BABAR ISR $K_S^0\ K_L^0\ \pi^0\ (\pi^0)$

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on behalf of the *BABAR* collaboration

Tau 2016, Beijing
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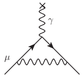
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA

Motivation

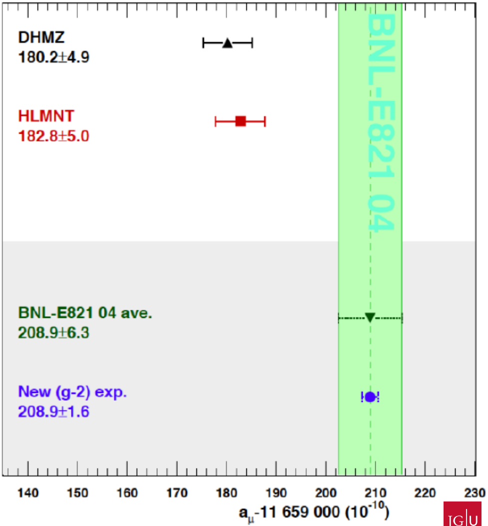


QED is precision physics

- $a_\ell \equiv \frac{1}{2}(g-2)_\ell$ testbed for QED
- experimentally: electron ok
- muon:
  currently $> 3\sigma$ discrepancy btw.
  theory and experiment

$$
\begin{aligned}
a_\mu^{\text{theo}} \times 10^{10} &= 11\,659\,180.2 \pm 4.9 \\
a_\mu^{\text{exp}} \times 10^{10} &= 11\,659\,208.9 \pm 6.3 \\
\Delta a_\mu \times 10^{10} &= 28.7 \pm 8.0
\end{aligned}
$$

- Test SM
  new physics?



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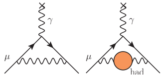


Muon anomalous magnetic moment
sensitive to hadronic vacuum polarisation

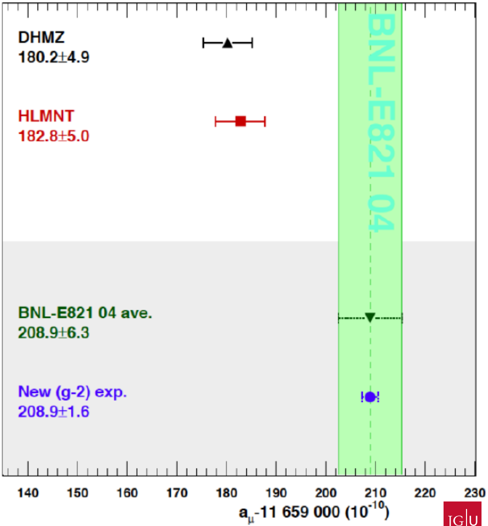
ab-initio calculations difficult
experimental input required:
$\sigma(e^+e^- \to \text{hadrons})$

$$a_\mu^{\text{had,LO}} \times 10^{10} = 692.3 \pm 4.2$$

Davier *et al.*, EPJ C71, 1515

$$a_\mu^{\text{had,LO}} \times 10^{10} = 694.9 \pm 4.3$$
$$a_\mu^{\text{had,NLO}} \times 10^{10} = -9.84 \pm 0.06 \pm 0.04$$

Hagiwara *et al.*, JP G38, 085003



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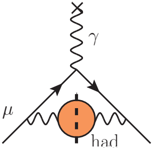
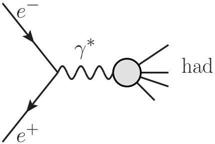


dispersion relation



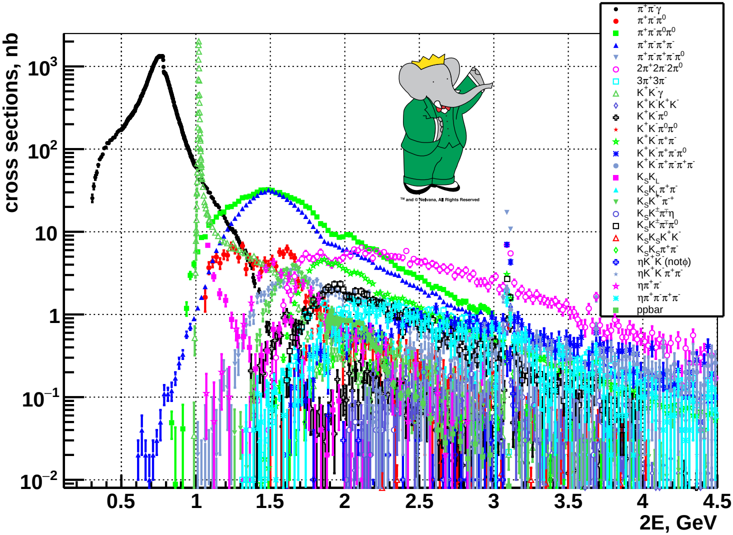
$K(s)$: analytically known kernel function

$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} \mathrm{d}s \, \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$ experimental input

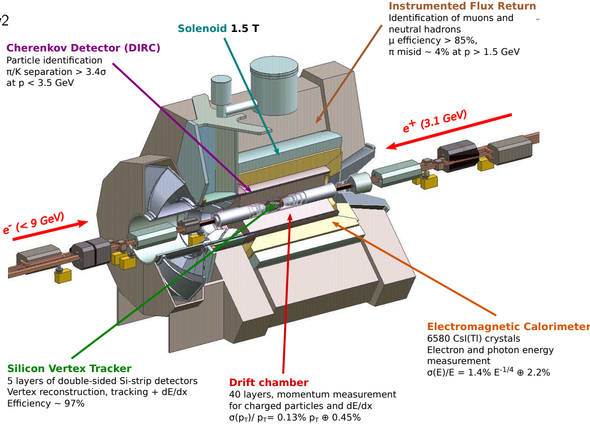
dominated by low-energy cross sections
improve precision by measuring exclusive final states

$e^+e^- \to$ hadrons cross sections from *BABAR*



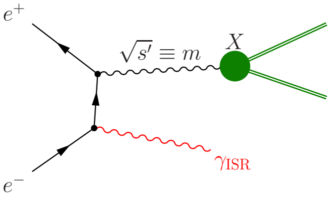
The *BABAR* experiment

- PEP-II: e^+e^- collider, 3.1×9 GeV^2
  $\sqrt{s} = 10.58$ GeV $[\Upsilon(4S)]$
- Asymmetric beam energies
  c.m. lab boost $\beta\gamma = 0.56$
- Asymmetric detector
  - acceptance in c.m.
    $-0.9 \lesssim \theta^* \lesssim 0.85$
  - detects $\approx 15\%$ of ISR γ
  - contains $\approx 50\%$ of events with fwd/bwd γ_{ISR}
- excellent performance
  - Good tracking, mass resolution
  - Good γ, π^0 reco.
  - Full PID for e, μ, π, K, p



- High luminosity
  - $\mathcal{L}_{\text{peak}} = 12.069 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$
  - $513.7(18)$ fb^{-1} accumulated
    (1.7 billion $e^+e^- \to q\bar{q}$ events)

Initial state radiation in e^+e^-



- $e^+e^- \to \gamma_{\text{ISR}} e^+e^- \to \gamma_{\text{ISR}} X$
- X is any allowed (hadronic) system, e.g.
  - a resonance with $J^{PC} = 1^{--}$
  - 2 particle system with appropriate quantum numbers
  - …
- Cross section factorises into

$$\frac{\mathrm{d}\sigma(s; s', \theta_\gamma)}{\mathrm{d}s'\,\mathrm{d}\,\theta_\gamma} = W(s; s', \theta_\gamma) \cdot \sigma_X(s')$$

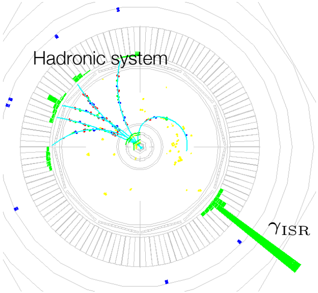
Radiator function known to $\lesssim 0.5\%$

cross section $\sigma_X(e^+e^- \to X)$

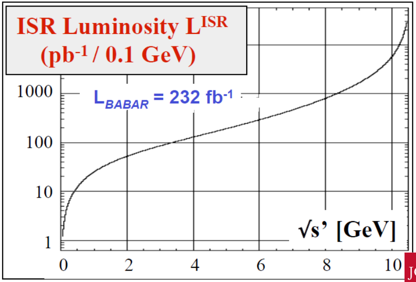
- Use W or normalise to $e^+e^- \to \mu^+\mu^-\gamma$ (many systematics cancel)

ISR at $\Upsilon(4S)$ energies

- Rely on tagged (= measured) photon to identify ISR events
- Excellent momentum resolution by means of kinematic fit
- High fiducial efficiency: hadronic system forced into detector fiducial region



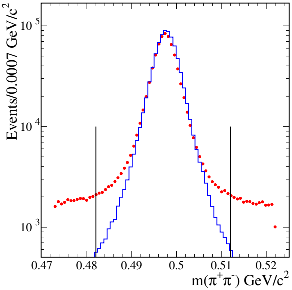
- Harder momentum spectrum due to boost
  - fewer problems with soft particles
  - measure down to threshold
- Simultaneous access to wide range of s' in single experiment
  $\Rightarrow$ very small point-to-point systematic errors
- Large integrated luminosity




$K_S^0 K_L^0 \pi^0 (\pi^0)$

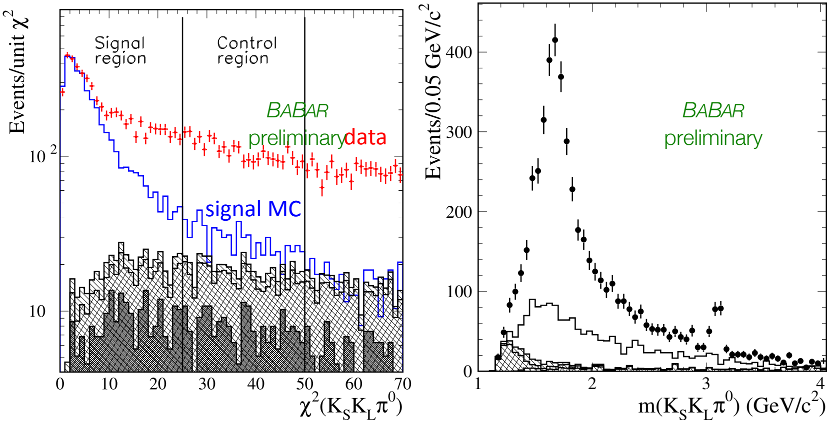
General event selection and reconstruction

- Using 469 fb^{-1} of data near $\Upsilon(4S)$
- At least two charged tracks and at least four neutral clusters
- $K^0_S \to \pi^+\pi^-$, pointing back to IP
- K^0_L reconstruction:
  cluster in EMC with $E \geq 200$ MeV,
  take direction from cluster, and energy from kinematic fit
- Apply kinematic fits for different signal hypotheses
- Invariant mass resolution
  for the hadronic system ≈ 25 MeV

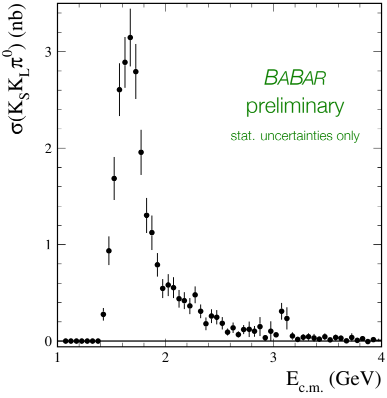


$K_S^0 K_L^0 \pi^0$ reconstruction

Select events with kinematic fit $\chi^2 < 25$
Estimate backgrounds from control region in χ^2



$K_S^0 K_L^0 \pi^0$ cross section



Systematic uncertainties include

- Background subtraction:
  $\approx 10\%$ for $M(K_S^0 K_L^0 \pi^0) < 2.2$ GeV, increasing to $\approx 80\text{-}100\%$ above 3.2 GeV
- Efficiency corrections
  overall data-MC difference of $(-9.5 \pm 1.6)\%$

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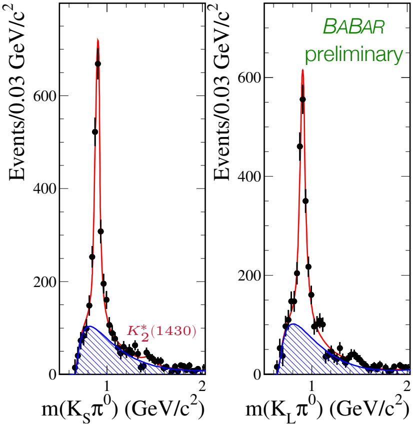
$K_S^0 K_L^0 \pi^0$ resonant substructure



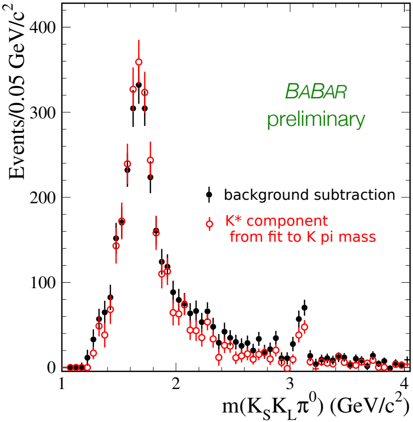
background-subtracted $K_S^0\pi^0$ and $K_L^0\pi^0$ mass distributions.

Fit: red line — coherent resonant; blue histogram — non-resonant component

Dominated by $K^{*0}\overline{K}^0 + c.c.$:

- dominant contribution from $K^*(892)^0\overline{K}^0 + c.c.$
- small $K_2^*(1430)^0\overline{K}^0 + c.c.$

$K_S^0 K_L^0 \pi^0$ resonant substructure: $K^{*0}\,\overline{K}^0$



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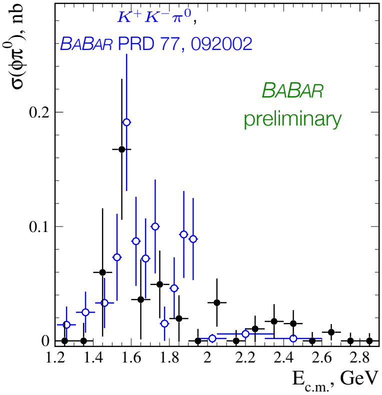
- dominant contribution from $K^*(892)^0\,\overline{K}^0 + c.c.$
- small $K_2^*(1430)^0\,\overline{K}^0 + c.c.$

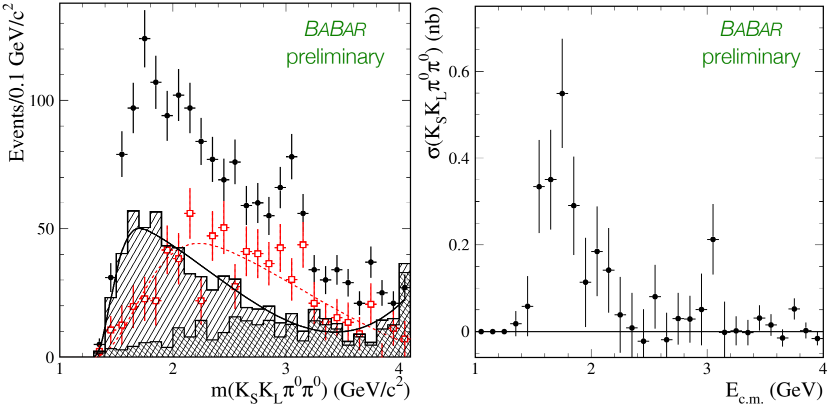
$K^*(892)^0\,\overline{K}^0 + c.c.$ almost saturates cross section

$K_S^0 K_L^0 \pi^0$ resonant substructure: $\phi\pi^0$

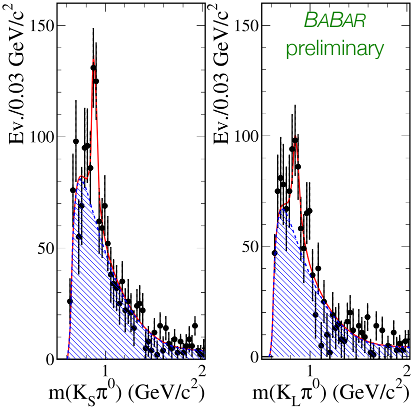


Small contribution from $\phi\pi^0$; compatible with cross section measured in $K^+K^-\pi^0$
Isospin $I = 1$, OZI suppressed
Possible resonant structure around 1.6 GeV

$K_S^0 K_L^0 \pi^0 \pi^0$ cross section



$K_S^0 K_L^0 \pi^0 \pi^0$ resonant substructure



Some $K^*(892)^0$ evident ($190 \pm 44\ K_S^0\pi^0$, $171 \pm 32\ K_L^0\pi^0$)
but statistics too low to study further
No indication for $K^*(892)^0 \overline{K}^*(892)^0$

Consistent with $K^*(892)^0 \overline{K}^0 \pi^0 + c.c.$ as expected from $K^+K^-\pi^+\pi^-$

Charmonium $\to K_S^0 K_L^0 \pi^0 (\pi^0)$

Previous measurements of J/ψ decays:

$J/\psi(1S) \to K\overline{K}\pi$

INSPIRE search

$\Gamma(J/\psi(1S) \to K\overline{K}\pi)/\Gamma_{total}$ — Γ_{95}/Γ

Value (10^{-4})	EVTS	Document ID		TECN	Comment
$61. \pm 10.$	OUR AVERAGE				
55.2 ± 12.0	25	FRANKLIN	1983	MRK2	$e^+ e^- \to K^+ K^- \pi^0$
78.0 ± 21.0	126	VANNUCCI	1977	MRK1	$e^+ e^- \to K_S^0 K^\pm \pi^\mp$

References

FRANKLIN	1983	PRL 51 963	Measurement of $\psi(3097)$ and $\psi'(3686)$ Decays into Selected Hadronic Modes
VANNUCCI	1977	PR D15 1814	Mesonic Decays of the $\psi(3095)$

$J/\psi(1S) \to \pi^0 \pi^0 K^+ K^-$

INSPIRE search

$\Gamma(J/\psi(1S) \to \pi^0 \pi^0 K^+ K^-)/\Gamma_{total}$ — Γ_{94}/Γ

$\Gamma(J/\psi(1S) \to \pi^0 \pi^0 K^+ K^-) \times \Gamma(J/\psi(1S) \to e^+ e^-)/\Gamma_{total}$ — $\Gamma_{94}\Gamma_5/\Gamma$

Value (eV)	EVTS	Document ID		TECN	Comment
$13.6 \pm 1.1 \pm 1.3$	203 ± 16	AUBERT	2007AK	BABR	10.6 $e^+ e^- \to \pi^0 \pi^0 K^+ K^- \gamma$

References

AUBERT	2007AK	PR D76 012008	$e^+ e^- \to K^+ K^- \pi^+ \pi^-$, $K^+ K^- \pi^0 \pi^0$ and $K^+ K^- K^+ K^-$ Cross Sections Measured with Initial-State Radiation

Not all possible isospin combinations in final state included in PDG $KK\pi$

$$\sigma(e^+e^- \to X) \propto \Gamma(J/\psi \to e^+e^-) \times B(J/\psi \to X)$$

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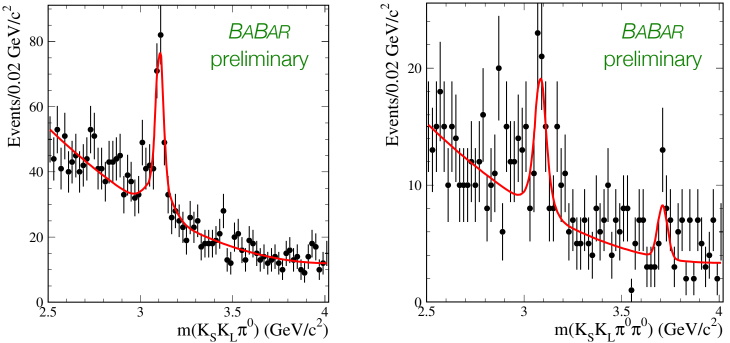
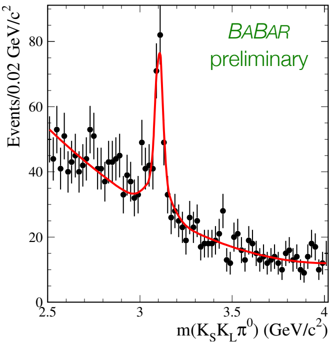
Charmonium region

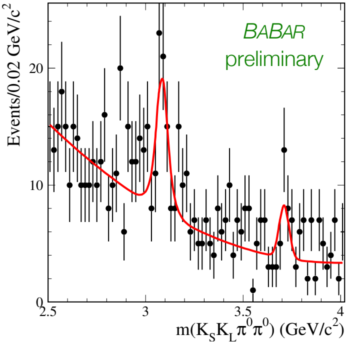


Fit with MC signal shape + second-order polynomial (background)

J/ψ	$K_S^0\ K_L^0\ \pi^0$	182 ± 21
	$K_S^0\ K_L^0\ \pi^0\ \pi^0$	47 ± 11
$\psi(2S)$	$K_S^0\ K_L^0\ \pi^0$	< 8
	$K_S^0\ K_L^0\ \pi^0\ \pi^0$	14 ± 6

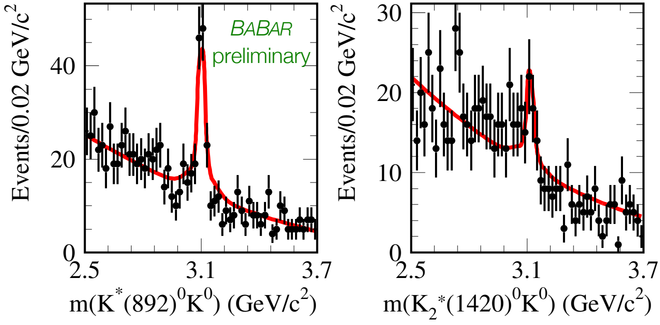
Charmonium region





	$B/10^{-3}$		
	BABAR prelim.	PDG 2014	
$J/\psi \to K_S^0 K_L^0 \pi^0$	$2.06 \pm 0.24 \pm 0.10$		
$J/\psi \to K_S^0 K_L^0 \pi^0 \pi^0$	$1.86 \pm 0.43 \pm 0.10$	2.35 ± 0.41	(from $K^+K^-\pi^0\pi^0$)
$\psi(2S) \to K_S^0 K_L^0 \pi^0$	< 0.3	—	
$\psi(2S) \to K_S^0 K_L^0 \pi^0 \pi^0$	$1.24 \pm 0.54 \pm 0.06$	—	

Charmonium decays to $K^* \overline{K}^0$



See significant yields for $J/\psi \to$

	Events	$B(J/\psi \to X) \times B(X \to K^0\pi^0) \times 10^3$
$K^*(892)^0\overline{K}^0 + c.c. \to K^0_S K^0_L \pi^0$	106 ± 13	$1.20 \pm 015 \pm 0.06$
$K^*_2(1430)^0\overline{K}^0 + c.c. \to K^0_S K^0_L \pi^0$	37 ± 11	$0.43 \pm 0.12 \pm 0.02$

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Summary

- Measure cross sections for $e^+e^- \to K_S^0 K_L^0 \pi^0(\pi^0)$
- Resonant substructure explored with $\mathcal{O}(10^2)$ events
- Contribution to a_μ:

$$a_\mu^{KK\pi\pi}(E_{\rm CM} < 2\,\text{GeV}) \times 10^{10} = 3.31 \pm 0.58 \qquad \text{HLMNT 2011}$$

$$a_\mu^{\text{all}\,KK\pi\pi}(E_{\rm CM} < 2\,\text{GeV}) \times 10^{10} = 2.41 \pm 0.11$$

- All $KK\pi$ and $KK\pi\pi$ now directly measured by *BABAR*
  no isospin relations needed any more for cross sections and dispersion relation!

- Branching fractions for J/ψ and ψ' to $K_S^0 K_L^0 \pi^0(\pi^0)$
  improved precision, first measurements

- Final word from *BABAR* for these channels.
  More progress: BESIII, Belle II, VEPP-2000