Production of $B_1\overline{B}_2$ pairs in e+e-

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Time-like elastic (and transition) Form Factors

J/ψ and ψ(2S) decays to $B_1\overline{B}_2$

Spin polarization

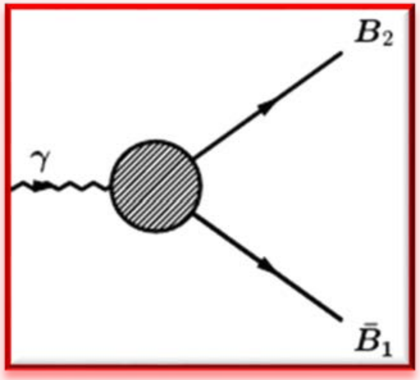
Hyperons from J/ψ and ψ(2S): decay parameters and CP tests

Prospects for Super tau-charm factory (vs BelleII, PANDA)

HIEPA , 2018-03-19

Baryon Electromagnetic Form Factors

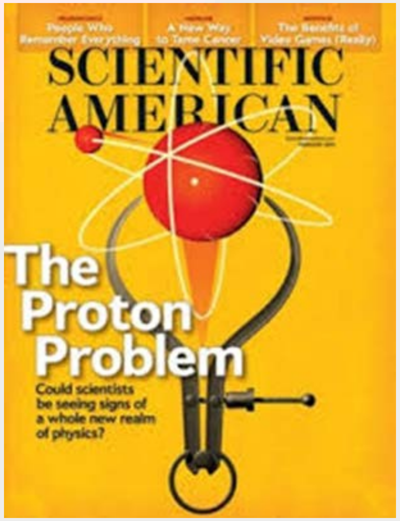
γ*BB vertex functions – Form Factors (FFs)



Baryon with spin s ⇨ $2s$+1 FFs

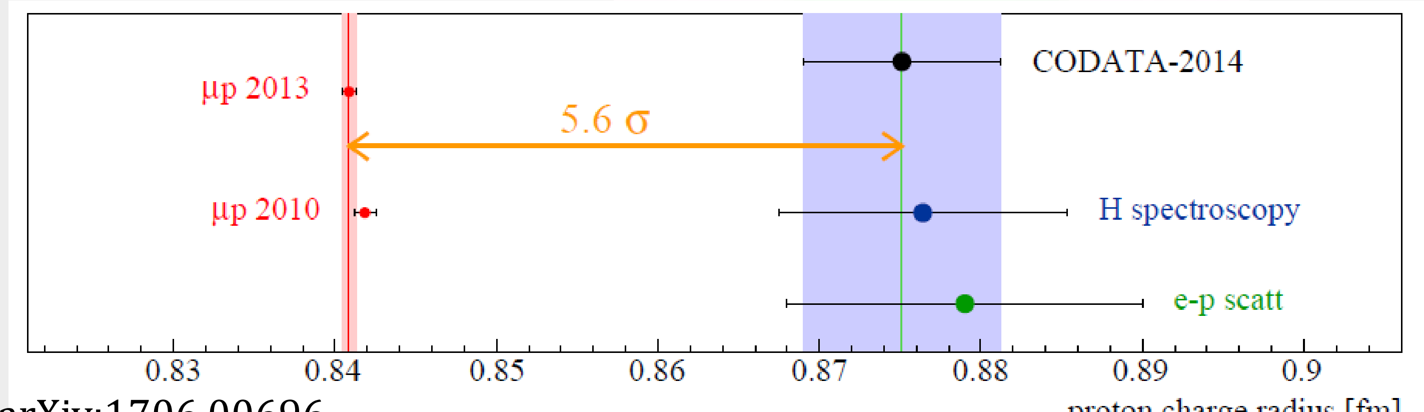
- Functions of photon virtuality q^2
- Distribution of charge + magnetization
  ⇨ radius is related to FFs slope at q^2=0
- Connect to distribution, dynamics of quarks in hadrons

Considered to be well understood for nucleons (space-like)



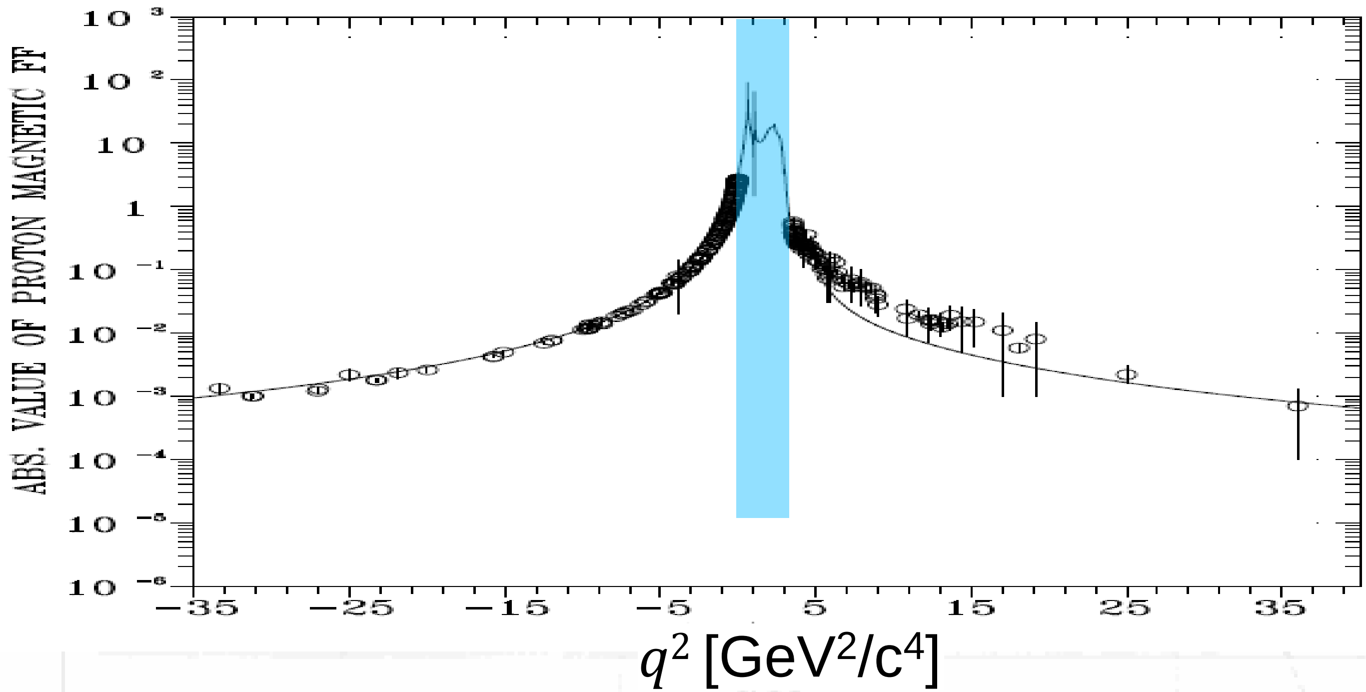
Unexpected results + old paradigms falsified:

- Proton radius puzzle
- New type of experiments
- High statistics and precision



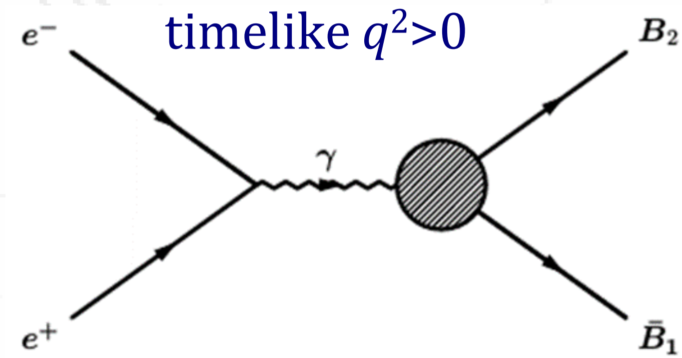
arXiv:1706.00696

Baryon Electromagnetic Form Factors



timelike $q^2>0$

spacelike $q^2<0$



$\gamma^* \to B_1 \bar{B}_2$

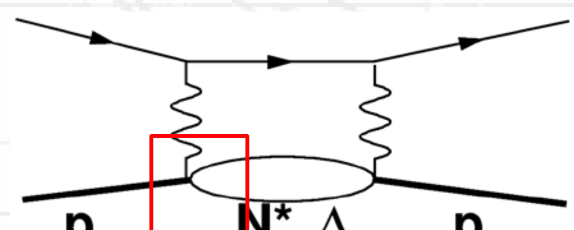
$B_1 \to B_2 e^+e^-$

$p\bar{p} \to e^+e^-$

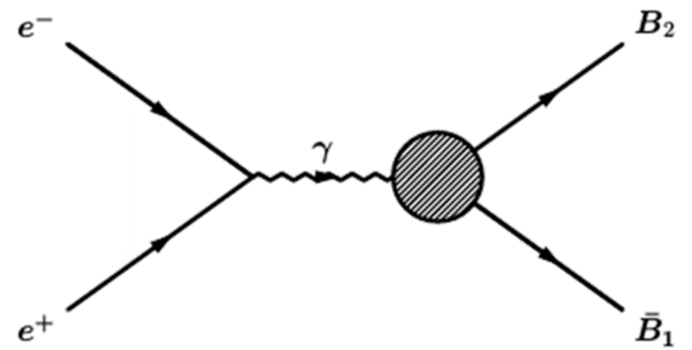
$p\bar{p} \to \pi^0 e^+e^-$

elastic: $B_2=B_1$

($B_2 \neq B_1$ transition)



$e^+e^- \to \gamma^* \to B_1\bar{B}_2$



Spin one-half baryon FFs

$$G_E(q^2) \qquad G_M(q^2)$$

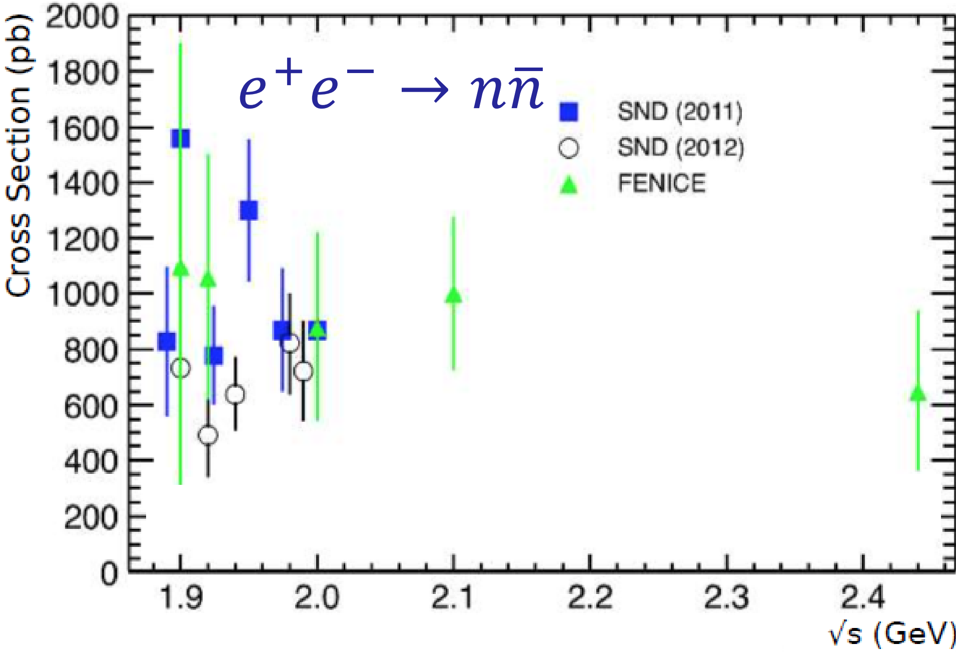
$$R = \left|\frac{G_E}{G_M}\right| \qquad G_E = G_M e^{i\Delta\Phi}$$

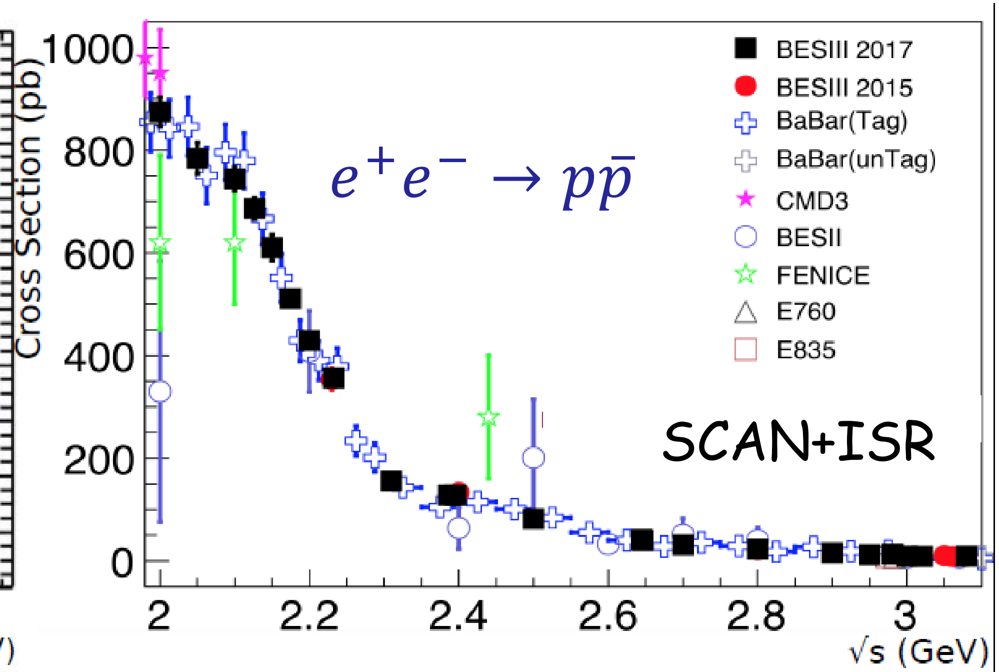
$$\frac{d\sigma}{d\cos\theta} = \frac{\alpha^2\beta}{4q^2}|G_M|^2\left[(1+\cos^2\theta) + \frac{1}{\tau}R^2\sin^2\theta\right]$$

Polarization of baryons:
Dubnickova, Dubnicka, Rekalo
Nuovo Cim. A109 (1996) 241
Gakh, Tomasi-Gustafsson Nucl.Phys. A771 (2006) 169
Czyz, Grzelinska, Kuhn PRD75 (2007) 074026
Fäldt EPJ A51 (2015) 74; EPJ A52 (2016)141

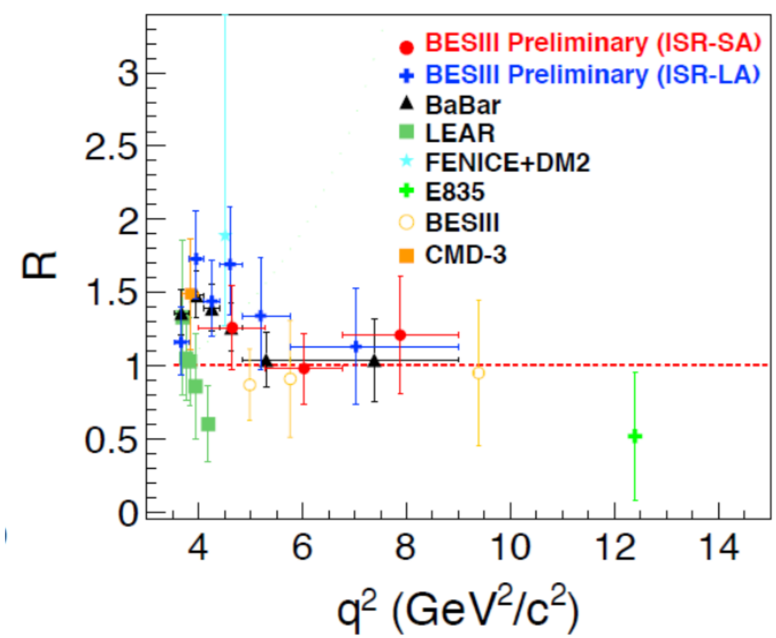
$$\tau = \frac{q^2}{(m_{B_1} + m_{\bar{B}_2})^2}$$

Nucleon anti-nucleon cross sections

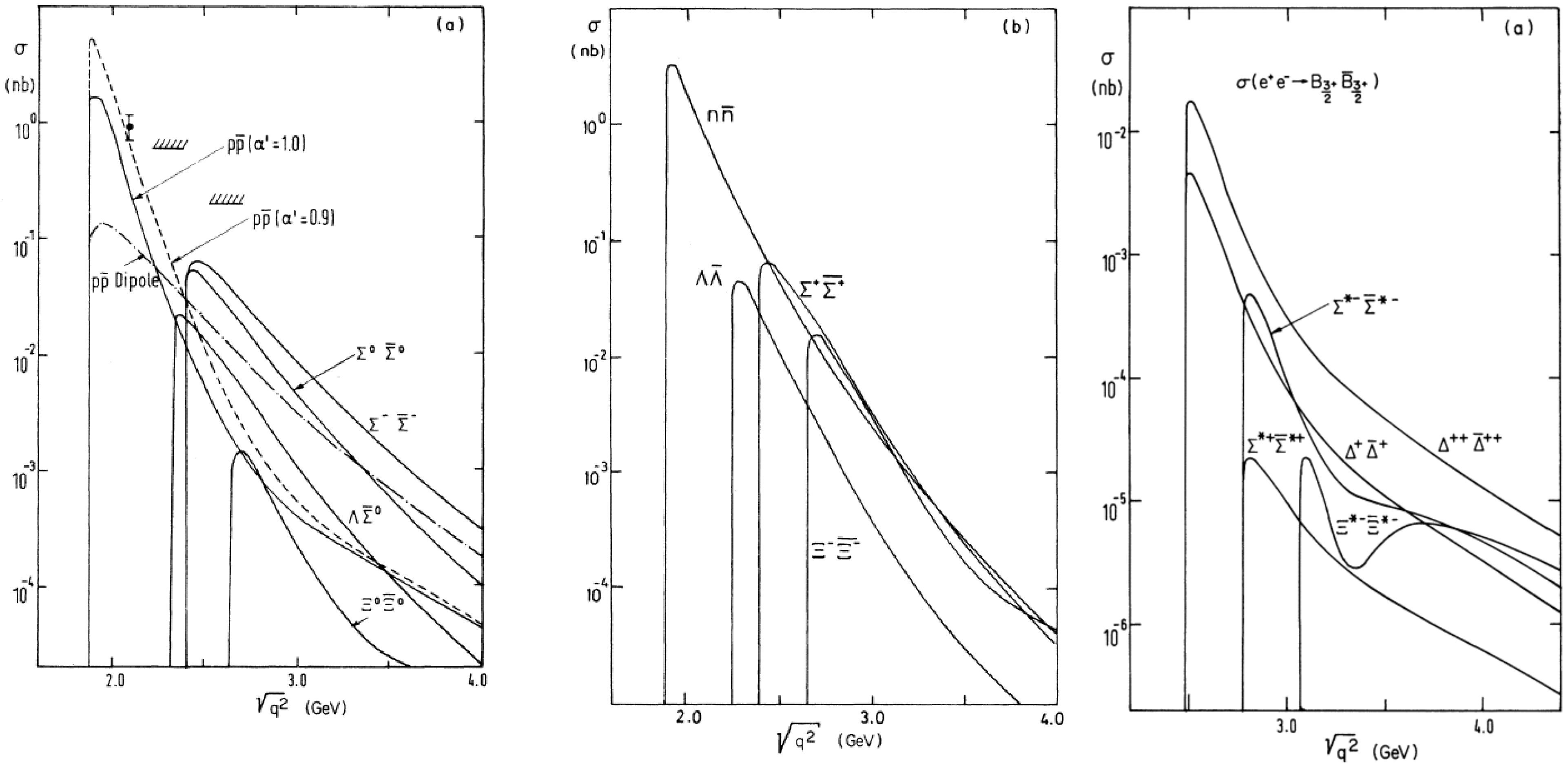




R is given by the angular distribution at fixed q^2

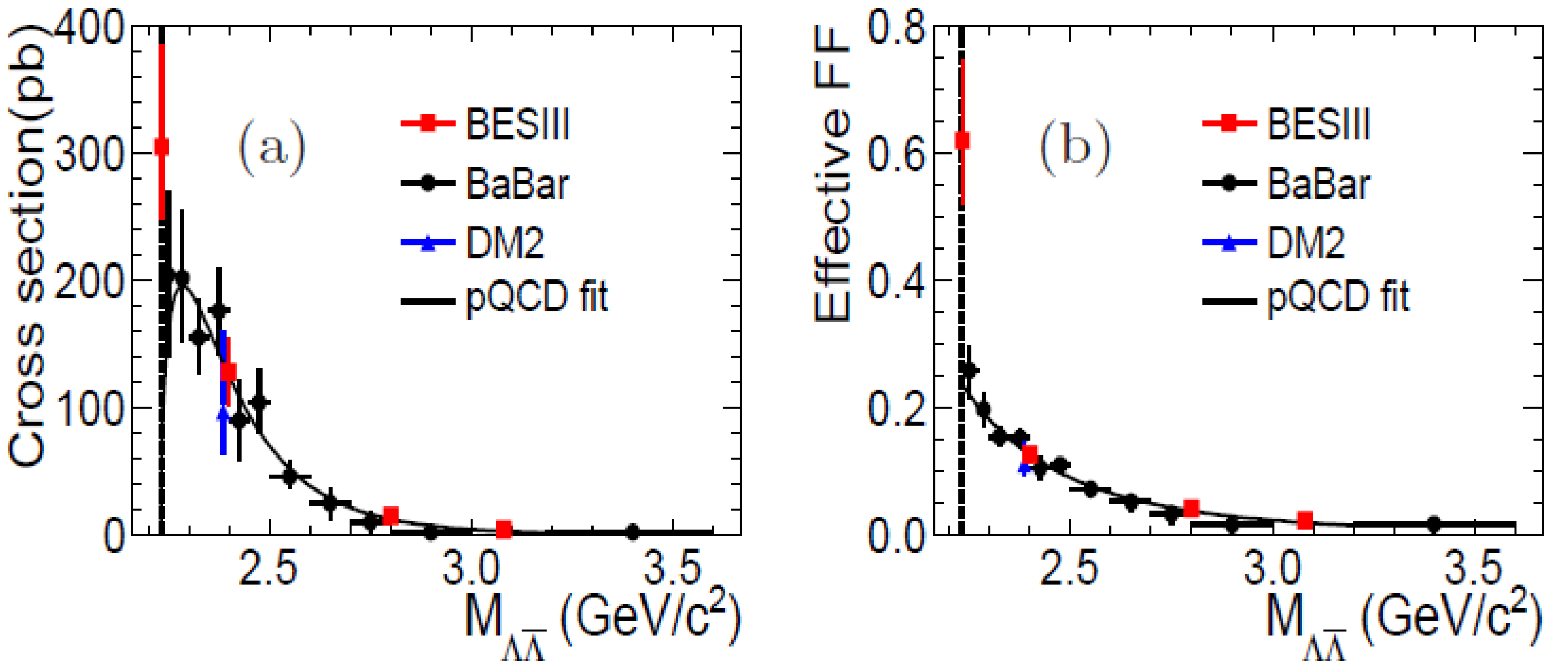


e+e− annihilation into baryon-antibaryon pairs



J. G. Körner and M. Kuroda
Phys. Rev. D 16, 2165 1977

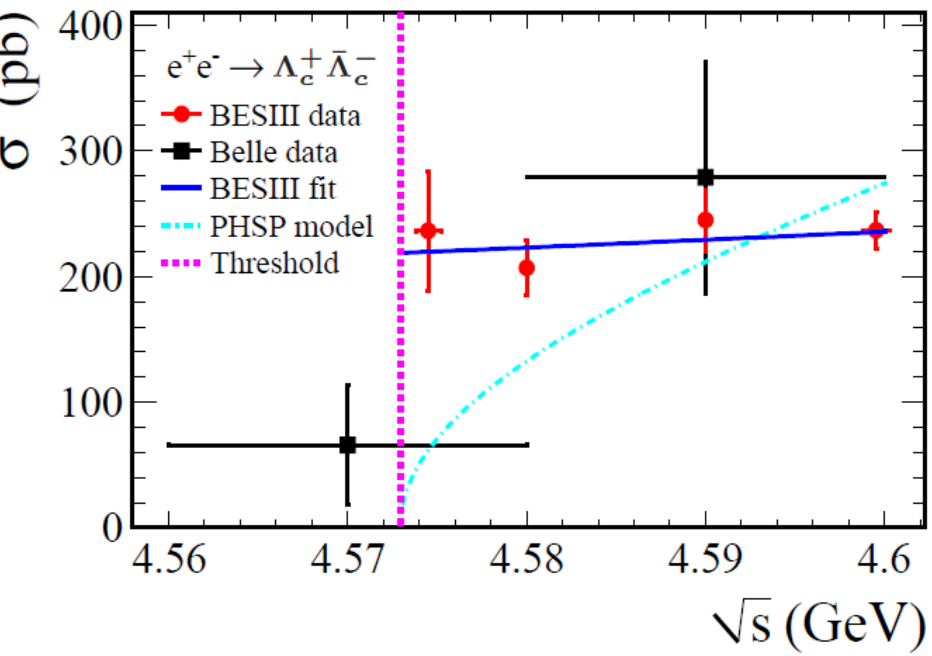
$e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}$

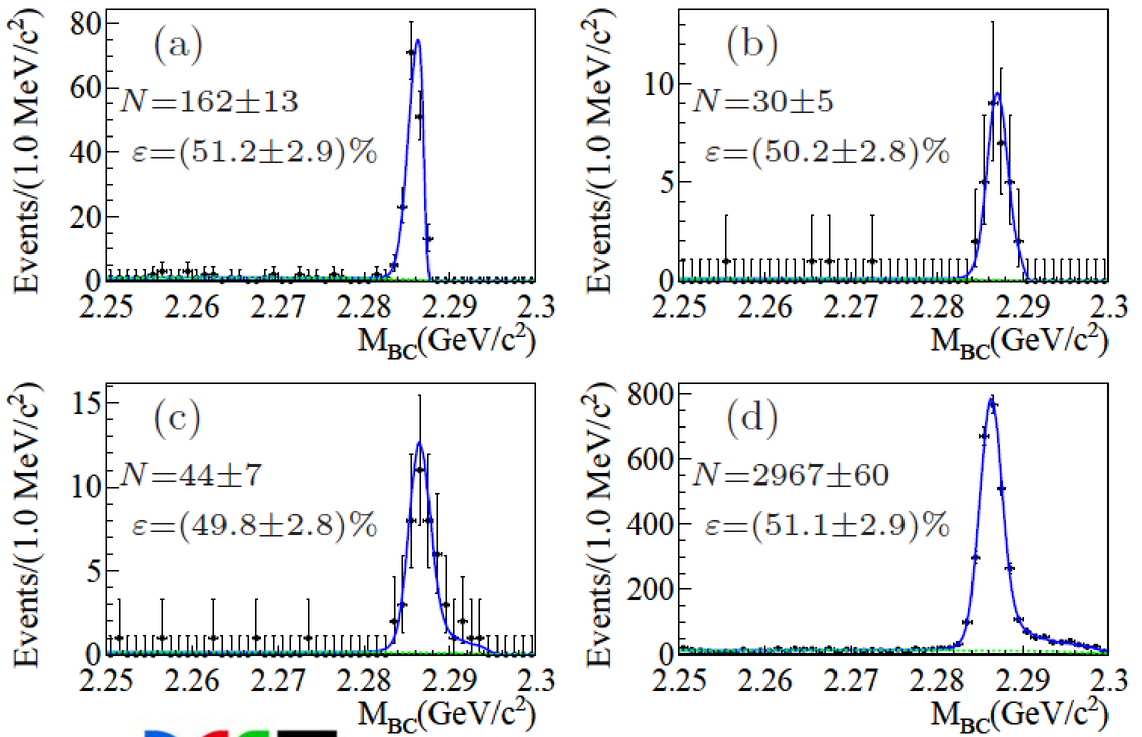


Enhancement at threshold for Λ ...

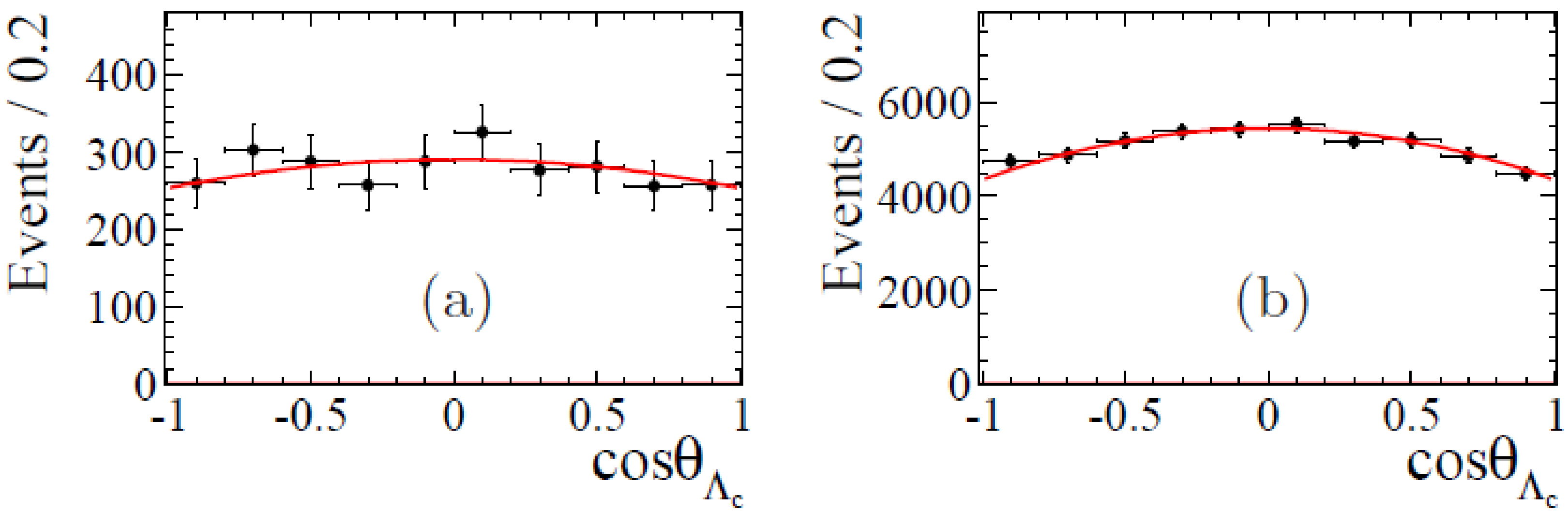
Phys.Rev. D97 (2018) 032013

$e^+e^- \to \gamma^* \to \Lambda_c\bar{\Lambda}_c$

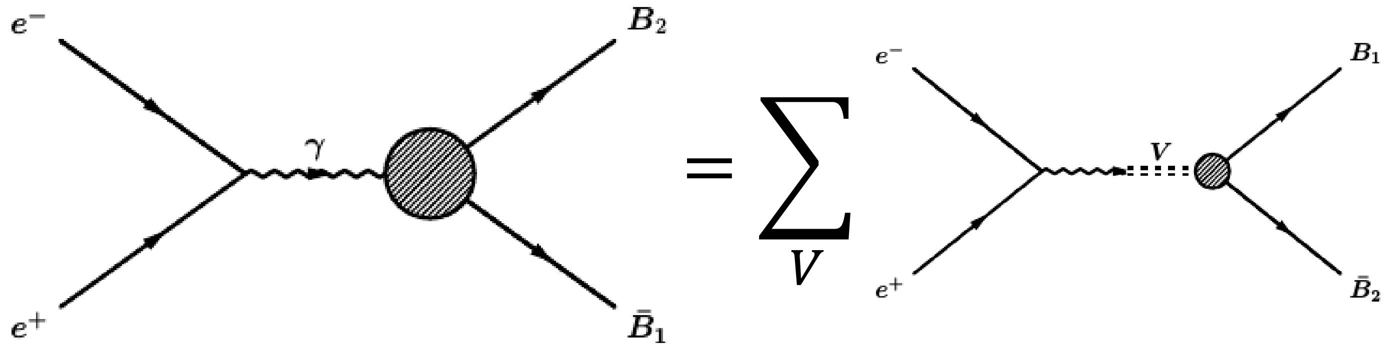




BESIII arXiv:1710.00150 ->PRL



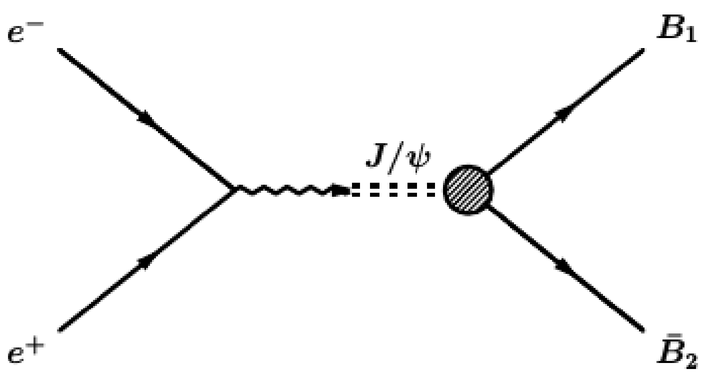
Baryon FFs: (elastic and transition FFs)



Baryons B_1 and $\bar{B}_2$
(spin 1/2, 3/2, ...)

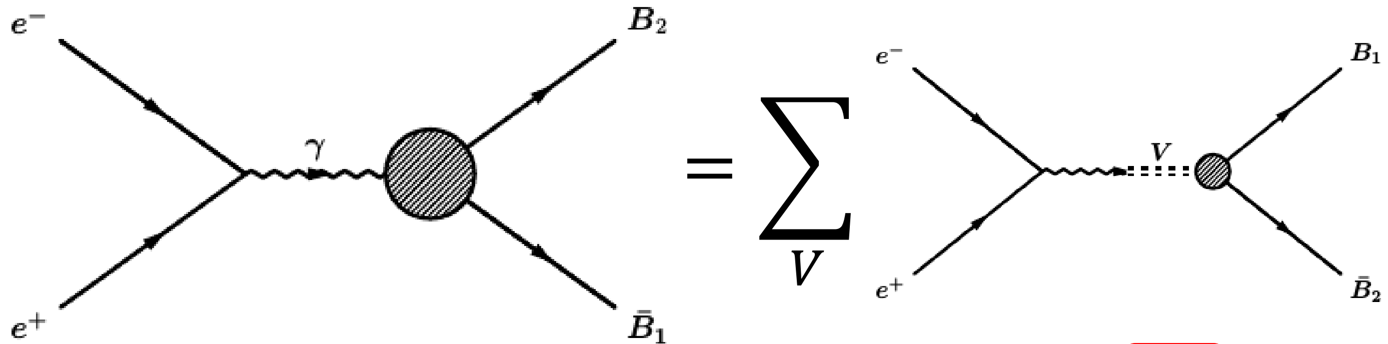
$V = \rho, \omega, \varphi, \ldots, J/\psi, \psi(2S), \ldots$

vs J/ψ decay:



$$\frac{d\Gamma}{d\Omega} \propto 1 + \boldsymbol{\alpha_\psi} \cos^2\theta$$

Baryon FFs: (elastic and transition FFs)



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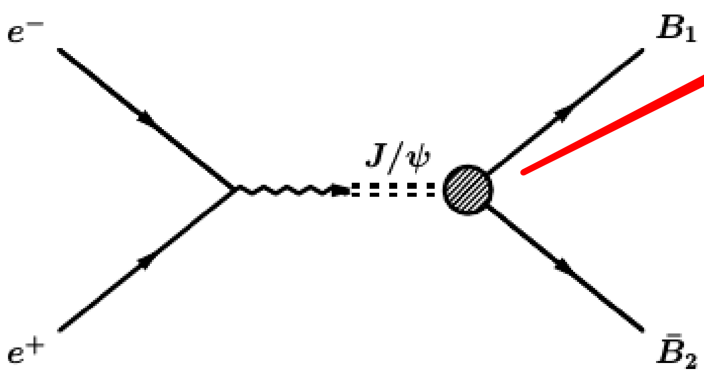


$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta$$

$J/\psi, \psi(2S) \to B\bar{B}$

Decay mode	Events	$\mathcal{B}(\times 10^{-4})$
$J/\psi \to \Lambda\bar{\Lambda}$	440675 ± 670	$19.43 \pm 0.03 \pm 0.33$
$\psi(2S) \to \Lambda\bar{\Lambda}$	31119 ± 187	$3.97 \pm 0.02 \pm 0.12$
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	111026 ± 335	$11.64 \pm 0.04 \pm 0.23$
$\psi(2S) \to \Sigma^0\bar{\Sigma}^0$	6612 ± 82	$2.44 \pm 0.03 \pm 0.11$
$J/\psi \to \Sigma(1385)^0\bar{\Sigma}(1385)^0$	102762 ± 852	10.71 ± 0.09
$J/\psi \to \Xi^0\bar{\Xi}^0$	134846 ± 437	11.65 ± 0.04
$\psi(2S) \to \Sigma(1385)^0\bar{\Sigma}(1385)^0$	2214 ± 148	0.69 ± 0.05
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	10839 ± 123	2.73 ± 0.03
$J/\psi \to \Xi^-\bar{\Xi}^+$	42811 ± 231	10.40 ± 0.06
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$	42595 ± 467	10.96 ± 0.12
$J/\psi \to \Sigma(1385)^+\bar{\Sigma}(1385)^-$	52523 ± 596	12.58 ± 0.14
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	5337 ± 83	2.78 ± 0.05
$\psi(2S) \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$	1375 ± 98	0.85 ± 0.06
$\psi(2S) \to \Sigma(1385)^+\bar{\Sigma}(1385)^-$	1470 ± 95	0.84 ± 0.05

Only α_ψ extracted

BESIII

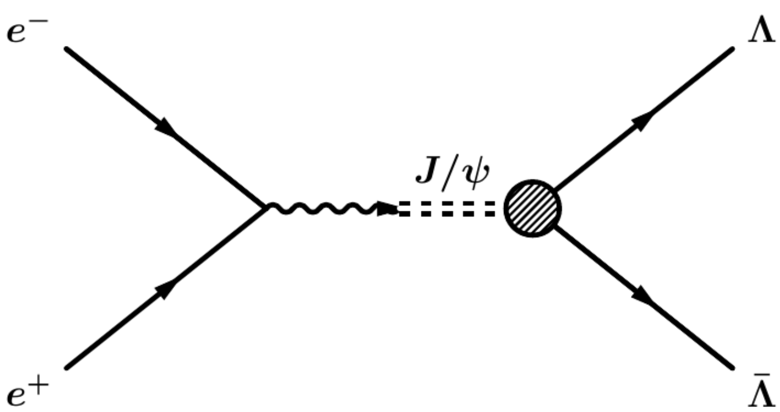
Phys. Rev. D 93, 072003 (2016)
PLB770(2017)217

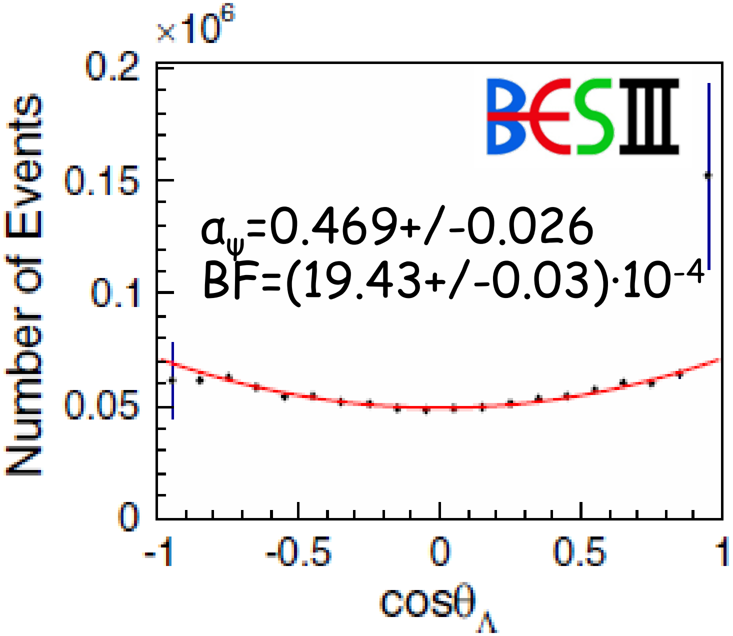
Phys. Rev. D 95, 052003 (2017)

With $(1.31)\times10^9$ J/ψ and $(4.48)\times10^8$ ψ(2S)

	$\mathcal{B}(\times 10^{-4})$
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	5.9 ± 1.5
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	3.3 ± 1.4
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$	3.1 ± 0.5
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.47 ± 0.10

$e^+e^- \rightarrow \gamma^* \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$





BESIII,PRD 95, 052003 (2017)

Process also described by two Form Factors
(two complex numbers)
i.e. three real parameters:

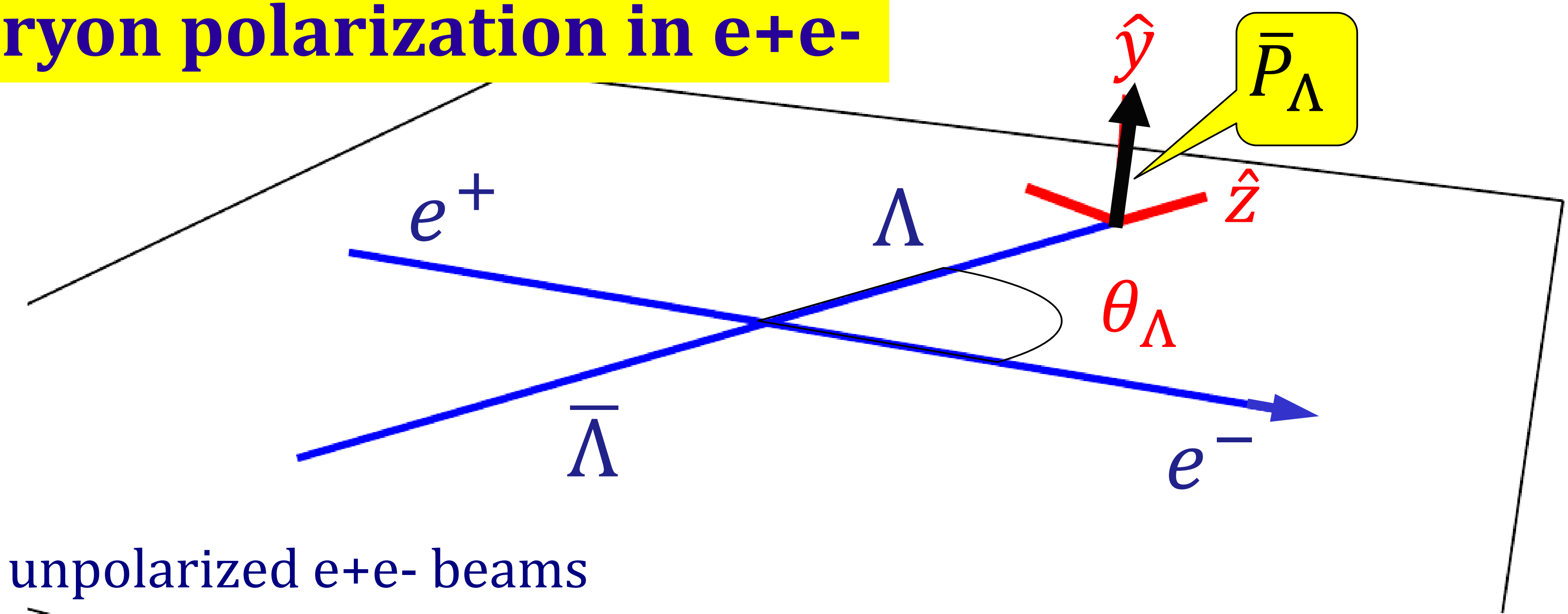
$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta$$

BF,α_ψ and phase $\Delta\Phi$

form factors: G_M^ψ and G_E^ψ

$$G_E^\psi = \frac{\sqrt{s}}{2M_\Lambda}\sqrt{\frac{1-\alpha_\psi}{1+\alpha_\psi}}\, e^{i\Delta\Phi}\, G_M^\psi$$

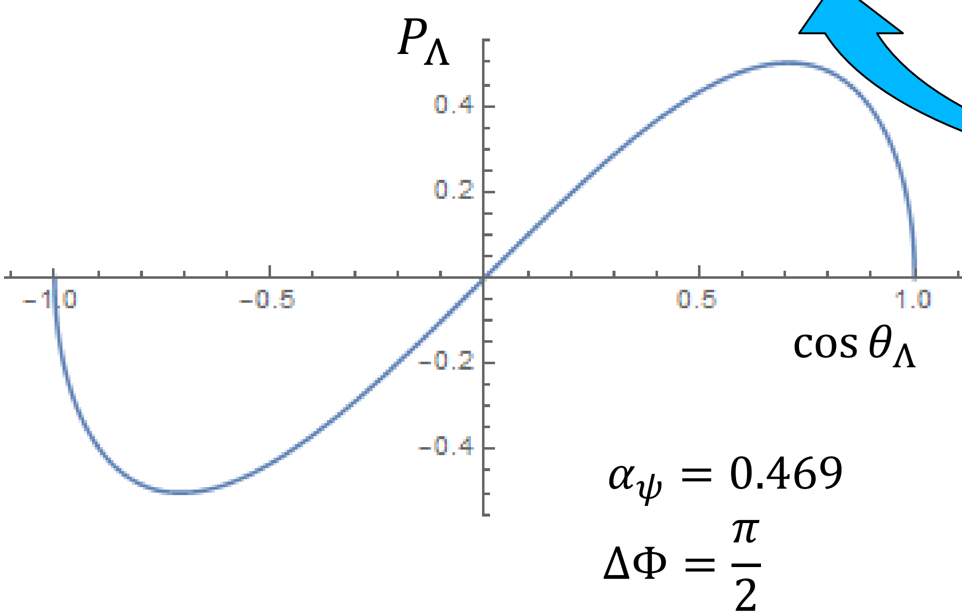
Baryon polarization in e+e-



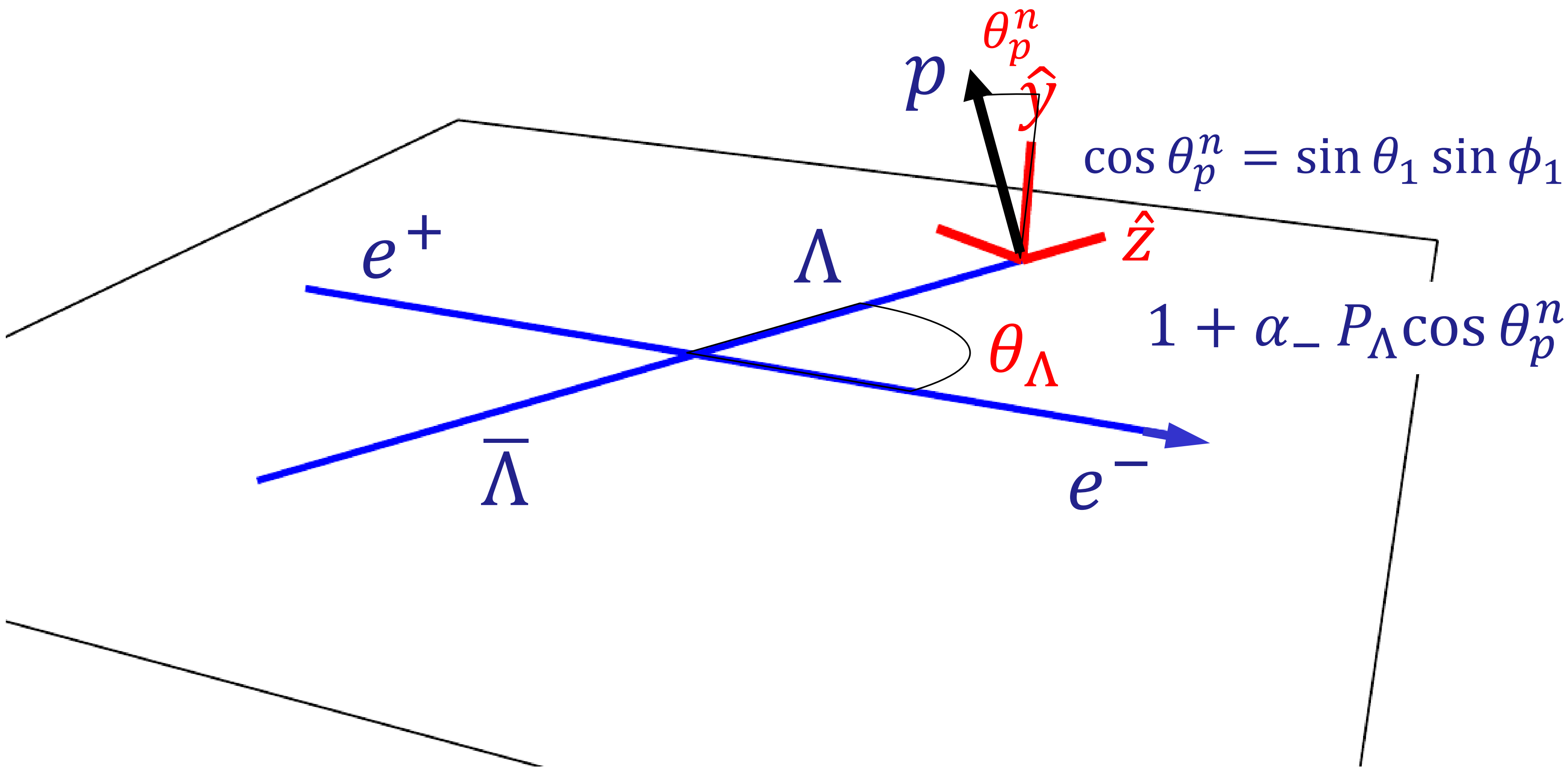
For unpolarized e+e- beams

$$\bar{P}_\Lambda(\theta_\Lambda) = \frac{\sqrt{1-\alpha_\psi}\cos\theta_\Lambda \sin\theta_\Lambda}{1+\alpha_\psi \cos^2\theta_\Lambda}\sin(\Delta\Phi)\hat{y}$$

$\Delta\Phi \neq 0$



$e^+e^- \to (\Lambda \to p\pi^-)\,\bar{\Lambda}$



$\Lambda \to p\pi^-$: $\Omega_1 = (\cos\theta_1, \phi_1)$ α_-

Hyperon polarization determined using
angular distribution of the baryon from weak decay

Exclusive decay distributions

$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ $e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{n}\pi^0)$

$$d\Gamma \propto \mathcal{W}(\boldsymbol{\xi})d\boldsymbol{\xi} = \mathcal{W}(\boldsymbol{\xi})d\cos\theta_\Lambda d\Omega_1 d\Omega_2$$

$\boldsymbol{\xi}: (\cos\theta_\Lambda, \Omega_1, \Omega_2)$

$\Lambda \to p\pi^-$: $\Omega_1 = (\cos\theta_1, \phi_1)$ $\alpha_1 \to \alpha_-$

$\bar{\Lambda} \to \bar{p}\pi^+(or\ \bar{n}\pi^0)$: $\Omega_2 = (\cos\theta_2, \phi_2)$

$\bar{\Lambda} \to \bar{n}\pi^0: \alpha_2 \to \bar{\alpha}_0$ $\bar{\Lambda} \to \bar{p}\pi^+: \alpha_2 \to \alpha_+$

$$\begin{aligned}\mathcal{W}(\boldsymbol{\xi}) = 1 &+ \alpha_\psi \cos^2\theta_\Lambda \\ &+ \alpha_1\alpha_2 \left(\sin^2\theta_\Lambda \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta_\Lambda \cos\theta_1 \cos\theta_2\right) \\ &+ \alpha_1\alpha_2 \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\left\{\sin\theta_\Lambda \cos\theta_\Lambda \left(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2\right)\right\} \\ &+ \alpha_1\alpha_2\, \alpha_\psi \left(\cos\theta_1 \cos\theta_2 - \sin^2\theta_\Lambda \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2\right) \\ &+ \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\sin\theta_\Lambda \cos\theta_\Lambda \left(\alpha_1 \sin\theta_1 \sin\phi_1 + \alpha_2 \sin\theta_2 \sin\phi_2\right)\end{aligned}$$

Spin correlations

Fäldt, Kupsc PLB772 (2017) 16

General two spin ½ particle state

$$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\nu} C_{\mu\bar{\nu}}\sigma_\mu \otimes \sigma_{\bar{\nu}}$$

16 parameters for each θ:
I(θ), polarizations (6)
Spin correlations (9)

$$\mathcal{W}(\boldsymbol{\xi}) = \mathcal{I}(\theta)\left\{1 + \alpha_\Lambda \sum_k P_k(\theta)\mathbf{n}_k + \alpha_{\bar{\Lambda}} \sum_{\bar{k}} P_{\bar{k}}(\theta)\mathbf{n}_{\bar{k}} + \alpha_\Lambda\alpha_{\bar{\Lambda}} \sum_{\bar{k}k} C_{\bar{k}k}(\theta)\mathbf{n}_{\bar{k}}\mathbf{n}_k\right\}$$

polarizations (6)

Spin correlations (9)

$$P_y(\theta) = \sqrt{1-\alpha_\psi^2}\,\frac{\cos\theta\sin\theta}{1+\alpha_\psi\cos^2\theta}\sin(\Delta\Phi)$$

$$P_{\bar{y}}(\theta) = P_y(\theta).$$

$$\mathcal{I}(\theta) = 1 + \alpha_\psi\cos^2\theta.$$

$$C_{\bar{z}z}(\theta)\mathcal{I}(\theta) = -\alpha_\psi + \cos^2\theta$$

$$C_{\bar{x}x}(\theta)\mathcal{I}(\theta) = -\sin^2\theta$$

$$C_{\bar{y}y}(\theta)\mathcal{I}(\theta) = -\alpha_\psi\sin^2\theta$$

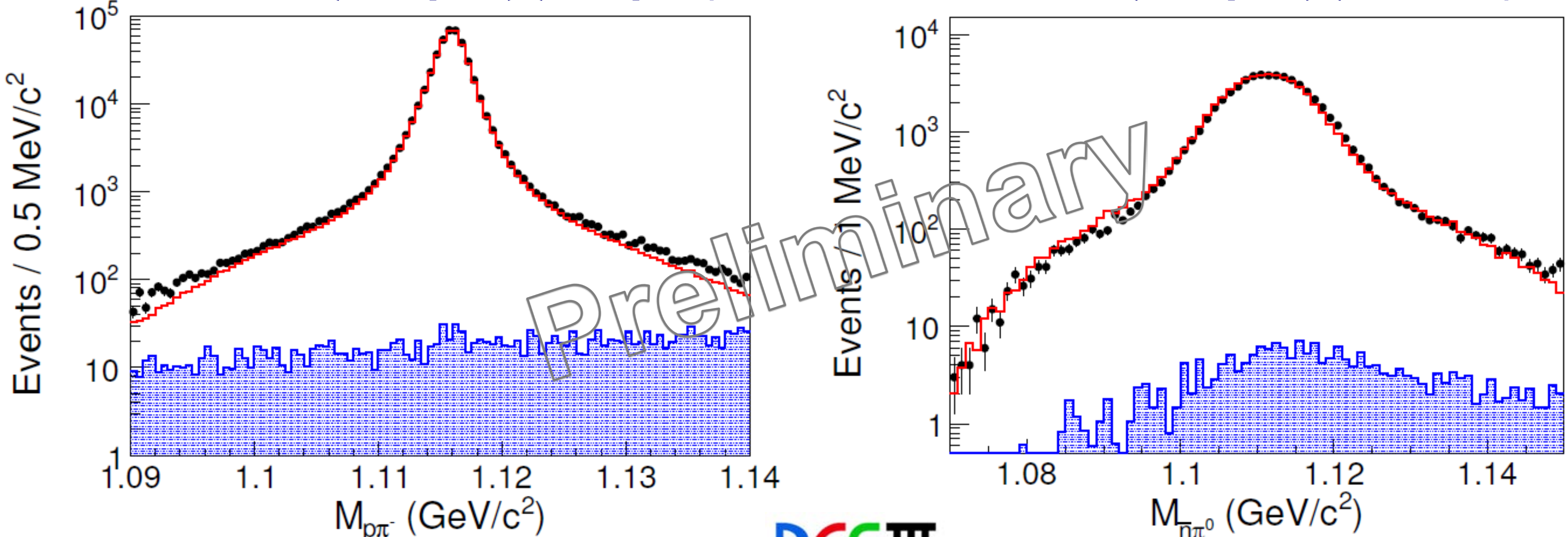
$$C_{\bar{x}z}(\theta)\mathcal{I}(\theta) = -\sqrt{1-\alpha_\psi^2}\cos\theta\sin\theta\cos(\Delta\Phi)$$

$$C_{\bar{z}x}(\theta) = C_{\bar{x}z}(\theta)$$

moments: $$M(\theta) = \sum_i^{N(\theta)} \mathbf{n}_\mu^i \mathbf{n}_\nu^i$$

(uncorrected for acceptance)

$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ $e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{n}\pi^0)$



420593 events

399 background

47009 events

66 background

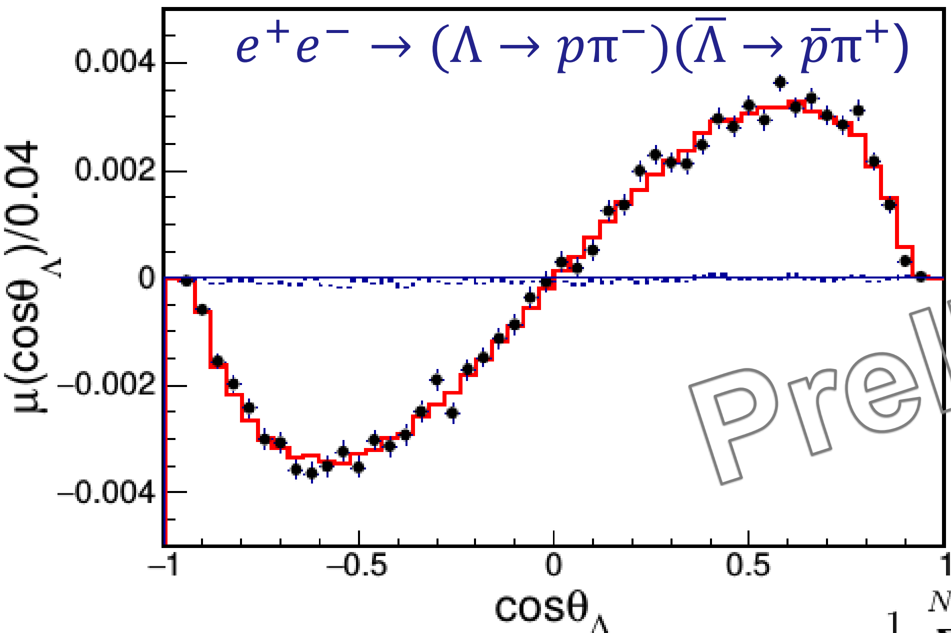
Global unbinned maximum log likelihood fit to the two data sets with the likelihood function constructed from probability function:

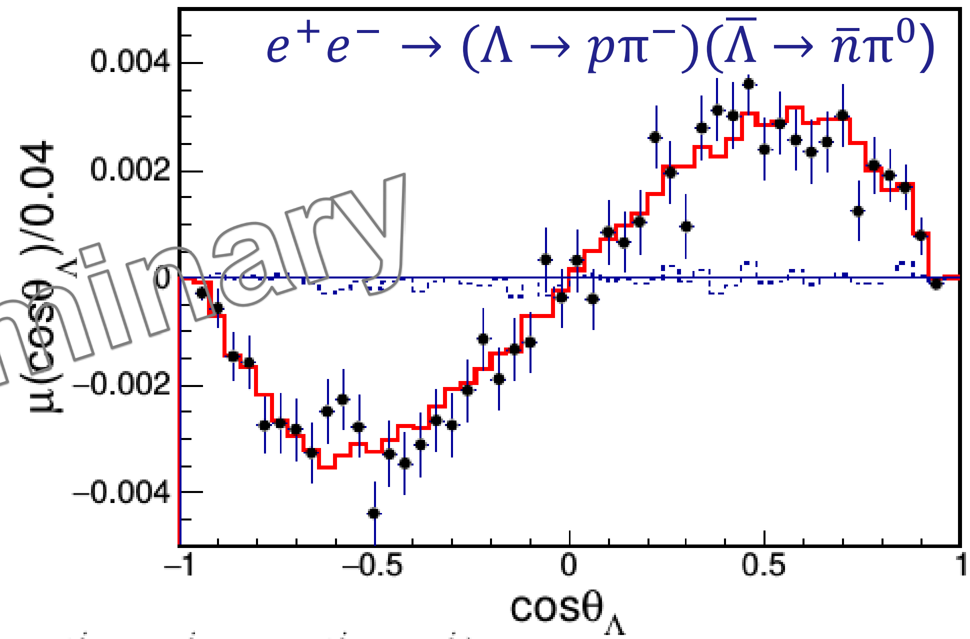
$$\mathcal{C}(\alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)\mathcal{W}(\boldsymbol{\xi}_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)$$

Where $\mathcal{C}(\alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)$ is the normalization factor obtained from $\mathcal{W}(\boldsymbol{\xi}_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)$ weighted sum for flat phase space model MC events after detector reconstruction.

Fit results

$\Delta\Phi = 42.3^o \pm 0.6^o \pm 0.5^o$





$$\mu(\cos\theta_\Lambda) = \frac{1}{N}\sum_{i}^{N(\theta_\Lambda)}(\sin\theta_1^i \sin\phi_1^i - \sin\theta_2^i \sin\phi_2^i)$$

BESIII

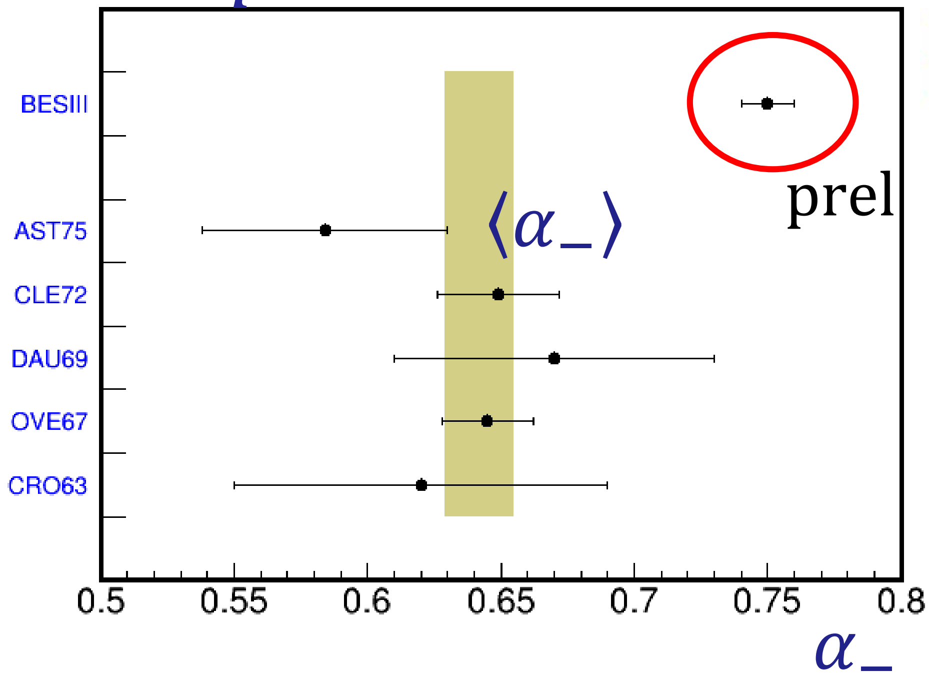
Parameters	This work	Previous results	
α_ψ	$\mathbf{0.461 \pm 0.006 \pm 0.007}$	0.469 ± 0.027	BESIII
$\Delta\Phi$ (rad)	$\mathbf{0.740 \pm 0.010 \pm 0.008}$	–	
α_-	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013	PDG
α_+	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08	PDG
$\bar{\alpha}_0$	$\mathbf{-0.692 \pm 0.016 \pm 0.006}$	–	
A_{CP}	$\mathbf{-0.006 \pm 0.012 \pm 0.007}$	0.006 ± 0.021	PDG
$\bar{\alpha}_0/\alpha_+$	$\mathbf{0.913 \pm 0.028 \pm 0.012}$	–	

CP asymmetry:

$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

Observation of the spin polarization of Λ hyperons in the $J/\psi \to \Lambda\bar{\Lambda}$ decay

$\Lambda \to p\pi^-$: α_-



17% larger than PDG avg
> 5 σ difference

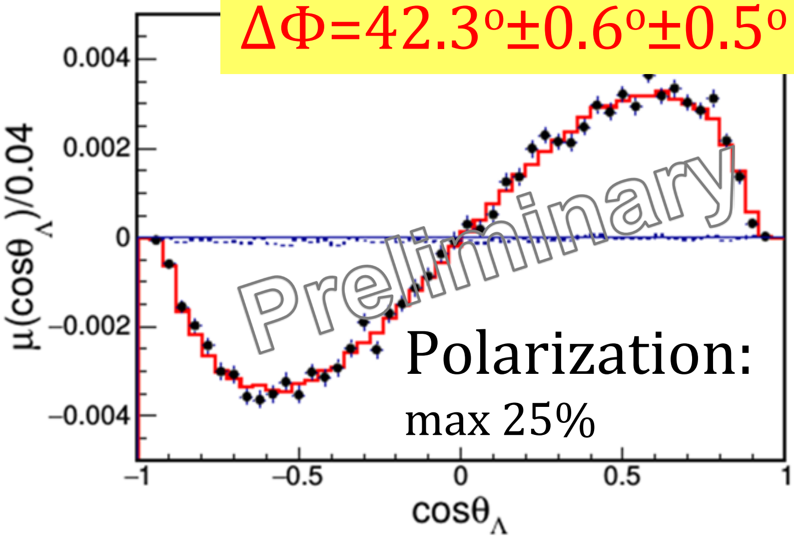
CP test

$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

A_{CP} = -0.006 ± 0.012 ± 0.007 prel

A_{CP} = 0.013 ± 0.021
PS185 PRC54(96)1877
CKM $A_{CP} \sim 10^{-4}$

ΔΦ=42.3°±0.6°±0.5°



Polarization:
max 25%

Prospects for other hyperons

What if phase is non-zero also for other J/ψ or $\psi(2S)$ decays into hyperon antihyperon?

⇨ measure simultaneously for two body weak decays α and $\bar{\alpha}$ and test CP: $A_{CP}=(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$

⇨ For cascades: $\Xi^-\boldsymbol{\Xi^+} \rightarrow \Lambda\pi^- \boldsymbol{\Lambda}\pi^+ \rightarrow p\pi^-\pi^- \boldsymbol{p}\pi^+\pi^+$

could also measure ϕ_{Ξ^-} , ϕ_{Ξ^+}
and do more (10x) sensitive CP test: $B_{CP}= (\beta_{\Xi^-} + \beta_{\Xi^+})/(\beta_{\Xi^-} - \beta_{\Xi^+})$

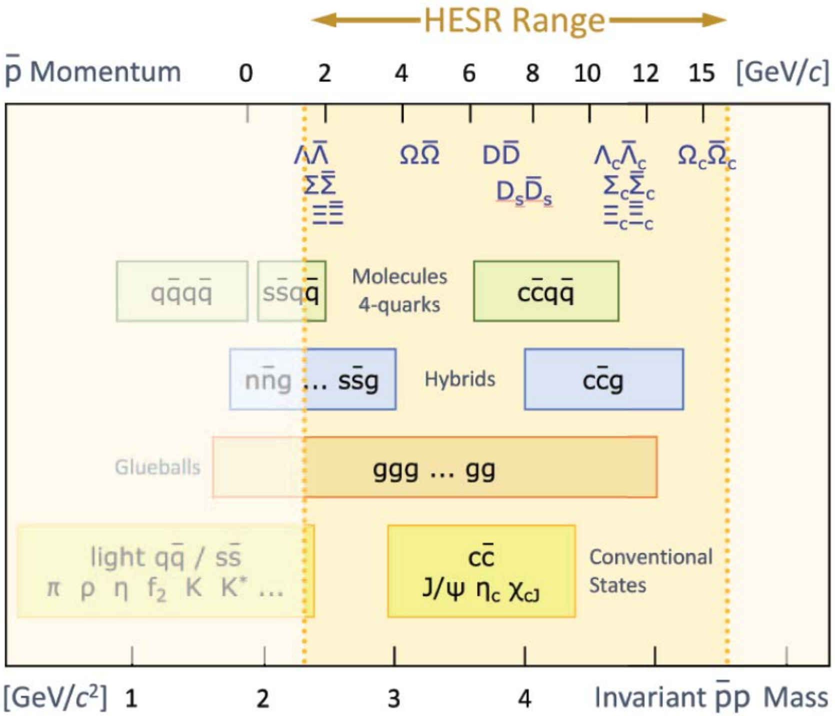
... or if there is a way to measure p and $\bar{p}$ polarization also ϕ_Λ ...

$$\alpha = 2\,\mathrm{Re}(s^* p)/(\,|\,s\,|^2 + \,|\,p\,|^2)\ ,$$

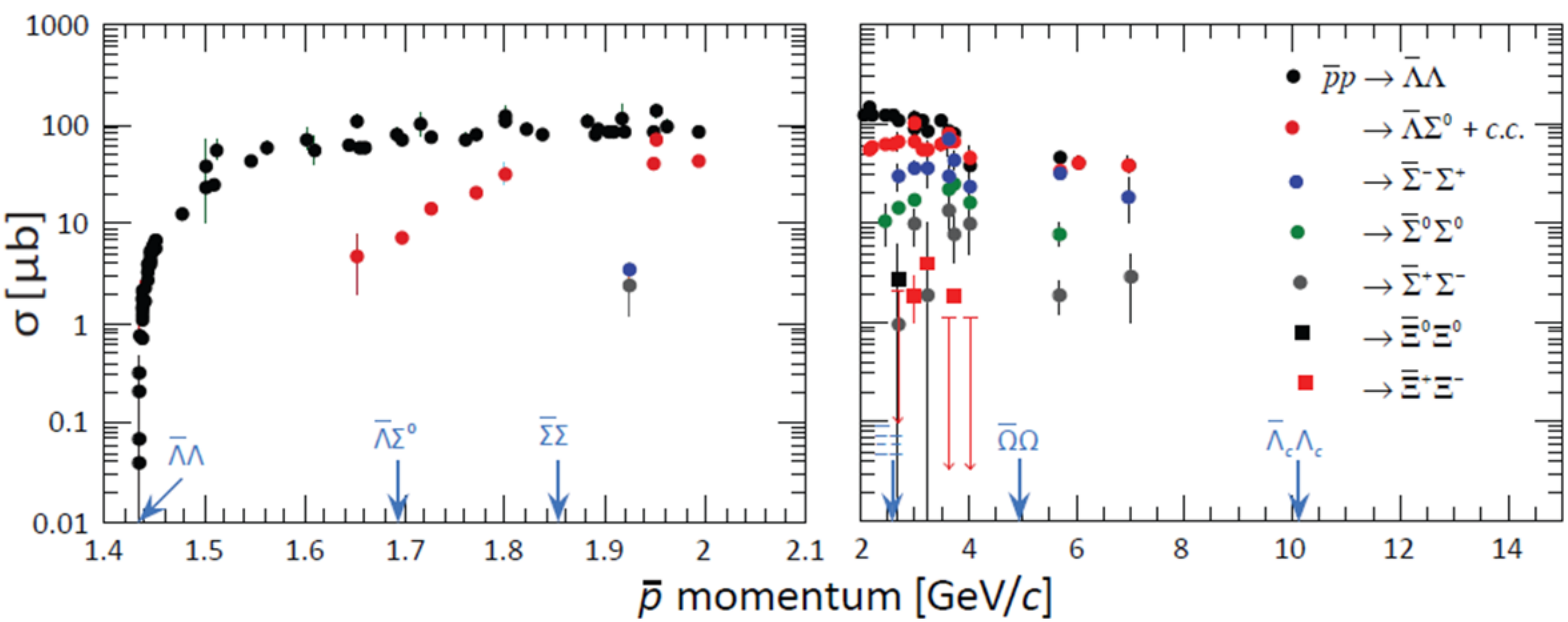
$$\beta = 2\,\mathrm{Im}(s^* p)/(\,|\,s\,|^2 + \,|\,p\,|^2)\ ,$$

$$\gamma = (\,|\,s\,|^2 - \,|\,p\,|^2)/(\,|\,s\,|^2 + \,|\,p\,|^2)$$

PDG

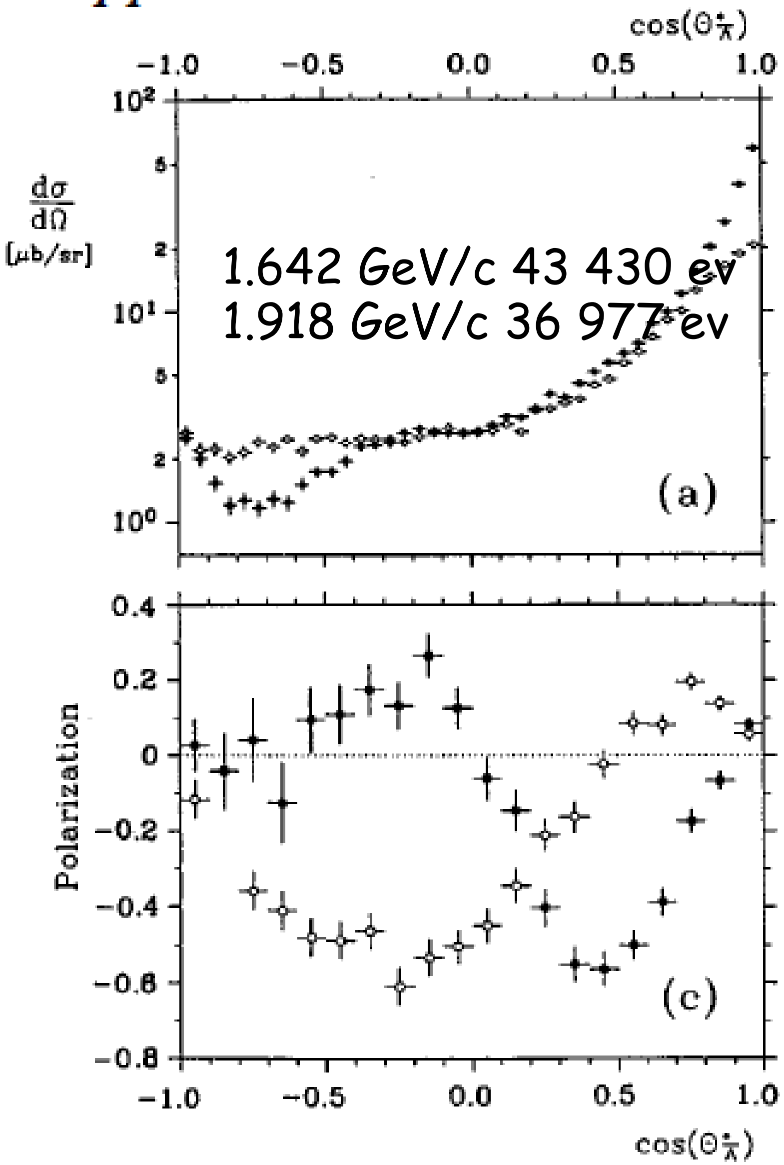


Reaction	σ (μb)	Efficiency (%)	Rate (with 10^{31} $cm^{-1}s^{-1}$)
$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	30 s^{-1}
$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$	~40	30	30 s^{-1}
$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~2	20	2 s^{-1}
$\bar{p}p \rightarrow \bar{\Omega}\Omega$	~0.002	30	~4 h^{-1}
$\bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c$	~0.1	35	~2 day^{-1}



Nuclear Physics News, Vol. 27, No. 3, 2017

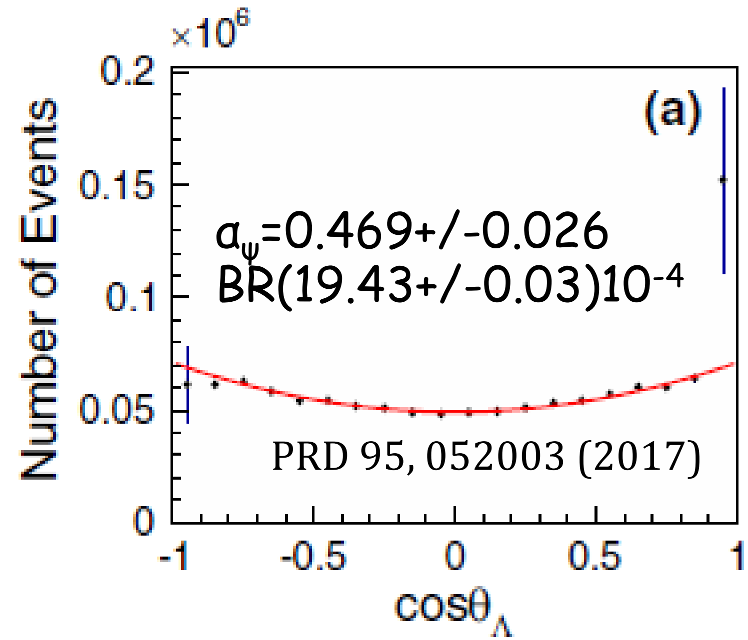
$\bar{p}p \to \bar{\Lambda}\Lambda$

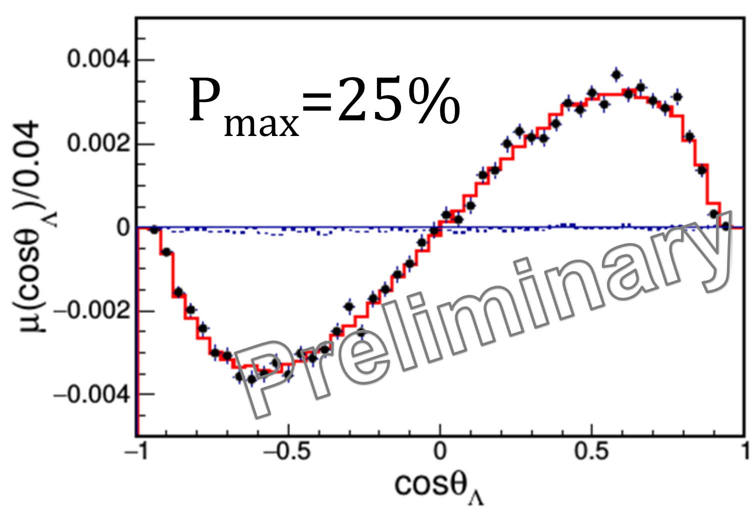


PS185, PRC54 (1996) 1877

5 parameters at each θ_Λ
Can't determine Λ decay param.

$e^+e^- \to \gamma^* \to J/\psi \to \Lambda\bar{\Lambda}$





2 global parameters
extract Λ decay par. α

Conclusions:

Prospects for $e^+e^- \to B_1 \, \overline{B}_2$ at Super tau-charm factory

Scan competitive if search for narrow structures
(other BelleII + ISR?)

Beam Polarization for FFs (phase between FFs)
[proton polarimeter??]

Entangled (and polarized?) $B_1\overline{B}_2$ pairs from J/ψ and ψ(2S) for CP tests and hyperon decay parameters

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For the moment:
A new puzzle: the value of the Λ decay parmeter ...
... and lot of fun searching for polarized hyperons from J/ψ and ψ(2S)

Thank you!