A study of $B^0_{(s)} \to J/\psi\eta^{(\prime)}$ decays at LHCb

Defence of the PhD Thesis of

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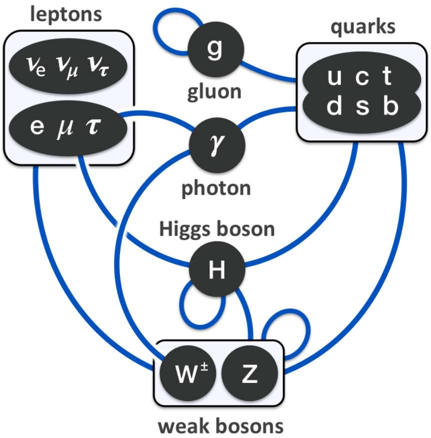
LHCb

Outline

1. Physics introduction
2. The LHCb experiment
3. η-η' mixing in $B^0_{(s)} \to J/\psi\eta^{(\prime)}$ decays
4. Photon reconstruction efficiencies
5. Absolute branching ratios of $B^0_{(s)} \to J/\psi\eta^{(\prime)}$
6. Discussion of results & conclusions

The Standard Model of Particle Physics



Fermions - most observed matter

- Quarks: q, up-type$= \mathrm{u, c, t}$,
  dw-type$= \mathrm{d, s, b}$
- Leptons: $\ell = \mathrm{e}, \mu, \tau$ and ν_ℓ

Gauge bosons - force mediators

- Gluon: g
- Photon: γ
- Z boson: Z
- W bosons: $\mathrm{W}^\pm$

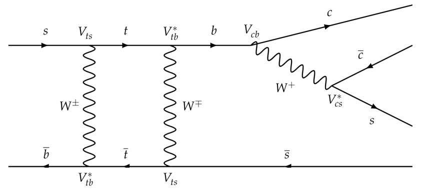
Scalar boson - mass generation

- Higgs boson: H^0

The Flavour Sector of the Standard Model

- Needed an explanation of the origin of CP violation in quark sector
- The Cabibbo-Kobayashi-Maskawa matrix describes quark flavour transitions via $\mathrm{W}^{\pm}$ and the entering CP violation

$$V_{CKM} \approx \begin{pmatrix} |V_{\mathrm{ud}}| & |V_{\mathrm{us}}| & |V_{\mathrm{ub}}|e^{-i\gamma} \\ |V_{\mathrm{cd}}| & |V_{\mathrm{cs}}| & |V_{\mathrm{cb}}| \\ |V_{\mathrm{td}}|e^{-i\beta} & -|V_{\mathrm{ts}}|e^{i\beta_{\mathrm{s}}} & |V_{\mathrm{tb}}| \end{pmatrix}$$



- Wolfenstein's parameterisation

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\bar{\rho}-i\bar{\eta})] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(\bar{\rho}-i\bar{\eta})] & -A^2+\frac{1}{2}A\lambda^4[1-2(\bar{\rho}-i\bar{\eta})] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

- Unitarity relations arise from $V_{CKM}V_{CKM}^{\dagger} = 1$, orthogonally we get:

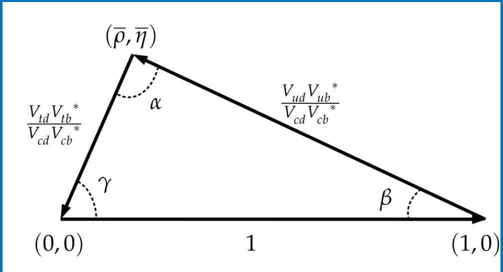
$$V_{\mathrm{ud}}V_{\mathrm{ub}}{}^* + V_{\mathrm{cd}}V_{\mathrm{cb}}{}^* + V_{\mathrm{td}}V_{\mathrm{tb}}{}^* = 0 \qquad V_{\mathrm{us}}V_{\mathrm{ub}}{}^* + V_{\mathrm{cs}}V_{\mathrm{cb}}{}^* + V_{\mathrm{ts}}V_{\mathrm{tb}}{}^* = 0$$

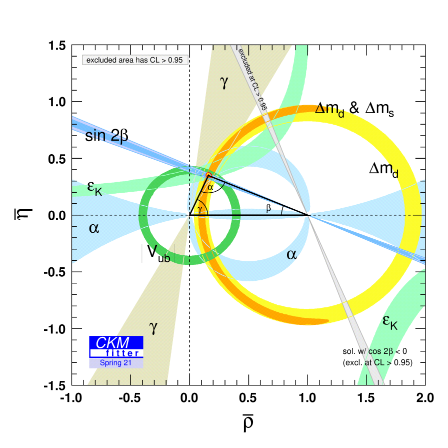
Unitarity Triangles: the B_d^0 system

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$1 + V_{ud}V_{ub}^*/V_{cd}V_{cb}^* + V_{td}V_{tb}^*/V_{cd}V_{cb}^* = 0$$

$$(\bar\rho - i\bar\eta) \equiv \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$





$$\alpha = (91.98^{+0.82}_{-1.40})^\circ \quad w/\ \mathrm{B}\to \rho\rho/\pi\pi/\rho\pi$$

$$\beta = (22.42^{+0.64}_{-0.37})^\circ \quad w/\ \mathrm{B}^0 \to \mathrm{J}/\psi \mathrm{K}_S^0$$

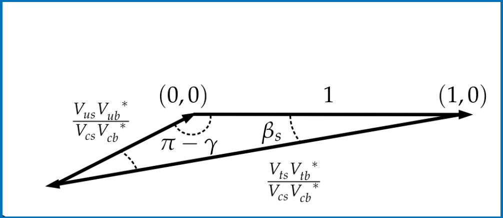
$$\gamma = (65.5^{+1.3}_{-1.2})^\circ \quad w/\ \mathrm{B}\to \mathrm{DK}$$

All from [CKMFitter Spring 2021]

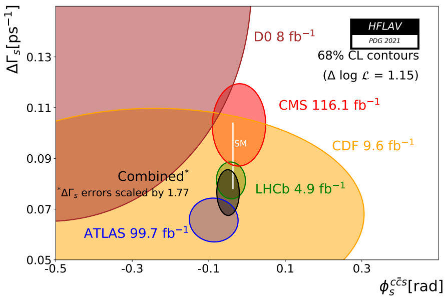
Unitarity Triangles: the B_s^0 system

$$V_{us}V_{ub}{}^* + V_{cs}V_{cb}{}^* + V_{ts}V_{tb}{}^* = 0$$

$$1 + V_{us}V_{ub}{}^*/V_{cs}V_{cb}{}^* + V_{ts}V_{tb}{}^*/V_{cs}V_{cb}{}^* = 0$$



$\phi_s \equiv -2\beta_s$



$HFLAV : \phi_s{}^{c\bar{c}s} = -0.050 \pm 0.019$ rad

LHCb : $\phi_s = -0.042 \pm 0.025$ rad

$SM : \phi_s{}^{c\bar{c}s} = -0.0368^{+0.0006}_{-0.0009}$ rad

- Golden Modes: $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$
- Hopefully a measurement of ϕ_s with $B_s^0 \to J/\psi\eta^{(\prime)}$ is possible with more statistics in the ongoing data-taking of LHCb
- Advantage 1: not requiring an angular analysis
- Advantage 2: penguin pollution can be controlled by $B^0 \to J/\psi\eta^{(\prime)}$

Conventional meson spectroscopy

Quark Model of Mesons

- Mesons are typically bound $q\bar{q}$ states
- Categorised by J^{PC} multiplets

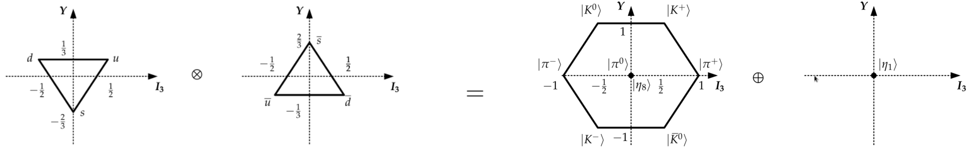
$$|l-s| \leq J \leq |l+s|$$

$$C = (-1)^{l+s} \quad P = (-1)^{l+1}$$

- $q\bar{q}$ relative angular momenta l
- $q\bar{q}$ net spin $s = \frac{1}{2} \pm \frac{1}{2} = 1, 0$

Categories of Mesons

- $J^{PC} = 0^{-+}$: pseudoscalars $\leftarrow$ focus
- $J^{PC} = 0^{++}$: scalars
- $J^{PC} = 1^{--}$: vectors
- $J^{PC} = 1^{+-}, 1^{++}$: axial vectors
- and $J > 1$ mesons

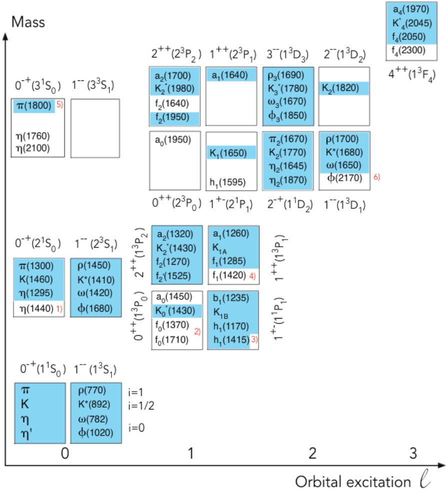


isospin-1 pions
π^+, π^-, π^0

isospin-$\frac{1}{2}$ kaons
$K^+, K^-, K^0, \overline{K}^0$

isospin-0 etas
η_8, η_1

Conventional meson spectroscopy



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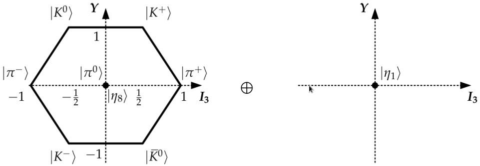

isospin-1 pions
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isospin-$\frac{1}{2}$ kaons
$K^+, K^-, K^0, \overline{K}^0$

isospin-0 etas
η_8, η_1

η-η′ meson mixing

The isoscalar pseudoscalars

$$|\eta_8\rangle = \frac{1}{\sqrt{6}}(|u\bar{u}\rangle + |d\bar{d}\rangle - 2|s\bar{s}\rangle) \quad |\eta_1\rangle = \frac{1}{\sqrt{3}}(|u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle)$$

Description of η (548) and η′ (958) mass eigenstates in the quark-flavour basis

- Isoscalars mix due to $\mathrm{SU}(3)$ symmetry breaking

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_P & -\sin\theta_P \\ \sin\theta_P & \cos\theta_P \end{pmatrix} \begin{pmatrix} |\eta_8\rangle \\ |\eta_1\rangle \end{pmatrix} \xrightarrow{rotation} \begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \end{pmatrix} = \begin{pmatrix} \cos\varphi_P & -\sin\varphi_P \\ \sin\varphi_P & \cos\varphi_P \end{pmatrix} \begin{pmatrix} |\eta_q\rangle \\ |\eta_s\rangle \end{pmatrix}$$

$$|\eta_q\rangle = \frac{1}{\sqrt{2}}(|u\bar{u}\rangle + |d\bar{d}\rangle) \quad |\eta_s\rangle = |s\bar{s}\rangle$$

- ideal mixing is when η is pure $s\bar{s} \Rightarrow \varphi_P \approx 90^\circ$ (nearly true for vectors with ϕ as $s\bar{s}$)
- $\varphi_P = \theta_P - \arctan\sqrt{2} = \theta_P - 54.7^\circ$

Non-conventional meson spectroscopy

Multiquarks

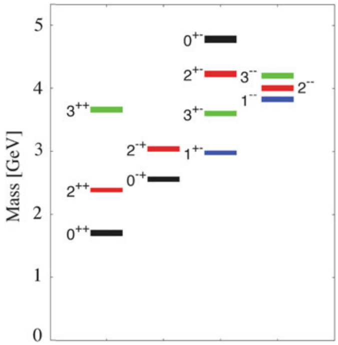
- Tetraquarks are mesons with 4 valence quarks in a $q\bar{q}q\bar{q}$ composition
- Seen: heavy with at least one c quark (*e.g.*$c\bar{c}u\bar{s}$, $c\bar{c}c\bar{c}$, $c\bar{s}u\bar{d}$, etc.) [Nature Commun. 13 (2022) 1]
- Not seen of light tetraquark states (just u,d,s)

Hybrid mesons

- Hybrid mesons can be considered as $q\bar{q}\,g$
- Not always isospin-0 and can be charged
- Could have exotic J^{PC} numbers (*e.g.* 1^{-+})

Glueballs

- Meson of two or three valence gluons
- Always isospin-0 and neutral
- Can mix with isospin-0 $q\bar{q}$ mesons and have impacts on the masses and decay rates of these mesons
- Many contradictory results for candidates
  - Scalar: one of $f_0(1500)$ or $f_0(1710)$
  - Pseudoscalar: $\eta(1405/1475)$



[Phys. Rev. D 73(2006)]
LQCD result: colour = J, x-axis = PC

η-η' mixing in connection to gluonium

A way to explain the heaviness of $\eta^{(\prime)}$

- The η and η' masses are higher than the π and K and higher than expected from just a $q\bar{q}$ description, but why?
- An extended mixing scheme can be made where η' mixes with a heavy pseudoscalar made of valence gluons, a glueball (η_G), can provide an answer
- The physical η and η' and η_G states can be described in terms of $q\bar{q}$ and a gluonium state $|gg\rangle$

We have a description with two angles:

- η-η': φ_P
- η'-η_G: φ_G

$$|\eta\rangle = \cos\varphi_P|\eta_q\rangle - \sin\varphi_P|\eta_s\rangle$$

$$|\eta'\rangle = \cos\varphi_G(\sin\varphi_P|\eta_q\rangle + \cos\varphi_P|\eta_s\rangle) - \sin\varphi_G|gg\rangle$$

- We measured these angles in this mixing scheme

Mixing angles predictions

Mass formulae

- From the diagonalisation $\begin{pmatrix} m_8 & m_{81} \\ m_{18} & m_1 \end{pmatrix} \begin{pmatrix} \cos\theta_P \\ -\sin\theta_P \end{pmatrix} = m_\eta \begin{pmatrix} \cos\theta_P \\ -\sin\theta_P \end{pmatrix}$

  $\Rightarrow \tan(\varphi_P - 54.7°) = \frac{4m_K - m_\pi - 3m_\eta}{2\sqrt{2}(m_\pi - m_K)}$
- gives: $\varphi_P = 43.0°$, $\varphi_P = 48.4° (m^2)$
- From its unitarity $\begin{pmatrix} m_8 & m_{81} \\ m_{18} & m_1 \end{pmatrix} = \begin{pmatrix} \cos\theta_P & \sin\theta_P \\ -\sin\theta_P & \cos\theta_P \end{pmatrix} \begin{pmatrix} m_\eta & 0 \\ 0 & m_{\eta'} \end{pmatrix} \begin{pmatrix} \cos\theta_P & -\sin\theta_P \\ \sin\theta_P & \cos\theta_P \end{pmatrix}$

  $\Rightarrow \tan(\varphi_P - 54.7°) = -\frac{4m_K - m_\pi - 3m_\eta}{4m_K - m_\pi - 3m_{\eta'}}$
- gives: $\varphi_P = 30.2°$, $\varphi_P = 43.3° (m^2)$

Chiral Perturbation Theory

- $\varphi_P = (39.3 \pm 1.0)°$ [Gan, Kubis, Passemar and Tulin (2020)]

Lattice QCD

- $\varphi_P = (38.8 \pm 2.2\,(\text{stat}) \pm 2.4(\chi_{\text{PT}}))°$ [Gan, Kubis, Passemar and Tulin (2020)]

Mixing angle experimental status

KLOE

- Studied $\phi \to \gamma\eta$ and $\phi \to \gamma\eta'$
- $\varphi_P = (39.7 \pm 0.7)^\circ$ and $\varphi_G = (22 \pm 3)^\circ$ [Phys.Lett.B 648 (2007)]
- $\varphi_P = (41.4 \pm 1.3)^\circ$ and $\varphi_G = (12 \pm 13)^\circ$ determined by a refit to $\phi \to \gamma\eta^{(\prime)}$ experimental data [JHEP 05 (2007) 006]

BES-II

- Studied $J/\psi \to \gamma\eta$ and $J/\psi \to \gamma\eta'$
- $\varphi_P = (38.8 \pm 1.2)^\circ$ [Phys.Rev.D 73 (2006)]
- $\varphi_P = (44.6 \pm 4.4)^\circ$ and $\varphi_G = (32^{+11}_{-22})^\circ$ in a fit of $J/\psi \to VP$ experimental data by [Eur.Phys.J.C 65 (2010) 467-473]
  - In 3 angles: $\varphi_P = (44.3 \pm 4.2)^\circ$, $\varphi_G^{\eta} = (1.6^{+5.4}_{-6.6})^\circ$ and $\varphi_G^{\eta'} = (33^{+12}_{-21})^\circ$

LHCb

- Moscow groups studied $B^0_{(s)} \to J/\psi\eta^{(\prime)}$ with $3\,\text{fb}^{-1}$ of data
- $\varphi_P = (43.5^{+1.4}_{-2.8})^\circ$ and $\varphi_G = (0 \pm 24.6)^\circ$ [JHEP 01 (2015) 024]
- This thesis replaces these results with more statistics and refined analysis methods
- Future studies should include $D^+_{(s)} \to \pi^+\eta^{(\prime)}$ [CPV study submitted to JHEP] or $B^0_{(s)} \to \overline{D}^0\eta^{(\prime)}$, for example

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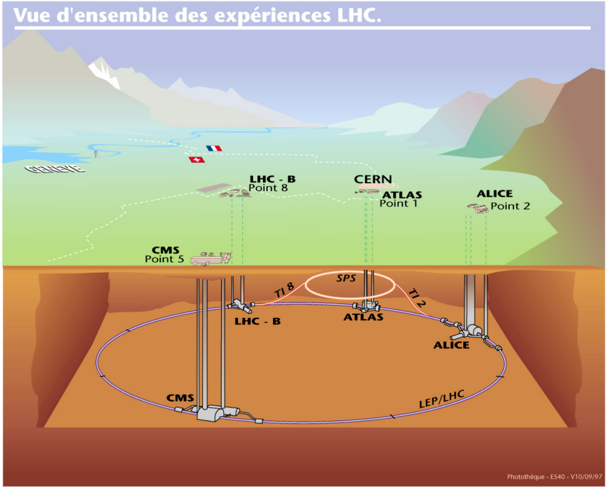
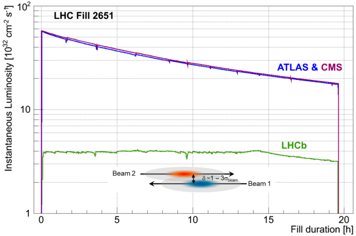
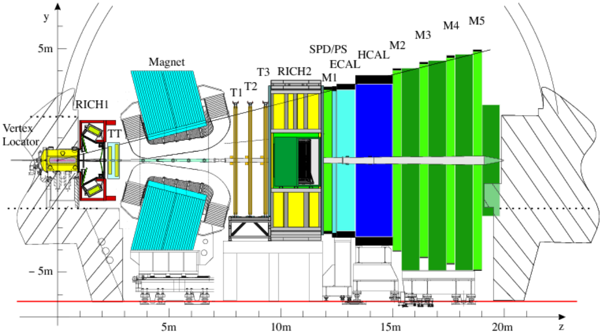
The Large Hadron Collider

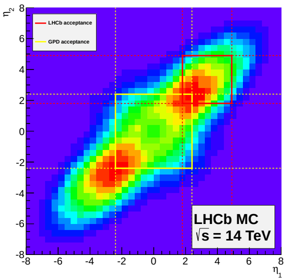




- proton-proton collisions at $7, 8, 13$ TeV from 2011 to 2018 (energy record recently broken)
- Four large experiments:
  - General purpose: ATLAS and CMS
  - Heavy ion physics: ALICE
  - Flavour physics: LHCb

The LHCb experiment

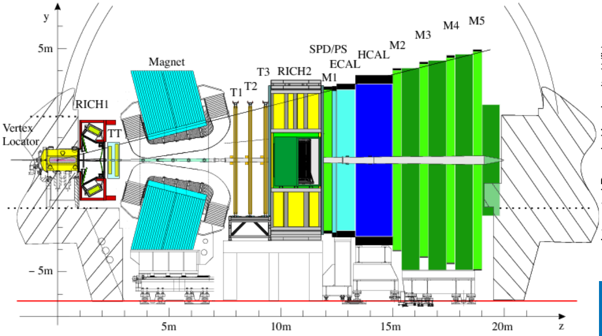


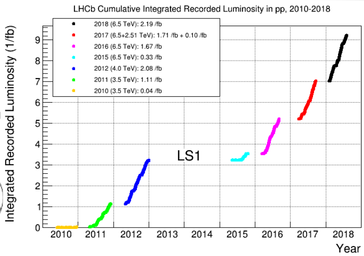


- Target: high precision heavy-flavour physics
- Tests of CKM paradigm (CP violation), electroweak and QCD physics, searches of rare decays and hadron spectroscopy.
- Also ion physics with fixed target or Pb-p/Pb-Pb beam

- $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ production
- Forward geom.: 25% $\mathrm{b\bar{b}}$ pairs produced in LHCb acceptance
- $\mathrm{c\bar{c}}$ is ~ 20 times $\mathrm{b\bar{b}}$

LHCb detector performance





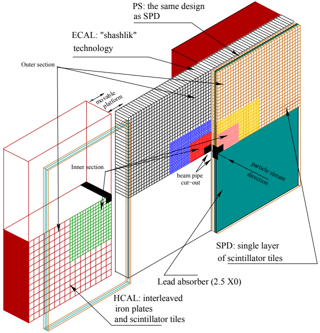
Detector performance

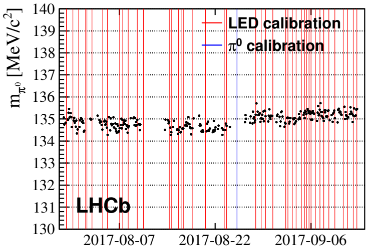
- Tracking: $\Delta p/p = 0.5 - 1.0\%$, $\Delta IP = (15 + 29/p_{\mathrm{T}}[\text{GeV}])\ \mu\text{m}$
- Calo: $\Delta E/E_{ECAL} = (1 + 10/\sqrt{E[\text{GeV}]})\%$
- PID: μ ID $\sim 97\%$ and $K^{\pm}/\pi^{\pm}$ ID $\gtrsim 80\%$

Two Runs (w/ third ongoing)

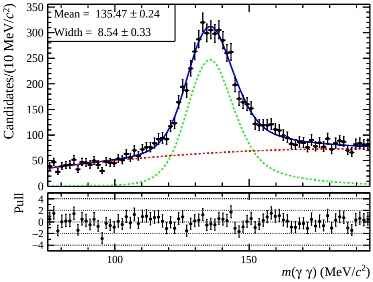
- Run-1: 2011 and 2012 at 7 and 8 TeV respectively - $3\ \text{fb}^{-1}$
- Run-2: 2015-2018 at 13 TeV - $6\ \text{fb}^{-1}$
- Both used in analyses of this thesis

LHCb Calorimeter





PMT gains calibrated w/ LEDs
Fine calibrations w/ π^0 mass



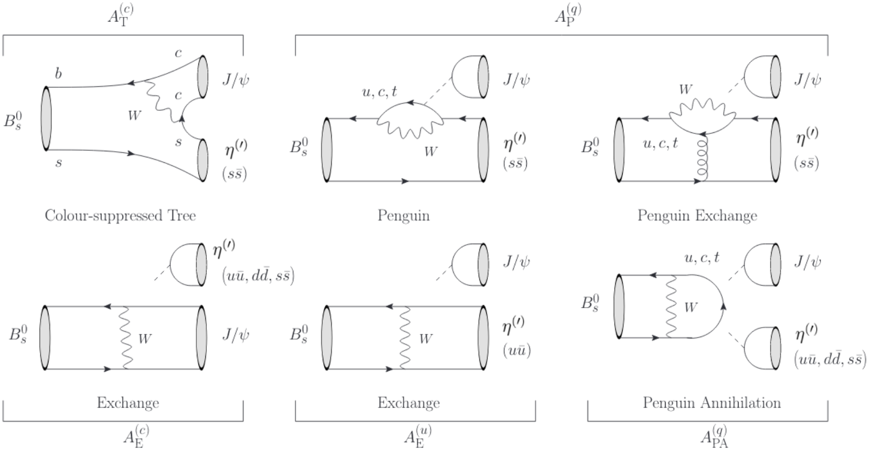
- ECAL - shashlik lead and scintillator layers $25\mathrm{X}^0$
- HCAL - interleaved iron and scintillator layers 5.6λ
- Scintillating Pad Detector (SPD) and Pre-Shower (PS) w/ $2.5\mathrm{X}^0$ lead converter in-between

- Energy measurement, PID and trigger
  - ECAL & PS: e (w/SPD) & γ
  - HCAL: $\mathrm{K}/\pi^{\pm}$

Branching ratios

- The branching ratios of $\mathrm{B}_q^0 \to \mathrm{J}/\psi\eta^{(\prime)}$ with $q = s, d$ can be expressed as:

$$\mathcal{B}(\mathrm{B}_q^0 \to \mathrm{J}/\psi\eta^{(\prime)}) = \frac{\tau_{\mathrm{B}_q^0} M_{\mathrm{B}_q^0} (\Phi_q^{\eta^{(\prime)}})^3}{64\pi} |V_{cq} V_{cb}^*|^2 \left|F(\mathrm{B}_q^0 \to \mathrm{J}/\psi q\bar{q})\right|^2 \left|\langle q\bar{q}|\eta^{(\prime)}\rangle\right|^2$$



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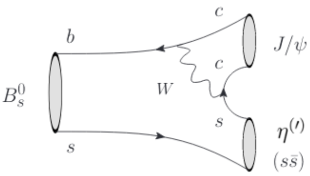


Colour-suppressed Tree

$$A_T^{(c)} \gg A_E^{(c,u)}, A_P^{(q)}, A_{PA}^{(q)}$$

Branching ratios (1)

- The branching ratios of $\mathrm{B_q^0} \to \mathrm{J/\psi\eta^{(\prime)}}$ with $\mathrm{q} = \mathrm{s, d}$ can be expressed as:

$$\mathcal{B}(\mathrm{B_q^0} \to \mathrm{J/\psi\eta^{(\prime)}}) = \frac{\tau_{\mathrm{B_q^0}} M_{\mathrm{B_q^0}} (\Phi_{\mathrm{q}}^{\eta^{(\prime)}})^3}{64\pi} |V_{\mathrm{cq}} V_{\mathrm{cb}}^*|^2 \left|F(\mathrm{B_q^0} \to \mathrm{J/\psi q\bar{q}})\right|^2 \left|\langle \mathrm{q\bar{q}} | \eta^{(\prime)} \rangle\right|^2$$

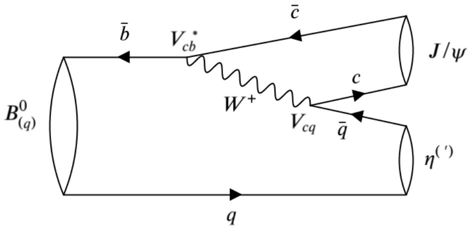
- $\Phi_{(s)}^{\eta^{(\prime)}} = \sqrt{\left[1 - \left(M_{\eta^{(\prime)}} + M_{\mathrm{J/\psi}}\right)^2 / M_{\mathrm{B^0_{(s)}}}^2\right]\left[1 - \left(M_{\eta^{(\prime)}} - M_{\mathrm{J/\psi}}\right)^2 / M_{\mathrm{B^0_{(s)}}}^2\right]}$ are the phase-space factors for $\mathrm{P} \to \mathrm{VP}$
- $\tau_{\mathrm{B_q^0}}$ is the lifetime of $\mathrm{B_q^0}$
- $M_{\mathrm{B_q^0}}$ is the mass of $\mathrm{B_q^0}$

Branching ratios (2)

- The branching ratios of $\mathrm{B_q^0} \to \mathrm{J/\psi\eta^{(\prime)}}$ with $\mathrm{q = s, d}$ can be expressed as:

$$\mathcal{B}(\mathrm{B_q^0} \to \mathrm{J/\psi\eta^{(\prime)}}) = \frac{\tau_{\mathrm{B_q^0}} M_{\mathrm{B_q^0}} (\Phi_{\mathrm{q}}^{\eta^{(\prime)}})^3}{64\pi} |V_{\mathrm{cq}} V_{\mathrm{cb}}^*|^2 \left|F(\mathrm{B_q^0} \to \mathrm{J/\psi q\bar{q}})\right|^2 \left|\langle \mathrm{q\bar{q}} | \eta^{(\prime)} \rangle\right|^2$$

- From $\mathrm{b} \to \mathrm{c\bar{c}q}$ transitions
  - $|V_{\mathrm{cb}}|^2 \sim \lambda^4 \sim 0.2\%$
  - $|V_{\mathrm{cd}}|^2 \sim \lambda^2 \sim 4\%$ for $\mathrm{B^0}$ mode
  - $|V_{\mathrm{cs}}|^2 \sim 100\%$ for $\mathrm{B_s^0}$ mode
- $\Rightarrow$ CKM/Cabibbo suppression of $\mathrm{B^0}$ mode
- Partially mitigated as $\mathrm{B^0}$ has four times the production rate of $\mathrm{B_s^0}$ in LHCb



Branching ratios (3)

- The branching ratios of $\mathrm{B_q^0} \to \mathrm{J/\psi\eta^{(\prime)}}$ with $\mathrm{q} = \mathrm{s}, \mathrm{d}$ can be expressed as:

$$\mathcal{B}(\mathrm{B_q^0} \to \mathrm{J/\psi\eta^{(\prime)}}) = \frac{\tau_{\mathrm{B_q^0}} M_{\mathrm{B_q^0}} (\Phi_{\mathrm{q}}^{\eta^{(\prime)}})^3}{64\pi} |V_{\mathrm{cq}} V_{\mathrm{cb}}^*|^2 \left|F(\mathrm{B_q^0} \to \mathrm{J/\psi q\bar{q}})\right|^2 \left|\langle \mathrm{q\bar{q}} | \eta^{(\prime)} \rangle\right|^2$$

- The form factors for $\mathrm{B_q^0} \to \mathrm{J/\psi q\bar{q}}$
- Assuming $\mathrm{SU(3)}_F$ symmetry: $F(\mathrm{B_d^0} \to \mathrm{J/\psi d\bar{d}}) = F(\mathrm{B_s^0} \to \mathrm{J/\psi s\bar{s}})$
- A test of this is shown later

Branching ratios (4)

- The branching ratios of $\mathrm{B_q^0} \to \mathrm{J/\psi\eta^{(\prime)}}$ with $\mathrm{q} = \mathrm{s}, \mathrm{d}$ can be expressed as:

$$\mathcal{B}(\mathrm{B_q^0} \to \mathrm{J/\psi\eta^{(\prime)}}) = \frac{\tau_{\mathrm{B_q^0}} M_{\mathrm{B_q^0}} (\Phi_{\mathrm{q}}^{\eta^{(\prime)}})^3}{64\pi} |V_{\mathrm{cq}} V_{\mathrm{cb}}^*|^2 \left|F(\mathrm{B_q^0} \to \mathrm{J/\psi q\bar{q}})\right|^2 \left|\langle \mathrm{q\bar{q}} | \eta^{(\prime)} \rangle\right|^2$$

- The projections of $|\eta^{(\prime)}\rangle$ states to $\mathrm{d\bar{d}}$ or $\mathrm{s\bar{s}}$
- $\langle \mathrm{d\bar{d}} | \eta \rangle = \cos\varphi_P / \sqrt{2}$
- $\langle \mathrm{d\bar{d}} | \eta' \rangle = \cos\varphi_G \sin\varphi_P / \sqrt{2}$
- $\langle \mathrm{s\bar{s}} | \eta \rangle = -\sin\varphi_P$
- $\langle \mathrm{s\bar{s}} | \eta' \rangle = \cos\varphi_G \cos\varphi_P$

Ways to measure η-η' mixing: $\mathcal{R}_{\eta^{(\prime)}}$

- A way to measure φ_P is to measure $\mathcal{R}_{\eta^{(\prime)}}$

$$R_{\eta^{(\prime)}} = \frac{\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\eta^{(\prime)})}{\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\eta^{(\prime)})}$$

- Assuming $\mathrm{SU}(3)_F$ symmetry $F(\mathrm{B}^0 \to \mathrm{J}/\psi \mathrm{d}\bar{\mathrm{d}}) = F(\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi \mathrm{s}\bar{\mathrm{s}})$ and $\tan^2\theta_c = |V_{\mathrm{cd}}/V_{\mathrm{cs}}|^2$

$$\mathcal{R}_{\eta'} = \frac{\tau_{\mathrm{B}^0}}{\tau_{\mathrm{B}^0_\mathrm{s}}} \frac{m_{\mathrm{B}^0}}{m_{\mathrm{B}^0_\mathrm{s}}} \left(\frac{\Phi_d^{\eta'}}{\Phi_s^{\eta'}}\right)^3 \times \frac{\tan^2\theta_c}{2} \times \tan^2\varphi_P$$

$$\mathcal{R}_{\eta} = \frac{\tau_{\mathrm{B}^0}}{\tau_{\mathrm{B}^0_\mathrm{s}}} \frac{m_{\mathrm{B}^0}}{m_{\mathrm{B}^0_\mathrm{s}}} \left(\frac{\Phi_d^{\eta}}{\Phi_s^{\eta}}\right)^3 \times \frac{\tan^2\theta_c}{2} \times \cot^2\varphi_P$$

- Although this is not sensitive to φ_G
- If $\mathrm{SU}(3)_F$ symmetry is broken then $\mathcal{R}_\eta$ and $\mathcal{R}_{\eta'}$ will produce different φ_P
- $\varphi_P = (46.3 \pm 2.3)^\circ$ LHCb Run-1 value [JHEP 01 (2015) 024]

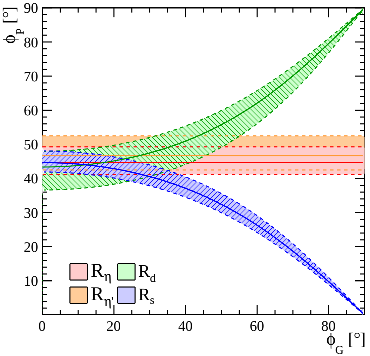
Ways to measure η-η′ mixing: $\mathcal{R}_{\rm d,s}$

- A way to measure both φ_P and φ_G is to measure $R_{\rm d,s}$

$$\mathcal{R}_{\rm d} = \frac{\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\eta')}{\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\eta)} \qquad \mathcal{R}_{\rm s} = \frac{\mathcal{B}(\mathrm{B}_s^0 \to \mathrm{J}/\psi\eta')}{\mathcal{B}(\mathrm{B}_s^0 \to \mathrm{J}/\psi\eta)}$$

$$\mathcal{R}_d = \left(\frac{\Phi_d^{\eta'}}{\Phi_d^{\eta}}\right)^3 \times \cos^2\varphi_G \times \tan^2\varphi_P$$

$$\mathcal{R}_s = \left(\frac{\Phi_s^{\eta'}}{\Phi_s^{\eta}}\right)^3 \times \cos^2\varphi_G \times \cot^2\varphi_P$$



PDG 2020 Branching Ratios

- Note $\frac{\mathcal{R}_d}{\mathcal{R}_s} \equiv \frac{\mathcal{R}_{\eta'}}{\mathcal{R}_\eta}$
- LHCb Run-1: $\varphi_P = (43.5^{+1.4}_{-2.8})^\circ$, $\varphi_G = (0 \pm 24.6)^\circ$ [JHEP 01 (2015) 024]

Analysis strategy: η-η' mixing with $B^0_{(s)} \to J/\psi\eta^{(\prime)}$

- Four $\eta^{(\prime)}$ final states are used to measure both the absolute $\mathcal{B}$ and η-η' mixing of $B^0{}_{(s)} \to J/\psi\eta^{(\prime)}$ with $J/\psi \to \mu^+\mu^-$

Channel	$\mathcal{B}/\%$
$\eta \to \pi^+\pi^-\gamma$	4.22 ± 0.08
$\eta \to \pi^+\pi^-\pi^0$	22.92 ± 0.28
where $\pi^0 \to \gamma\gamma$	98.823 ± 0.034

Channel	$\mathcal{B}/\%$
$\eta' \to \rho^0[\pi^+\pi^-]\gamma$	29.5 ± 0.4
$\eta' \to \pi^+\pi^-\eta$	42.5 ± 0.5
where $\eta \to \gamma\gamma$	39.41 ± 0.20

- Using pp collision data (Run-1 and 2) $\Rightarrow \int \mathcal{L} = 9$ fb^{-1} at $7, 8, 13$ TeV.

$$\mathcal{R}_{\eta^{(\prime)}} = \frac{\mathcal{B}(B^0_d \to J/\psi\eta^{(\prime)})}{\mathcal{B}(B^0_s \to J/\psi\eta^{(\prime)})} = \frac{N^s_{B^0_d \to J/\psi\eta^{(\prime)}}}{N^s_{B^0_s \to J/\psi\eta^{(\prime)}}} \times \frac{\varepsilon^{MC}_{B^0_d \to J/\psi\eta^{(\prime)}}}{\varepsilon^{MC}_{B^0_s \to J/\psi\eta^{(\prime)}}} \times \left(\frac{f_s}{f_d}\right)^{-1}$$

$$\mathcal{R}_{d,s} = \frac{\mathcal{B}(B^0_{d,s} \to J/\psi\eta')}{\mathcal{B}(B^0_{d,s} \to J/\psi\eta)} = \frac{N^s_{B^0_{d,s} \to J/\psi\eta'}}{N^s_{B^0_{d,s} \to J/\psi\eta}} \times \frac{\varepsilon^{MC}_{B^0_{d,s} \to J/\psi\eta}}{\varepsilon^{MC}_{B^0_{d,s} \to J/\psi\eta'}} \times \frac{\mathcal{B}(\eta \to \pi^+\pi^-\gamma(\gamma))}{\mathcal{B}(\eta' \to \pi^+\pi^-\gamma(\gamma))}$$

- $f_s/f_d(13\text{ TeV}) = 0.2539 \pm 0.0079$ [Phys. Rev. D 104, 032005]
- All measurements are made twice:
  - with one or two photons in the final state
  - averages are then made from each set of results

Analysis strategy: $\mathcal{B}$ with $B^0_{(s)} \to J/\psi\eta^{(\prime)}$

- Four $\eta^{(\prime)}$ final states are used to measure both the absolute $\mathcal{B}$ and η-η' mixing of $B^0{}_{(s)} \to J/\psi\eta^{(\prime)}$ with $J/\psi \to \mu^+\mu^-$

Channel	$\mathcal{B}/\%$
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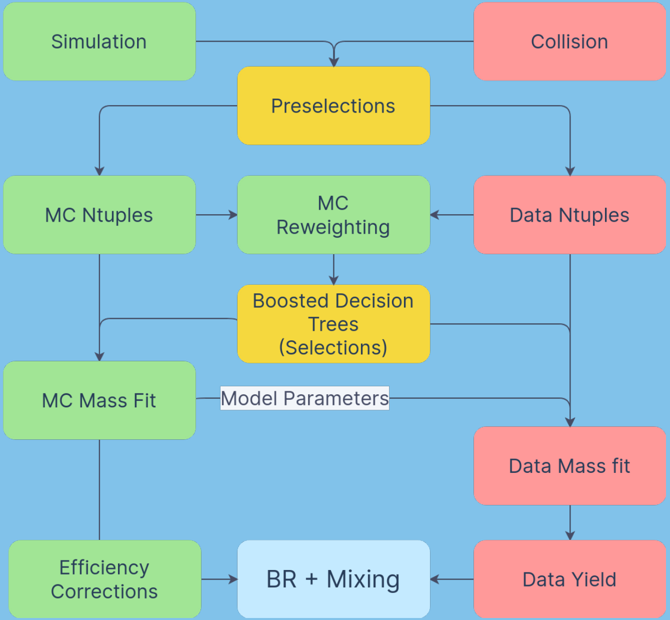
where $\eta \to \gamma\gamma$	39.41 ± 0.20

- Using pp collision data (Run-1 and 2) $\Rightarrow \int \mathcal{L} = 9\,\text{fb}^{-1}$ at $7, 8, 13$ TeV.

$$\mathcal{B}(B^0{}_{(s)} \to J/\psi\eta^{(\prime)}) = \frac{N^s_{B^0{}_{(s)} \to J/\psi\eta^{(\prime)}}}{N^s_{B^0 \to J/\psi\rho^0}} \times \frac{\varepsilon^{MC}_{B^0 \to J/\psi\rho^0}}{\varepsilon^{MC}_{B^0{}_{(s)} \to J/\psi\eta^{(\prime)}}} \times \frac{\mathcal{B}(B^0 \to J/\psi\rho^0)}{\mathcal{B}(\eta^{(\prime)} \to \pi^+\pi^-\gamma(\gamma))} \times \left(\frac{f_s}{f_d}\right)^{-1}$$

- $f_s/f_d(13\,\text{TeV}) = 0.2539 \pm 0.0079$ [Phys. Rev. D 104, 032005]
- All measurements are made twice:
  - with one or two photons in the final state
  - averages are then made from each set of results
- Normalisation: $\mathcal{B}(B^0 \to J/\psi\rho^0[\pi^+\pi^-]) = (2.55^{+0.18}_{-0.16}) \times 10^{-5}$ [PDG 2022]

Analysis steps



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Event selections & MC corrections

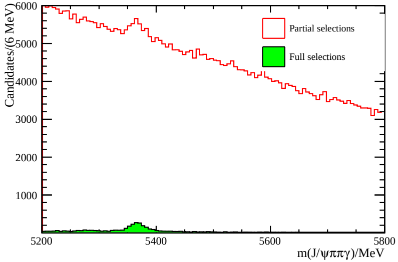
Selection strategy

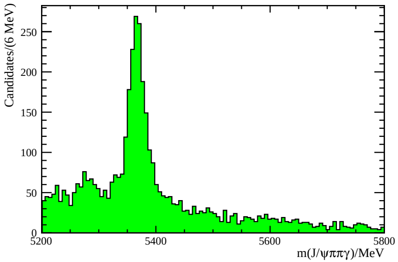
- Preselections
- Mass windows and vetoes
- Trigger requirements
- Boosted Decision Trees
- Neural network based PID variables

Correcting MC efficiencies

- Trigger efficiencies
- Gradient Boosted Reweighting (GBR)
- PID efficiencies
- Photon reconstruction

Run-2 plots of $B^0_{(s)} \to J/\psi\eta[\pi^+\pi^-\gamma]$ presel. $\to$ full selections





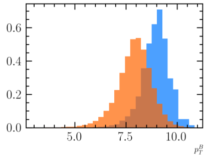
$$\varepsilon^{MC} = \varepsilon^{gen.}\varepsilon^{presel}\varepsilon^{trigger}\varepsilon^{BDT}\varepsilon^{PID}$$

Multivariate Analysis for event selection

Boosted Decision Trees

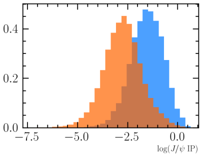
- Creating a powerful signal-background discriminator
- Signal: Monte Carlo samples
- Background: J/ψ mass side-bands
- using 14 or 15 inputs chosen for signal-background differences in:

kinematics



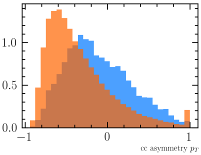
e.g. $p_{\mathrm{T}}^{\mathrm{B}}$

vertex

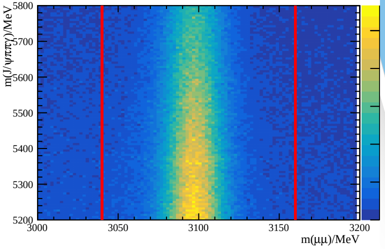


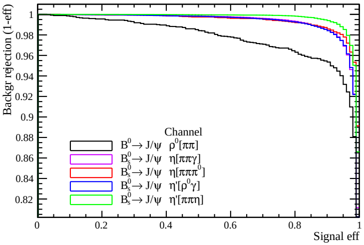
IP of J/ψ

event kinematics



asy.$p_z = \frac{p_z^{\mathrm{B}} - \Sigma p_z^{cone}}{p_z^{\mathrm{B}} + \Sigma p_z^{cone}}$





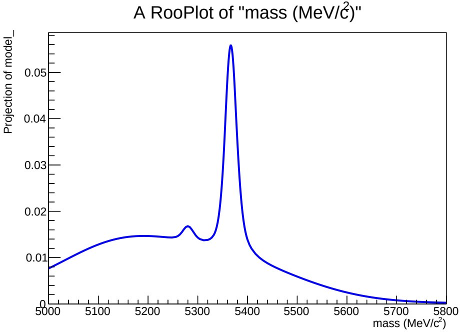
$$\varepsilon^{MC} = \varepsilon^{acc.}\varepsilon^{presel}\varepsilon^{trigger}\varepsilon^{BDT}\varepsilon^{PID}$$

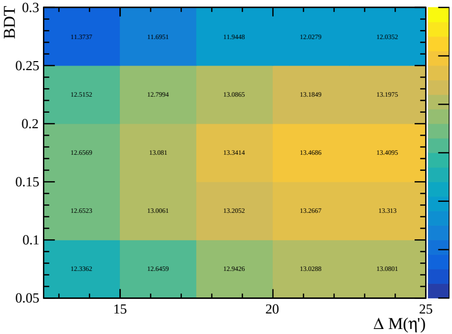
BDT cut 2D optimisation (with $\eta^{(\prime)}$ mass window)

Pseudoexperiments - FOM: B^0 significance

1. Fit MC distributions $h_0(m_{\mathrm{B}})$
2. Combine model into one pdf $f_0(m_{\mathrm{B}})$ with estimate yields from $\mathrm{B}^0 \to \mathrm{J}/\psi\rho^0$
3. Compute significance $(S/\sqrt{S+B})$
4. Generate new MC distributions from model: $h_i(m_{\mathrm{B}})$
5. Repeat $1 \to 4$ for 10^3 "toys"

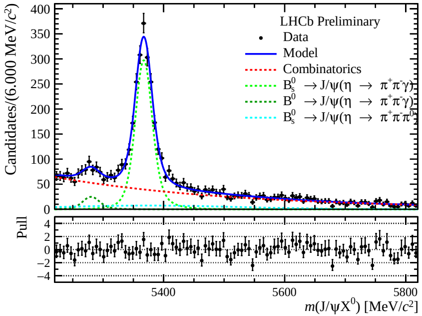
Plotting means of the significance values for each set of cuts (BDT,$\Delta m(\eta^{(\prime)})$)





Single photon mass fits: $B^0_{(s)} \to J/\psi\eta$ Run-1+2

$\eta \to \pi^+\pi^-\gamma$



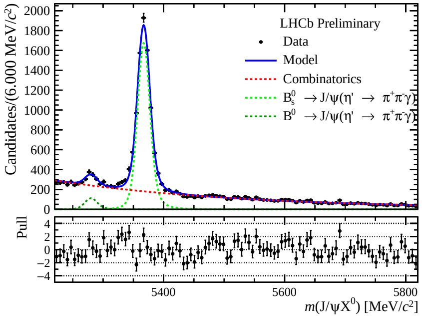
- $N(B^0) = 162 \pm 36$
- $N(B^0_s) = 1938 \pm 60$

- Kinematic fit (DTF): PV, $m(J/\psi)$, $m(\eta)$
- Fit with 7 params:
- Signal and background PDF sharing energy calibration, $\Delta m = 0.6 \pm 0.5$ MeV, and detector resolution factor, $r_\sigma = 1.045 \pm 0.039$
- $p_0 = (-3.32 \pm 0.15) \times 10^{-3}$, $N^b_{comb} = (2.79 \pm 0.10 \times 10^3)$
- $\frac{N^b_{\pi^+\pi^-\pi^0}}{N^s} = 0.204 \pm 0.006$

$$f(\Delta m, r_\sigma, p_0, N^s_{B^0_s}, N^s_{B^0}, N^b_{comb}, N^b_{\eta\to\pi^+\pi^-\pi^0}) = \frac{N^s_{B^0_s}}{N^{tot}} f^s_{B^0_s}(\Delta m, r_\sigma) + \frac{N^s_{B^0}}{N^{tot}} f^s_{B^0}(\Delta m, r_\sigma) + \frac{N^b}{N^{tot}} f^b_{comb}(p_0) + \frac{N^b_{\eta\to\pi^+\pi^-\pi^0}}{N^{tot}} f^b_{\eta\to\pi^+\pi^-\pi^0}(\Delta m, r_\sigma)$$

Single photon mass fits: $B^0_{(s)} \to J/\psi\eta'$ Run-1+2

$\eta' \to \rho^0\gamma$



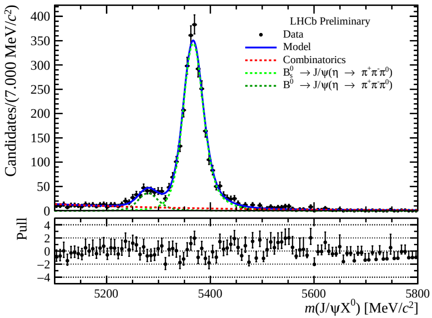
- $N(B^0) = 515 \pm 56$
- $N(B^0_s) = 7764 \pm 107$

- Kinematic fit (DTF): PV, $m(J/\psi)$, $m(\eta')$
- Fit with 6 params:
- $\Delta m = 0.35 \pm 0.16$ MeV, $r_\sigma = 1.074 \pm 0.017$
- $p_0 = (-3.25 \pm 0.06) \times 10^{-3}$, $N^b_{comb} = (1.282 \pm 0.014 \times 10^4)$

$$f(\Delta m, r_\sigma, p_0, N^s_{B^0_s}, N^s_{B^0}, N^b) = \frac{N^s_{B^0_s}}{N^{tot}} f^s_{B^0_s}(\Delta m, r_\sigma) + \frac{N^s_{B^0}}{N^{tot}} f^s_{B^0}(\Delta m, r_\sigma) + \frac{N^b}{N^{tot}} f^b_{comb}(p_0)$$

Two photon mass fits: $B^0_{(s)} \to J/\psi\eta$ Run-1+2

$\eta \to \pi^+\pi^-\pi^0[\gamma\gamma]$



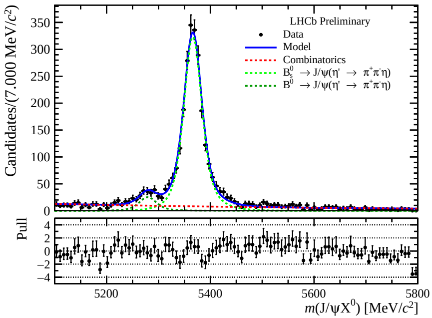
- $N(B^0) = 278 \pm 23$
- $N(B^0_s) = 2695 \pm 55$

- Kinematic fit (DTF): PV, $m(J/\psi)$, $m(\eta)$, $m(\pi^0)$
- Fit with 6 params:
- $\Delta m = 0.3 \pm 0.5$ MeV, $r_\sigma = 1.162 \pm 0.026$
- $p_0 = (-3.61 \pm 0.28) \times 10^{-3}$, $N^b_{comb} = 498 \pm 31$

$$f(\Delta m, r_\sigma, p_0, N^s_{B^0_s}, N^s_{B^0}, N^b) = \frac{N^s_{B^0_s}}{N^{tot}} f^s_{B^0_s}(\Delta m, r_\sigma) + \frac{N^s_{B^0}}{N^{tot}} f^s_{B^0}(\Delta m, r_\sigma) + \frac{N^b}{N^{tot}} f^b_{comb}(p_0)$$

Two photon mass fits: $B^0_{(s)} \to J/\psi\eta'$ Run-1+2

$\eta' \to \pi^+\pi^-\eta[\gamma\gamma]$

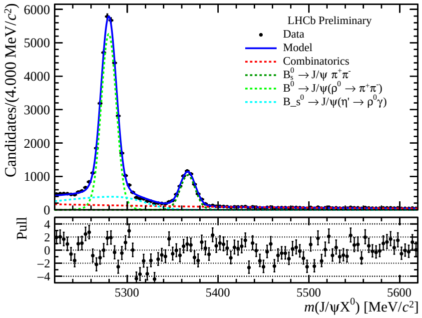


- $N(B^0) = 172 \pm 20$
- $N(B^0_s) = 2305 \pm 52$

- Kinematic fit (DTF): PV, $m(J/\psi)$, $m(\eta')$
- Fit with 6 params:
- $\Delta m = -0.4 \pm 0.5$ MeV, $r_\sigma = 1.151 \pm 0.031$
- $p_0 = (-1.66 \pm 0.19) \times 10^{-3}$, $N^b_{comb} = 752 \pm 36$

$$f(\Delta m, r_\sigma, p_0, N^s_{B^0_s}, N^s_{B^0}, N^b) = \frac{N^s_{B^0_s}}{N^{tot}} f^s_{B^0_s}(\Delta m, r_\sigma) + \frac{N^s_{B^0}}{N^{tot}} f^s_{B^0}(\Delta m, r_\sigma) + \frac{N^b}{N^{tot}} f^b_{comb}(p_0)$$

Normalisation Mode Fit: $B^0 \to J/\psi\rho^0$ Run-1+2

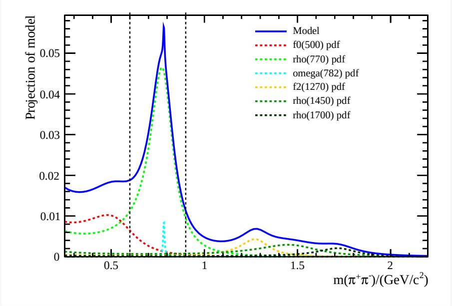


- $N(B_s^0) = 5498 \pm 90$
- $N(B^0) = (2.788 \pm 0.021) \times 10^4$

- Kinematic fit (DTF): PV, $m(J/\psi)$
- Fit with 7 params:
- $\Delta m = -3.83 \pm 0.06$ MeV, $r_\sigma = 1.070 \pm 0.007$
- $p_0 = (-3.49 \pm 0.24) \times 10^{-3}$, $N^b_{comb} = (8.99 \pm 0.28 \times 10^3)$
- $N^b_{\rho^0\gamma} = (9.39 \pm 0.31) \times 10^3$
  - More than as signal! - shows cost of reconstructing a photon

$$f(\Delta m, r_\sigma, p_0, N^s_{B_s^0}, N^s_{B^0}, N^b_{comb}, N^b_{\eta'\to\rho^0\gamma}) = \frac{N^s_{B_s^0}}{N^{tot}} f^s_{B_s^0}(\Delta m, r_\sigma) + \frac{N^s_{B^0}}{N^{tot}} f^s_{B^0}(\Delta m, r_\sigma) + \frac{N^b}{N^{tot}} f^b_{comb}(p_0) + \frac{N^b_{\eta'\to\rho^0\gamma}}{N^{tot}} f^b_{\eta'\to\rho^0\gamma}(\Delta m, r_\sigma)$$

Normalisation Mode Fit: $B^0 \to J/\psi\rho^0$ Run-1+2

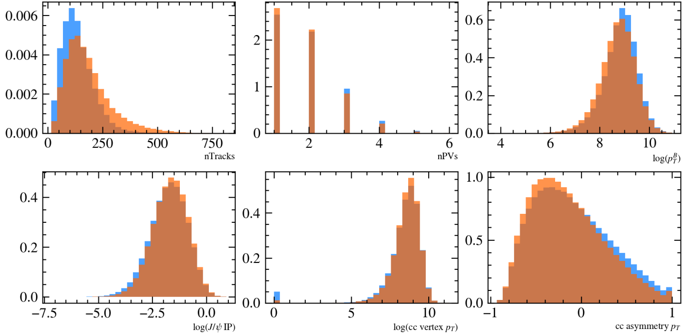


- Corrections to $B^0 \to J/\psi\rho^0$ yield were needed
- There are several resonances in the $m(\pi^+\pi^-)$ mass range
- Using the 4D resonance model of a previous LHCb analysis which measured $\mathcal{B}(B^0 \to J/\psi\rho^0)$ [Phys.Rev.D 90 (2014)]
- Integrated the projection of $m(\pi^+\pi^-)$ in our range of $[600, 900]$ MeV $\Rightarrow (87.0 \pm 4.3)\%$ of B^0 is from $J/\psi\rho^0$
- as a check: full integration reproduces quoted fit fractions

$$f_\rho(m_{\pi^+\pi^-}, \theta_{\pi^+\pi^-}, \theta_{J/\psi}, \chi) = \left(\frac{p_R}{m_{\pi^+\pi^-}}\right)^2 \frac{m_{\pi^+\pi^-} \sin^2\theta_{\pi^+\pi^-} \sin^2\theta_{J/\psi}}{(m_\rho^2 - m_{\pi^+\pi^-}^2)^2 + m_\rho^2\Gamma_\rho^2} (1 + p_{b1}\cos\chi + p_{b2}\cos 2\chi)$$

Gradient Boosted Reweighting

- A reweighting procedure using Boosted Decision Trees [Rogozhnikov (2016)]
- Data-driven corrections of MC for BDT training and ε^{MC}
- Using sWeighted $\mathrm{J}/\psi\mathrm{K}^{+}\pi^{-}$ (for high stats and high purity) data compared to MC to train the reweighter



real data
vs.
MC
before

$\varepsilon_{\mathrm{BDT}}^{MC} = (58.73 \pm 0.10)\%$
$\varepsilon_{\mathrm{BDT}}^{data} = (66.04 \pm 0.13)\%$

$$\varepsilon^{MC} = \varepsilon^{acc.}\varepsilon^{presel}\varepsilon^{trigger}\varepsilon^{BDT}\varepsilon^{PID}$$

Gradient Boosted Reweighting

- A reweighting procedure using Boosted Decision Trees [Rogozhnikov (2016)]
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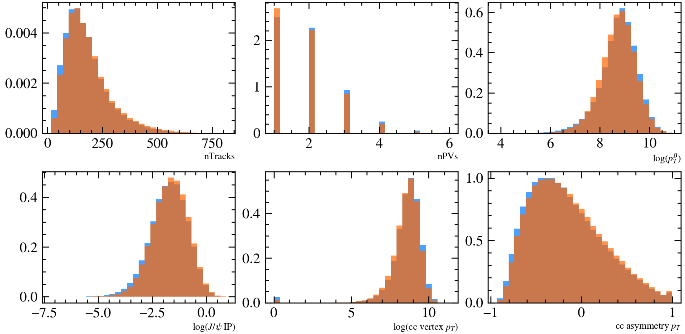


real data

vs.

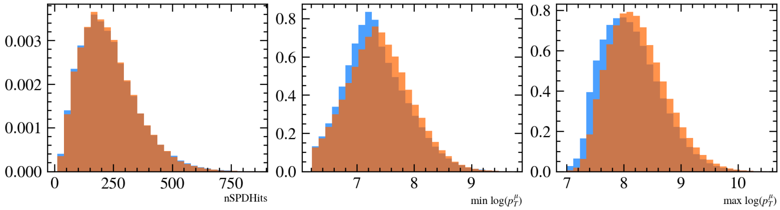
MC

after

$$\varepsilon_{\mathrm{BDT}}^{MC} = (61.11 \pm 0.10)\%$$
$$\varepsilon_{\mathrm{BDT}}^{data} = (66.04 \pm 0.13)\%$$

$$\varepsilon^{MC} = \varepsilon^{acc.}\varepsilon^{presel}\varepsilon^{trigger}\varepsilon^{BDT}\varepsilon^{PID}$$

Trigger efficiency corrections

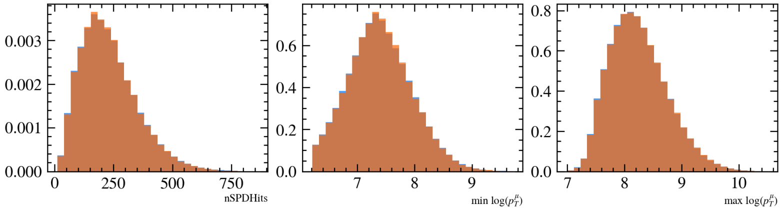


$B^+ \to \chi_{c1} K^+$ MC
vs.
$B^+ \to J/\psi K^+$ MC
before

- $B^+ \to J/\psi K^+$ offers excellent mode for studying efficiencies
- The muon triggers used were L0Muon and L0DiMuon
  - Hardware trigger requirements with high p_T^{μ} and $\mathrm{nSPDhits}$
- Weights from p_T^{μ} and $\mathrm{nSPDhits}$ are determined with MC $B^+ \to J/\psi K^+$ vs. other modes and then applied to real data
- $\varepsilon_{trigger}^{data}$ vs. $\varepsilon_{trigger}^{MC}$ for corrections were $\sim (100 \pm 0.3)\%$

$$\varepsilon^{MC} = \varepsilon^{acc.} \varepsilon^{presel} \varepsilon^{trigger} \varepsilon^{BDT} \varepsilon^{PID}$$

Trigger efficiency corrections



$B^+ \to \chi_{c1} K^+$ MC
vs.
$B^+ \to J/\psi K^+$ MC
after

- $B^+ \to J/\psi K^+$ offers excellent mode for studying efficiencies
- The muon triggers used were L0Muon and L0DiMuon
  - Hardware trigger requirements with high p_T^μ and $\mathrm{nSPDhits}$
- Weights from p_T^μ and $\mathrm{nSPDhits}$ are determined with MC $B^+ \to J/\psi K^+$ vs. other modes and then applied to real data
- $\varepsilon_{trigger}^{data}$ vs. $\varepsilon_{trigger}^{MC}$ for corrections were $\sim (100 \pm 0.3)\%$

$$\varepsilon^{MC} = \varepsilon^{acc.}\varepsilon^{presel}\varepsilon^{trigger}\varepsilon^{BDT}\varepsilon^{PID}$$

Selection efficiencies: $\sigma\mathcal{L}$-weighted average

single photon efficiencies/%

Year	$B_s^0 \to J/\psi\eta^{(\prime)}$ $\eta \to \pi^+\pi^-\gamma$	$B_s^0 \to J/\psi\eta^{(\prime)}$ $\eta' \to \rho^0\gamma$	$B^0 \to J/\psi\eta^{(\prime)}$ $\eta \to \pi^+\pi^-\gamma$	$B^0 \to J/\psi\eta^{(\prime)}$ $\eta' \to \rho^0\gamma$
Acceptance	11.59 ± 0.17	15.442 ± 0.09	15.63 ± 0.28	15.93 ± 0.29
Reco. and presel.	3.724 ± 0.016	2.116 ± 0.009	2.514 ± 0.016	1.887 ± 0.014
Trigger requirements	85.24 ± 0.40	85.59 ± 0.37	83.9 ± 0.6	84.5 ± 0.7
BDT selection	89.88 ± 0.45	84.41 ± 0.40	88.6 ± 0.6	83.5 ± 0.7
PID selection	95.32 ± 0.08	94.69 ± 0.08	94.85 ± 0.07	94.05 ± 0.07
Total	0.3110 ± 0.0016	0.2203 ± 0.0011	0.2769 ± 0.0020	0.1997 ± 0.0017

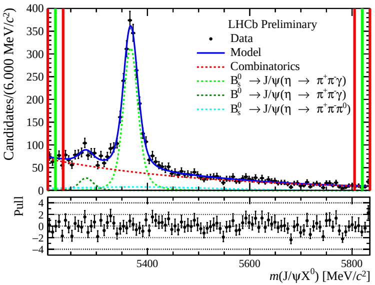
two photon efficiencies/%

Year	$B_s^0 \to J/\psi\eta^{(\prime)}$ $\eta \to \pi^+\pi^-\pi^0$	$B_s^0 \to J/\psi\eta^{(\prime)}$ $\eta' \to \rho^0\gamma$	$B^0 \to J/\psi\eta^{(\prime)}$ $\eta \to \pi^+\pi^-\gamma$	$B^0 \to J/\psi\eta^{(\prime)}$ $\eta' \to \rho^0\gamma$
Acceptance	13.37 ± 0.08	10.34 ± 0.14	15.52 ± 0.04	14.68 ± 0.27
Reco. and presel.	1.281 ± 0.009	2.275 ± 0.013	0.960 ± 0.007	1.388 ± 0.012
Trigger requirements	86.3 ± 0.6	87.2 ± 0.5	85.4 ± 0.7	86.8 ± 0.8
BDT selection	72.0 ± 0.6	71.5 ± 0.5	69.7 ± 0.6	69.2 ± 0.8
PID selection	95.32 ± 0.06	96.18 ± 0.11	95.266 ± 0.035	95.94 ± 0.09
Total	0.0912 ± 0.0008	0.1339 ± 0.0010	0.0845 ± 0.0008	0.1176 ± 0.0013

$$\varepsilon^{MC} = \varepsilon^{acc.}\varepsilon^{presel}\varepsilon^{trigger}\varepsilon^{BDT}\varepsilon^{PID}$$

Systematic uncertainties

Channel	$\mathcal{R}_d^{\gamma}/\%$	$\mathcal{R}_s^{\gamma}/\%$	$\mathcal{R}_d^{\gamma\gamma}/\%$	$\mathcal{R}_s^{\gamma\gamma}/\%$
Signal pdf	1.1	0.8	4.3	1.7
Bkg pdf	1.0	1.7	6.5	2.0
Bkg composition	7.4	1.3	4.6	1.3
PID cal	0.4	0.6	0.1	0.1
Mass cut	2.6	2.8	9.2	3.0
Trigger eff	0.2	0.2	0.2	0.2
BDT eff	0.8	0.9	0.1	0.7
Total	8.0	3.8	12.9	4.3
			Average	
Channel	$\mathcal{R}_d$	$\mathcal{R}_s$	-	-
Total	6.8	2.8	-	-



Background composition

- Imperfect background model at low mass as assumption that part. reco. backgrounds are accounted for in combinatoric pdf
- Tested by altering the mass fit boundaries and seeing the effect on the signal yield
- Uncertainty = RMS error on ± 25 MeV and nominal

η-η′ mixing angles: φ_P and φ_G

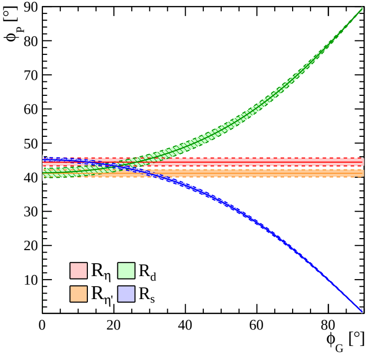
$$\mathcal{R}_{\eta^{(\prime)}} = \frac{\mathcal{B}(B^0 \to J/\psi\eta^{(\prime)})}{\mathcal{B}(B^0_s \to J/\psi\eta^{(\prime)})} \qquad \mathcal{R}_{(s)} = \frac{\mathcal{B}(B^0_{(s)} \to J/\psi\eta^{\prime})}{\mathcal{B}(B^0_{(s)} \to J/\psi\eta)}$$

$$\mathcal{R}_d = 0.77 \pm 0.10\,\text{(stat)} \pm 0.05\,\text{(syst)} \pm 0.01(\mathcal{B})$$

$$\mathcal{R}_s = 0.990 \pm 0.023\,\text{(stat)} \pm 0.028\,\text{(syst)} \pm 0.014(\mathcal{B})$$

$$\mathcal{R}_\eta = 0.0291 \pm 0.0023\,\text{(stat)} \pm 0.0016\,\text{(syst)} \pm 0.0006(\frac{f_s}{f_d})$$

$$\mathcal{R}_{\eta'} = 0.0213 \pm 0.0017\,\text{(stat)} \pm 0.0010\,\text{(syst)} \pm 0.0005(\frac{f_s}{f_d})$$

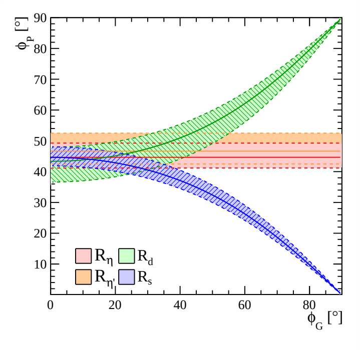


$\Rightarrow$ $\varphi_P = (43.2 \pm 1.0\,\text{(stat)} \pm 0.5\,\text{(syst)})^\circ$ $\varphi_G = (20.8 \pm 4.8\,\text{(stat)} \pm 2.8\,\text{(syst)} \pm 0.8(\mathcal{B}))^\circ$

- Mixing results used complementary channels with same number of photons
- Fraction to determine absolute branching ratios are more complicated $\frac{J/\psi\pi^+\pi^-\gamma(\gamma)}{J/\psi\pi^+\pi^-}$

Comparison with Run-1: η-η' mixing

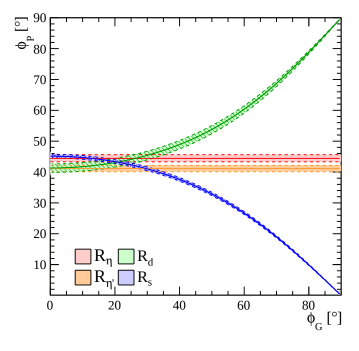
Run-1 [JHEP 01 (2015) 024]



$$\varphi_P = (43.5^{+1.4}_{-2.8})^\circ$$

$$\varphi_G = (0 \pm 24.6)^\circ$$

Run-1+2



$$\varphi_P = (43.2 \pm 1.1)^\circ$$

$$\varphi_G = (20.8 \pm 5.3)^\circ$$

- φ_P are completely compatible with only a small improvement
- greatest improvement from $\mathcal{R}_d \to \varphi_G$ is now $\sim 4\sigma$ away from 0

$\mathcal{R}_{\eta^{(\prime)}}$ as a test of $\mathrm{SU}(3)_F$ symmetry breaking

What if we don't assume $\mathrm{SU}(3)_F$ symmetry

- $F(\mathrm{B}^0 \to \mathrm{J}/\psi d\bar{d}) \neq F(\mathrm{B}_s^0 \to \mathrm{J}/\psi s\bar{s})$

$$\mathcal{R}_{\eta'} = \frac{\tau_{\mathrm{B}^0}}{\tau_{\mathrm{B}_s^0}} \frac{m_{\mathrm{B}^0}}{m_{\mathrm{B}_s^0}} \left(\frac{\Phi_d^{\eta'}}{\Phi_s^{\eta'}}\right)^3 \times \frac{\tan^2\theta_c}{2} \times \tan^2\varphi_P \times \left|\frac{F(\mathrm{B}^0 \to \mathrm{J}/\psi d\bar{d})}{F(\mathrm{B}_s^0 \to \mathrm{J}/\psi s\bar{s})}\right|^2$$

$$\mathcal{R}_{\eta} = \frac{\tau_{\mathrm{B}^0}}{\tau_{\mathrm{B}_s^0}} \frac{m_{\mathrm{B}^0}}{m_{\mathrm{B}_s^0}} \left(\frac{\Phi_d^{\eta}}{\Phi_s^{\eta}}\right)^3 \times \frac{\tan^2\theta_c}{2} \times \cot^2\varphi_P \times \left|\frac{F(\mathrm{B}^0 \to \mathrm{J}/\psi d\bar{d})}{F(\mathrm{B}_s^0 \to \mathrm{J}/\psi s\bar{s})}\right|^2$$

- and cancelling the $\tan^2\varphi_P$

$$\Rightarrow \left|\frac{F(\mathrm{B}^0 \to \mathrm{J}/\psi d\bar{d})}{F(\mathrm{B}_s^0 \to \mathrm{J}/\psi s\bar{s})}\right| = \sqrt{\frac{\tau_{\mathrm{B}_s^0} m_{\mathrm{B}_s^0}}{\tau_{\mathrm{B}^0} m_{\mathrm{B}^0}}} \left(\frac{\Phi_s^{\eta}\Phi_s^{\eta'}}{\Phi_d^{\eta}\Phi_d^{\eta'}}\right)^{3/4} \times \frac{\sqrt{2}}{\tan\theta_c} \times (\mathcal{R}_\eta \mathcal{R}_{\eta'})^{1/4}$$

$$= (94.3 \pm 2.3\,\text{(stat)} \pm 1.5\,\text{(syst)} \pm 0.6(f_s/f_d))\%$$

- Found asymmetry $\sim 2\sigma$ from 1 with these channels

Photon correction factors

- Normalising decay modes with photons in the final state to those without $\Rightarrow$need ε corrections

$$\varepsilon^{\mathrm{data}}(\gamma) = \mathcal{R}_{\gamma}^{\mathrm{corr}} \times \varepsilon^{\mathrm{MC}}(\gamma)$$

- To be applied in

$$\mathcal{B}(\mathrm{B^0}_{(s)} \to \mathrm{J/\psi\eta^{(\prime)}}) = \frac{N^s_{\mathrm{B^0}_{(s)}\to \mathrm{J/\psi\eta^{(\prime)}}}}{N^s_{\mathrm{B^0}\to\mathrm{J/\psi\rho^0}}} \times \frac{\varepsilon^{MC}_{\mathrm{B^0}\to\mathrm{J/\psi\rho^0}}}{\varepsilon^{MC}_{\mathrm{B^0}_{(s)}\to\mathrm{J/\psi\eta^{(\prime)}}} \times \mathcal{R}_{\gamma}} \times \frac{\mathcal{B}(\mathrm{B^0}\to \mathrm{J/\psi\rho^0})}{\mathcal{B}(\eta^{(\prime)}\to\pi^+\pi^-\gamma(\gamma))}\left(\frac{f_s}{f_d}\right)^{-1}$$

- Can be done using $\mathrm{B^+}\to\mathrm{J/\psi K^+}$ vs. $\mathrm{B^+}\to\chi_{c1}\mathrm{K^+}$ where $\chi_{c1}\to\mathrm{J/\psi}\gamma$
- At LHCb, comparing decays year-by-year

$$N^{\mathrm{s}}_{\mathrm{B^+}\to X} \propto \varepsilon^{\mathrm{data}}_{\mathrm{B^+}\to X} \times \mathcal{B}_{\mathrm{B^+}\to X}$$

$$\Rightarrow \frac{N^{\mathrm{s}}_{\mathrm{B^+}\to\mathrm{J/\psi K^+}}}{N^{\mathrm{s}}_{\mathrm{B^+}\to(\mathrm{J/\psi}\gamma)_{\chi_{c1}}\mathrm{K^+}}} = \frac{\varepsilon^{\mathrm{data}}_{\mathrm{B^+}\to\mathrm{J/\psi K^+}}}{\varepsilon^{\mathrm{data}}_{\mathrm{B^+}\to(\mathrm{J/\psi}\gamma)_{\chi_{c1}}\mathrm{K^+}}} \times \frac{\mathcal{B}_{\mathrm{B^+}\to\mathrm{J/\psi K^+}}}{\mathcal{B}_{\mathrm{B^+}\to\chi_{c1}\mathrm{K^+}} \times \mathcal{B}_{\chi_{c1}\to\mathrm{J/\psi}\gamma}}$$

- Decays have the same tracks so only γ related effects remain in data$\leftrightarrow$MC

$$\mathcal{R}_{\gamma}^{\mathrm{cor}} = \frac{N^{\mathrm{s}}_{\mathrm{B^+}\to(\mathrm{J/\psi}\gamma)_{\chi_{c1}}\mathrm{K^+}}}{N^{\mathrm{s}}_{\mathrm{B^+}\to\mathrm{J/\psi K^+}}} \times \frac{\varepsilon^{\mathrm{MC}}_{\mathrm{B^+}\to\mathrm{J/\psi K^+}}}{\varepsilon^{\mathrm{MC}}_{\mathrm{B^+}\to(\mathrm{J/\psi}\gamma)_{\chi_{c1}}\mathrm{K^+}}} \times \frac{\mathcal{B}_{\mathrm{B^+}\to\mathrm{J/\psi K^+}}}{\mathcal{B}_{\mathrm{B^+}\to\chi_{c1}\mathrm{K^+}} \times \mathcal{B}_{\chi_{c1}\to\mathrm{J/\psi}\gamma}}$$

Neutral pion correction factors

- Normalising decay modes with photons in the final state to those without $\Rightarrow$need ε corrections

$$\varepsilon^{\text{data}}(\pi^0) = \mathcal{R}^{\text{corr}}_{\pi^0} \times \varepsilon^{\text{MC}}(\pi^0)$$

- To be applied in

$$\mathcal{B}(\mathrm{B^0}_{(s)} \to \mathrm{J}/\psi\eta^{(\prime)}) = \frac{N^s_{\mathrm{B^0}_{(s)}\to \mathrm{J}/\psi\eta^{(\prime)}}}{N^s_{\mathrm{B^0}\to \mathrm{J}/\psi\rho^0}} \times \frac{\varepsilon^{MC}_{\mathrm{B^0}\to \mathrm{J}/\psi\rho^0}}{\varepsilon^{MC}_{\mathrm{B^0}_{(s)}\to \mathrm{J}/\psi\eta^{(\prime)}} \times \mathcal{R}_{\pi^0}} \times \frac{\mathcal{B}(\mathrm{B^0} \to \mathrm{J}/\psi\rho^0)}{\mathcal{B}(\eta^{(\prime)} \to \pi^+\pi^-\gamma(\gamma))} \left(\frac{f_s}{f_d}\right)^{-1}$$

- Can be done using $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$ vs. $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^{*+}$ where $\mathrm{K}^{*+} \to \mathrm{K}^+\pi^0[\gamma\gamma]$
- At LHCb, comparing decays year-by-year

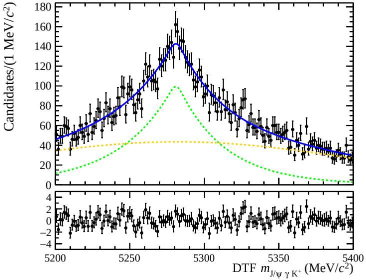
$$N^{\mathrm{s}}_{\mathrm{B}^+\to X} \propto \varepsilon^{\text{data}}_{\mathrm{B}^+\to X} \times \mathcal{B}_{\mathrm{B}^+\to X}$$

$$\Rightarrow \frac{N^{\mathrm{s}}_{\mathrm{B}^+\to \mathrm{J}/\psi\mathrm{K}^+}}{N^{\mathrm{s}}_{\mathrm{B}^+\to \mathrm{J}/\psi(\mathrm{K}^+\pi^0)_{\mathrm{K}^{*+}}}} = \frac{\varepsilon^{\text{data}}_{\mathrm{B}^+\to \mathrm{J}/\psi\mathrm{K}^+}}{\varepsilon^{\text{data}}_{\mathrm{B}^+\to \mathrm{J}/\psi(\mathrm{K}^+\pi^0)_{\mathrm{K}^{*+}}}} \times \frac{\mathcal{B}_{\mathrm{B}^+\to \mathrm{J}/\psi\mathrm{K}^+}}{\mathcal{B}_{\mathrm{B}^+\to \mathrm{J}/\psi\mathrm{K}^{*+}} \times \mathcal{B}_{\mathrm{K}^{*+}\to \mathrm{K}^+\pi^0} \times \mathcal{B}_{\pi^0\to\gamma\gamma}}$$

- Decays have the same tracks so only π^0 related effects remain in data$\leftrightarrow$MC

$$\mathcal{R}^{\text{cor}}_{\pi^0} = \frac{N^{\mathrm{s}}_{\mathrm{B}^+\to \mathrm{J}/\psi(\mathrm{K}^+\pi^0)_{\mathrm{K}^{*+}}}}{N^{\mathrm{s}}_{\mathrm{B}^+\to \mathrm{J}/\psi\mathrm{K}^+}} \times \frac{\varepsilon^{\text{MC}}_{\mathrm{B}^+\to \mathrm{J}/\psi\mathrm{K}^+}}{\varepsilon^{\text{MC}}_{\mathrm{B}^+\to \mathrm{J}/\psi(\mathrm{K}^+\pi^0)_{\mathrm{K}^{*+}}}} \times \frac{\mathcal{B}_{\mathrm{B}^+\to \mathrm{J}/\psi\mathrm{K}^+}}{\mathcal{B}_{\mathrm{B}^+\to \mathrm{J}/\psi\mathrm{K}^{*+}} \times \mathcal{B}_{\mathrm{K}^{*+}\to \mathrm{K}^+\pi^0} \times \mathcal{B}_{\pi^0\to\gamma\gamma}}$$

Corrections to the random photon background



The problem

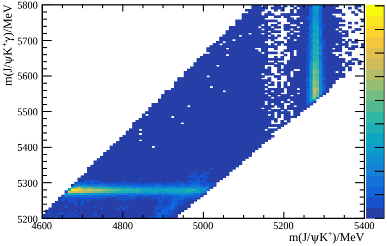
- Signal tracks + γ from the underlying event make a background peaking directly underneath the B^+ mass
- The $\eta^{(\prime)}$ resonances were narrow enough to minimise this, χ_{c1} and K^{*+} were not
- Need to control the efficiency of this background as MC does not perfectly model the occupancy of photons

The solution

- To study this type of background, $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$ + γ from the underlying event is used
- The correction is

$$K_\gamma = \frac{N^s(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+ + \gamma)}{N^s(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+)} \frac{\varepsilon^{MC}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+)}{\varepsilon^{MC}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+ + \gamma)}$$

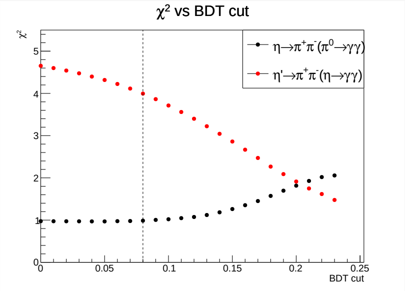
- Data-MC corrections are determined in fits of $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$: $K_\gamma \sim (80 \pm 0.3)\%$



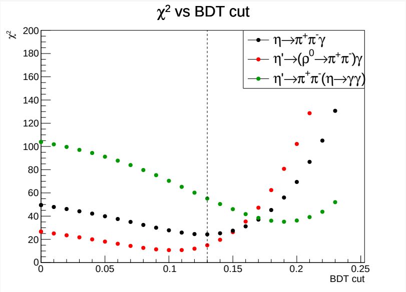
BDT optimisation: photon p_{T} alignment

- Same strategy and variables used as for $\mathrm{B}^0_{(\mathrm{s})} \to \mathrm{J}/\psi\eta^{(\prime)}$
- We expect kinematic dependence on the ε corrections
- Best alignment (via χ^2 test) of p_{T}^{γ} would fine-tune these corrections for use in $\mathrm{B}^0_{(\mathrm{s})} \to \mathrm{J}/\psi\eta^{(\prime)}$
- Note: poor agreement for $\eta \to \gamma\gamma$ and $\pi^0 \to \gamma\gamma$ - better w/ single photons

$\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^{*+}$

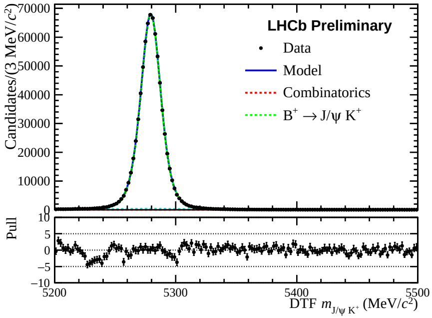


$\mathrm{B}^+ \to \chi_{c1}\mathrm{K}^+$



- Ideally a dedicated analysis of $\eta \to \gamma\gamma$ efficiencies would be complementary (*e.g.* with $\mathrm{B}^+ \to \psi(2S)\mathrm{K}^+$ where $\psi(2S) \to \eta\mathrm{J}/\psi$)

Single photon mass fit: $B^+ \to J/\psi K^+$ 2018 data

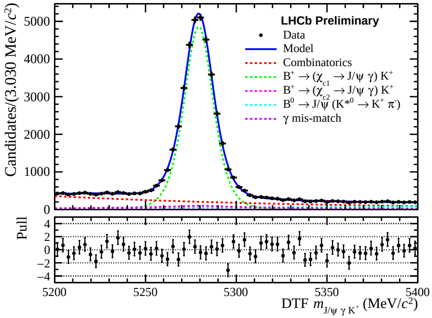


- $N(B^+) = 771941 \pm 1506$

- Kinematic fit (DTF): PV, $m(J/\psi)$
- Fit with 5 params:
- $\Delta m = 0.525 \pm 0.009$ MeV, $r_\sigma = 1.0921 \pm 0.0024$
- $p_0 = (-3.4 \pm 1.0) \times 10^{-3}$, $N^b_{comb} = (6.5 \pm 1.2 \times 10^3)$

$$f(\Delta m, r_\sigma, p_0, N^s, N^b) = \frac{N^s}{N^{tot}} f^s(\Delta m, r_\sigma) + \frac{N^b}{N^{tot}} f^b_{comb}(p_0)$$

Single photon mass fit: $B^+ \to \chi_{c1} K^+$ 2018 data



- $N(B^+) = 34728 \pm 186$

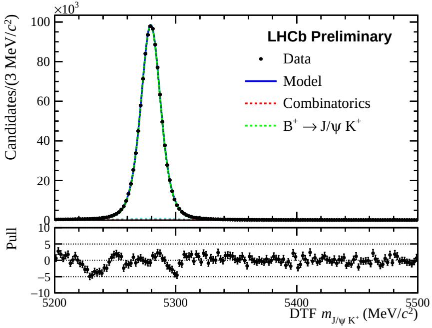
- Kinematic fit (DTF): PV, $m(J/\psi)$, $m(\chi_{c1})$
- Fit with 8 params:
- $\Delta m = 0.371 \pm 0.005$ MeV, $r_\sigma = 1.135 \pm 0.008$
- $p_0 = (-7.0 \pm 0.8) \times 10^{-3}$, $N^b_{comb} = (1.27 \pm 0.10 \times 10^4)$
- $\frac{N^b_\gamma}{N^s} = 0.0953 \pm 0.0010$
- $N^b_{\chi_{c2}K^+} = 411 \pm 99$, $N^b_{J/\psi K^{*0}} = (3.4 \pm 0.9) \times 10^3$

$$\varepsilon^{data}(\gamma) = \frac{N^s_{B^+\to\chi_{c1}K^+}}{N^s_{B^+\to J/\psi K^+}} \frac{\mathcal{B}(B^+\to J/\psi K^+)}{\mathcal{B}(B^+\to\chi_{c1}K^+)}$$

$$\varepsilon^{data}(\gamma) = (28.2 \pm 0.2\,(\text{stat}) \pm 1.6(\mathcal{B}))\%$$

$$f(\Delta m, r_\sigma, p_0, N^s, N^b_{comb}, N^b_{\chi_{c2}K^+}, N^b_{J/\psi K^{*0}}, N^b_\gamma) = \frac{N^s}{N^{tot}} f^s(\Delta m, r_\sigma) + \frac{N^b}{N^{tot}} f^b_{comb}(p_0)$$
$$+ \frac{N^b_{\chi_{c2}K^+}}{N^{tot}} f^b_{\chi_{c2}K^+}(\Delta m, r_\sigma) + \frac{N^b_{J/\psi K^{*0}}}{N^{tot}} f^b_{J/\psi K^{*0}}(\Delta m, r_\sigma) + \frac{N^b_\gamma}{N^{tot}} f^b_\gamma(\Delta m, r_\sigma)$$

π^0 mode mass fit: $B^+ \to J/\psi K^+$ 2018 data



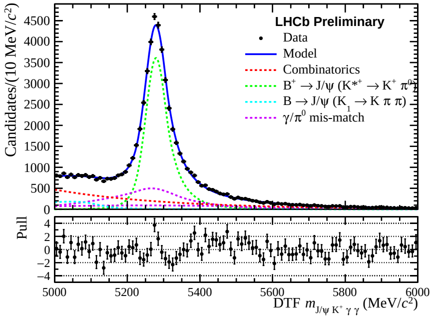
- $N(B^+) = (1.1107 \pm 0.0011) \times 10^6$

- Kinematic fit (DTF): PV, $m(J/\psi)$
- Fit with 5 params:
- $\Delta m = 0.544 \pm 0.009$ MeV, $r_\sigma = 1.0929 \pm 0.0016$
- $p_0 = (-3.18 \pm 0.24) \times 10^{-3}$, $N^b_{comb} = (1.418 \pm 0.044 \times 10^4)$

$$f(\Delta m, r_\sigma, p_0, N^s, N^b) = \frac{N^s}{N^{tot}} f^s(\Delta m, r_\sigma) + \frac{N^b}{N^{tot}} f^b_{comb}(p_0)$$

π^0 mode mass fit: $B^+ \to J/\psi K^{*+}$ 2018 data

$B^+ \to J/\psi K^{*+}$



- $N(B^+) = 31949 \pm 452$

- Kinematic fit (DTF): PV, $m(J/\psi)$, $m(\pi^0)$
- Fit with 8 params
- $\Delta m = -2.00 \pm 0.29$ MeV,
  $r_\sigma = 1.192 \pm 0.015$
- $p_0 = (-3.30 \pm 0.15) \times 10^{-3}$,
  $N^b_{comb} = (1.34 \pm 0.12 \times 10^4)$
- $\frac{N^b_\gamma}{N^s} = 0.398 \pm 0.029, \frac{N^b_{\gamma\gamma}}{N^s} = 0.1837 \pm 0.0043$
- $N^b_{J/\psi K_1} = (2.7 \pm 0.7) \times 10^3$

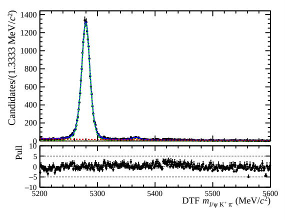
$$\varepsilon^{data}(\pi^0) = \frac{N^s_{B^+\to J/\psi K^{*+}}}{N^s_{B^+\to J/\psi K^+}} \frac{\mathcal{B}(B^+ \to J/\psi K^+)}{\mathcal{B}(B^+ \to J/\psi K^{*+})}$$

$$\varepsilon^{data}(\pi^0) = (4.53 \pm 0.09\,(\text{stat}) \pm 0.27(\mathcal{B}))\%$$

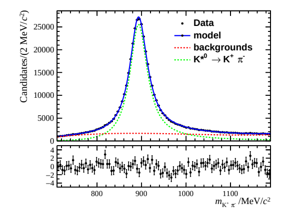
$$f(\Delta m, r_\sigma, p_0, N^s, N^b_{comb}, N^b_{J/\psi K_1}, N^b_\gamma, N^b_{\gamma\gamma}) = \frac{N^s}{N^{tot}} f^s(\Delta m, r_\sigma) + \frac{N^b}{N^{tot}} f^b_{comb}(p_0)$$
$$+ \frac{N^b_{J/\psi K_1}}{N^{tot}} f^b_{J/\psi K_1}(\Delta m, r_\sigma) + \frac{N^b_\gamma}{N^{tot}} f^b_\gamma(\Delta m, r_\sigma) + \frac{N^b_{\gamma\gamma}}{N^{tot}} f^b_{\gamma\gamma}(\Delta m, r_\sigma)$$

π^0 mode mass fit: Non-resonant $K^+\pi^0$ correction w/ $B^0 \to J/\psi K^{*0}$

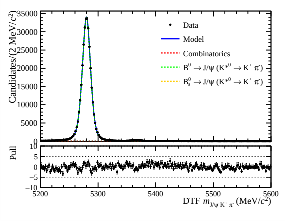
$m(J/\psi K^+\pi^-)$ **for** $m(K^+\pi^-) > 1100$ **MeV**



$m(K^+\pi^-)$



$m(J/\psi K^+\pi^-)$ **for** $m(K^+\pi^-)$ **in** K^{*+} **mass range**



- Assuming isospin symmetry the non-resonant component to K^{*+} equals that of K^{*0}
- Fit 1: the $B^0 \to J/\psi K^{*0}$ mass in the high $K^+\pi^-$ region is used to find number of non-resonant $K^+\pi^-$
- Fit 2: the $K^+\pi^-$ mass is used to extrapolate the amount within the signal region of $K^+\pi^0$ in $B^+ \to J/\psi K^{*+}$ (N^{nr})
- Fit 3: of $B^0 \to J/\psi K^{*0}$ in the signal region to determine the yield of non-resonant + resonant (N^s)
- Correction to signal yield

$$\mathcal{R}_{nr} = \frac{N^{nr}}{(N^s - N^{nr})} = (73.32 \pm 0.38)\%(2018)$$

Selection efficiencies: 2018

single photon

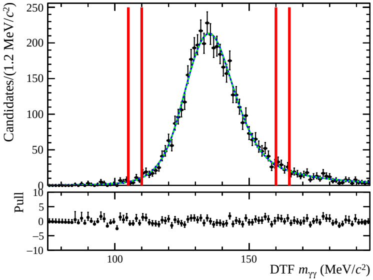
Year	$\varepsilon^{MC}_{B^+\to J/\psi K^+}/\%$	$\varepsilon^{MC}_{B^+\to (J/\psi\gamma)_{\chi_{c1}} K^+}/\%$	$\frac{\varepsilon^{MC}_{B^+\to (J/\psi\gamma)_{\chi_{c1}} K^+}}{\varepsilon^{MC}_{B^+\to J/\psi K^+}}/\%$
Acceptance	17.346 ± 0.033	10.672 ± 0.025	61.52 ± 0.18
Reco. and presel.	23.438 ± 0.015	10.654 ± 0.024	45.45 ± 0.11
Trigger requirements	82.37 ± 0.06	86.07 ± 0.21	104.50 ± 0.26
BDT selection	62.19 ± 0.06	59.23 ± 0.19	95.24 ± 0.31
PID selection	85.32 ± 0.05	88.00 ± 0.05	103.15 ± 0.09
Total	1.7770 ± 0.0020	0.5101 ± 0.0016	28.71 ± 0.10 $= \varepsilon^{MC}(\gamma)$

neutral pion

Year	$\varepsilon^{MC}_{B^+\to J/\psi K^+}/\%$	$\varepsilon^{MC}_{B^+\to J/\psi (K^+\pi^0)_{K^{*+}}}/\%$	$\frac{\varepsilon^{MC}_{B^+\to J/\psi (K^+\pi^0)_{K^{*+}}}}{\varepsilon^{MC}_{B^+\to J/\psi K^+}}/\%$
Acceptance	17.346 ± 0.033	7.278 ± 0.019	41.96 ± 0.13
Reco. and presel.	23.438 ± 0.015	3.007 ± 0.012	12.83 ± 0.05
Trigger requirements	82.37 ± 0.06	83.95 ± 0.37	101.9 ± 0.5
BDT selection	84.74 ± 0.07	82.53 ± 0.40	97.4 ± 0.5
PID selection	86.36 ± 0.05	93.085 ± 0.043	107.79 ± 0.08
Total	2.4507 ± 0.0025	0.1411 ± 0.0007	5.759 ± 0.029 $= \varepsilon^{MC}(\pi^0)$

Systematic uncertainties

Year	Unc. on $\mathcal{R}_\gamma$/%	Unc. on $\mathcal{R}_{\pi^0}$/%
Signal pdf	0.3	2.7
Bkg pdf	0.2	0.3
PID cal	1.0	0.9
Fit bounds	0.6	0.3
Mass cut	0.3	1.6
Trigger eff	0.3	0.3
BDT eff	2.9	1.5
Total	3.2	3.6

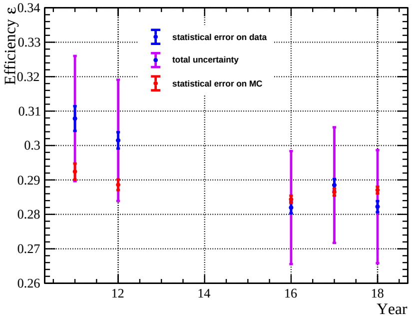


Mass windows

- $\chi_{c1} \to J/\psi\gamma$ and $K^{*+} \to K^+\pi^0$: had $\pm3\sigma$ mass windows so looked at the variation of N^s/ε^{MC} for $\pm2.5, 3, 3.5\sigma$
- $\pi^0 \to \gamma\gamma$: had a $\pm6\sigma$ mass window so looked at two tighter cuts of $\pm2.5, 3\sigma$
- Uncertainty = RMS error of the three N^s/ε^{MC} ratios for each selection

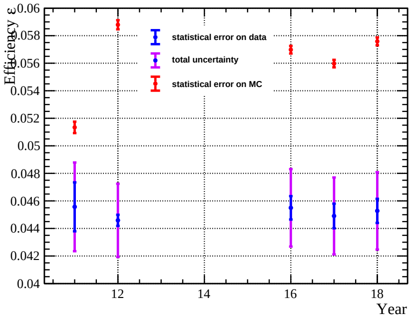
Reconstruction efficiencies

γ efficiencies



- Run-1 and Run-2 gap driven by data
- Flat efficiencies in MC

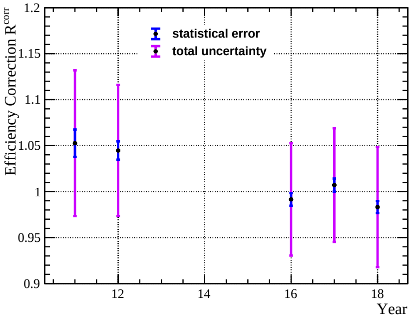
π^0 efficiencies



- Flat efficiencies in data
- Fluctuations in Run-1 driven by MC

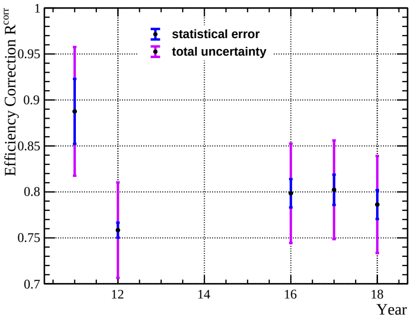
Correction factors

γ corrections



- Run-1 and Run-2 gap driven by data
- Flat efficiencies in MC

π^0 corrections



- Flat efficiencies in data
- Fluctuations in Run-1 driven by MC

Relative: $\mathcal{B}\,(B^0_{(s)} \to J/\psi\eta^{(\prime)})/\mathcal{B}\,(B^0 \to J/\psi\rho^0)$

$$\mathcal{B}(B^0{}_{(s)} \to J/\psi\eta^{(\prime)}) = \frac{N^s_{B^0{}_{(s)}\to J/\psi\eta^{(\prime)}}}{N^s_{B^0\to J/\psi\rho^0}} \times \frac{\varepsilon^{MC}_{B^0\to J/\psi\rho^0}}{\varepsilon^{MC}_{B^0{}_{(s)}\to J/\psi\eta^{(\prime)}} \times \mathcal{R}_{\gamma/\pi^0}} \times \frac{\mathcal{B}(B^0\to J/\psi\rho^0)}{\mathcal{B}(\eta^{(\prime)}\to\pi^+\pi^-\gamma(\gamma))} \left(\frac{f_s}{f_d}\right)^{-1}$$

- There are two measurements per branching ratio
  - for γ with corrected efficiency: $\varepsilon^{MC}_{\eta\to\pi^+\pi^-\gamma} \times \mathcal{R}_\gamma$ and $\varepsilon^{MC}_{\eta'\to\rho^0\gamma} \times \mathcal{R}_\gamma$
  - for $\gamma\gamma$ with corrected efficiency: $\varepsilon^{MC}_{\eta\to\pi^+\pi^-\pi^0} \times \mathcal{R}_{\pi^0}$ and $\varepsilon^{MC}_{\eta'\to\pi^+\pi^-\eta} \times \mathcal{R}^2_\gamma$

B^0 or B^0_s	Channel	$\mathcal{B}(B^0_{(s)} \to J/\psi\eta^{(\prime)})/\mathcal{B}(B^0 \to J/\psi\rho^0)$
B^0_s	$\eta\to\pi^+\pi^-\gamma$	17.03 ± 0.55 (stat) $\pm 0.32(\mathcal{B}) \pm 1.10(\mathcal{R}_\gamma) \pm 0.53(f_s/f_d)$
B^0_s	$\eta\to\pi^+\pi^-\pi^0$	18.99 ± 0.45 (stat) $\pm 0.23(\mathcal{B}) \pm 1.29(\mathcal{R}_{\pi^0}) \pm 0.59(f_s/f_d)$
B^0	$\eta\to\pi^+\pi^-\gamma$	0.405 ± 0.091 (stat) $\pm 0.008(\mathcal{B}) \pm 0.026(\mathcal{R}_\gamma)$
B^0	$\eta\to\pi^+\pi^-\pi^0$	0.537 ± 0.045 (stat) $\pm 0.007(\mathcal{B}) \pm 0.037(\mathcal{R}_\gamma)$
B^0_s	$\eta'\to\rho^0\gamma$	13.77 ± 0.23 (stat) $\pm 0.19(\mathcal{B}) \pm 0.89(\mathcal{R}_\gamma) \pm 0.43(f_s/f_d)$
B^0_s	$\eta'\to\pi^+\pi^-\eta$	11.79 ± 0.30 (stat) $\pm 0.15(\mathcal{B}) \pm 1.08(\mathcal{R}_\gamma) \pm 0.37(f_s/f_d)$
B^0	$\eta'\to\rho^0\gamma$	0.256 ± 0.028 (stat) $\pm 0.003(\mathcal{B}) \pm 0.017(\mathcal{R}_\gamma)$
B^0	$\eta'\to\pi^+\pi^-\eta$	0.255 ± 0.030 (stat) $\pm 0.003(\mathcal{B}) \pm 0.023(\mathcal{R}_\gamma)$

- Tension between γ and $\gamma\gamma$ modes at $< 1.5\sigma$
- Format open to updates in the normalisation branching

Absolute $\mathcal{B}\,(B^0_{(s)} \to J/\psi\eta^{(\prime)})$

Averaging using PDG method

- Calculating averages between single and two-photon channels
- Uses error-weighting

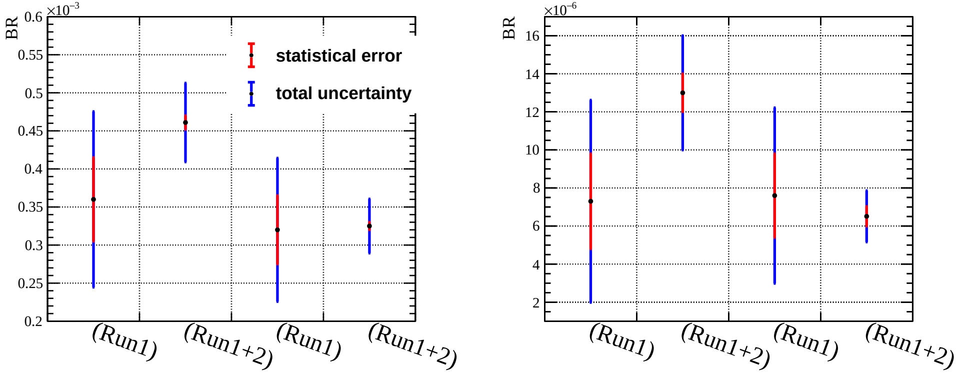
$$\overline{x} = \frac{\sum_i^n w_i x_i}{\sum_i^n w_i},$$

- where $w_i = 1/\sigma_i^2$ and each measurement is $x_i \pm \sigma_i$

$$\sigma_{\overline{x}} = \frac{1}{\sqrt{\sum_i^n w_i}},$$

$\eta^{(\prime)}$	$\mathcal{B}(B^0_s \to J/\psi\eta^{(\prime)}) \times 10^4$
η	$4.61 \pm 0.09\,\text{(stat)} \pm 0.15\,\text{(syst)} \pm 0.05(\mathcal{B}) \pm 0.21(\mathcal{R}_\gamma)^{+0.33}_{-0.29}(\mathcal{B}_{B^0\to J/\psi\rho^0}) \pm 0.10(f_s/f_d)$
η'	$3.25 \pm 0.05\,\text{(stat)} \pm 0.08\,\text{(syst)} \pm 0.03(\mathcal{B}) \pm 0.18(\mathcal{R}_\gamma)^{+0.23}_{-0.20}(\mathcal{B}_{B^0\to J/\psi\rho^0}) \pm 0.07(f_s/f_d)$
$\eta^{(\prime)}$	$\mathcal{B}(B^0 \to J/\psi\eta^{(\prime)}) \times 10^6$
η	$13.0 \pm 1.0\,\text{(stat)} \pm 0.6\,\text{(syst)} \pm 1.3(\mathcal{B}) \pm 0.5(\mathcal{R}_\gamma)^{+0.9}_{-0.8}(\mathcal{B}_{B^0\to J/\psi\rho^0})$
η'	$6.51 \pm 0.52\,\text{(stat)} \pm 0.33\,\text{(syst)} \pm 0.06(\mathcal{B}) \pm 0.34(\mathcal{R}_\gamma)^{+0.46}_{-0.41}(\mathcal{B}_{B^0\to J/\psi\rho^0})$

Comparison with Run-1: branching ratios



- $B_s^0 \to J/\psi\eta$ $B_s^0 \to J/\psi\eta'$ $B^0 \to J/\psi\eta$ $B^0 \to J/\psi\eta'$

- $\sim 4-6$ times improvement to statistics from Run-1 to Run-1+2 (expected 3.3 from $\sigma\mathcal{L}$)
- Central value shift for $\eta \to \pi^+\pi^-\pi^0$ stems from new π^0 correction
- Largest contributions to the error budget were the branching ratios of $B^0 \to J/\psi\rho^0$, $B^+ \to \chi_{c1}K^+$, $\chi_{c1} \to J/\psi\gamma$ and $B^+ \to J/\psi K^{*+}$. Belle2 is in the best position to improve these due to the clean e^+e^- event conditions.

What next with $B^0_{(s)} \to J/\psi\eta^{(\prime)}$ at LHCb

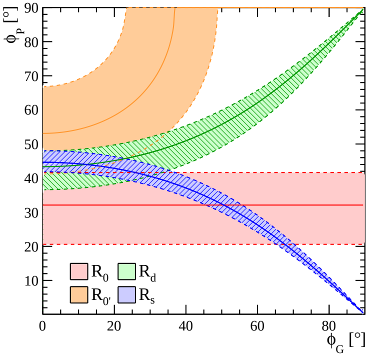
With Run-1&2: more channels $\eta^{(\prime)} \to \gamma\gamma$ vs. $\pi^0 \to \gamma\gamma$

$$\mathcal{R}_0 = \frac{\mathcal{B}(B^0 \to J/\psi\eta)}{\mathcal{B}(B^0 \to J/\psi\pi^0)} = \left(\frac{\Phi_d^{\eta}}{\Phi_d^{\pi^0}}\right)^3 \times \cos^2 \varphi_P$$

$$\mathcal{R}_0' = \frac{\mathcal{B}(B^0 \to J/\psi\eta')}{\mathcal{B}(B^0 \to J/\psi\pi^0)} = \left(\frac{\Phi_d^{\eta'}}{\Phi_d^{\pi^0}}\right)^3 \times \cos^2 \varphi_G \sin^2 \varphi_P$$

With future Runs: Continuation of this work

- The results in the mixing are statistically limited
- Total luminosity by end of Run-3&4 $\sim 50\,\text{fb}^{-1}$
- Pile up will be higher so performance is unknown: assume the same here
- Stat uncertainties of φ_P and φ_G could catch up with syst. after the addition of Run-3&4 data
  $\Rightarrow \sigma_{\varphi_P}$ (stat) $= 1.0^\circ \to 0.4^\circ$
  σ_{φ_G} (stat) $= 4.8^\circ \to 2.3^\circ$



PDG Averages

Summary

Study of $B_s^0 \to J/\psi\eta^{(\prime)}$ decays

- Refined two previous studies of Run-1 data
  - Studied mixing with more decay channels (single photons)
  - First study of $\eta \to \pi^+\pi^-\gamma$ final state with $B_{(s)}^0 \to J/\psi\eta^{(\prime)}$ decays
  - Used newer analysis methods (*e.g.* GBR and a BDT)
- Most precise measurements of $\mathcal{B}\,(B_{(s)}^0 \to J/\psi\eta^{(\prime)})$ to date
- Statistical improvement was almost double the expected from $\sigma\mathcal{L}$ alone
- Determined the gluonic component of η' by providing a 4σ significant mixing angle

Photon efficiency study

- Created corrections to the Run-1 and Run-2 photon efficiencies
  - Refined the methods of a previous Run-1 study of just π^0 (non-resonant correction to $K^{*+} \to K^+\pi^0$, random γ description, GBR+BDT)
  - Finished and extended work on single γ with $B^+ \to \chi_{c1}K^+$ started at Edinburgh
- Found corrections that can be used in a number of Run-1 & Run-2 analyses w/ γ/π^0 which are still numerous

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Thank you!

Continuation/extension of previous work

Photon reconstruction efficiencies

- A Run-1 study of efficiency corrections using photons from $B^+ \to J/\psi K^{*+}$ with $K^{*+} \to K^+\pi^0$ and $\pi^0 \to \gamma\gamma$:
  - Assuming single photon corrections are the square root of the π^0 correction
  - A simple model of the background was used
  - Misses important non-resonant $K^+\pi^0$ correction
  - Performed by Moscow groups
- A study of 2015/2016 data was started by Edinburgh looking at $B^+ \to \chi_{c1} K^+$ with $\chi_{c1} \to J/\psi\gamma$:
  - Master's project of M. Lehuraux under the supervision of G. Cowan

Measurement of $\mathcal{B}\,(B^0_{(s)} \to J/\psi\eta^{(\prime)})$ and η-η' mixing

- A study of $B^0_s \to J/\psi\eta^{(\prime)}$ with 2011 data
  - Studied many final states to create current best $\mathcal{B}$
  - Performed by Moscow groups
- A Run-1 study of η-η' mixing with $B^0_{(s)} \to J/\psi\eta^{(\prime)}$
  - Supplied ratio for $\mathcal{B}\,(B^0 \to J/\psi\eta^{(\prime)})$ to be calculated
  - Performed by Moscow groups

Recent experimental publications

- LHCb
  - Run-1 η-η' mixing measurement with $B^0_{(s)} \to J/\psi\eta^{(\prime)}$ [JHEP 01 (2015) 024]
  - Search for decay $\Lambda^0_b \to \Lambda\eta^{(\prime)}$ [JHEP 09 (2015) 006]
  - Search for decay $B^0_s \to \eta'\phi$ [JHEP 05 (2017) 158]
  - CP Violation in $D^+{}_{(s)} \to h^+\eta$ [JHEP 06 (2021) 019]
- Belle-I&II
  - Search for $B^0_s \to \eta'\eta$ [Phys.Rev.D 104 (2021) 3, L031101]
  - CP Violation in decays $D^0 \to \pi^+\pi^-\eta$, $D^0 \to K^+K^-\eta$ and $D^0 \to \phi\eta$ [JHEP 09 (2021) 075]
  - Many searches planned in [The Belle II Physics Book]
- BaBar
  - Light meson spectroscopy in $\eta_c \to \eta^{(\prime)}h^+h^-$ [Phys.Rev.D 104 (2021) 7, 072002]
  - LFV in $D^0 \to X^0 e^{\pm}\mu^{\pm}$ (including $X^0 = \eta$) [Phys.Rev.D 101 (2020) 11, 112003]
  - Measurement of the form factors of $\gamma^*\gamma^* \to \eta'$ [Phys.Rev.D 98 (2018) 11, 112002]

Connection to gluonium in full(?)

- We have considered mixing between the heavier mass state η′ (958), but what about η (548)?
- Typically expected to have much smaller mixing (negligible in today's experimental precision) because of the lower mass

A description with three angles:

- η-η′: φ_P
- η′-η_G: $\varphi_G^{\eta'}$
- η-η_G: φ_G^{η}

$$|\eta\rangle = \cos\varphi_P \cos\varphi_G^{\eta}|\eta_q\rangle - \sin\varphi_P \cos\varphi_G^{\eta}|\eta_s\rangle - \sin\varphi_G^{\eta}|gg\rangle$$

$$|\eta'\rangle = (\sin\varphi_P \cos\varphi_G^{\eta'} - \cos\varphi_P \sin\varphi_G^{\eta'} \sin\varphi_G^{\eta})|\eta_q\rangle + (\cos\varphi_P \cos\varphi_G^{\eta'} + \sin\varphi_P \sin\varphi_G^{\eta'} \sin\varphi_G^{\eta})|\eta_s\rangle - \cos\varphi_G^{\eta} \sin\varphi_G^{\eta'}|gg\rangle$$

- where $\varphi_G^{\eta} = 0$ reproduces the previous scheme
- Was found to be true in phenomenological fits

Connection to charmonium!

- Mass hierarchy as approximations for what mixes with what

A description with three angles:

- η-η': φ_P
- η'-η_G: φ_G
- η_G-η_c: φ_Q

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \\ |\eta_G\rangle \\ |\eta_c\rangle \end{pmatrix} = \begin{pmatrix} c\varphi & -s\varphi & 0 & 0 \\ s\varphi_P & c\varphi_P & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c\varphi_G & -s\varphi_G & 0 \\ 0 & s\varphi_G & c\varphi_G & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c\varphi_Q & -s\varphi_Q \\ 0 & 0 & s\varphi_Q & c\varphi_Q \end{pmatrix} \begin{pmatrix} |\eta_q\rangle \\ |\eta_s\rangle \\ |gg\rangle \\ |c\bar{c}\rangle \end{pmatrix}$$

- where $\varphi_Q = 0$ reproduces the previous scheme

Ways to measure η-η' mixing outside of LHCb: $\mathcal{R}_{\phi}$ & $\mathcal{R}_{J/\psi}$

$\mathcal{R}_{J/\psi}$

- A way to measure θ_P is to measure $\Gamma(J/\psi \to \gamma\eta')/\Gamma(J/\psi \to \gamma\eta)$

$$\mathcal{R}_{J/\psi} = \frac{\Gamma(J/\psi \to \gamma\eta')}{\Gamma(J/\psi \to \gamma\eta)} = \left(\frac{\Phi^{\eta'}}{\Phi^{\eta}}\right)^3 \cot^2 \theta_P$$

- This is the method used by BES Collaboration in [Phys.Rev.D 73 (2006)]
- Yielded $\varphi_P = (38.8 \pm 1.2)^\circ$ from 6×10^7 J/ψ in BES-II (now BES-III has 10^{10})

$\mathcal{R}_{\phi}$

- A way to measure
  varphi $and \varphi_G$ is to measure $\Gamma(\phi \to \gamma\eta')/\Gamma(\phi \to \gamma\eta)$

$$\mathcal{R}_{\phi} = \frac{\Gamma(\phi \to \gamma\eta')}{\Gamma(\phi \to \gamma\eta)} = \left(1 - \frac{m_s}{\hat{m}} \frac{tan \varphi_V}{\sin 2\varphi_P}\right)^2 \left(\frac{\Phi^{\eta'}}{\Phi^{\eta}}\right)^3 \cot^2 \varphi \cos^2 \varphi_G$$

- This is the method used by KLOE in [Phys.Lett.B 648 (2007)]
- Yielded $\varphi_P = (39.7 \pm 0.7)^\circ$ and $\varphi_G = (22 \pm 3)^\circ$ from 10^9 ϕ

Ways to measure η-η' mixing outside of LHCb: $\Gamma(\eta^{(\prime)} \to \gamma\gamma)$

- A way to measure θ_P is to measure $\Gamma(\eta^{(\prime)} \to \gamma\gamma)$ at e^+e^- colliders and Primakoff experiments

$$\Gamma(\eta^{(\prime)} \to \gamma\gamma) = \frac{M^3_{\eta^{(\prime)}}}{4\pi} \left|\kappa_{\eta^{(\prime)}}\right|^2$$

$$\begin{pmatrix} \kappa_\eta \\ \kappa_{\eta'} \end{pmatrix} = -i\alpha \left(\frac{1}{4\pi} \frac{1}{\sqrt{3}} ((M(\theta_P)F)^{-1})^T \begin{pmatrix} 1 \\ \sqrt{8} \end{pmatrix} + \pi \frac{t_1}{9/\sqrt{3}F_\pi} M(\theta_P) \begin{pmatrix} 7M_\pi^2 - 4M_K^2 \\ \sqrt{8}(2M_\pi^2 + M_K^2) \end{pmatrix} \right)$$

- where there are the form factors $F = \begin{pmatrix} F_{88} & F_{81} \\ F_{81} & F_{11} \end{pmatrix}$,

  mixing matrix $M(\theta_P) = \begin{pmatrix} \cos\theta_P & -\sin\theta_P \\ \sin\theta_P & \cos\theta_P \end{pmatrix}$ and a Low Energy Constant $t_1 = \frac{F_\pi^2}{m_\rho^4}$
- More detail in JLAB η proposals (2009)
- Will be the method of the JLAB Eta Factory (JEF) at GlueX

Future $\eta^{(\prime)}$ factories

JLAB Eta Factory (JEF) at GlueX

- Boosted production via $\gamma + \mathrm{p} \to \eta^{(\prime)} + \mathrm{p}$
- Producing $\sim 5 \times 10^7\ \eta^{(\prime)}$ per 100 days
- Focus is rare decay channels (not accessible by B decays)

REDTOP at CERN, Fermilab or BNL

- REDTOP: Rare Eta Decays with a TPC for Optical Photons
- Production via $\mathrm{p}Li \to \eta^{(\prime)}\mathrm{X}$
- Expected $\sim 10^13\ \eta^{(\prime)}$ mesons per year
- See [Contribution to:2022 Snowmass Summer Study]

Available physics - $\eta^{(\prime)}$ factories

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^0 \pi^+ \pi^-$
- CP Violation (Type I – P and T odd , C even): $\eta \to 4\pi^0 \to 8\gamma$
- CP Violation (Type II - C and T odd , P even): $\eta \to \pi^0 \ell^+\ell^-$ and $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$
- CP inv. via γ^* polarization studies: $\eta \to \pi^+\pi^- e^+ e^-$ & $\eta \to \pi^+\pi^- \mu^+\mu^-$
- CP invariance in angular correlation studies: $\eta \to \mu^+\mu^- e^+ e^-$
- T invariance via μ transverse polarization: $\eta \to \pi^0 \mu^+\mu^-$ and $\eta \to \gamma \mu^+\mu^-$
- CPT violation: μ polar. in $\eta \to \pi^+ \mu^- \nu$ vs $\eta \to \pi^- \mu^+ \nu$ and γ polar. in $\eta \to \gamma\gamma$

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \to \pi^0 H$ with $H \to e^+e^-$ and $H \to \mu^+\mu^-$
- Dark photon searches: $\eta \to \gamma A'$ with $A' \to \ell^+\ell^-$
- Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to e^+e^-$
- QCD axion searches : $\eta \to \pi\pi a_{17}$ with $a_{17} \to e^+e^-$
- New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^0$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
- Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$
- Lepton Universality

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+ e^- + c.c.$
- Double lepton Flavor Violation: $\eta \to \mu^+\mu^+ e^- e^- + c.c.$

Other Precision Physics measurements

- Proton radius anomaly: $\eta \to \gamma \mu^+\mu^-$ vs $\eta \to \gamma e^+e^-$
- All unseen leptonic decay mode of η / η' (SM predicts 10^{-6} - 10^{-9})

Non-η/η' based BSM Physics

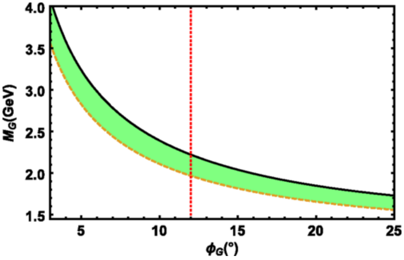
- Dark photon and ALP searches in Drell-Yan processes: $q\bar{q} \to A'/a \to \ell^+\ell^-$
- ALP's searches in Primakoff processes: $p\,Z \to p\,Z\,a \to \ell^+\ell^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+e^-$ and $K^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+e^-$
- Neutral pion decay: $\pi^0 \to \gamma A' \to \gamma e^+e^-$

High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

See REDTOP physics site: [https://redtop.fnal.gov/the-physics/]

Pseudoscalar glueball suggestions



Uses η-η'-η_G-η_c mixing scheme with $\varphi_P = 43.7^\circ$ and $\varphi_Q = 11.6^\circ|_{\eta_G-\eta_c}$

- According to [Phys. Rev. D 97(2018)] we can determine the mass of a physical glueball state from the η'-η_G mixing angle
  - So $\varphi_G = (20.8 \pm 4.8\,\text{(stat)} \pm 2.8\,\text{(syst)} \pm 0.8(\mathcal{B}))^\circ$ suggests a mass of $1.6 - 2.1$ GeV for glueballs in this particular model
  - In slight tension with LQCD which expects a mass around 2.5 GeV
  - This mass range would point to $\eta(1760)$ or $X(1835)$ measured by Belle and BES.

- phenomenological studies [Phys.Rev.D 79 (2009)] of the KLOE results of $\varphi_P \approx 40^\circ$ and $\varphi_G \approx 22^\circ$ have been performed in the η-η'-η_G scheme
  - This suggested the mass would actually be 1.4 GeV!
  - In excellent agreement with η (1405)
  - Even further from the LQCD results
- The situation remains unclear

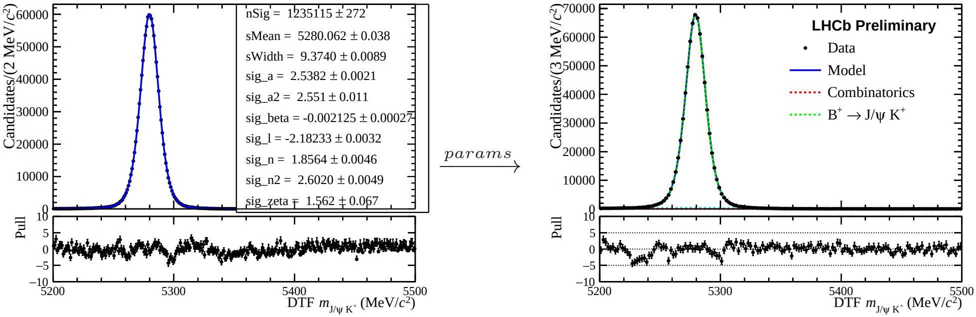
Chiral perturbation theory (χ_{PT})

- The masses of the pseudoscalars η and η' are small enough that the strong coupling constant becomes very large
- At these energies an effective field theory to describe QCD based on chiral symmetries were needed
- With the limit of a large number of colours $N_c \to \infty$ η' can be included in this theory
- Then pseudo-Goldstone bosons are produced by spontaneous chiral symmetry breaking including the full octet and singlet of pseudoscalars introduced before:

$$\begin{pmatrix} \pi^0/\sqrt{2}+\eta_8/\sqrt{6}+\eta_1/\sqrt{3} & \pi^+ & K^+ \\ \pi^- & -\pi^0/\sqrt{2}+\eta_8/\sqrt{6}+\eta_1/\sqrt{3} & K^0 \\ K^- & \overline{K}^0 & -2\eta_8/\sqrt{6}+\eta_1/\sqrt{3} \end{pmatrix}$$

- Today, it is this theory that is typically relied on for phenomenological analysis of η-η'
- Most precise parts of the theory are just from expansions of m_d and m_u so for the kaons and $\eta^{(\prime)}$ there are issues with the descriptions
- Extrapolation to higher energies is very difficult

Data Fits to Extract Signal Yields



Fit PDF Models

- Signal and peaking/physics background: 2-sided Crystal ball (or derivative)
- Combinatorial background: exponential
- Model shape parameters taken from Monte Carlo
- Background yields are Gaussian constrained

Fit results $B^0_{(s)} \to J/\psi\eta^{(\prime)}$: single photon

$\eta \to \pi^+\pi^-\gamma$

```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=-8268.33 FROM HESSE     STATUS=OK            50 CALLS         290 TOTAL
                     EDM=0.00080709    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                INTERNAL      INTERNAL
 NO.   NAME      VALUE            ERROR       STEP SIZE       VALUE
  1  GlobalShift  -1.01478e+00   4.76689e-01   6.01358e-04  -1.01653e-01
  2  GlobalSmear   7.78202e-01   2.93116e-02   9.89574e-05  -1.04116e+00
  3  nbd          1.31682e+02   2.51690e+01   1.82250e-04  -8.28083e-01
  4  nbkg         9.19831e+02   7.15308e+01   1.95169e-04  -9.54516e-01
  5  nsig         1.01213e+03   2.29588e+01   7.14709e-05  -9.23262e-01
  6  p0          -1.00754e-07   1.44266e-04   3.93770e-03   1.57135e+00
                                 WARNING -   - ABOVE PARAMETER IS AT LIMIT.
  7  pi0_f        2.99999e+00   1.84786e+00   5.26465e-03   1.56655e+00
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  7     ERR DEF=0.5
 2.274e-01  1.687e-03  5.015e-01 -3.767e+00  8.167e-01 -1.389e-11 -6.039e-06
 1.687e-03  8.592e-04  6.523e-02 -1.525e+00  3.653e-01 -1.004e-10 -1.643e-06
 5.015e-01  6.523e-02  6.347e+02 -1.675e+02 -8.508e+01 -3.982e-08 -6.700e-04
-3.767e+00 -1.525e+00 -1.675e+02  5.118e+03 -1.008e+03  4.898e-07  1.974e-03
 8.167e-01  3.653e-01 -8.508e+01 -1.008e+03  5.271e+02 -1.125e-07 -4.242e-03
-1.389e-11 -1.004e-10 -3.982e-08  4.898e-07 -1.125e-07  4.373e-13  4.545e-14
-6.039e-06 -1.643e-06 -6.700e-04  1.974e-03 -4.242e-03  4.545e-14  4.068e-05
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4      5      6      7
        1  0.12880   1.000  0.121  0.042 -0.110  0.075 -0.000 -0.002
        2  0.74052   0.121  1.000  0.088 -0.727  0.543 -0.005 -0.009
        3  0.28729   0.042  0.088  1.000 -0.093 -0.147 -0.002 -0.004
        4  0.77851  -0.110 -0.727 -0.093  1.000 -0.614  0.010  0.004
        5  0.66420   0.075  0.543 -0.147 -0.614  1.000 -0.007 -0.029
        6  0.01133  -0.000 -0.005 -0.002  0.010 -0.007  1.000  0.000
        7  0.03603  -0.002 -0.009 -0.004  0.004 -0.029  0.000  1.000
```

$\eta' \to \rho^0\gamma$

```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=-66096 FROM HESSE     STATUS=OK            40 CALLS         418 TOTAL
                     EDM=5.20419e-05    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                INTERNAL      INTERNAL
 NO.   NAME      VALUE            ERROR       STEP SIZE       VALUE
  1  GlobalShift   3.54369e-01   1.64005e-01   5.80852e-04  -3.17704e+00
  2  GlobalSmear   1.07437e+00   1.69678e-02   3.71133e-05  -9.32576e-01
  3  nbd          5.14623e+02   5.56575e+01   6.75602e-04   2.92496e-02
  4  nbkg         1.28188e+04   1.44963e+02   1.30463e-04  -8.38474e-01
  5  nsig         7.76373e+03   1.06927e+02   1.67768e-04   2.55594e+00
  6  p0          -3.24695e-03   6.28956e-05   4.33254e-04   2.78336e+00
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  6     ERR DEF=0.5
 2.690e-02 -1.244e-04  1.296e-03 -1.187e-01 -1.174e-01 -3.072e-07
-1.244e-04  2.879e-04  1.971e-01 -7.907e-01 -5.937e-01 -1.980e-07
 1.296e-03  1.971e-01  3.111e+03 -3.560e+03 -9.644e+02 -1.362e-03
-1.187e-01 -7.907e-01 -3.560e+03  2.101e+04  4.637e+03  2.483e-03
-1.174e-01 -5.937e-01 -9.644e+02  4.637e+03  1.144e+04  1.121e-03
-3.072e-07 -1.980e-07 -1.362e-03  2.483e-03  1.121e-03  3.956e-09
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4      5      6
        1  0.06319   1.000 -0.045  0.000 -0.005 -0.007 -0.030
        2  0.41550  -0.045  1.000  0.208 -0.321 -0.327 -0.186
        3  0.52290   0.000  0.208  1.000 -0.440 -0.162 -0.388
        4  0.53103  -0.005 -0.321 -0.440  1.000  0.299  0.272
        5  0.39139  -0.007 -0.327 -0.162  0.299  1.000  0.167
        6  0.41797  -0.030 -0.186 -0.388  0.272  0.167  1.000
```

Fit results $B^0_{(s)} \to J/\psi\eta^{(\prime)}$: two photon

$\eta \to \pi^+\pi^-\pi^0$

```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=-5931.81 FROM HESSE     STATUS=OK             40 CALLS          230 TOTAL
                    EDM=0.000221923    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                INTERNAL      INTERNAL
 NO.   NAME      VALUE            ERROR       STEP SIZE       VALUE
  1  GlobalShift   2.73101e-01   4.88797e-01   2.62843e-03   1.36978e-01
  2  GlobalSmear   1.15910e+00   2.63224e-02   4.40897e-04   5.38672e-01
  3  nbd          2.75596e+02   2.25789e+01   5.12907e-04  -4.65432e-01
  4  nbkg         4.67954e+02   3.03137e+01   1.39122e-04  -1.13470e+00
  5  nsig         2.62065e+03   5.44562e+01   2.56372e-05  -4.95952e-01
  6  p0          -3.58238e-03   2.84704e-04   6.20529e-04   2.87468e-01
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  6    ERR DEF=0.5
 2.439e-01  5.305e-04  1.211e+00 -2.237e-01 -9.870e-01 -8.087e-06
 5.305e-04  6.933e-04  1.682e-03 -2.263e-01  2.246e-01 -9.763e-07
 1.211e+00  1.682e-03  5.102e+02 -1.702e+02 -6.440e+01  2.372e-04
-2.237e-01 -2.263e-01 -1.702e+02  9.190e+02 -2.806e+02  1.068e-03
-9.870e-01  2.246e-01 -6.440e+01 -2.806e+02  2.966e+03 -1.305e-03
-8.087e-06 -9.763e-07  2.372e-04  1.068e-03 -1.305e-03  8.115e-08
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4      5      6
       1  0.13792   1.000  0.041  0.109 -0.015 -0.037 -0.057
       2  0.32412   0.041  1.000  0.003 -0.284  0.157 -0.130
       3  0.29876   0.109  0.003  1.000 -0.249 -0.052  0.037
       4  0.41215  -0.015 -0.284 -0.249  1.000 -0.170  0.124
       5  0.23082  -0.037  0.157 -0.052 -0.170  1.000 -0.084
       6  0.18712  -0.057 -0.130  0.037  0.124 -0.084  1.000
```

$\eta' \to \pi^+\pi^-\eta$

```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=-5019.57 FROM HESSE     STATUS=OK             40 CALLS          193 TOTAL
                    EDM=0.000137405    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                INTERNAL      INTERNAL
 NO.   NAME      VALUE            ERROR       STEP SIZE       VALUE
  1  GlobalShift  -4.30246e-01   4.82201e-01   1.20935e-02  -2.16818e-01
  2  GlobalSmear   1.15124e+00   3.05903e-02   1.49910e-03   1.06774e-01
  3  nbd          1.72276e+02   2.00391e+01   2.45537e-03  -7.14776e-01
  4  nbkg         7.52182e+02   3.62808e+01   6.11228e-04  -1.01516e+00
  5  nsig         2.30543e+03   5.21781e+01   5.84549e-04  -5.69147e-01
  6  p0          -1.66454e-03   1.94230e-04   2.51414e-03   7.30300e-01
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  6    ERR DEF=0.5
 2.374e-01  2.479e-05  8.649e-01 -2.188e-01 -6.453e-01 -3.593e-06
 2.479e-05  9.361e-04 -1.665e-02 -3.107e-01  3.274e-01  7.738e-08
 8.649e-01 -1.665e-02  4.019e+02 -1.880e+02 -4.146e+01  6.017e-04
-2.188e-01 -3.107e-01 -1.880e+02  1.316e+03 -3.759e+02 -6.952e-04
-6.453e-01  3.274e-01 -4.146e+01 -3.759e+02  2.723e+03  9.344e-05
-3.593e-06  7.738e-08  6.017e-04 -6.952e-04  9.344e-05  3.776e-08
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4      5      6
       1  0.10554   1.000  0.002  0.089 -0.012 -0.025 -0.038
       2  0.33101   0.002  1.000 -0.027 -0.280  0.205  0.013
       3  0.32784   0.089 -0.027  1.000 -0.258 -0.040  0.154
       4  0.41895  -0.012 -0.280 -0.258  1.000 -0.199 -0.099
       5  0.26492  -0.025  0.205 -0.040 -0.199  1.000  0.009
       6  0.17368  -0.038  0.013  0.154 -0.099  0.009  1.000
```

Fit results γ reco: signal channels

$B^+ \to \chi_{c1} K^+$

```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=-287538 FROM HESSE     STATUS=OK             50 CALLS         427 TOTAL
                     EDM=4.88306e-05    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                INTERNAL      INTERNAL
 NO.   NAME      VALUE            ERROR       STEP SIZE       VALUE
  1  GlobalShift   3.70040e-01   5.71599e-02   4.20874e-04   3.70124e-02
  2  GlobalSmear   1.13530e+00   7.84064e-03   3.44444e-05  -9.12195e-01
  3  expSlope     -6.96713e-03   8.49860e-04   3.67353e-06   1.55410e+00
  4  fgg           9.52631e-02   1.01808e-03   5.46069e-05  -9.58146e-01
  5  nB0           3.44528e+03   9.01027e+02   1.79174e-04  -1.04504e+00
  6  nexp          1.26523e+04   9.89674e+02   1.05665e-04  -1.34535e+00
  7  nsig          3.47275e+04   2.20719e+02   1.56197e-05  -1.19590e+00
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  7    ERR DEF=0.5
 3.267e-03 -9.190e-06  4.258e-06  9.995e-08 -3.536e+00  3.682e+00 -1.415e-01
-9.190e-06  6.148e-05 -1.930e-06 -1.302e-07  2.031e+00 -2.616e+00  5.345e-01
 4.258e-06 -1.930e-06  7.223e-07 -3.239e-08 -7.426e-01  8.074e-01 -5.870e-02
 9.995e-08 -1.302e-07 -3.239e-08  1.036e-06  2.352e-02 -5.257e-02 -6.337e-03
-3.536e+00  2.031e+00 -7.426e-01  2.352e-02  8.136e+05 -8.776e+05  6.090e+04
 3.682e+00 -2.616e+00  8.074e-01 -5.257e-02 -8.776e+05  9.795e+05 -7.945e+04
-1.415e-01  5.345e-01 -5.870e-02 -6.337e-03  6.090e+04 -7.945e+04  4.872e+04
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4      5      6      7
       1  0.11349   1.000 -0.021  0.088  0.002 -0.069  0.065 -0.011
       2  0.43897  -0.021  1.000 -0.290 -0.016  0.287 -0.337  0.309
       3  0.96990   0.088 -0.290  1.000 -0.037 -0.969  0.960 -0.313
       4  0.19050   0.002 -0.016 -0.037  1.000  0.026 -0.052 -0.028
       5  0.98876  -0.069  0.287 -0.969  0.026  1.000 -0.983  0.306
       6  0.98694   0.065 -0.337  0.960 -0.052 -0.983  1.000 -0.364
       7  0.48451  -0.011  0.309 -0.313 -0.028  0.306 -0.364  1.000
```

$B^+ \to J/\psi K^{*+}$

```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=-266475 FROM HESSE     STATUS=OK             69 CALLS         631 TOTAL
                     EDM=0.000405044    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                INTERNAL      INTERNAL
 NO.   NAME      VALUE            ERROR       STEP SIZE       VALUE
  1  GlobalShift   1.00269e+00   3.21546e-01   4.14994e-03   1.00438e-01
  2  GlobalSmear   1.15498e+00   1.15971e-02   7.63743e-04  -9.05726e-01
  3  fg            4.15771e-01   3.30185e-02   2.03615e-03  -1.02653e+00
  4  fgg           1.83906e-01   4.26313e-03   1.90794e-03  -1.10050e+00
  5  nexp          1.39233e+04   1.28101e+03   6.00307e-04  -1.33425e+00
  6  nk1           2.65974e+03   6.73655e+02   8.58000e-04  -1.46761e+00
  7  nsig_         3.19486e+04   4.52203e+02   3.14660e-04  -1.21138e+00
  8  p0           -3.23330e-03   1.68230e-04   3.92481e-03   3.61140e-01
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  8    ERR DEF=0.5
 1.034e-01  2.277e-03 -2.947e-03 -2.171e-05 -3.210e+01  1.914e+01  6.751e+01
 2.277e-03  1.345e-04 -1.244e-04 -3.201e-06 -2.290e+00  1.202e+00  3.234e+00
-2.947e-03 -1.244e-04  1.090e-03  6.239e-06 -3.061e+01  1.415e+01 -1.167e+01
-2.171e-05 -3.201e-06  6.239e-06  1.817e-05 -8.547e-01  2.312e-01 -9.930e-02
-3.210e+01 -2.290e+00 -3.061e+01 -8.547e-01  1.641e+06 -8.307e+05  1.327e+05
 1.914e+01  1.202e+00  1.415e+01  2.312e-01 -8.307e+05  4.538e+05 -5.086e+04
 6.751e+01  3.234e+00 -1.167e+01 -9.930e-02  1.327e+05 -5.086e+04  2.045e+05
-4.351e-06 -2.938e-07  4.234e-06 -7.552e-10 -1.868e-01  1.014e-01 -3.139e-02
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4      5      6      7      8
       1  0.63215   1.000  0.611 -0.277 -0.016 -0.078  0.088  0.464 -0.080
       2  0.82553   0.611  1.000 -0.325 -0.065 -0.154  0.154  0.617 -0.151
       3  0.97410  -0.277 -0.325  1.000  0.044 -0.724  0.636 -0.782  0.762
       4  0.58290  -0.016 -0.065  0.044  1.000 -0.156  0.081 -0.052 -0.001
       5  0.98807  -0.078 -0.154 -0.724 -0.156  1.000 -0.963  0.229 -0.867
       6  0.98292   0.088  0.154  0.636  0.081 -0.963  1.000 -0.167  0.894
       7  0.93923   0.464  0.617 -0.782 -0.052  0.229 -0.167  1.000 -0.413
       8  0.95201  -0.080 -0.151  0.762 -0.001 -0.867  0.894 -0.413  1.000
```

Fit results γ reco: normalisation an control channels

$B^+ \to J/\psi K^+$

```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=-1.01487e+07 FROM HESSE     STATUS=OK             52 CALLS          755 TOT
                      EDM=0.000196926    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                   INTERNAL      INTERNAL
 NO.   NAME      VALUE            ERROR          STEP SIZE       VALUE
  1  GlobalShift   5.44178e-01   9.41322e-03   8.27789e-05   5.44447e-02
  2  GlobalSmear   1.09288e+00   1.59392e-03   1.19637e-05  -9.26327e-01
  3  bkgSlope    -3.18145e-03   2.43326e-04   2.59841e-04   1.21215e+00
  4  ghFrac       9.78703e-01   1.02800e-03   1.04048e-03  -2.18721e-01
  5  ghWidthMC    2.69813e+01   8.95089e-01   5.34269e-03   8.10573e-01
  6  nbkg         1.41773e+04   4.38859e+02   1.80292e-05  -1.49547e+00
  7  nsig         1.10706e+06   1.13378e+03   2.96379e-05  -8.92697e-01
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  7    ERR DEF=0.5
 8.861e-05  2.330e-08  1.390e-07 -5.972e-08  3.101e-04 -2.160e-01  2.160e-01
 2.330e-08  2.541e-06  1.181e-07  1.223e-06  8.227e-04 -2.532e-01  2.532e-01
 1.390e-07  1.181e-07  5.921e-08  4.995e-08  1.478e-04 -8.974e-02  8.973e-02
-5.972e-08  1.223e-06  4.995e-08  1.058e-06  6.283e-04 -1.156e-01  1.156e-01
 3.101e-04  8.227e-04  1.478e-04  6.283e-04  8.365e-01 -3.029e+02  3.029e+02
-2.160e-01 -2.532e-01 -8.974e-02 -1.156e-01 -3.029e+02  1.926e+05 -1.784e+05
 2.160e-01  2.532e-01  8.973e-02  1.156e-01  3.029e+02 -1.784e+05  1.285e+06
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4      5      6      7
       1  0.06474   1.000  0.002  0.061 -0.006  0.036 -0.052  0.020
       2  0.77319   0.002  1.000  0.305  0.746  0.564 -0.362  0.140
       3  0.84597   0.061  0.305  1.000  0.200  0.664 -0.840  0.325
       4  0.87091  -0.006  0.746  0.200  1.000  0.668 -0.256  0.099
       5  0.90559   0.036  0.564  0.664  0.668  1.000 -0.755  0.292
       6  0.89842  -0.052 -0.362 -0.840 -0.256 -0.755  1.000 -0.359
       7  0.36320   0.020  0.140  0.325  0.099  0.292 -0.359  1.000
```

$B^0 \to J/\psi K^{*0}$

```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY
FCN=-2.68979e+06 FROM HESSE     STATUS=OK             65 CALLS          570 TOT
                      EDM=0.000191084    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                   INTERNAL      INTERNAL
 NO.   NAME      VALUE            ERROR          STEP SIZE       VALUE
  1  SigMean      5.28020e+03   1.48735e-02   3.35794e-04   1.98645e-02
  2  SigWidth     8.93495e+00   1.75102e-02   3.48562e-04  -3.25302e-02
  3  bkgSlope    -5.66930e-03   2.30863e-04   1.49449e-03  -6.41736e+00
  4  ghFrac       9.87705e-01   1.03058e-03   1.86862e-03   3.02005e-01
  5  ghWidth      4.05000e+01   9.94967e-01   5.00000e-01   1.56940e+00
  6  nbs          3.21156e+03   6.88466e+01   6.41217e-04  -3.65791e-01
  7  nexp         5.25815e+03   1.99929e+02   2.40713e-05  -1.52493e+00
  8  nsig         3.31581e+05   6.05109e+02   5.65535e-05  -3.57936e-01
                               ERR DEF= 0.5
EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  8    ERR DEF=0.5
 2.212e-04  1.862e-05 -1.519e-07  8.369e-07 -3.634e-07 -5.204e-03  1.121e-01
 1.862e-05  3.066e-04 -3.172e-07  7.485e-06 -9.734e-06  7.797e-02  2.591e-01
-1.519e-07 -3.172e-07  5.334e-08 -1.232e-07 -2.809e-07 -4.066e-04 -3.198e-02
 8.369e-07  7.485e-06 -1.232e-07  1.063e-06 -8.176e-09  5.827e-03  1.259e-01
-3.634e-07 -9.734e-06 -2.809e-07 -8.176e-09  3.716e-05  6.814e-02  3.221e-01
-5.204e-03  7.797e-02 -4.066e-04  5.827e-03  6.814e-02  4.740e+03 -8.309e+02
 1.121e-01  2.591e-01 -3.198e-02  1.259e-01  3.221e-01 -8.309e+02  3.997e+04
-1.069e-01 -3.370e-01  3.238e-02 -1.317e-01 -3.902e-01 -6.971e+02 -3.388e+04
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4      5      6      7      8
       1  0.08262   1.000  0.072 -0.044  0.055 -0.004 -0.005  0.038 -0.012
       2  0.47699   0.072  1.000 -0.078  0.415 -0.091  0.065  0.074 -0.032
       3  0.70677  -0.044 -0.078  1.000 -0.517 -0.200 -0.026 -0.693  0.232
       4  0.74440   0.055  0.415 -0.517  1.000 -0.001  0.082  0.611 -0.211
       5  0.40044  -0.004 -0.091 -0.200 -0.001  1.000  0.162  0.264 -0.106
       6  0.28096  -0.005  0.065 -0.026  0.082  0.162  1.000 -0.060 -0.017
       7  0.79298   0.038  0.074 -0.693  0.611  0.264 -0.060  1.000 -0.280
       8  0.29172  -0.012 -0.032  0.232 -0.211 -0.106 -0.017 -0.280  1.000
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LHCb

Selections: $\mathrm{B} \to \mathrm{J}/\psi \mathrm{X}$

$\mathrm{B} \to \mathrm{J}/\psi \mathrm{X}$

	Variable	Requirement
$B \to J/\psi X$	DIRA	> 0.9995
	IP	< 0.2
	χ^2_{IP}	< 20
	$\chi^2_{\mathrm{vtx}}/\mathrm{ndf}$	< 10
$J/\psi \to \mu^+\mu^-$	$\chi^2_{\mathrm{IP}}(\mu^\pm)$	> 4
	$p_{\mathrm{T}}(\mu^\pm)$	$> 550\,\mathrm{MeV}$

Stripping

	Variable	Requirement
$J/\psi \to \mu^+\mu^-$	Best PV $\lvert\mathrm{DLS}\rvert$	> 3
	Min. $\Delta \log \mathcal{L}_{\mu-\pi}$	> 0
	Min. $p_{\mathrm{T}}(\mu)$	$> 500\,\mathrm{MeV}$
	Max. $\chi^2_{\mathrm{tr}}/\mathrm{ndf}(\mu)^*$	< 5
	$\chi^2_{\mathrm{vtx}}/\mathrm{ndf}$	< 20
	$\lvert m(\mu^+\mu^-) - m(J/\psi)\rvert$	$< 100\,\mathrm{MeV}$

Stripping container	Variable	Requirement
StdLooseKaons	$p_{\mathrm{T}}(K^+)$	$> 250\,\mathrm{MeV}$
	χ^2_{IP}	> 4
StdLoosePions	$p_{\mathrm{T}}(K^+)$	$> 250\,\mathrm{MeV}$
	χ^2_{IP}	> 4
StdLoosePhotons	$p_{\mathrm{T}}(\gamma)$	$> 200\,\mathrm{MeV}$
StdLoosePi02gg	$\lvert m(\pi^0) - m(\gamma\gamma)\rvert$	$< 60\,\mathrm{MeV}$

Selections: γ reco.

p_{T} and PID

	Variable	Requirement
K^+	$p_{\mathrm{T}}(K^+)$	> 150 MeV
	$\mathrm{ProbNN}_K(1-\mathrm{ProbNN}_\pi)$	> 0.2
γ in $\chi_{c1}\to J/\psi\gamma$	$p_{\mathrm{T}}(\gamma)$	> 500 MeV
	IsNotH	> 0.05
$\pi^0\to\gamma\gamma$	$p_{\mathrm{T}}(\gamma)$	> 200 MeV
	IsNotH	> 0.05
	$p_{\mathrm{T}}(\pi^0)$	> 1 GeV
π^- in $K^{*0}\to K^+\pi^-$	$\mathrm{ProbNN}_\pi(1-\mathrm{ProbNN}_K)$	> 0.2

Mass windows

Channel	Mass range	
$B^+\to J/\psi K^+$	$m(J/\psi K^+)$	$\in [5200, 5500]$ MeV
$B^+\to \chi_{c1}K^+$	$m(J/\psi K^+\gamma)$	$\in [5200, 5400]$ MeV
$\chi_{c1}\to J/\psi\gamma$	$\lvert m(J/\psi\gamma)-m(\chi_{c1})\rvert$	< 90 MeV
$B^+\to J/\psi K^{*+}$	$m(J/\psi K^+\gamma\gamma)$	$\in [5000, 6000]$ MeV
$K^{*+}\to K^+\pi^0$	$\lvert m(K^+\gamma\gamma)-m(K^{*+})\rvert$	< 75 MeV
$B^0\to J/\psi K^{*0}$	$m(J/\psi K^+\pi^-)$	$\in [5200, 5600]$ MeV
$K^{*0}\to K^+\pi^-$	$\lvert m(K^+\pi^-)-K^{*0}\rvert$	< 75 MeV

Selections: $B^0_{(s)} \to J/\psi\eta^{(\prime)}$

1 γ

	Variable	Requirement
$\pi^\pm$	$\mathcal{P}_\pi$	> 0.1
	$\mathcal{P}_\pi(1-\mathcal{P}_K)$	> 0.2
$\eta \to \pi^+\pi^-\gamma$	$\chi^2_{\text{vtx}}/\text{ndf}$	< 25
	$p_T(\gamma)$	> 500 MeV
	IsNotH	> 0.05
	$p_T(\eta)$	> 1.5 GeV
	$\lvert m(\pi^+\pi^-\gamma) - m(\eta)\rvert$	< 100 MeV
$\eta' \to \rho^0\gamma$	$p_T(\gamma)$	> 500 MeV
	IsNotH	> 0.05
	$p_T(\eta')$	> 1.5 GeV
	$\lvert m(\pi^+\pi^-\gamma) - m(\eta')\rvert$	< 100 MeV
$\rho^0 \to \pi^+\pi^-$	$\chi^2_{\text{vtx}}/\text{ndf}$	< 25
	$m(\rho^0)$	$\in [600, 900]$ MeV

2 γ

$\eta \to \pi^+\pi^-\pi^0$	$\chi^2_{\text{vtx}}/\text{ndf}$	< 25
	$p_T(\pi^0)$	> 1 GeV
	$p_T(\eta)$	> 1.5 GeV
	$\lvert m(\pi^+\pi^-\gamma\gamma) - m(\eta)\rvert$	< 100 MeV
$\pi^0 \to \gamma\gamma$	$p_T(\gamma)$	> 200 MeV
	Min. IsNotH	> 0.05
	$\lvert m(\gamma\gamma) - m(\pi^0)\rvert$	< 60 MeV
$\eta' \to \pi^+\pi^-\eta$	$\chi^2_{\text{vtx}}/\text{ndf}$	< 25
	$p_T(\eta)$	> 1 GeV
	$p_T(\eta')$	> 1.5 GeV
	$\lvert m(\pi^+\pi^-\gamma\gamma) - m(\eta')\rvert$	< 100 MeV
$\eta \to \gamma\gamma$	$p_T(\gamma)$	> 200 MeV
	Min. IsNotH	> 0.05
	$\lvert m(\gamma\gamma) - m(\eta)\rvert$	< 100 MeV