; thus, CP$\Leftrightarrow$T

- under CP, an operator $O(x,t)$ transforms as $O(\bar{x},t) \rightarrow O^\dagger(\bar{x},t)$
- the effective Lagrangian ($L=L^\dagger$) has the structure $\mathcal{L} = aO + a^*O^\dagger$ $\quad CP, aO^\dagger + a^*O = \mathcal{L}$
  - CP violation thus requires $a^* \neq a$, i.e. a complex phase

- Yuakawa term
- Charged current term

\begin{align*}
-\mathcal{L}_{\text{Yukawa}} &= Y_{ij}\bar{\psi}_i \phi \psi_j + Y_{ij}^*\bar{\psi}_j \phi^\dagger \psi_i \\
\mathcal{L}_W &= \frac{g}{\sqrt{2}}\bar{u}_L V_{ij} \gamma_\mu W^{-\mu} d_i L + \frac{g}{\sqrt{2}}\bar{d}_L V_{ij}^* \gamma_\mu W^{\mu} u_i L
\end{align*}

Exercise: verify that CP invariance applied to Yukawa and W currents would imply $Y_{ij} = Y_{ij}^*$ and $V_{ij} = V_{ij}^*$ using CP transformations recalled in tables below

<table>
<thead>
<tr>
<th>Field</th>
<th>P</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar field</td>
<td>$\phi(\bar{x},t)$</td>
<td>$\phi(-\bar{x},t)$</td>
</tr>
<tr>
<td>Dirac spinor</td>
<td>$\psi(\bar{x},t)$</td>
<td>$\gamma^0 \psi(-\bar{x},t)$</td>
</tr>
<tr>
<td></td>
<td>$\bar{\psi}(\bar{x},t)$</td>
<td>$\bar{\psi}(-\bar{x},t)\gamma^0$</td>
</tr>
<tr>
<td>Axial vector field</td>
<td>$A_\mu(\bar{x},t)$</td>
<td>$-A^\mu(-\bar{x},t)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Field</th>
<th>Bilinear</th>
<th>P</th>
<th>C</th>
<th>T</th>
<th>CP</th>
<th>CPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>scalar</td>
<td>$\psi_1\psi_2$</td>
<td>$\psi_1\psi_2$</td>
<td>$\psi_2\psi_1$</td>
<td>$\psi_1\psi_2$</td>
<td>$\psi_2\psi_1$</td>
<td>$\psi_2\psi_1$</td>
</tr>
<tr>
<td>pseudo scalar</td>
<td>$\psi_1\gamma_5\psi_2$</td>
<td>$-\psi_1\gamma_5\psi_2$</td>
<td>$\psi_2\gamma_5\psi_1$</td>
<td>$-\psi_1\gamma_5\psi_2$</td>
<td>$\psi_2\gamma_5\psi_1$</td>
<td></td>
</tr>
<tr>
<td>vector</td>
<td>$\psi_1\gamma_\mu\psi_2$</td>
<td>$\psi_1\gamma_\mu\psi_2$</td>
<td>$\psi_2\gamma_\mu\psi_1$</td>
<td>$-\psi_1\gamma_\mu\psi_2$</td>
<td>$-\psi_2\gamma_\mu\psi_1$</td>
<td></td>
</tr>
<tr>
<td>axial vector</td>
<td>$\psi_1\gamma_5\gamma_\mu\psi_2$</td>
<td>$-\psi_1\gamma_5\gamma_\mu\psi_2$</td>
<td>$\psi_2\gamma_5\gamma_\mu\psi_1$</td>
<td>$-\psi_1\gamma_5\gamma_\mu\psi_2$</td>
<td>$-\psi_2\gamma_5\gamma_\mu\psi_1$</td>
<td></td>
</tr>
<tr>
<td>tensor</td>
<td>$\psi_1\sigma_{\mu\nu}\psi_2$</td>
<td>$-\psi_1\sigma_{\mu\nu}\psi_2$</td>
<td>$\psi_2\sigma_{\mu\nu}\psi_1$</td>
<td>$-\psi_1\sigma_{\mu\nu}\psi_2$</td>
<td>$-\psi_2\sigma_{\mu\nu}\psi_1$</td>
<td></td>
</tr>
</tbody>
</table>
quantum mechanics (iv)

- consider neutral meson $P^0$ decays to a final state $f$
- the time dependent decay rates may be expressed as

$$\Gamma_{P^0 \rightarrow f}(t) = |A_f|^2 \left( 1 + |\lambda_f|^2 \right) \frac{e^{-\Gamma t}}{2} \left( \cosh \frac{1}{2} \Delta \Gamma t + D_f \sinh \frac{1}{2} \Delta \Gamma t + C_f \cos \Delta m t - S_f \sin \Delta m t \right)$$

$$\Gamma_{\bar{P}^0 \rightarrow f}(t) = |A_f|^2 \left| \frac{p}{q} \right|^2 \left( 1 + |\lambda_f|^2 \right) \frac{e^{-\Gamma t}}{2} \left( \cosh \frac{1}{2} \Delta \Gamma t + D_f \sinh \frac{1}{2} \Delta \Gamma t - C_f \cos \Delta m t + S_f \sin \Delta m t \right)$$

- with
  - $\lambda_f = \frac{q \bar{A}_f}{p A_f}$
  - $D_f = \frac{2 \Re \lambda_f}{1 + |\lambda_f|^2}$
  - $C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$
  - $S_f = \frac{2 \Im \lambda_f}{1 + |\lambda_f|^2}$

- sin and sinh terms are associated to interference of decays with and without oscillation
- CP violation classification

- CPV in decay
  - $\Gamma(P^0 \rightarrow f) \neq \Gamma(\bar{P}^0 \rightarrow f)$
  - $|\frac{\bar{A}_f}{A_f}| \neq 1$

- CPV in mixing
  - $\text{Prob}(P^0 \rightarrow \bar{P}^0) \neq \text{Prob}(\bar{P}^0 \rightarrow P^0)$
  - $|\frac{q}{p}| \neq 1$
  - $\Im \left( \frac{q \bar{A}_f}{p A_f} \right) \neq 0$

- CPV in interference between decay with and without mixing
  - $\Gamma(P^0(\sim \bar{P}^0) \rightarrow f)(t) \neq \Gamma(\bar{P}^0(\sim P^0) \rightarrow f)(t)$
CPV in interference w/or w/o mixing

- defined by $\text{Im } \lambda_f \neq 0$
- available to modes in which both $B$ and $\bar{B}$ decay to a same final state $f$
- example: $B_s \rightarrow J/\psi KK, J/\psi \pi \pi$

\[ \beta_s = \text{arg}\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right) = O(\lambda^2) \]
\[ 2\beta_s \approx -\phi \]
$\mathcal{B}_s \to J/\psi \Phi$

$\Delta \Gamma_s = 0.068 \pm 0.026 \text{(stat)} \pm 0.009 \text{(syst)} \text{ ps}^{-1}$

$\phi_s = 0.15 \pm 0.18 \text{ (stat)} \pm 0.06 \text{ (syst)} \text{ rad}$

$\Delta \Gamma_s = 0.123 \pm 0.029 \text{ (stat)} \pm 0.011 \text{ (syst)} \text{ ps}^{-1}$

Removal of sign ambiguity: physical solution $\Delta \Gamma_s > 0$

$\phi_s = 0.07 \pm 0.09 \text{(stat)} \pm 0.01 \text{(syst)} \text{ rad}$

$\Delta \Gamma_s = 0.100 \pm 0.016 \text{(stat)} \pm 0.003 \text{(syst)} \text{ ps}^{-1}$
$\Phi_s$ & $\Delta\Gamma_s$  [world summary]
rare decays
rare NP probes

- search for virtual contributions of new heavy particles in loops
- most interesting processes are those highly suppressed in SM
  - flavor-changing neutral current (FCNC), forbidden at tree level in SM
  - lepton flavor violation (LFV)
  - CKM suppressed
  - helicity suppressed
  - dominance of short distance effects, SM uncertainties under control
- experimental probes with precise theory prediction
  - uncertainty typically dominated by QCD; e.g. prefer leptonic to hadronic final states
- processes that may be modified (enhanced or suppressed) by orders of magnitude by NP
  - SUSY, 2HDM, LHT, Z’, RS models ....

\[ A(b \rightarrow d)_{FCNC}^{s} \sim c_{SM} \frac{y_{t}^{2} V_{td} V_{tb}}{16\pi^{2} M_{W}^{2}} + c_{NP} \frac{\delta_{3d}}{16\pi^{2} \Lambda_{NP}^{2}} \]
quantum mechanics (v)

- **Effective Hamiltonian** (describing weak decay of hadron M into final state F)
  - expressed by means of an operator product expansion (OPE)

\[
A(M \rightarrow F) = \langle F | \mathcal{H}_{\text{eff}} | M \rangle = \frac{G_F}{\sqrt{2}} \sum_i V_{\text{CKM}} C_i(\mu) \langle F | Q_i(\mu) | M \rangle
\]

- new physics can modify $C_i$ couplings and/or add new operators $Q_i$
- **EFT for $b \rightarrow s l^+ l^-$ FCNC transitions**

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- Wilson coefficient
- short distance coupling (perturbative)
- hadronic matrix element
- long distance/non-perturbative
$B^0 \rightarrow K^{*0}\mu\mu$

- $b\rightarrow s\ell\ell$ transitions, governed by FCNCs
- experimentally clean signature $\Rightarrow$ superb laboratory for NP tests
- with clean theoretical predictions (at least at low $q^2 := m_{\mu\mu}^2$)
- and not so rare $\Rightarrow$ allow measurements of many sensitive kinematic variables and asymmetries
- measure differential decay distributions
  - multivariate analysis in mass, proper time
  - and angular distributions
$B^0 \rightarrow K^{*0} \mu \mu$

First measurement of zero-crossing point of $A_{FB}$

$q^2_0 = (4.9 \pm 0.9) \text{ GeV}^2/c^4$

Consistent with SM expectation
• new set of variables proposed ➡ less sensitive to hadronic form factors
• $P_5'$: LHCb measures 4 new observables in 6 bins of $q^2$; one of the 24 measurements deviates from SM by $\sim 3.7\sigma$
• possible interpretation as a NP contribution to Wilson coefficient $C_9$
• interesting (correlated?) tensions with SM prediction
• ➡ to be explored with priority with more data and additional decays

$B \rightarrow K\mu\mu$
the ‘golden’ rare decay
searching for an ultra-rare decay: $\text{B} \to \mu \mu$

- the decay $\text{B}_s \to \mu \mu$ is very suppressed in SM, $\mathcal{O} \left(10^{-9}\right)$
- it can be sizably enhanced by various BSM models
- search has been pursued for 3 decades
searching for an ultra-rare decay: $B \rightarrow \mu \mu$

1. Online Selection (Trigger)

![Graph showing dimuon trigger with criteria]

**Dimuon Trigger**
- **L1 Hardware Trigger**
  - $p_T > 3$ GeV (few kHz)
- **HLT Full tracking and vertexing**
- **HLT $B_s \rightarrow \mu \mu$**
  - Leading and sub-leading $\mu$ $p_T > 3.4$ (4,4) GeV $|\eta_{\mu\mu}| < 1.8$ ($1.8 < |\eta_{\mu\mu}| < 2.2$)
  - $p_T (\mu \mu) > 5$ (4.8-6) GeV
  - $4.8 < m(\mu \mu) < 6.0$ GeV
  - $P(\chi^2/dof) > 0.5\%$
searching for an ultra-rare decay: $B \rightarrow \mu \mu$

1. **Online Selection (Trigger)**

2. **Blind the Data (Avoid Bias)**

analysis procedure and event selection developed without inspecting the data in region where signal is expected

“box opening” only later, at final analysis stages
searching for an ultra-rare decay: $B \rightarrow \mu\mu$

1. **ONLINE SELECTION (TRIGGER)**
2. **BLIND THE DATA (AVOID BIAS)**
3. **MULTIVARIATE SELECTION**
searching for an ultra-rare decay: \( \text{B} \rightarrow \mu\mu \)

1. **Online Selection (Trigger)**
2. **Blind the Data (Avoid Bias)**
3. **Multivariate Selection**
4. **Fit the Data (Likelihood)**

Fit the data accounting for the various signal and background components.
searching for an ultra-rare decay: $B \rightarrow \mu \mu$

1. **Online Selection (Trigger)**
2. **Blind the Data (Avoid Bias)**
3. **Multivariate Selection**
4. **Fit the Data (Likelihood)**
5. **Statistical Significance**

is the observed excess a genuine signal, or just a fluctuation of the background?
searching for an ultra-rare decay: \( B \rightarrow \mu \mu \)

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. FIT THE DATA (LIKELIHOOD)
5. STATISTICAL SIGNIFICANCE
6. EXTRACT MEASUREMENT

\[ BR(B_s \rightarrow \mu \mu) = (3.0^{+0.9}_{-0.8} \text{ (stat)}^{+0.6}_{-0.4} \text{ (syst)}) \times 10^{-5} \]
searching for an ultra-rare decay: $B \rightarrow \mu \mu$

1. **Online Selection (Trigger)**
2. **Blind the Data (Avoid Bias)**
3. **Multivariate Selection**
4. **Fit the Data (Likelihood)**
5. **Statistical Significance**
6. **Extract Measurement**
7. **Compare to Theory**

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**The SM...**

**AND BEYOND**

---

$BR(B_s \rightarrow \mu \mu) = \left(3.0^{+0.9}_{-0.8}\right)$ (stat)$^{+0.6}_{-0.4}$ (syst) $\times 10^{-4}$
summary

• broad and successful flavor physics programme at the LHC

• advancements and breakthroughs in the different areas during Run I
  ‣ rare decays, CP violation, production, spectroscopy, QGP hard probes

• no large discrepancies wrt the Standard Model found, yet
  ‣ several ~3σ level tensions will be pursued and clarified in next LHC runs

• exploring highly sensitive phenomena, including
  ‣ fast: $B_s$ oscillations occur at 3 trillion times a second
  ‣ rare: $B_s$ decays to muon pairs 3 times in a billion
  ‣ hot: created medium in ion collisions 5 trillion °C

• continuing flavor physics program complementary to direct searches into
  the high luminosity LHC runs
  ‣ in the quest of finding evidence of New Physics and setting its scale
  ‣ to differentiate amongst NP models and characterize their flavor structure
References

‣ **experiment**: Matter antimatter fluctuations, N.Leadnardo, LAP (2011)


  note: references available from LIP/IST/CERN libraries

  multiple excellent reviews exist on each of the core topics presented
**f fresh from lhcb**

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![Graph](image)

**LHCb**

BDT > 0.5

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![Graph](image)

**LHCb**

Weighted $B^0 \rightarrow \mu^+\mu^-$ candidates (1 ps)

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extra material
CPV in decay: $B \to K\pi$

\[
A_{CP}^{dir} = \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)}
\]


- Tevatron: CDF (2012)

\[
A_{CP}(B^0 \to K^+\pi^-) = -0.083 \pm 0.013 \pm 0.003
\]
\[
A_{CP}(B_s^0 \to K^-\pi^+) = +0.22 \pm 0.07 \pm 0.02
\]

- LHC: LHCb (2013)
  - first observation ($>5\sigma$) of CPV in $B_s$
$B_s \rightarrow KK$

- **time-dependent asymmetry**

$$\mathcal{A}(t) = \frac{\Gamma_{\bar{B}^0(s)} f(t) - \Gamma_{B^0(s)} f(t)}{\Gamma_{\bar{B}^0(s)} f(t) + \Gamma_{B^0(s)} f(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh \left(\frac{\Delta \Gamma_{d(s)} t}{2}\right) - A_f \Delta \Gamma \sinh \left(\frac{\Delta \Gamma_{d(s)} t}{2}\right)}$$

$$C_{KK} = 0.14 \pm 0.11 \text{ (stat)} \pm 0.03 \text{ (syst)}$$

$$S_{KK} = 0.30 \pm 0.12 \text{ (stat)} \pm 0.04 \text{ (syst)}$$

- first time-dependent CPV measurement in $B_s \rightarrow KK$ decays

**JHEP 10 (2013) 183**
**ACP**

- extensive set of measurements of CPV in charmless B decays
- example, $B \rightarrow hhh(h)$ from LHCb
\( B_u \rightarrow \psi h, \ D h \)

- direct CPV is *only* type possible for charged B
- hidden charm
  - no direct CPV expected for the Cabbibo-favored decay \( B \rightarrow J/\psi K \)
  - Cabbibo-suppressed decays \( B^+ \rightarrow J/\psi \pi^+, \psi' \pi^+, \psi' K^+ \), with \( \psi \rightarrow \mu \mu \):
    - tree and penguin contribute different phases ⇒ possible CPV
- open charm
  - \( B \rightarrow DK \) with \( D \rightarrow KK, \pi \pi, \pi K \), w/ first observation of \( B^\pm \rightarrow [\pi^{\pm}K]_D K^\pm \)
  - interference through D final state accessible to both \( D^0 \) and \( \bar{D}^0 \)

\[
A^{\psi \pi} = \frac{B(B^- \rightarrow \psi \pi^-) - B(B^+ \rightarrow \psi \pi^+)}{B(B^- \rightarrow \psi \pi^-) + B(B^+ \rightarrow \psi \pi^+)}
\]

\[
A_{CP}^{J/\psi \pi} = 0.005 \pm 0.027 \pm 0.011
\]

\[
A_{CP}^{\psi(2S)\pi} = 0.048 \pm 0.090 \pm 0.011
\]

\[
A_{CP}^{\psi(2S)K} = 0.024 \pm 0.014 \pm 0.008
\]

- \( J/\psi K \) and \( J/\psi \pi \) contribution to CPV

- No evidence of direct CPV in \( B^+ \rightarrow \psi h \)

<table>
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<tr>
<th>Experiment</th>
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<td>LHCb</td>
<td>LHCb:</td>
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<td>Measurement (5.8σ)</td>
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<td>LHCb</td>
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CPV in mixing

• defined by condition $|q/p| \neq 1$

• induces charge asymmetry in semileptonic B decays
  ‣ eg, $B_s \rightarrow \mu^+ D_s \nu X$

• dilepton asymmetry

\[
A_{SL}(t) = \frac{\Gamma[\bar{B}^0(t) \rightarrow \ell^+ X] - \Gamma[B^0(t) \rightarrow \ell^- X]}{\Gamma[\bar{B}^0(t) \rightarrow \ell^+ X] + \Gamma[B^0(t) \rightarrow \ell^- X]} \\
\approx 2(1 - |q/p|),
\]

‣ $A_{SL}$ is, actually, time-independent

‣ sensitive to deviations of $|q/p|$ from 1

D0 reported 3.9σ discrepancy with SM both $B_s$ and $B_d$ contribute to the asymmetry
⇒ evidence for anomalous CPV in the mixing of B mesons

D0, PRD 82, 032001 (2010)


**a_{sl} asymmetry**

**inclusive measurements:**

- single and like-sign dimuon charge asymmetries

**PRD 89 (2014) 012002**

\[
\begin{align*}
a_{sl}^d &= (\frac{-0.62 \pm 0.43}{\Gamma_d}) \times 10^{-2} \\
a_{sl}^s &= (\frac{-0.82 \pm 0.99}{\Gamma_d}) \times 10^{-2}
\end{align*}
\]

assuming \(\Delta \Gamma_d/\Gamma_d\) SM value:

\[
\begin{align*}
a_{sl}^d &= (\frac{-0.62 \pm 0.42}{\Gamma_d}) \times 10^{-2} \\
a_{sl}^s &= (\frac{-0.86 \pm 0.74}{\Gamma_d}) \times 10^{-2}
\end{align*}
\]

**semileptonic decays:**

**PRD 86 (2012) 072009:** \(a_{sl,d}^d\) from \(B_d \to \mu D_s\)\(^{(*)}\)X

\[
\begin{align*}
a_{sl}^d &= (0.51 \pm 0.86)\% \ (\mu D \text{ channel}), \\
a_{sl}^d &= (1.25 \pm 0.87)\% \ (\mu D^* \text{ channel})
\end{align*}
\]

**PRL 110 (2013) 011801:** \(a_{sl,s}^s\) from \(B_s \to \mu D_s\)X

\[
\begin{align*}
a_{sl}^s &= [-1.12 \pm 0.74 \text{ (stat)} \pm 0.17 \text{ (syst)}] \%
\end{align*}
\]

\[
\begin{align*}
a_{sl}^d(\text{comb.}) &= (0.07 \pm 0.27)\%, \\
a_{sl}^s(\text{comb.}) &= (-1.67 \pm 0.54)\%
\end{align*}
\]

**LHCb + Y(4S) results appear consistent with SM expectation**

\(D0\) final Run II results yield 3\(\sigma\) discrepancy with SM

\(N.\ Leonardo\) flavor physics & rare decays
\[ \text{CP-odd final state: no need for angular analysis!} \]

\[ \Gamma(B_s^0 \rightarrow f_-) + \Gamma(B_s^0 \rightarrow f_-) \]
\[ = N e^{-\Gamma_s t} \left\{ e^{\Delta \Gamma_s t/2} (1 + \cos \phi_s) + e^{-\Delta \Gamma_s t/2} (1 - \cos \phi_s) \right\} \]

\[ \Gamma(B_s^{-} \rightarrow f_-) \]
\[ = N e^{-\Gamma_s t} \left\{ \frac{e^{\Delta \Gamma_s t/2}}{2} (1 + \cos \phi_s) + \frac{e^{-\Delta \Gamma_s t/2}}{2} (1 - \cos \phi_s) \pm \sin \phi_s \sin(\Delta m_s t) \right\} \]

**CP-odd final state:**
- **Untagged:**
  \[ \Gamma(B_s^0 \rightarrow f_-) + \Gamma(B_s^0 \rightarrow f_-) \]
  \[ = N e^{-\Gamma_s t} \left\{ e^{\Delta \Gamma_s t/2} (1 + \cos \phi_s) + e^{-\Delta \Gamma_s t/2} (1 - \cos \phi_s) \right\} \]

**Tagged:**
- \[ \Gamma(B_s^{-} \rightarrow f_-) \]
  \[ = N e^{-\Gamma_s t} \left\{ \frac{e^{\Delta \Gamma_s t/2}}{2} (1 + \cos \phi_s) + \frac{e^{-\Delta \Gamma_s t/2}}{2} (1 - \cos \phi_s) \pm \sin \phi_s \sin(\Delta m_s t) \right\} \]

**Lifetime-like measurement:**
- \[ \phi_s = -0.19 + 0.173 + 0.004 \]
  \[ -0.174 - 0.003 \]

**Mixing-like measurement:**
- \[ \text{first observation} \]
- \[ \Phi_s \text{ measurement:} \]

**References:**
- **PRD 85 (2012) 011103**
- **PRD 84 (2011) 052012**
- **PLB 698 (2011) 11**
- **PLB 713 (2012) 378**
$D^0 \rightarrow \mu \mu$

- FCNC search in up-type quark sector
  - complement B and K searches
- decay $D^0 \rightarrow \mu^+ \mu^-$ highly suppressed in SM ($\sim 10^{-13}$), but enhanced by NP scenarios
- use normalization channel; e.g. at CMS
  \[ D^{*+} \rightarrow D^0 (K^+ \mu^+ \nu) \pi^+ \]
  - no excess observed, place upper limit (@90% CL)

**exclusion limits**

- CDF $< 2.1 \times 10^{-7}$ PRD 82 (2010) 091195
- BABAR: $[0.6, 8.1] \times 10^{-7}$ PRD 86 (2012)032001
- BELLE $< 1.4 \times 10^{-7}$ PRD 81 (2010) 091102
- LHCb $< 1.3 \times 10^{-8}$ LHCb-CONF-2012-005
- CMS $< 5.4 \times 10^{-7}$ CMS-PAS-BPH-11-017
probing beyond (the SM)

• central goal of LHC physics program:
  ‣ discover new physics (NP) aka BSM

• complementary approaches
  ‣ direct searches for new heavy particles produced (on-shell) in LHC collisions
  ‣ indirect searches via virtual NP contributions via high-precision measurements of SM processes
  ‣ search for rare decays, highly suppressed (or forbidden) in SM and sensitive to NP

• virtual contributions provide sensitivity to higher mass scales, well beyond the TeV scale
LHC Run II has just re-started

• something absolutely unexpected and exotic yet?

(Tevatron!) Tetraquarks, pentaquarks, ... and other exotic beasts

The “ridge” and a new, exciting bump?

Too early to tell, need more data! Just getting ready for Run2 surprises...!