η–η' Mixing-From Electromagnetic Transitions to Weak Decays of Charm and Beauty Hadrons

Giulia Ricciardi

Università di Napoli “Federico II”, Italy

Work in collab. with C. Di Donato and I.Bigi

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Outline of the talk

1. Review on theoretical and experimental progresses in $\eta-\eta'$ mixing—probing their gluonic content

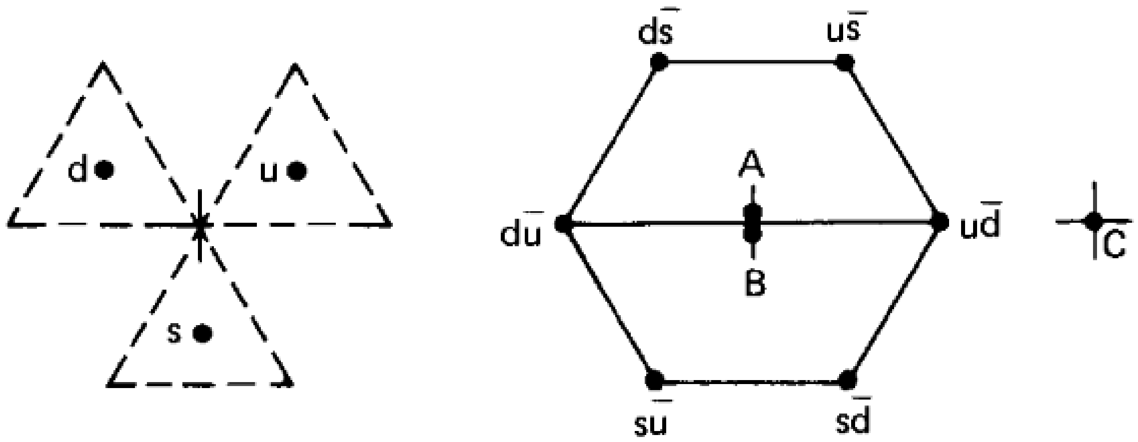
2. Analysis one by one of relevant processes at different energy scales

   ❖ electromagnetic and strong decays

   ❖ electroweak D and B decays

3. Conclusions and future prospects

$SU(3)_{flavor}$



$$3 \otimes \bar{3} = 8 \oplus 1$$

$SU(3)$ decomposition in the I_3, Y plane

$$B = \eta_8 = \frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right)$$

$$C = \eta_0 = \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

$q\bar{q}$ Orbital Ang. Mom.	$q\bar{q}$ Spin	J^{PC}	Observed Nonet $I = 1$	$I = \frac{1}{2}$	$I = 0$	Typical Mass (MeV)
$L = 0$	$S = 0$	0^{-+}	π	K	η, η'	500
	$S = 1$	1^{--}	ρ	K*	ω, ϕ	800

η-η' physical states originated by the mixing of neutral I = 0 octet η_8 and singlet η_0 states

Motivations

- knowing the $\eta-\eta'$ wave functions probes our understanding of non-perturbative QCD dynamics---Showing there is a purely gluonic component would establish for the first time that gluons play an independent role also in hadronic spectroscopy.
  - Also essential to disentangle SM hadronic uncertainties vs. New Physics

- Great effort has been given to this challenge { yet no clear picture has emerged }

- We point out which measurements and theoretical analysis would be most helpful for a more definite conclusion.

$\eta - \eta'$ Mixing

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta_P & -\sin\theta_P \\ \sin\theta_P & \cos\theta_P \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix}$$

Just for orientation:

quadratic (linear) Gell-Mann-Okubo

mass formula $\theta_P \approx -10^o$ ($\theta_P \approx -23^o$)

quark-flavor basis:

$$\begin{cases} \eta_{NS} = \frac{1}{\sqrt{2}}\left(u\bar{u} + d\bar{d}\right) \\ \eta_S = s\bar{s} \end{cases}$$

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\varphi_P & -\sin\varphi_P \\ \sin\varphi_P & \cos\varphi_P \end{pmatrix} \begin{pmatrix} \eta_{NS} \\ \eta_S \end{pmatrix}$$

$\theta_P = \varphi_P - \arctan\sqrt{2} = \varphi_P - 54.7^o$ ⟹ $\varphi_P \approx 45^o$ ($\varphi_P \approx 32^o$)

Two Mixing Angles Scenario: octet-singlet basis

- From the late 90's *(Leutwyler , Kraiser , Kroll, Stech , Feldmann etc.)* been shown the mixing cannot be adequately described by a single angle; the fact that the decay constants follow the pattern of state mixing is an a-priori assumption

- Due to SU(3) breaking ($f_K \neq f_\pi$), mixing of decay constants does not follow the same pattern of state mixing

$$J^a_{\mu\,L} = \bar{q}\,\frac{\lambda^a}{\sqrt{2}}\gamma_\mu\,\frac{1-\gamma_5}{2}\,q$$
$$J^a_{\mu\,R} = \bar{q}\,\frac{\lambda^a}{\sqrt{2}}\gamma_\mu\,\frac{1+\gamma_5}{2}\,q$$

$$J^a_\mu = J^a_{\mu\,R} + J^a_{\mu\,L}$$

$$f_\eta^8 \neq f_\eta^0 \neq f_{\eta'}^8 \neq f_{\eta'}^0$$

$$\begin{pmatrix} f_\eta^8 & f_\eta^0 \\ f_{\eta'}^8 & f_{\eta'}^0 \end{pmatrix} = \begin{pmatrix} f_8\cos\theta_8 & -f_0\sin\theta_0 \\ f_8\sin\theta_8 & f_0\cos\theta_0 \end{pmatrix}$$

$$\langle 0 \,|\, J^a_{\mu 5}(0) \,|\, P(q)\rangle = i\, f_p^a\, q_\mu$$

The estimated difference θ_8-θ_0 can be large [-12º-19º]

Quark flavor basis

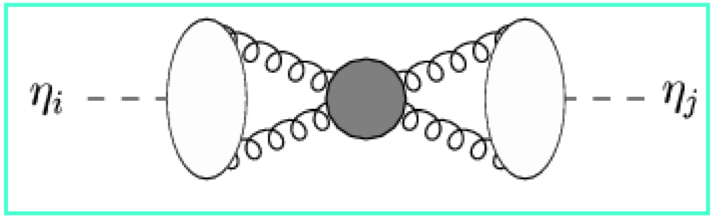
- The smallness of the mixing angles is consistent with the OZI-rule, i.e. amplitudes that involve quark-antiquark annihilation into gluons are suppressed
  - vector meson sector: mixing angle ≈ 3∘

    $\omega \approx q\bar{q} \qquad \phi \approx s\bar{s}$

$$\begin{cases} \eta_{NS} = \frac{1}{\sqrt{2}}\left(u\bar{u} + d\bar{d}\right) \\ \eta_S = s\bar{s} \end{cases}$$

- In the pseudoscalar sector, $U(1)_A$ anomaly induces a significant mixing between the fields η_{NS} and η_S .

$$\partial^\mu J^u_{\mu 5} = \partial^\mu(\bar{u}\,\gamma_\mu\gamma_5\,u) = 2\,m_u\,(\bar{u}\,i\gamma_5\,u) + \frac{\alpha_s}{4\pi}\,G\,\tilde{G}$$

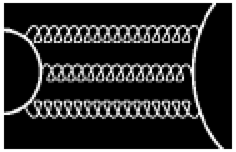


Two mixing angle scenario: flavor basis

In principle we have

$$\begin{pmatrix} f_\eta^q & f_\eta^s \\ f_{\eta'}^q & f_{\eta'}^s \end{pmatrix} = \begin{pmatrix} f_q \cos\phi_q & -f_s \sin\phi_s \\ f_q \sin\phi_q & f_s \cos\phi_s \end{pmatrix}$$

- However, while the mixing is large (≈ 40º), the difference between the two mixing angles is determined by OZI-rule violating contribution
- OZI-rules rigorous when Nc→∞ or α →0



ϕ_q and ϕ_s nearly coincide

Mix with Gluonium

- The η′ meson is a good candidate to have a sizeable gluonic content, (while the η meson is well understood as an SU(3)-flavor octet with a small singlet admixture)

$$\begin{cases} \eta' = X_{\eta'} \dfrac{1}{\sqrt{2}} | u\bar{u} + d\bar{d} > + Y_{\eta'} | s\bar{s} > + Z_{\eta'} | glue > \\ \eta = X_{\eta} \dfrac{1}{\sqrt{2}} | u\bar{u} + d\bar{d} > + Y_{\eta} | s\bar{s} > \end{cases}$$

$$\begin{cases} X_{\eta'} = \cos\phi_G \sin\phi_P ; Y_{\eta'} = \cos\phi_G \cos\phi_P ; Z_{\eta'} = \sin\phi_G \\ X_{\eta} = \cos\phi_P ; Y_{\eta} = -\sin\phi_P \end{cases}$$

Mixing with heavier pseudoscalar mesons is ignored

Electromagnetic and strong transitions

1. Radiative vector and pseudoscalar meson decays

$$\psi', \psi, \phi \to \gamma\eta' \;\; vs. \;\; \gamma\eta$$

$$\rho, \omega \to \gamma\eta$$

$$\eta' \to \gamma\omega, \gamma\rho$$

2. Decays into two photons or production in collisions:

$$\eta' \to 2\gamma \quad vs. \quad \eta \to 2\gamma$$

$$\gamma\gamma \to \eta \quad vs. \quad \gamma\gamma \to \eta'$$

3. Decays of ψ into PV final states with the vector meson acting as a `flavor filter':

$$\psi \to \rho/\omega/\phi + \eta \;\; vs. \;\; \eta'$$

Radiative ρ/ω/φ Decays: first modern analyses

	no gluonium hyphotesis	allowing for gluonium
KLOE 07:	$\phi_P = (41.3 \pm 0.3_{stat} \pm 0.7_{sys} \pm 0.6_{th})^\circ$	$\begin{cases} \phi_P = (39.7 \pm 0.7)^\circ \\ Z_{\eta'}^2 = 0.14 \pm 0.04 \end{cases}$
Escribano, Nadal 07	$\phi_P = (42.7 \pm 0.7)^\circ$	$\begin{cases} \phi_P = (42.6 \pm 1.1)^\circ \\ Z_{\eta'}^2 = 0.01 \pm 0.07 \end{cases}$
Thomas 07: no form factors	$\phi_P = (41.7 \pm 0.5)^\circ$	$\begin{cases} \phi_P = (41.7 \pm 0.5)^\circ \\ Z_{\eta'}^2 = 0.04 \pm 0.04 \end{cases}$
with form factors $\exp\left(-\lvert p\rvert^2/(8\beta^2)\right)$	$\phi_P = (42.8 \pm 0.8)^\circ$	$\begin{cases} \phi_P = (41.9 \pm 0.7)^\circ \\ Z_{\eta'}^2 = 0.10 \pm 0.08 \end{cases}$

Radiative Decays

<u>KLOE vs. th analyses:</u>

OZI-rule reduces considerably possible transitions and their respective VP wave-functions overlaps ($P \to V\gamma$, $V \to P\gamma$)

- KLOE: VP-overlap parameters without gluonium, (from *Bramon, Escribano and Scadron 01*)
- Theory: VP-overlap parameters determined allowing for gluonium $\Rightarrow$ new values

Differently from the th analyses, Kloe use also constraints from $\eta' \to \gamma\gamma$, where no VP-overlap parameters enter in the analysis: this guarantee "independence" from the parameters in a reasonable range.

KLOE:

$$\Gamma(\phi \to \eta'\gamma)/\Gamma(\phi \to \eta\gamma)$$

$$\Gamma(\eta' \to \rho\gamma)/\Gamma(\omega \to \pi^0\gamma)$$

$$\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$$ → no VP overlap

$$\Gamma(\eta' \to \omega\gamma)/\Gamma(\omega \to \pi^0\gamma)$$

Escribano,Nadal:

$$\Gamma(\phi \to \eta\gamma)$$

$$\Gamma(\phi \to \eta'\gamma)$$

$$\Gamma(\eta' \to \rho\gamma)$$

$$\Gamma(\eta' \to \omega\gamma)$$

New KLOE data (2009)

- Message not truly inconsistent (considering the stated uncertainties), but ambivalent
  - Some studies (KLOE) point to a significant gluonic component, others not

- the th discussion has prompted a new KLOE update (2009)
  - Results confirmed
    - no gluons $$\phi = (41.4 \pm 0.5)^\circ$$
    - allowing gluons $$\begin{cases} \phi = (40.4 \pm 0.6)^\circ \\ Z_{\eta'}^2 = 0.115 \pm 0.036 \end{cases}$$

- the actual difference with KLOE values appears <u>not due</u> to a wrong set of variables, but to the inclusion in the analysis of $\eta' \to 2\gamma$

η' decays

- In lowest order all possible η′ strong decays are forbidden by C, CP invariance and G-parity conservation.
- First order electromagnetic decays are forbidden as well, or occur at a suppressed rate because involving an anomaly.
  - The first allowed decay is therefore the second-order electromagnetic transition

$$\eta' \to 2\gamma$$

- key role in the mixing parameters determination
  - MD-1@Novosibirsk (1985), ASP@SLAC 85

$$\phi_P = 34.9^\circ \pm 2.2^\circ$$

- can be exploited also looking at the inverse processes, namely $\gamma\gamma \to \eta^{(\prime)}$
  - Crystal Ball Collab@DESY (1983)

$$\phi_P = 32.3^\circ \pm 1.2^\circ$$

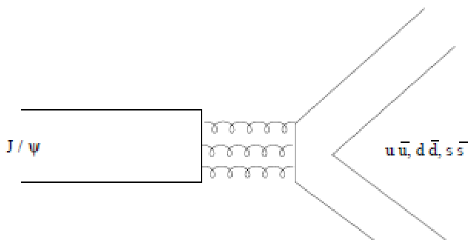
Significantly below previous results

- NEW Results BaBar (2011) disagree with theoretical prediction: (*Bakulev et al 2001*): admixture of the two-gluon component?

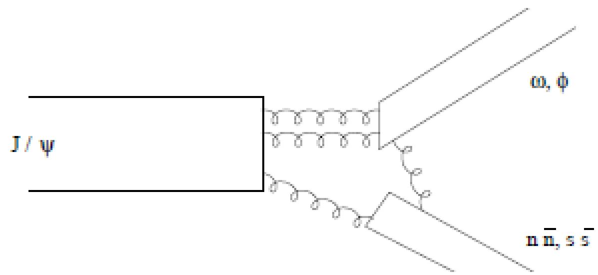
$\psi \rightarrow PV$: also ambivalent results

- Mark III (1985) : (35±18)% of the η' wave function can be attribute to gluonium or radial excitation
  - analysis is based on the assumption that decays proceed via singly disconnected diagram (SOZI), omitting the doubly disconnected (DOZI) diagram
- Mark III (1988) : any gluonium contribution to the η' wave function is ruled out
  - including DOZI diagrams

SOZI



DOZI



- More recent re-analyses of the hadronic J/ψ and ψ′ decays (including DOZI) furnish a consistent description in terms of one mixing angle with a suggestion of some gluonic component of the η'. F.i.
  - no form factors $\phi_P = (45 \pm 4)^\circ \quad \phi_{glue} = (33 \pm 13)^\circ$
  - form factors $\phi_P = (46^{+4}_{-5})^\circ \quad \phi_{glue} = (44 \pm 9)^\circ$ *(Thomas 2007)*

Possible future experimental scenarios

Processes	$(\delta\Gamma/\Gamma)_I$	$(\delta\Gamma/\Gamma)_{II}$	$(\delta\Gamma/\Gamma)_{III}$	$(\delta\Gamma/\Gamma)_{IV}$	$(\delta\Gamma/\Gamma)_V$
$\phi \to \eta'\gamma$	3.5%	3.5%	1.7%	1.7%	1%
$\phi \to \eta\gamma$	2%	2%	1%	1%	1%
$\eta' \to \omega\gamma$	9%	4.5%	9%	4.5%	1.7%
$\eta' \to \rho\gamma$	5%	5%	5%	2.5%	1.7%
$\rho \to \eta\gamma$	7%	7%	7%	3.4%	7%
$\omega \to \eta\gamma$	9%	9%	9%	4.5%	9%
ϕ_P	$(40.6 \pm 0.9)^\circ$	$(40.1^{+1.0}_{-0.8})^\circ$	$(40.6^{+0.6}_{-0.5})^\circ$	$(40.4 \pm 0.5)^\circ$	$(40.1^{+0.3}_{-0.4})^\circ$
$Z^2_{\eta'}$	(0.09 ± 0.05)	(0.13 ± 0.06)	(0.09 ± 0.03)	(0.10 ± 0.03)	(0.13 ± 0.02)
$\chi^2/Ndof$	6.11/4	11.12/4	6.12/4	21.44/4	82.36/4

- "*I*" :actual uncertainties in the exp input values (PDG 2010)
- "*II*" :improvement by studying η'→ωγ using 1) 20 fb^{-1} (KLOE2) 2) selection efficiency 20% 3) neglecting background subtraction—
  - limiting factor : uncertainty in the total η' width
- "*III*" :improvement in determination of the partial widths for $\phi \to \eta^{(\prime)}\gamma$
- "*IV*" : improvement in determination of the partial widths for $\eta^{(\prime)} \to \rho\gamma$
- "*V*" : un uncertainty of 1% on the measure of branching ratios for η' decays and of 1.4% for the η' full width.

Experimental status and prospects

Conclusions from previous table :

both BR($\eta^{(')} \to \rho\gamma$) and $\Gamma_{\eta'}$ to be measured more accurately.

- $\eta' \to \omega\gamma$ partial width with relative error 9% (PDG 2010) Relevant experiment (ANL-E-397, 1977) bases on 68 events.
- $\phi \to \eta^{(')}\gamma$ partial width mainly due to KLOE07; error dominated by systematics due to the secondary η' branching ratio
- $\eta' \to \rho\gamma$ partial width with relative error 5% (PDG 2010) Relevant experiment (1969) bases on 298 events

- $\Gamma_{\eta'} = 0.194 \pm 0.009$ (PDG 2010); $\Gamma_{\eta'} = 0.30 \pm 0.09$ direct meas.(1996,1979)
  - Crystal Ball@MAMI (started 2009)
  - New insight could come from production in γγ fusion (KLOE)

Weak Decays of Charm and Beauty Hadrons

- η/η' wave functions important input for several weak *D* and *B* decays
  - CP asymmetries involving η/η' in the final states
  - Control NP vs SM hadronic uncertainties
- Phenomenological approach (while waiting for lattice)
  - pioneering calculation RBC-UKQCD of η/η' masses and mixing using Nf = 2+1 (2010)

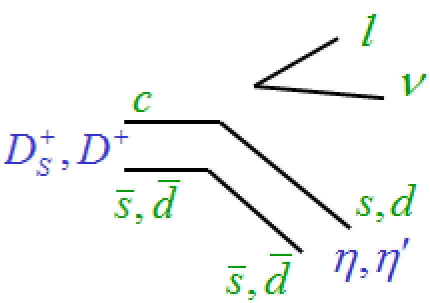
$$\theta_P = -14.1(2.8)^\circ \qquad (\varphi \approx 40.7^\circ)$$

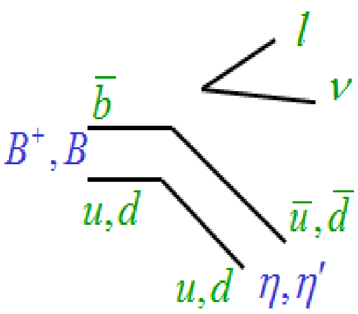
Light Flavour Spectroscopy in Semileptonic Decays

$D_s^+ \to \eta^{(\prime)} l^+ \nu$ $D^+ \to \eta^{(\prime)} l^+ \nu$ $B^+ \to \eta^{(\prime)} l^+ \nu$

- **Spectator diagram dominance**

- Cabibbo allowed c →s, suppressed c →d and CKM suppressed b →u





- If η/η′ without gluonic content and pole ansatz for form factors

$$\Gamma\left(D_s \to \eta' e^+ \nu\right)/\Gamma\left(D_s \to \eta e^+ \nu\right) \propto \cot^2 \phi$$

ϕ=(41.3±5.3)° *Feldmann, Kroll, Stech 98*

- Allowing gluonic content

$$|\eta'\rangle \simeq \cos\phi_G \sin\phi_P |\eta_q\rangle + \cos\phi_G \cos\phi_P |\eta_s\rangle + \sin\phi_G |gg\rangle$$

$$|\eta\rangle \simeq \cos\phi_P |\eta_q\rangle - \sin\phi_P |\eta_s\rangle$$

$$\Gamma\left(D_s \to \eta' e^+ \nu\right)/\Gamma\left(D_s \to \eta e^+ \nu\right) \propto \cot^2 \phi \cos^2 \phi$$

Given ϕ=(37.74±2.6)° ⟶ ϕ_G ≈ 20.3 *Anisovic al. 97*

- new (compatible) CLEO-c 09 data

$$\frac{\Gamma(D_s^+ \to \eta' l^+ \nu)/\Gamma(D_s^+ \to \eta l^+ \nu)}{\Gamma(D^+ \to \eta' l^+ \nu)/\Gamma(D^+ \to \eta l^+ \nu)} \simeq \cot^4 \phi_P$$

ϕp ≈ 40°

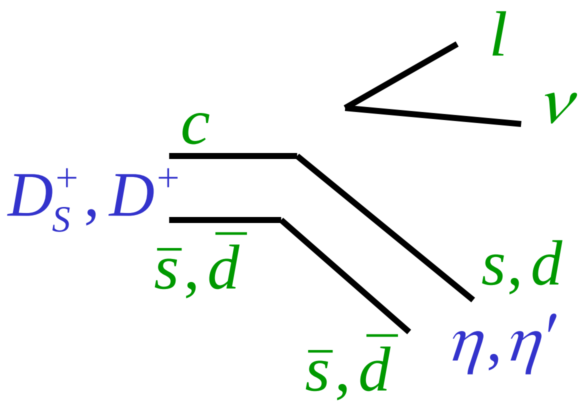
BESIII expects errors on ϕ going down to 2%

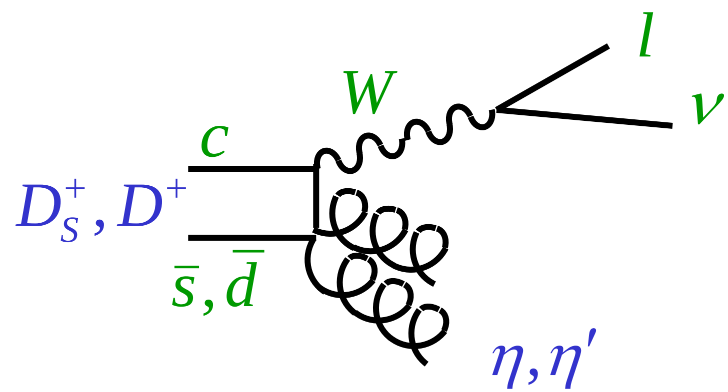
Weak annihilation (WA) diagrams

Spectator | WA (gluonic)

$D_S^+ \to \eta(\eta')l^+\nu$

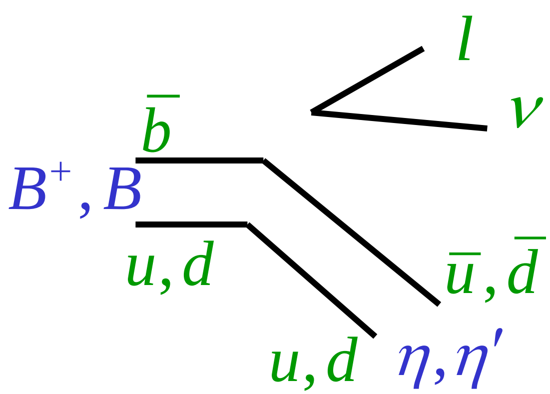
$D^+ \to \eta(\eta')l^+\nu$

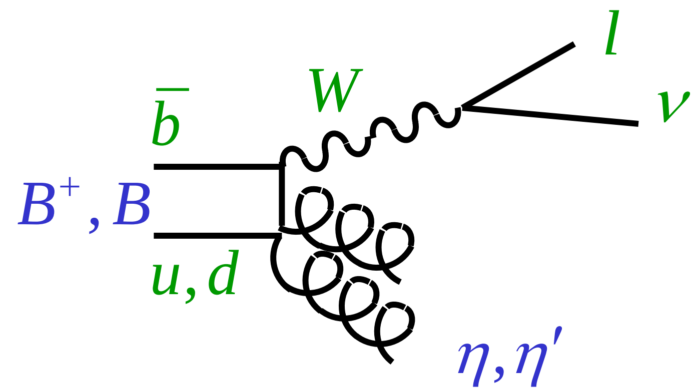




$B^+ \to \eta(\eta')l^+\nu$

$B \to \eta(\eta')l^+\nu$





WA for precision studies

- WA no more than a nonleading contribution to <u>inclusive</u> rates, BUT could affect <u>exclusive</u> modes considerably

- strength depends on:
  - size of the gg component in the wave functions
  - how much gg radiation one can expect in each semileptonic channel
  - might come from the interference with the spectator amplitude, it can a priori enhance or reduce those

- A recent analysis based on <u>inclusive</u> semileptonic D decays, which considers both the widths and the lepton energy moments, shows no clear evidence of WA effects *Gambino, Kamenik 2010*

- No extensive <u>exclusive</u> theoretical analysis yet

$B^{\pm}$ *semileptonic decays*

Same than $D^{\pm}$ only large q^2 and CKM suppressed by $|V_{ub}|^2$

- first evidence of $B^+ \to \eta' l^+ \nu$ by CLEO in 2008
- newest BaBar results (2011) (with a significance of 3.0 σ).
  - an order of magnitude smaller than the CLEO result

$$\mathcal{B}(B^+ \to \eta' l^+ \nu)/\mathcal{B}(B^+ \to \eta l^+ \nu) = 0.67 \pm 0.24_{stat} \pm 0.11_{syst}$$

seems to allow a large gluonic singlet contribution

- $\mathcal{B}(B_s \to \eta' l^+ l^-)$ potentially informative on the gluonic content, exp challenging. In SM BR 10^{-7}-10^{-8} (Super-flavour factories)

Charmless Hadronic B Decays

- Charmless hadronic *B* decays provide valuable tests for the pattern of CP violation in the CKM framework

- CP asymmetries

$$A(t) \equiv \frac{\Gamma(\bar{B}^0(t) \to \eta' K_S) - \Gamma(B^0(t) \to \eta' K_S)}{\Gamma(\bar{B}^0(t) \to \eta' K_S) + \Gamma(B^0(t) \to \eta' K_S)} = -C_{\eta' K} \cos(\Delta m t) + S_{\eta' K} \sin(\Delta m t)$$

$$S_{\eta' K} \equiv \frac{2\mathrm{Im}(\lambda_{\eta' K})}{1 + |\lambda_{\eta' K}|^2}\,, \quad C_{\eta' K} \equiv \frac{1 - |\lambda_{\eta' K}|^2}{1 + |\lambda_{\eta' K}|^2}\,, \quad \lambda_{\eta' K} \equiv -e^{-2i\beta} \frac{A(\bar{B}^0 \to \eta' \bar{K}^0)}{A(B^0 \to \eta' K^0)}$$

in the SM, if one single dominant amplitude

$$C_{\eta' K_S} = 0 \qquad\qquad S_{\eta' K_S} = \sin 2\beta$$

CP violation

- Decays dominated by single b⟶ s penguin amplitude; In the SM

$C_{\eta' K_S} = 0$ $\qquad$ $S_{\eta' K_S} = \sin 2\beta$

Corrections for suppressed diagrams $\Delta S_f = S_f - \sin 2\beta$

Estimates in the ranges (-0.03, 0.03) (QCDF and SCET) and in the range (-0.05, 0.09) from SU(3) symmetry bounds

Beneke 05, Williamson,Zupan 06, Cheng,Chia,Soni 05, Gronau, Rosner, Zupan, 06

$\boxed{C_{\eta' K_S} = 0.03 \pm 0.07}$

$\boxed{S_{\eta' K_S} = +0.67 \pm 0.11}$

Belle 11

- Compatible with SM and $\boxed{\sin 2\beta = 0.657 \pm 0.036 \pm 0.012}$ *(Babar 11)* from

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

Experimental puzzle

$$\mathcal{B}(B^0 \to K^0\eta') = (6.6 \pm 0.4) \times 10^{-5} \;>>\; \mathcal{B}(B^0 \to K^0\eta) = (1.1 \pm 0.4) \times 10^{-6}$$

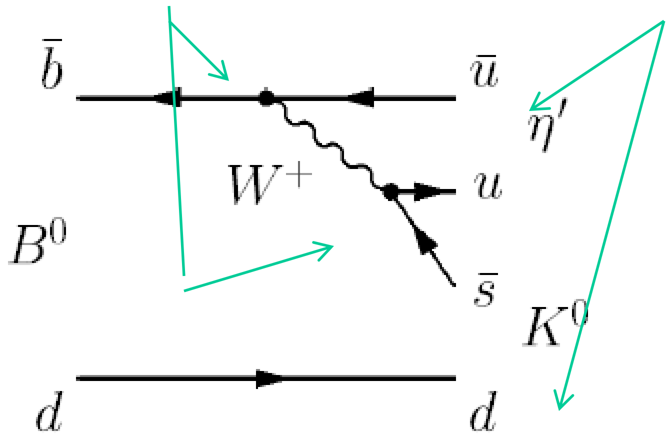
$$\mathcal{B}(B^\pm \to \eta' K^\pm) = (71.5 \pm 1.3 \pm 3.2)10^{-6} \;>>\; \mathcal{B}(B^\pm \to \pi^0 K^\pm) = (13.6 \pm 0.6 \pm 0.7)10^{-6}$$

- SU(3)fl singlet penguin (B$_i$ meson triplet, M^l_j meson nonet), including gluonic contributions

- Anomaly effects, large charm content, NP?

Penguin dominated decays

- Tree level CKM and color suppressed

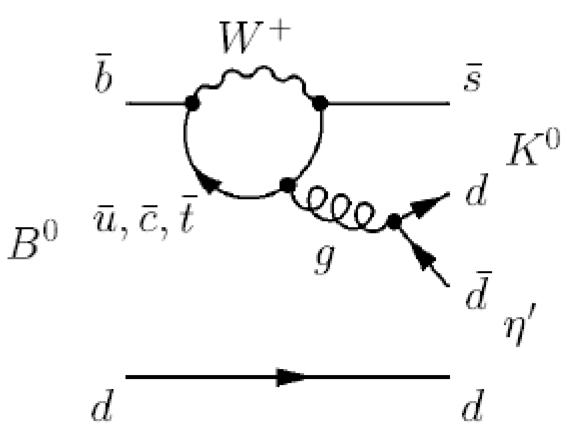


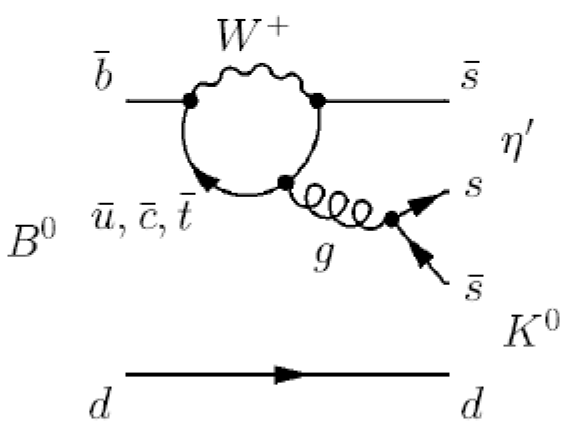
$\lambda \approx 0.22$

$|V_{ub} V_{us}| \approx \lambda^4$

- Penguins CKM not suppressed

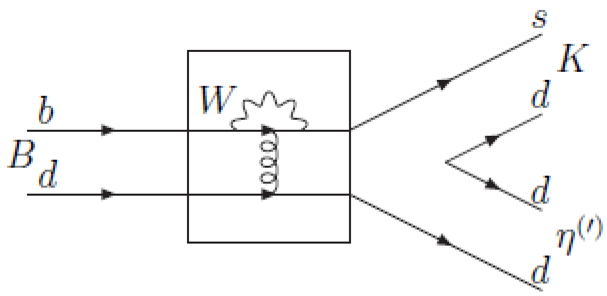
$|V_{tb} V_{ts}| \approx \lambda^2$

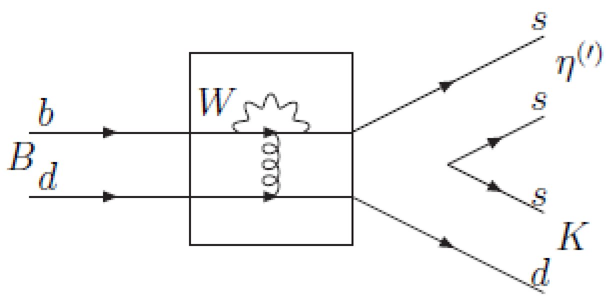




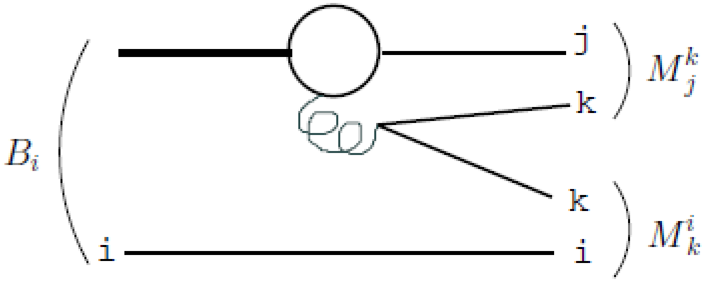
Other contributing penguins

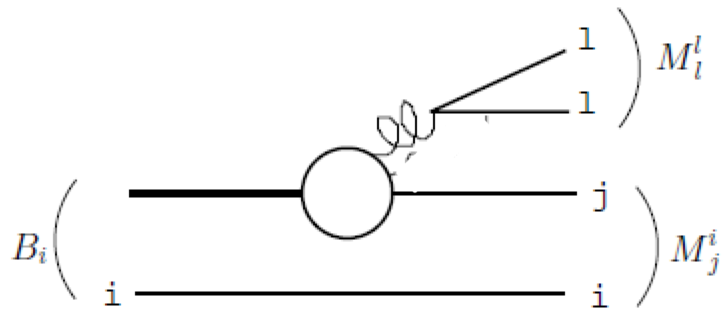
- Annihilation penguin contribution



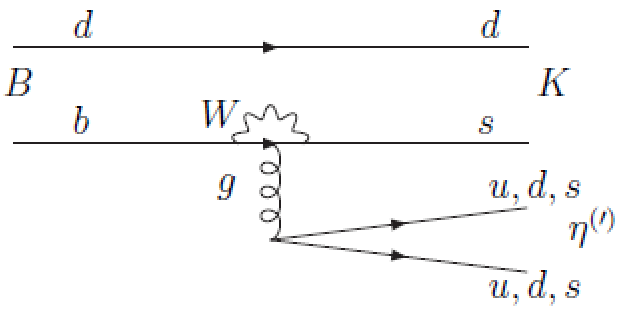


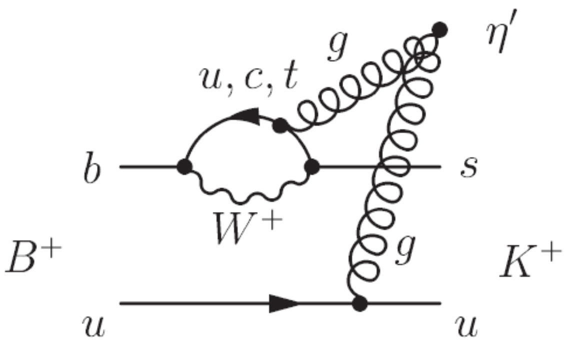
- SU(3)fl singlet penguin (B$_i$ meson triplet, M^l_j meson nonet)





Singlet contribution





- Additional contribution to the SU(3) singlet contribution: fusion of gluons, one gluon from $b \to sg$ process and another one from spectator.

  A sizeable gluonium contribution to the η' meson could play an important role: the contribution of the diagram in which two gluons are directly attached to gluonium in η' in principle important

Theoretical approaches

Within large errors BR compatible with interference among different contributions

- QCDF and SCET : sizable gluonic contributions to the B $\rightarrow \eta'$ form factor

Beneke, Neubert 03;
Williamson, Zupan 06

- pQCD : impact of the gluonic component numerically very small

Y.-Y. Charng, T. Kurimoto, H.-n. Li 06

Major analyses prior to 06, relying on old experimental data

More recent data

2008-2010 CLEO/BaBar

B semileptonic $\mathcal{B}(B^+ \to \eta' l^+ \nu) < \mathcal{B}(B^+ \to \eta l^+ \nu)$

- 2010 BaBar

$$\Gamma(B \to K^\star \eta') < \Gamma(B \to K^\star \eta)$$

- 2007 CLEO

$$D_s^+ \to K^+ \eta' \approx D_s^+ \to K^+ \pi^0$$

Conclusions

Radiative ρωφ	θ_P	$Z_{\eta'}^2$
KLOE (+η′→γγ)	(39.7±0.7)°	0.14±0.04
Escribano	(41.4±1.3)°	0.04±0.09
Thomas	(41.7±0.5)°	0. 04±0.04
Thomas F.F.	(41.9±0.7)°	0.10±0.04

J/ψ→VP	θ_P	$Z_{\eta'}^2$
Thomas	(45±4)°	0.30±0.21
Thomas F.F.	(46+4/-5)°	0.48 ±0.16
Escribano	(44.6±4.4)°	0.29+0.28/-0.26

Semileptonic decay	θ_P	$Z^2_{\eta'}$
$\frac{\Gamma(D_s^+ \to \eta' l^+ \nu)}{\Gamma(D_s^+ \to \eta l^+ \nu)}$	$(37.7 \pm 2.6)°$	0.12

- The different determinations of η–η′ mixing angle are generally consistent, but show relevant model and mode dependence
- the message concerning η′ gluonium content remains ambivalent
- More dedicated studies are necessary (including theoretical updates with new data) while waiting for lattice (but wait seated…)
- Also D^+, D_S^+ and B^+ decays must be included in traditional investigations to check η′ gluonium role