Recent Highlights from the LHCb experiment
looking for the Mass in the Flavour Shop

Giacomo Graziani (INFN Firenze)
on behalf of the LHCb Collaboration

Origin of Mass 2016
CP³-Origins, SDU
Odense, Denmark
May 30, 2016
The Flavour problem

- The flavour sector is probably the most demanding test-bench for any model beyond the Standard Model

- Indirect bounds on the scale for generic New Physics couplings from flavour measurements (and in particular from $\Delta F = 2$ transitions) go well beyond the scale accessible for production of new particles at the LHC

- New Physics at TeV scale is not “natural” for flavour, models need *ad hoc* requirements to comply with current measurements (MFV, alignment, ...)

![Plot from Neubert, EPS-HEP 2011](plot.png)
Example: $B_s \rightarrow \mu^+\mu^-$

$B_{(s)}^0 \rightarrow \mu^+\mu^-$ is helicity suppressed FCNC decay, predicted with high accuracy in the SM:

### THEORY

- $B(B_s^0 \rightarrow \mu^+\mu^-) = (3.56 \pm 0.18) \times 10^{-9}$
- $B(B^0 \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$

High sensitivity to new neutral mediators in loops!

Observation by LHCb and CMS in good agreement with SM:

Nature 522 (2015) 68

- $B(B_s^0 \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$
- $B(B^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$
The killer of MSSM parameter space!

modified from Straub arXiv:1012.3893

$10^9 \times BR(B_d \to \mu^+\mu^-)$

$10^9 \times BR(B_s \to \mu^+\mu^-)$

LHCb+CMS 68% CL

SM

MSSM-LL

MSSM-RVV2

MSSM-AKM

MSSM-AC

CDF 95% C.L.

pre-LHC

RSc
Outline

Principles of LHCb

A selection from recent bounds and hints from b Physics @ LHCb

- Results from semileptonic b decays:
  - mixing frequency $\Delta m_d$
  - CP Violation in B mixing
  - $|V_{ub}|$ from b baryon decays
  - Lepton universality in b decays

Results and plans beyond b Physics

- Charm and strange
- Production studies @ 13 TeV
- Spectroscopy: new exotic states
- Fixed target Physics
**LHCb Principles**

**LHC** is the biggest \( b \) quark factory on earth

\( b \) is the richest flavour physics laboratory:

- Many decay channels
- Relatively large CPV effects from 3 generation mixing
- High mass reduce theory uncertainty
- Lifetime (\( \sim 1.5 \) ps) large enough to study CPV effects as a function of time

**Detector requirements:**

**Forward geometry** optimize acceptance for \( b\bar{b} \) pairs (\( \sim 25 \% \))

**Tracking** : best possible proper time and momentum resolution

**Particle ID** excellent capabilities

**Trigger** with high efficiency down to \( p_T \sim 1 \) GeV/c

**Low pileup** : running with \( \sim 1 \) collision per crossing (lower luminosity wrt ATLAS/CMS)
LHCb Detector

Decay time resolution: \(\sim 50\) fs
IP resolution: \(\sim 20\) \(\mu\)m

Tracking efficiency: \(> 96\%\)
\(\Delta p/p : 0.5\) - \(1\) %

Muon identification:
\(\varepsilon(\mu \to \mu) \sim 97\%\) with \(\varepsilon(\pi \to \mu) \sim 2\%\)

Hadron identification:
\(\varepsilon(K \to K) \sim 95\%\) with \(\varepsilon(\pi \to K) \sim 10\%\)

Phase space:
2 < \(\eta\) < 5
5 GeV/c < \(p\) < 200 GeV/c

Capable to resolve fast \(B^0_s\) oscillations
LHCb Dataset

- Luminosity leveled to $4 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$ since 2012 (stable DAQ conditions with fixed rate)
- $3 \text{ fb}^{-1} @ 7$-$8 \text{ TeV}$ from Run 1 corresponding to $\sim 2.2 \times 10^{11} \bar{b}b$ pairs in LHCb
- Run2 @ 13 TeV
- $\sim 50\%$ increase in b prod.
- 0.4 fb$^{-1}$ collected so far
- aiming at 5 fb$^{-1}$
Golden modes for CPV in Neutral B mesons

Tree level decays to common final states for $B^0_{(s)}$ and $\bar{B}^0_{(s)}$ allow clean determination of weak phases from CPV in interference between decays with/without mixing

“Golden” modes:
- $B^0 \to J/\psi K^0_S \leftrightarrow \sin(2\beta)$, large CPV effect (B factories, confirmed by LHCb)
- $B^0_{s} \to J/\psi \phi$ and similar $\leftrightarrow \phi_s$, suppressed in SM. best measurement from LHCb
  [PRL 736 (2014) 186]
- $B \to DK$ and similar $\leftrightarrow \gamma$ angle (more difficult), LHCb combined result lowering uncertainty below 8 degrees [LHCB-CONF-2016-001]

All results consistent with CKM picture
Measurements from B semileptonic decays

Tagging $b$ mixing

Lepton Universality

$\Delta m$

CP violation

$V_{ub} / V_{cb}$

CKM matrix

Tensions in previous measurements
Using abundant and relatively clean sample of $B^0 \to D(\ast)^-\mu^+\nu_\mu X$ decays

$\delta m = M(D^\ast) - M(D)$ for $D^\ast \to D^0(\to K\pi)\pi$

$D\mu$ background from $B^\pm$ and other $b$ hadrons suppressed to $< 10\%$ through Multi Variate Analysis using kinematic and isolation criteria

Average correction applied to decay time to account for the missing momentum ($k$-factor method)
ideally \( A(t) = \frac{N^{\text{unmix}}(t) - N^{\text{mix}}(t)}{N^{\text{unmix}}(t) + N^{\text{mix}}(t)} = \cos(\Delta m_d t) \), diluted by mistagging and backgrounds

\[ \Delta m_d = (505.0 \pm 2.1(\text{stat}) \pm 1.0(\text{syst})) \text{ ns}^{-1} \]

- Most precise single measurement!
- Agrees with previous World Average
  \( \Delta m_d = 510 \pm 3 \text{ ns}^{-1} \)
- Recent improvements in lattice calculations allow tighter constraints on the CKM triangle
  (A. Bazarov et al., arXiv:1602.03560)

\[ \begin{align*}
B^0 \rightarrow D\mu\nu X \text{ sample, 2012 data} \\
4 \text{ plots for different tagging categories}
\end{align*} \]
The Semileptonic charge asymmetry $a_{\text{sl}}$

$\Delta \Gamma_{q} \Delta m_{q} \tan(\phi_{12}^{q})$

CP violation in the $B \leftrightarrow \bar{B}$ mixing probability

$$a_{\text{sl}}^{q} = \frac{P(\bar{B}_{q} \rightarrow B_{q}) - P(B_{q} \rightarrow \bar{B}_{q})}{P(\bar{B}_{q} \rightarrow B_{q}) + P(B_{q} \rightarrow \bar{B}_{q})} \sim \frac{\Delta \Gamma_{q}}{\Delta m_{q}} \tan(\phi_{12}^{q})$$

is predicted to be small in SM due to the smallness of $\Delta \Gamma$ and of the CPV phase $\phi_{12}^{q}$:

$$a_{\text{sl}}^{d} = (-4.7 \pm 0.6) \times 10^{-4} \quad a_{\text{sl}}^{s} = (-2.22 \pm 0.27) \times 10^{-5}$$

Artuso, Borissov, Lenz, arXiv:1511.09466
New Physics in B mixing?

Intriguing like-sign dimuon event asymmetry observed by D0 (without distinguishing $B^0$ and $B_s^0$):

3.9σ from SM.

Not confirmed so far by B factories and LHCb

LHCb can measure $a_{sl}$ from charge asymmetry of inclusive semileptonic decays

$B^0 \rightarrow D^{(*)-} \mu^+ \nu_\mu X$

$B^0 \rightarrow D_s^- \mu^+ \nu_\mu X$
Measured from time-dependent asymmetry in $B^0 \to D^- (\to K^+\pi^-\pi^-) \mu^+\nu_\mu X$ and $B^0 \to D^{*-} (\to D^0\pi^- \to K^+\pi^-\pi^-) \mu^+\nu_\mu X$

$$A_{raw}(t) = \frac{N(f, t) - N(\bar{f}, t)}{N(f, t) + N(\bar{f}, t)} \sim A_D + \frac{a_{sl}}{2} + \left( A_P - \frac{a_{sl}}{2} \right) \cos(\Delta m_{\alpha}t)$$

where $N$ are bkg-subtracted rates

$$A_D = \frac{\varepsilon(D^-\mu^+) - \varepsilon(D^+\mu^-)}{\varepsilon(D^-\mu^+) + \varepsilon(D^+\mu^-)}$$

is the detection asymmetry, measured from control channels, and

$$A_P = \frac{N(B) - N(\bar{B})}{N(B) + N(\bar{B})}$$

is the production asymmetry, obtained from the fit

Using full Run1 sample

$$a_{sl}^d = (-0.02 \pm 0.19\text{(stat.)} \pm 0.30\text{(syst.)})\%$$
Time integrated analysis of $B^0 \rightarrow D_s^- (\rightarrow K^+ K^- \pi^-) \mu^+ \nu_\mu X$ decays (fast oscillations suppress the integral of time-dependent component)

- Backgrounds are main source of systematic
- Split measurement in 3 regions of Dalitz plot with different background contamination: $D_s^+ \rightarrow \phi \pi$, $D_s^+ \rightarrow K^* K$, Non Resonant $D_s^+ \rightarrow K^+ K^- \pi$
Result for $a_{sl}^s$

LHCb-PAPER-2016-013

Most precise measurement of CPV in $B^0_s$ mixing
Compatible with no CPV and SM prediction
Does not confirm D0 anomaly
The smallest and least known CKM element: $\sigma(\vert V_{ub} \vert) / \vert V_{ub} \vert = 12\%$

Long standing puzzle: inclusive and exclusive measurements do not agree

**Exclusive**
- use $B^0 \rightarrow \pi^+ \ell^- \bar{\nu}_\ell$ decay
- experimentally clean
- needs theory for hadronization

PDG 2014:
\[
\vert V_{ub} \vert = (3.28 \pm 0.29) \times 10^{-3}
\]

**Inclusive**
- use $B \rightarrow X_u \ell \nu$ decays
- experimentally less clean
- theory still needed to account for phase space region not accessible

PDG 2014:
\[
\vert V_{ub} \vert = (4.14 \pm 0.15^{+0.15}_{-0.19}) \times 10^{-3}
\]

$\Leftrightarrow 2.4 \sigma$

all most precise measurements so far from B factories
|V_{ub}| in LHCb using Λ_b baryons

- Measurement using exclusive decay Λ_b → pμ⁻\bar{ν}_μ
- Profiting of large Λ_b production at hadron colliders (20% fragm. fraction)
- Reduced background from other b hadrons
- Using only high\( -q^2\) region where theoretical errors are smaller (\(q^2\) has 2-fold ambiguity, cut applied to both solutions)
- Normalization to Λ_b → Λ_cμ⁻\bar{ν}_μ, using only
  \[
  \frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(Λ_b → pμ⁻\bar{ν}_μ)_{q^2>15}}{\mathcal{B}(Λ_b → Λ_cμ⁻\bar{ν}_μ)_{q^2>7}} \times R_{FF}
  \]
- Ratio of form factors from recent lattice calculations \(R_{FF} = 0.68 \pm 0.07\) ➞ 5% uncertainty on \(|V_{ub}|/|V_{cb}|\)
- Relative efficiency for signal and normalization controlled within few %
- Largest single systematic source if BR of normalization mode, known to 5% accuracy (from Belle)
- Analysis based on fit to “corrected mass”
  \[
  M_{corr} = \sqrt{p_{\perp}^2 + M(hμ) + p_{\perp}} \quad h = p, Λ_c
  \]
Result for $|V_{ub}|$ from $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$

$$\frac{|V_{ub}|}{|V_{cb}|} = (83 \pm 4 \pm 4) \times 10^{-3}$$

- Result agrees with previous exclusive measurements
- $3.5 \sigma$ from inclusive measurements
- Puzzle confirmed
Possible solution to the puzzle suggested by previous results: significant right handed component in the SM current [PRD 90, 094003 (2014)]

This measurement has different sensitivity to the right handed fraction $\varepsilon_R$ due to the spin of the proton

The result does not support this explanation
Another intriguing anomaly from B factories: possible breaking of lepton universality in

\[ R(D^{(*)}) = \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)} + \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)} + \mu^- \bar{\nu}_\mu)} \]

Very clean theoretically (2% uncertainty)

Sensitive to charged Higgs, Leptoquark...

Both Babar and Belle find excess of \( \tau \) mode wrt SM

3 neutrinos in final state, challenging measurement!

Missing mass can’t be well measured at hadron colliders (B factories can use opposite side reconstruction)

PRD 88 (2013) 072012
First measurement of $R(D^*)$ at hadron colliders from LHCb

Totally different technique wrt B factories:

- estimate B momentum assuming $(\beta_z \gamma)_{\text{visible}} = (\beta_z \gamma)_B$ ($B$ energy $\gg$ Q-value)
  - $18\%$ resolution
- then compute $q^2, E_\mu, m^2_{\text{missing}}$ in $B$ rest frame
- candidates dominated by background from partially reconstructed $b$ decays and combinatorial: carefully model all components using control sample or simulation validated on data
Result for $R(D^*)$

$R(D^*) = 0.336 \pm 0.027\text{(stat.)} \pm 0.030\text{(syst.)}\%$

In agreement with B factories, 2.1$\sigma$ larger than SM

Combination of results (including latest one from Belle) disagrees with SM at 4$\sigma$ level
Other hints from rare decays in LHCb

Another test for lepton universality:

\[ R_K = \frac{B(B^+ \rightarrow K^+\mu^+\mu^-)}{B(B^+ \rightarrow K^+e^+e^-)} \]

- expected = 1 in SM with negligible error
- measured value in LHCb is 2.6 \( \sigma \):

\[ R_K(1 < q^2 < 6 \text{ GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036 \]

Angular analysis of \( B^0 \rightarrow K^*\mu^+\mu^- \)

- dynamics of 4-body decay can be described with 8 observables that can receive many possible NP contributions
- theorists proposed combination of observables with reduced hadronic uncertainty \( P'_5 \) variable, sensible to \( Z' \), exhibits 3\( \sigma \) deviation from SM \( \text{JHEP 02 (2016) 104} \)
- Result recently confirmed by Belle

Performing the same test on other modes…

arXiv:1604.04042
Conclusions on b Physics

- LHCb and B factories confirm the triumph of CKM paradigm at tree level
- Entering era of precision (\(\sim 1\%\)) measurement of flavour observables
- Semileptonic decays are well manageable also at hadron colliders!
- Models beyond SM severely constrained by results on CPV and rare b decays
- But a pattern of possible NP signals is starting to emerge:
  - \(|V_{ub}|, R(D^*), B^0 \to K^*\mu^+\mu^- \ldots\)
  - soon to exclude fluctuations or systematics (in theory or data interpretation)
- Nice interplay between experimental and theoretical development

**What about the underlying event?**

- Progress in understanding hadronic interactions, including soft regime, is also essential for flavour physics
- LHCb is also committed to hadronic physics, exploiting its unique coverage of forward region...5 of our 10 most cited topics are production/spectroscopy studies!
**Interlude: LHCb Trigger**

- Single Hardware level (L0) ➔ up to 1 MHz to software trigger (HLT)
- Evolution following expansion of physics program:
  
  original output bandwidth for core program (TDR 2003) : 200 Hz → now 12500 Hz

- Pioneering new concepts:
  - asynchronous software trigger, running after up to date calibrations are available: same reconstruction quality in trigger and offline
  - well consolidated analysis can run directly in HLT (TURBO lines)
  - More space for charm and strange, hadronic (production and spectroscopy), EW physics, heavy ions, exotic searches and more
LFV in charm decays

- Charm sample: $\sim 5 \times 10^{12} D^0$ and $2 \times 10^{12} D^*$ mesons within LHCb acceptance in Run1 sample (20-30 $\times$ CDF sample in 10 fb$^{-1}$)

- Example: search for lepton flavour violating $D^0 \rightarrow e\mu$ decay

- Forbidden in SM, suggested in several extensions (including some leptoquark scenarios) with BR up to $10^{-6}$

- Previous best limit from Belle: $< 2.6 \times 10^{-7}$ at 90% CL

- Normalizing to $D^0 \rightarrow K^-\pi^+$

LHCb result:

$\mathcal{B}(D^0 \rightarrow e\mu) < 1.3 \times 10^{-8}$ @ 90% CL
LHC is also the largest kaon factory: $\sim 3 \times 10^{13} K^0_S$ produced within LHCb acceptance, 40% decaying within vertex detector.

Main limitation is the trigger ($K^0_S$ products have too low $p_T$).

Only result so far: search for $K^0_S \rightarrow \mu^+\mu^-$ in 2011 data.

very suppressed in SM: $(5.0 \pm 1.5) \times 10^{-12}$

LHCb result:

$\mathcal{B}(K^0_S \rightarrow \mu^+\mu^-) < 9 \times 10^{-9} @ 90\% \text{ CL}$

improves previous limit by factor 30

trigger efficiency was $\sim 1\%$, improvement in place in 2012 (updated analysis in progress)

Effort ongoing in dedicated trigger lines also for other $K^0_S$ decays ($\pi^0 \mu^+\mu^-, \pi^+\pi^- e^+e^-, \ldots$)
First prompt analysis obtained in the trigger (TURBO lines) from 3 pb$^{-1}$ of 13 TeV data

LHCb can measure production in forward region, distinguishing prompt (direct + feed-down from strong decays of higher states) and detached ($b$ decays) components.
Results for $J/\psi$ @ 13 TeV

NRQCD: Shao et al., JHEP 05 (2015) 103
FONLL: Cacciari et al., arXiv:1507.06197
Heavy hadron decays provide clean samples for study of “exotic” heavy resonances.

LHCb confirmed the tetraquark candidate $Z(4430)^-$ in $B^0 \rightarrow Z(\rightarrow \psi'\pi^-)K^+$ decays [PRL 112 (2014) 222002].

Sample of 26000 $\Lambda_b \rightarrow J/\psi p K^-$ candidates used to study $J/\psi p$ resonances, with minimum quark content $c\bar{c}uud$.

6D amplitude analysis performed on Dalitz plot.

PRL 115 (2015) 072001
**Pentaquarks!**

- $M(J/\psi p)$ distribution not explained by known resonances
- At least 2 new resonances needed to fit the data:

<table>
<thead>
<tr>
<th></th>
<th>$P_c(4380)$</th>
<th>$P_c(4450)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/c^2)</td>
<td>$4380 \pm 8 \pm 29$</td>
<td>$4449.8 \pm 1.7 \pm 2.5$</td>
</tr>
<tr>
<td>Width (MeV/c^2)</td>
<td>$205 \pm 18 \pm 86$</td>
<td>$39 \pm 5 \pm 19$</td>
</tr>
<tr>
<td>fraction (%)</td>
<td>$8.4 \pm 0.7 \pm 4.2$</td>
<td>$4.1 \pm 0.5 \pm 1.1$</td>
</tr>
<tr>
<td>Spin (best fit)</td>
<td>3/2−</td>
<td>5/2+</td>
</tr>
</tbody>
</table>
New ideas: exploit fixed-target-like geometry for doing... fixed target physics!

Gas target available since 2012 and used for luminosity determination:
System for Measuring the Overlap with Gas (SMOG)

Can introduce small amount of noble gas (He, Ne, Ar) in the beam pipe around the vertex detector

Increasing by two orders of magnitudes local vacuum pressure ($10^{-9}$ to $10^{-7}$ mbar)

Combined with Van Der Meer scan, allowed to determine the luminosity in LHCb with 1.2% accuracy  [2014 JINST 9 P12005]

But gas target can also be exploited for physics...
An obvious advantage of the gas target is the possibility to change the target nucleus.

Nuclear effects in heavy hadron production can be studied for different atomic number and at energy scale in between those explored at SPS and RHIC.

Together with p-p, p-Pb and Pb-Pb collision data, quark-gluon plasma effects on heavy probes can be disentangled from cold nuclear matter effects.

- **Collider mode**
  - $\sqrt{s_{NN}} = 5$ to $8$ TeV

- **Fixed-target mode**
  - $\sqrt{s_{NN}}^{SPS} \approx 20$ GeV
  - $\sqrt{s_{NN}}^{RHIC} = 200$ GeV
  - $\sqrt{s_{NN}}^{LHC} = 5$ TeV
  - $\sqrt{s_{NN}} = 90$ to $110$ GeV
  - $\sqrt{s_{NN}} = 70$ GeV
Heavy flavour production in fixed target data

- Measurements with He, Ne and Ar were taken during the 2015 run to study nuclear effect in heavy hadron production.
- $J/\psi$ and $D^0$ signals with $\sim$ 8 hours of proton-Neon data
The other advantage of fixed target is the possibility for production studies in wider $x_F$ regions, notably in the target fragmentation region $x_F \ll 0$, where perturbative QCD and Bjorken scaling break. Such measurements are particularly useful to tune simulation of cosmic ray interactions in cosmos and atmosphere. LHCb is carrying out the measurement of antiproton production in p-He collision, whose poor knowledge is currently limiting the interpretation of recent AMS results on antiproton flux in cosmic rays.
LHCb is pushing the precision of flavour physics
Acting as a SM gatekeeper…

…but also suggesting possible new signatures…

Physics program continuously expanding, also toward unexpected directions
Actively preparing for near and long term future… upgrade of most detectors being prepared for Run 3 (2021)

increase of instantaneous luminosity by factor 5, aiming at collecting 50 fb$^{-1}$ within Run4 for pushing sensitivity to rarest processes
Additional Material
rare FCNC decay in the SM (BR $\sim 10^{-6}$).
Analysis of decay kinematics provides a rich test-bench of effective operators describing the
decay dynamics. NP can contribute in many ways

Most studied variables are traditionally:
- $A_{FB}$: forward-backward asymmetry
- $F_L$: fraction of the $K^*$ longitudinal polarization

Differential branching fraction as a function of $q^2$

$$\frac{1}{\Gamma} \frac{d^3(\Gamma + \Gamma^*)}{d \cos \theta_\ell d \cos \theta_K d\Phi} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell ight.$$
$$- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\Phi$$
$$+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \Phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \Phi$$
$$+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \Phi$$
$$+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \Phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\Phi \left. \right]$$
The $P'_5$ anomaly

New basis of observables, less dependent on hadronic form factors (i.e. on long-distance effects), introduced by theorists in recent years [JHEP 05 (2013) 137]

Measurements in new basis exhibit significant discrepancy in the $P'_5$ variable. Could be explained by the contribution of a new vector current ($Z'$). A global fit of the observables results in a value of the vector coupling strength $Re(C_9)$ which is $3.4\,\sigma$ away from the SM prediction.

\[
A_T^{(2)} = \frac{2S_3}{1 - F_L} A_T^{Re} = \frac{S_6}{1 - F_L},
\]

\[
P'_4 = \frac{S_4}{\sqrt{(1 - F_L)F_L}} P'_5 = \frac{S_5}{\sqrt{(1 - F_L)F_L}}
\]

\[
P'_6 = \frac{S_7}{\sqrt{(1 - F_L)F_L}} P'_8 = \frac{S_8}{\sqrt{(1 - F_L)F_L}}
\]
\[ \gamma = \arg \left( - \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right) \] is the least known CKM angle

Measured from

- tree level \( B \to D K \) decays, expected to be nearly insensitive to New Physics
- loop processes like \( B \to h h \)
- comparison can reveal NP

LHCb combination: \( \gamma = (70.9^{+7.1}_{-8.5})^\circ \)

B factories:
- BaBar: \( \gamma = (70 \pm 18)^\circ \)
- Belle: \( \gamma = (73^{+18}_{-15})^\circ \)
Status of $\phi_s$ from $B_s^0 \to J/\psi KK$ and $B_s^0 \to J/\psi \pi^+\pi^-$

**NEW HFAG spring '16 combination (summer '15 + latest ATLAS results):**

\[
\phi_s^{c\bar{c}s} = -0.033 \pm 0.033 \text{ rad}
\]
\[
\Delta \Gamma_s = 0.083 \pm 0.006 \text{ ps}^{-1}
\]

Compatible with SM estimations:

[arXiv:1511.09466] [CKMfitter, PRD 84 (2011) 033005]

\[
\phi_s^{c\bar{c}s} = -0.0376 \pm 0.0008 \text{ rad}
\]
\[
\Delta \Gamma_s = 0.088 \pm 0.020 \text{ ps}^{-1}
\]

Prospects:

- Add new modes to increase $\phi_s^{c\bar{c}s}$ statistics:
  - $B_s^0 \to \psi(2S)\phi$,
  - $B_s^0 \to J/\psi(\to e^+e^-)\phi$,
  - $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ update.

Gluonic penguin pollution to $\phi_s^{c\bar{c}s}$ measured at LHCb:

- Observation of the mode $\overline{B}_s^0 \to \psi(2S)K^+\pi^-$ which can contribute to these estimations,
- Penguin pollution to $\phi_s^{c\bar{c}s}$ measured through $B^0 \to J/\psi \rho^0$ and $B_s^0 \to J/\psi \overline{K}^*0$ modes:
  - Pollution found to be small and not greater than 21 mrad!
Implications of $\phi_s$ and $B_s^0 \rightarrow \mu^+\mu^-$

Argand plots for tetra/pentaquark candidates

- The resonant character of the new exotic states can be tested by fitting the Re and Im part of their amplitude in bins of the invariant mass. For a physical resonance, the resulting Argand plot is expected to show the typical circular trajectory;
- The technique was used in LHCb to assess the resonant character of the $Z(4430)^-$ state
- For the pentaquark candidates, statistics is more limited, though the circular behavior can be seen for the 4450 MeV state
<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 [138]</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 [214]</td>
<td>0.045</td>
<td>0.014</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$d_{sl}^s$</td>
<td>$6.4 \times 10^{-3}$ [43]</td>
<td>$6 \times 10^{-3}$</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>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow K^{*0} \bar{K}^{*0})$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B^0 \rightarrow \phi K_S^0)$</td>
<td>0.17 [43]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed</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>currents</td>
<td>$\tau^{\text{eff}} (B_s^0 \rightarrow \phi \gamma) / \tau_{B_s^0}$</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak</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 [67]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td>penguins</td>
<td>$s_0 A_{FB} (B^0 \rightarrow K^{*0} \mu^+ \mu^-)$</td>
<td>25% [67]</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 [76]</td>
<td>0.08</td>
<td>0.025</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B (B^+ \rightarrow \pi^+ \mu^+ \mu^-) / B (B^+ \rightarrow K^+ \mu^+ \mu^-)$</td>
<td>25% [85]</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>$1.5 \times 10^{-9}$ [13]</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</td>
<td>$\gamma (B \rightarrow D^{(<em>)} K^{(</em>)})$</td>
<td>$\sim 10$ [244, 258]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td>triangle angles</td>
<td>$\gamma (B_s^0 \rightarrow D_s K)$</td>
<td>–</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \rightarrow J/\psi \ K_S^0)$</td>
<td>0.8° [43]</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T$</td>
<td>$2.3 \times 10^{-3}$ [43]</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>$2.1 \times 10^{-3}$ [18]</td>
<td>$0.65 \times 10^{-3}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>