A look at $\eta - \eta'$ mixing

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η and η'

- Light unflavoured pseudoscalars mesons.
- combination of $u\bar{u},\ d\bar{d},$ and $s\bar{s}$ with [1]:

$$M(\eta) = 547.862 \pm 0.017 \text{ MeV}/c^2$$

$$M(\eta') = 957.78\ \pm 0.06\ \text{ MeV}/c^2$$

η and η' are linear combination of the singlet ($|1\rangle$) and the octet ($|8\rangle$) states with mixing angle: $\theta \in [-25°, -10°]$ [2].

$$|1\rangle = \frac{1}{\sqrt{3}} \left[|u\bar{u} + d\bar{d} + s\bar{s}\rangle \right]$$

$$|8\rangle = \frac{1}{\sqrt{6}} \left[|u\bar{u} + d\bar{d} - 2s\bar{s}\rangle \right]$$

Theory: Flavour Basis

Combination of $|\eta_q\rangle$, $|\eta_s\rangle$ the mixing angle (ϕ_P).

$$|\eta_q\rangle = \frac{1}{\sqrt{2}}\left[|u\bar{u} + d\bar{d}\rangle\right]$$
$$|\eta_s\rangle = |s\bar{s}\rangle$$

Due to the mass difference, 409.92 ± 0.06 MeV/c^2, one can assume a gluonic/glueball component ($|G\rangle$) contribution in the singlet state in η', leading to additional mixing angle ϕ_G [3]:

$$|\eta\rangle = \cos\phi_P\,|\eta_q\rangle - \sin\phi_P\,|\eta_s\rangle$$
$$|\eta'\rangle = \cos\phi_G\,(\sin\phi_P\,|\eta_q\rangle + \cos\phi_P\,|\eta_s\rangle) + \sin\phi_G\,|G\rangle$$

Experimental Results

In the LHCb analysis [3] led by prof. Matthew and prof. Maximilien, the gluon component were studied using $B_{d/s} \to J/\Psi\eta^{(')}$ with:

$$\eta' \to (\pi^+\pi^-(\eta \to \gamma\gamma)) \qquad \mathcal{B} = 42.5\ \%$$
$$\eta' \to ((\rho^0 \to \pi^+\pi^-)\gamma) \qquad \mathcal{B} = 29.48\%$$
$$\eta \to (\pi^+\pi^-(\pi^0 \to \gamma\gamma)) \qquad \mathcal{B} = 23.02\%$$
$$\eta \to (\pi^+\pi^-\gamma) \qquad \mathcal{B} = 4.28\%$$

Using Run1 and Run2 data, Only tree diagram contribution, and under glueball state assumption the measured mixing angles are [3]:

$$\phi_P = \left(41.8^{+1.0}_{-1.2}\right)^\circ$$
$$\phi_G = \left(28.1^{+3.9}_{-4.0}\right)^\circ \qquad (\phi_G = 0) \text{ with } > 4\sigma$$

Experimental Results [3] cont.

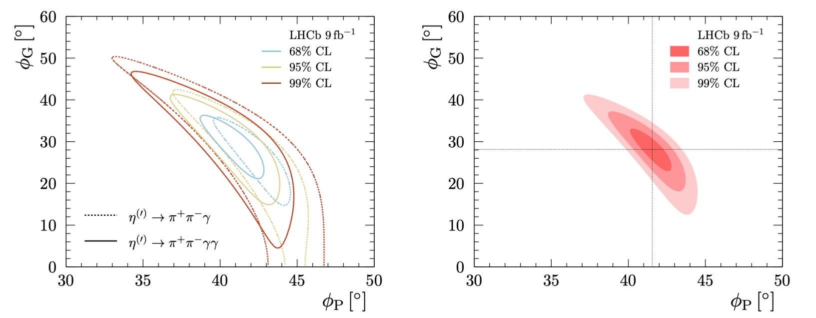


Figure 1: Left: Double and Single γ modes; Right: Combined results.

Alternative Interpretation

- Proposed by Chen and Li [4], no glueball contribution is needed to get similar results, instead the gluonic interaction can be enhanced by $U_A(1)$ anomalies.
- These interactions are present in the other, higher order, diagrams.
- Taking the same decay but including the W exchange diagram[4]:

$$R_d \equiv \frac{\mathcal{B}(B0 \to J/\psi\eta')}{\mathcal{B}(B0 \to J/\psi\eta)} \cdot \frac{\Phi^3(B0 \to J/\psi\eta')}{\Phi^3(B0 \to J/\psi\eta)}$$

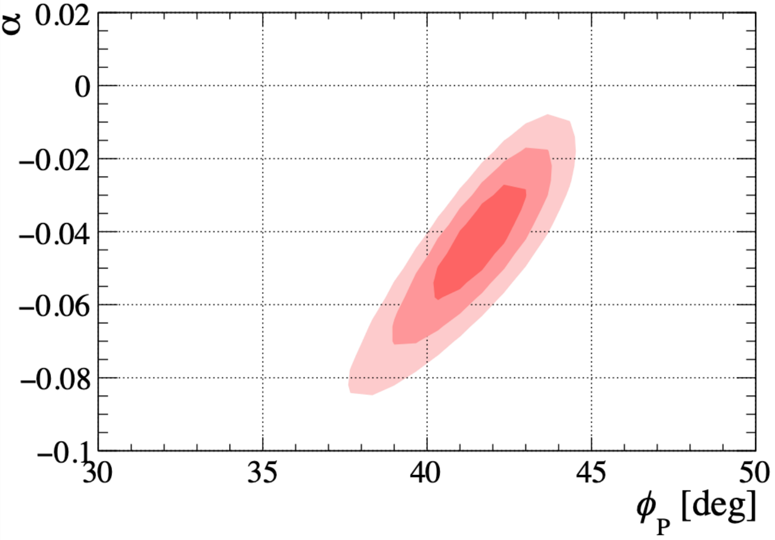
$$= \tan^2\phi_P \cos^2\phi_G \to R_d = \tan^2\phi_P \left(\frac{1+4\alpha}{1+\alpha}\right)^2$$

$$R_s \equiv \frac{\mathcal{B}(B_s \to J/\psi\eta')}{\mathcal{B}(B_s \to J/\psi\eta)} \cdot \frac{\Phi^3(B_s \to J/\psi\eta')}{\Phi^3(B_s \to J/\psi\eta)}$$

$$= \cot^2\phi_P \cos^2\phi_G \to R_s = \cot^2\phi_P \left(\frac{1+2\alpha}{1-\alpha}\right)^2$$

$$\alpha \equiv \frac{A_{\text{exchange}}}{A_{\text{tree}}}$$

Alternative Interpretation [4] cont.



Using Other Modes with Similar Topologies

Using: $J/\Psi \to \bar{D}^0$, $\mathrm{B}_{d/s} \to \bar{D}^0\eta^{(\prime)}$ with:

$$\eta' \to (\,\pi^+\pi^-(\eta \to \gamma\gamma)\,) \qquad \eta' \to (\,(\rho^0 \to \pi^+\pi^-\,)\,\gamma)$$

$$\eta \to (\,\pi^+\pi^-(\pi^0 \to \gamma\gamma)\,) \qquad \eta \to (\,\pi^+\pi^-\gamma\,)$$

$$B_d \to \bar{D}^0\eta^{(\prime)} \implies T(A\lambda^2) + E[u](A\lambda^2); \qquad V_{cb}$$

$$B_d \to D^0\eta^{(\prime)} \implies T(A\lambda^3(\rho - i\eta)) + E[c](-A\lambda^4(\rho - i\eta)); \qquad V_{ub}$$

$$B_s \to \bar{D}^0\eta^{(\prime)} \implies T(A\lambda^3) + E[u](A\lambda^3); \qquad V_{cb}$$

$$B_s \to D^0\eta^{(\prime)} \implies T(A\lambda^3(\rho - i\eta)) + E[c](A\lambda^3(\rho - i\eta)); \qquad V_{ub}$$

With branching fraction, respectively: [5][6]

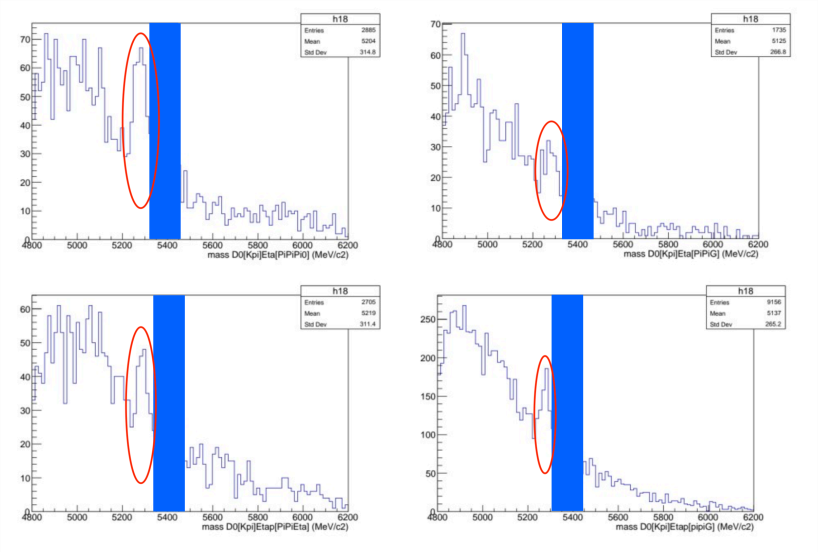
(1) $\mathcal{B}_{ex} = (3.94 \pm 0.20) \times 10^{-4}$;

(2) $\mathcal{B}_{th} = (0.25 \pm 0.05) \times 10^{-6}$;

(3) $\mathcal{B}_{th} = (0.86 \pm 0.28) \times 10^{-4}$

(4) $\mathcal{B}_{th} = (3.5 \pm 0.1) \times 10^{-6}$

2018 Data ONLY, Simple Cuts, stripping34r0p3 [7]



What Can Be Done

1. Using Run2 data $\mathrm{B_s}$ mode is likely to measured.
2. Expected $\mathcal{B}(B_s)/\mathcal{B}(B_d) < 4\%$.
3. Thus statistically limited but first Observation for these modes for $\mathrm{B_s}$.
4. To Study the mixing angle Run3 data is required.
5. Sprucing lines for Run 3 are prepared and merge request is created.
6. Additional modes to look for with run3 data, sprucing line for 2025 are being prepared:

$$B^{+/-} \rightarrow D_s \eta^{(\prime)}$$

7. The mode above can be used to study α contribution.

What has been done + what are we doing

- Simulation: configuration files (.decfile) was created.
    - EvtType: 11464401 ”Bd_D0bareta,Kpicocktail=TightCut.dec”
    - EvtType: 11464402 ”Bd_D0baretap,Kpicocktail=TightCut.dec”
    - EvtType: 13464401 ”Bs_D0bareta,Kpicocktail=TightCut.dec”
    - EvtType: 13464402 ”Bs_D0baretap,Kpicocktail=TightCut.dec”
- Simulation: Requested 12M event for Run2 (1M/year/mode)
- Simulation: generation is completed.
- Training MVA: current step.

Conclusion

- $\eta - \eta'$ mixing and the gluonic components need more investigation.
- Run 3 data: mixing angle measurement in $B_{d/s} \rightarrow \bar{D}^0 \eta^{(\prime)}$.
- Run 2 data: Loose cuts reveal the B_d signal.
- Run 2 data: MC generated and planning to train MVA.

Questions?

References

[1] S. Navas et al. **"Review of particle physics".** In: *Phys. Rev. D* 110.3 (2024), p. 030001. DOI: *10.1103/PhysRevD.110.030001*.

[2] D. R. Entem et al. ***The Constituent Quark Model.*** 2025. arXiv: *2504.07897 [hep-ph]*. URL: *https://arxiv.org/abs/2504.07897*.

[3] LHCb collaboration and R. Aaij et al. ***Improved measurement of η/η' mixing in $B^0_{(s)} \to J/\psi\eta^{(\prime)}$ decays.*** 2025. arXiv: *2507.13914 [hep-ex]*. URL: *https://arxiv.org/abs/2507.13914*.

[4] Ying Chen and Geng Li. ***Comment on "Improved measurement of η/η' mixing in $B^0_{(s)} \to J/\psi\eta^{(\prime)}$ decays".*** 2025. arXiv: *2507.19872 [hep-ph]*. URL: *https://arxiv.org/abs/2507.19872*.

[5] J. P. Lees et al. “Branching Fraction Measurements of the Color-Suppressed Decays $\bar{B}^0 \to D^{(*)0}\pi^0$, $D^{(*)0}\eta$, $D^{(*)0}\omega$, and $D^{(*)0}\eta'$ and Measurement of the Polarization in the Decay $\bar{B}^0 \to D^{*0}\omega$”. In: *Phys. Rev. D* 84 (2011). [Erratum: Phys.Rev.D 87, 039901 (2013)], p. 112007. DOI: *10.1103/PhysRevD.84.112007*. arXiv: *1107.5751 [hep-ex]*.

[6] Si-Hong Zhou et al. “Analysis of two-body charmed<mml:math xmlns:mml=”http://www.w3.org/1998/Math/MathML” display=”inline”><mml:mi>B</mml:mi></mml:math>meson decays in factorization-assisted topological-amplitude approach”. In: *Physical Review D* 92.9 (Nov. 2015). ISSN: 1550-2368. DOI: *10.1103/physrevd.92.094016*. URL: *http://dx.doi.org/10.1103/PhysRevD.92.094016*.

[7] *stripping34r0p3*. URL: *https://lhcbdoc.web.cern.ch/lhcbdoc/stripping/config/stripping34r0p3/bhadroncompleteevent/strippingb02d0eta2pipigamma_beauty2charmline.html*.

Backup

Quarks States and Mesons

$J^P = 0^-$		$J^P = 1^-$		S
π^+	$\|u\bar{d}\rangle$	ρ^+	$\|u\bar{d}\rangle$	0
π^0	$\frac{1}{\sqrt{2}}\|d\bar{d} - u\bar{u}\rangle$	ρ^0	$\frac{1}{\sqrt{2}}\|d\bar{d} - u\bar{u}\rangle$	0
π^-	$-\|d\bar{u}\rangle$	ρ^-	$-\|d\bar{u}\rangle$	0
K^+	$\|u\bar{s}\rangle$	K^{*+}	$\|u\bar{s}\rangle$	+1
K^0	$\|d\bar{s}\rangle$	K^{*0}	$\|d\bar{s}\rangle$	+1
$\overline{K}^0$	$-\|s\bar{d}\rangle$	$\overline{K}^{*0}$	$-\|s\bar{d}\rangle$	-1
K^-	$-\|s\bar{u}\rangle$	K^{*-}	$-\|s\bar{u}\rangle$	-1

Decfile for $B_d \to \eta$

```
#EventType: 11464401
# Descriptor: [ [B0 => ^(D~0 => ^K+ ^pi-) ^(eta => pi+ pi- ^(pi0=> ^gamma ^gamma)) ]CC, [B0 => ^(D~0 => ^K+ ^pi-) ^(eta => ^pi+ ^pi- ^gamma) ]CC ]
#
# NickName: Bd_D0bareta,Kpicocktail=TightCut
#
# Cuts: LoKi::GenCutTool/TightCut
#
# InsertPythonCode:
#
# from Configurables import LoKi__GenCutTool
# Generation().SignalRepeatedHadronization.addTool ( LoKi__GenCutTool , 'TightCut' )
# tightCut = Generation().SignalRepeatedHadronization.TightCut
# tightCut.Decay = "[ [B0 => ^(D~0 => ^K+ ^pi-) ^(eta => pi+ pi- ^(pi0=> ^gamma ^gamma)) ]CC, [B0 => ^(D~0 => ^K+ ^pi-) ^(eta => ^pi+ ^pi- ^gamma) ]CC ]"
# tightCut.Preambulo += [
#  "from LoKiCore.functions import in_range"  ,
#  "from GaudiKernel.SystemOfUnits import GeV, MeV",
#  "AccCut = in_range ( 0.005 , GTHETA , 0.400 )",
#  "goodGamma = ( (GPT > 150 * MeV) & AccCut ) ",
#  "ErrSuppress = ( GPT > 150 * MeV )"
# ]
# tightCut.Cuts = {"gamma" : "goodGamma", "pi+" : "ErrSuppress", "pi-" : "ErrSuppress", \
# "pi0" : "ErrSuppress", "K+" : "ErrSuppress", "K-" : "ErrSuppress", \
# "eta" : "ErrSuppress", "D~0" : "ErrSuppress", "D0" : "ErrSuppress"}
# EndInsertPythonCode

#
# Documentation: Bd is forced to 4 charged tracks,
#                D0bar is forced into K+ pi-,and
#                eta can decay to either pi+ pi- gamma
#                or pi+ pi- (pi0 -> gamma gamma).
#                The TightCuts are relevant for the gammas,
#                the others are there to supress the error
#                which will cause the pipeline to fail.
# EndDocumentation
#
# PhysicsWG: B2OC
# Tested: Yes
# Responsible: Hussain Al Saleh
# Email: halsaleh@cern.ch
# Date: 20251008
# CPUTime: <1min
```

Decfile for $B_d \to \eta$ cont.

```
#
Alias           MyD0            D0
Alias           MyantiD0        anti-D0
Alias           Myeta           eta
Alias           Mypi0           pi0
ChargeConj      MyantiD0        MyD0
ChargeConj      Myeta           Myeta
ChargeConj      Mypi0           Mypi0
#
Decay B0sig
        1.0000  MyantiD0        Myeta           PHSP;
Enddecay
CDecay anti-B0sig
#
Decay MyantiD0
        1.0000  K+              pi-             PHSP;
Enddecay
CDecay MyD0
#
Decay Myeta
        0.6666  pi+             pi-     Mypi0   ETA_DALITZ;
        0.3334  pi+             pi-     gamma   PHSP;
Enddecay
#
Decay Mypi0
        1.0000  gamma           gamma           PHSP;
Enddecay
#
End
```

Decfile for $B_s \to \eta'$

```
#EventType: 13464402
# Descriptor: [ [B_s0 => ^(D~0 => ^K+ ^pi-) ^(eta_prime => ^pi+ ^pi- ^(eta=> ^gamma ^gamma)) ]CC, [B_s0 => ^(D~0 => ^K+ ^pi-) ^(eta_prime => ^(rho(770)0 => ^pi+ ^pi-) ^gamma) ]CC ]
#
# NickName: Bs_D0baretap,Kpicocktail=TightCut
#
# Cuts: LoKi::GenCutTool/TightCut
#
# InsertPythonCode:
#
# from Configurables import LoKi__GenCutTool
# Generation().SignalRepeatedHadronization.addTool ( LoKi__GenCutTool , 'TightCut' )
# tightCut = Generation().SignalRepeatedHadronization.TightCut
# tightCut.Decay = "[ [B_s0 => ^(D~0 => ^K+ ^pi-) ^(eta_prime => ^pi+ ^pi- ^(eta => ^gamma ^gamma)) ]CC, [B_s0 => ^(D~0 => ^K+ ^pi-) ^(eta_prime => ^(rho(770)0 => ^pi+ ^pi-) ^gamma) ]CC ]"
# tightCut.Preambulo += [
#  "from LoKiCore.functions import in_range"  ,
#  "from GaudiKernel.SystemOfUnits import GeV, MeV",
#  "AccCut = in_range ( 0.005 , GTHETA , 0.400 )",
#  "goodGamma = ( (GPT > 150 * MeV) & AccCut ) ",
#  "ErrSuppress = ( GPT > 150 * MeV )"
# ]
# tightCut.Cuts = {"gamma" : "goodGamma", "pi+" : "ErrSuppress", "pi-" : "ErrSuppress", \
# "K+" : "ErrSuppress", "K-" : "ErrSuppress", "rho(770)0" : "ErrSuppress", "eta" : "ErrSuppress", \
# "eta_prime" : "ErrSuppress", "D~0" : "ErrSuppress", "D0" : "ErrSuppress"}
# EndInsertPythonCode

#
# Documentation: Bs is forced to 4 charged tracks,
#                D0bar is forced into K+ pi-, Tight Cuts.
#                eta_prime can decay to either pi+ pi- (eta -> gamma gamma)
#                or (rho0 -> pi+ pi-) gamma.
#                The TightCuts are relevant for the gammas,
#                the others are there to supress the error which
#                will cause the pipeline to fail.
# EndDocumentation
#
# PhysicsWG: B2OC
# Tested: Yes
# Responsible: Hussain Al Saleh
# Email: halsaleh@cern.ch
# Date: 20251008
# CPUTime: <1min
#
```

Decfile for $B_s \to \eta'$ cont.

```
#
Alias           MyD0            D0
Alias           MyantiD0        anti-D0
Alias           Myetap          eta'
Alias           Myeta           eta
Alias           Myrho0          rho0
ChargeConj      MyantiD0        MyD0
ChargeConj      Myetap          Myetap
ChargeConj      Myeta           Myeta
ChargeConj      Myrho0          Myrho0
#
Decay B_s0sig
        1.0000  MyantiD0        Myetap          PHSP;
Enddecay
CDecay anti-B_s0sig
#
Decay MyantiD0
        1.0000  K+              pi-             PHSP;
Enddecay
CDecay MyD0
#
Decay Myetap
        0.6666  pi+     pi-     Myeta   PHSP;
        0.3334  Myrho0  gamma           PHSP;
Enddecay
#
Decay Myeta
        1.0000  gamma   gamma           PHSP;
Enddecay
#
```