Recent results from LHCb

19\textsuperscript{th} of July 2013

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\textbf{on behalf of the LHCb collaboration}

Dubna International Advanced School of Theoretical Physics / DIAS-TH

Helmholtz International Summer School

“Physics of Heavy Quarks and Hadrons”

Dubna, Russia / July 15-28, 2013
Outline

• Standard Model (SM) and its difficulties [just to remind]
  – Why and where to find New Physics (NP)?
  – Power of indirect measurements

• LHCb setup (apparatus, trigger, physical program etc.) [brief]

• Selected results [main part of the talk]
  – Rare decays (M → 2μ, M → M’2μ, B → eμ)
  – Mixing, CP violation, CKM γ in B systems
  – Mixing and CP violation in charm sector
  – Production and spectroscopy of heavy quarks

• Summary and Outlook (what can be achieved after upgrade?)
Introduction
Standard Model

No doubt that SM is great achievement!
(self consistent, no conflict with HEP)

Reasons for NP:

1) Neutrino sector
   - mass
   - oscillations

2) Astrophysics
   - baryon asymmetry of our Universe
   - dark matter

3) Radiative correction to M(Higgs)
   - fine tuning
   - desert between $M_{EW}$ and $M_{GUT}$

SUSY good candidate to solve 2) & 3)
Power of indirect measurements

**Example #1: CP violation in kaon system**
Has been done when only 3 quark were known
1972 Kabayashi-Maskawa 6-quark model
~ 13 years before Upsilon discovery

**Example #2: Weak neutral current (Gargamelle bubble chamber)**
~ 10 years before Z discovery at UA1/2

**Example #3: ARGUS collaboration report large B-mixing**
Suggest large mass of top quark
~8 years $t$ has been discovered at Tevatron
Indirect measurements at LHC

- How NP related to flavour physics?
- Is NP weakly coupled to flavour sector (MFV) or at very high scale?
  
  **Important** to have probes beyond LHC energies (direct observation)!

- Better to use processes which are either forbidden either highly suppressed in SM

  **Flavour Changing Neutral Currents (FCNC)** can be such a probe

- Other possibilities **Lepton Flavour Violation (LFV), CPV in charm sector**
LHCb features
Beauty and charm production

- **LHCb: forward spectrometer** $2 < \eta < 5$
  
  (ATLAS & CMS: $|\eta|<2.5$)

- In LHCb acceptance ($pp$-collisions $\sqrt{s} = 7\text{TeV}$)
  
  $\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0 \ \mu b$
  

  $\sigma(c\bar{c}) = 1419 \pm 12 \pm 116 \ \mu b \sim 20 \times \sigma(b\bar{b})$

  Largest charm samples in the world
  
Experimental setup

- $\epsilon_{PID}(\mu) \approx 97\%$
  - MisID ($\pi \rightarrow \mu$) $\approx 3\%$

- $\epsilon_{PID}(K) \approx 95\%$
  - MisID ($K \rightarrow \pi$) $\approx 5\%$

- Muon System
- RICH Detectors specific for LHCb
- Vertex Detector

- $\sigma(\text{IP}) \approx 20\mu m$
- $\delta p/p = 0.4 - 0.6\%$
- $\epsilon_{\text{track}} > 96\%$

- Calorimeters
- Tracking System

- $\frac{\sigma}{E} \approx 1\% \oplus \frac{10\%}{\sqrt{E\, [\text{GeV} ]}}$
- $\epsilon_{PID}(e) \approx 95\%$
- MisID ($e \rightarrow h$) $\approx 5\%$
Operation in 2010/12

- **p-p at 3.5 / 4 TeV**
- **p-Pb at $\sqrt{s_{NN}} = 5$ TeV in 2013**

- LHCb operates with high efficiency
- Take data at constant instantaneous luminosity rate: $\mathcal{L} \approx 4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$ (factor 2 larger than design luminosity)
- Visible pp interactions per bunch crossing $\mu = 1.7$ (50 ns bunch spacing)
LHCb trigger

Level 0:
- Largest $p_T$ (E) used
- Typical thresholds 1.5 – 3.5 GeV/c

Software HLT1:
- Partial event reconstruction
- Selection based on $p_T$, IP

Software HLT2:
- Full event reconstruction
- Mass cuts

On-line charm and strange signals
Data quality from sig-to-bkg ratio.
LHCb data analysis

Tagging if needed

Event selection

Kinematical and topological info
(pT, p, IP, vertex and track quality)

PID information

Cut based or multivariate selection
BDT, Neurobayes, etc.

Optimization of selection
Using MC
Using small sample of real data

Angular analysis++

Check for systematics

And a lot of other checks!
Physics program of LHCb

GOAL: Search for evidence of NP in CP violation and rare decays of beauty and charm hadrons. (Probing large mass scales via study of virtual quantum loops of new particles)

LHCb results are available in more than 130 papers submitted to journals and 110 conference contributions

Main direction of searches:

1) Rare decays
   RD with di-muons, LFV searches
2) Properties of the B systems
   CPV, Δms; Γs, ΔΓ, φs ; CKM γ determination
3) Mixing and CPV in the D systems
   Mixing observ., ΔA(CP)
4) Spectroscopy and production of heavy quarks
   X(3872) quantum num.; mass of D mesons
5) Electroweak physics
6) Soft QCD physics, pA and Ap results

[Link to LHCb results: https://cds.cern.ch(collection/LHCb%20Conference%20Contributions?ln=en]
Rare decays

1) $B_{d,s}^0 \rightarrow \mu^+ \mu^-, B \rightarrow \mu^+ \mu^- \mu^+ \mu^-, D^0 \rightarrow \mu^+ \mu^-, K_S^0 \rightarrow \mu^+ \mu^-$

2) $B$-hadron $\rightarrow$ Hadron $+ \mu^+ \mu^-, D \rightarrow \pi \mu^+ \mu^-$

3) $B \rightarrow \mu^+ e^-$

4) $B_s \rightarrow \phi K^+$
Rare decays $B_{(s)}^0 \rightarrow \mu^+\mu^-$

Helicity suppressed in SM [arXiv 1303.3820]

\[
\mathcal{B}(B_s \rightarrow \mu^+\mu^-) = (3.25 \pm 0.17) \times 10^{-9}
\]

\[
\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}
\]

$\Delta\Gamma_s$ correction [PRD 86, 014027]

\[
\mathcal{B}(B_s \rightarrow \mu^+\mu^-) < t > = \frac{1 + A_{\mu\mu} \cdot \Delta\Gamma_s / 2\Gamma_s}{1 - (\Delta\Gamma_s / 2\Gamma_s)^2} \cdot \mathcal{B}(B_s \rightarrow \mu^+\mu^-)
\]

\[
= (3.56 \pm 0.18) \times 10^{-9}
\]

5% precision SM calculations!

Sensitive to new scalar, pseudoscalar, axial-vector particles in loops

In MSSM:

\[
c_{S,P}^{MSSM} \propto \frac{m_b^2 m_\mu^2 \tan^6 \beta}{M_A^4}
\]
# Table with different scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>would point to ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{BR}(B_s \to \mu\mu) \gg SM$</td>
<td>Big enhancement from NP in scalar sector, SUSY high $\tan\beta$</td>
</tr>
<tr>
<td>$\mathcal{BR}(B_s \to \mu\mu) \neq SM$</td>
<td>SUSY ($C_S$, $C_P$), ED’s, LHT, TC2 ($C_{10}$)</td>
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<td>$\mathcal{BR}(B_s \to \mu\mu) \sim SM$</td>
<td>Anything ((\Rightarrow) rule out regions of parameter space that predict sizable departures from SM. Obviously)</td>
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<td>$\mathcal{BR}(B_s \to \mu\mu) / \mathcal{BR}(B_d \to \mu\mu) \neq SM$</td>
<td>CMFV ruled out. New FCNC sources fully independent of CKM matrix (RPV SUSY, ED’s etc...)</td>
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Here we are now!

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Some words about analysis strategy

- Blind analysis
- Robust selection cuts for reduction of combinatorics
- Boosting Decision Tree (BDT) method using 9 topological variables (to avoid correlation with $M_{inv}$)
- BDT trained on signal and bkg MC
- BDT calibrated on data using $B \rightarrow h^+h^-$ as signal and mass sidebands for bkg.
- 15 BDT bins. In each bin, the compatibility of the observed events with bkg only and SM+bkg hypotheses is calculated.
Result: first evidence of $B_{s}^{0} \rightarrow \mu^{+}\mu^{-}$

- Compatibility with background only hypothesis (1-CL$_{b}$):
  - $B^{0} \rightarrow \mu^{+}\mu^{-}$: 0.11
  - $B_{s}^{0} \rightarrow \mu^{+}\mu^{-}$: $5.3 \times 10^{-4} \rightarrow 3.5\sigma$, evidence of decay!
- $\mathcal{B}(B^{0} \rightarrow \mu^{+}\mu^{-}) < 9.4 \times 10^{-10}$ (at 95% CL)
  - Set using the CL$_{s}$ method
- $\mathcal{B}(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$
  - Profile likelihood scan of $\mathcal{B}(B_{s}^{0} \rightarrow \mu^{+}\mu^{-})$ by simultaneously fitting $m_{\mu^{+}\mu^{-}}$ across all BDT bins for 7 & 8 TeV datasets

Should be compared with time-integrated branching fraction $(3.54 \pm 0.30) \times 10^{-9}$

PRL 110, 021801
Any model that violates flavour via (pseudo)scalar is constrained.

High $\tan\beta$ SUSY too

arXiv:1205:6494
$B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

Non-resonant SM contribution

PDG, JPG 37, 1
$\mathcal{B}(B_{(s)}^0 \rightarrow J/\psi \phi) = (2.3 \pm 0.9) \times 10^{-8}$

PRD 70, 114028
$\mathcal{B}(B_{(s)}^0 \rightarrow \mu^+ \mu^- \gamma(\rightarrow \mu^+ \mu^-)) < 10^{-10}$

PRD 85, 077701 & PRL 94, 021801

Possible enhancement scenarios with new particles ($\rightarrow 2\mu$), HyperCP ...

Dataset: 1.0 fb$^{-1}$ @ 7 TeV

First limits on these decays:

$\mathcal{B}(B_s^0 \rightarrow 4\mu) < 1.6 \times 10^{-8}$
$\mathcal{B}(B^0 \rightarrow 4\mu) < 6.6 \times 10^{-9}$
Rare decay $D^0 \to \mu^+ \mu^-$

- FCNC in charm sector suppressed by GIM (absence of a high mass downtype quark)
- Small D mixing & small BR
- $D^0 \to \mu\mu$ dominated by long distance contribution (via two-photon intermediate state)
- **SM:** BR $\sim 6 \times 10^{-11}$; **Belle:** $< 1.4 \times 10^{-7}$
- **Three orders of magnitude to go!**
- R-parity violation models

$$B^{R_p}_{D^0 \to \mu^+ \mu^-} \leq 4.8 \times 10^{-9} \left( \frac{300 \text{ GeV}}{m_{\tilde{d}_k}} \right)^2$$

supersymmetric partner of down-type quarks

Using 1 fb$^{-1}$ (at $\sqrt{s} = 7$ TeV) LHCb sets a limit of:

$$B(D^0 \to \mu^+ \mu^-) < 6.8 \times 10^{-9} \text{ at 95\% CL}$$

(preliminary)
Rare decay $K_S^0 \to \mu^+\mu^-$

- FCNC $s \to d$ **is very suppressed**
- **SM:** BF $\sim 5 \times 10^{-12}$; **EXP:** $< 3.1 \times 10^{-7}$
- NP at $10^{-11}$ level still possible [JHEP 0401, 9]

Using 1 fb$^{-1}$ dataset at 7 TeV

BF($K_S \to \mu\mu$) $< 9 \times 10^{-9}$ at 90% CL

**New world best limit**
Factor $\sim 35$ of improvement
**B-hadron \rightarrow Hadron + \mu^+\mu^-, \ D \rightarrow \pi\mu^+\mu^-**

FCNC processes with **a lot of observables**

Clear experimental signatures with low background

Well developed SM calculations

NP can be found in

- Rates
- Angular distributions
- Asymmetries

As an example zero-crossing point at forward-backward asymmetry for \(B^0 \rightarrow K^*\mu^+\mu^-\) is well predicted within SM and has potential for NP searches.
$b \to x l^+ l^-$ and $c \to x l^+ l^-$ menu @ LHCb

A lot of channels = a lot of new (Apr-Jun 2013) results

$b \to s l^+ l^-$

- $B^0 \to K^* \mu^+ \mu^-$ arXiv:1304.6325 1st multiD angular analysis
- $B^0 \to K \mu^+ \mu^-$ PRL 110, 031801 CP asymmetry
- $B^0 \to \phi^* \mu^+ \mu^-$ arXiv:1305.2168 1st angular analysis
- $B^0 \to K^* e^+ e^-$ JHEP 05,(2013)159 1st evidence in low q2
- $\Lambda_b \to \Lambda \mu^+ \mu^-$ arXiv:1306.2577 baryons, 1st @ LHC

$c \to u l^+ l^-$

- $D_{(s)}^+ \to \pi^+ \mu^+ \mu^-$ arXiv:1304.6365 factor $\sim$50 improvement in limit
- $D_{(s)}^+ \to \pi^- \mu^+ \mu^+$
Analysis of $B \rightarrow K^* \mu^+ \mu^-$

- Loose preselection cuts
- Using BDT trained on proxy $B \rightarrow K^* J/\psi$
- Background from upper B sideband
- Choice of variables to avoid biases on angles and $q^2 = m^2(\mu\mu)$
- Final selection from BDT decay time, flight direction, trk/vtx quality, $p_T$, PID
- BR measured relative to $B \rightarrow K^* J/\psi$
Analysis of $B \rightarrow K^* \mu^+ \mu^-$

- Branching fraction measured differential in $q^2$ and 3 decay angles
- Limited statistics: $\phi + \pi$ if $\phi < 0$
- Parametric in 4 angular observables $F_L, A_{FB}, S_3, A_9$, from CP asymmetries and averages of decay amplitudes
- Theoretical uncertainties smaller in angular analysis (hadronic form factors)

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos \theta_\ell d\cos \theta_K d\phi} \propto \begin{align*}
F_L \cos^2 \theta_K + & \frac{3}{4}(1-F_L)(1-\cos^2 \theta_K) - \\
F_L \cos^2 \theta_K(2\cos^2 \theta_\ell - 1) + & \\
\frac{1}{4}(1-F_L)(1-\cos^2 \theta_K)(2\cos^2 \theta_\ell - 1) + \\
S_3(1-\cos^2 \theta_K)(1-\cos^2 \theta_\ell) \cos 2\phi + \\
\frac{4}{3} A_{FB}(1-\cos^2 \theta_K) \cos \theta_\ell + \\
A_9(1-\cos^2 \theta_K)(1-\cos^2 \theta_\ell) \sin 2\phi \end{align*}
\]
Analysis of $B \rightarrow K^{*} \mu^{+} \mu^{-}$

Typical SM prediction: $q^2_0 = 4.9 \pm 0.9 \text{ GeV}^2/c^4$

zero-crossing point

Typical SM prediction: $3.9 - 4.4 \text{ GeV}^2/c^4$
Analysis of $B \rightarrow K^{*} \mu^{+} \mu^{-}$

All experiments consistent with SM
Babar: Phys. Rev. D. 73. 092001
ATLAS: ATLAS-CONF-2013-038
CMS: CMS-PAS-BPH-11-009

SM predictions
Analysis of $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$

Normalize to $\Lambda_b^0 \rightarrow \Lambda J/\psi (\mu^+ \mu^-)$:

$$\text{BR}(\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-) = (0.96 \pm 0.16_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.21(\text{BR})) \times 10^{-6}$$
LHCb result

 Compatible with previous measurement by CDF
 [PRL 107 (2011) 201802]

 Binned SM
 [PRD87 (2012) 074502]

 $d\mathcal{B}/dq^2$

 limit on $d\mathcal{B}/dq^2$
 at 90 % CL.
Search for $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$

- SM predictions: $\sim 10^{-9}$

- Resonances ($\eta, \rho, \omega, \phi$): $> 10^{-6}$

- Low and high M(\(\mu\mu\)) regions

- BaBar and D0 gives limits $10^{-6}$ and $10^{-7}$ on $D^+$ and $D_{s}^+$ respectively
  [PRL 100, 101801; PRD 84, 072006]

**At LHCb:**

- Good probe for NP in non-resonant region

- Resonances as control channel

- Low and high M(\(\mu\mu\)) regions
LHCb results

LHCb limits ×10^{-8} at 90% (95%) CL

<table>
<thead>
<tr>
<th>Region</th>
<th>B(D^{+}\to \pi^{+}\mu^{+}\mu^{-})</th>
<th>B(D_s^{+}\to \pi^{+}\mu^{+}\mu^{-})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total 1</td>
<td>7.3 (8.3)</td>
<td>41.0 (47.7)</td>
</tr>
<tr>
<td>Low M(\mu\mu)</td>
<td>2.0 (2.5)</td>
<td>6.9 (7.7)</td>
</tr>
<tr>
<td>High M(\mu\mu)</td>
<td>2.6 (2.9)</td>
<td>16.0 (18.6)</td>
</tr>
</tbody>
</table>

Acceptor by PLB, arXiv:1304.6365

1 fb^{-1} sample

~ 50 times better than previous measurements
Rare decay $B \rightarrow \mu^+ e^-$

- Lepton flavour violating decays occur at $\sim < 10^{-50}$ in the SM.
- The decay $B^0_s \rightarrow e^+ \mu^-$ is allowed in models with a local gauge symmetry with leptons and quarks.

So-called lepto-quarks have been directly searched for at the LHC, with limits of around 0.5-1 TeV/c$^2$ (no mixing assumed).
LHCb result on $B \rightarrow \mu^+ e^-$

- Search for $B_s^0 \rightarrow e^+ \mu^-$ at LHCb using 2011 dataset.
  [LHCb-PAPER-2013-030]

- No significant signal observed, set limits,
  \[
  B(B_s^0 \rightarrow e^+ \mu^-) < 1.4 \times 10^{-8} \quad @ \quad 95\% \quad CL \\
  B(B^0 \rightarrow e^+ \mu^-) < 3.7 \times 10^{-9} \quad @ \quad 95\% \quad CL
  \]
Lower limit on $m_{LQ}$ from $B \rightarrow \mu^+ \mu^-$


- No significant signal observed, set limits,
  
  $m_{LQ}(B_s^0 \rightarrow e^+ \mu^-) > 101 \text{ TeV}/c^2 \ @ \ 95\% \ \text{CL}$
  
  $m_{LQ}(B^0 \rightarrow e^+ \mu^-) > 135 \text{ TeV}/c^2 \ @ \ 95\% \ \text{CL}$

[LHCb-PAPER-2013-030]
LHCb has already reported about 1st observation of decays $B^0_s \rightarrow \phi \phi$ and $B^0_s \rightarrow K^*0K^*0$

SM prediction:

$$\mathcal{B}(B^0_s \rightarrow \phi K^*0) = (0.4 \pm 0.1 \pm 0.5) \times 10^{-6}$$

30 ± 6 $B^0_s \rightarrow (K^+K^-)(K^-\pi^+)$

- Loose preselection cuts
- S-wave KK an Kπ contribution
- 6.1σ significance, 1σ from SM

- Presented here to demonstrate quite rare gluonic penguin decay, but further analysis of $B \rightarrow VV$ is also very interesting!
Properties of the $B$ ($B^+, B^0, B_s$) systems

1) $B_s^0$ oscillation frequency measurement

2) Mixing induced CPV in $B_s^0$, e.g: $B_s^0 \rightarrow J/\psi\phi$ and $B_s^0 \rightarrow J/\psi f (980)$

3) Direct CP asymmetry in $B_{(s)}^0$ decays

4) CKM angle $\gamma$
Oscillation frequency for $B_s$:

$B_s$: Fast oscillations

Excellent time resolution required!

$\Gamma = (\Gamma_L + \Gamma_H) / 2$;

$\Delta m_s = M_H - M_L$

$x = (M_H - M_L) / \Gamma$; \hspace{1em} $y = (\Gamma_L - \Gamma_H) / 2\Gamma$

Measure time dependent decay rate of $B_s \rightarrow D_s^- \pi^+$ and $\bar{B}_s \rightarrow D_s^+ \pi^-$

$PDF \propto \left[ e^{-\Gamma t} \cdot \left( \cosh \left( \frac{\Delta \Gamma}{2} t \right) \pm D \cos(\Delta m t) \right) \right] \otimes R(\sigma_t)$

Mean decay time resolution 44 fs

event-by-event decay time resolution

flavour tagging

Monte-Carlo

Data

LHCb

LHCb Technical proposal (1998)

Entries per 0.02 ps

Proper time (ps)

$\Delta m_s = 30 \text{ ps}^{-1}$

Data

LHCb

NJOP 15, 053021 (2013)

candidates / (0.1 ps)

decay time [ps]

Most precise measurement up to date

Agreement with world average & SM

Monte-Carlo

Fast oscillations

Excellent time resolution required!

$B_s$: $x = 25.194$

$y = 0.046$

$M_H - M_L$

$\Gamma_L + \Gamma_H$
Mixing induced CP violation in $B_s$

- Decay of particle and antiparticle to same state
- **CP violating phase** predicted to be **very small in SM**
  
  \[ \phi_{s}^{SM} = -2\beta_s = (-0.0363 \pm 0.0016) \text{ rad} \]

- **Observable very sensitive to NP !**

- LHCb measured it in two modes (1 fb$^{-1}$ dataset)
  
  [arXiv: 1304.2600]

- Measurement of time-dependent CP asymmetry

  \[ A_{CP}(t) \sim (1 - 2\omega_{tag}) D(\sigma_t) \sin(\Delta m_s(t)) \sin(\phi_{s}) \]

- **Tagging and high decay time resolution required!**
Mixing induced CP violation in $B_s$

$B_s^0 \rightarrow J/\psi\phi$

- narrow $\phi$ resonance: experimentally clean
- VV final state: mixture of CP even/odd components
- Time-dependent angular analysis to disentangle the amplitudes and extract $\phi_s$
- Fit for more than 10 physics parameters: amplitudes, $\Gamma_s$, $\Delta\Gamma_s$, $\phi_s$
- $\Delta m_s$ taken from $B_s \rightarrow D_s\pi$

$\phi_s = 0.07 \pm 0.09\,(stat) \pm 0.01\,(syst)\,rad$

$\Gamma_s = 0.663 \pm 0.005\,(stat) \pm 0.006\,(syst)\,ps^{-1}$

$\Delta\Gamma_s = 0.100 \pm 0.016\,(stat) \pm 0.003\,(syst)\,ps^{-1}$

$\epsilon_{tag}D^2 = 3.13\%$

Proper time resolution: $\sim 45\,fs$
Mixing induced CP violation in $B_s$

$B_s^0 \rightarrow J/\psi \pi \pi$

- dominated by $f_0 \rightarrow \pi^+ \pi^-$
- BF $\sim 35\%$ of $B_s^0 \rightarrow J/\psi \phi$
- CP-odd final state
  \[[775 < M(\pi \pi) < 1550 \text{ MeV}]\]
  [arXiv 1204.5643]: no angular analysis is required
- Constrain $\Gamma_s$ and $\Delta \Gamma_s$ to the $B_s^0 \rightarrow J/\psi \phi$ result

Consistent with SM prediction!

Combined fit $B_s^0 \rightarrow J/\psi \phi$ e $B_s^0 \rightarrow J/\psi \pi \pi$ [arXiv:1304.2600]

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

$\Gamma_s = 0.661 \pm 0.004(\text{stat}) \pm 0.006(\text{syst}) \text{ ps}^{-1}$

$\Delta \Gamma_s = 0.106 \pm 0.011(\text{stat}) \pm 0.007(\text{syst}) \text{ ps}^{-1}$
Constrain on NP parameters

Consistent with SM prediction

and data from other experiments!

HFAG preliminary

based on [arXiv:1107.0266]
Direct CP asymmetry in $B^{0}_{(s)}$ decays

Direct CP asymmetry hard to calculate, but “easy” to measure.

1 fb$^{-1}$ dataset, PRL 110, 221601

Oscillation considered in the analysis!

Detection asymmetry

Production asymmetry

$A_{CP} = A_{\text{raw}} - A_{\Delta}$

$A_{\Delta}(B^{0}_{(s)} \rightarrow K\pi) = \zeta_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^{0}_{(s)})$

1$^{st}$ observation (6.5$\sigma$) of direct CP asymmetry in $B^{0}$ system

A_{\text{CP}}(B^{0}_{s} \rightarrow K^{-}\pi^{+}) =

= 0.27 \pm 0.04^{\text{stat}} \pm 0.01^{\text{syst}}$

A_{\text{CP}}(B^{0}_{s} \rightarrow K^{+}\pi^{-}) =

= -0.080 \pm 0.007^{\text{stat}} \pm 0.003^{\text{syst}}
Parameters of CKM triangle

1) There are another fitting group and another triangles
2) CKM angle $\gamma$ measured with high uncertainty! (but very precise SM prediction for these observable)
Parameters of CKM triangle

CKM angle $\gamma$ measured with high uncertainty!

(but very precise SM prediction for these observable)

$\gamma = \arg[-V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)]$  

$\delta \gamma / \gamma < \mathcal{O}(10^{-6})$

Very high potential for NP searches!

<table>
<thead>
<tr>
<th>Probe</th>
<th>$\Lambda_{NP}$ for (N)MFV NP</th>
<th>$\Lambda_{NP}$ for gen. FV NP</th>
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<td>$\gamma$ from $B \to DK$</td>
<td>$\Lambda \sim \mathcal{O}(10^2 \text{ TeV})$</td>
<td>$\Lambda \sim \mathcal{O}(10^3 \text{ TeV})$</td>
</tr>
<tr>
<td>$B \to \tau\nu$</td>
<td>$\Lambda \sim \mathcal{O}(1 \text{ TeV})$</td>
<td>$\Lambda \sim \mathcal{O}(30 \text{ TeV})$</td>
</tr>
<tr>
<td>$b \to s sd$</td>
<td>$\Lambda \sim \mathcal{O}(1 \text{ TeV})$</td>
<td>$\Lambda \sim \mathcal{O}(10^3 \text{ TeV})$</td>
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<tr>
<td>$\beta$ from $B \to J/\psi K_S$</td>
<td>$\Lambda \sim \mathcal{O}(50 \text{ TeV})$</td>
<td>$\Lambda \sim \mathcal{O}(200 \text{ TeV})$</td>
</tr>
<tr>
<td>$K - \bar{K}$ mixing</td>
<td>$\Lambda &gt; 0.4 \text{ TeV (6 TeV)}$</td>
<td>$\Lambda &gt; 10^3(4) \text{ TeV}$</td>
</tr>
</tbody>
</table>
GLW / ADS / GGLZ methods

Gronau-London-Wyler (GLW) \( D \) in \( CP \)-eigenstate \((D \to KK', \pi\pi)\)

\[
R_{CP \pm} = \frac{2[\Gamma(B^- \to D_{CP \pm}K^-) + \Gamma(B^+ \to D_{CP \pm}K^+)]}{\Gamma(B^- \to D^0K^-) + \Gamma(B^+ \to D^0K^+)} \\
A_{CP \pm} = \frac{\Gamma(B^- \to D_{CP \pm}K^-) - \Gamma(B^+ \to D_{CP \pm}K^+)}{\Gamma(B^- \to D_{CP \pm}K^-) + \Gamma(B^+ \to D_{CP \pm}K^+)}.
\]

[PLB 265, 172 (1991)]

Atwood-Dunietz-Sony (ADS)

\( D \) Cabibbo-allowed \((D^0 \to K^-\pi^+)\) and doubly Cabibbo-suppressed \((D^0 \to K^+\pi^-)\) states.

\[
R_{ADS} = \frac{\Gamma(B^- \to D[\to \pi^-K^+]K^-) + \Gamma(B^+ \to D[\to \pi^+K^-]K^+)}{\Gamma(B^- \to D[\to K^-\pi^+]K^-) + \Gamma(B^+ \to D[\to K^+\pi^-]K^+)} \\
A_{ADS} = \frac{\Gamma(B^- \to D[\to \pi^-K^+]K^-) - \Gamma(B^+ \to D[\to \pi^+K^-]K^+)}{\Gamma(B^- \to D[\to K^-\pi^+]K^-) + \Gamma(B^+ \to D[\to K^+\pi^-]K^+)}.
\]

[PRL 78, 3257 (1997)]

Giri, Grossman, Soffer and Zupan (GGSZ) deals with self conjugate 3-body final states:
\( f = D \to K_S\pi\pi \) and \( K_S KK \).


Strong phase varies over the 3-body phase space.

\[
x_\pm = r_B \cos(\delta_B \pm \gamma) \quad y_\pm = r_B \sin(\delta_B \pm \gamma)
\]

\[
N_{+} = h_B[K_{\pi_1} + (x_1^2 + y_1^2)K_{\pi_2} + 2\sqrt{K_{\pi_1}K_{\pi_2}}(x_1x_{\pi_1} + y_1y_{\pi_1})]
\]

\[
N_{-} = h_B[K_{\pi_1} + (x_1^2 + y_1^2)K_{\pi_2} + 2\sqrt{K_{\pi_1}K_{\pi_2}}(x_1x_{\pi_1} - y_1y_{\pi_1})]
\]

Binned Dalitz plot phase variation measured by CLEO-c:

Result on CKM $\gamma$

- **(Four-body ADS)**: $B \rightarrow Dh$, $D \rightarrow K \pi \pi \pi$ [LHCb-PAPER-2012-055; arxiv:1303.4646]

The combined results for $B \rightarrow DK$ decays using 1 fb$^{-1}$ (7 TeV) from GLW/ADS/GGSZ plus 2 fb$^{-1}$ (8 TeV) from GGSZ:

Confidence intervals:
- $\gamma \in [43.9, 89.5]^\circ$ at 95% CL
- $\gamma \in [55.1, 79.1]^\circ$ at 68% CL

Best fit value:
- $\gamma = (67 \pm 12)^\circ$ at 68% CL


LHCb-CONF-2013-006  LHCb-CONF-2013-004
Mixing and CPV in charm sector
**D⁰ mixing**

Flavor eigenstates
- Well defined flavor

Hamiltonian eigenstates
- Well defined m and Γ
- Define the mixing parameters

Mixing determines the time evolution of the flavor eigenstates

\[
|D_{1,2}\rangle = p|D^{0}\rangle \pm q|\bar{D}^{0}\rangle
\]

- \(x = \frac{m_1 - m_2}{\Gamma}\)
- \(y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}\)
- \(\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}\)

**Event classes - flavour tagging at production and decay**

- **No Mixing**
  - \(D^{*+} \rightarrow \pi^{+} D^{0}\)

- **Mixing**
  - \(\bar{D}^{0} \rightarrow \pi^{-} K^{+}\)

- **Right Sign Decay (RS)**
  - \(D^{0} \rightarrow \pi^{-} K^{-}\)
  - \(R \approx 1\)
  - DCS unmixed 0.3%
  - CF 0.006%

- **Wrong Sign Decay (WS)**
  - \(D^{0} \text{ Mixing}\)

**Time evolution of the WS decay rate**

- Assume CP conservation and \(|x| \ll 1; |y| \ll 1\)

\[
T_{WS}(t) \propto e^{-\Gamma t} \left( R_D + \sqrt{R_D y' \Gamma t + \frac{x'^2 + y'^2}{4} (\Gamma t)^2} \right)
\]

- DCS
- Interference
- Mixing

\(\delta_{K\pi}^{K\pi}\) is the strong phase between CF and DCS amplitudes (\(D^{0} \rightarrow K\pi\))

\[
x' = x \cos \delta_{K\pi}^{K\pi} + y \sin \delta_{K\pi}^{K\pi}
y' = -x \sin \delta_{K\pi}^{K\pi} + y \cos \delta_{K\pi}^{K\pi}
\]

\(y'^2 + x'^2 = x^2 + y^2\)
D⁰ mixing

- Measure the Number of WS and RS D⁰ decays in 13 bins of the lifetime.
  \[ N_{RS}^{tot} = 8.4 \times 10^6 \quad N_{WS}^{tot} = 3.6 \times 10^4 \]
- Fit the \( N_{WS}^{tot} / N_{RS}^{tot} \) vs the D⁰ decay time
  \[ R(t) \propto e^{-R \Gamma t} \left( R_D + \sqrt{R_D y'} \Gamma t + \frac{x'^2 + y'^2}{4} (\Gamma t)^2 \right) \]

- Mixing Parameter
  \[ R_D = (0.352 \pm 0.015)\% \]
  \[ y' = (0.72 \pm 0.24)\% \]
  \[ x'^2 = (-0.009 \pm 0.013)\% \]

Errors include sys. uncertainties

- First single measurement larger 5\(\sigma\)
- Exclude at 9.1 \(\sigma\)
CP violation in $D$ decays

In SM direct CP violation predicted to be small $\sim 10^{-3} - 10^{-4}$

Access via asymmetry measurement

$$A_{CP}(f; t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} = a_{CP}^{dir}(f) + \frac{t}{\tau} a_{CP}^{ind}$$

LHCb: Time integrated difference of asymmetries

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = [a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)] + \frac{\Delta < t >}{\tau} a_{CP}^{ind}$$

With 0.6fb$^{-1}$ data sample LHCb found $3.5\sigma$ evidence of direct CP violation

$$\Delta(A^{CP}) = A^{CP}(D^0 \to K^+K^-) - A^{CP}(D^0 \to \pi^+\pi^-) = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]$$

Later some indication came from other experiments

Led to discussion: “Is it sign from NP?”
CP violation in $D$ decays

In **SM direct CP violation** predicted to be **small** $\sim 10^{-3} - 10^{-4}$

Access via asymmetry measurement

\[
A_{CP}(f, t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to \bar{f})}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to \bar{f})} = a_{CP}^{dir} + \frac{t}{\tau} a_{CP}^{ind}
\]

LHCb measured **time integrated difference of asymmetries**

\[
\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = [a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)] + \frac{\Delta < t >}{\tau} a_{CP}^{ind}
\]

**Two complimentary analysis** with 1 fb$^{-1}$ data sample

[arXiv:1303.2614] [LHCb-CONF-2013-003]
CP violation in $D$ decays

**LHCb results:**

- $D^*$ tagged sample (preliminary)
  \[ \Delta A_{CP} = (-0.34 \pm 0.15 \text{ (stat)} \pm 0.10 \text{ (sys)}) \%
  \]

- $\mu$ tagged sample
  \[ \Delta A_{CP} = (+0.49 \pm 0.30 \text{ (stat)} \pm 0.14 \text{ (sys)}) \%
  \]

**Consistent with no CPV hypothesis!**

**HFAG averages:**

\[ a_{CP}^{\text{ind}} = (-0.010 \pm 0.162) \%
\]

\[ \Delta a_{CP}^{\text{dir}} = (-0.329 \pm 0.121) \%
\]

**Note:** $\Delta A_{CP}$ measurements in $D^+ \rightarrow \phi \pi^+$ and $D_s^+ \rightarrow K_s^0 \pi^+$ are compatible with 0 \[ \text{arXiv:1303.4906, not discussed here} \]
Production & Spectroscopy

1) $X(3872)$ quantum numbers

2) Mass of $D$ mesons
X(3872) quantum numbers

- It is extremely narrow. Only upper limits on its width (<1.2 MeV)
  None of the known c\bar{c} states above DD threshold is so narrow
  - This automatically eliminates all c\bar{c} excitations which can decay to DD
- Its mass is not near any of the predicted c\bar{c} masses. Closest predicted c\bar{c} states which could be narrow: 2^3P_{1++}, 1^1D_{2--}
- Its mass is nearly equal m(D^0)+m(D^{0*}):
  - It is loosely bound D^0\bar{D}^{0*}=(c\bar{u})\bar{(c\bar{u})} molecule or (c\bar{c}u\bar{u}) tetraquark?
    Both models require J^{PC}=1^{++}

CDF's binned 3D angular $\chi^2$ fit:

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>decay</th>
<th>LS</th>
<th>$\chi^2$ (11 d.o.f.)</th>
<th>$\chi^2$ prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1^{++}</td>
<td>$J/\psi \rho^0$</td>
<td>01</td>
<td>13.2</td>
<td>0.28</td>
</tr>
<tr>
<td>2^{++}</td>
<td>$J/\psi \rho^0$</td>
<td>11,12</td>
<td>13.6</td>
<td>0.26</td>
</tr>
<tr>
<td>1^{+-}</td>
<td>$J/\psi (\pi\pi)_S$</td>
<td>01</td>
<td>35.1</td>
<td>$2.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>2^{+-}</td>
<td>$J/\psi (\pi\pi)_S$</td>
<td>11</td>
<td>38.9</td>
<td>$5.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>1^{-+}</td>
<td>$J/\psi (\pi\pi)_S$</td>
<td>11</td>
<td>39.8</td>
<td>$3.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>2^{-+}</td>
<td>$J/\psi (\pi\pi)_S$</td>
<td>21</td>
<td>39.8</td>
<td>$3.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>3^{-+}</td>
<td>$J/\psi (\pi\pi)_S$</td>
<td>21</td>
<td>41.0</td>
<td>$2.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>2^{++}</td>
<td>$J/\psi \rho^0$</td>
<td>01</td>
<td>43.0</td>
<td>$1.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>1^{-+}</td>
<td>$J/\psi \rho^0$</td>
<td>10,11,12</td>
<td>45.4</td>
<td>$4.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>0^{-+}</td>
<td>$J/\psi \rho^0$</td>
<td>11</td>
<td>104</td>
<td>$3.5 \times 10^{-17}$</td>
</tr>
<tr>
<td>0^{+-}</td>
<td>$J/\psi \rho^0$</td>
<td>11</td>
<td>129</td>
<td>$&lt; 1 \times 10^{-20}$</td>
</tr>
</tbody>
</table>

Cannot distinguish between 1^{++} and 2^{++}
All other ruled out.

Previous angular analysis - CDF

CDF $p\bar{p} \rightarrow X(3872) + \ldots$
0.8 fb^{-1}
2292±113 events

PRL98(2007)132002

20285±228 ψ(2S)

56
X(3872) quantum numbers

\[ B^+ \rightarrow X(3872)K^+, \ X(3872) \rightarrow J/\psi \ \rho, \ J/\psi \rightarrow l^+l^-, \ \rho \rightarrow \pi^+\pi^- \]

\[ P(\Omega | J_X, A^{J_X}_{\lambda_\psi, \lambda_\rho}) \propto \sum_{\Delta \lambda_\mu = -1,1} \sum_{\lambda_\psi = -1,0,1} \sum_{\lambda_\rho = -1,0,1} A^{J_X}_{\lambda_\psi, \lambda_\rho} d^{J_X}_{0, \lambda_\psi - \lambda_\rho} (\theta_X) d^1_{\lambda_\psi, \Delta \lambda_\mu} (\theta_\psi) e^{i\lambda_\psi (\phi_\psi - \phi_X)} d^1_{-\lambda_\rho, 0} (\theta_\rho) e^{i\lambda_\rho (\phi_\rho - \phi_X)} \]

LHCb:
- 1fb\(^{-1}\) sample
- 313±26 ev.

5D analysis
- Unbinned data
- Likelihood ratio test

arXiv:1302.6269
Accepted by PRL
$X(3872)$ quantum numbers

The Gaussian approximation conservative since the actual distribution to the left of the Gaussian fit.

- The $2^+$ hypothesis is ruled out at $8.4\sigma$ (>8 after systematics)
- $1^{++}$ C.L. is high (34%).

- The state $\eta_c(2^3 P_1)$ is excluded, favour unconventional interpretations $\chi_{c1}(2^3 P_1), D^* D^0$ molecule, tetra quarks or charmonium-molecules

arXiv: 1302.6269
Accepted by PRL
Interpreting $X(3872)$ as $D^* D^0$ molecule $E_B$ is determined by D mass measurements: $E_B = 0.16 \pm 0.26 \text{ MeV}/c^2$

- **Mass measurements in the D system**
  
  - Determine $D^0$ mass in $D^0 \rightarrow K^+ K^- K^- \pi^+$
    
    $M(D^0) = 1864.75 \pm 0.15 \text{(stat)} \pm 0.11 \text{(sys)} \text{ MeV}/c^2$

  - Mass difference measurements
    
    $M(D^+) - M(D^0) = 4.76 \pm 0.12 \text{(stat)} \pm 0.07 \text{(sys)} \text{ MeV}/c^2$

    $M(D_s^+) - M(D^+) = 98.68 \pm 0.03 \text{(stat)} \pm 0.04 \text{(sys)} \text{ MeV}/c^2$

  - Derive a significantly more precise $D_s^+$ mass
    
    $M(D_s^+) = 19684.19 \pm 0.20 \pm 0.14 \pm 0.08 \text{ MeV}/c^2$

  - Dominant syst. uncertainty on the mass is due to the momentum scale of 0.03%

  - $D^0$ mass: $0.09 \text{ MeV}/c^2$
  
  - Mass difference: $0.04 \text{ MeV}/c^2$
Summary

LHCb, the forward spectrometer for precision studies in flavour physics domain

Excellent performance of the LHC and LHCb has led to a lot of physics results

- Test of SM (which still holds its ground!)
- Search for NP
- Make CP violation measurements in b- and c-sectors

World best quality of the results in charm and beauty physics!

Remember, that presented here measurements use mainly the 1 fb\(^{-1}\) dataset

(70% of the 2010-12 data still in progress)

OUTLOOK:

1) Plan to have more than 5 fb\(^{-1}\) at \(\sqrt{s} = 13\) TeV during next LHC run (2015-18)
   => 8 times higher statistics in 2019 (in comparison with presented results)

2) Upgrade (next slide)
### Outlook. **Theory vs. 50 fb$^{-1}$**

**EPJ C 73, 2373**

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb$^{-1}$)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$</td>
<td>0.10 [30]</td>
<td>0.025</td>
<td>0.008</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$</td>
<td>0.17 [32]</td>
<td>0.045</td>
<td>0.014</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$a_{s}^{q_{l}}$</td>
<td>$6.4 \times 10^{-3}$ [63]</td>
<td>$0.6 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-3}$</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gluonic penguins</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi\phi)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow K^{*0}K^{*0})$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi K_s^0)$</td>
<td>0.17 [63]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi\gamma)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{s}^{\text{eff}} (B_s^0 \rightarrow \phi\gamma)/\tau_{B_s^0}$</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguins</td>
<td>$S_3 (B^0 \rightarrow K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.08 [64]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB} (B^0 \rightarrow K^{*0}\mu^+\mu^-)$</td>
<td>25% [64]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>$A_1 (K\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.25 [9]</td>
<td>0.08</td>
<td>0.025</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B (B^+ \rightarrow \pi^+\mu^+\mu^-)/B (B_s^0 \rightarrow \mu^+\mu^-)$</td>
<td>25% [29]</td>
<td>8%</td>
<td>2.5%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguins</td>
<td>$B (B_s^0 \rightarrow \mu^+\mu^-)$</td>
<td>$1.5 \times 10^{-9}$ [4]</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$B (B^0 \rightarrow \mu^+\mu^-)/B (B_s^0 \rightarrow \mu^+\mu^-)$</td>
<td>–</td>
<td>$\sim 100%$</td>
<td>$\sim 35%$</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma (B \rightarrow D^{(<em>)}K^{(</em>)})$</td>
<td>$\sim 10$–$12^\circ$ [40,41]</td>
<td>4$^\circ$</td>
<td>0.9$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\gamma (B_s^0 \rightarrow D_sK)$</td>
<td>–</td>
<td>11$^\circ$</td>
<td>2.0$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \rightarrow J/\psi K_s^0)$</td>
<td>0.8$^\circ$ [63]</td>
<td>0.6$^\circ$</td>
<td>0.2$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T$</td>
<td>$2.3 \times 10^{-3}$ [63]</td>
<td>$0.40 \times 10^{-3}$</td>
<td>$0.07 \times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td>$CP$ violation</td>
<td>$\Delta A_{CP}$</td>
<td>$2.1 \times 10^{-3}$ [8]</td>
<td>$0.65 \times 10^{-3}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>
Thank you for your attention!