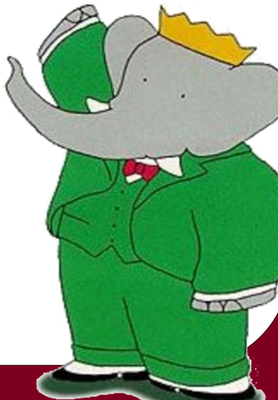
Mixing-induced CP asymmetry in semileptonic B-meson decays at BABAR

EPS HEP 2013 Stockholm



OUTLINE

- Introduction & Definition
- Description of the Measurement
- Results
- Conclusions

Mixing Induced CP-V

- B^0 mass eigenstates differ from flavor eigenstate:

$$|B_{L/H}> = \frac{1}{\sqrt{p^2+q^2}}[p|B^0>\pm q|\overline{B^0}>]$$

$q=p=\sqrt{1/2}$
CP conserved

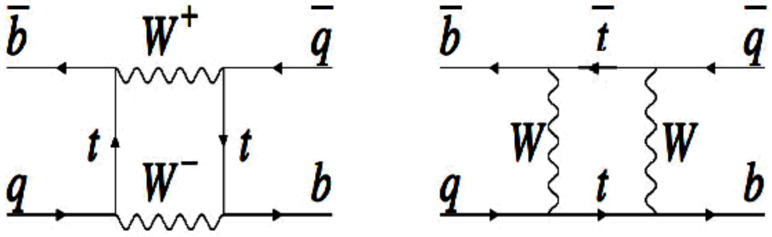
- CP asymmetry :

$$\mathcal{A}_{sl} = \frac{\Gamma(B^0(0)\rightarrow\overline{B^0}(\infty))-\Gamma(\overline{B^0}(0)\rightarrow B^0(\infty))}{\Gamma(B^0(0)\rightarrow\overline{B^0}(\infty))+\Gamma(\overline{B^0}(0)\rightarrow B^0(\infty))} = \frac{1-|q/p|^4}{1+|q/p|^4}\simeq 1-|q/p|^2$$

- Standard Model : very tiny effect

$$\mathcal{A}_{sl}(B_d) = (-4.1\pm0.6)\cdot10^{-4}$$

$$\mathcal{A}_{sl}(B_s) = (1.9\pm0.3)\cdot10^{-5}$$



(Lenz, Nierste, arXiv:1102.4274 (2011)):

- Positive observation : DISCOVERY OF NEW PHYSICS

MIXING-INDUCED CPV

- Colliders : B produced in opposite flavor pairs
- Mixing : find two equal-flavor mesons at decay time
- CP asymmetry is usually measured through B semileptonic decays :

$$\mathcal{A}_{\ell\ell} = \frac{N(B^0B^0)-N(\overline{B}^0\overline{B}^0)}{N(B^0B^0)+N(\overline{B}^0\overline{B}^0)} = \frac{N(\ell^+\ell^+)-N(\ell^-\ell^-)}{N(\ell^+\ell^+)+N(\ell^-\ell^-)}$$

Negligible CP asymmetry in direct semileptonic decay (model independent)

- Consider also single – tag asymmetry:

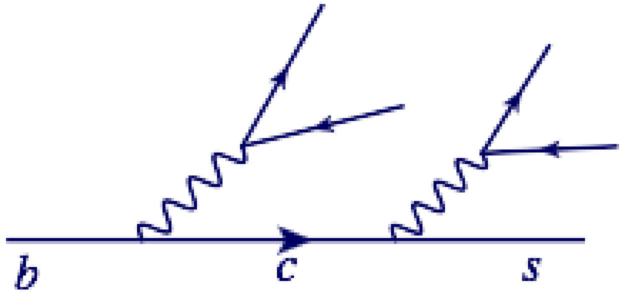
$$\mathcal{A}_{\ell} = \frac{N(B^0)-N(\overline{B}^0)}{N(B^0)+N(\overline{B}^0)} = \frac{N(\ell^+)-N(\ell^-)}{N(\ell^+)+N(\ell^-)} = \chi\,\mathcal{A}_{\ell\ell}$$

This Result

New approach, pioneered by BABAR:

- "Reco" 1st B : partial reconstruction of $B^0 \rightarrow \ell^+ \nu_\ell D^{*-}$
- "Tag" 2nd B : using charged Kaons

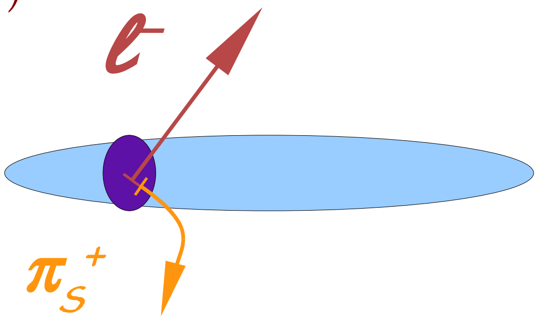
$$\mathcal{A}_{\ell\ell} = \frac{N(B_d B_d) - N(\overline{B_d}\,\overline{B_d})}{N(B_d B_d) + N(\overline{B_d}\,\overline{B_d})} = \frac{N(\ell^+ K^+) - N(\ell^- K^-)}{N(\ell^+ K^+) + N(\ell^- K^-)}$$



Cabibbo favored decays:
K^- tags a b quark

B -> D*ℓν Partial Reconstruction

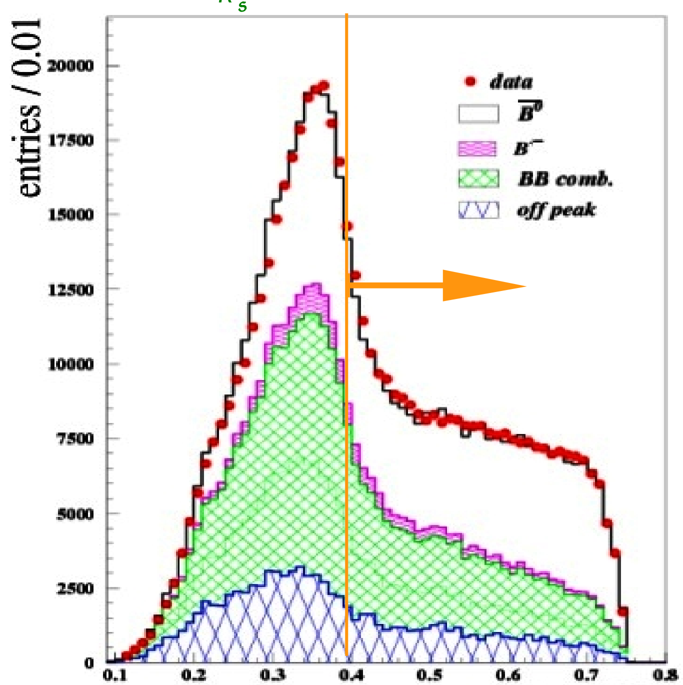
- Use only ℓ and low momentum π_s from the decay $D^{*-} \to \pi_s^- \overline{D}^0$
- Assume B^0 at rest in Y(4S) frame : $\vec{P}_B \sim 0$
- Get D* from π_s : $\vec{P}_{D*} = \vec{f}(\vec{P}_{\pi_s})$
- B decay point intersecting beamspot, ℓ, π_s tracks



B -> D*ℓν Partial Reconstruction

- Use only ℓ and low momentum π_s from the decay $D^{*-} \to \pi_s^- \overline{D}^0$
- Assume B^0 at rest in Υ(4S) frame : $\vec{P}_B \sim 0$
- Get D* from π_s : $\vec{P}_{D*} = \vec{f}(\vec{P}_{\pi_s})$
- B decay point intersecting beamspot, ℓ, π_s tracks
- Selection : likelihood ratio combining $p_\ell, p_{\pi s}, Prob(Vtx)$
- Cut $\mathcal{L} > 0.4$

$\mathcal{L}(\mathcal{P}_{\pi_s}, \mathcal{P}_\ell, \mathrm{Prob}(\mathrm{Vtx}))$



B -> D*ℓν Partial Reconstruction

- Use only ℓ and low momentum π_s from the decay $D^{*-} \rightarrow \pi_s^- \overline{D}^0$
- Assume B^0 at rest in $\Upsilon(4S)$ frame : $\vec{P}_B \sim 0$
- Get D^* from π_s : $\vec{P}_{D*} = \vec{f}(\vec{P}_{\pi_s})$
- Missing mass from four momenta difference:

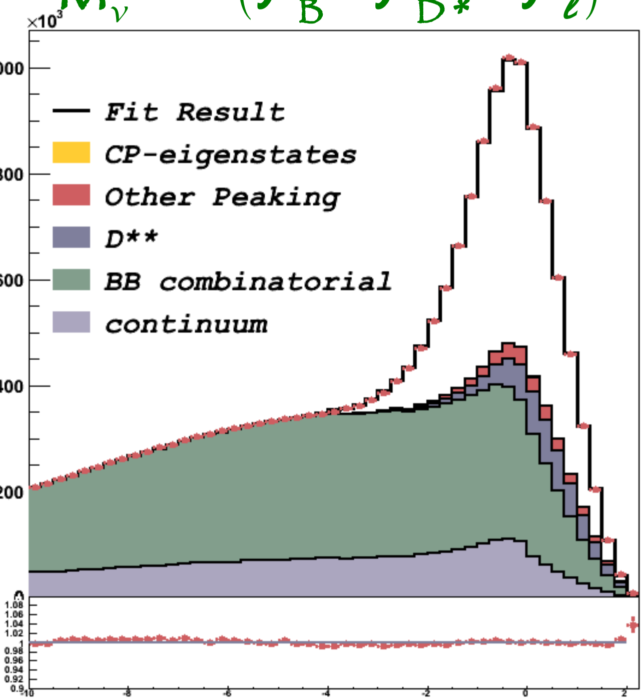
$$M_\nu^2 = (\mathcal{P}_B - \mathcal{P}_{D*} - \mathcal{P}_\ell)^2$$

- Fit :

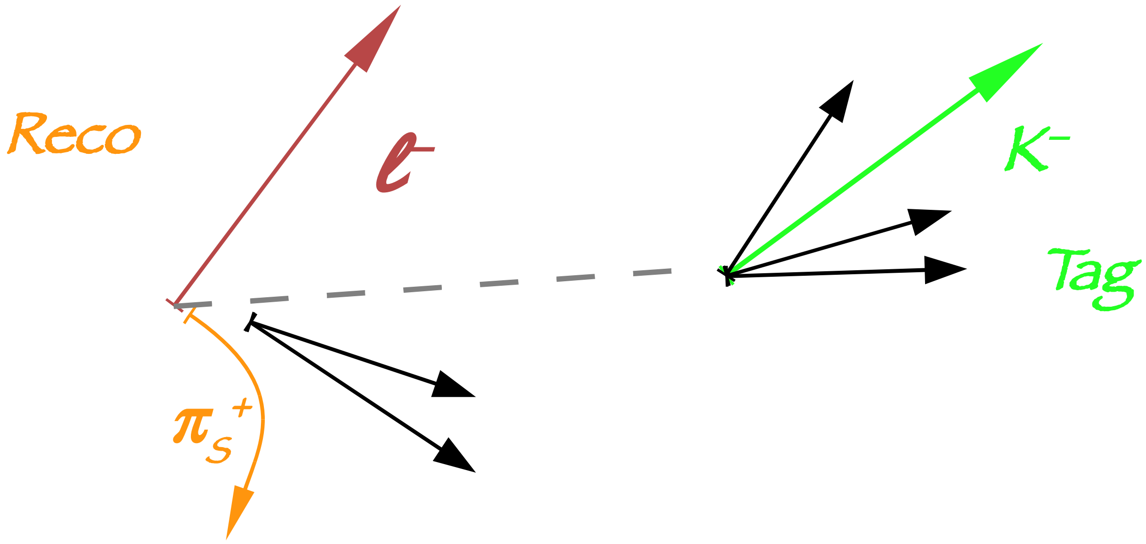
$$(5370 \pm 6) \times 10^3 \text{ Peaking Events}$$

BABAR Preliminary

$$M_\nu^2 = (\mathcal{P}_B - \mathcal{P}_{D*} - \mathcal{P}_\ell)^2$$



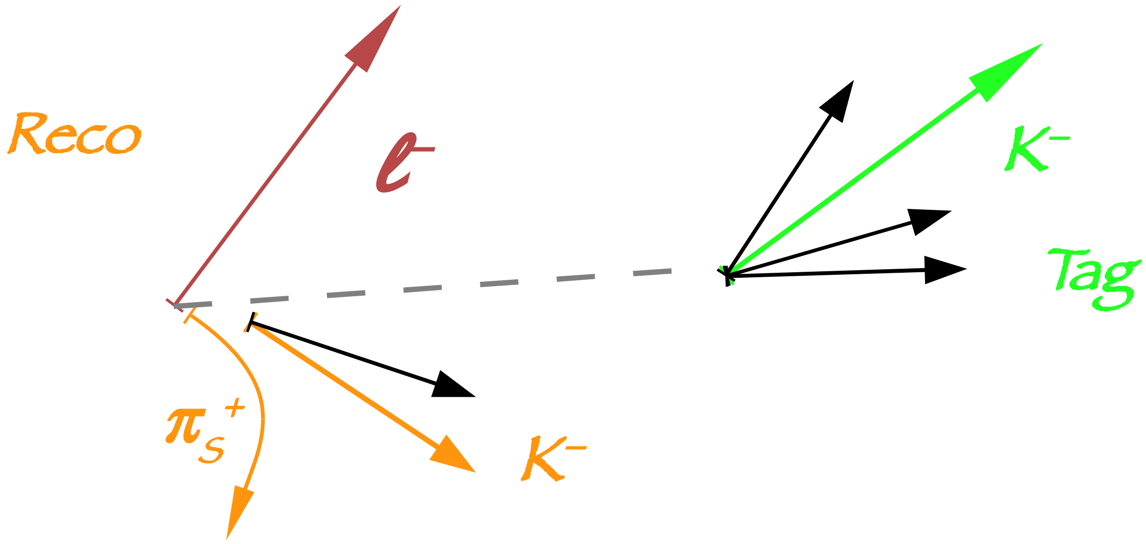
The Kaon Tag



- K identified using dE/dX & Cherenkov with high purity
- Tag-B decay point from intersection of Kaon track and beamspot
- Define

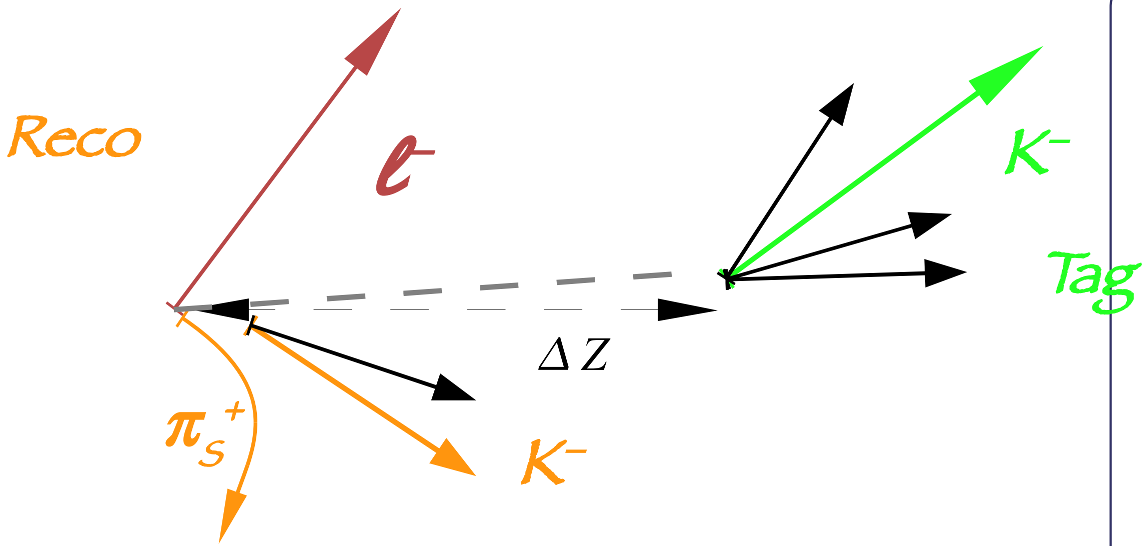
$$\Delta t = \frac{Z_{RECO} - Z_{TAG}}{\gamma \beta c}$$

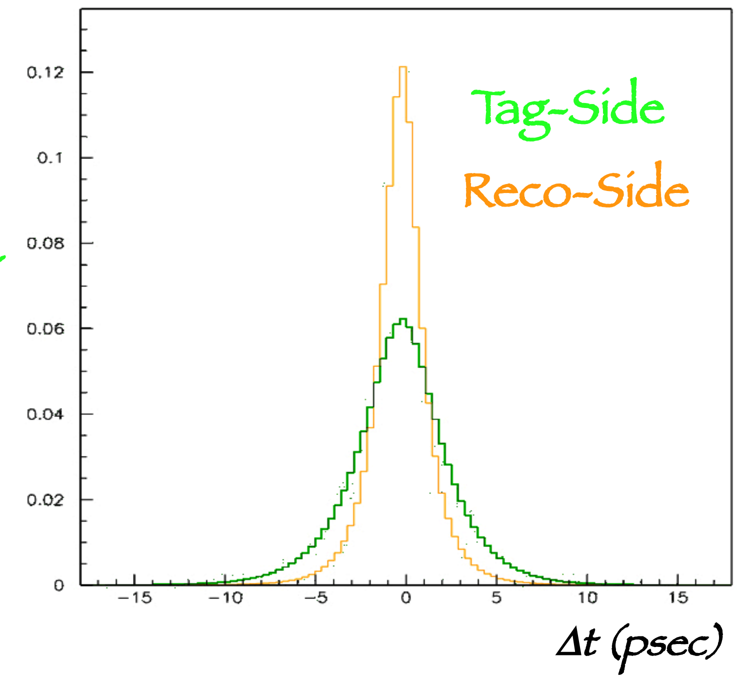
The Kaon Tag



- Equal charge Kaons also from the reco side, mimick a mixed event .

The Kaon Tag





- Equal charge Kaons also from the reco side, mimick a mixed event .
- Separated *on statistical basis* by:
  - $\Delta t \approx \Delta Z / (c\beta\gamma)$ (in the Lab)

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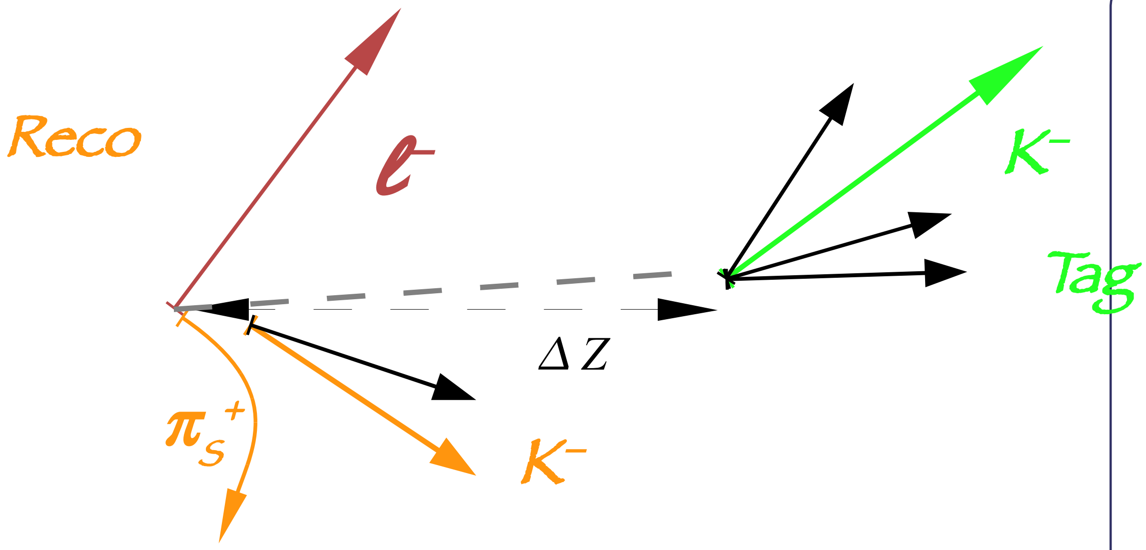
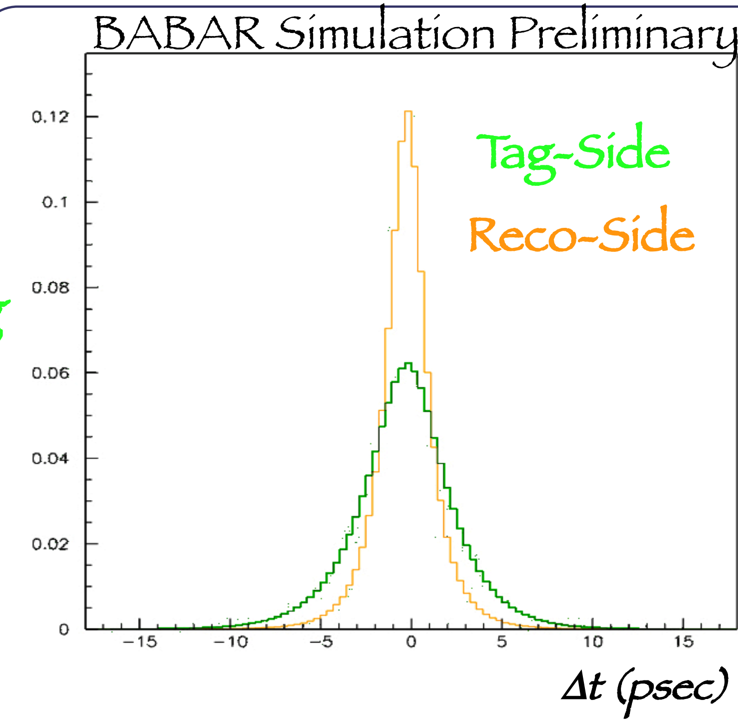
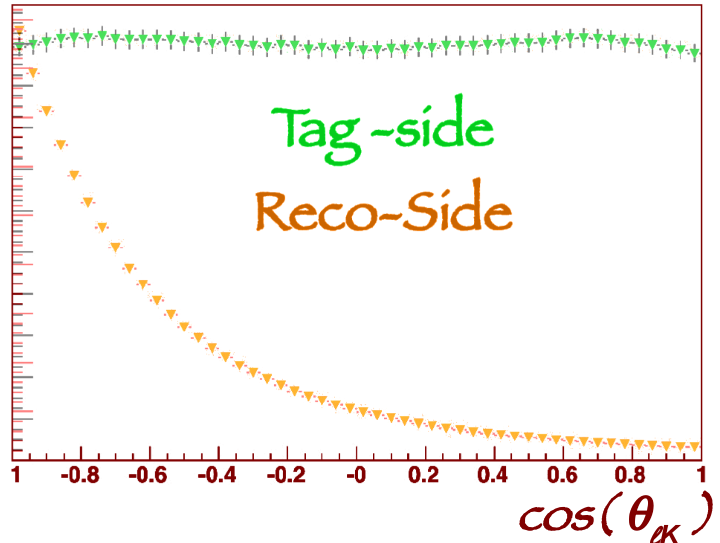


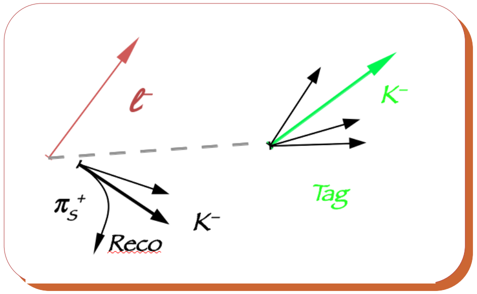


- Equal charge Kaons also from the reco side, mimick a mixed event .
- Separated *on statistical basis* by:
  - $\Delta t \approx \Delta Z / (c\beta\gamma)$ (in the Lab)
  - $\cos(\theta_{\ell K})$ (in $\Upsilon(4S)$ rest frame)



Asymmetry

- Observed asymmetries for mixed reflect RECO-side charge asymmetry, K-id charge asymmetry and Physical asymmetry:



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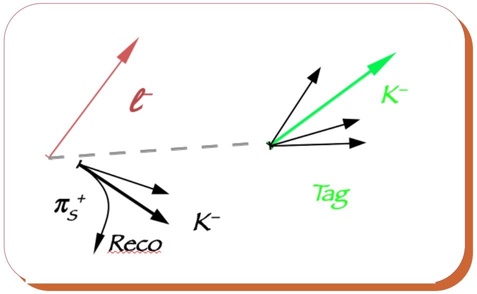

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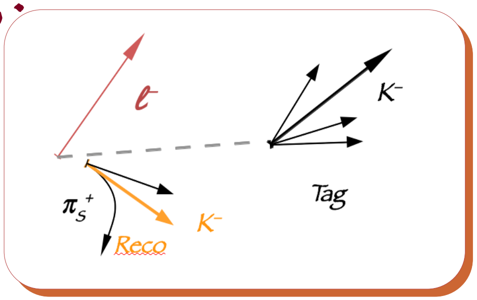
- Kaons from reco side have tiny contribution from mixing :



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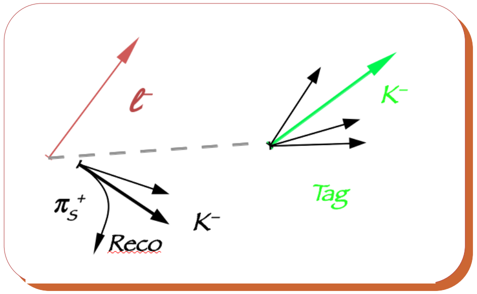

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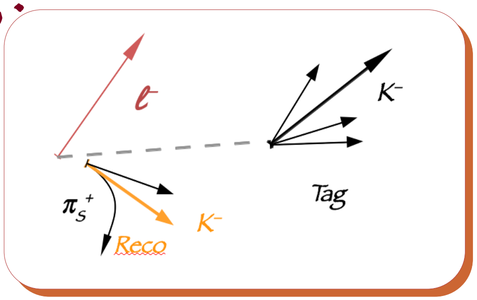

$$\mathcal{A}_{obs,K\text{-}Rec} \simeq \mathcal{A}_{Rec} + \mathcal{A}_{K} + \chi_d \mathcal{A}_{\ell\ell}$$

- Measure also single lepton asymmetry (before tagging) :

$$\mathcal{A}_{obs,Rec} = \frac{\ell^+ \pi_s^- - \ell^- \pi_s^+}{\ell^+ \pi_s^- + \ell^- \pi_s^+} \simeq \mathcal{A}_{Rec} + \chi_d \mathcal{A}_{\ell\ell}$$

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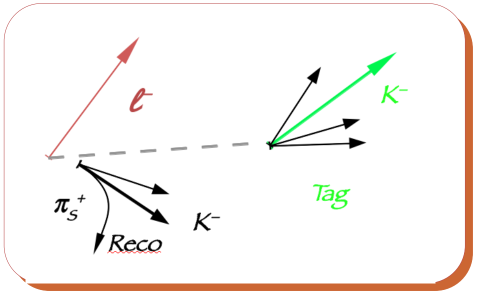

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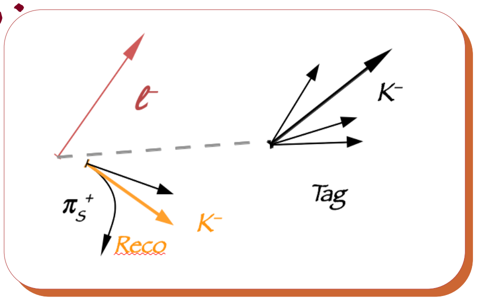

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- Measure also single lepton asymmetry (before tagging) :

$$\mathcal{A}_{obs,Rec} \simeq \mathcal{A}_{Rec} + \chi_d \mathcal{A}_{\ell\ell}$$

- Constrained system:

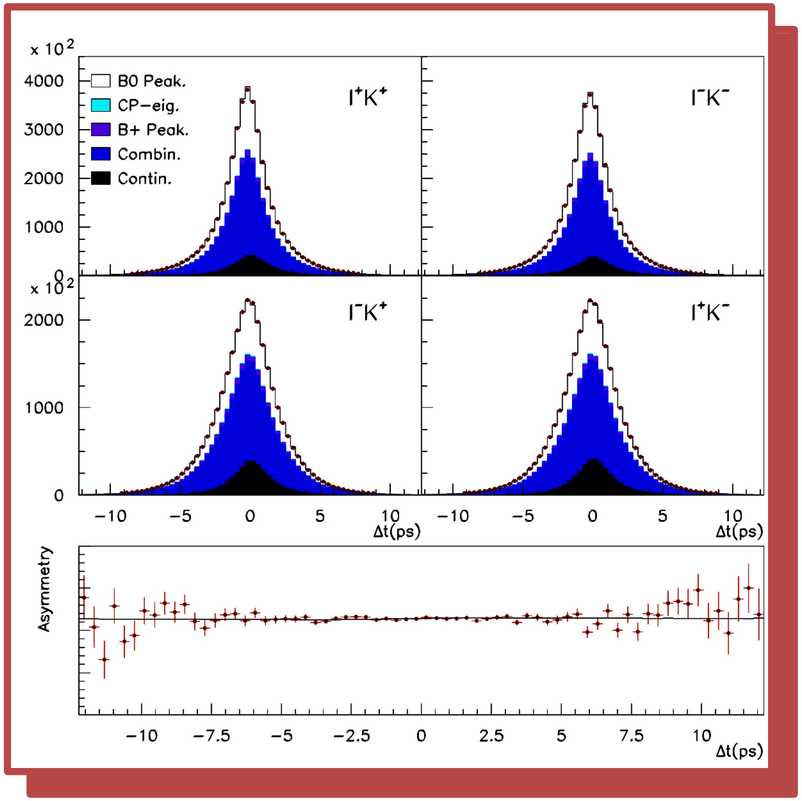
determine $\mathcal{A}_{\ell\ell}$, $\mathcal{A}_{K}$, and $\mathcal{A}_{Rec}$ from the data

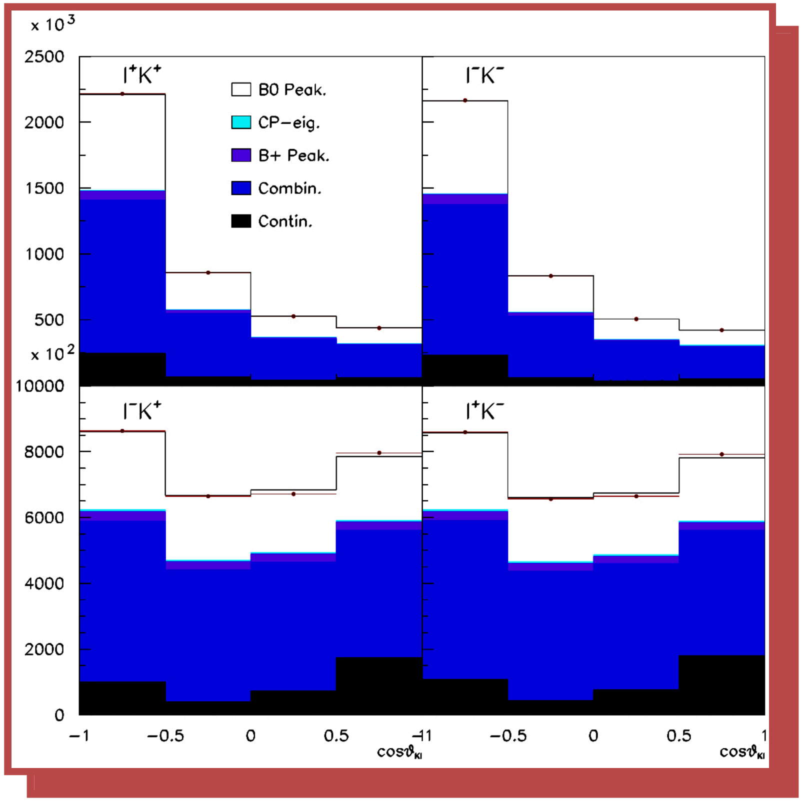
MEASUREMENT

- Asymmetry is not time dependent, however ...
- ... 5D binned fit to (Δt, $\sigma(\Delta t)$, $cos\theta_{\ell K}$, M_ν^2, p_K) space to separate signal from background, tag side from reco side Kaons
- Use also opposite sign ℓ^+K^- / ℓ^-K^+ to improve precision on resolution parameters, mis-tagging etc.
- More than 100 free parameters:
  - $\mathcal{A}_{\ell\ell}$, $\mathcal{A}_{REC}$, $\mathcal{A}_K$, K-Rec fraction,
  - fraction of wrong tags (charge dependent),
  - fraction of DCSC Kaons, ΔZ resolution parameters,
  - $\tau(B_d)$, Δm_d, ...

BABAR Preliminary Result

$$\mathcal{A}_{\ell\ell} = (0.06 \pm 0.16^{+0.36}_{-0.32})\%$$





ΔT (ps)

$\cos\theta_{\ell K}$

BaBar Preliminary Result

- Physical parameters (τ, Δm_d) consistent with WA
- Tiny (0 per mille) reconstruction asymmetry
- Large (0 per cent) K tag asymmetry
- Dominant systematic: sample composition, propagated from $\mathcal{M}^2_\nu$ fits

Parameter	Fit to the data	Fit to the simulation	MC truth
δ_{CP}	$(0.29 \pm 0.84) \times 10^{-3}$	$(0.35 \pm 0.46) \times 10^{-3}$	0
$\mathcal{A}_{re}$	0.0030 ± 0.0004	0.0097 ± 0.0002	
$\mathcal{A}_{r\mu}$	0.0031 ± 0.0005	0.0084 ± 0.0003	
$\mathcal{A}_K$	0.0137 ± 0.0003	0.0147 ± 0.0001	
τ_{B^0}	1.5535 ± 0.0019	1.5668 ± 0.0012	1.540
Δm_d	0.5085 ± 0.0009	0.4826 ± 0.0006	0.489

Source	$\Delta\lvert q/p\rvert$
Peaking Sample Composition	$^{+1.17}_{-1.50} \times 10^{-3}$
Combinatoric Sample Composition	$\pm 0.39 \times 10^{-3}$
ΔT Resolution Model	$+0.60 \times 10^{-3}$
Dtag fraction	$\pm 0.11 \times 10^{-3}$
Dtag ΔT distribution	$\pm 0.65 \times 10^{-3}$
Fit Bias	$^{+0.46}_{-0.58} \times 10^{-3}$
CP-eigenstate description	—
Physical Parameters	$+0.28 \times 10^{-3}$
Total	$^{+1.61}_{-1.78} \times 10^{-3}$

Conclusions

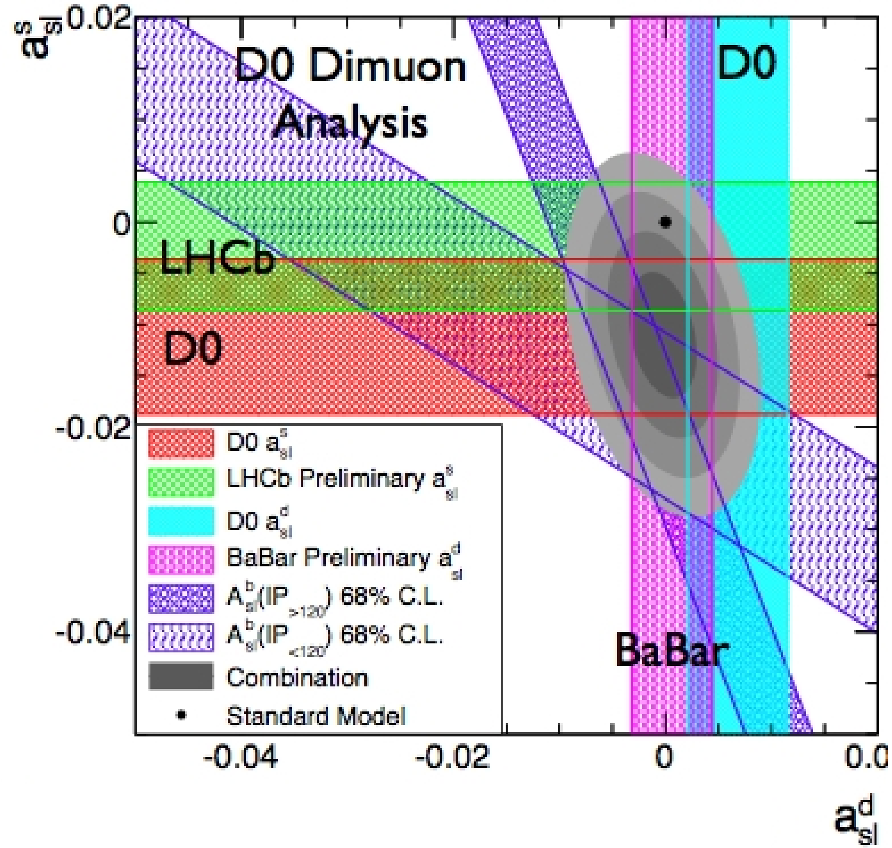
BABAR Preliminary

$$\mathcal{A}_{\ell\ell} = (0.06 \pm 0.16^{+0.36}_{-0.32})\%$$

- Consistent and more precise than previous B-Factories average:

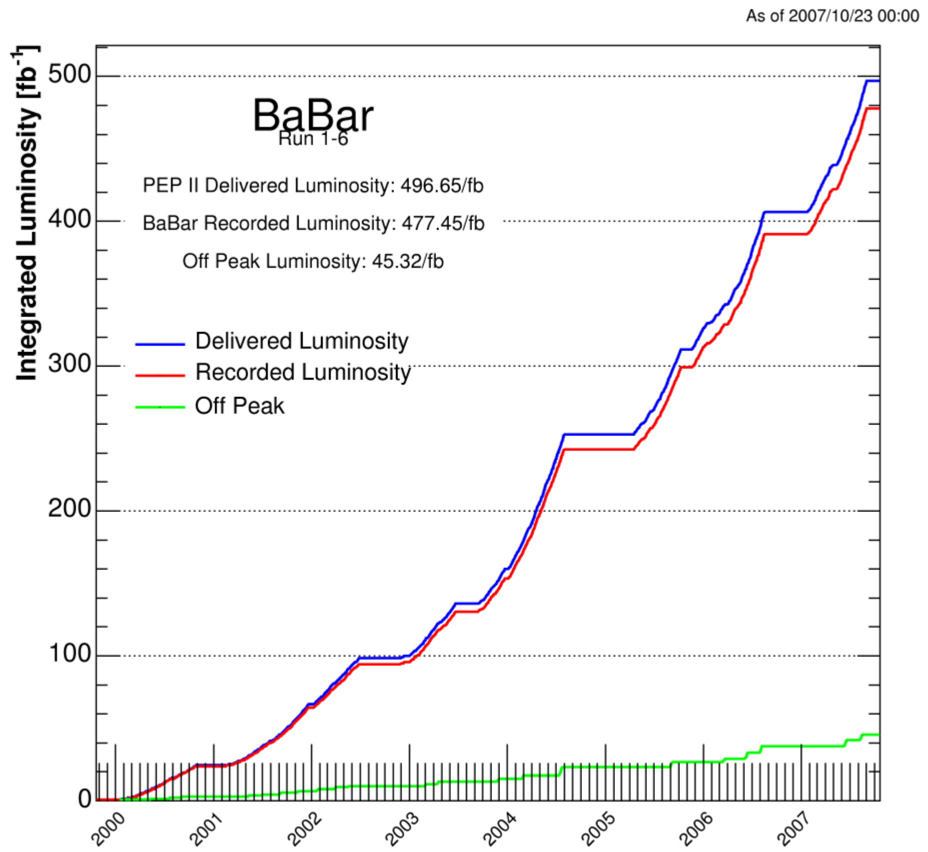
$$\mathcal{A}_{\ell\ell} = (-0.05 \pm 0.56)\%$$

- Competitive and complementary to similar measurements at hadron colliders
- Contributing to world class precision in the determination of B-mixing CP asymmetries
- WA (grey) consistent with SM @ less than 2 σ



Backup

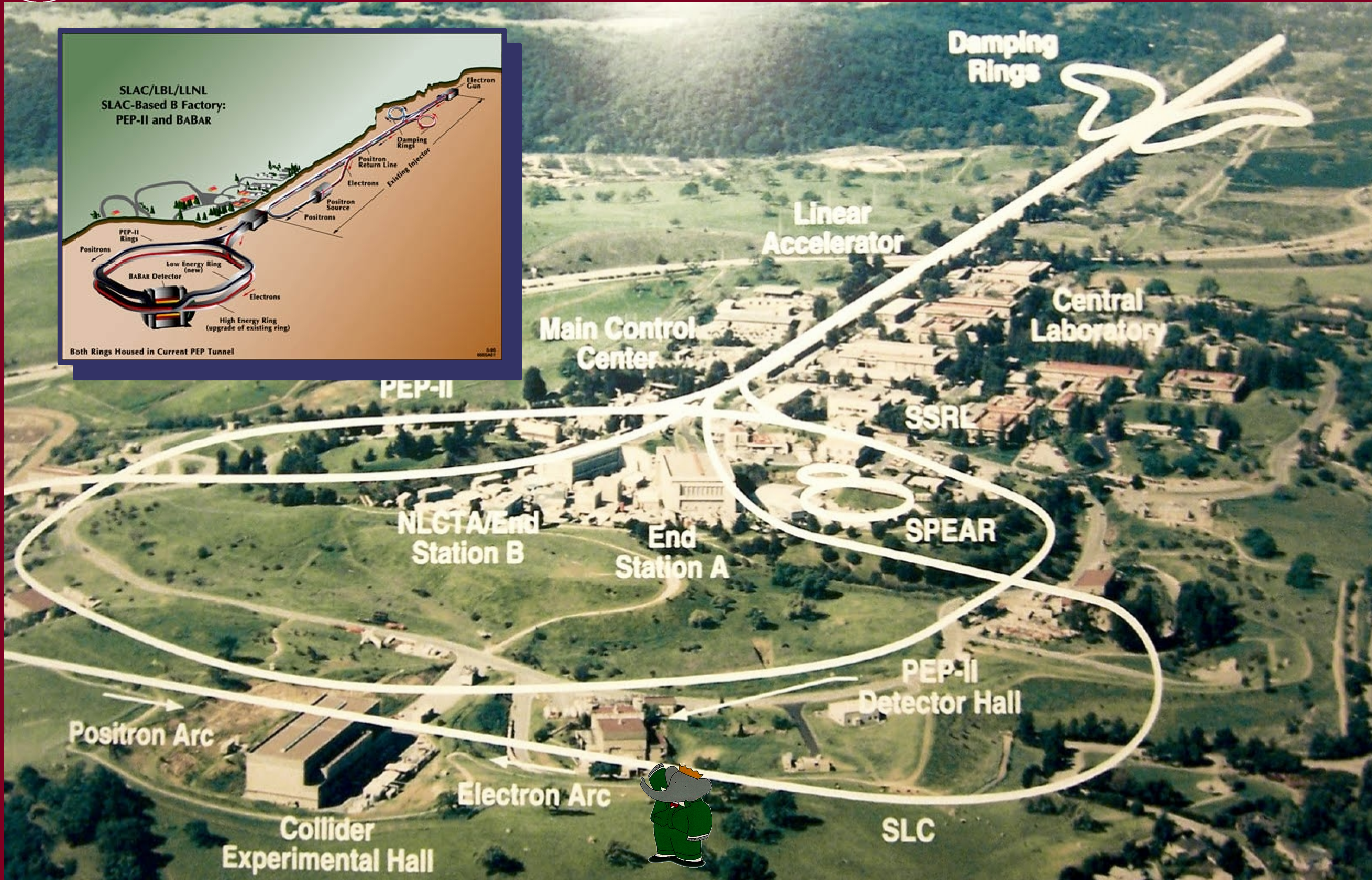
BaBar : history of a success



22/10/1999 -> 07/04/2008 :

- 530 fb^{-1} collected
- > 500 million BB, cc, ττ pairs
- 516 published papers

Tools for a success : the factory



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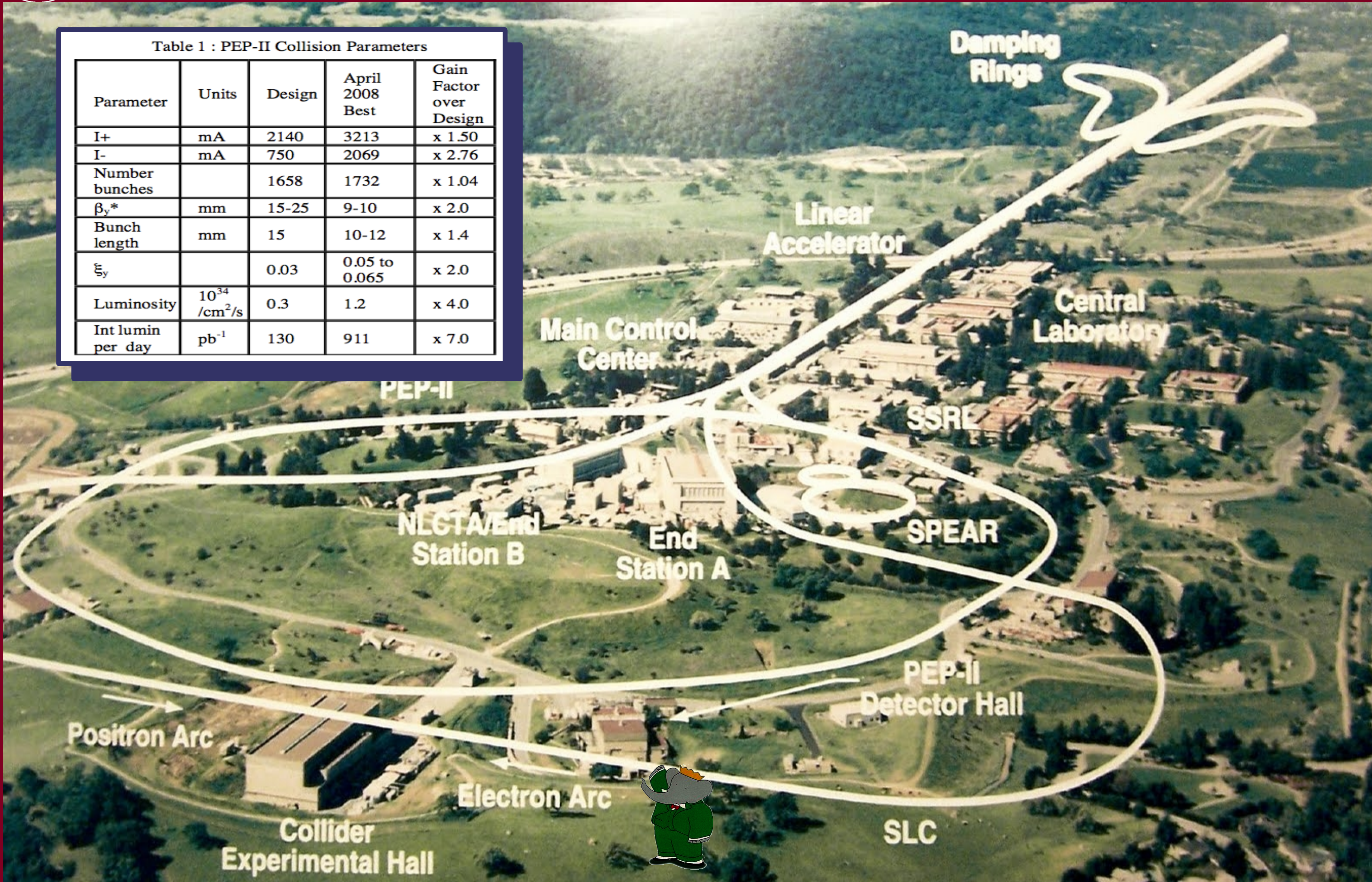
Tools for a success : the factory

INFN

Table 1 : PEP-II Collision Parameters

Parameter	Units	Design	April 2008 Best	Gain Factor over Design
I+	mA	2140	3213	x 1.50
I-	mA	750	2069	x 2.76
Number bunches		1658	1732	x 1.04
β_y*	mm	15-25	9-10	x 2.0
Bunch length	mm	15	10-12	x 1.4
ξ_y		0.03	0.05 to 0.065	x 2.0
Luminosity	10^{34} /cm^2/s	0.3	1.2	x 4.0
Int lumin per day	pb^{-1}	130	911	x 7.0



Peaking B^0 Pdf – Tag Side

- $\cos\theta_{\ell K}$, M_ν^2, p_K : from simulation
- Δt: convolve resolution with Physics-motivated functions :

$$
\begin{aligned}
\mathcal{F}_{\bar{B}^0 B^0}(\Delta t') &= \mathcal{E}(\Delta t')\left[\left(1+\left|\frac{q}{p}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t'/2)+\left(1-\left|\frac{q}{p}\right|^2 r'^2\right)\cos(\Delta m_d\Delta t')-\left|\frac{q}{p}\right|(b+c)\sin(\Delta m_d\Delta t')\right]\\
\mathcal{F}_{B^0 \bar{B}^0}(\Delta t') &= \mathcal{E}(\Delta t')\left[\left(1+\left|\frac{p}{q}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t'/2)+\left(1-\left|\frac{p}{q}\right|^2 r'^2\right)\cos(\Delta m_d\Delta t')+\left|\frac{p}{q}\right|(b-c)\sin(\Delta m_d\Delta t')\right]\\
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\mathcal{F}_{B^0 B^0}(\Delta t') &= \mathcal{E}(\Delta t')\left[\left(1+\left|\frac{q}{p}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t'/2)-\left(1-\left|\frac{q}{p}\right|^2 r'^2\right)\cos(\Delta m_d\Delta t')+\left|\frac{q}{p}\right|(b+c)\sin(\Delta m_d\Delta t')\right]\left|\frac{p}{q}\right|^2\\
\mathcal{E}(\Delta t') &= \frac{\Gamma_0}{2(1+r'^2)}e^{-\Gamma_0|\Delta t'|},
\end{aligned}
$$

CP violation in the tag side :

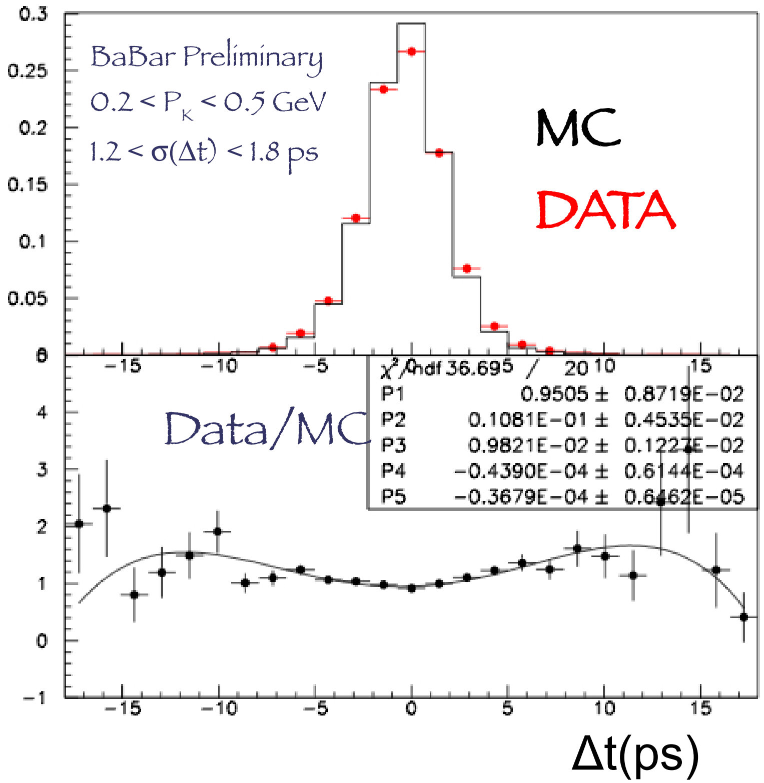
r'

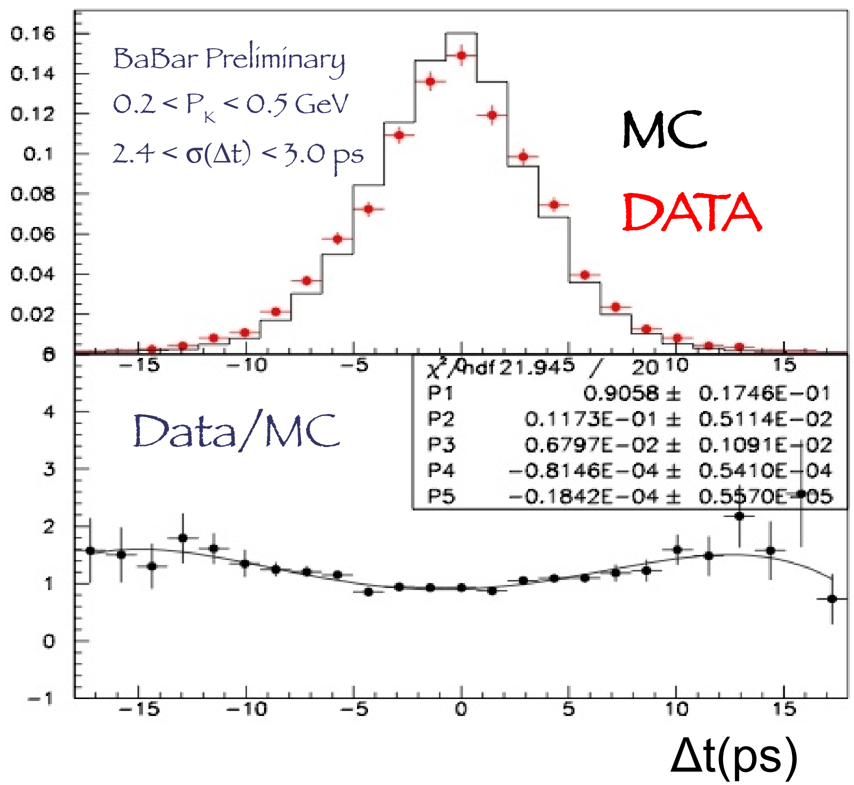
$b = 2r' \sin(2\beta+\gamma) \cos\delta'$,

$c = -2r' \sin(2\beta+\gamma) \sin\delta'$

Peaking B0 Pdf - Reco Side

- $\cos\theta_{\ell K}$, M_{ν}^{2}, p_K : from simulation
- Δt : use enriched Reco-side sample



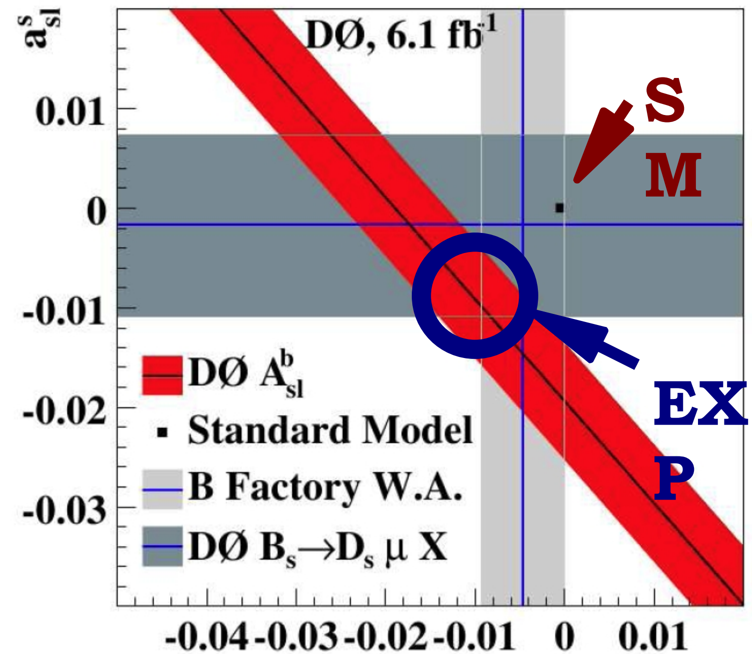


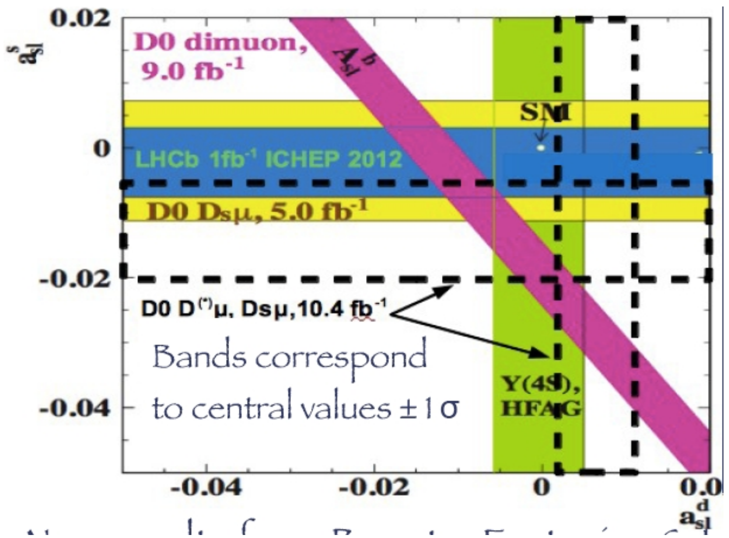
Background PDF

- Combinatorial B^0 : similar to peaking B^0, many common parameters, including $|q/p|$ and detector asymmetries
- Peaking and combinatorial B^+ : same approach, use pure lifetime Δt PDF, helps constraining detector asymmetries, resolution parameters, etc.
- Continuum : parameterized PDF from off-peak events

Dilepton Asymmetry @ colliders

- D0 claims large unexpected asymmetry in equal charge dilepton B decays at ICHEP 2010
- Lifetime analysis : effect connected to B_s mixing
- D0 and LHCb then measure asymmetry in the rates of $B_s \to D^{(*)}_s \mu \nu$ decays
- These measurements are consistent both with the SM and with D0 dilepton results





Peaking B^0 PDF

- Four terms, one per each ℓK charge combination:

$\vec{j} = (\cos\theta_{\ell K}, M_\nu^2, p_K, \Delta t, \sigma(\Delta t))$ bin

$\mathcal{G}_{BB}$ = PDF for tag side K

$\mathcal{G}_{K r}$ = PDF for reco side K

ω = wrong charge tag frac.

$$\mathcal{G}_{\ell^+ K^+}(\vec{j}) = (1+\mathcal{A}_{rec})(1+\mathcal{A}_K) \times \{ (1-f^{++}_{K r})[(1-\omega^+)\mathcal{G}_{B^0 B^0}(\vec{j}) + \omega^- \mathcal{G}_{B^0 \overline{B^0}}(\vec{j})] + f^{++}_{K r}(1-\omega'^+)\mathcal{G}_{\ell r}(\vec{j}) + (1+\chi_d \mathcal{A}_{\ell\ell}) \}$$

$$\mathcal{G}_{\ell^- K^-}(\vec{j}) = (1-\mathcal{A}_{rec})(1-\mathcal{A}_K) \times \{ (1-f^{--}_{K r})[(1-\omega^-)\mathcal{G}_{\overline{B^0}\,\overline{B^0}}(\vec{j}) + \omega^+ \mathcal{G}_{\overline{B^0} B^0}(\vec{j})] + f^{--}_{K r}(1-\omega'^-)\mathcal{G}_{\ell r}(\vec{j}) + (1-\chi_d \mathcal{A}_{\ell\ell}) \}$$

Peaking B^0 PDF

- Four terms, one per each ℓK charge combination, including DETECTION asymmeties:

$\vec{j} = (\cos\theta_{\ell K}, M_\nu^2, p_K, \Delta t, \sigma(\Delta t))$ bin

$\mathcal{G}_{BB} =$ PDF for tag side K

$\mathcal{G}_{Kr} =$ PDF for reco side K

ω = wrong charge tag frac.

$$\mathcal{G}_{\ell^+ K^+}(\vec{j}) = (1+\mathcal{A}_{rec})(1+\mathcal{A}_K) \times$$
$$\{ (1-f^{++}_{Kr})[(1-\omega^+)\mathcal{G}_{B^0 B^0}(\vec{j}) + \omega^- \mathcal{G}_{B^0 \overline{B^0}}(\vec{j})] +$$
$$f^{++}_{Kr}(1-\omega'^+)\mathcal{G}_{kr}(\vec{j}) + (1+\chi_d \mathcal{A}_{\ell\ell}) \}$$

$$\mathcal{G}_{\ell^- K^-}(\vec{j}) = (1-\mathcal{A}_{rec})(1-\mathcal{A}_K) \times$$
$$\{ (1-f^{--}_{Kr})[(1-\omega^-)\mathcal{G}_{\overline{B^0}\,\overline{B^0}}(\vec{j}) + \omega^+ \mathcal{G}_{\overline{B^0} B^0}(\vec{j})] +$$
$$f^{--}_{Kr}(1-\omega'^-)\mathcal{G}_{kr}(\vec{j}) + (1-\chi_d \mathcal{A}_{\ell\ell}) \}$$

Peaking B0 PDF

$\vec{j}=(\cos\theta_{\ell K}, M_\nu^2, p_K, \Delta t, \sigma(\Delta t))$ bin

$\mathcal{G}_{BB}$ = PDF for tag side K

$\mathcal{G}_{Kr}$ = PDF for reco side K

ω = wrong charge tag frac.

- Four terms, one per each ℓK charge combination, … TAG-SIDE contributions:

$$\mathcal{G}_{\ell^+ K^+}(\vec{j}) = (1+\mathcal{A}_{rec})(1+\mathcal{A}_K) \times$$
$$\{ (1-f^{++}_{Kr})[(1-\omega^+)\mathcal{G}_{B^0 B^0}(\vec{j})+\omega^- \mathcal{G}_{B^0 \overline{B^0}}(\vec{j})]+$$
$$f^{++}_{Kr}(1-\omega'^+)\mathcal{G}_{kr}(\vec{j})+(1+\chi_d \mathcal{A}_{\ell\ell}) \}$$

$$\mathcal{G}_{\ell^- K^-}(\vec{j}) = (1-\mathcal{A}_{rec})(1-\mathcal{A}_K) \times$$
$$\{ (1-f^{--}_{Kr})[(1-\omega^-)\mathcal{G}_{\overline{B^0}\,\overline{B^0}}(\vec{j})+\omega^+ \mathcal{G}_{\overline{B^0} B^0}(\vec{j})]+$$
$$f^{--}_{Kr}(1-\omega'^-)\mathcal{G}_{kr}(\vec{j})+(1-\chi_d \mathcal{A}_{\ell\ell}) \}$$

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$\vec{j} = (\cos\theta_{\ell K}, M_\nu^2, p_K, \Delta t, \sigma(\Delta t))$ bin

$\mathcal{G}_{BB}$ = PDF for tag side K

$\mathcal{G}_{Kr}$ = PDF for reco side K

ω = wrong charge tag frac.

- Four terms, one per each ℓK charge combination and RECO-SIDE contributions:

$$\mathcal{G}_{\ell^+ K^+}(\vec{j}) = (1+\mathcal{A}_{rec})(1+\mathcal{A}_K) \times$$
$$\{ (1-f^{++}_{Kr})[(1-\omega^+)\mathcal{G}_{B^0 B^0}(\vec{j}) + \omega^- \mathcal{G}_{B^0 \overline{B^0}}(\vec{j})] +$$
$$f^{++}_{Kr}(1-\omega'^+)\mathcal{G}_{kr}(\vec{j}) + (1+\chi_d \mathcal{A}_{\ell\ell}) \}$$

$$\mathcal{G}_{\ell^- K^-}(\vec{j}) = (1-\mathcal{A}_{rec})(1-\mathcal{A}_K) \times$$
$$\{ (1-f^{--}_{Kr})[(1-\omega^-)\mathcal{G}_{\overline{B^0}\,\overline{B^0}}(\vec{j}) + \omega^+ \mathcal{G}_{\overline{B^0} B^0}(\vec{j})] +$$
$$f^{--}_{Kr}(1-\omega'^-)\mathcal{G}_{kr}(\vec{j}) + (1-\chi_d \mathcal{A}_{\ell\ell}) \}$$