Новости физики тяжелых кварков

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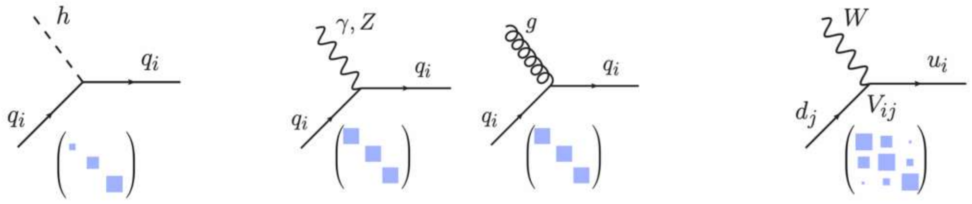
23 июля, выездное собрание дискуссионного клуба

Поколения кварков и не только



Higgs couplings diagonal by construction

Gauge boson couplings diagonal by symmetry

EXCEPT

Charged gauge bosons which are sensitive to V_{CKM}

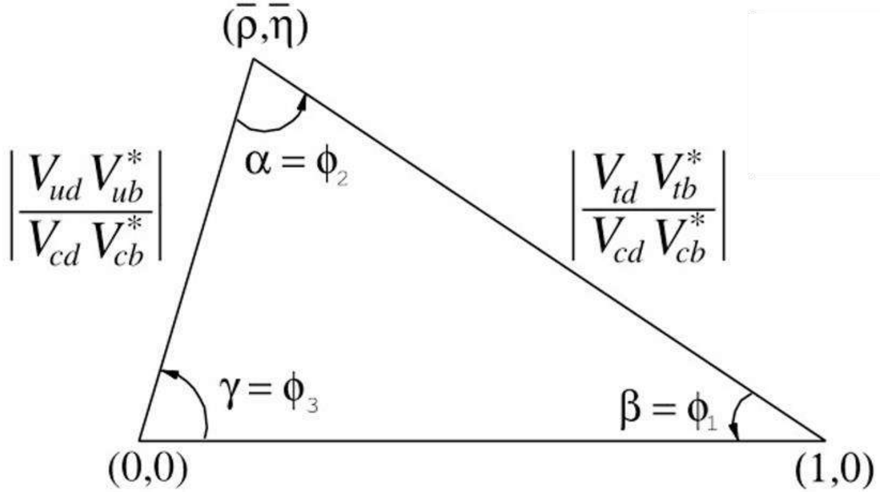
$$V_{CKM} = U_Q^{(u)} U_Q^{(d)\dagger}$$

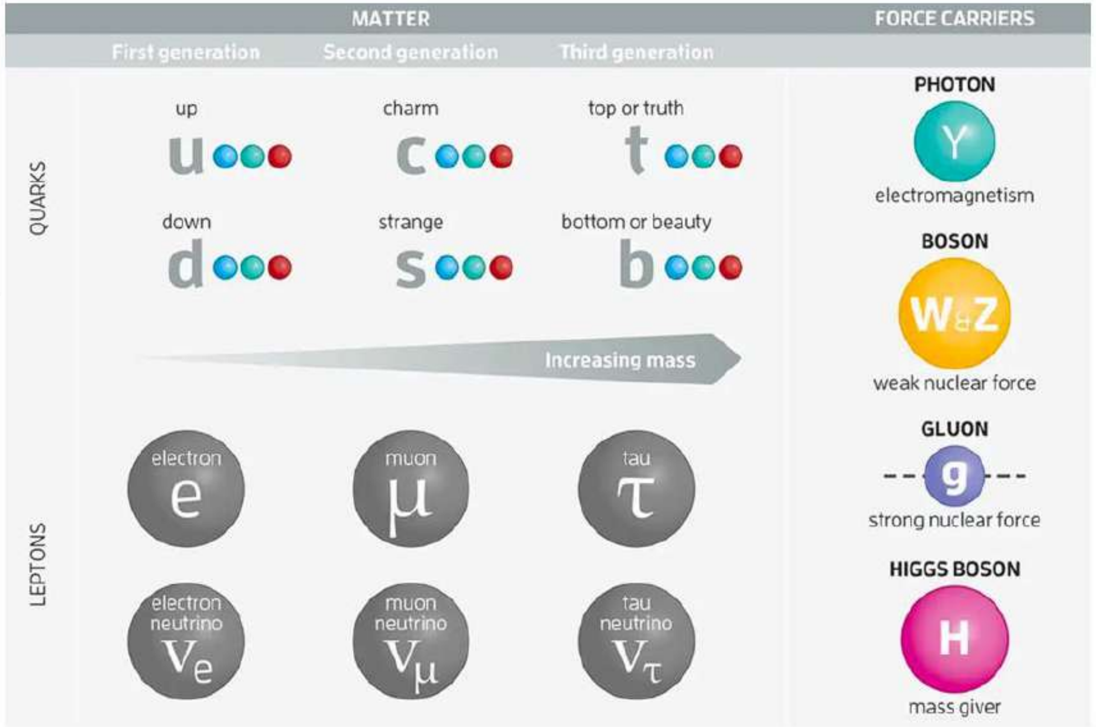
where $U_Q^{(u)}$ diagonalizes Y_u and $U_Q^{(d)}$ diagonalizes Y_d

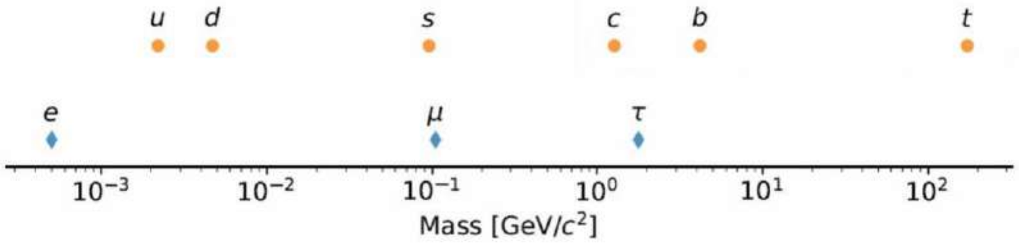
$$V_{CKM} V^{+}_{CKM} = 1$$

Треугольник унитарности

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

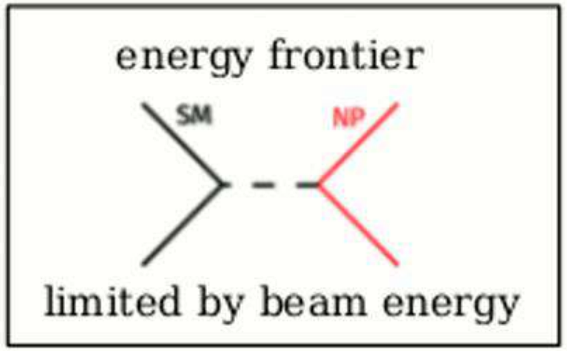


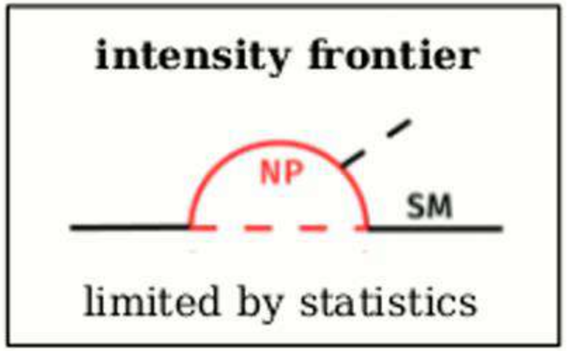




Методы поиска Новой Физики

Прямые *vs* Косвенные

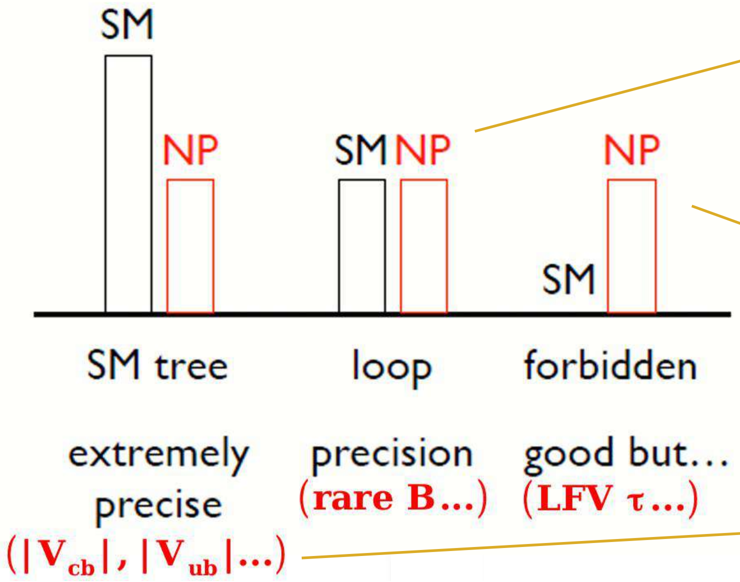




новые взаимодействия?

4-е поколение?

$$\mathcal{O}_{\rm obs} = \mathcal{O}_{\rm SM} + \mathcal{O}_{\rm NP}$$



$\mathrm{Br}(D \to \mu\mu)_{\rm SM} \approx 3 \times 10^{-13}$ $\mathrm{Br}(D \to \mu\mu)_{\rm CMS} < 2.4 \times 10^{-9}$

$\mathrm{Br}(B_s \to \mu\mu)_{\rm SM} = (3.67 \pm 0.15) \times 10^{-9}$ $\mathrm{Br}(B_s \to \mu\mu)_{\rm PDG} = (3.34 \pm 0.27) \times 10^{-9}$

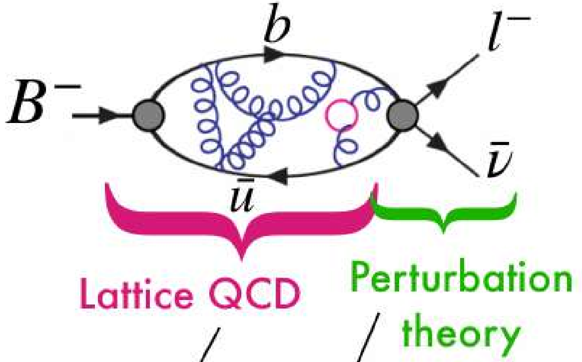
$\mathrm{Br}(\mu \to e\gamma)_{\rm SM} < 10^{-54}$ $\mathrm{Br}(\mu \to e\gamma)_{\rm MEGII} < 1.5 \times 10^{-13}$

Прямое измерение вероятностей / CPV

Прямые измерения V_{CKM}

Flavour measurements are done at a scale where quarks are bound into hadrons
Need model independent way to calculate non-perturbative QCD (+QED) contributions

EXAMPLE: leptonic B decay

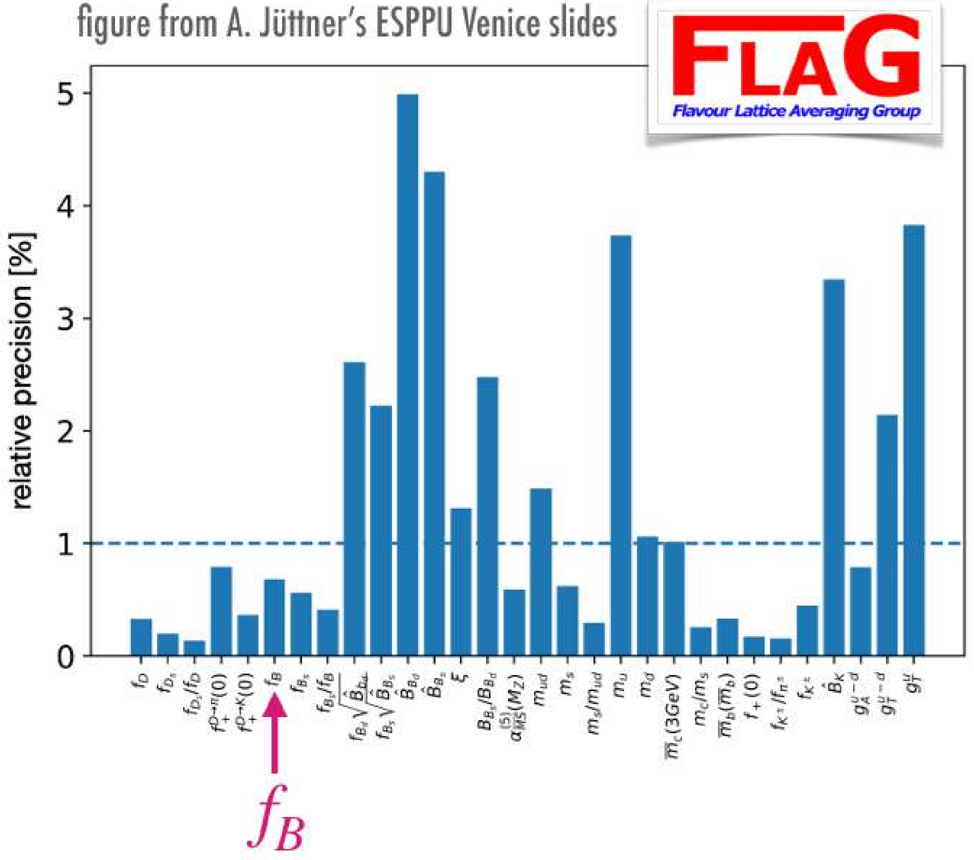


kinematics

$$\Gamma(B^- \to l^-\bar{\nu}) = \frac{m_B}{8\pi}\left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 \; |V_{ub}|^2 G_F^2$$

Under the assumption that this is dominated by SM, can then compare with measured decay rate to extract V_{ub}

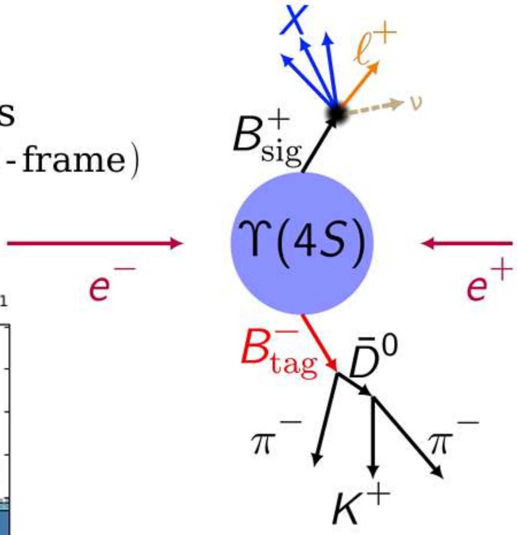
figure from A. Jüttner's ESPPU Venice slides

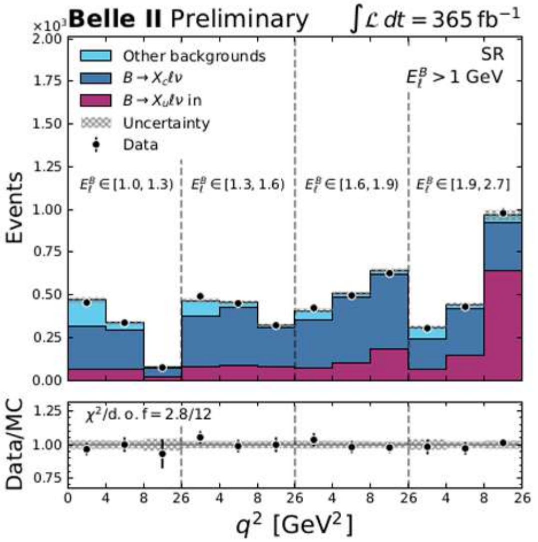


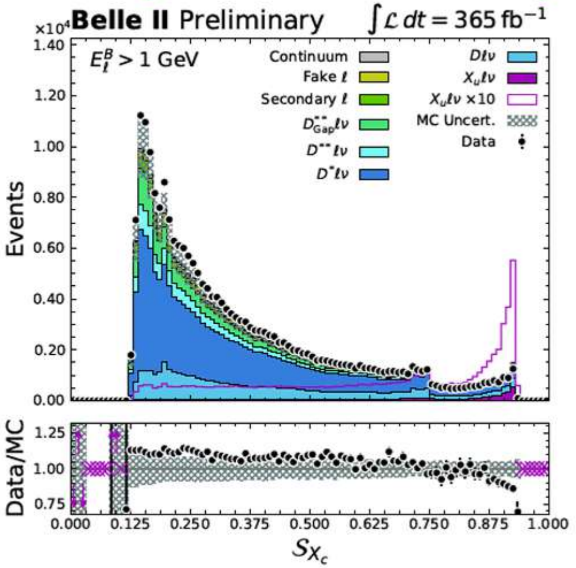
$|V_{ub}|$ from inclusive $B \to X_u l \nu$ decays (had tag)

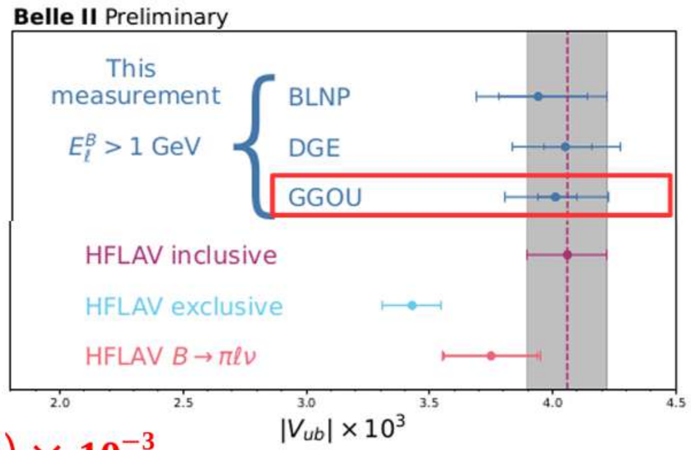
[PRELIMINARY]

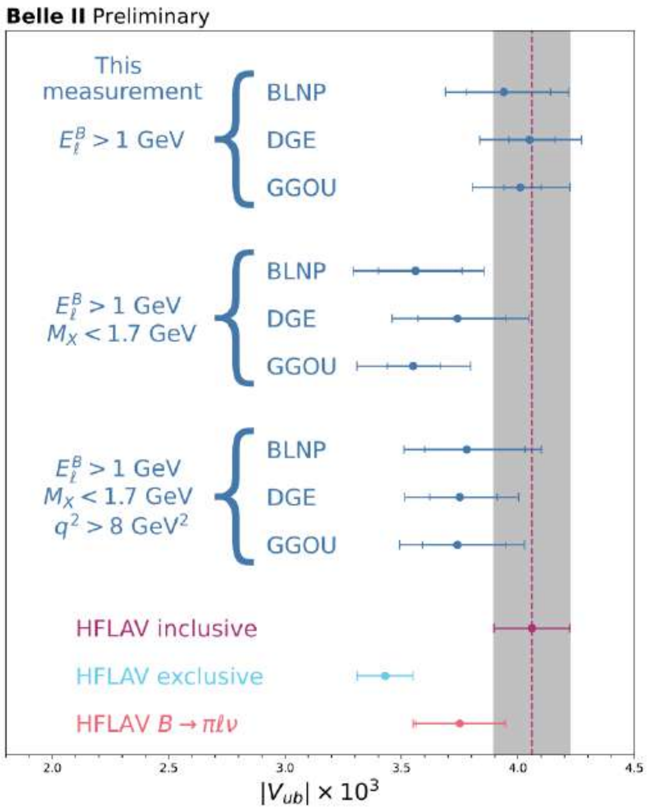
- First Belle II measurement
- Hadronic B-tagging
- 3 main kinematical variables
  - $E_l^{(B)}$: lepton energy (in B_{sig} rest-frame)
  - M_X: mass of hadronic system
  - q^2: momentum transfer











Extract $|V_{ub}|$ from partial BR using the predicted partial decay rate over a given phase-space region

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell \nu)}{\tau_B \Delta\Gamma(B \to X_u \ell \nu)}}$$

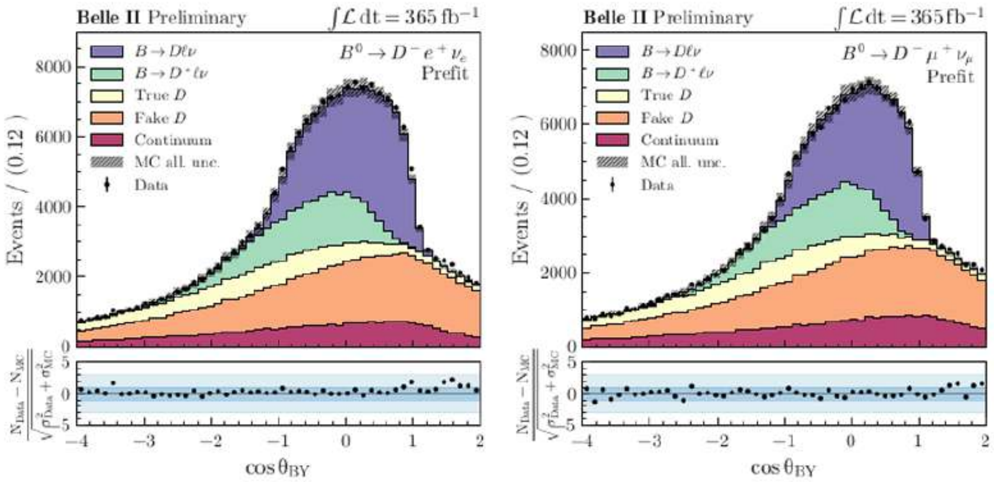
$$|V_{ub}|_{GGOU} = (4.01 \pm 0.11(\text{stat}) \pm 0.16(\text{syst})\, ^{+0.09}_{-0.07}(\text{theo})) \times 10^{-3}$$

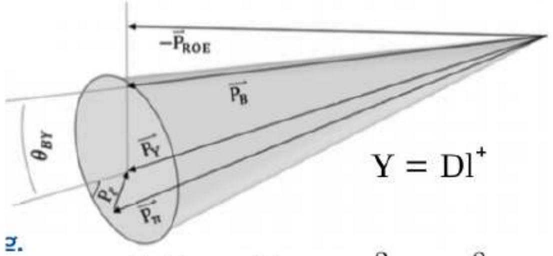
$$|V_{ub}|^{HFLAV}_{incl} = (4.06 \pm 0.16) \times 10^{-3}$$

$|V_{cb}|$ from $B \to D l \nu$

[arXiv:2506.15256]

- $B^0 \to D^- l^+ \nu$ and $B^+ \to \overline{D}^0 l^+ \nu$, with $l\,(e, \mu)$ and $D \to K\pi(\pi)$
- smaller BF than $D^* l \nu$, significant background
- described by single form factor $f_+(q^2)$, no soft pion rec.
- inclusive tag side





$$\cos\theta_{BY} = \frac{2E_{\mathrm{Beam}}E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$

Simultaneous maximum likelihood fit to 10 bins (w) of $\cos\theta_{BY}$

$$w = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}$$

$$\frac{d\Gamma(B \to D\ell\nu_\ell)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2(w^2-1)^{3/2}\,\eta_{EW}^2(1+\delta_C^{+,0})\mathcal{G}^2(w)|V_{cb}|^2\,,$$

$$\mathcal{G}^2(w) = \frac{4r}{(1+r)^2} f_+^2(w)$$

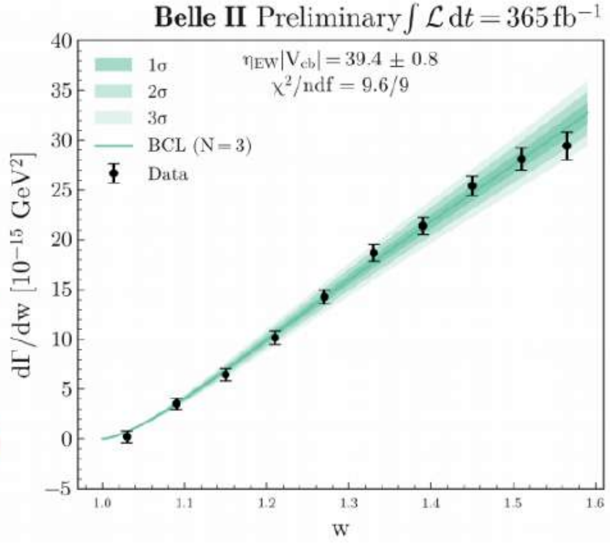
$|V_{cb}|$ extraction:

Fit differential decay rates using Bourrely-Caprini-Lellouch (BCL) parameterization of form factor

$|V_{cb}|_{BCL} = (39.2 \pm 0.4(\mathrm{stat}) \pm 0.6(\mathrm{syst}) \pm 0.5(\mathrm{theo})) \times 10^{-3}$

Most precise measurement to date using $B \to Dl\nu$ decays (2.3 % precision, even more precise than our $|V_{cb}|$ with $D^* l \nu$)

$$|V_{cb}|_{\mathrm{CLN}} = (38.5 \pm 1.3) \times 10^{-3}$$



$$\mathcal{B}(B^0 \to D^-\ell^+\nu_\ell) = (2.06 \pm 0.05\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{sys.}))\%$$
$$\mathcal{B}(B^+ \to \bar{D}^0\ell^+\nu_\ell) = (2.31 \pm 0.04\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{sys.}))\%$$

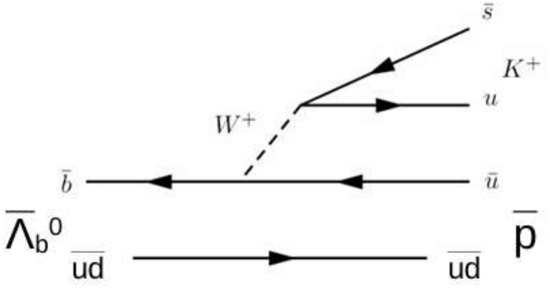
We also probe lepton flavor universality in the $b \to c$ weak transition and determine

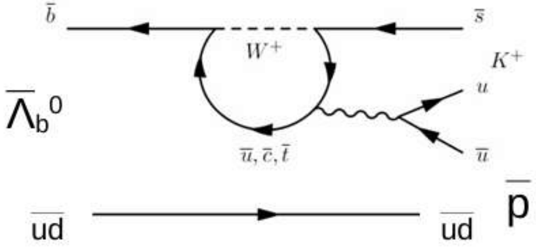
$$\mathcal{B}(B \to De\nu_e)/\mathcal{B}(B \to D\mu\nu_\mu) = 1.020 \pm 0.020\,(\mathrm{stat.}) \pm 0.022\,(\mathrm{sys.})$$

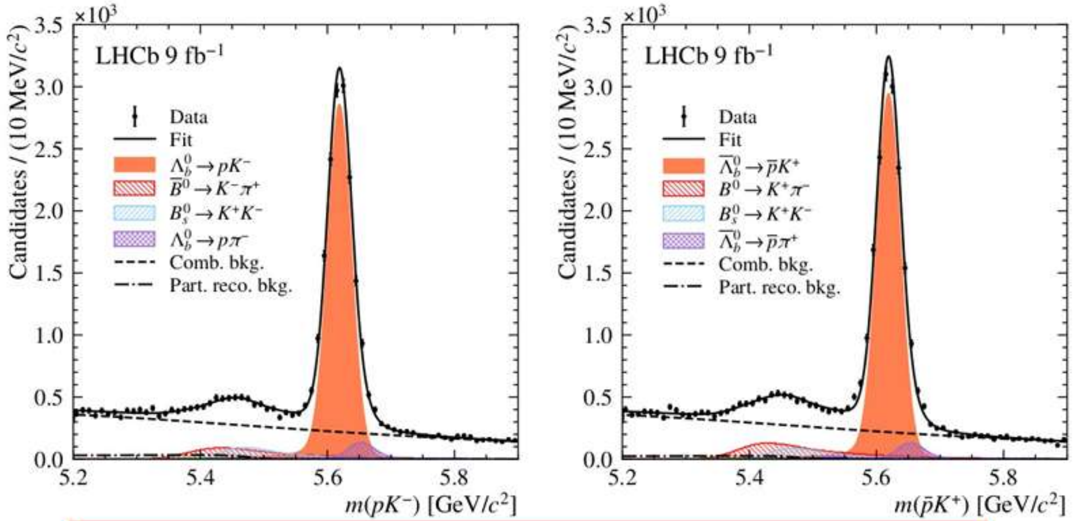
Прямое нарушение CP

- Caused by interference between two amplitudes with different weak (CP violating) and strong (CP conserving) phases
- Often realised by “tree” and “penguin” diagrams
  - e.g. for $B^0 \to K^+\pi^-$
  - so why not for $\overline{\Lambda}_b^0 \to \overline{p}K^+$?

PR D111 (2025) 092004







Relative weak phase ~ $\arg(-V_{ub}^* V_{us}/(V_{tb}^* V_{ts}))$ ~ γ

$A_{CP}(\overline{\Lambda}_b^0 \to \overline{p}K^+) = (-1.1 \pm 0.7 \pm 0.4)\%$

9

Results account for small corrections due to production & detection asymmetries

$$A_{CP}^{ph^-} = A_{\text{raw}}^{ph^-} - A_{\text{D}}^{p} - A_{\text{D}}^{h^-} - A_{\text{PID}}^{ph^-} - A_{\text{T}}^{ph^-} - A_{\text{P}}^{\Lambda_b^0}$$

$$A_{CP}^{p\pi^-} = (\ \ 0.2 \pm 0.8 \pm 0.4)\%$$

Observation of CP violation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays

arXiv:2503.16954
to appear in Nature

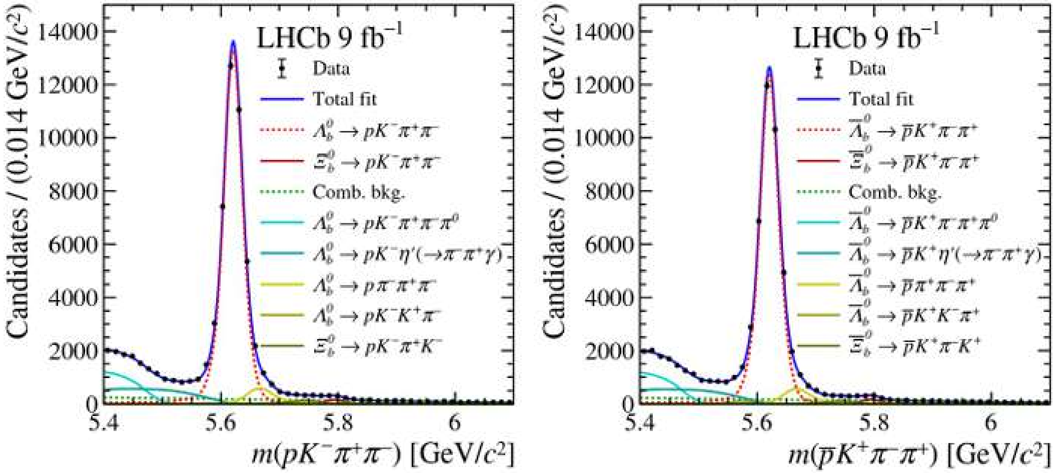
- Large samples of charmless 4-body Λ_b^0 decays available
- Use $\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-$ as reference channel

$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$ 5.2σ from zero

Enhanced CP violation effects appear in localised regions of phase space

- Largest for $m(p\pi^+\pi^-) < 2.7\ \mathrm{GeV}/c^2$

$$A_{CP} = (5.4 \pm 0.9 \pm 0.1)\%$$



Significant milestone in CP violation history!

But, theoretical predictions for CP asymmetries, integrated over multiple resonances, are extremely challenging
Important next step: amplitude analysis to associate effects to resonances including interference effects

CPV in isospin-related $D^{0,+} \to \pi^{0,+} \pi^0$ modes

Sum-rule for CPV in $D \to \pi\pi$, to determine the source of CPV:

$$R = \frac{A^{\rm dir}_{CP}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A^{\rm dir}_{CP}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A^{\rm dir}_{CP}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}$$

if $R \neq 0$, CPV from $\Delta I = 1/2$ amplitude; if $R = 0$ and at least one $A^{\rm dir}_{CP} \neq 0$, CPV from beyond SM $\Delta I = 3/2$ amplitude

Raw asymmetry of $D^0 \to \pi^0 \pi^0$ using tagged events (D^{*+}) [arXiv:2505.02912]

$$A^{\pi^0\pi^0} = A_{CP}(D^0 \to \pi^0\pi^0) + A_{\rm P}^{D^{*+}} + A_{\epsilon}^{\pi_s}$$

$A_{\rm P}^{D^{*+}}$: forward-backward asymmetric production of D^{*+} in $e^+e^- \to c\bar{c}$ events

$A_{\epsilon}^{\pi_s}$: charge asymmetry in detection efficiency

$$A_{CP}(D^0 \to \pi^0\pi^0) = A^{\pi^0\pi^0}_{\rm avg} - A^{K\pi}_{\rm avg} + A^{K\pi,\,\rm untag}_{\rm avg}$$

$$A^f_{\rm avg} = (A^f(\cos\theta^* < 0) + A^f(\cos\theta^* > 0))/2$$

Belle II with 428 $\rm fb^{-1}$:

$$\boxed{\mathbf{A_{CP}(D \to \pi^0\pi^0) = (+0.30 \pm 0.72 \pm 0.20)\,\%}}$$

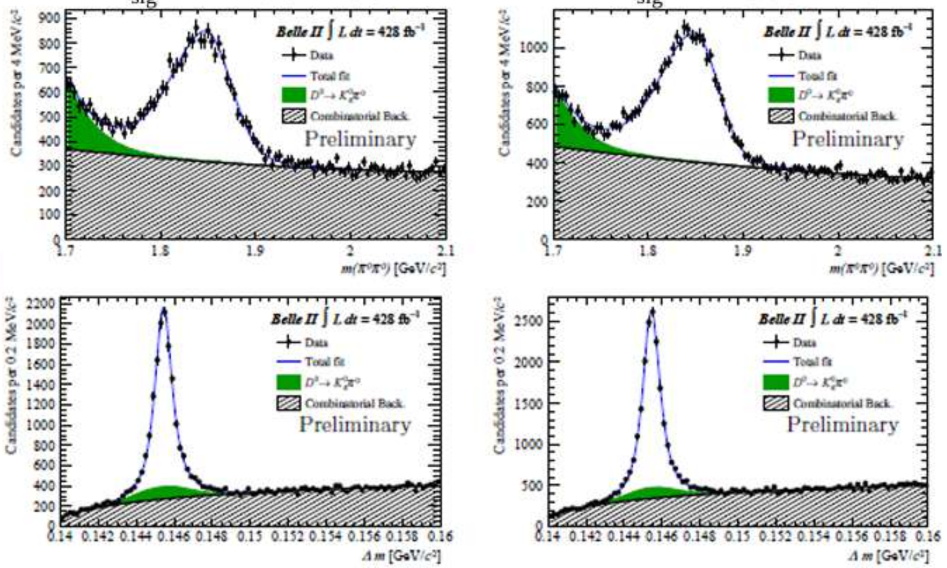
(Belle with 980 $\rm fb^{-1}$: $(-0.03 \pm 0.64 \pm 0.10)\%$)
[PRL 112 (2014) 211601]

$\Rightarrow$ **$R = (1.5 \pm 2.5) \times 10^{-3}$**

improve by ~20% w.r.t current HFLAV result

$\cos\theta^*(D^{*+}) > 0$ — $N_{\rm sig} = 14100 \pm 130$

$\cos\theta^*(D^{*+}) < 0$ — $N_{\rm sig} = 11550 \pm 110$

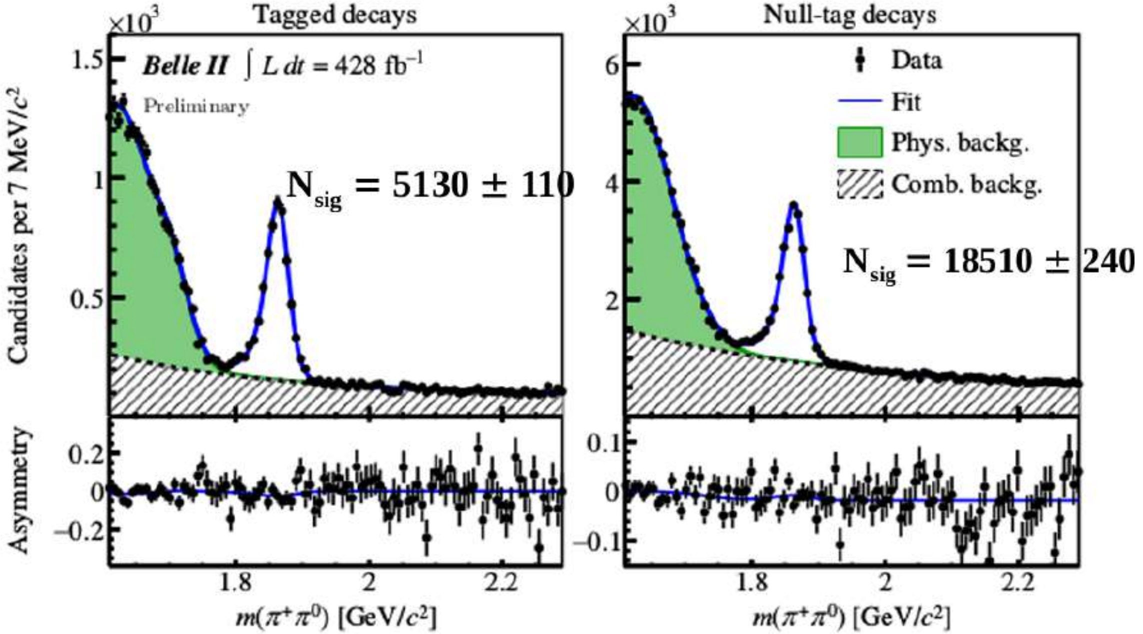


$A_{CP}(D^+ \to \pi^+ \pi^0)$ at Belle and Belle II [arXiv:2506.07879]

Split sample as tagged (from $D^{*+} \to D^+ \pi^0$) and not

Using $D^+ \to K^0_S \pi^+$ to eliminate common asymmetry sources: A^D_{prod} and $A^{\pi^+}_{\epsilon}$

$$A_{CP}^{\pi^+\pi^0} = A_{\rm raw}^{\pi^+\pi^0} - A_{\rm raw}^{K^0_S\pi^+} + A^{\overline{K}^0}$$



$A^{tag}_{CP} = (-3.9 \pm 1.8 \pm 0.2)\%$ $\quad$ $A^{null}_{CP} = (-1.1 \pm 1.0 \pm 0.1)\%$

Belle II combining A^{tag}_{CP} and A^{null}_{CP} with 428 fb^{-1}:

$$\boxed{A_{CP}(D \to \pi^+ \pi^0) = (-1.8 \pm 0.9 \pm 0.1)\%}$$

0 в SM

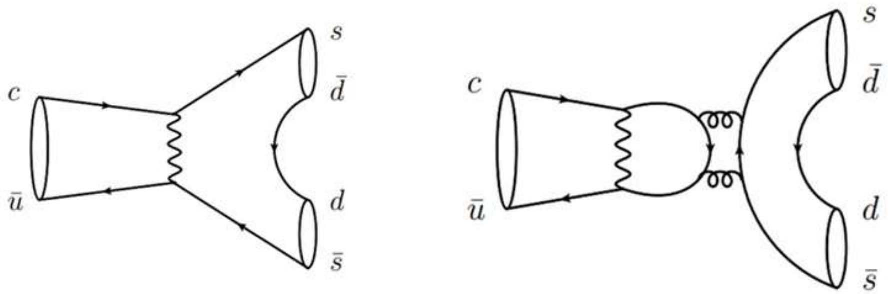
(Belle with 980 fb^{-1}: $(+2.31 \pm 1.24 \pm 0.23)\%$) [PRD 97 (2018) 011101]

improved by ~30 %, better purity achieved through an improved event selection thanks to Belle II's superior performance in reconstruction of neutral pions and displaced charged particles

$A_{CP}(D^0 \to K_S^0 K_S^0)$ measurement using D^{*+}-tagged sample

[arXiv:2411.00306 - PRD 111 (2025) 012015]

CPV in $D \to K_S^0 K_S^0$ enhanced to an observable level due to interference btw $c \to u s \bar{s}$ and $c \to u d \bar{d}$



$$A_{CP}(D^0 \to K_S^0 K_S^0) = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}.$$

Belle $(921\ \text{fb}^{-1})$: $(0.0 \pm 1.5 \pm 0.2)\%$
[PRL 119, 171801 (2017)]

LHCb $(6\ \text{fb}^{-1})$: $(-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$
[PRD 104, L031102 (2021)]

Unbinned fit to $(m(D^0 \pi_s), S_{min})$ of D^0 and $\bar{D}^0$ candidates for $D^0 \to K_S^0 K_S^0$

flight significance variable $S_{min} = \log(\min(L_i/\sigma_i))$: separate peaking background $D^0 \to K_S^0 \pi^+ \pi^-$

$$\mathbf{A_{CP}^{K_S^0 K_S^0} = (A_{raw}^{K_S^0 K_S^0} - A_{raw}^{K^+K^-}) + A_{CP}^{K^+K^-}}$$

$$A_{\text{raw}}^{K\bar{K}} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} = A_{\text{FB}}^{D^{*+}} + A_{CP}^{K\bar{K}} + A_{\varepsilon}^{\pi_s}$$

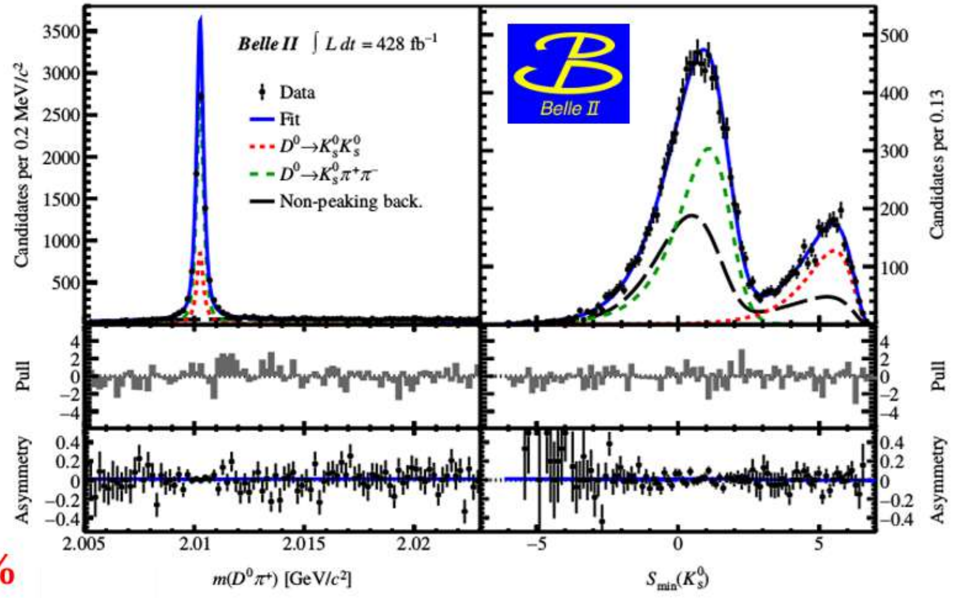
Control mode $D^0 \to K^+ K^-$:

$$A_{CP}^{K^+K^-} = A_{CP}^{dir} + \Delta Y = (6.7 \pm 5.4) \times 10^{-4}$$

Belle $(980\ \text{fb}^{-1})$: $(-1.1 \pm 1.6 \pm 0.1)\%$

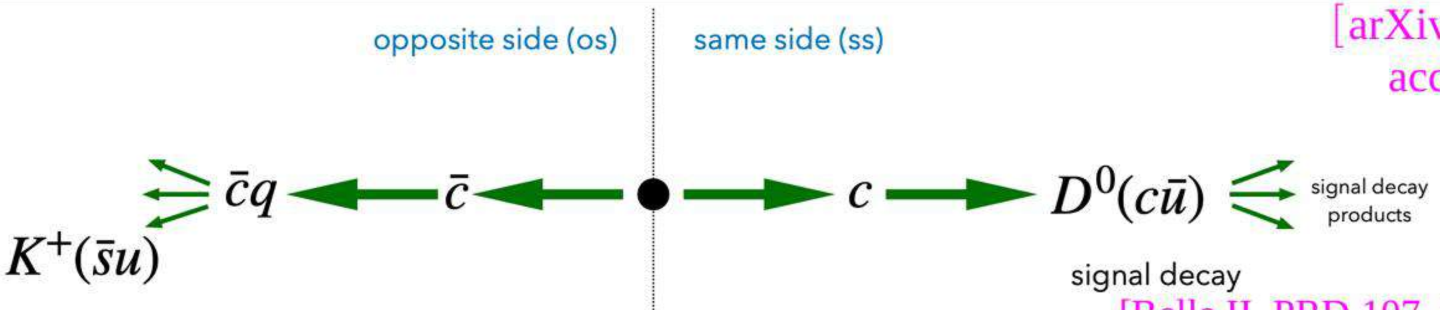
Belle II $(428\ \text{fb}^{-1})$: $(-2.2 \pm 2.3 \pm 0.1)\%$

$$\mathbf{A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.4 \pm 1.3 \pm 0.1)\%}$$



$A_{CP}(D^0 \to K_S^0 K_S^0)$ measurement using opposite-side flavor tagging

[arXiv: 2504.15881]
accepted PRD



[Belle II, PRD 107, 112010 (2023)]

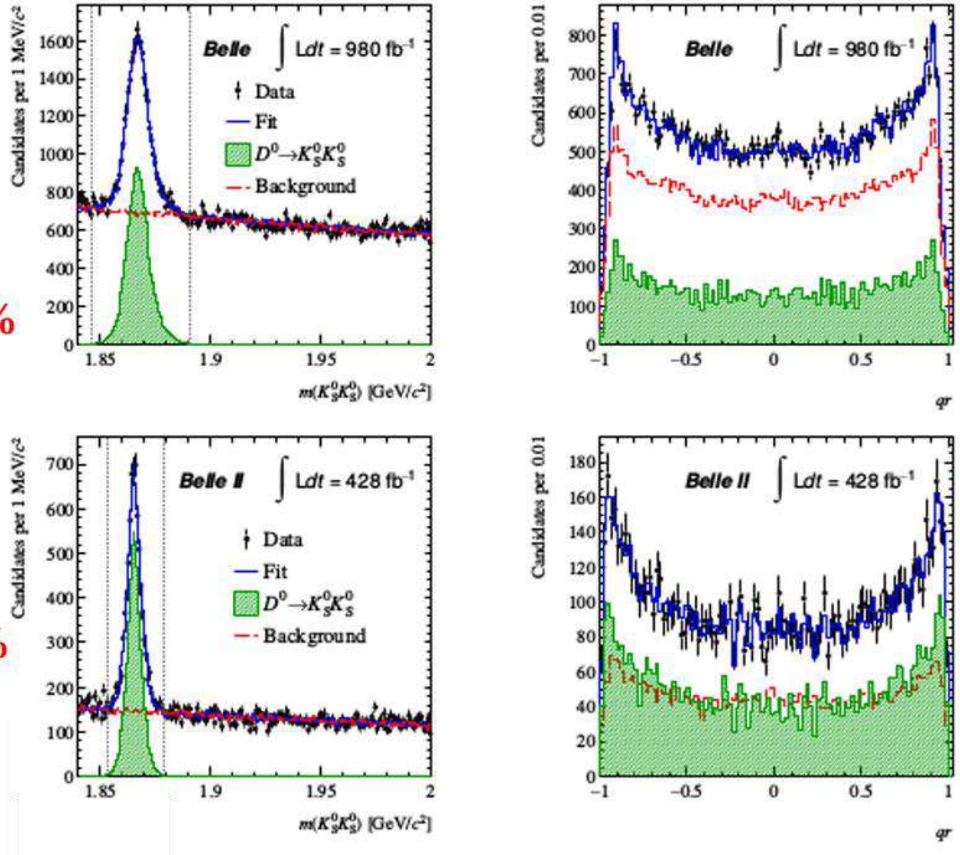
Candidates reconstructed in D^{*+}- tagged analysis are removed:

Belle (980 fb^{-1}): $(+2.5 \pm 2.7 \pm 0.4)\%$
Belle II (428 fb^{-1}): $(-0.1 \pm 3.0 \pm 0.3)\%$

$$A_{CP}(D^0 \to K_S^0 K_S^0) = (+1.3 \pm 2.0 \pm 0.2)\%$$

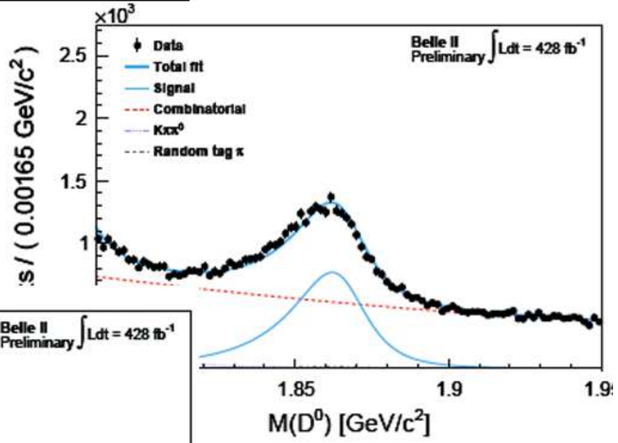
Final result (Belle + Belle II: 1.4 ab^{-1}) with two flavor tagging methods:

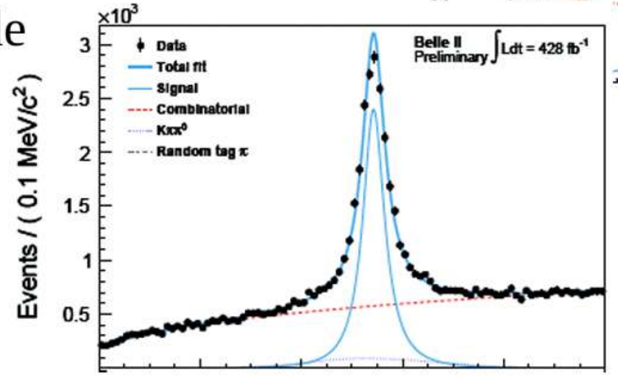
$$A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.6 \pm 1.1 \pm 0.1)\%$$

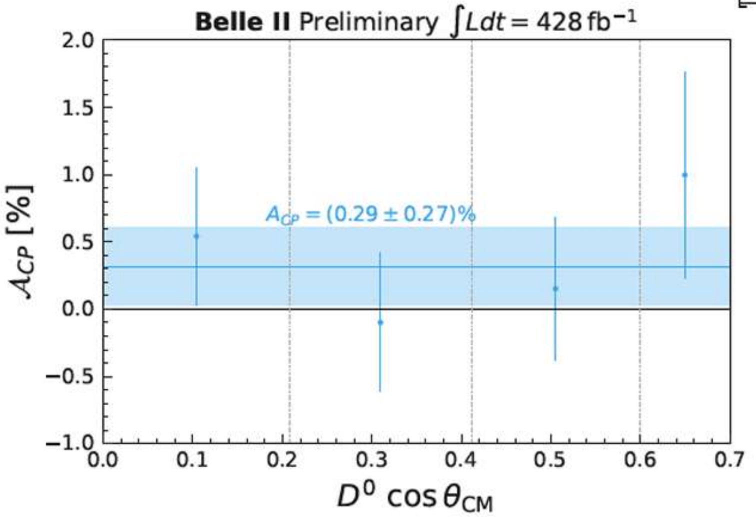


A_{CP} in $D \to \pi^+ \pi^- \pi^0$ with Belle II [PRELIMINARY]

- D^0 flavor tagged through $D^{*+} \to D^0 \pi^+$
- signl extraction with 2D fit in M_D and ΔM
- Split in 8 symmetric bins of $\cos\theta_{CM}$ to correct production asymmetry
- $D^0 \to K^- \pi^+$ as reference mode







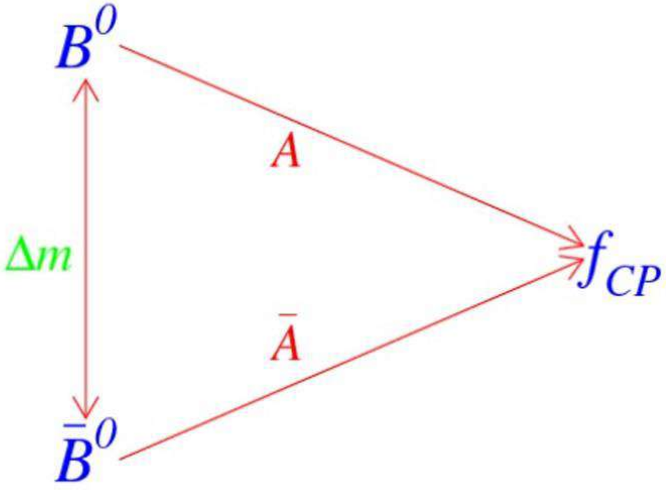
$$A_{CP} = (0.29 \pm 0.27 \pm 0.13)\,\%$$

- No asymmetry
- Compatible with previous measurements [Belle, BaBar]
- 34% improvement (stat) w.r.t world's best (BaBar)

CPV в смешивании мезонов

- For a B meson known to be B^0 or $\overline{B}^0$ at time t=0, then the rate to decay to a CP eigenstate f_{CP} at later time t is:

$$\Gamma\left(B^0_{phys} \rightarrow f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1-\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$
$$\Gamma\left(\overline{B}^0_{phys} \rightarrow f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1+\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$



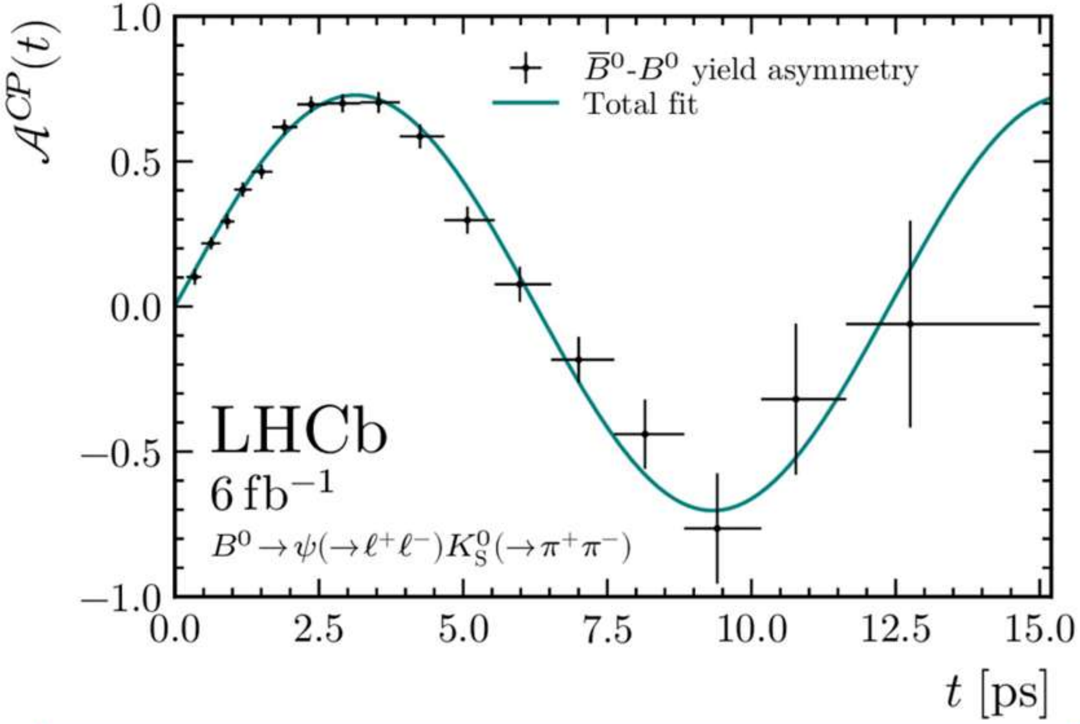
- If a single amplitude dominates, then $|\overline{A}/A|=1$ and C=0 (no CP violation in decay)
- For $B^0 \rightarrow J/\psi K_S$, if dominated by $V_{cb}V_{cs}^*$ amplitude, S = sin(2β)
- Possible subdominant penguin “pollution” → theoretical uncertainty in interpretation

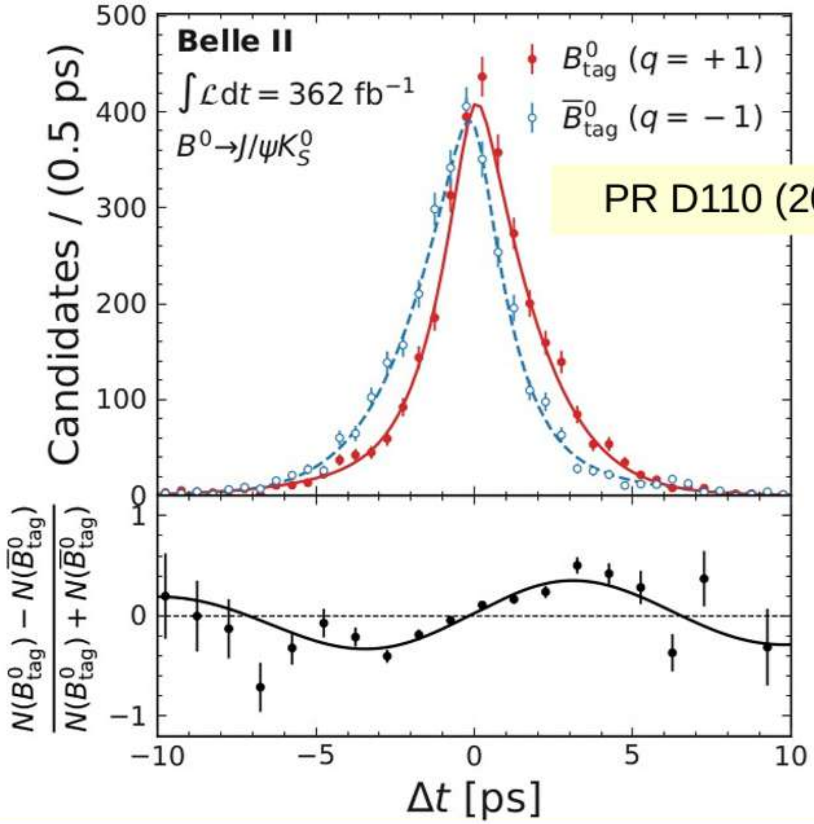
$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

Latest measurements of sin(2β)

Flavour-tagging corrected asymmetry

PRL 132 (2024) 021801





PR D110 (2024) 012001

$S(B^0 \to J/\psi K_S) = 0.722 \pm 0.014 \pm 0.007$

$S(B^0 \to J/\psi K_S) = 0.724 \pm 0.035 \pm 0.009$

Signal yield ~ 350,000
Tagging power ~ 4%

Signal yield ~ 6,400
Tagging power ~ 37%

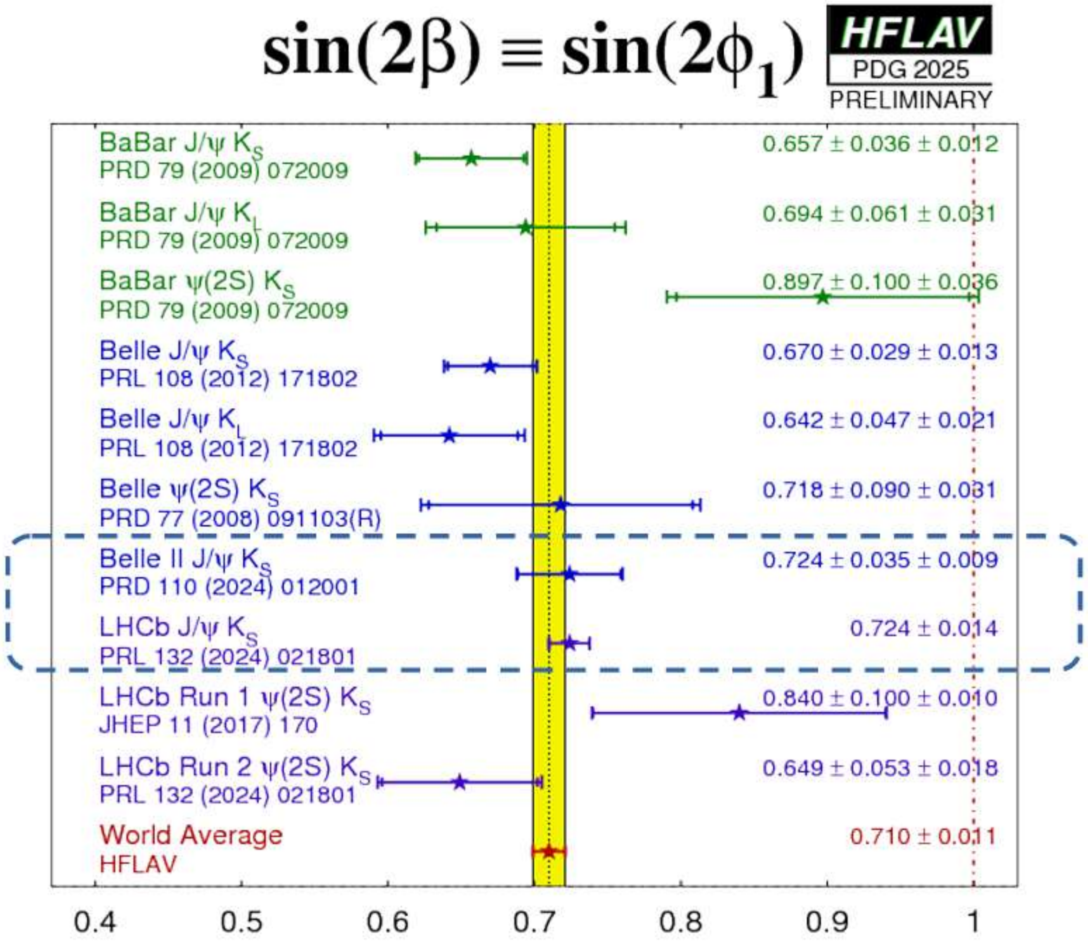
$S(B^0 \to J/\psi K_S)$ world average

- HFLAV average:

  $$S(B^0 \to J/\psi K_S) = 0.712 \pm 0.011$$

  0.710 ± 0.011 including all $b \to c\bar{c}s$

- Is it still safe to interpret this as $\sin(2\beta)$?
  – Or have we entered the realm of penguin pollution?
- Exploit flavour symmetries in $B \to J/\psi P$ ($P = K, \pi$) to test
  – See e.g. arXiv:2506.21675, arXiv:2505.06102



Results from previous slide

14

Загрязнение пингвинами ?

- Analysis of arXiv:2506.21675 combines 16 observables from $B_{u,d,s} \to J/\psi\, P$ ($P=K,\pi$) decays using flavour symmetry relations
  - 6 branching fractions
  - 6 parameters of CP violation in decay
  - 4 parameters of CP violation in mixing-decay interference
    - for $B_s \to J/\psi\pi^0$, only a branching fraction upper limit exists

Similar analysis done in arXiv:2505.06102 and other works

- Result:
  - $S(B^0 \to J/\psi K_S) - \sin(2\beta) = +0.001 \pm 0.015$

    c.f. experimental world average $S(B^0 \to J/\psi K_S) = 0.712 \pm 0.011$

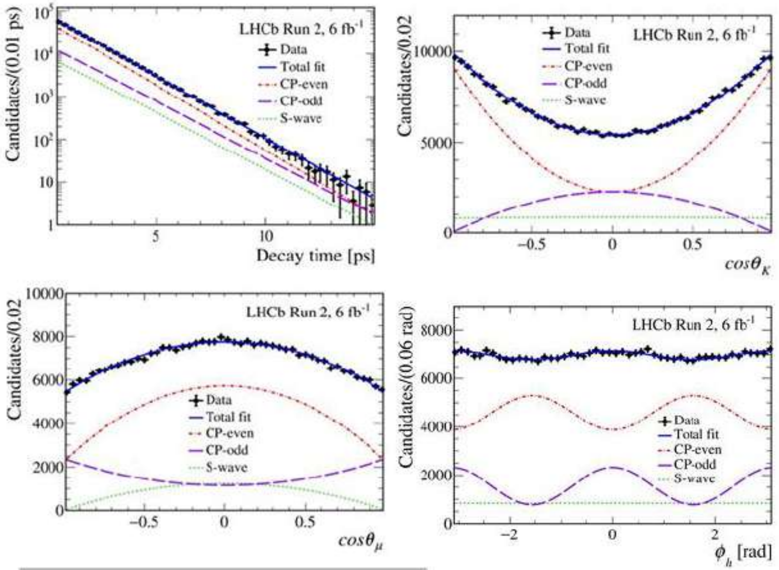
    - precision can be improved with new measurements of $S(B_s^0 \to J/\psi K_S)$

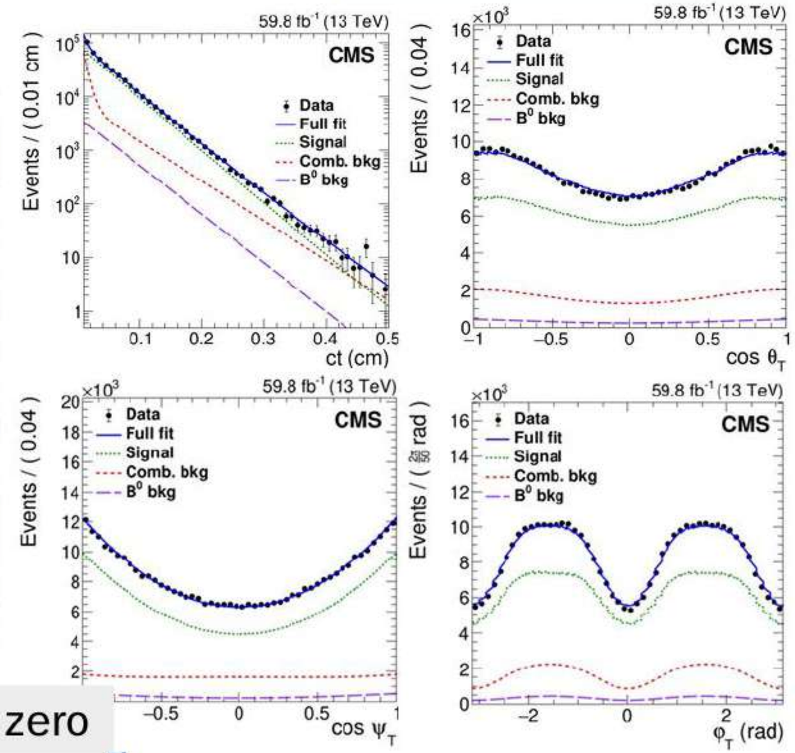
Latest results on $\varphi_s(B_s \to J/\psi\varphi)$

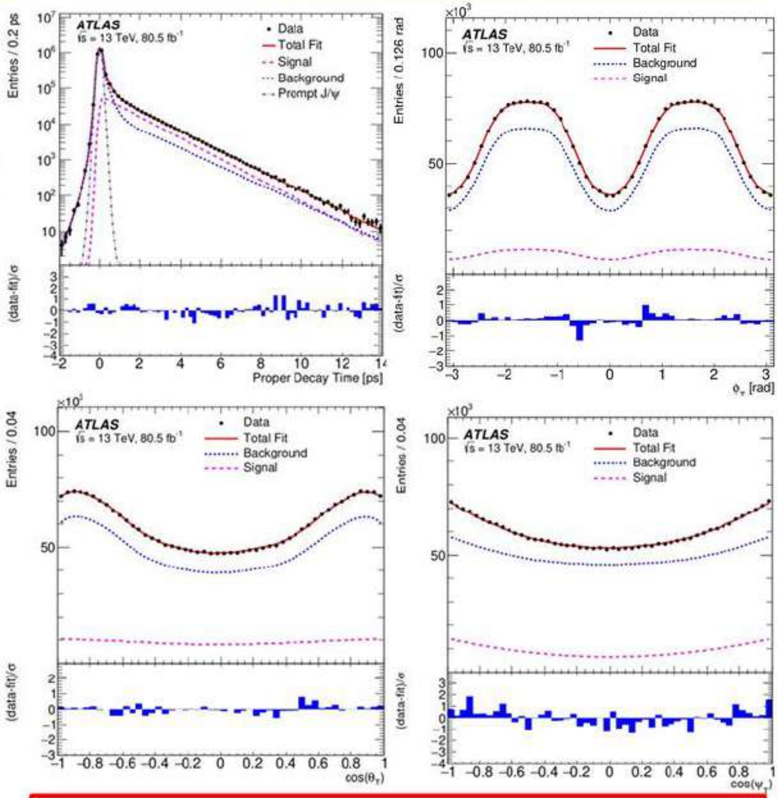
PRL 132 (2024) 051802

arXiv:2412.19952

EPJ C81 (2021) 342







Equality in absence of penguin pollution

3.2σ from zero

$\phi_s = -2\beta_s = -39 \pm 22 \pm 6$ mrad

$\phi_s = -2\beta_s = -73 \pm 23 \pm 7$ mrad

$\phi_s = -2\beta_s = -87 \pm 36 \pm 21$ mrad

Signal yield ~ 350,000
Tagging power ~ 4.3%

Signal yield ~ 490,000
Tagging power ~ 5.6%

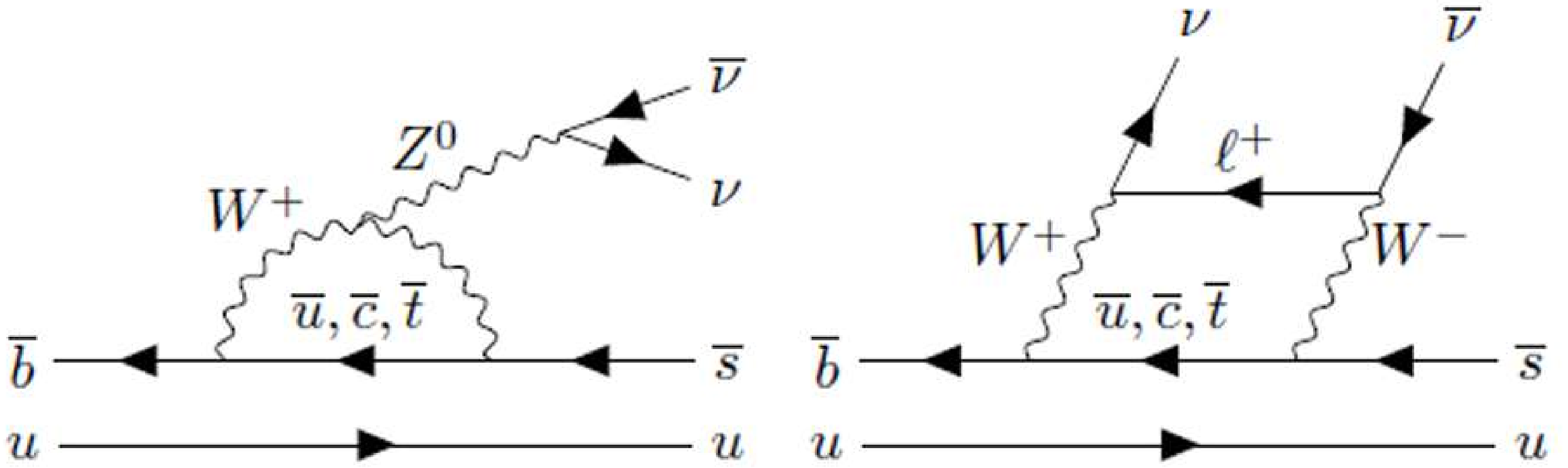
Signal candidates ~ 450,000
Tagging power ~ 1.8%

$$\beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

Редкие распады

New particles can for example contribute to loop or tree level diagrams **by enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles**

$B \rightarrow K \nu \bar{\nu}$

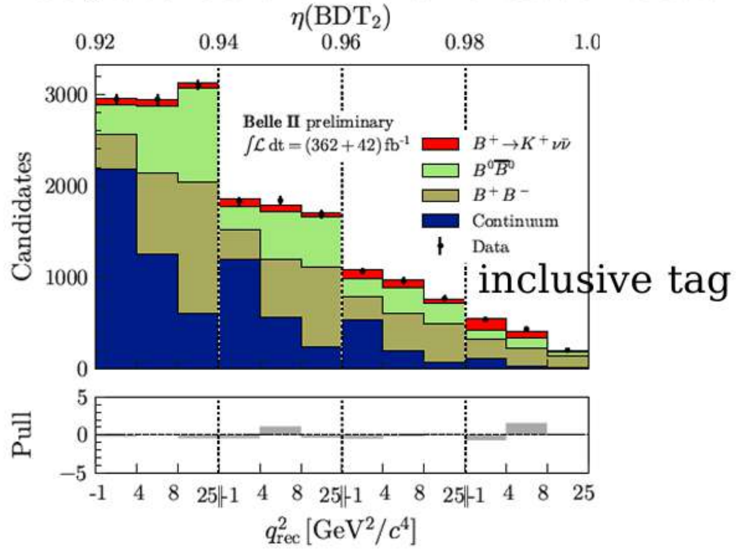


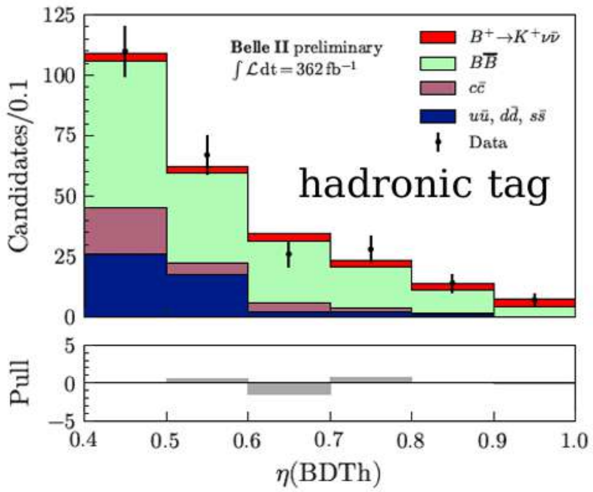
- $B \rightarrow K \nu \nu$ is known with high accuracy
  $B(B \rightarrow K \nu \nu) = (5.6 \pm 0.4) \times 10^{-6}$ [arXiv:2207.13371]
- Extensions beyond SM may lead to significant rate increase

Evidence of $B \to K \nu \bar{\nu}$

[arXiv:2311.14647]
PRD 109, 112006 (2024)

- Two analyses: more sensitive **inclusive** (eff = 8%), conventional **hadronic** tagging (eff = 0.4%)
- Use event properties to suppress background with multiple variables combined
- Use classifier output as (one of) the fit variables, use simulation for signal and background templates
- Use multiple control channels to validate simulation with data





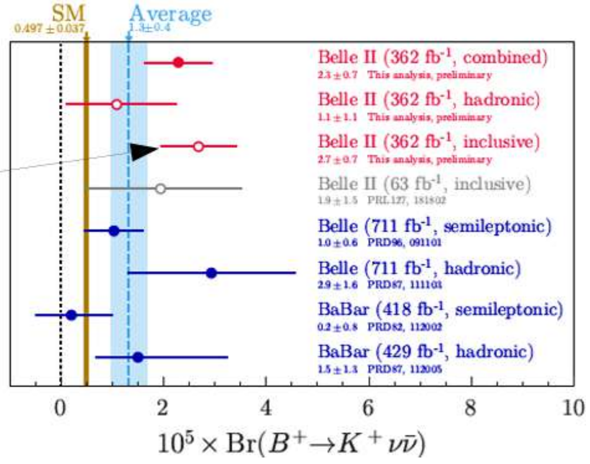
- Max. likelihood fit to data using signal and bckg templates

$B_{incl} = (2.7 \pm 0.5\,(stat) \pm 0.5\,(syst)) \times 10^{-5}$

$B_{had} = (1.1\,^{+0.9}_{-0.8}\,(stat)\,^{+0.8}_{-0.5}\,(syst)) \times 10^{-5}$

- For inclusive analysis, evidence for $B \to K \nu \bar{\nu}$ at 3.5σ branching fraction within 3σ of SM
- For hadronic tag, the result is consistent with null hypothesis and SM at $1.1\,\sigma$ and $0.6\,\sigma$

$\Rightarrow$ Combination of two analyses provides first evidence of the decay at $2.7\,\sigma$ from SM

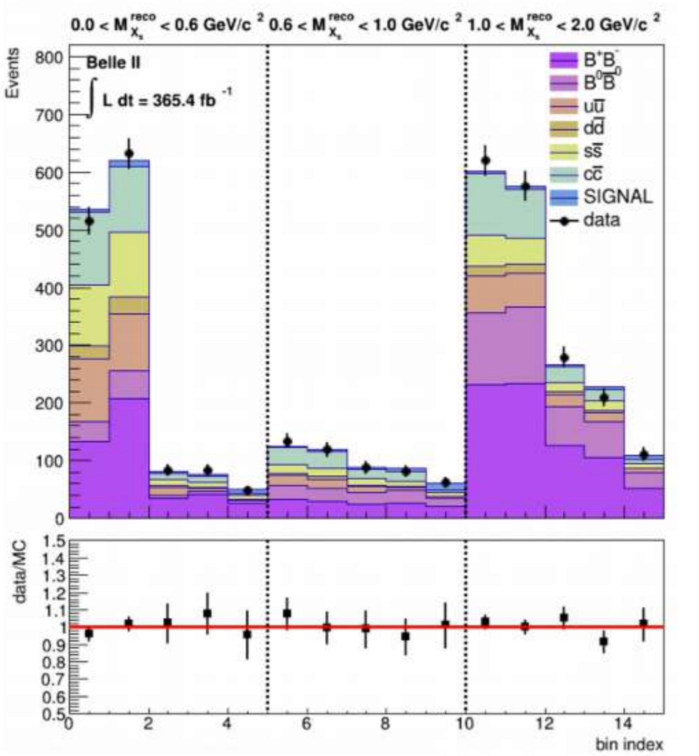


Search for $B \to X_s \nu \bar{\nu}$ decays [PRELIMINARY]

- $B_{SM} = (2.9 \pm 0.3) \times 10^{-5}$ [JHEP 02 (2015) 184]
- $B < 6.4 \times 10^{-4}$ at 90% C.L. [ALEPH, EPJC 19 (2001) 213]
- using Belle II sample of 362 fb^{-1}
- Hadronic B-tagging
- Sum-of-exclusive from 30 decay modes (~90% of inclusive)

	$B^0\bar{B}^0$			$B^\pm$		
K	K_S^0			$K^\pm$		
$K\pi$	$K^\pm\pi^\mp$	$K_S^0\pi^0$		$K^\pm\pi^0$	$K_S^0\pi^\pm$	
$K2\pi$	$K^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp$	$K_S^0\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0$	$K^\pm\pi^0\pi^0$
$K3\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0$	$K^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0\pi^0$
$K4\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0\pi^0$
$3K$	$K^\pm K^\mp K_S^0$			$K^\pm K^\mp K^\pm$		
$3K\pi$	$K^\pm K^\mp K^\pm\pi^\mp$	$K^\pm K^\mp K_S^0\pi^0$		$K^\pm K^\mp K^\pm\pi^0$	$K_S^0 K^\pm K^\mp\pi^\pm$	

- For background suppression, use BDT (include sum of remaining energy in ECL)
- signal extraction in (BDT output) $\times$ M_{X_s} plane



$$B(B \to X_s \nu \bar{\nu}) < \begin{cases} 2.5 \times 10^{-5} \ (0.0 < M_{X_s} < 0.6 \text{ GeV}/c^2) \\ 1.0 \times 10^{-4} \ (0.6 < M_{X_s} < 1.0 \text{ GeV}/c^2) \\ 3.5 \times 10^{-4} \ (1.0 < M_{X_s}) \end{cases}$$

$B(B \to X_s \nu \bar{\nu}) < 3.6 \times 10^{-4}$ at 90% C.L.

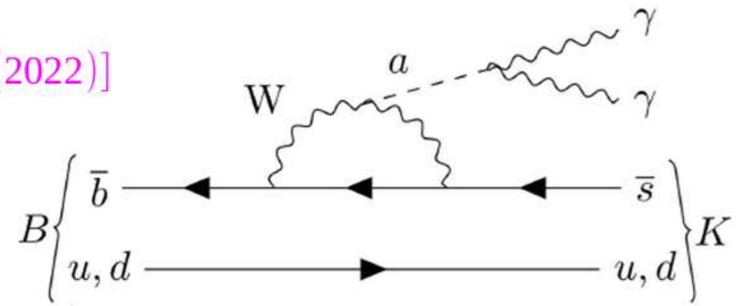
$\Rightarrow$ The most stringent upper limit on $B \to X_s \nu \bar{\nu}$ decay

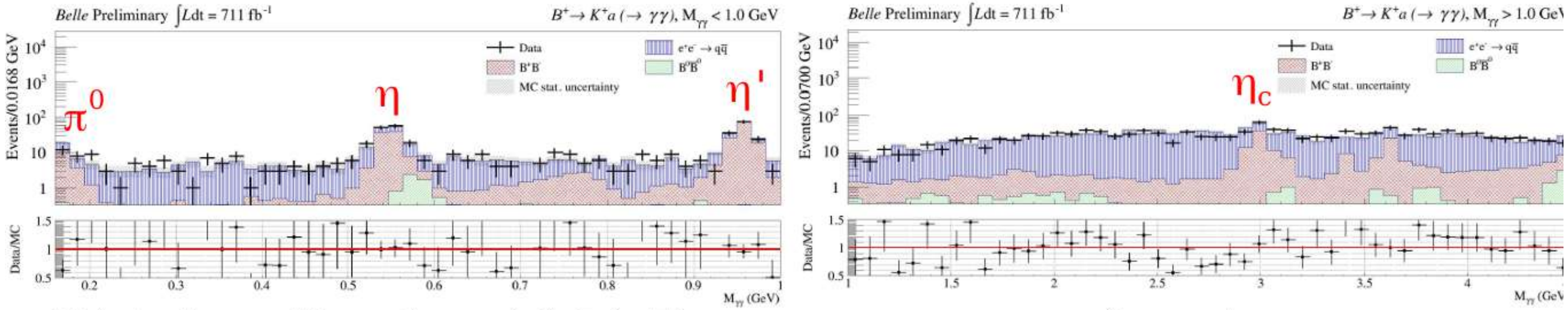
Search for $B \to K^{(*)} a(\to \gamma\gamma)$

[arXiv:2507.01249]
submitted to JHEP

- Search for an ALP in the MeV-GeV scale
- Previous result on $B^+ \to K^+ a$ [BaBar, PRL 128, 131802 (2022)]

- using Belle sample ($711\ \mathrm{fb}^{-1}$)
- four kaon modes included: K^0_S, K^+, K^{*+}, K^{*0}
- $\mathcal{B}(a \to \gamma\gamma) \sim 100\%$ when $m_a \ll m_{W^+}$
- m_a investigated from 160 MeV/c^2 to the kinematic end-point



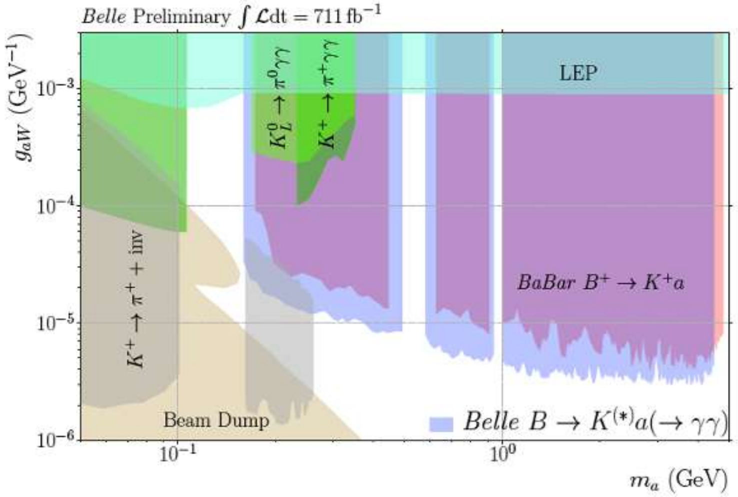


- Main background is continuum ($e^+e^- \to q\bar{q}$)
  rejected with BDTs based on kinematics and topology variables

- fit di-photon invariant mass to extract signal yield
- Peaking background regions vetoes (π^0, η, η')
- $B \to K\eta, K\eta'$ as validation modes

For each ALP mass hypothesis, simultaneous fit performed on four kaon modes to obtain the coupling constant g_{aW}

⇒ improved at least by factor 2 from BaBar

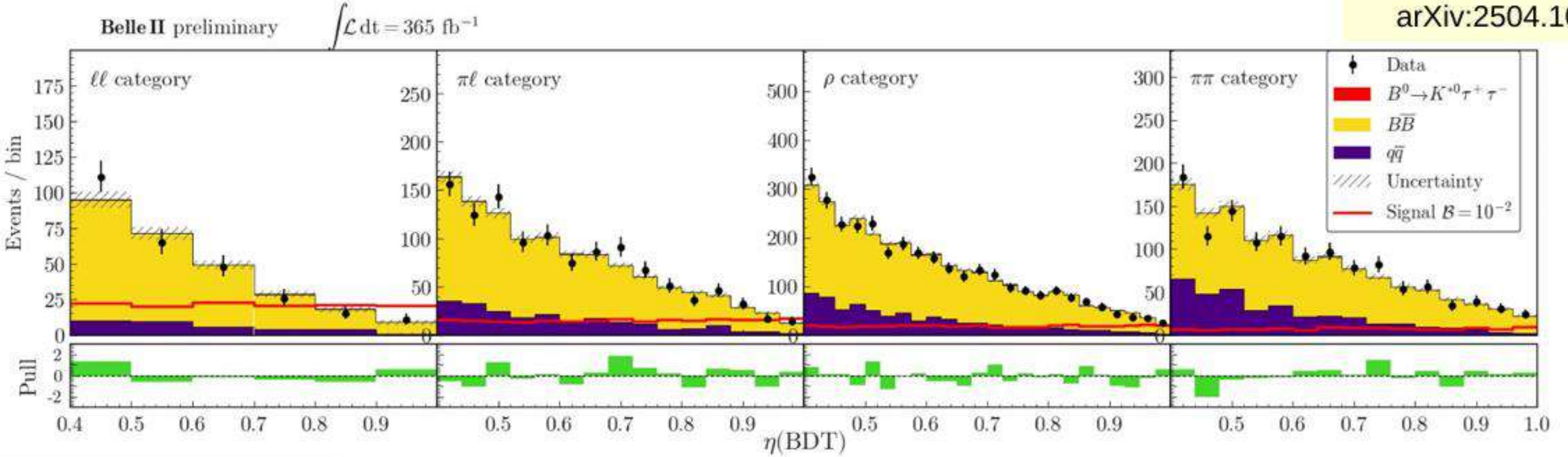


$B^0 \to K^{*0}\tau^+\tau^-$

[Not fundamentally cleaner theoretically, but BSM effects may be larger for heavier leptons]

- Experimentally highly challenging due to missing ν from τ decays & background from $D_{(s)}$ decays
- Exploit kinematic constraints in $e^+e^- \to B_{sig}B_{tag}$, with B_{tag} reconstructed in hadronic decay modes
- Signal-background separation through BDT, separately for different τ final states

arXiv:2504.10042



LHCb amplitude fit of $B^0 \to K^{*0}\mu^+\mu^-$ gives a limit
$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ at 90% CL
JHEP 09 (2024) 026

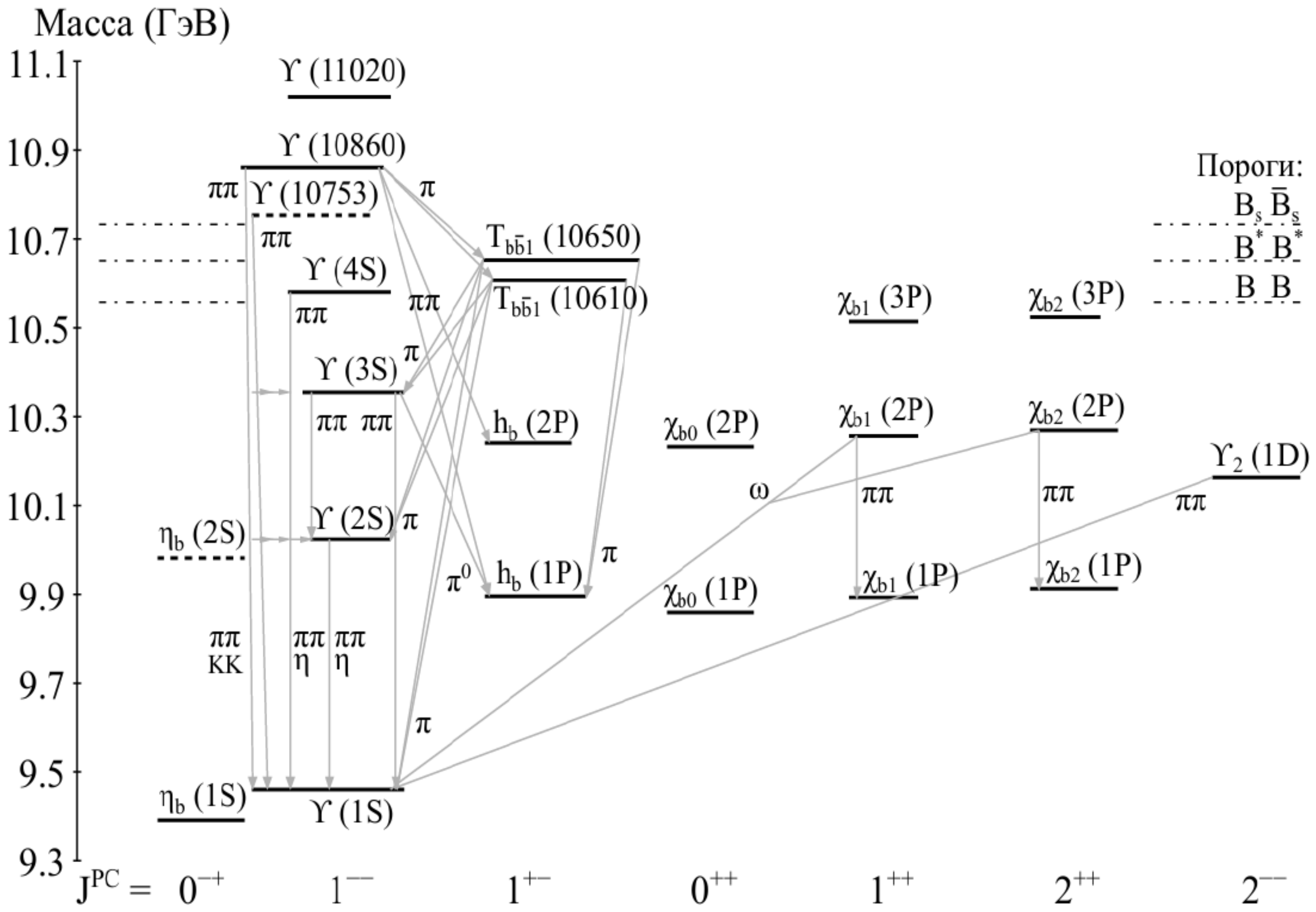
$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$ at 90% CL

SM prediction $O(10^{-7})$

Заключение

- Огромное количество усилий прикладывается к физике ароматов тяжелых кварков:
  - Прямое CPV: обнаружено в Λ_b, активно измеряется для D-мезонов
  - Измерение СКМ: прямое и через time-dependent CPV
  - Редкие распады B-мезонов
- Большой потенциал для поиска эффектов Новой физики при увеличении объема данных Belle II и LHCb

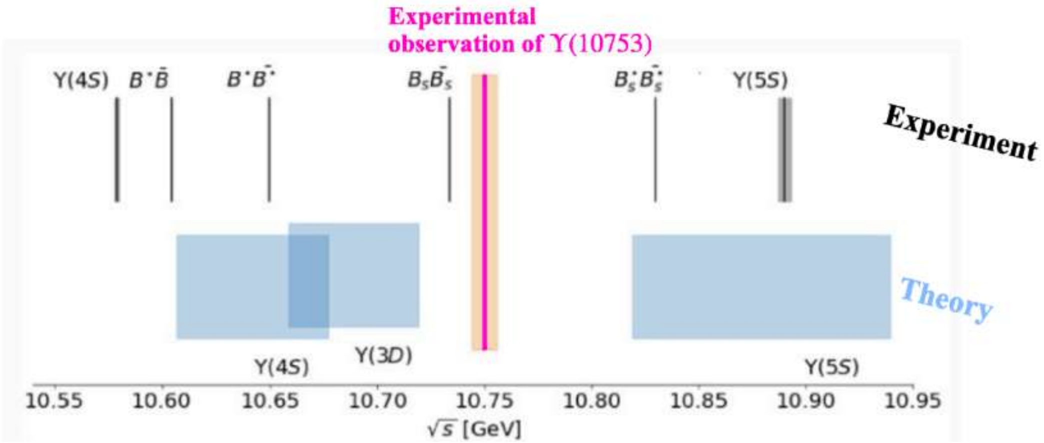
Семейство боттомония



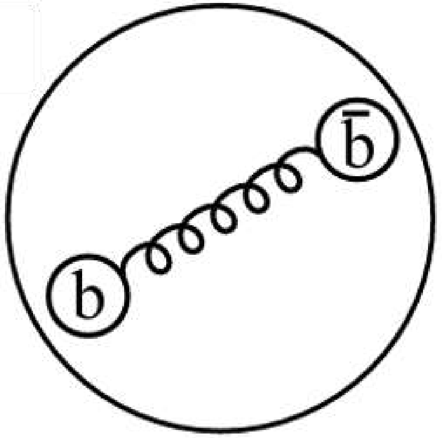
Спектр мезонов с $b\bar{b}$ парой и измеренные адронные переходы

Связанное состояние $b\bar{b}$

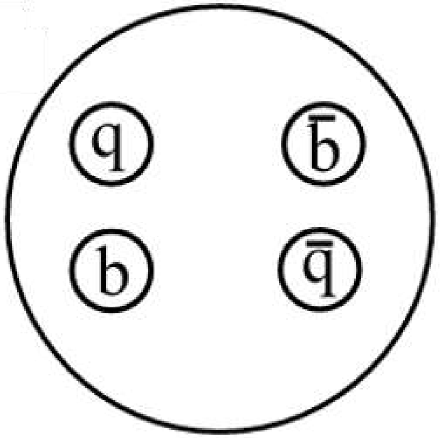
- Свойства ниже $B\bar{B}$ порога согласуются с ожидаемыми
- Выше $B\bar{B}$ - аномальные вероятности переходов с $\pi\pi, \eta^{(\prime)}$
- В $\pi\pi$ переходах обнаружены тетракварки $Z_b(10610, 10650)$ $(T_{b\bar{b}1})$ с $I^G(J^{PC}) = 1^+(1^{+-})$ и
  $Y(10753)$ — $Y(3D)$ или экзотика?



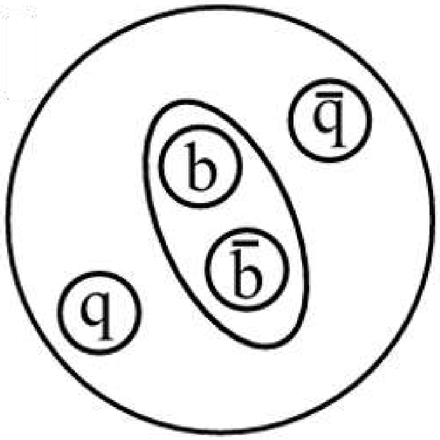
Экзотические состояния



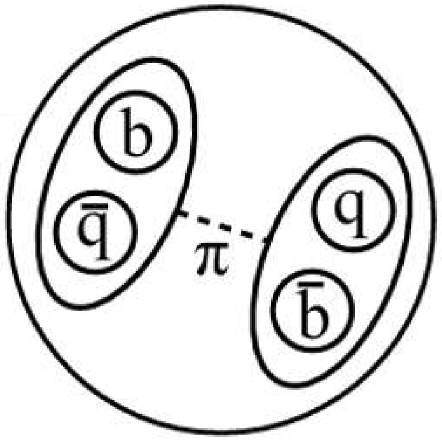
Гибрид



Компактный тетракварк



Адро-кварконий



Молекула

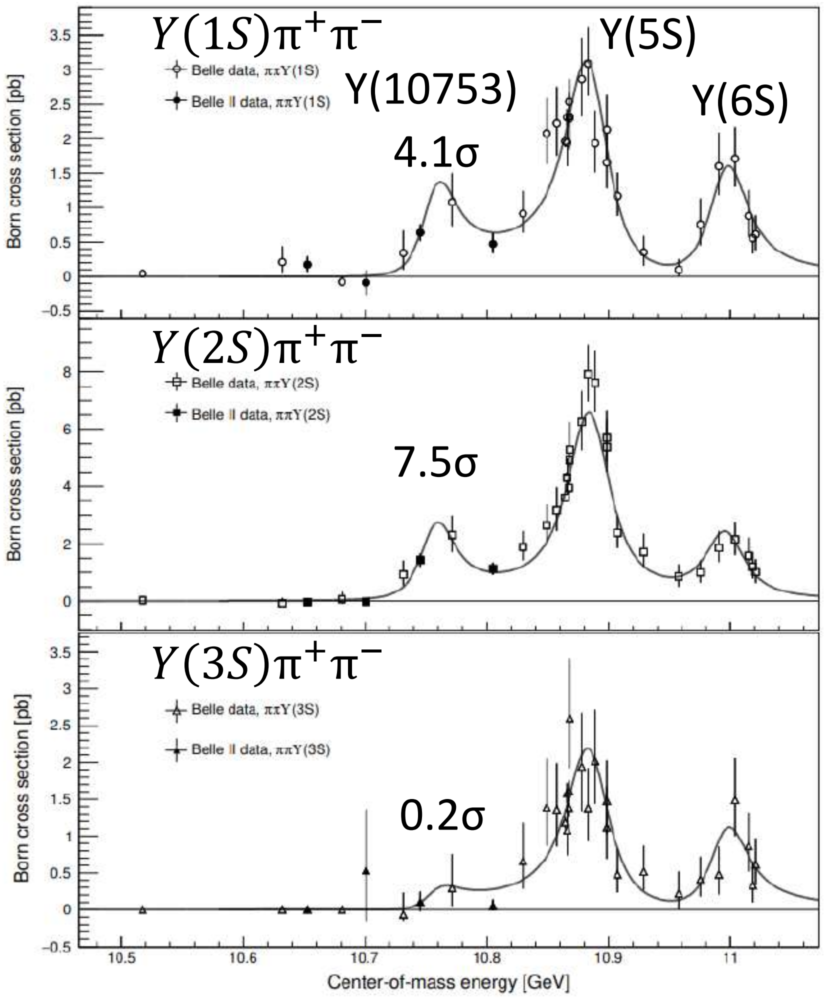
- Неожиданные резонансы обнаружены и в семействе чармония (например X(3872),Y(4260))
- Кроме $Y(10753)$, под вопросом и структура $Y(4S)$, $Y(5S)$
- Общая четкая интерпретация отсутствует
- Необходимо проводить дальнейшее изучение этих состояний, включая переходы с излучением легких адронов

Дипионные переходы

- $Y(2S)$—$Y(4S)$: $\Gamma \sim 5 \div 0.5$ КэВ, согласуется с $b\bar{b}$ структурой
- $Y(5S)$: обнаружен промежуточный Z_b

  $\Gamma \approx 180 \div 300$ КэВ

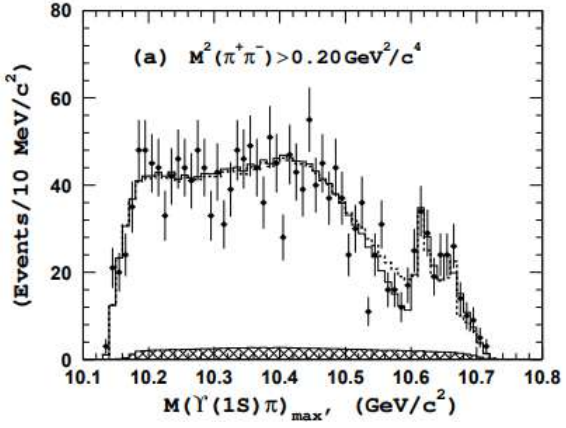
  За вычетом Z_b, ширина переходов все ещё на два порядка выше, чем для $Y(2S)$—$Y(4S)$
- $Y(5S) \to h_b(1P, 2P)\pi^+\pi^-$: только промежуточный Z_b
- $Y(10753)$: резонанс подтвержден, промежуточный Z_b отсутствует, структура - ?



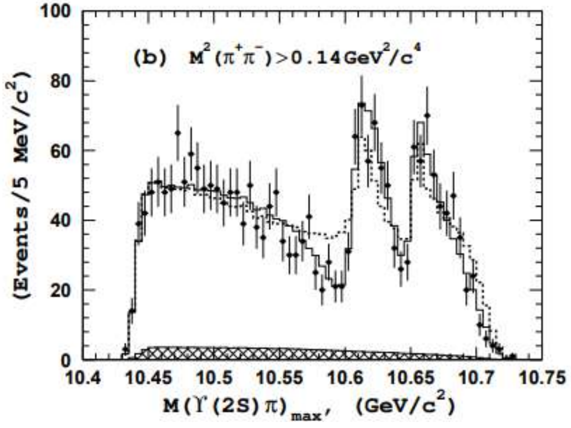
Зависимость сечения от энергии
JHEP 07 (2024) 116

Z_b в дипионных переходах

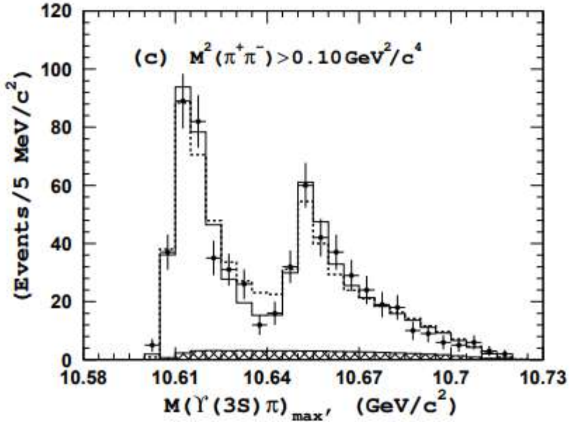
$Y(5S) \to Y(1S)\pi^+\pi^-$



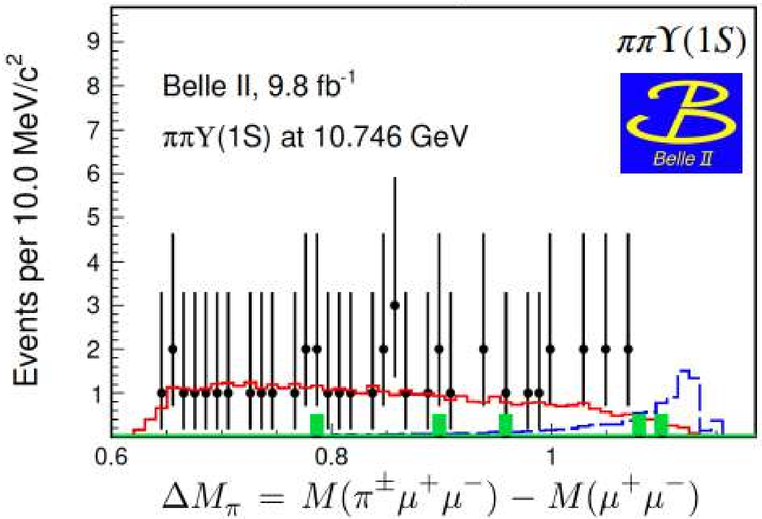
$Y(5S) \to Y(2S)\pi^+\pi^-$



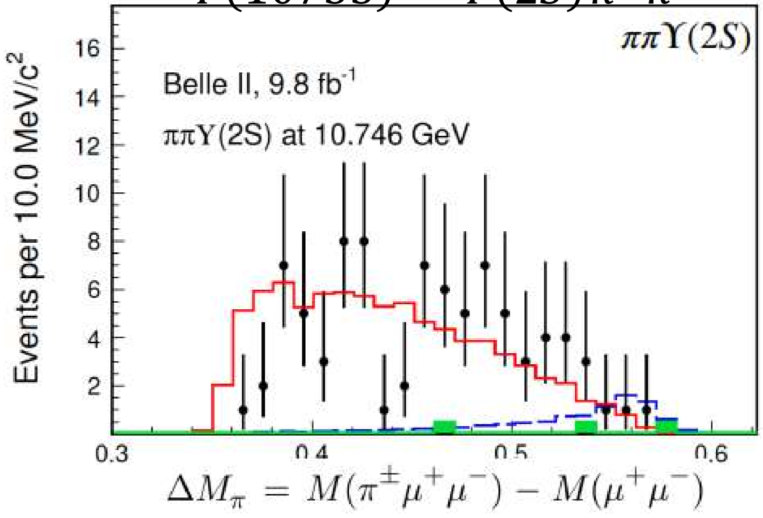
$Y(5S) \to Y(3S)\pi^+\pi^-$



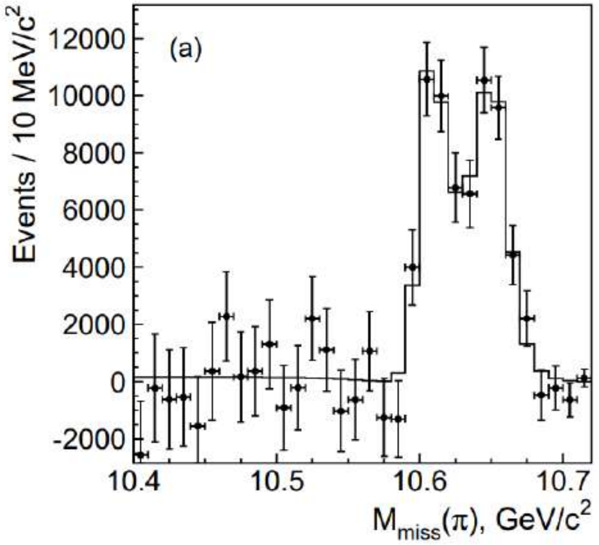
$Y(10753) \to Y(1S)\pi^+\pi^-$



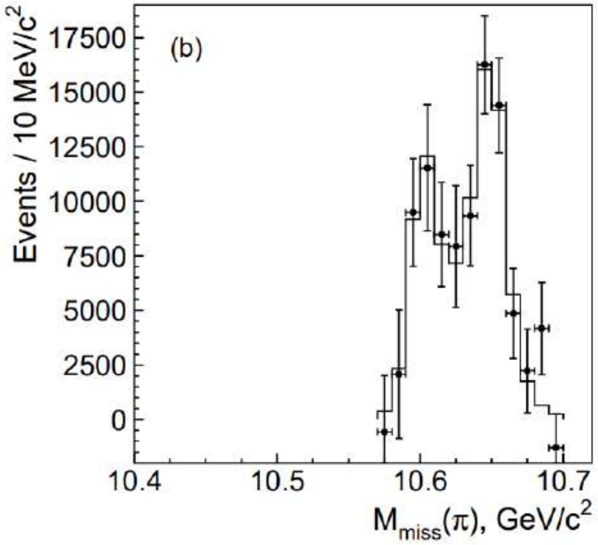
$Y(10753) \to Y(2S)\pi^+\pi^-$



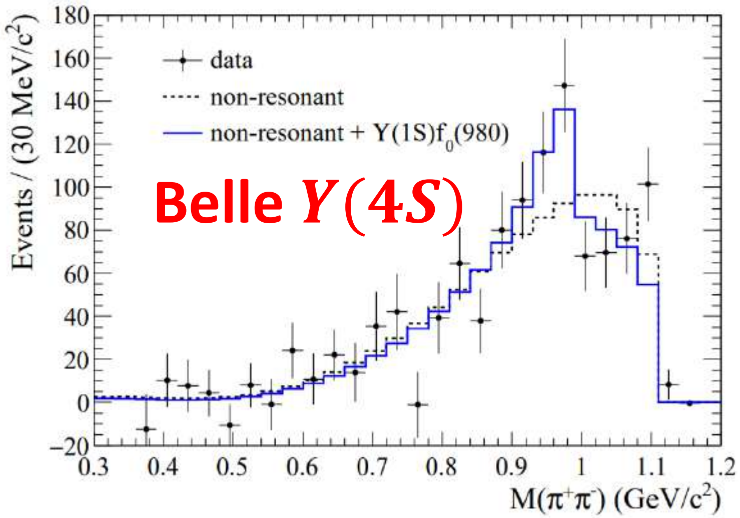
$Y(5S) \to h_b(1P)\pi^+\pi^-$



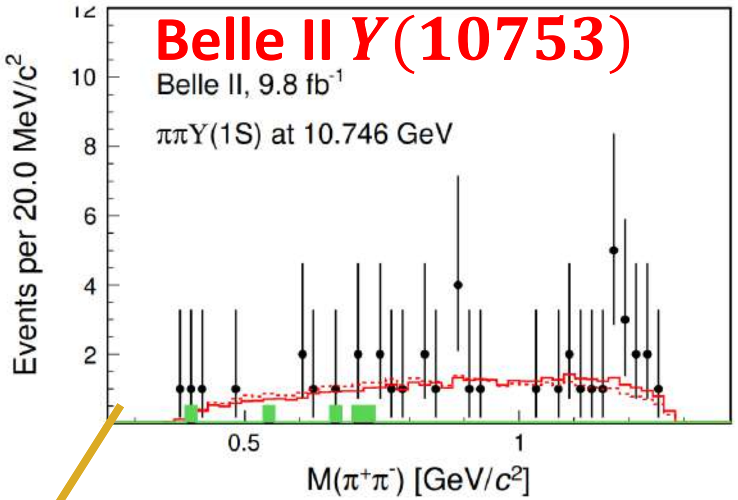
$Y(5S) \to h_b(2P)\pi^+\pi^-$



Спектр дипионной массы $\Upsilon(1S)\pi^+\pi^-$



PRD 96 (2017) 5, 052005



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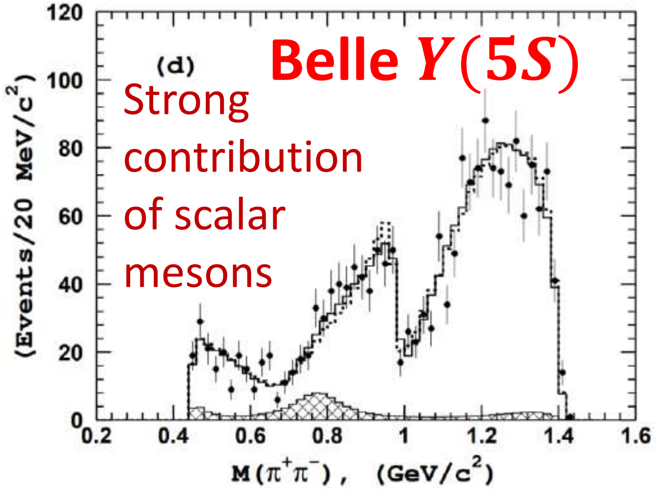
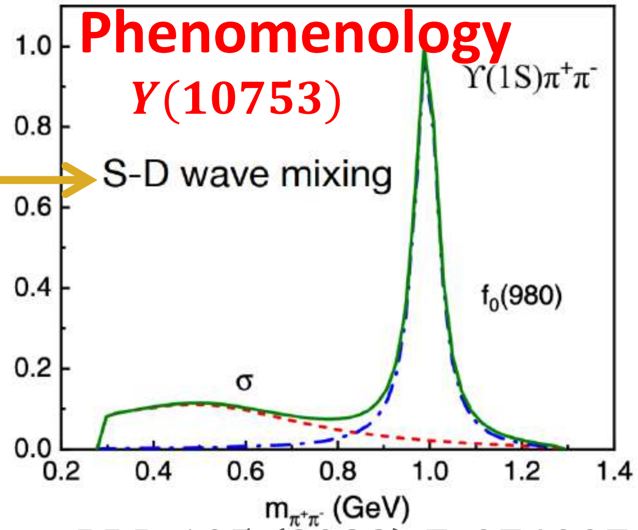
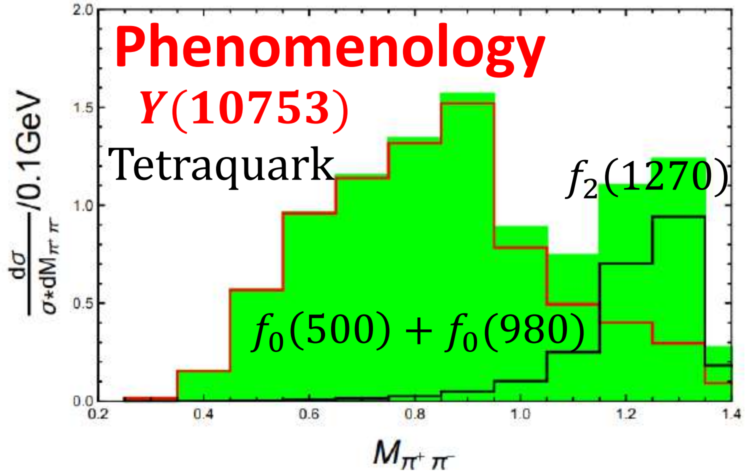


PRD 91 (2015) 7, 072003

- $\Upsilon(4S)$: указание на $f_0(980)$
- $\Upsilon(10753)$: нет $f_0(980)$, нет S-D смешивания, согласуется компактным тетракварком?
- $\Upsilon(5S)$: Z_b, $f_0(980)$, $(\pi^+\pi^-)_{D\ wave}$



PRD 105 (2022) 7, 074007



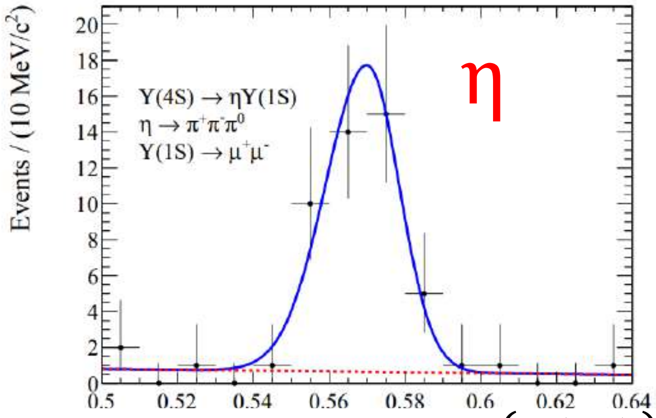
PLB 802 (2020) 135217

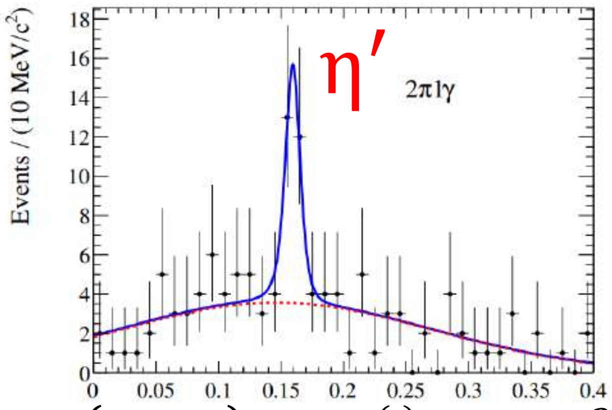
Переходы с η

- $\Upsilon(4S)$:
  $B[\Upsilon(4S) \to \Upsilon(1S)\eta] = (1.70 \pm 0.23 \pm 0.08) \times 10^{-4}$
  $B[\Upsilon(4S) \to \Upsilon(1S)\eta'] = (3.43 \pm 0.88 \pm 0.21) \times 10^{-5}$
  $R_{\eta/\pi\pi} = 2.07 \pm 0.24$ ($1/m_b^2$ подавление для $b\bar{b}$)
  $R_{\eta'/\eta} = 0.20 \pm 0.06$ ($\sim$5 для чистого $b\bar{b}$)
  $B[\Upsilon(4S) \to h_b(1P)\eta] = (2.18 \pm 0.21) \times 10^{-3}$
- $\Upsilon(5S)$:
  $B[\Upsilon(5S) \to \Upsilon(1S)\eta] = (8.5 \pm 1.7) \times 10^{-4}$
  $B[\Upsilon(5S) \to \Upsilon(1S)\eta'] < 6.9 \times 10^{-5}$
  $R_{\eta/\pi\pi} = 0.19 \pm 0.04$ ($1/m_b^2$ подавление для $b\bar{b}$)
  $R_{\eta'/\eta} < 0.09$ ($\approx$ 13 для чистого $b\bar{b}$)

  $B[\Upsilon(5S) \to \Upsilon(2S)\eta] = (4.1 \pm 0.6) \times 10^{-4}$
  $R_{\eta/\pi\pi}(2S) = 0.51 \pm 0.06$ ($1/m_b^2$ подавление для $b\bar{b}$)

Belle $\Upsilon(4S)$

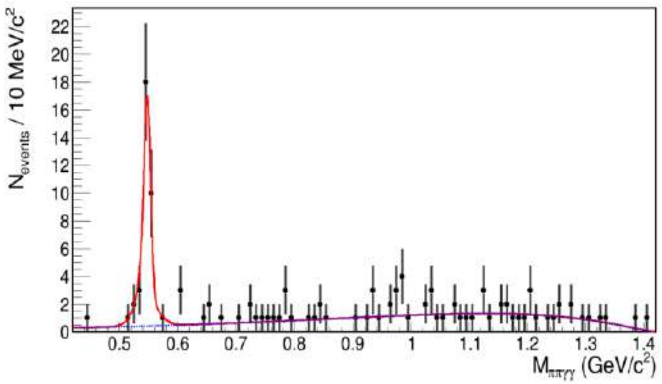


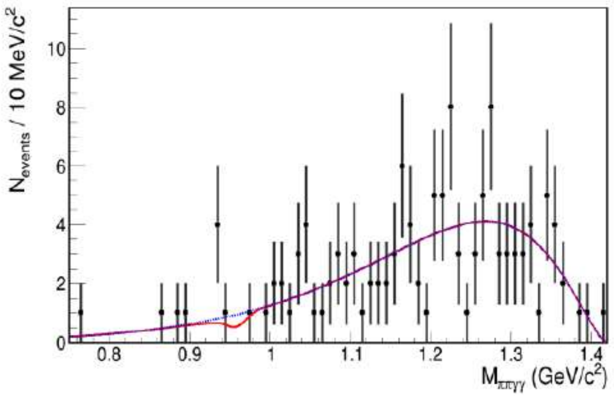


$\Delta M_{\eta^{(\prime)}} = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta^{(\prime)}), GeV/c^2$

PRD 96 (2017) 5, 052005 PRL 121 (2018) 6, 062001

Belle $\Upsilon(5S)$



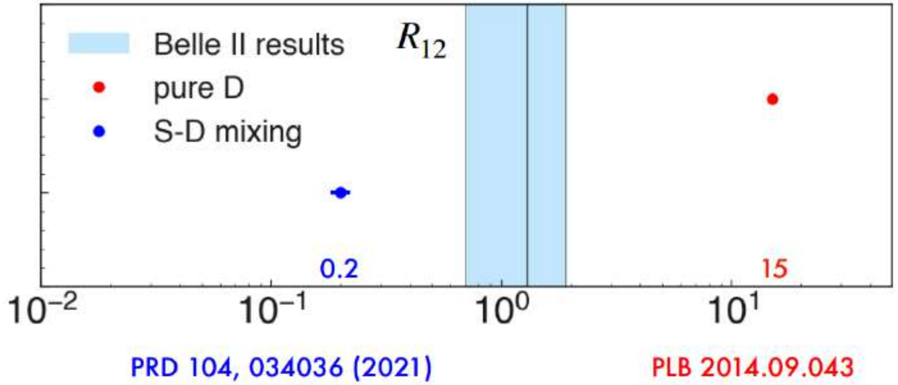


PRD 104 (2021) 11, 112006

$\Upsilon(10753, 5S) \to \chi_{bJ}(1P)\omega$

- $\Upsilon(10753)$: наблюдались ($J = 1,2$)

$$R_{12} = \frac{\Gamma_{ee} \times B[\Upsilon(10753) \to \chi_{b1}(1P)\omega]}{\Gamma_{ee} \times B[\Upsilon(10753) \to \chi_{b2}(1P)\omega]} = 1.3 \pm 0.6$$



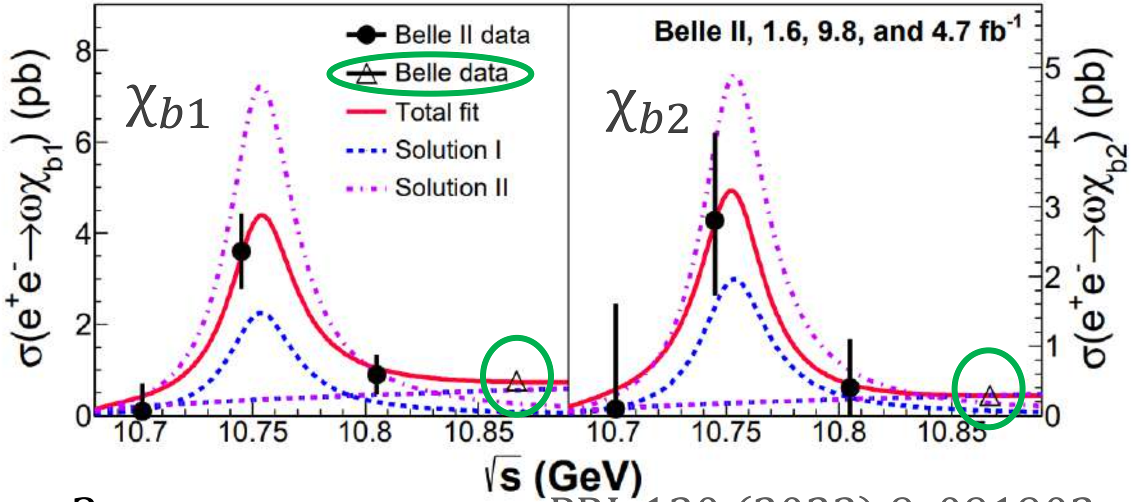
Не согласуется с 3D, 1.8σ отклонение от S-D смешивания

- $\Upsilon(5S)$: наблюдались ($J = 1,2$)

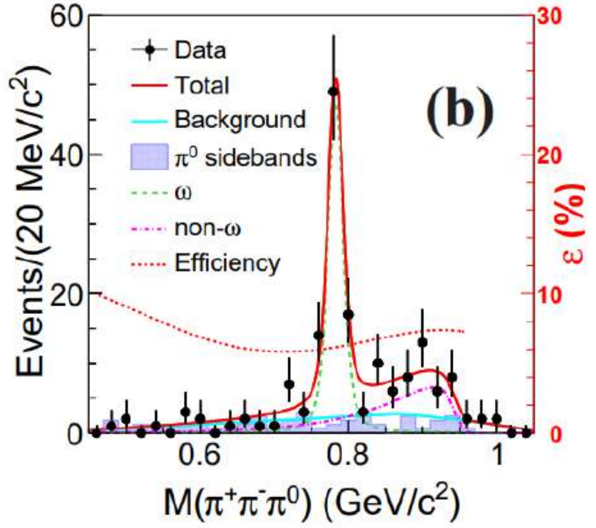
$$R_{12} = 2.6 \pm 1.1 \quad (0.63 \text{ ожидается для } b\bar{b}\ 5S)$$

$$\frac{\sigma[e^+e^- \to \chi_{b1}(1P)\omega]}{\sigma[e^+e^- \to \Upsilon(1S)\pi^+\pi^-]} \approx \begin{cases} 5.6\ @\ \Upsilon(10753) \\ 0.3\ @\ \Upsilon(5S) \end{cases}$$

Различная структура? Хвост от $\Upsilon(10753)$?



Зависимость сечения PRL 130 (2023) 9, 091902



Распределение на $\Upsilon(5S)$ PRL 113 (2014) 14, 142001

$\Upsilon(4S, 10753, 5S) \to \eta_b(1S)\omega$

- $\Upsilon(4S)$: PRD 102 (2020) 9, 092011

  $B[\Upsilon(4S) \to \eta_b(1S)\omega] < 1.8 \times 10^{-4}$

  $R = \frac{\sigma(e^+e^- \to \eta_b(1S)\omega)}{\sigma(e^+e^- \to \Upsilon(1S)\pi^+\pi^-)} < 2.2$

- $\Upsilon(10753)$: PRD 109 (2024) 7, 072013

  $\sigma(e^+e^- \to \eta_b(1S)\omega) < 2.5\ pb$

  $R < 1.25$

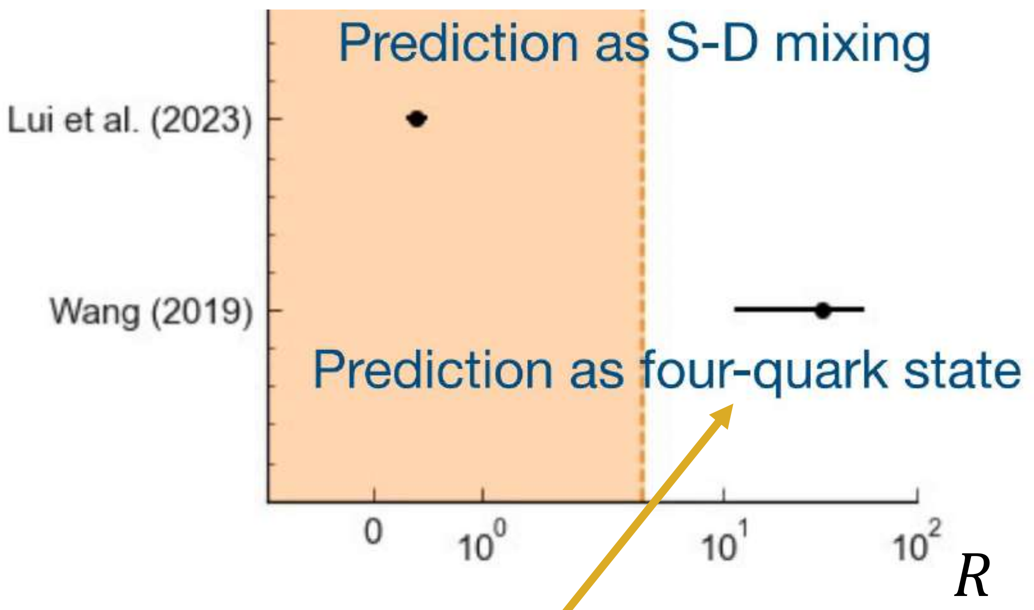
- $\Upsilon(5S)$: PRD 102 (2020) 9, 092011

  $B[\Upsilon(5S) \to \eta_b(1S)\omega] < 1.3 \times 10^{-3}$

  $B[\Upsilon(5S) \to \eta_b(2S)\omega] < 5.6 \times 10^{-3}$

  $R < 0.25$

$\Upsilon(10753)$



предполагает
$\Upsilon(10753) \to \Upsilon(1S) f_0(1370) \to \Upsilon(1S)\pi^+\pi^-$

Не согласуется с компактным тетракварком?

Заключение

- Адронные переходы между состояниями боттомония предоставляют важную информацию о его структуре
- Есть указания на то, что состояния $\Upsilon(4S, 10753, 5S)$ выше $B\bar{B}$ порога не являются чистыми $b\bar{b}$
- Четкого единого объяснения пока нет
- Необходимо приложить дополнительные усилия в этой области энергий, например

  $e^+e^- \to \Upsilon(1S, 2S)\eta^{(\prime)}$

  $e^+e^- \to \Upsilon(1S)K^+K^-$

  Дополнительные данные около $\Upsilon(10753, 5S, 6S)$