History of Belle & some of its best results

Stephen Lars Olsen Institute for Basic Science **Daejeon KOREA**

High Energy Physics and Quantum Field Theory
Samara, Russia June 24 – July 1, 2015

History of Belle & some of its ~~best~~ results

not well known, but important

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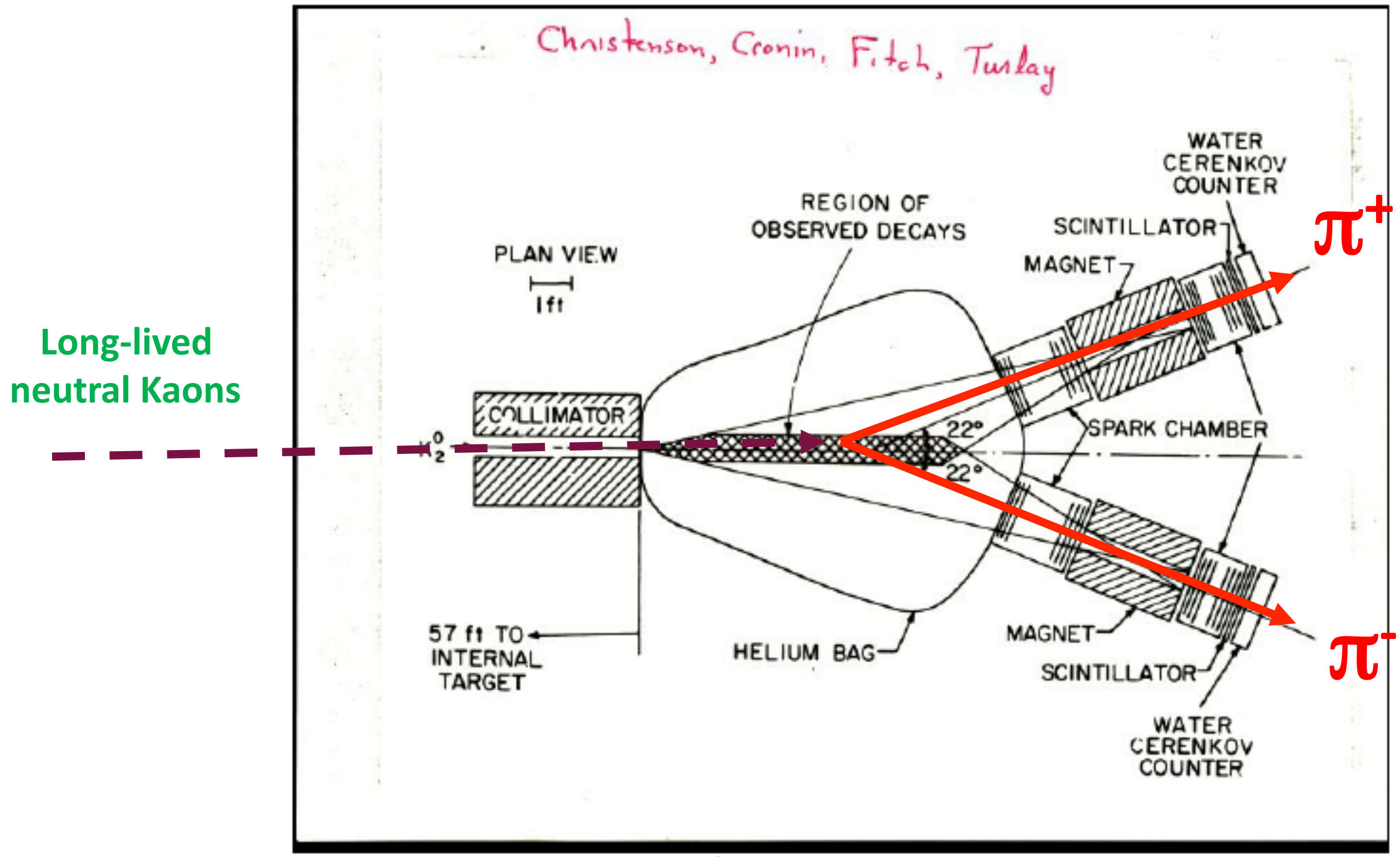
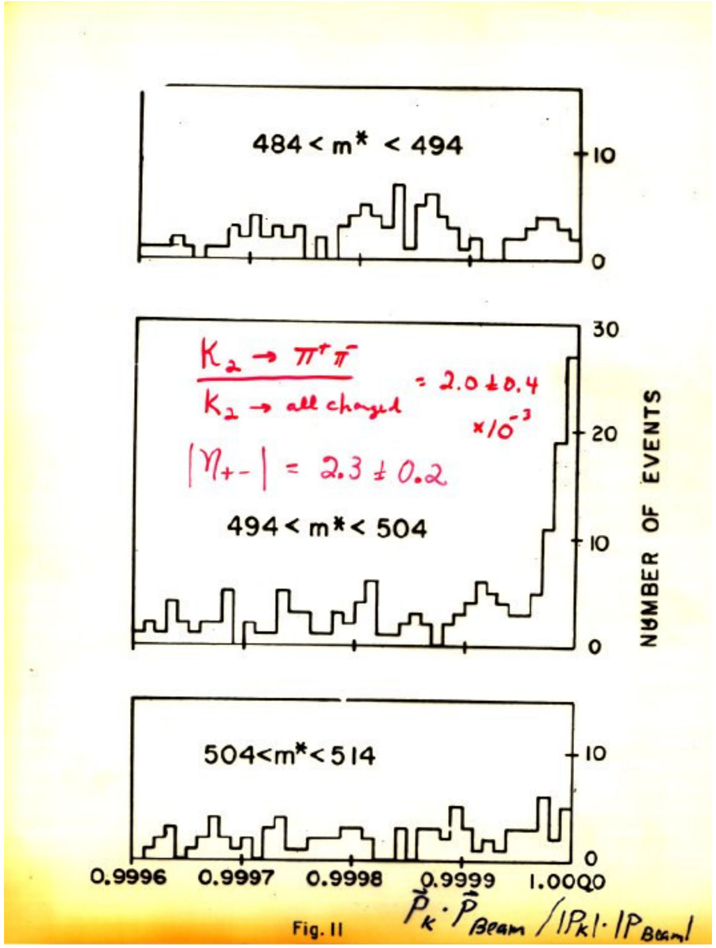
Christenson-Cronin-Fitch-Turlay Experiment (1964)

Search for long-lived neutral kaon → $\pi^+\pi^-$



Long-lived neutral K→$\pi^+\pi^-$

(~2 parts in 10^3)

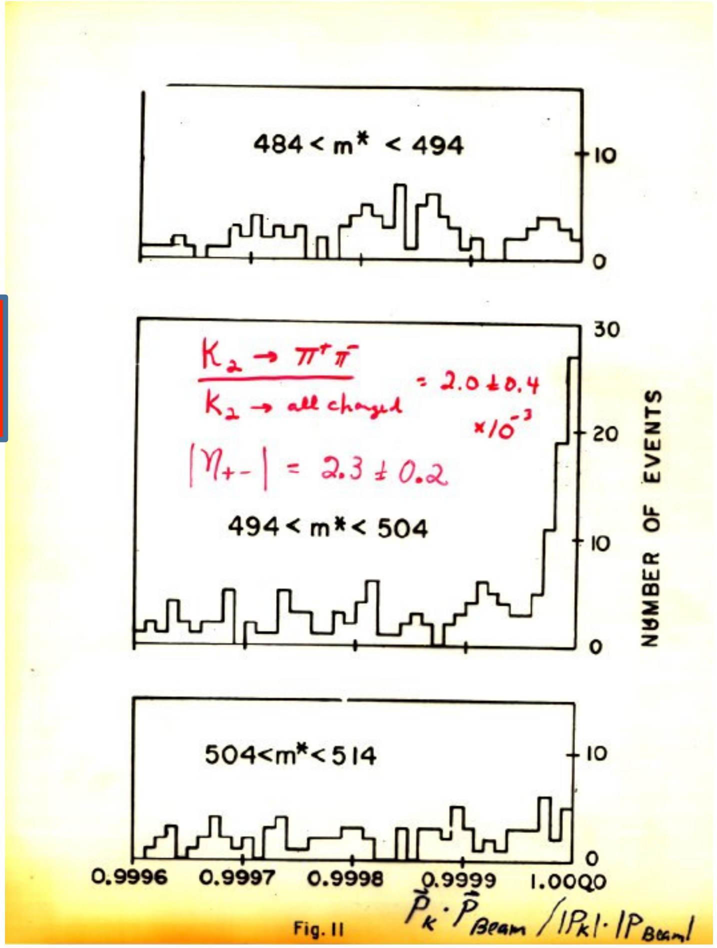


J. H. Christenson et al., PRL **13 (1964), 138.**

Long-lived neutral K→$\pi^+\pi^-$

(~2 parts in 10^3)

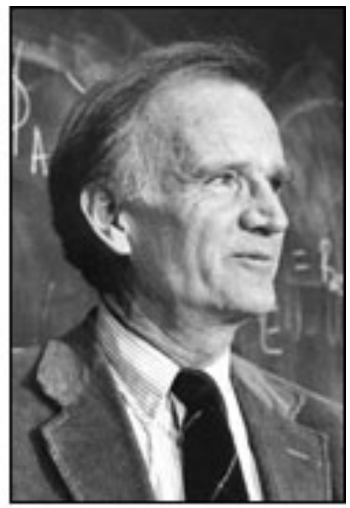
Small CP violation ($2x10^{-3}$) is seen



J. H. Christenson et al., PRL **13 (1964), 138.**

1980 Nobel Prize

James Cronin



Val Fitch

Why the interest in CP violation?

- Critical for understanding the early Universe
  - -Sakharov's 1967 paper on the Baryon Asymmetry of the Universe
- Hard to incorporate into the Standard Model
  - -Kobayashi & Maskawa's 1972 paper on 6-quark flavor mixing
- Promising probe of New Physics (as discussed in the following talk)
  - -SM CPV is too small to be the mechanism behind Sakharov's BAU; the BAU requires non-SM CPV mechanisms to explain it

Sakharov: CPV & the baryon asymmetry of the Universe (1967)

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

Out of S. Okubo's effect
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Pis'ma Zh. Eksp. Teor. Fis. **5**, 32–35 (1967)
[JETP Lett **5**, 24–27 (1967). Also S7, pp. 85–88]

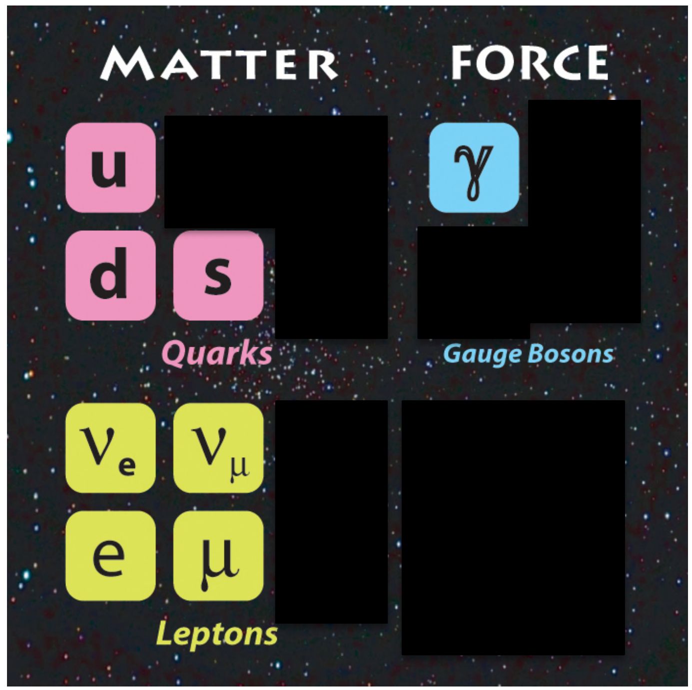
Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

Incorporating CPV into QM

CPV was big trouble for theorists!

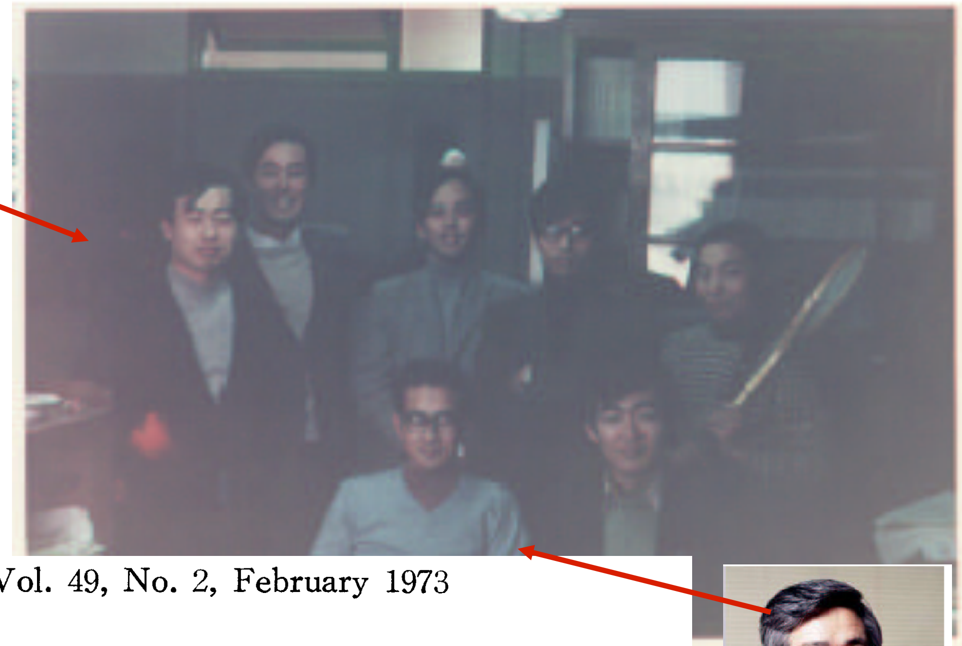
Elementary Particles
in 1964

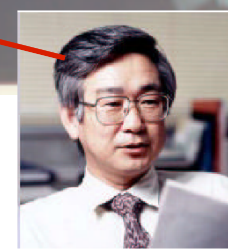
only 3 quark flavors
were known



1973 Kobayashi & Maskawa

Makoto Kobayashi





Toshihide Maskawa

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

PAGE 1

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme

"4 quark scheme"

KM paper, page 12

"6 quark model"

Next we consider a 6-plet model, another interesting model of CP-violation.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

3 Euler angles: θ_1 θ_2 & θ_3, plus 1 CP-violating phase: δ

Then, we have CP-violating effects through the interference among these different current components.

i.e., theory can accommodate CP violation, but only with 6 (or more) quarks

KM model predicts large differences between B^0 and $\bar{B}^0$ decays

VOLUME 45, NUMBER 12 PHYSICAL REVIEW LETTERS 22 SEPTEMBER 1980

CP Nonconservation in Cascade Decays of B Mesons

Ashton B. Carter and A. I. Sanda
Rockefeller University, New York, New York 10021
(Received 2 June 1980)

Ikaros Bigi

Ichiro Sanda

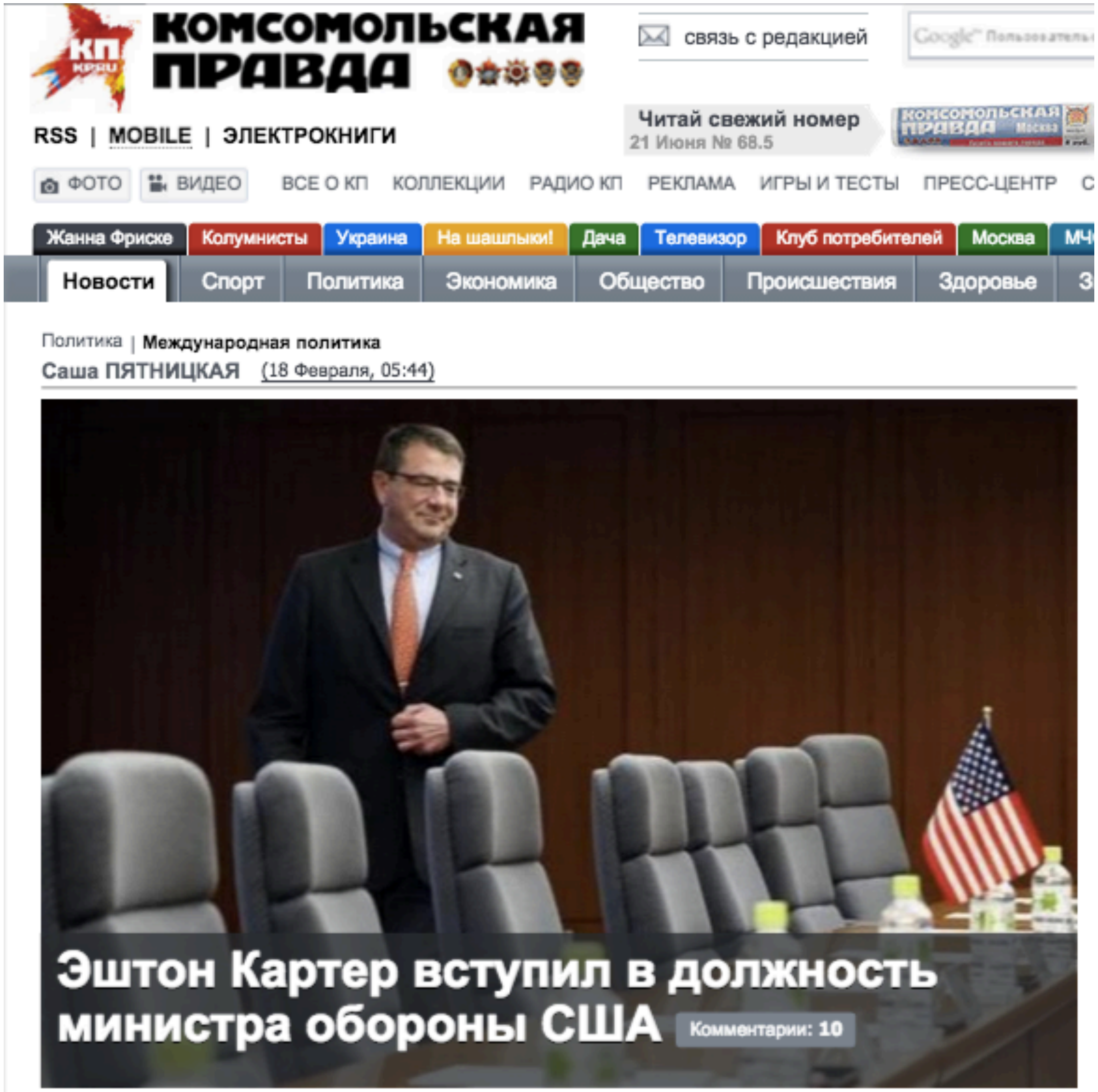
Ashton Carter

NOTES ON THE OBSERVABILITY OF CP VIOLATIONS IN B DECAYS

I.I. BIGI
Institut für Theor. Physik der RWTH Aachen, D-5100 Aachen, FR Germany

A.I. SANDA[1]
Rockefeller University, New York 10021, USA

Ashton Carter in 2015



CKM flavor-mixing matrix

The Kobayashi-Maskawa CPV complex phases are here

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} V_{us} V_{ub} \\ V_{cd} V_{cs} V_{cb} \\ V_{td} V_{ts} V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

and here

CKM flavor-mixing matrix

The Kobayashi-Maskawa CPV complex phases are here

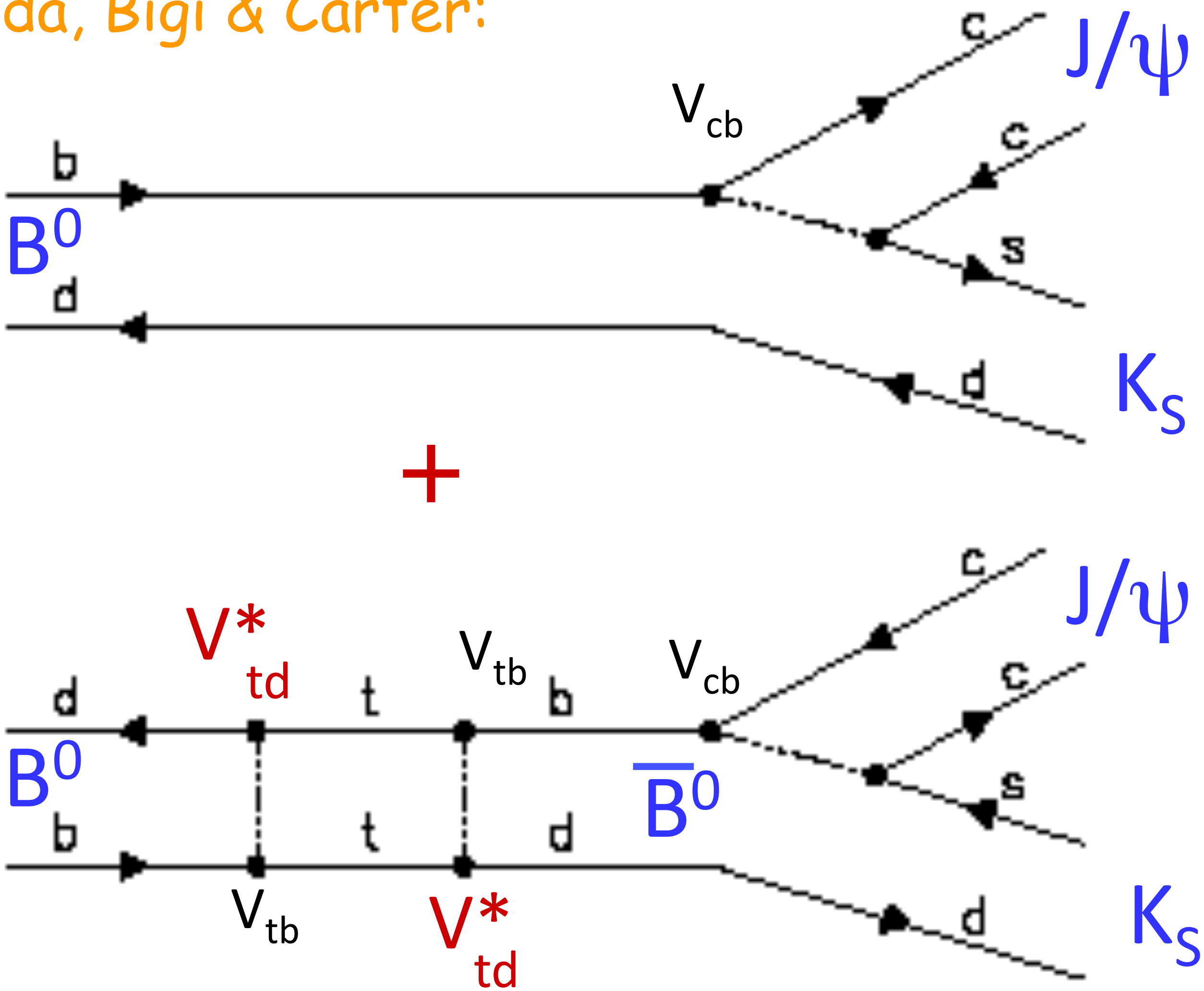
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

and here

How can these phases be measured?

phase measurements require interference

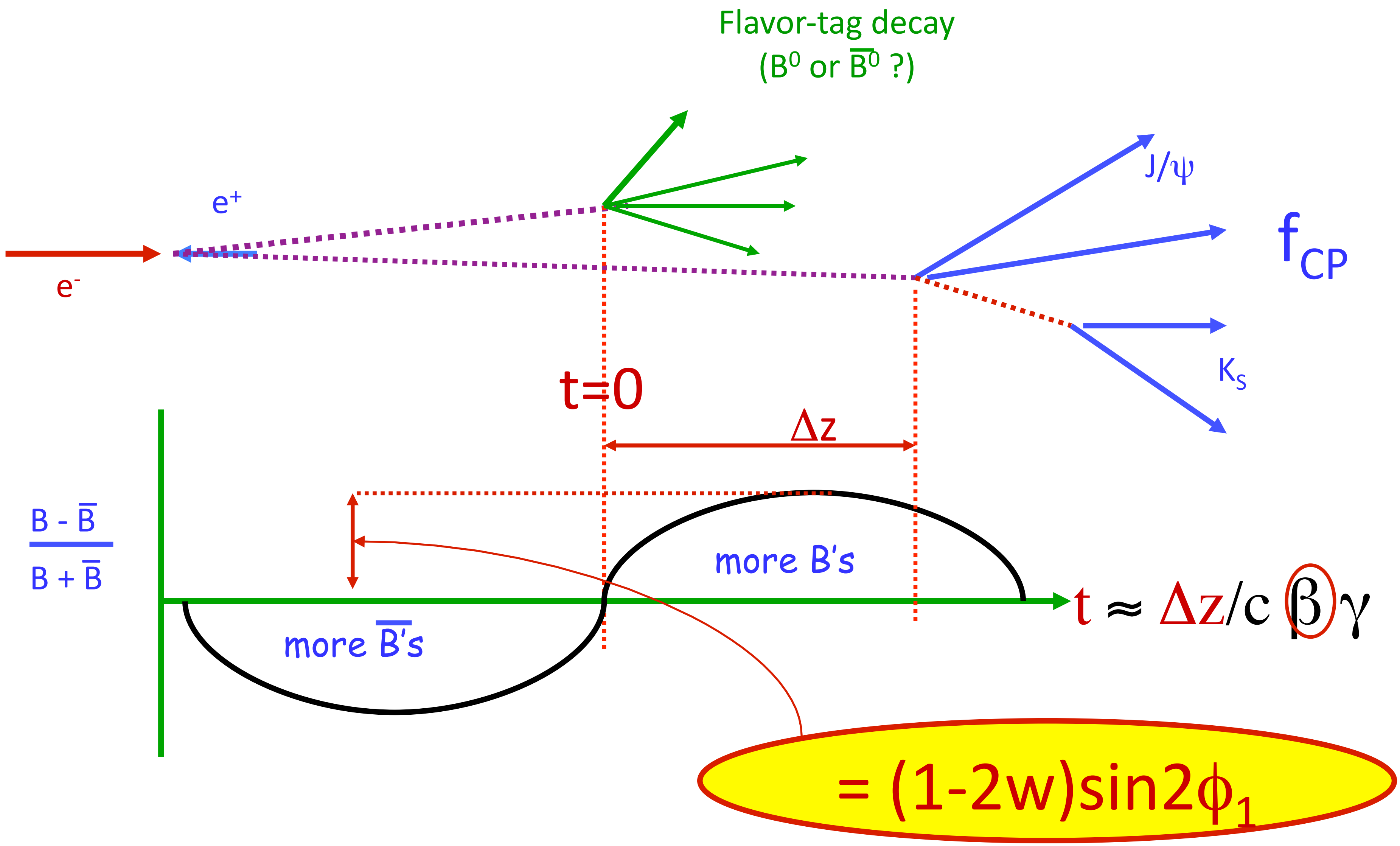
Sanda, Bigi & Carter:



$\propto V^{*2}_{td}$

(not $|V_{td}|^2$!)

Sanda-Carter-Bigi CPV asymmetry



Test of KM-mechanism for CPV require three miracles:

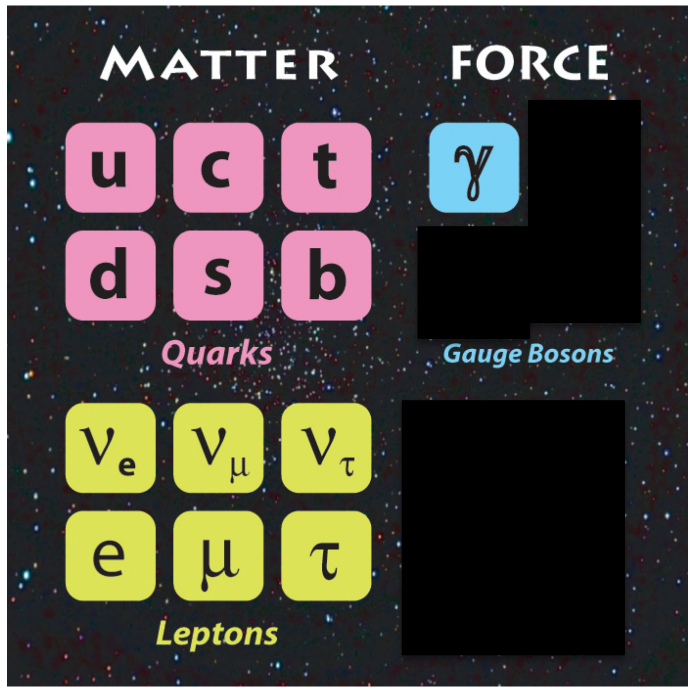
- 6 quark flavors
  - -instead of 3 (or 4)

- Long B-meson lifetime & large B↔B̄ mixing frequency
  - $\tau_{B_d} \propto G_F^2 |V_{ub}|^2 \Leftarrow$ small V_{ub} – $\Delta m_{B_d} \propto G_F^2 m_t^2 |V_{td}|^4 \Leftarrow$ large m_t

- huge improvements in accelerator & detector technology
  - -Luminosity increases by ~10^3; asymmetric beam energies
  - -High detection efficiency; excellent & efficient particle ID
  - -Exquisite vertex resolution, especially along beam direction

Miracle 1: c-, b- & t-quark discovered

Elementary Particles
In 2000

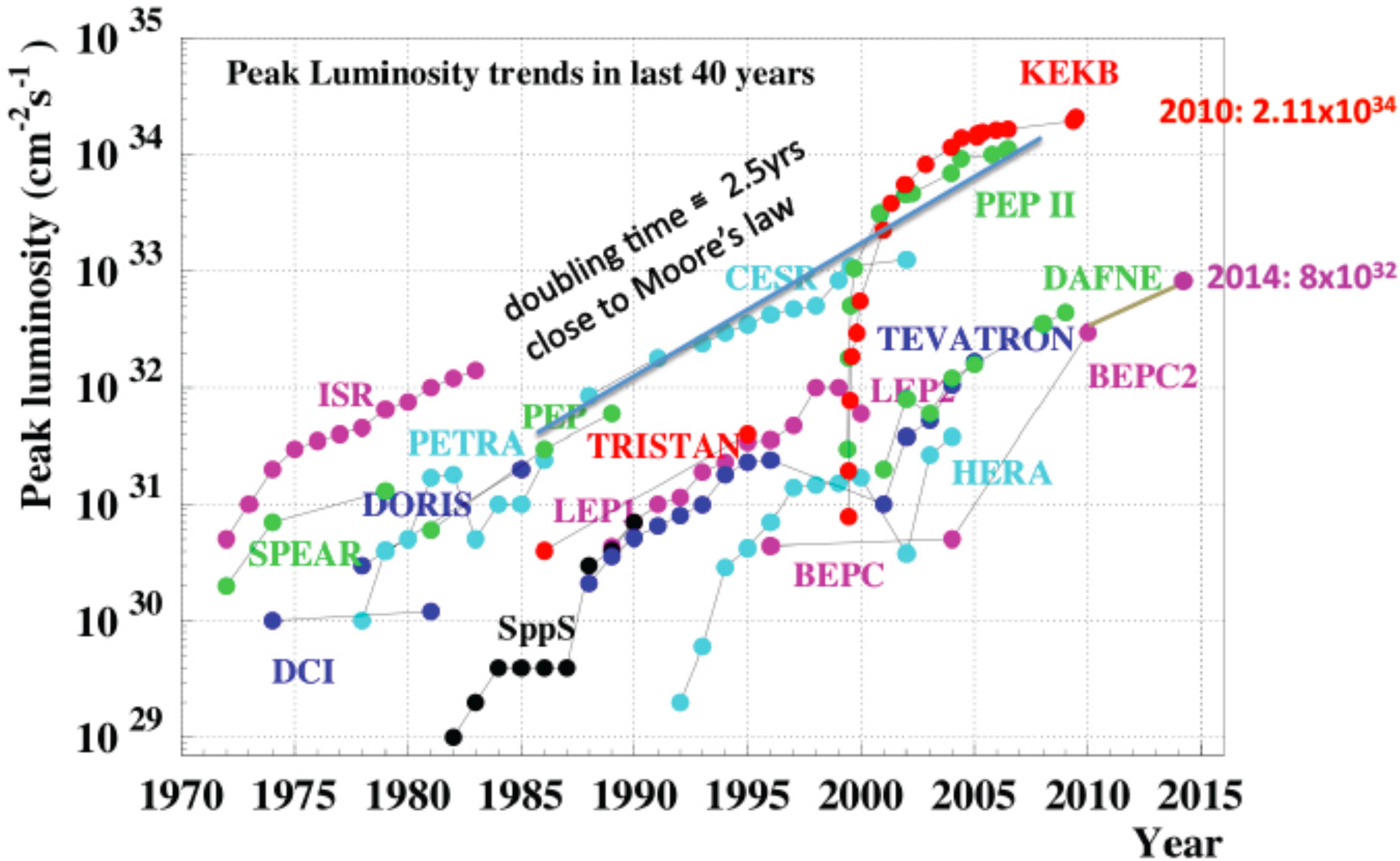


6quark flavors
established

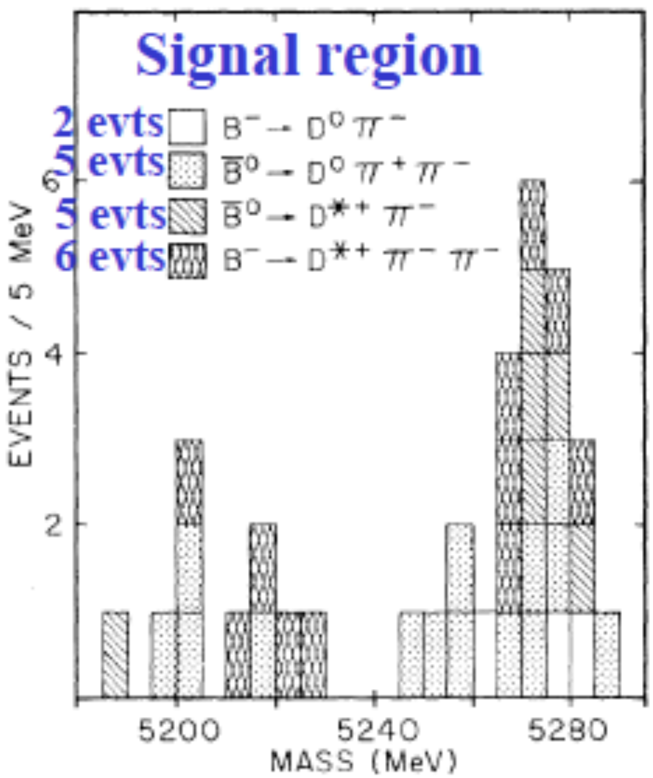
Miracle 2: τ_B, Δm_B & m_t are "just right"

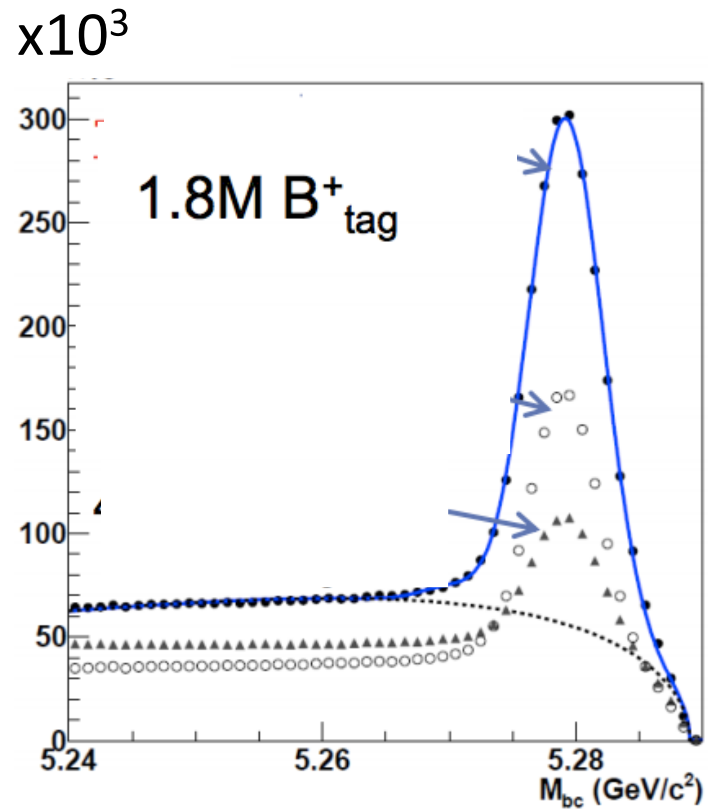
- ARGUS discovered $B \leftrightarrow \bar{B}$ mixing $\Delta m_B \approx 0.5\ ps^{-1}$
- PEP exp'ts (HRS, MAC & MarkII) find $\tau_B \approx 1.5ps$ ($\sim 3x\tau_D$)
- CDF & D0: $m_t \approx 174$ GeV

Miracle 3: e^+e^- luminosity ~ $2^{(t/2.5yr)}$



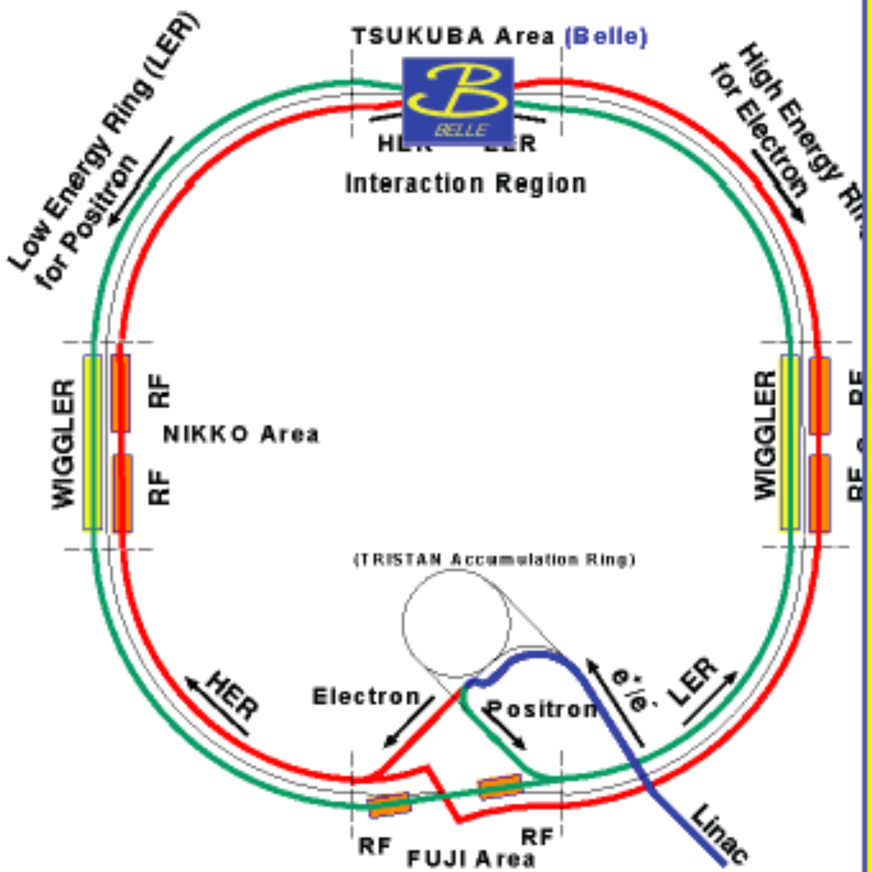
3 yrs of CLEO vs 3 years of Belle





Includes ~ 100X improvement in detector technology & reconstruction software

KEKB asymmetric e^+e^- collider



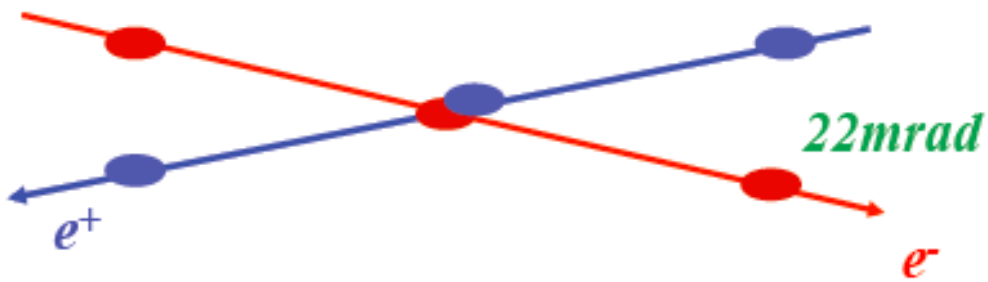
- Two separate rings
  - e^+ (LER) : 3.5 GeV
  - e^- (HER) : 8.0 GeV
- E_{CM} : 10.58 GeV at Υ(4S)
- Luminosity
  - target: 10^{34} cm^{-2}s^{-1}
  - achieved: 4×10^{33}cm^{-2}s^{-1}

Ultimately reached 2×10^{34}

- ±11 mrad crossing angle
- Small beam sizes:
- $\sigma_y \approx 3$ µm; $\sigma_x \approx 100$ µm

KEKB's Special Features

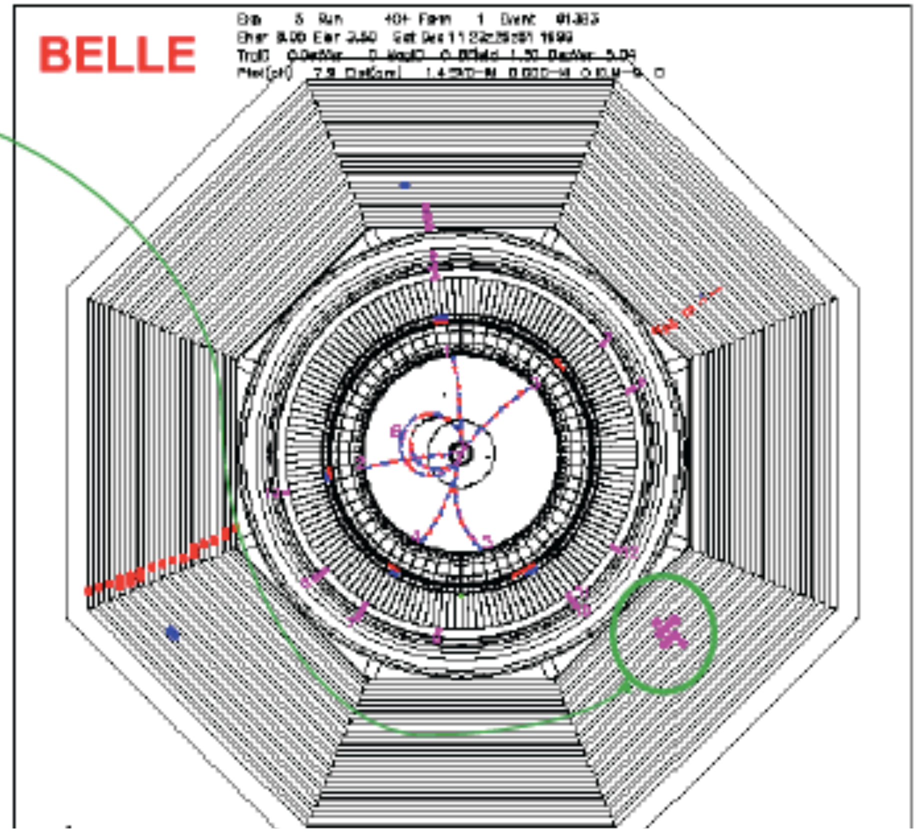
- Small beam sizes ⇒ low beam currents
  - 4.5×10^{33} with less than 1 Amp in each ring
- ± 11 mrad beam crossing angle



  - No bending magnets near the IR
  - Fewer spent particles into *Belle*
  - Synchrotron X-rays easily expelled

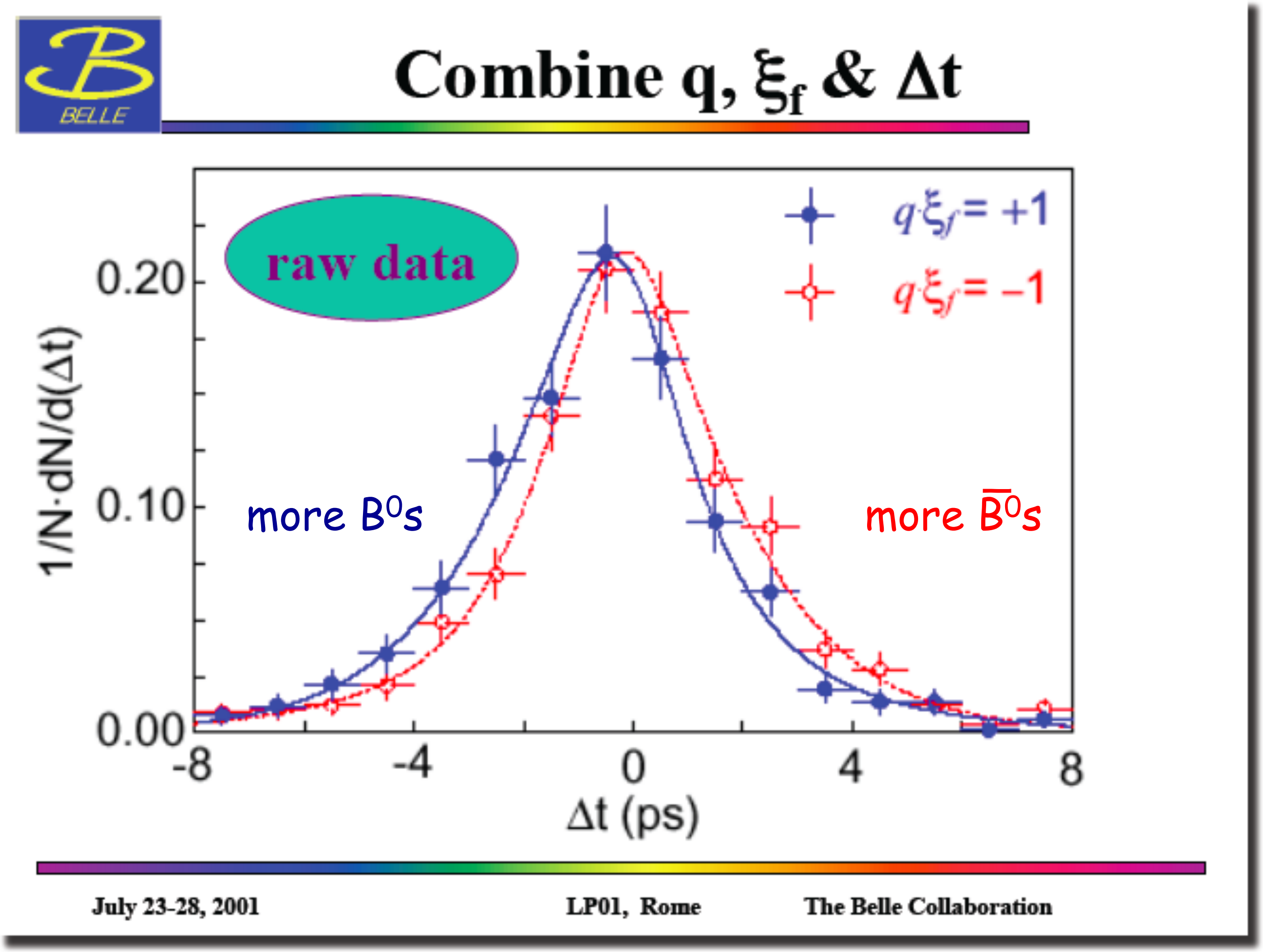
Belle special feature: Detect K_Ls

1) $J/\psi \rightarrow \ell^+\ell^-$ + K_L
2) Assume $B \rightarrow J/\psi K_L$:
   compute $\vec{P}_{KL}$
3) Remove reconstructed
   $B \rightarrow J/\psi K$, $J/\psi K^*$, …
4) Cut on a likelihood
   based on kinematical
   and shape quantities
5) Plot $P^*_B = |\vec{P}_{J/\psi} + \vec{P}_{KL}|$

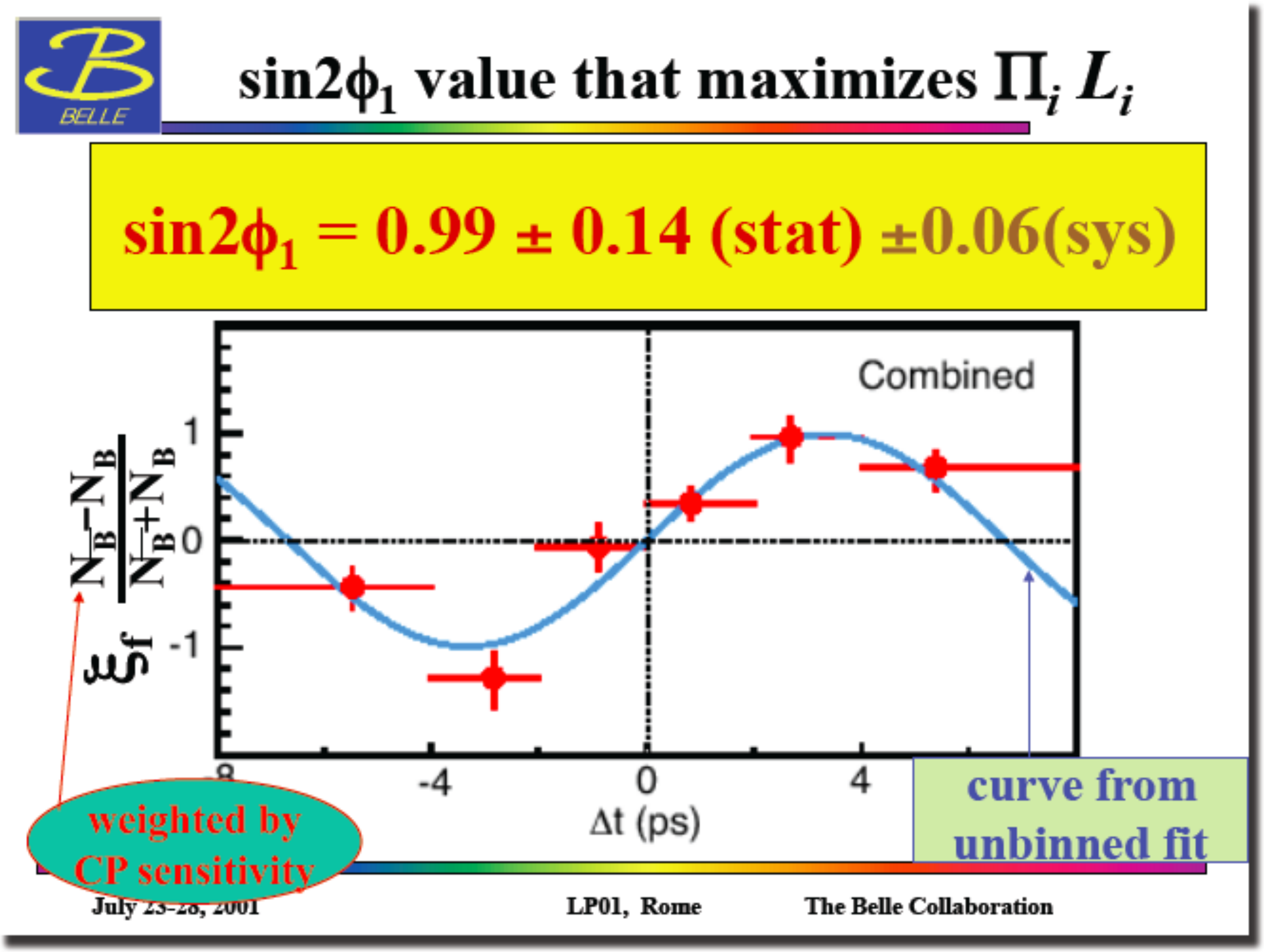


6) $B \rightarrow J/\psi K_L$ & $B \rightarrow J/\psi K_S$ have opposite CP & asymmetries

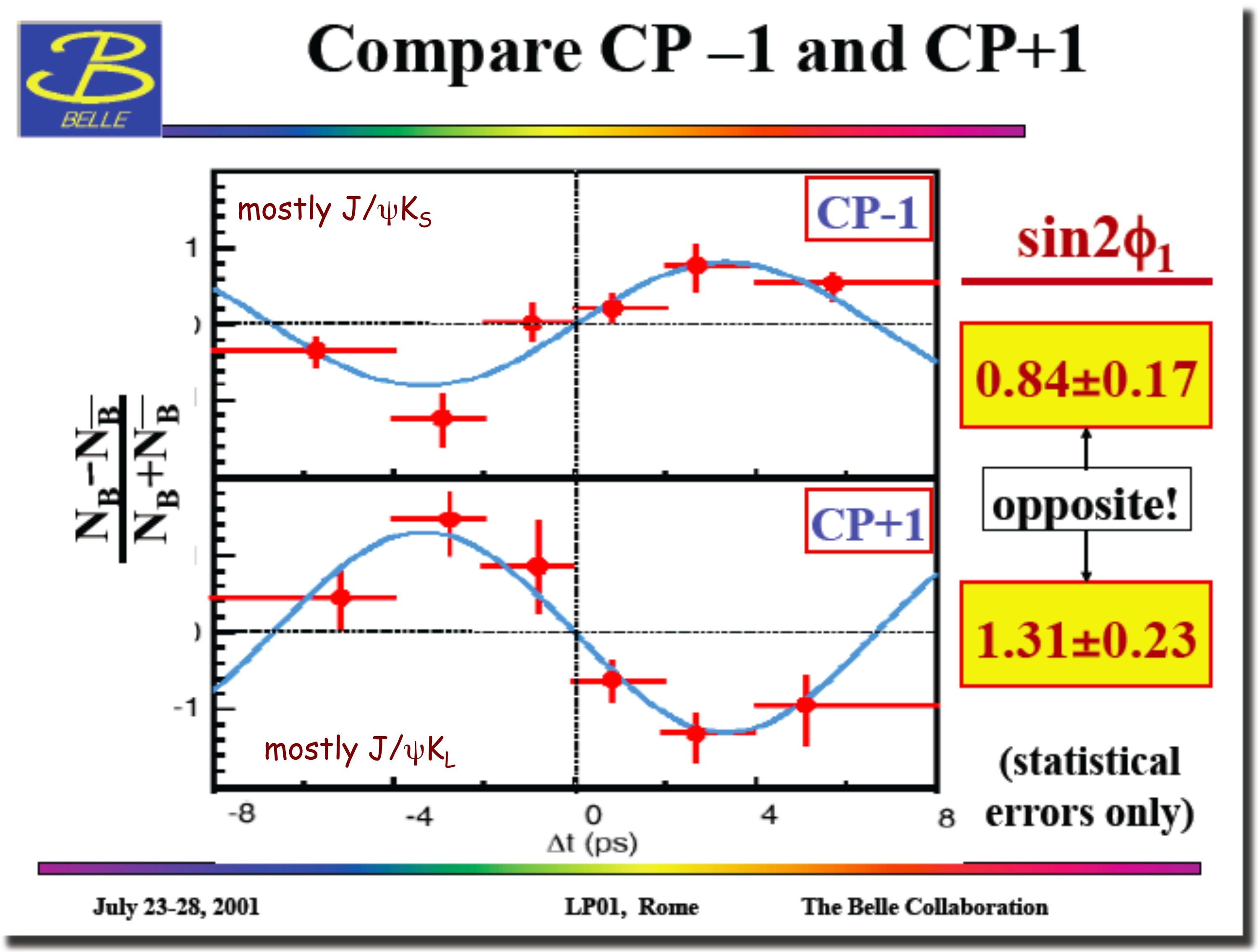
Belle results at LP-2001 Rome



Belle Results LP-2001 Rome



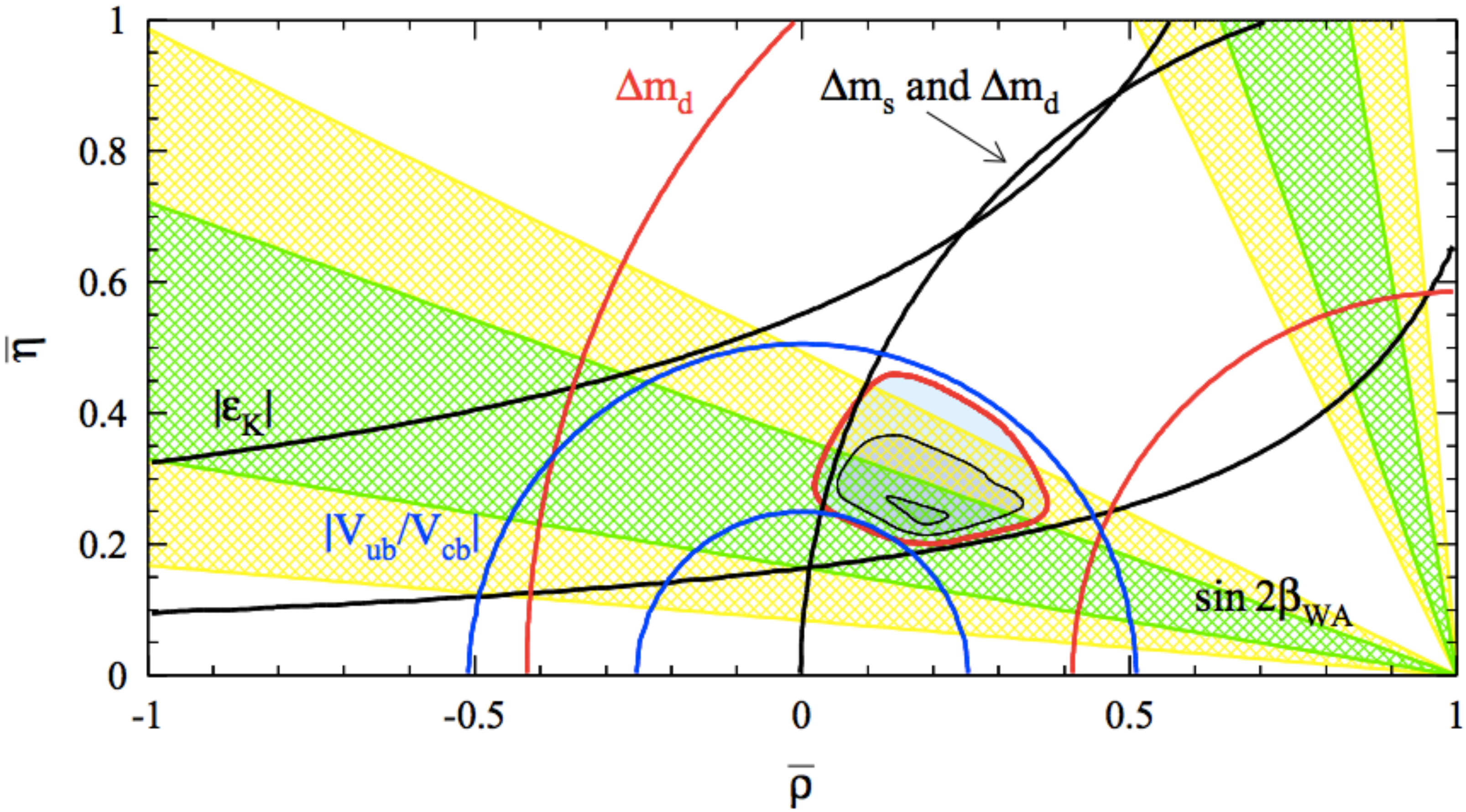
Belle Results LP-2001 Rome



BaBar/Belle comparison (LP2001)

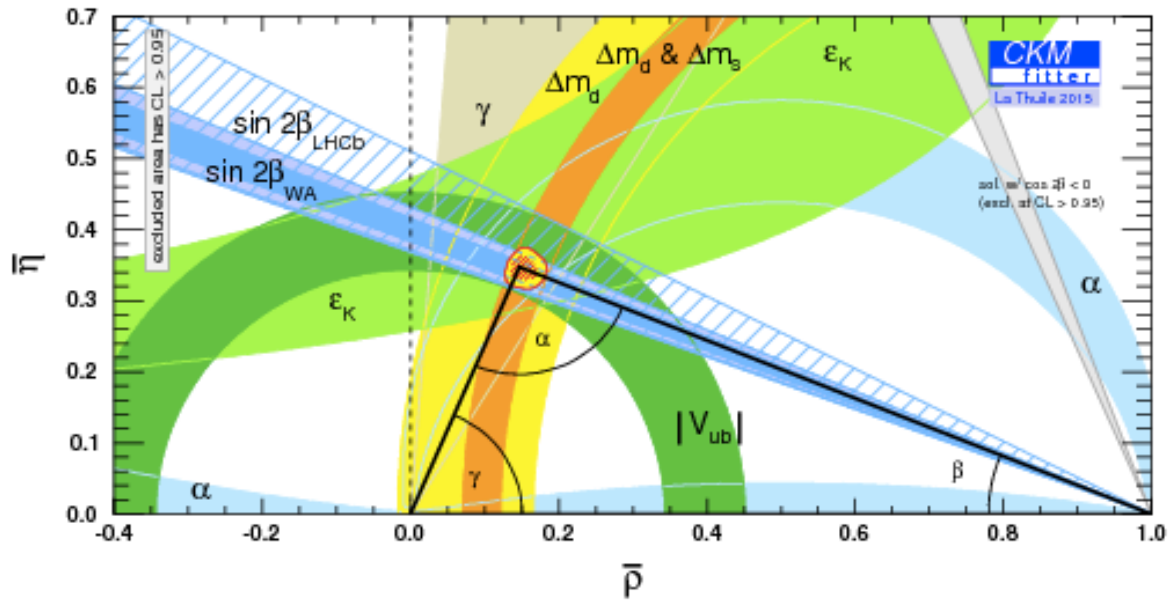
	BaBar	Belle
Integrated Luminosity	$23fb^{-1}$	$33fb^{-1}$
$K_S(\pi+\pi-)$ J/ψ events (purity)	316(96%)	457 (97%)
K_L J/ψ events (purity)	273(51%)	569 (61%)
Other CP modes	214	366
Effective tagging effic (w)	26%	27%
$\sin 2\phi_1$	0.59±0.14±0.05	0.99±0.14±0.06

Unitary Triangle: then



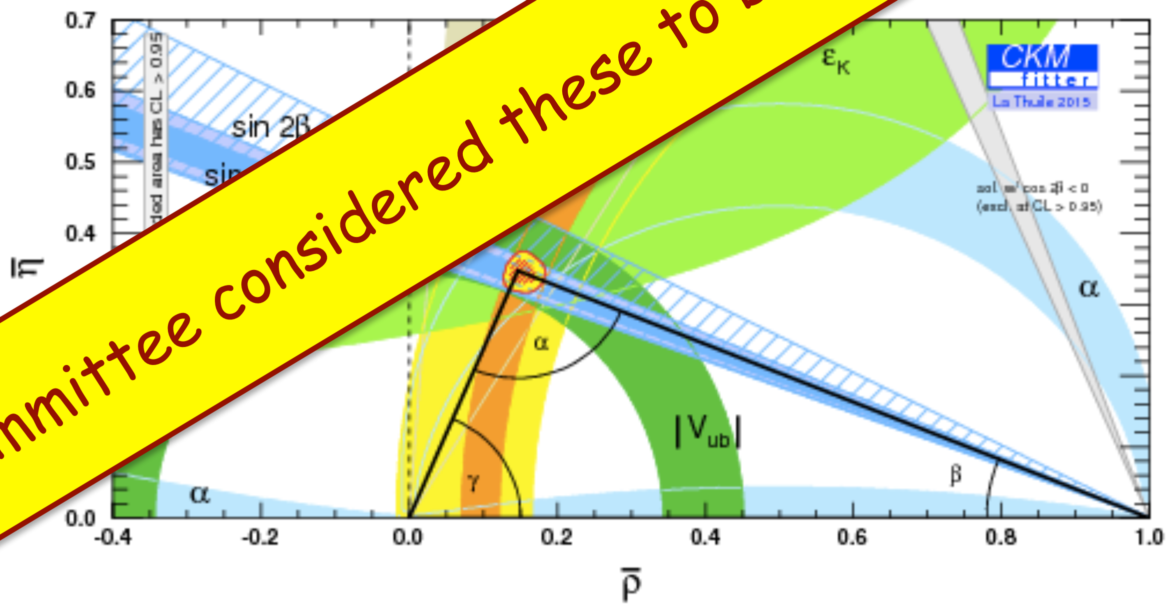
"CKM fitter" 2001: A. Hoecker et al., hep-ph/0104062v2

Unitary Triangle: & now



CKM fitter 2015

Unitary Triangle: & now



CKM fitter 2015

The Nobel committee considered these to be Belle's best results

Stockholm, December 2008

Not just B mesons

pioneering work in areas other than CPV & B physics

-- results with 100's of citations that non-specialists don't know about --

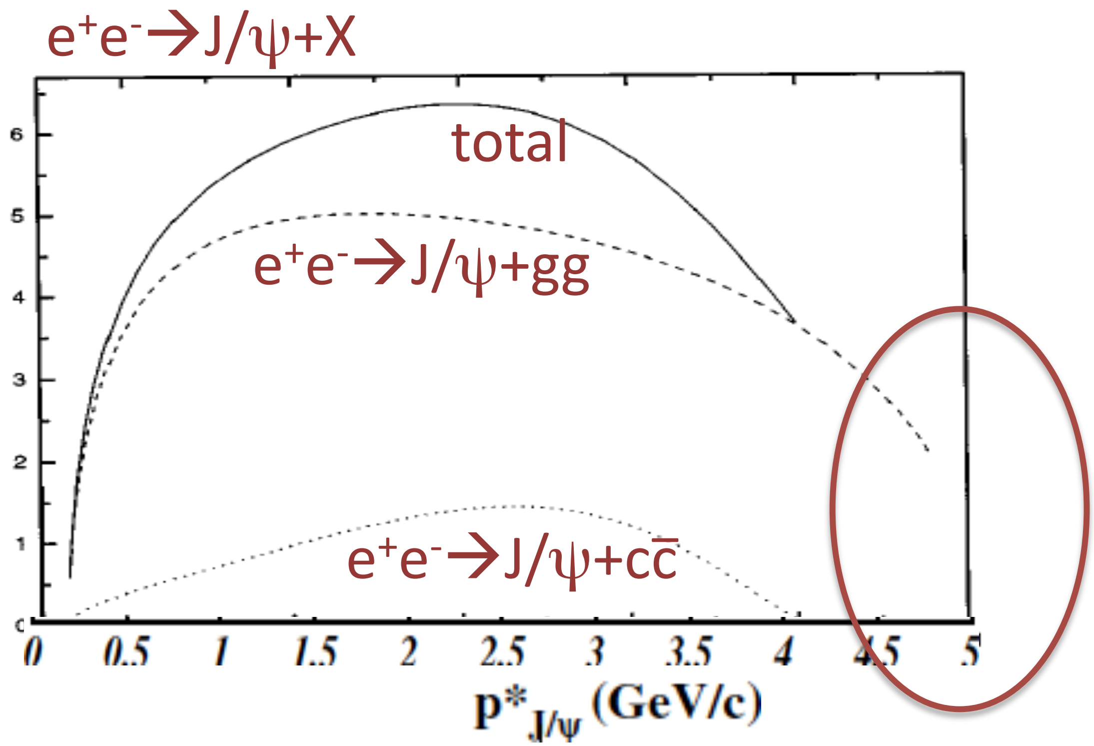
- Discovery of anomalous $e^+e^- \rightarrow c\bar{c}c\bar{c}$ annihilations
  - challenge to NRQCD

- Clarifying the nature of the light Scalar mesons
  - $\Gamma(f_0(980)\rightarrow\gamma\gamma)$ measurement

- Collins Spin Fragmentation Function
  - spin analyzer for quark jets

- Is the "$\Upsilon(5S)$" the $\Upsilon(5S)$?

Pre-Belle: NRQCD predictions for $e^+e^- \rightarrow J/\psi+X$



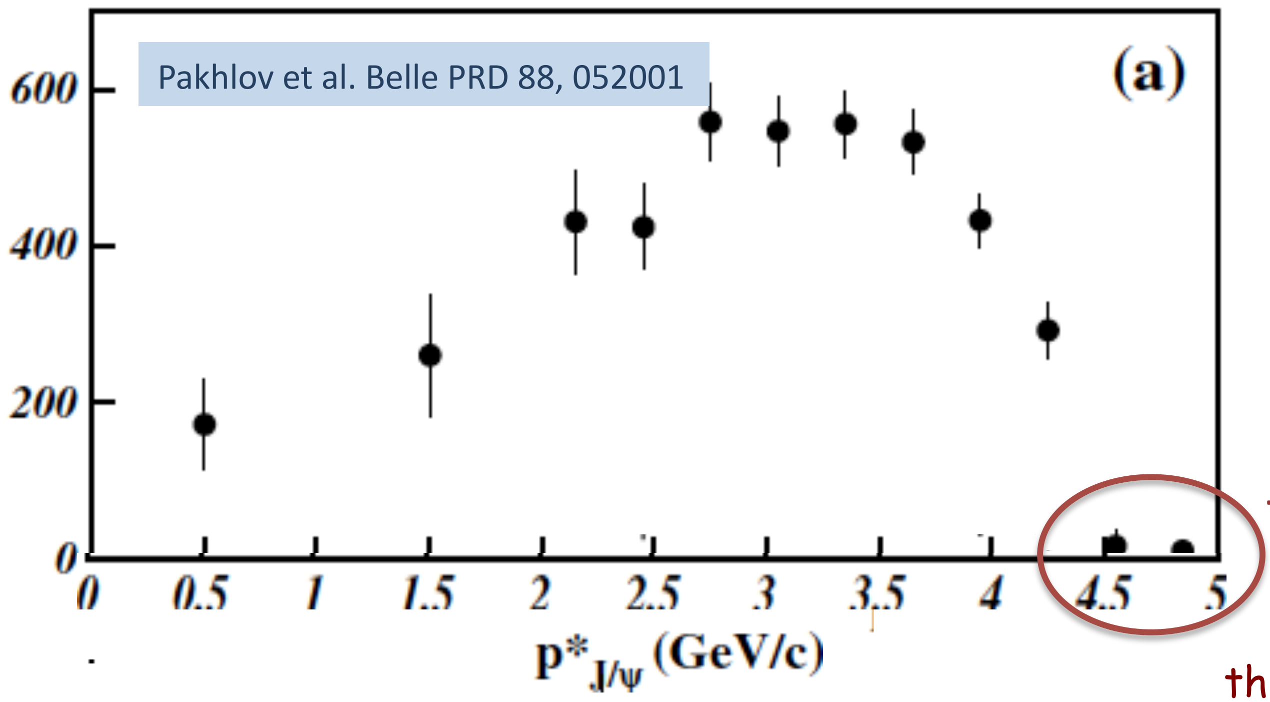
$e^+e^- \rightarrow J/\psi+gg$ expected to dominate

$\sigma(J/\psi+X)=(0.8\sim1.7)$pb

$\sigma(J/\psi+(c\bar{c}))\approx0.07$pb

strong signal expected near $p^*_{J/\psi}$=max

2002 Belle measurements of $e^+e^- \rightarrow J/\psi + X$



no signific. Signal for $p^*_{J/\psi}$>4.5 GeV

this is where color-octet $e^+e^- \rightarrow (J/\psi)_c + g$ would show up –if, in fact, it occurred

$\sigma(e^+e^- \rightarrow J/\psi + X) = 1.47 \pm 0.16$ pb

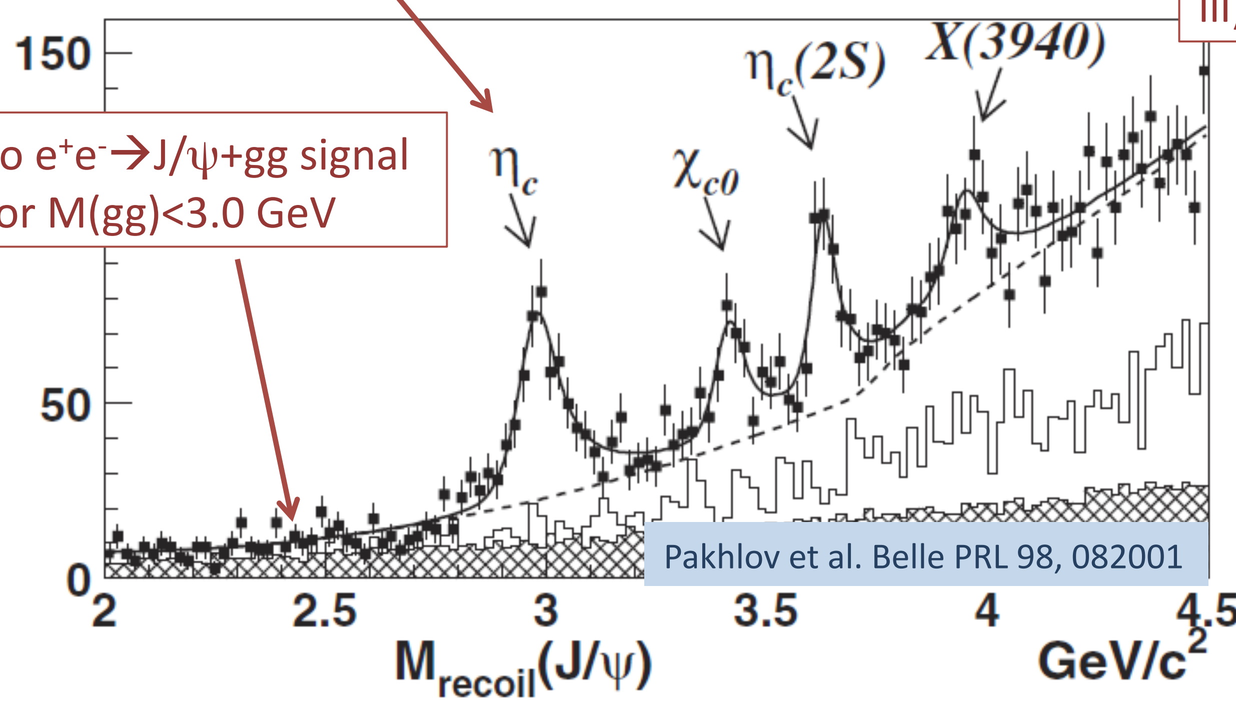
2005 Belle study of $e^+e^- \rightarrow J/\psi + X$

3 discoveries in one plot!

ii) $\sigma\{e^+e^- \rightarrow J/\psi\ \eta_c\}$ >10x NRQCD prediction

iii) New XYZ particle

i) no $e^+e^- \rightarrow J/\psi + gg$ signal for M(gg)<3.0 GeV

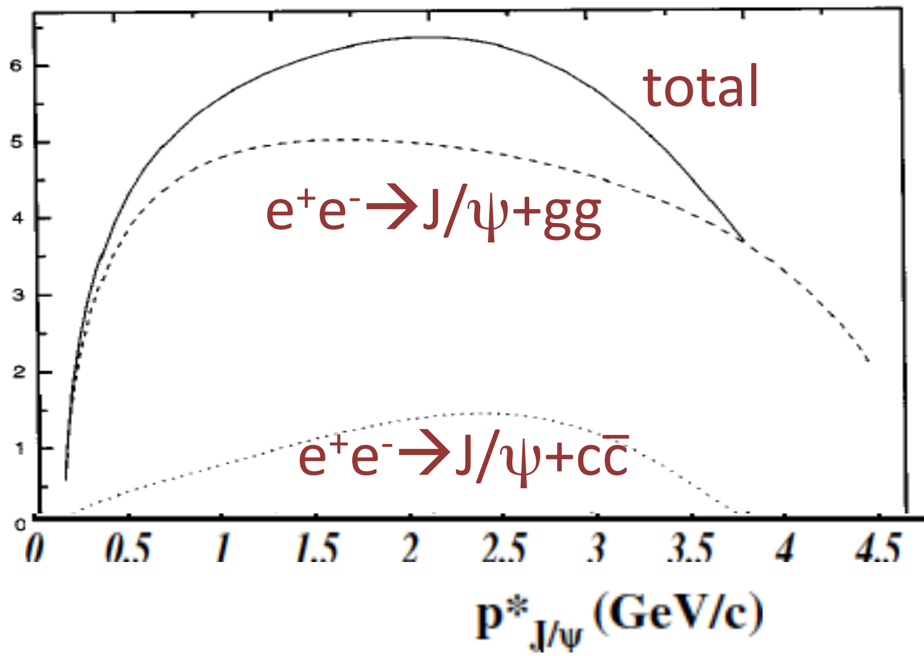


$\sigma(e^+e^- \rightarrow J/\psi\eta_c) \approx 25.6 \pm 4.4$ pb

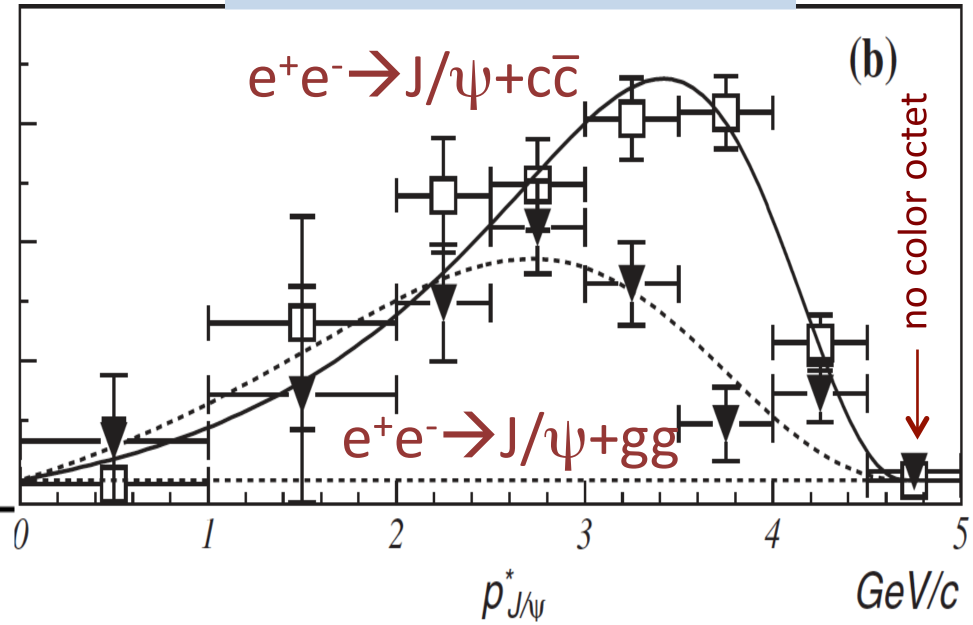
↳ >2chg

NRQCD<2fb

NRQCD vs Belle data



Pakhlov et al. Belle PRD 88, 052001



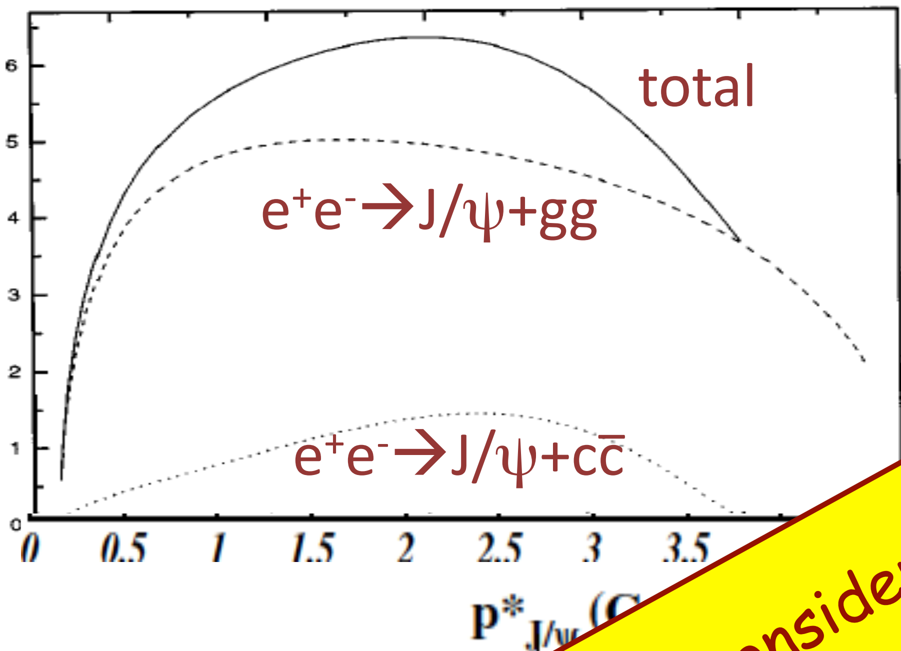
$$\frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi gg)} \leq 0.1 \quad \longleftrightarrow \quad \frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi gg)} = 1.72 \pm 0.14$$

$e^+e^- \to J/\psi+gg$ strong for p*≈4.5 ⟷ $e^+e^- \to J/\psi+gg$ ≈0 for p*≈4.5

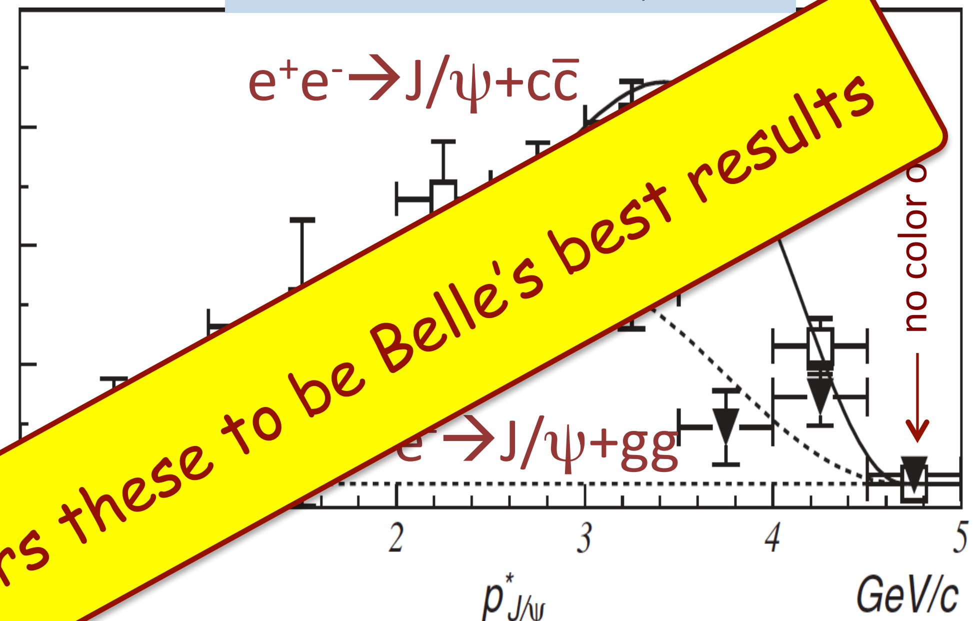
$\sigma(e^+e^- \to J/\psi\eta_c)$≈2 pb ⟷ $\sigma(e^+e^- \to J/\psi\eta_c)$≈25.6±4.4 pb

↳ >2chg

NRQCD vs Belle data



Pakhlov et al. Belle PRD 88, 052001



$$\frac{\sigma(e^+e^- \to J/\psi c\bar{c} \ldots}{\sigma(e^+e^- \ldots} \longleftrightarrow \frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi gg)} = 1.72 \pm 0.14$$

...gg strong for p*≈4.5 ⟷ $e^+e^- \to J/\psi+gg$ ≈0 for p*≈4.5

...$(e^+e^- \to J/\psi\eta_c)$≈2 pb ⟷ $\sigma(e^+e^- \to J/\psi\eta_c)$≈25.6±4.4 pb

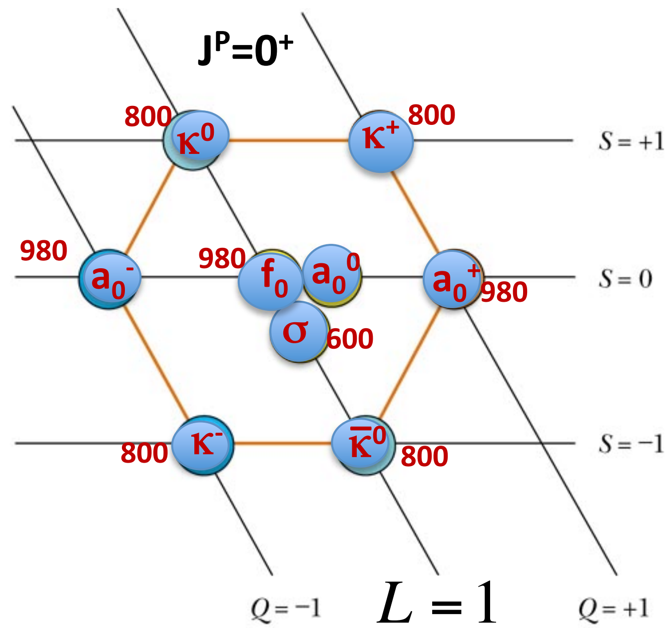
↳ >2chg

The NRQCD community considers these to be Belle's best results

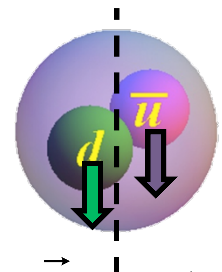
low-mass scalar meson puzzle

-- a 40 year-old puzzle in hadron physics --

the "light" scalar-meson nonet



$L = 1$

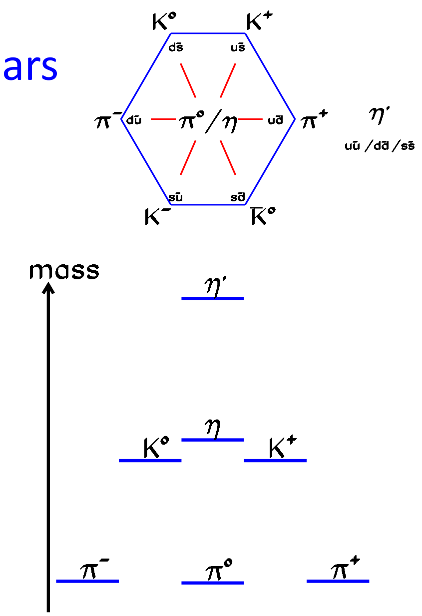


$\vec{S} = -1$

light scalar octet masses are inverted

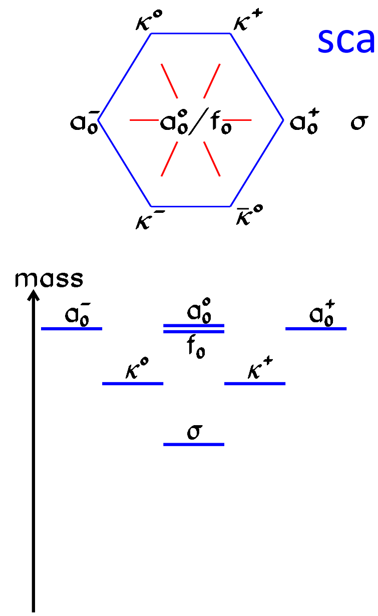
pseudoscalars

typical



scalars

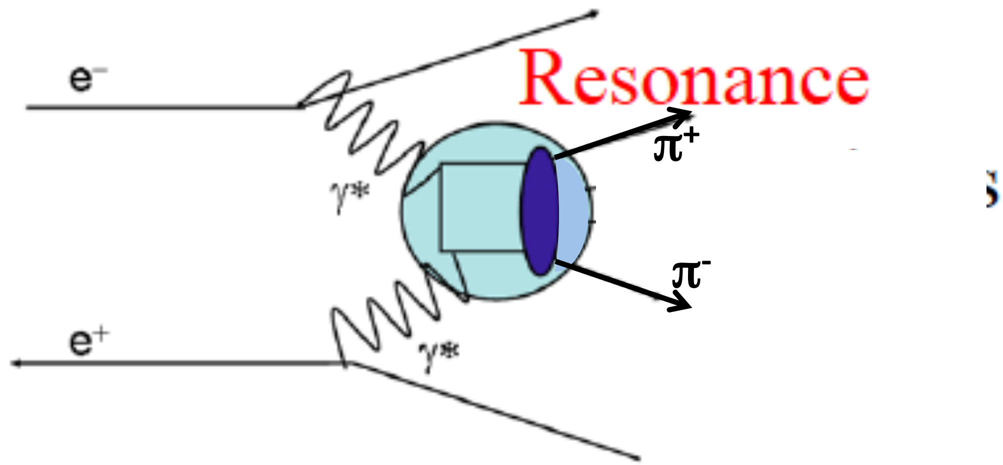
unique



Also:

- In $q\bar{q}$ meson octets, the I=1 state (here the $a_0(980)$) has no s-quarks, and and is the lightest. Here, the $a_0(980)$ Isospin triplet is the most massive.
- $m(f_0(980)) \approx m(a_0(980))$ implies "ideal" mixing & ***small*** s-quark content in $f_0(980)$.
- strong $a_0(980)$ & $f_0(980)$ couplings to $K\bar{K}$ indicate strong OZI-rule violations

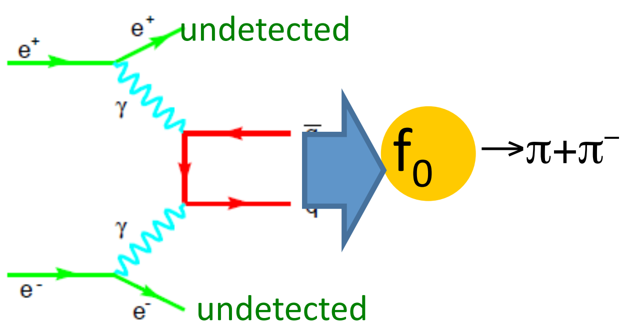
$\gamma\gamma \rightarrow \pi^+\pi^-$ as a probe $f_0(980)$ structure



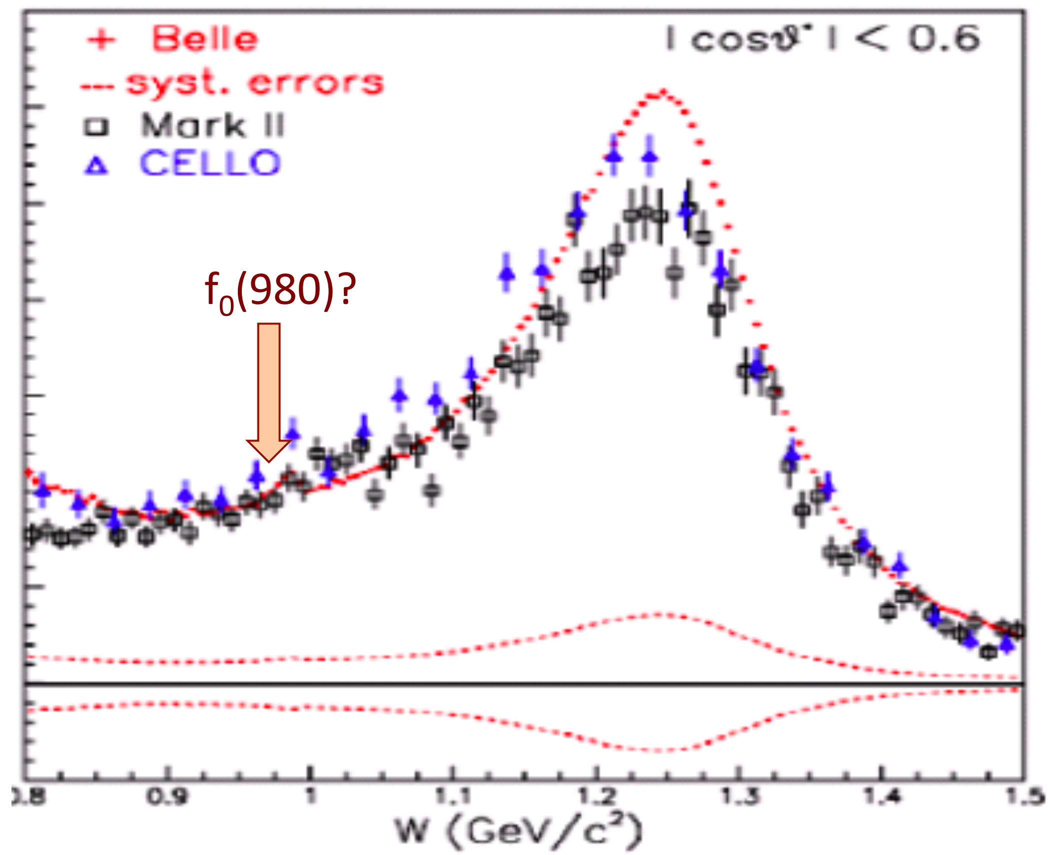
$$\sigma(\gamma\gamma \rightarrow R \rightarrow \pi^+\pi^-) \propto \Gamma(R \rightarrow \gamma\gamma) \times Bf(R \rightarrow \pi^+\pi^-)$$

World's data on $\gamma\gamma \rightarrow \pi^+\pi^-$

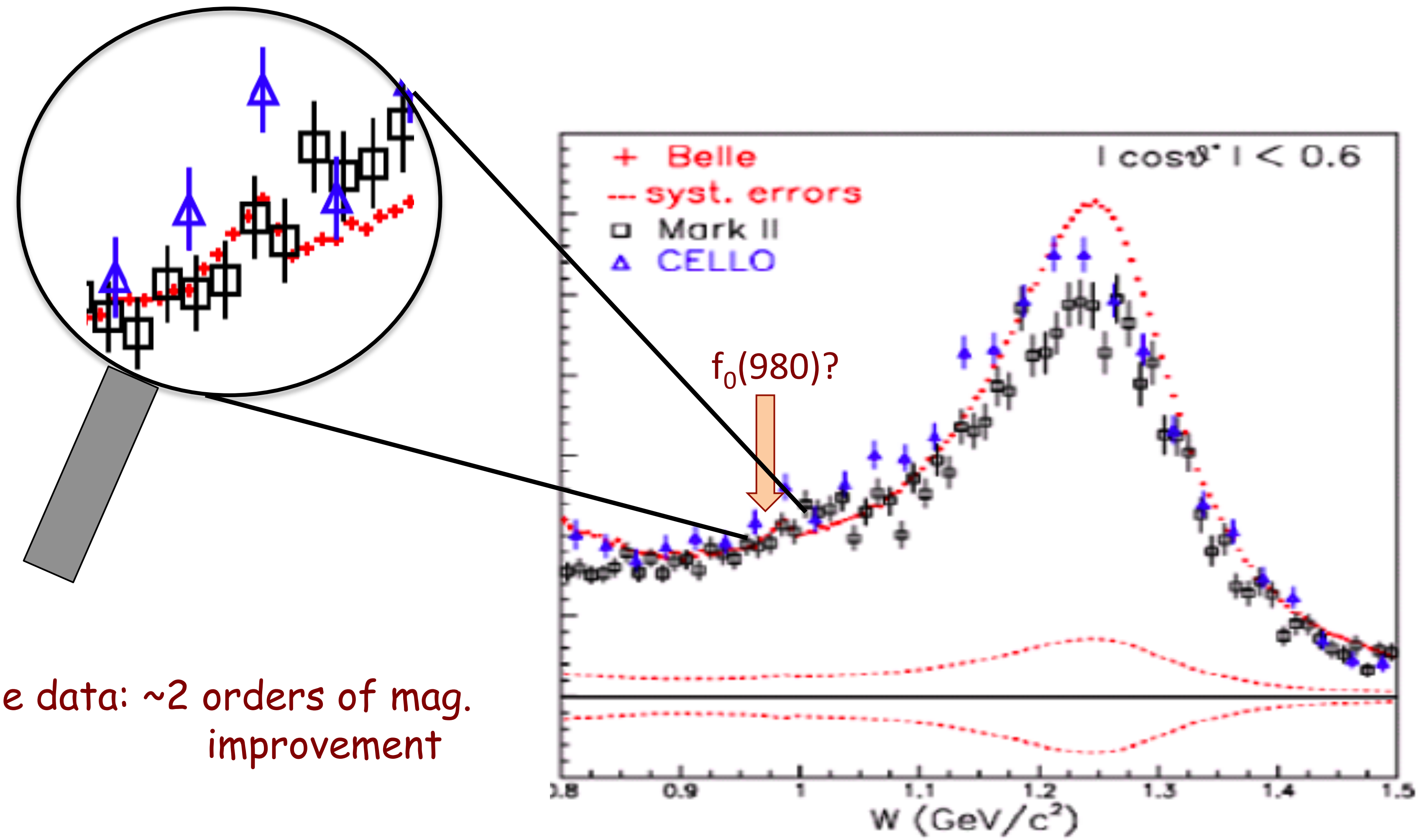
$\gamma\gamma \rightarrow \pi^+\pi^-$



Mori et al. Belle PRD 85, 051101



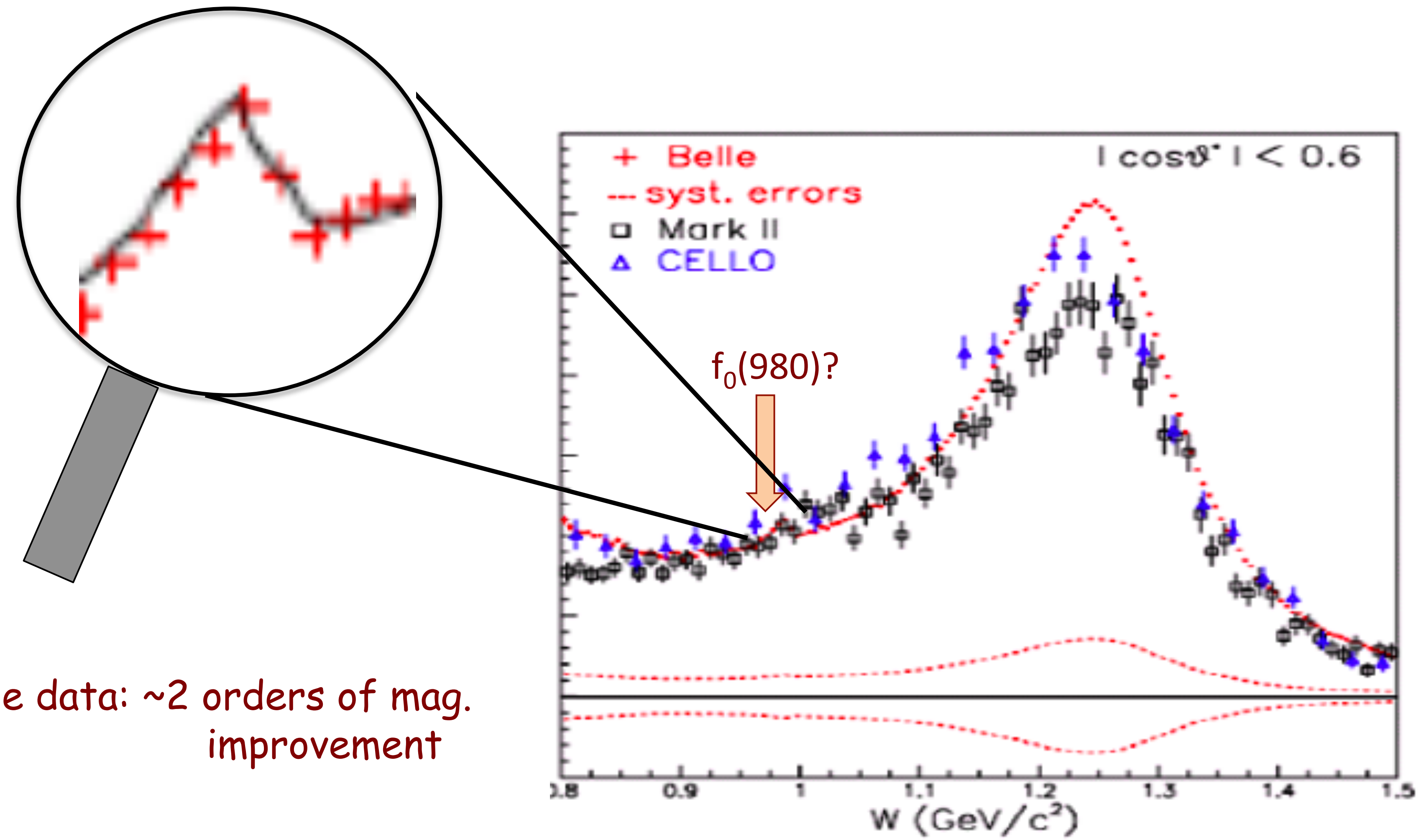
World's data on $\gamma\gamma \rightarrow \pi^+\pi^-$



Belle data: ~2 orders of mag. improvement

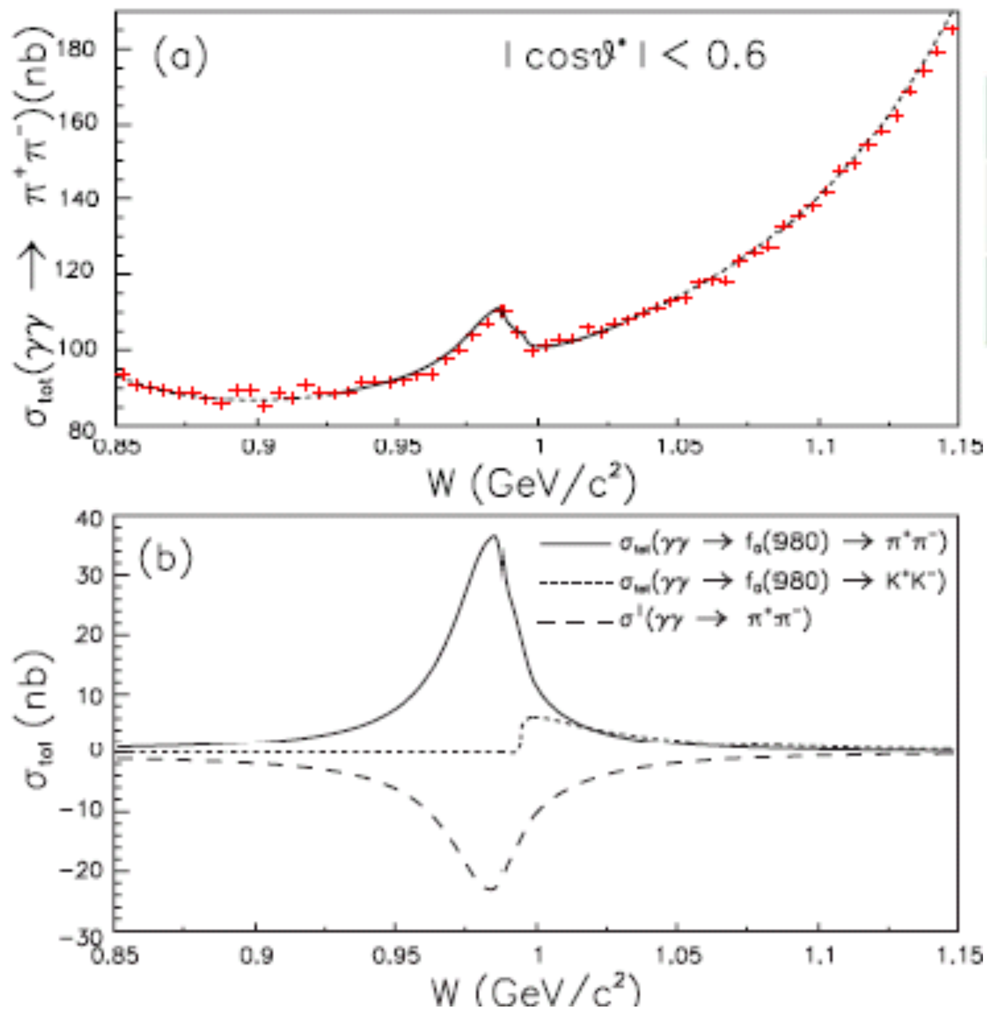
World's data on $\gamma\gamma \rightarrow \pi^+\pi^-$

Belle data only



Belle data: ~2 orders of mag. improvement

Results



Mori et al. Belle J.Phys.Soc.Jap76. 074102

$M[MeV/c^2]$	$985.6^{+1.2+1.1}_{-1.5-1.6}$
$\Gamma_{\pi\pi/tot}[MeV]$	$51.3^{+20.9+13.2}_{-17.7-3.8}$
$\Gamma_{\gamma\gamma}[eV]$	$205^{+95+147}_{-83-117}$

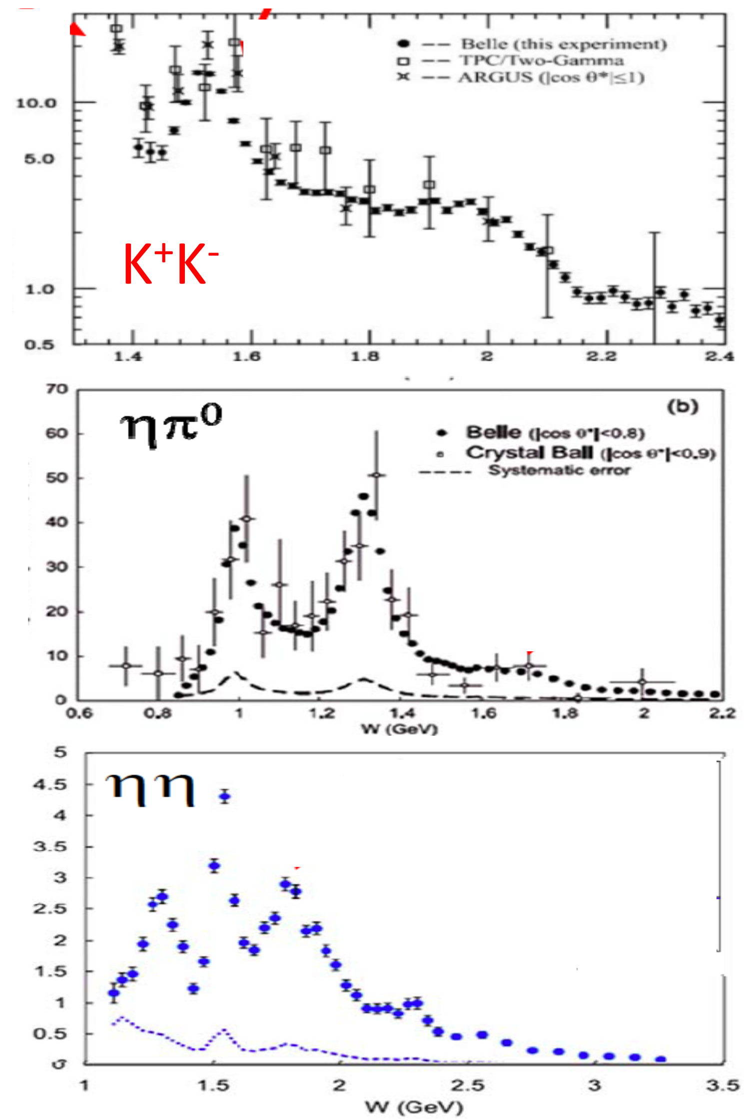
Predictions from different models

Model	$\Gamma_{\gamma\gamma}$ [eV]
*uu*bar,*dd*bar	1300 – 1800
*ss*bar	300 – 500
*KK*bar molecule	200 – 600
Four-quark	270

Probably a QM mixture of these with very little uubar & ddbar

Similar improvements on other channels, mass ranges

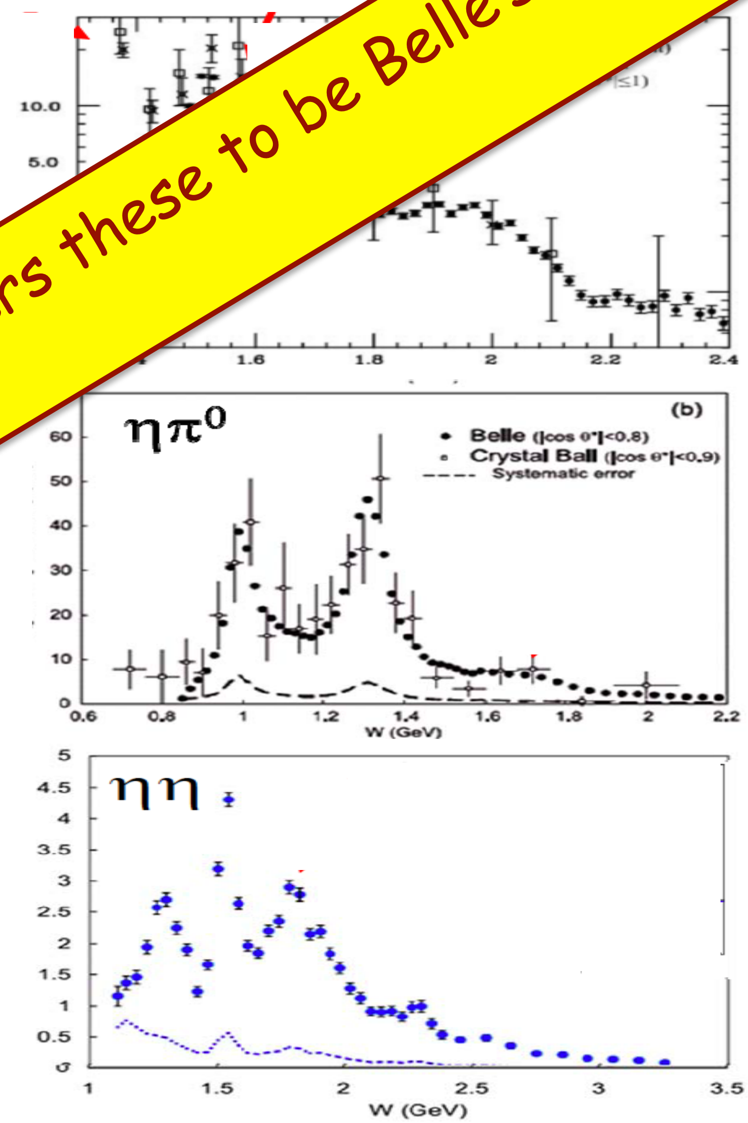
Process	Reference
$\pi^+\pi^-$	PLB 615, 39 (2005) PRD 75, 051101(R) (2007) J. Phys. Soc. Jpn. 76, 074102 (2007)
K^+K^-	EPJC 32, 323 (2003) PLB 615, 39 (2005)
$\pi^0\pi^0$	PRD 78, 052004 (2008) PRD 79, 052009 (2009)
$K^0_S K^0_S$	PLB 651, 15 (2007) PTEP 2013, 123C01 (2013)
$\eta\pi^0$	PRD 80, 032001 (2009)
$\eta\eta$	PRD 82, 114031 (2010)



Similar improvements on other channels, mass ranges

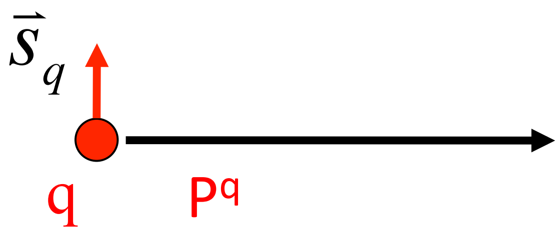
Process	Reference
$\pi^+\pi^-$	PLB 615, 39 (2005) PRD 75, 051101(R) (2007) J. Phys. Soc. Jpn. 76, 07410
K^+K^-	EPJC 32, 323 (2003) PLB 615, 39 (200
$\pi^0\pi^0$	PRD 78, 0 PRD
$K^0{}_SK^0$	7) 123C01 (2013)
	80, 032001 (2009)
	PRD 82, 114031 (2010)

The scalar-meson community considers these to be Belle's best results

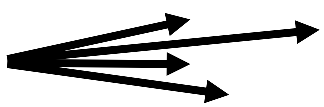


Analyzing the spin of quarks

Theorists deal with quarks & gluons



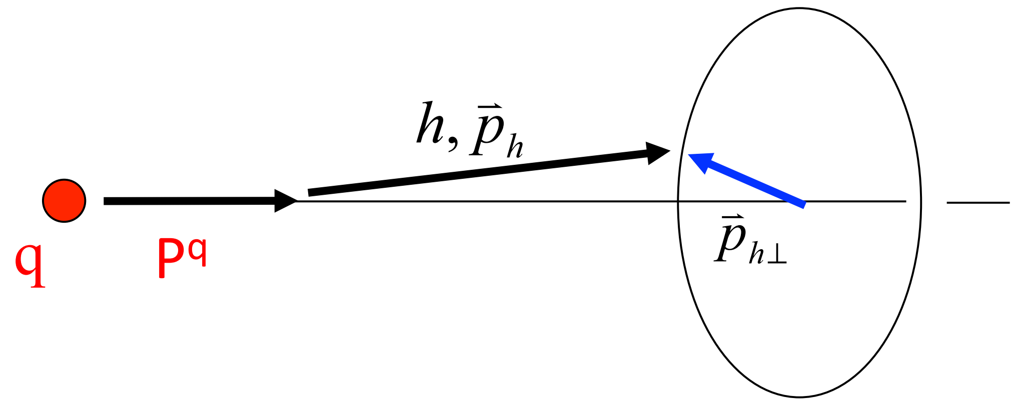
Experimenters deal with jets



Relating partons to hadrons is a critical issue

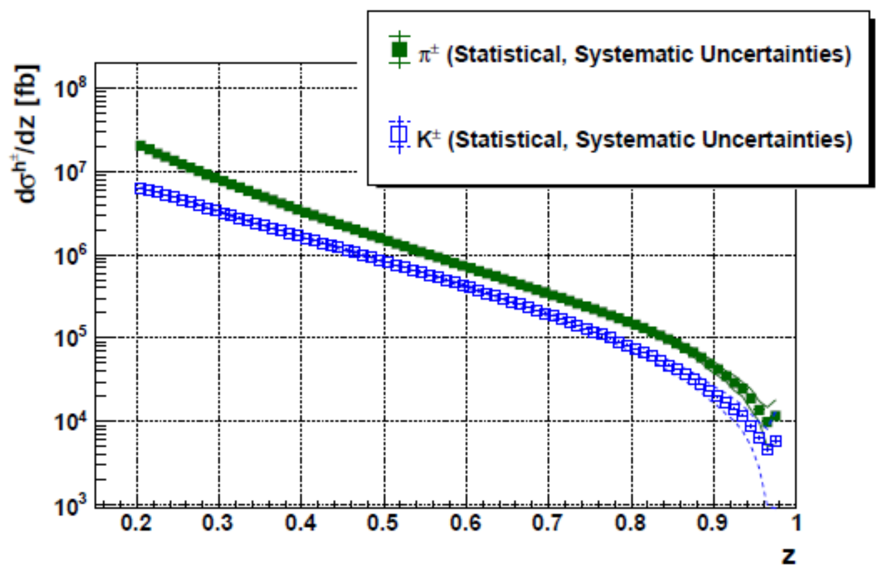
quark fragmentation functions

Unpolarized quarks:



$D_q^h\,(z, P_{h\perp})$ Density of finding a hadron h with energy fraction $z = P^h/P^q$ and $|\vec{p}_{h\perp}|$ in a jet produced by a parton q

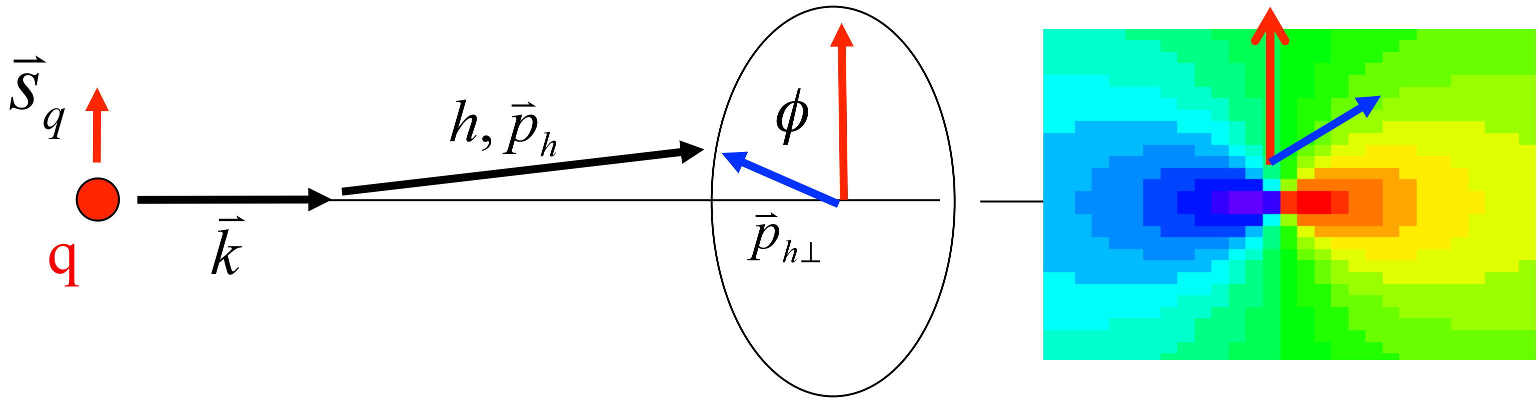
Belle has done a lot of work on these



Collins spin fragmentation functions

Polarized quarks:

Asymmetries like this are seen seen in Hermes and Compass



$$D_{q^{\uparrow}}^{h}(z, P_{h\perp}) = D_{1,q}^{h}(z, P_{h\perp}^{2}) + H_{1,q}^{\perp h}(z, P_{h\perp}^{2}) \frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{z M_h}$$

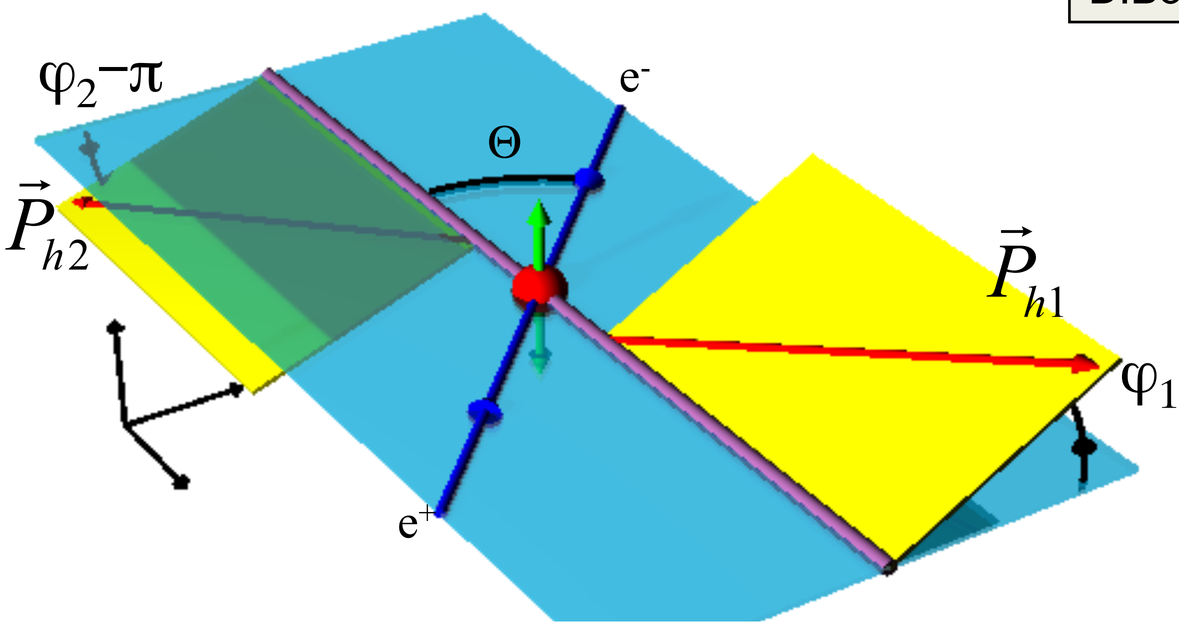
J. Collins, Nucl. Phys. B396, (1993) 161

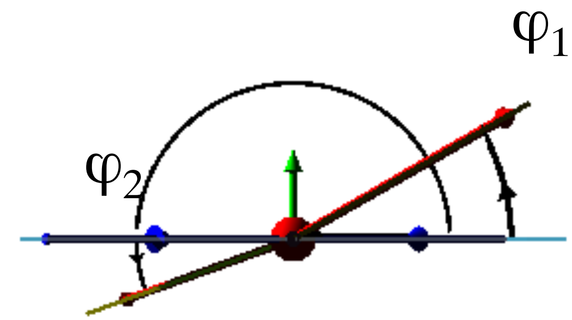
quark spin analyzing power

To measure *H*, a source of quarks with known polarization is needed

Use spin correlations in $e^+e^- \rightarrow q\bar{q}$

D.Boer: Nucl.Phys. B806 (2009) 23-6



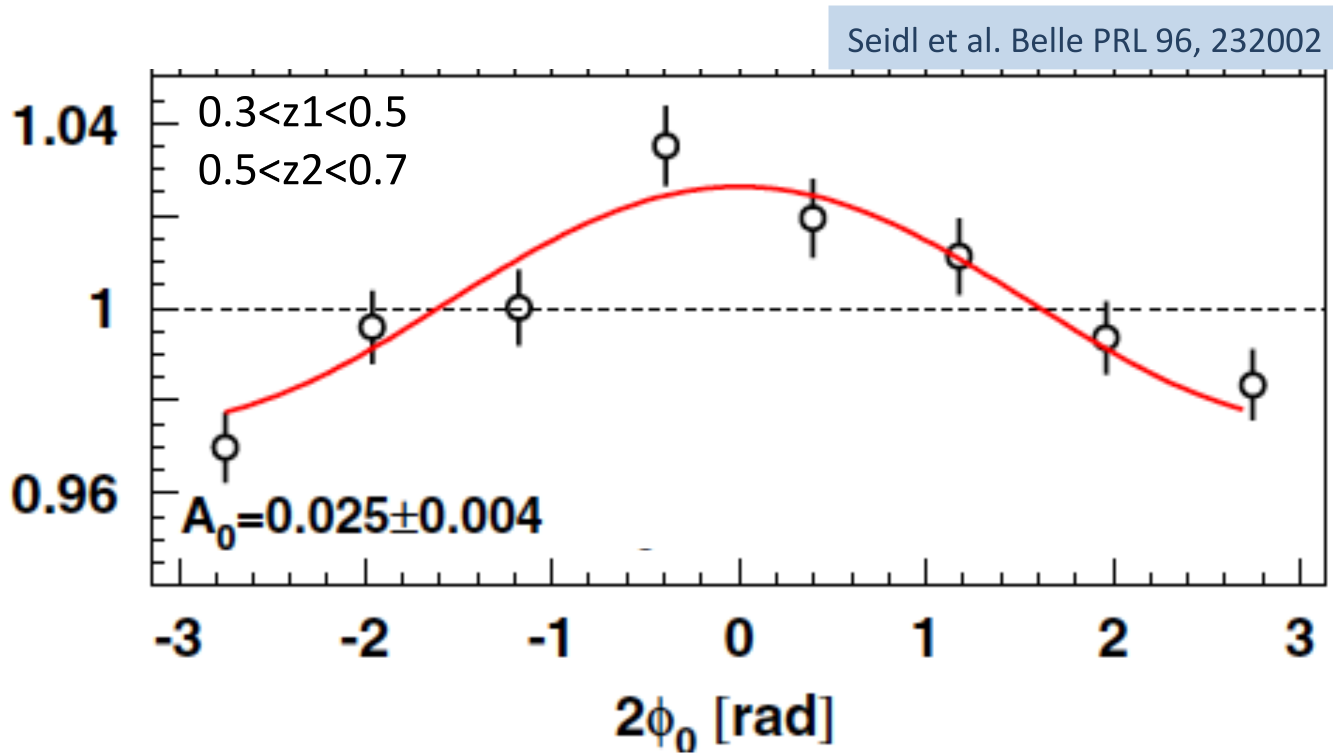


$$\frac{d\sigma\left(e^+e^- \rightarrow h_1 h_2 X\right)}{d\Omega dz_1 dz_2 d^2 q_T} = \cdots B(y)\cos\left(\varphi_1 + \varphi_2\right) H_1^{\perp[1]}\left(z_1\right) \overline{H}_1^{\perp[1]}\left(z_2\right)$$

$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net (anti-)alignment of transverse quark spins

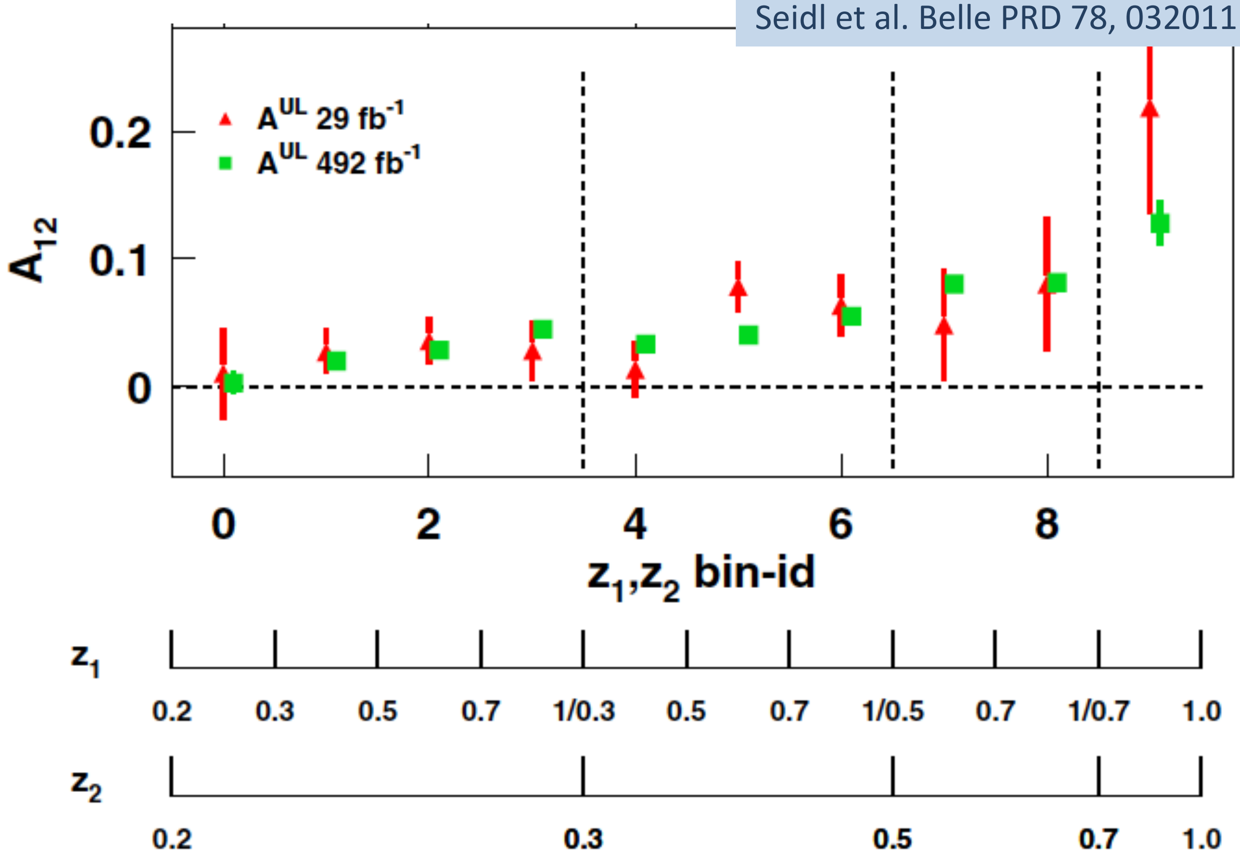
typical $\cos(\phi_1+\phi_2)$ distribution from Belle



1[st] observation of a Collins-type $\cos(\phi_1+\phi_2)$ asymmetry

Results

Seidl et al. Belle PRD 78, 032011

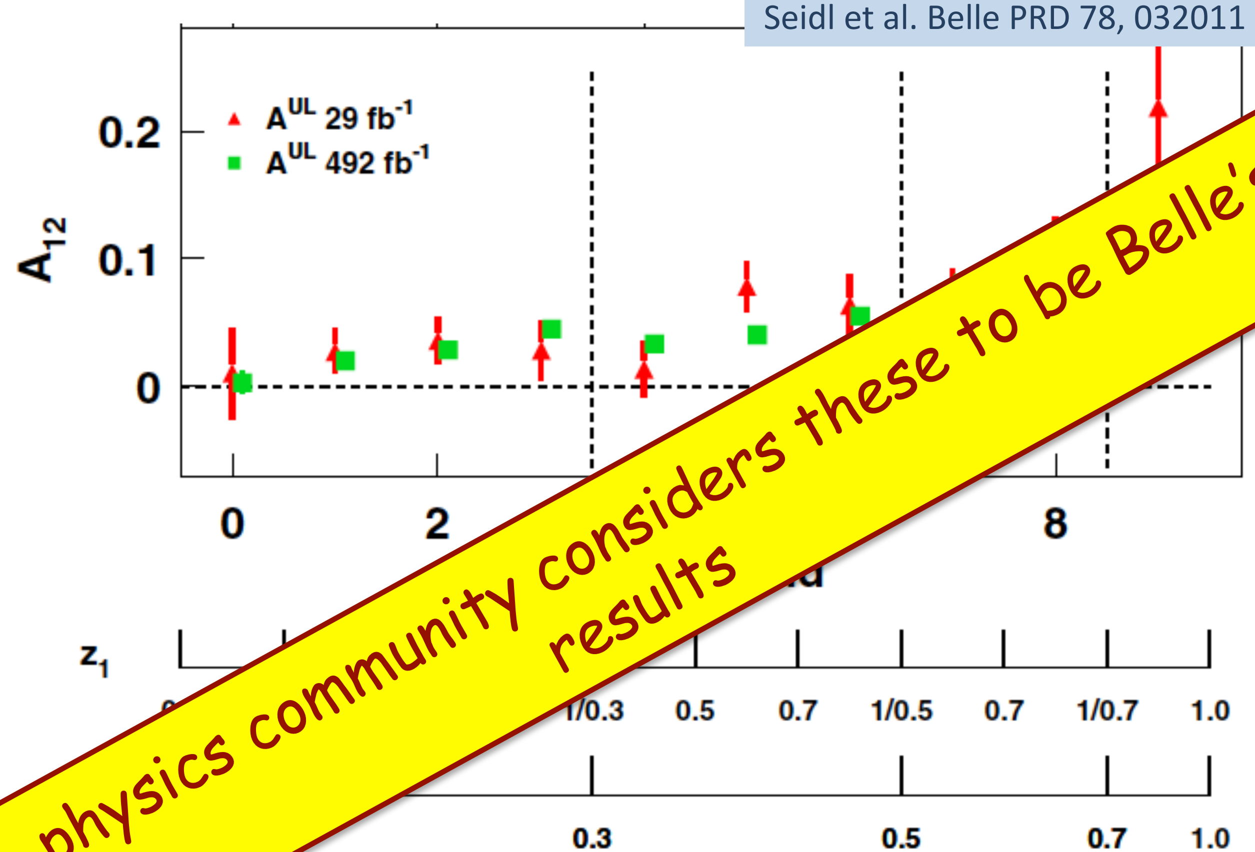


$$A_{12}(z_1,z_2) \propto H(z_1)\overline{H}(z_2)$$

5% A_{12} asymm → 22% $H(z)$ asymm

Results

Seidl et al. Belle PRD 78, 032011

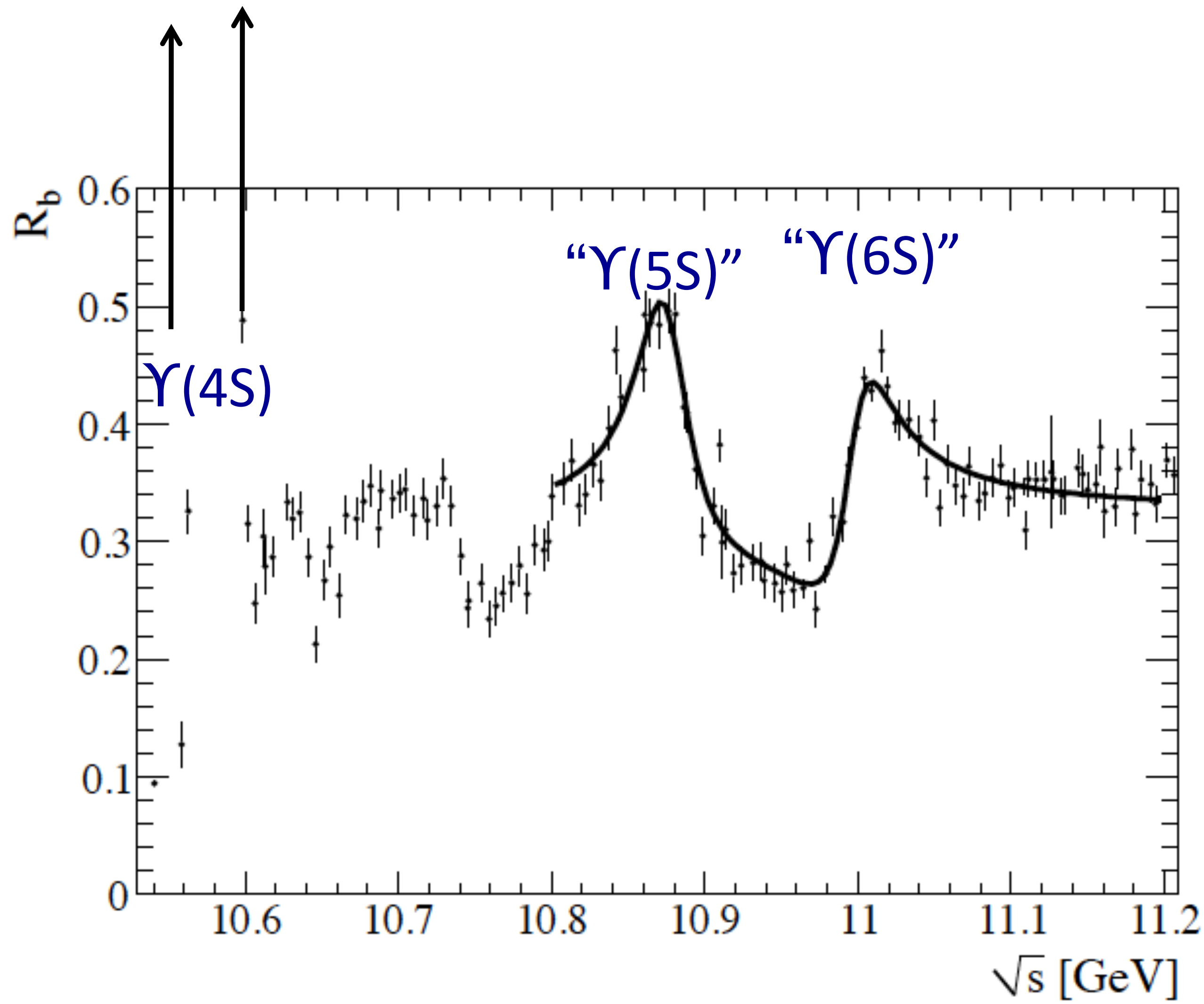


The spin-physics community considers these to be Belle's best results

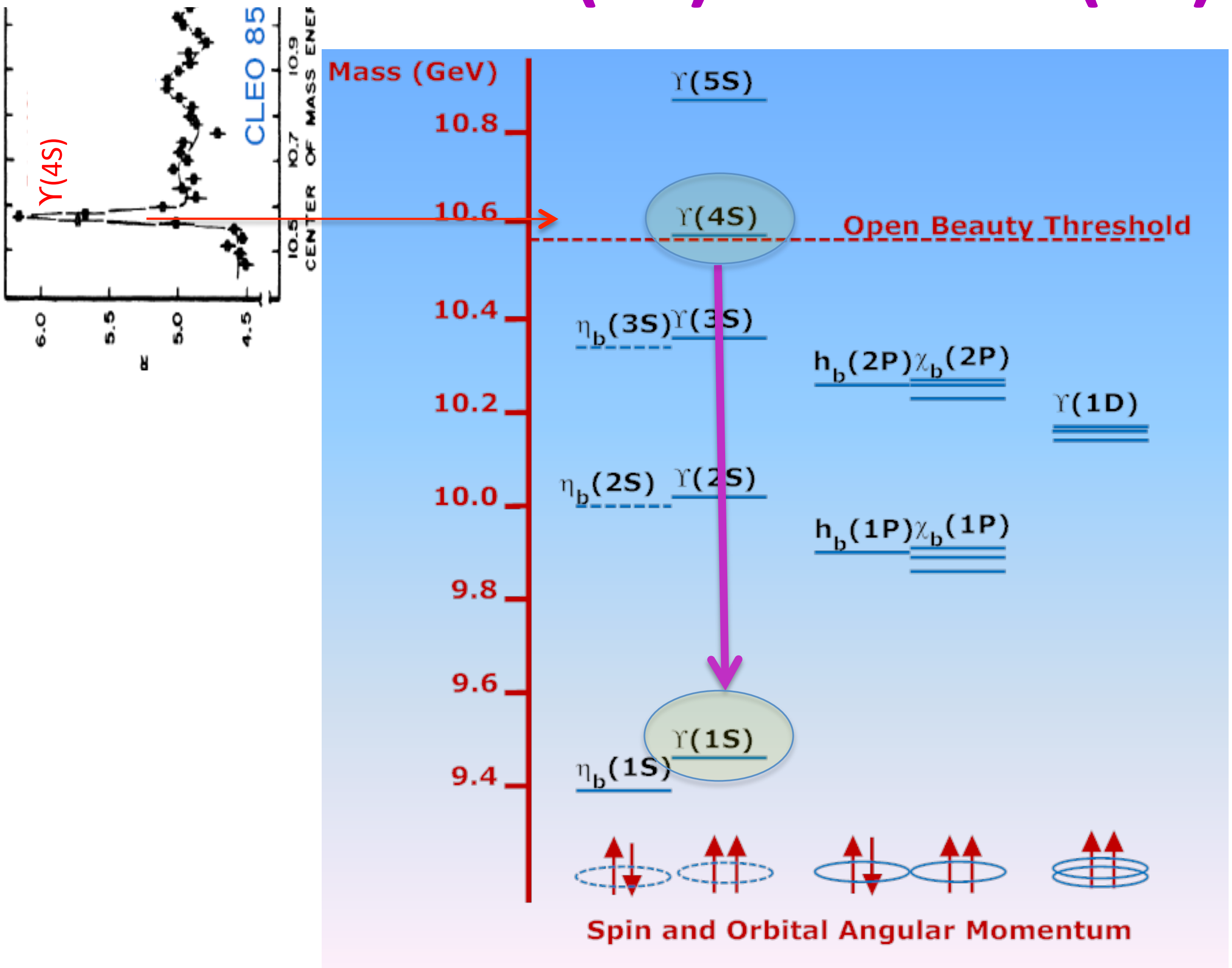
$$A_{12}(z_1,z_2) \propto H(z_1)\overline{H}(z_2)$$

5% A_{12} asymm → 22% $H(z)$ asymm

Is the "Υ(5S)" the Υ(5S)



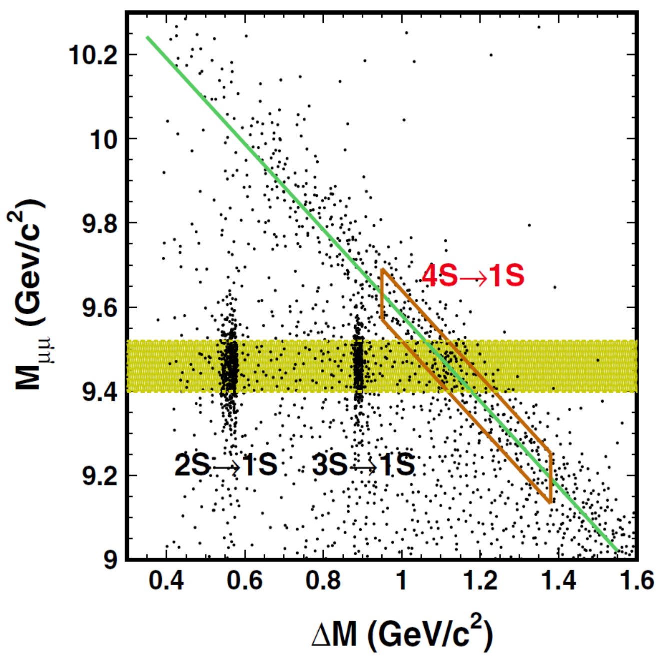
$\Upsilon(4S) \rightarrow \pi^+\pi^- \Upsilon(1S)$?

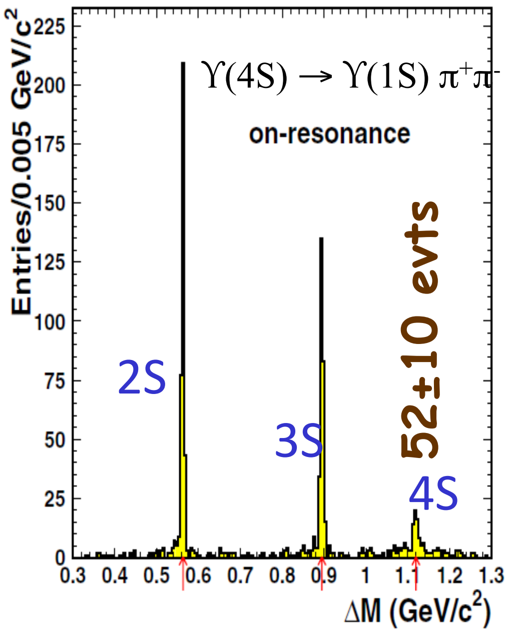


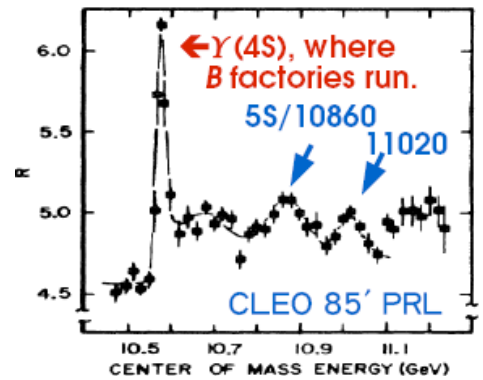
$2M_B = 10358.7$ MeV

Belle: $\Gamma_{\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)}$

477 fb^{-1}



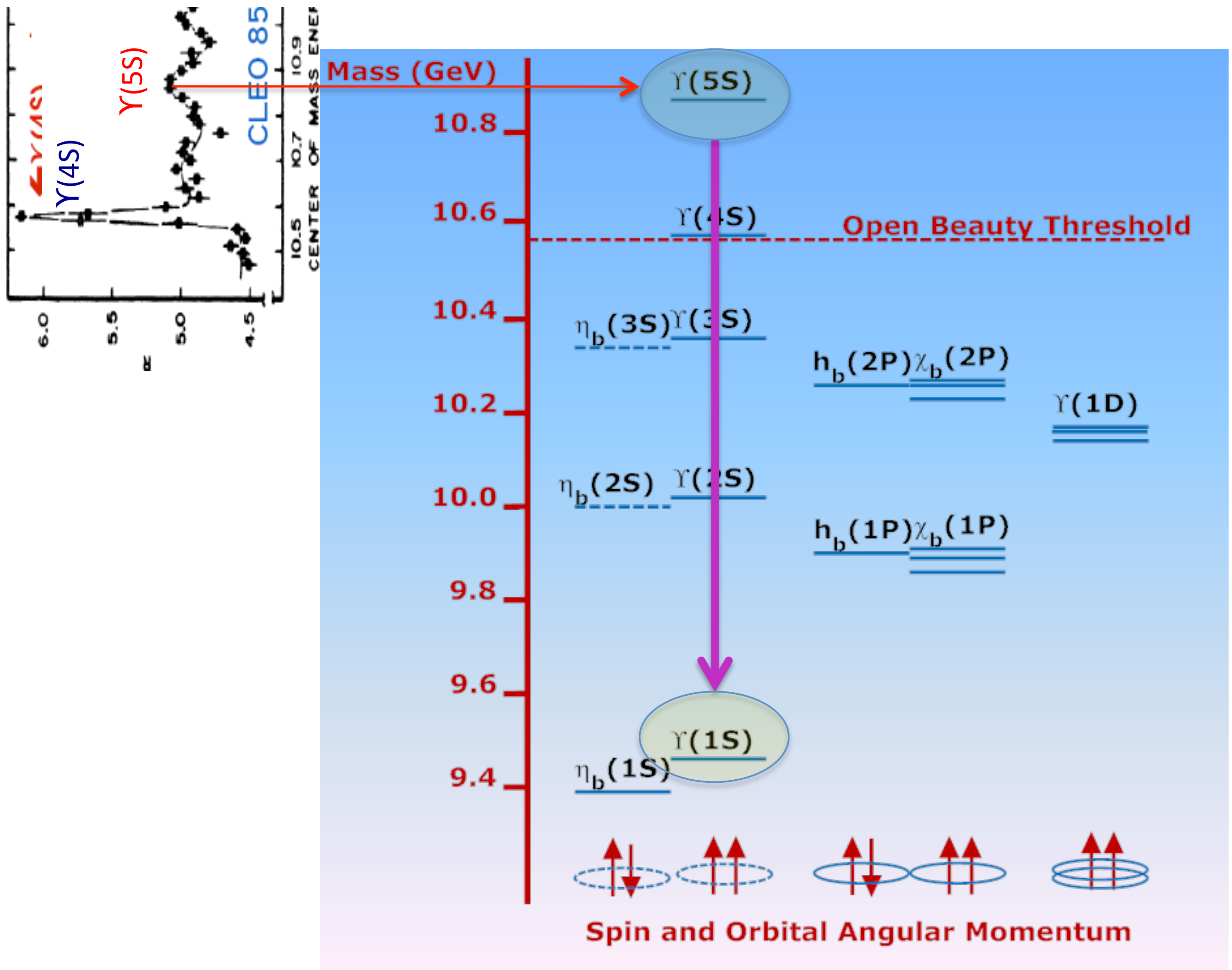




$N(\Upsilon_{4S})$	$N(\pi^+\pi^-\Upsilon_{1S})$	$B(Y_{4S}\rightarrow\pi\pi\Upsilon_{1S})$	$\Gamma(Y_{4S}\rightarrow\pi\pi\Upsilon_{1S})$	Γ_{theory}
535×10^6	52±10	$9 \pm 2 \times10^{-5}$	1.75 ± 0.35 keV	1.47±0.03 keV

Belle: PRD 75 071103

“Υ(5S)” → $\pi^+\pi^-$ Υ (1S) ?

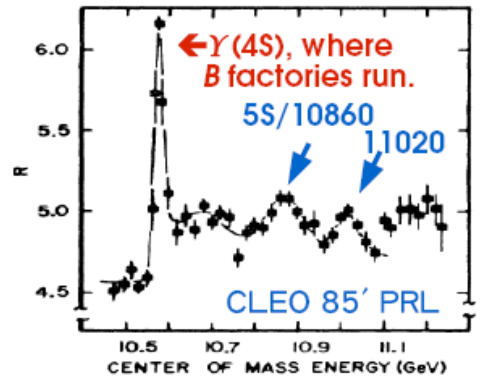


$2M_B$ = 10358.7 MeV

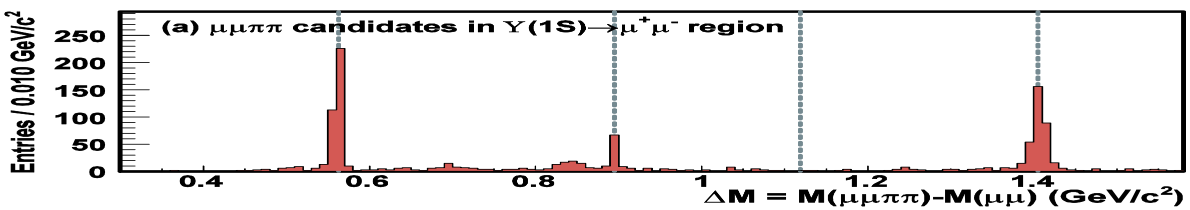
Belle: $\Gamma_{\text{“}\Upsilon(5S)\text{”} \to \pi^+\pi^-\Upsilon(1S)}$

~1/20th the data **23.6 fb^{-1} vs 477 fb^{-1}**

~1/5th the cross-section



325±20 evts!



Chen et al (Belle) PRL 100, 112001

$$\Gamma_{\text{“}\Upsilon(5S)\text{”}\rightarrow\pi^+\pi^-\Upsilon(1S)} \approx 300\times\ \Gamma_{\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)}$$

state	$N(\Upsilon_{nS})$	N_{evts}	$\Gamma(\Upsilon_{4S}\rightarrow\pi\pi\Upsilon_{1S})$	Γ_{theory}
Υ_{4S}	535M	52±10	1.8±0.4 keV	1.5keV
“Υ_{5S}”	4.4M	325±20	590±80 keV	<1.5keV

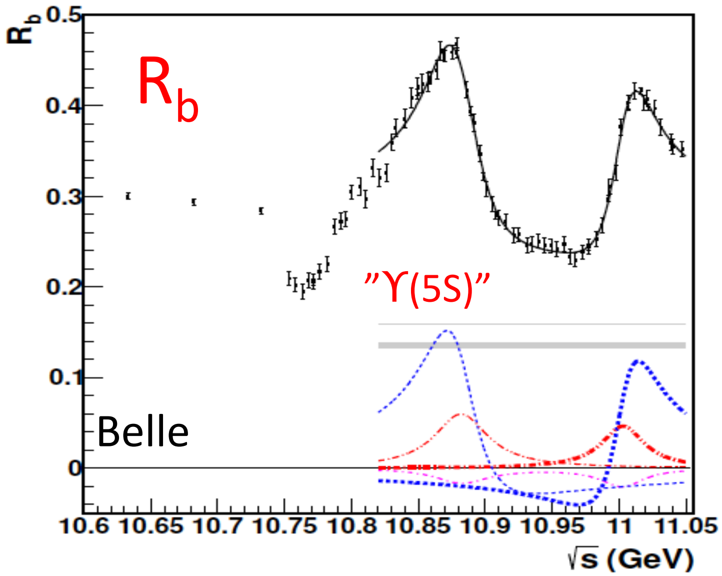
~300x too large!!

Something anomalous near "Υ(5S)"

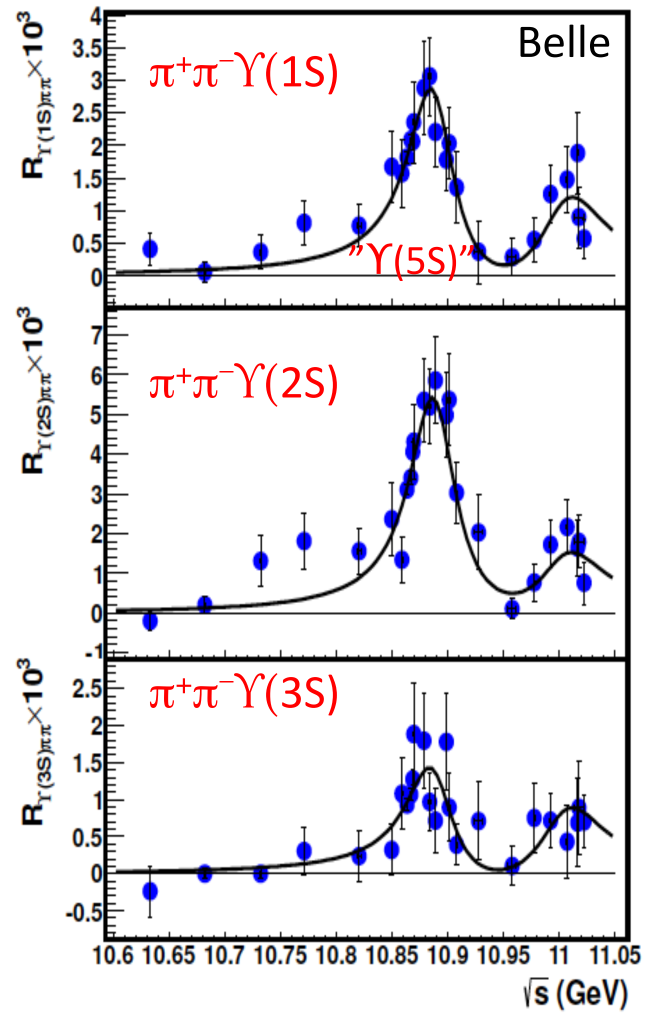
δM=(9 ± 3) MeV

M=(10,882 ± 2) MeV

M=(10,891 ± 3) MeV



Santel et al. (Belle) arXiv:1501.01137



-- two different, nearly overlapping states?

-- new dynamics at the Υ(5S)?

-- influence of b-sector XYZ states?

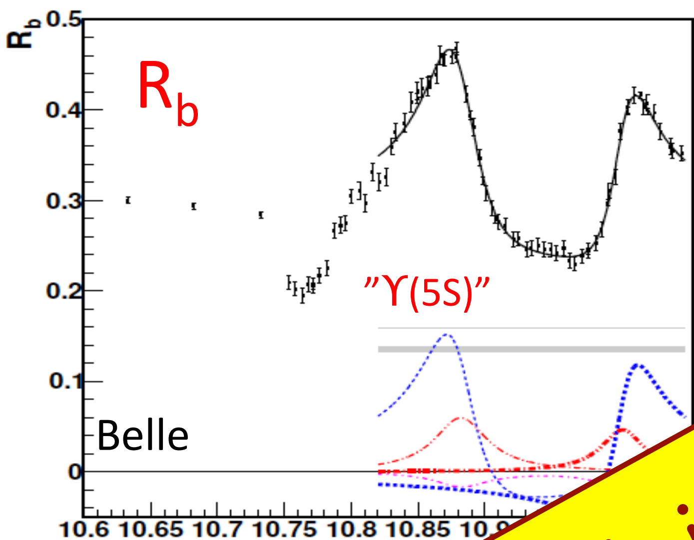
Bonder et al. (Belle) PRL, 108, 122001

Something anomalous near "Υ(5S)"

δM=(9 ± 3) MeV

M=(10,882 ± 2) MeV

M=(10,891 ± 3) MeV



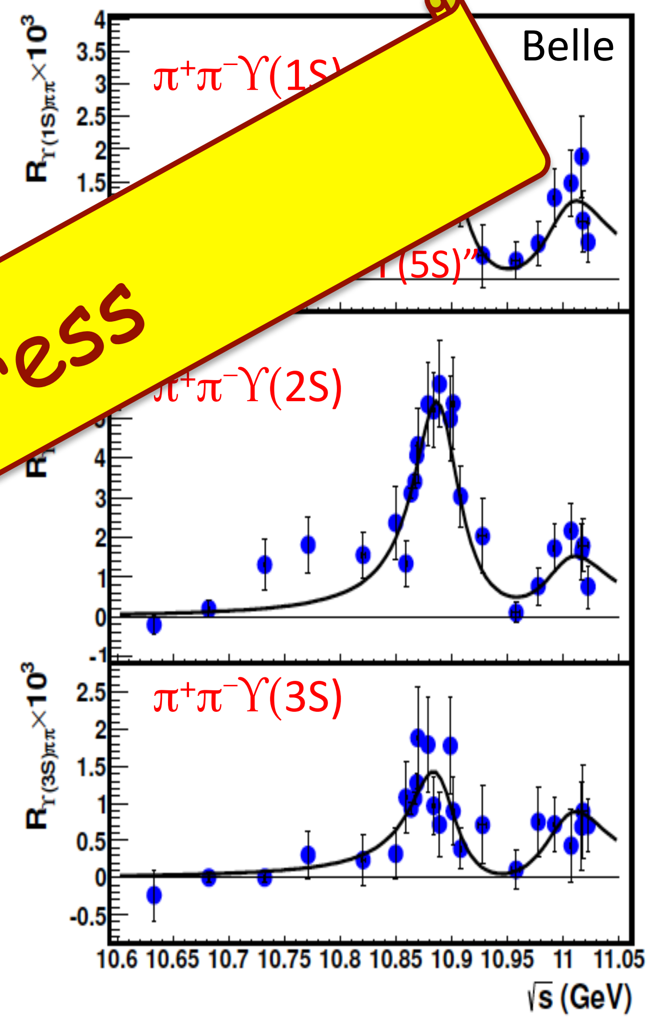
Santel et al. (Belle)

-- two dif... overlapping states?

... at the Υ(5S)?

... ence of b-sector XYZ states?

Bonder et al. (Belle) PRL, 108, 122001



A work in progress

Belle citation summary

Citation summary results	Citeable papers	Published only
Total number of papers analyzed:	1,371	602
Total number of citations:	33,539	28,901
Average citations per paper:	24.5	48.0
Breakdown of papers by citations:		
Renowned papers (500+)	3	3
Famous papers (250-499)	15	14
Very well-known papers (100-249)	66	63
Well-known papers (50-99)	97	84
Known papers (10-49)	322	225
Less known papers (1-9)	468	160
Unknown papers (0)	400	53
h_{HEP} index [?]	91	89

Summary

- Belle was successful
- It answered a number of questions
- And raised a number of new ones

Summary

- Belle was successfu

- It answer ... estions

- ... ber of new ones

We are looking for to BelleII,
-- and the next talk--

Thank You

Спасибо

감사합니다

どもう　ありがとう