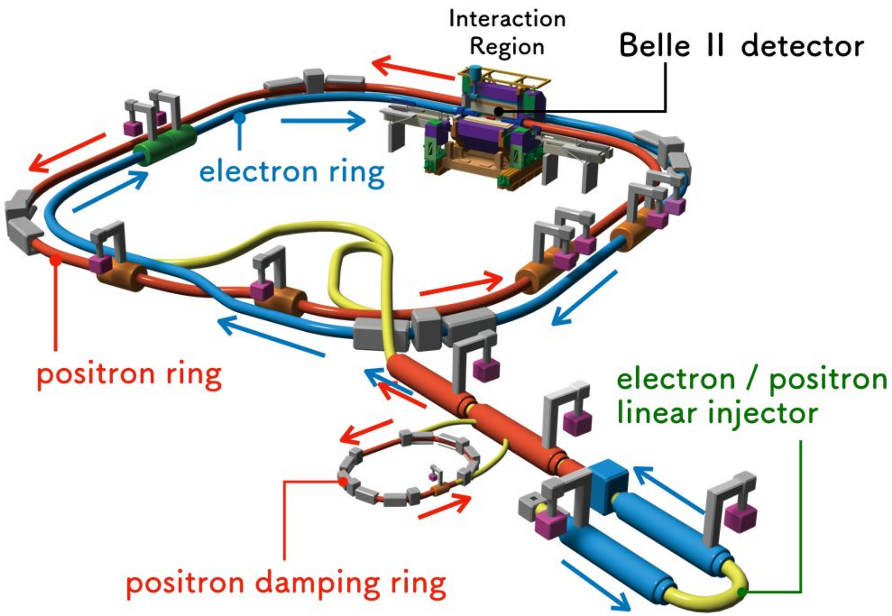
Demonstration of Tau Polarimetry for SuperKEKB Polarization Upgrade

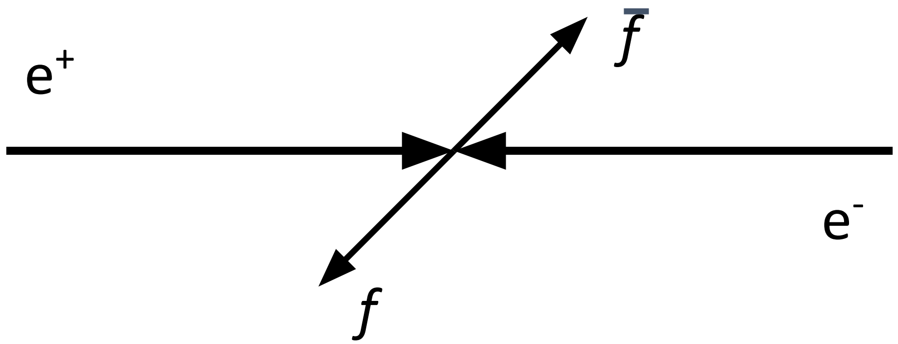
Caleb Miller

CAP 2023

Chiral Belle

- Beam polarization is being considered as a future upgrade to SuperKEKB
- For the full details see Mike Roney's talk from yesterday afternoon





- Plan is to achieve a 70% polarized e^- beam
- Enables a wide physics program

Caleb Miller. calebmiller@uvic.ca

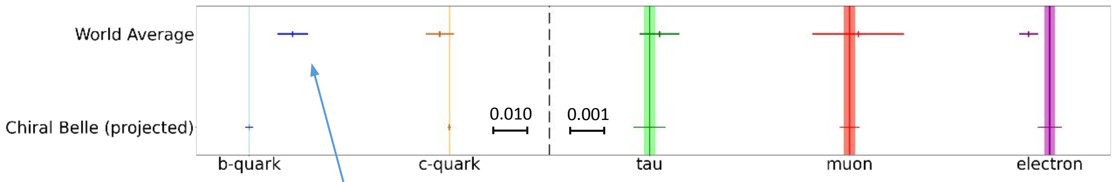
Beam Polarization Motivation

- Beam polarization is being considered as a future upgrade to SuperKEKB
- A polarized electron beam would allow Belle II to make many precise measurements of electroweak parameters. Including A_{LR} for e,μ,τ,c,b. For Born level s-channel process:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle P \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

Fermion	*Standard Model*	*World Average*	*Chiral Belle 40ab^{-1}*
b-quark	-0.3437±0.0001	-0.3220 ±0.0077	0.0020(4x improvement)
c-quark	0.1920±0.0002	0.1873 ±0.0070	0.0010(7x improvement)
Tau	-0.0371±0.0003	-0.0366 ±0.0010	0.0008
Muon	-0.0371±0.0003	-0.03667±0.0023	0.0005(4x improvement)
Electron	-0.0371±0.0003	-0.03816±0.00047	0.0006

Visualization of Chiral Belle projections of g_V^f vs World Averages and Standard Model(vertical line) from table



2.8σ between SM and WA

Assuming universality a combined lepton analysis reaches a uncertainty of $0.00033_{stat} \pm 0.00018_{sys}$, compared to a SM uncertainty of 0.0003

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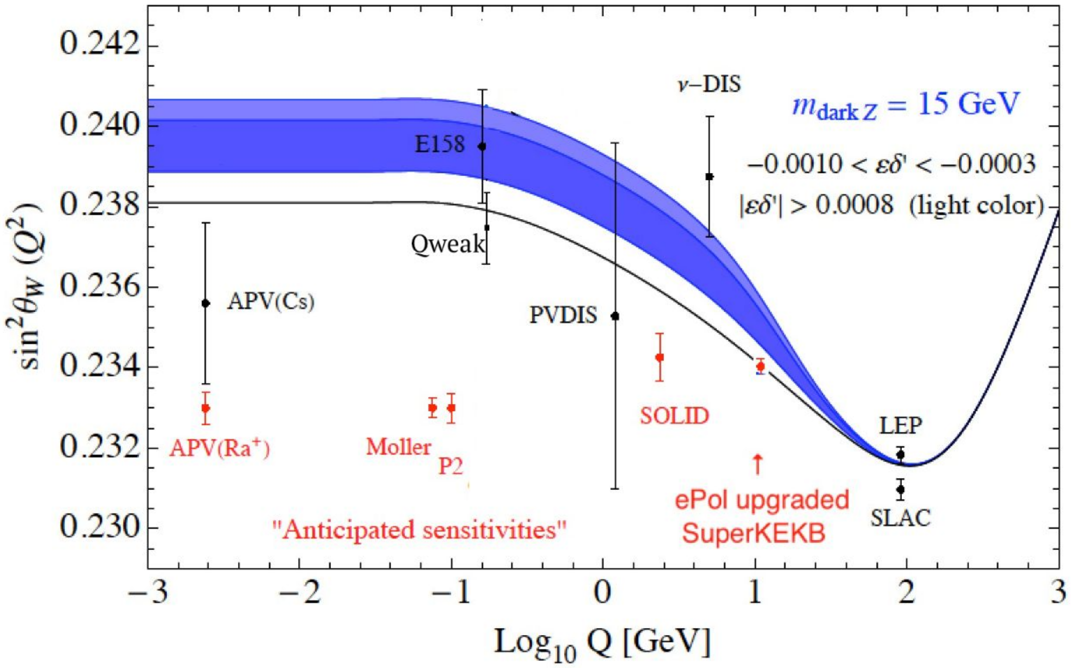


Red bars show expected sensitivity of future experiments. position arbitrary.

Chiral Belle expects:
$\sigma(\sin^2\theta_W) \approx 0.0002$ (40 ab^{-1})

adapted from figure 3 of H. Davoudiasl, H.S. Lee and W.J. Marciano, Phys.Rev.D 92(5),2015

Beam Polarization Motivation

The physics projections assume a 70% polarized e^- beam and requires measuring the polarization to within 0.5% to meet projections

Compton polarimeters, have an uncertainty associated with modelling the spin transport from the polarimeter to the interaction point (IP)

By using Tau Polarimetry we can extract the average beam polarization directly from the data at the IP

Chiral Belle White Paper
https://arxiv.org/abs/2205.12847

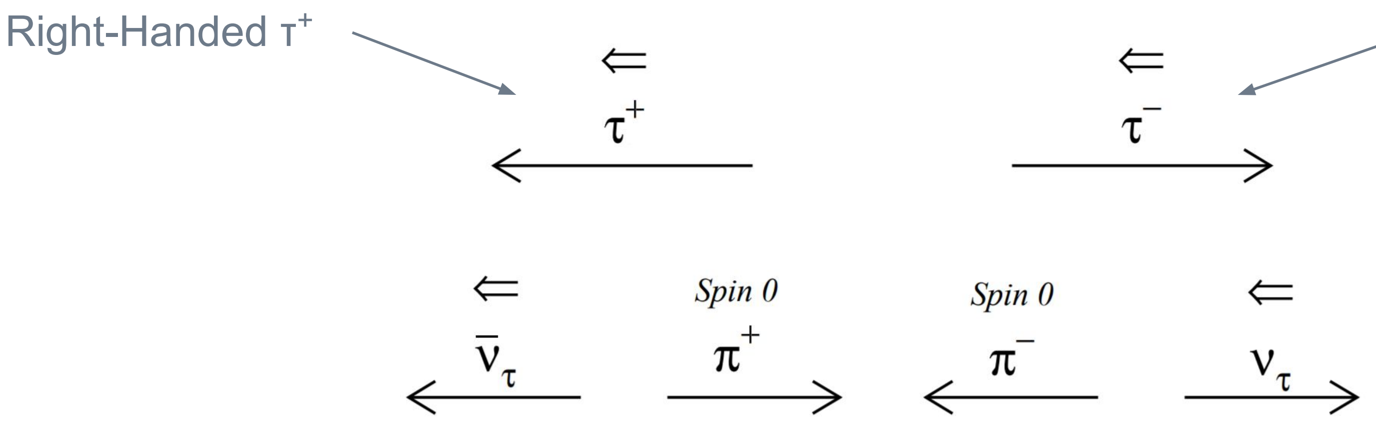
Tau Polarimetry

- The polarization of tau's (P_τ) produced in e^+e^- collisions at 10.58 GeV is related to the electron beam polarization (P_e) through:

$$P_{\tau^-} = P_e \frac{\cos\theta}{1+\cos^2\theta} - \frac{8G_F s g_V^\tau}{4\sqrt{2}\pi\alpha}\left(g_A^\tau \frac{|\vec{p}|}{p^0} + 2g_A^e \frac{\cos\theta}{1+\cos^2\theta}\right)$$

Note: cosθ defined as the polar angle of the τ^- with respect to the electron beam

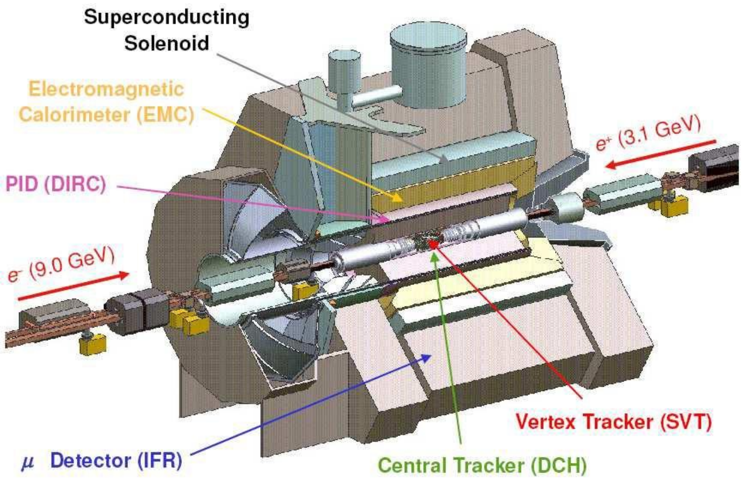
- Tau polarization information can be extracted from the kinematics of the tau decay

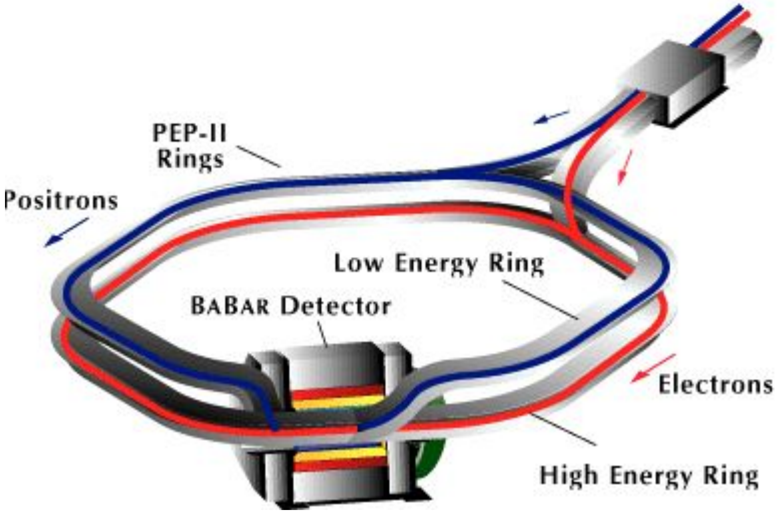


→: Momentum
⇒: Spin

BaBar and PEP-II

BaBar and PEP-II operated at SLAC from 1999-2008

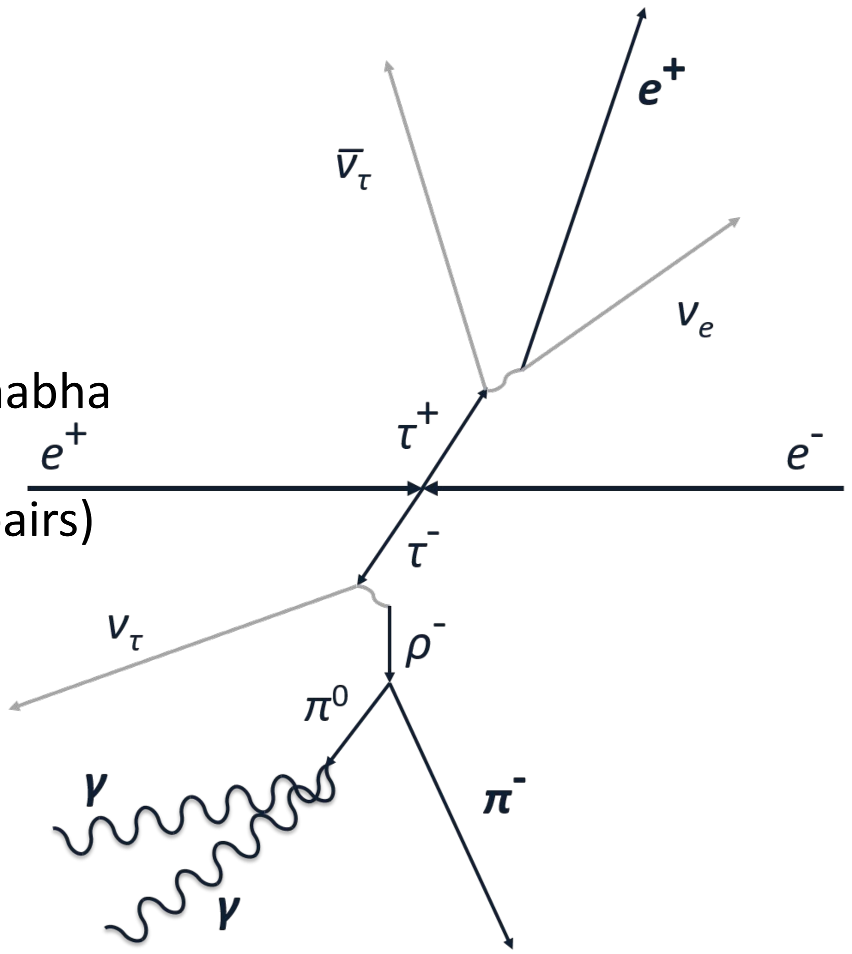




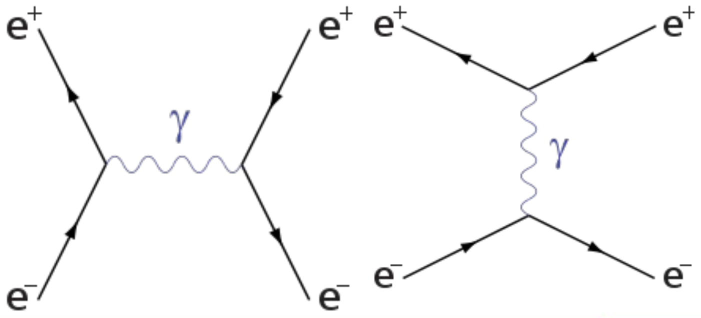
- Similar design of *BaBar* and Belle II also us to benchmark the technique on *BaBar*
  - Statistical sensitivity
  - Dominant systematic sources
- Over 6 run periods *BaBar* collected 432 fb^{-1} of data on the $\Upsilon(4S)$ resonance
- PEP-II collided electrons and positrons together at 9.0 and 3.1 GeV
- No beam polarization is expected at PEP-II

Tau Event Selection

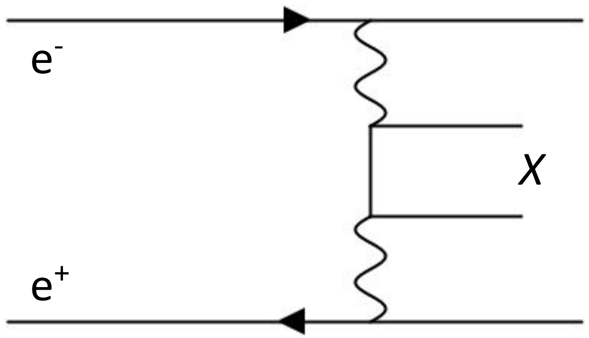
- Selected tau events in a 1v1 topology, (ρ vs. e or μ)
  - ρ has large branching fraction, lepton for clean tag
- Signal candidates are defined as a charged particle with a π^0
- $q\bar{q}$ events are eliminated with the lepton requirement
- Angular cuts and a minimum p_T of 350 MeV reduce two photon and Bhabha contamination
- Results in a 99.9% pure tau-pair sample (0.05% Bhabha, 0.05% muon pairs)
- 88% of selected events contain a $\tau^\pm \to \pi^\pm \pi^0 \nu_\tau$ decay
  - 12% other hadronic decays



Bhabha process



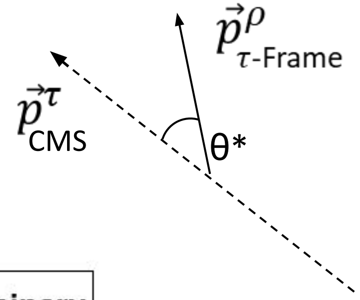
Two-photon process



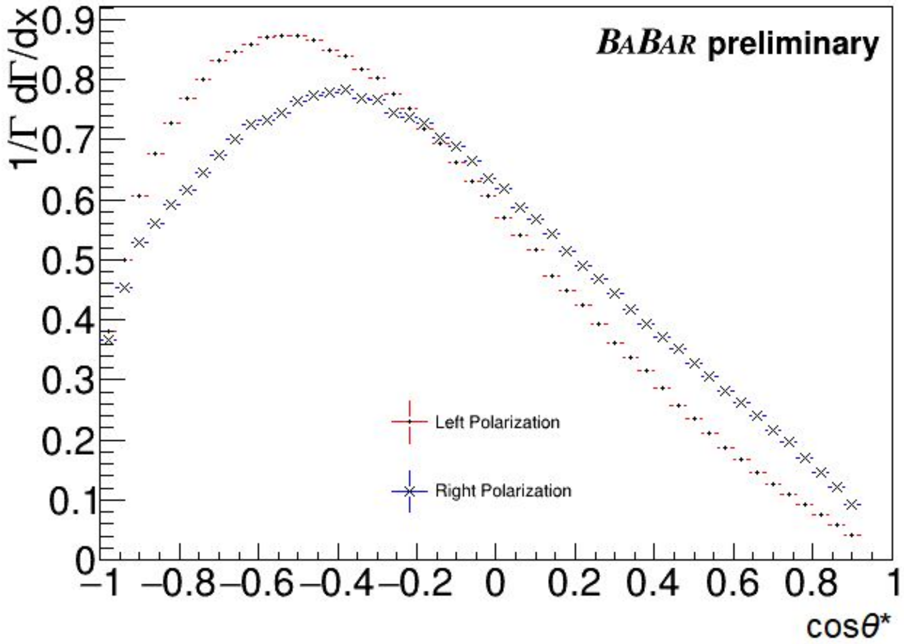
Polarization Observables

- Polarization sensitivity in a rho decay is maximized by analyzing two angular variables[2] in addition to cosθ

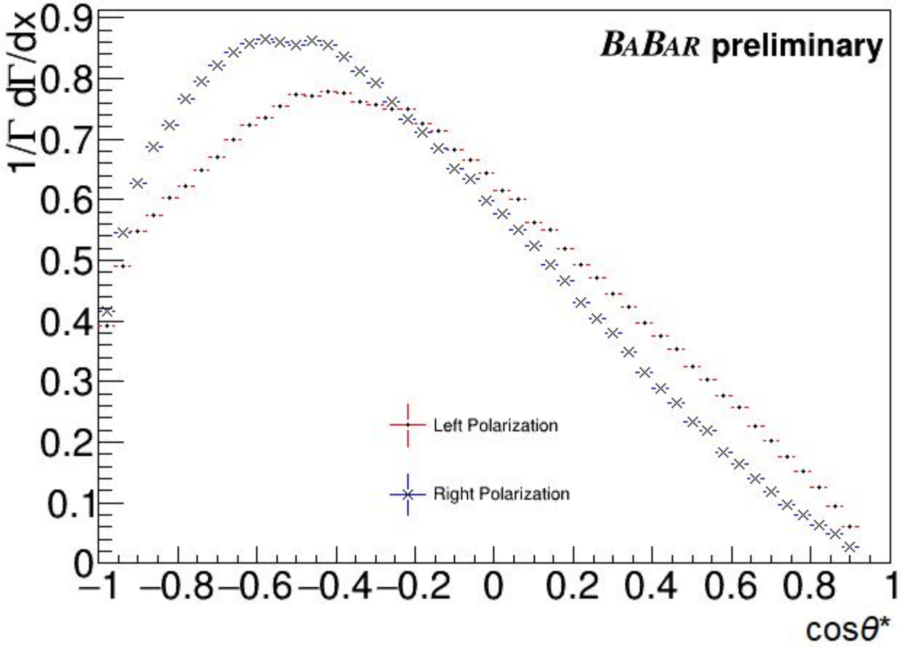
$$\cos\theta^* = \frac{2z - 1 - m_\rho^2/m_\tau^2}{1 - m_\rho^2/m_\tau^2} \qquad z \equiv {E_\rho}/{E_{\text{beam}}}$$



cosθ<0



cosθ>0



[2] K. Hagiwara, A. Martin, D. Zeppenfeld, Tau Polarization Measurements at LEP and SLC, Phys. Lett. B. 235, 1998, DOI: 10.1016/0370-2693(90)90120-U

Polarization Observables

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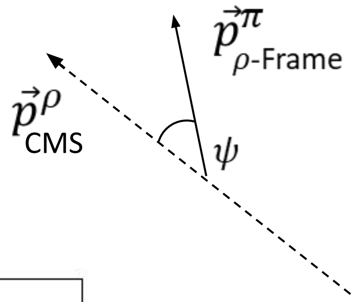
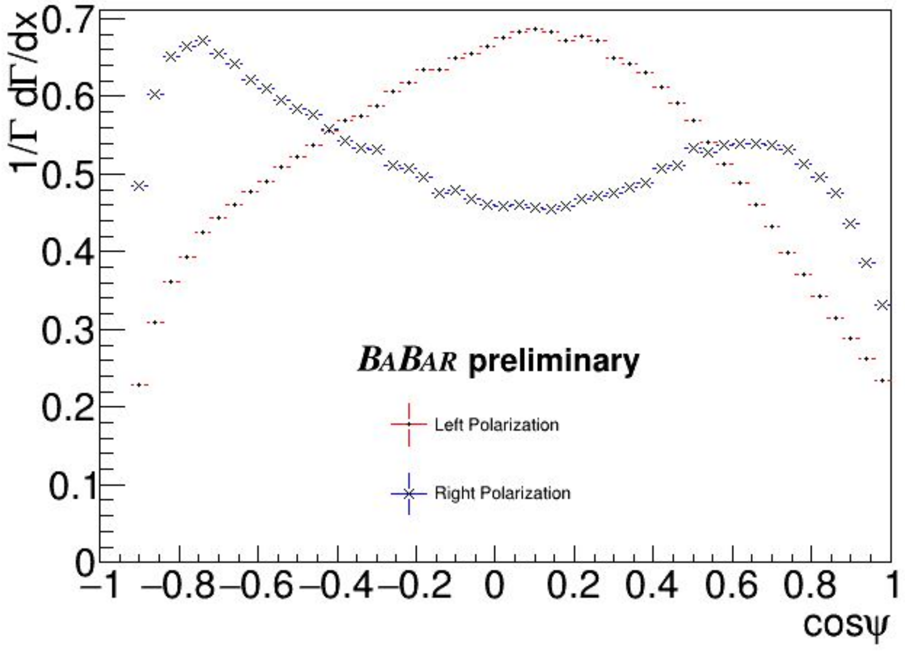
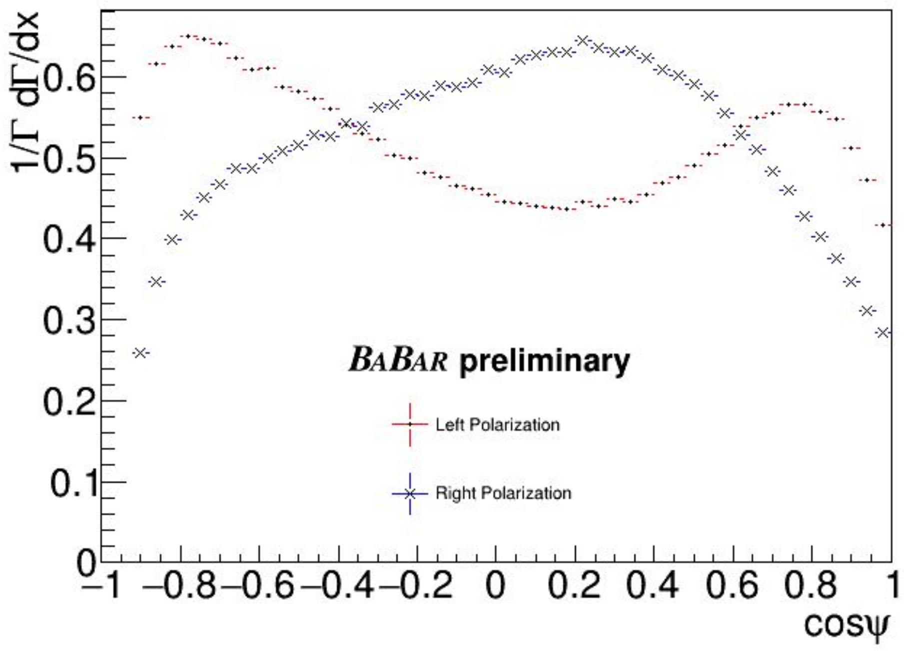
$$\cos\psi = \frac{2x-1}{\sqrt{1-4m_\pi^2/m_\rho^2}} \qquad x \equiv E_\pi / E_\rho$$



cosθ<0



cosθ>0



[2] K. Hagiwara, A. Martin, D. Zeppenfeld, Tau Polarization Measurements at LEP and SLC, Phys. Lett. B. 235, 1998, DOI: 10.1016/0370-2693(90)90120-U

Polarization Fit

- To extract the average beam polarization from a data set we employ a binned maximum likelihood fit using Barlow and Beeston[3] template fit methodology
- Data and MC is binned in 3D histograms of cosθ*, cosψ, and cosθ
- Tau MC was produced for a left and right polarized electron beam
- The data is fit as a linear combination of the histograms

a_l	0.499
a_r	0.499
a_b	3.8×10^{-5}
a_m	1.4×10^{-3}
a_u	3.8×10^{-4}
a_c	4.8×10^{-5}

$$D = a_l L + a_r R + a_b B + a_m M + a_u U + a_c C$$

$$\langle P \rangle \equiv a_l - a_r$$

D=data L=Left Polarized Tau MC R=Right Polarized Tau MC B=Bhabha(e^+e^-) M=μμ U=uds C=$c\bar{c}$

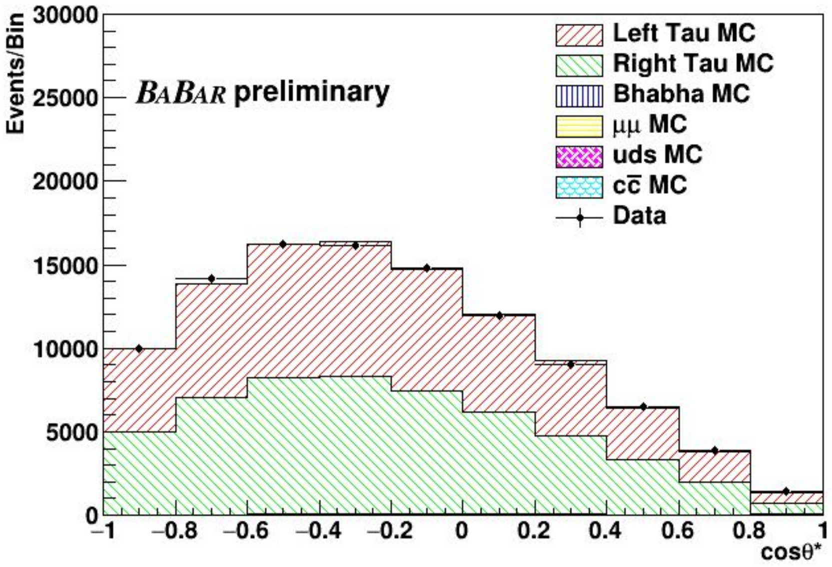
a_i = fit contribution

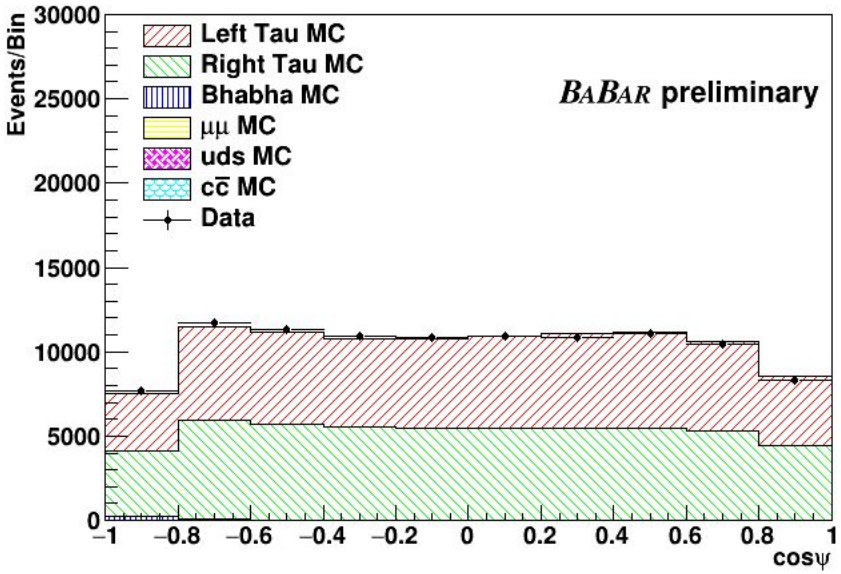
[3] R. Barlow, C. Beeston; Computer Physics Communications, Volume 77, Issue 2, 1993, Pages 219-228, https://doi.org/10.1016/0010-4655(93)90005-W

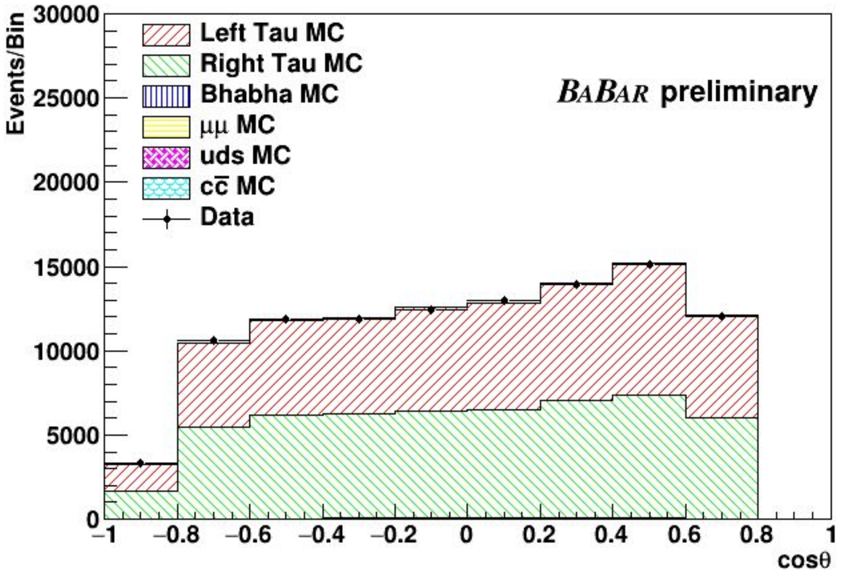
Example Fit Result

Sample	Positive	Negative	Total
Run 3 (32.28 fb^{-1})	0.0151±0.0120	-0.0047±0.0120	0.0048±0.0083

- Fit result projected to each of the fit variables
- Result from preliminary Run 3 fit, Negative charges
- <P>=-0.0031, χ^2/NDF=770/872







Full Measurement

- Performing the measurement on the full 424.2 fb^{-1}

Sample	Luminosity (fb^{-1})	Average Polarization
Run 1	20.37	0.0062±0.0157
Run 2	61.32	-0.0004±0.0090
Run 3	32.28	0.0048±0.0083
Run 4	99.58	-0.0114±0.0071
Run 5	132.33	-0.0040±0.0063
Run 6	78.31	0.0157±0.0082
Total	**424.2**	**0.0035±0.0024**

- Preliminary measurement:

$$\langle P \rangle = 0.0035 \pm 0.0024_{\text{stat}} \pm 0.0029_{\text{sys}}$$

PRELIMINARY

Source	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Combined
π^0 efficiency	0.0025	0.0016	0.0013	0.0018	0.0006	0.0017	**0.0013**
Muon PID	0.0018	0.0018	0.0029	0.0011	0.0006	0.0016	**0.0012**
Split-off modeling	0.0015	0.0017	0.0016	0.0006	0.0016	0.0020	**0.0011**
Neutral energy calibration	0.0027	0.0012	0.0023	0.0009	0.0014	0.0008	**0.0010**
π^0 mass	0.0018	0.0028	0.0010	0.0005	0.0004	0.0004	**0.0008**
ρ decay collinearity	0.0015	0.0009	0.0016	0.0007	0.0005	0.0005	**0.0007**
π^0 likelihood	0.0015	0.0009	0.0015	0.0006	0.0003	0.0010	**0.0006**
Electron PID	0.0011	0.0020	0.0008	0.0006	0.0005	0.0001	**0.0005**
Particle transverse momentum	0.0012	0.0007	0.0009	0.0002	0.0003	0.0006	**0.0004**
Boost modeling	0.0004	0.0019	0.0003	0.0004	0.0004	0.0004	**0.0004**
Momentum calibration	0.0001	0.0014	0.0005	0.0002	0.0001	0.0003	**0.0004**
Max EMC acceptance	0.0001	0.0011	0.0008	0.0001	0.0002	0.0005	**0.0003**
τ direction definition	0.0003	0.0007	0.0008	0.0003	0.0001	0.0004	**0.0003**
Angular resolution	0.0003	0.0008	0.0003	0.0003	0.0002	0.0003	**0.0003**
Background modeling	0.0005	0.0006	0.0010	0.0002	0.0003	0.0003	**0.0003**
Event transverse momentum	0.0001	0.0013	0.0005	0.0002	0.0002	0.0004	**0.0003**
Momentum resolution	0.0001	0.0012	0.0004	0.0002	0.0001	0.0005	**0.0003**
ρ mass acceptance	0.0000	0.0011	0.0003	0.0001	0.0002	0.0005	**0.0003**
τ branching fraction	0.0001	0.0007	0.0004	0.0002	0.0002	0.0002	**0.0002**
$\cos\theta^*$ acceptance	0.0002	0.0006	0.0004	0.0001	0.0001	0.0004	**0.0002**
$\cos\psi$ acceptance	0.0002	0.0003	0.0002	0.0002	0.0002	0.0003	**0.0002**
Total	0.0058	0.0062	0.0054	0.0030	0.0026	0.0038	**0.0029**

Conclusions

- BaBar has implemented the first application of the new Tau Polarimetery technique to preliminarily measure the PEP-II average beam polarization

$$\langle P \rangle = 0.0035 \pm 0.0024_{\text{stat}} \pm 0.0029_{\text{sys}}$$

PRELIMINARY

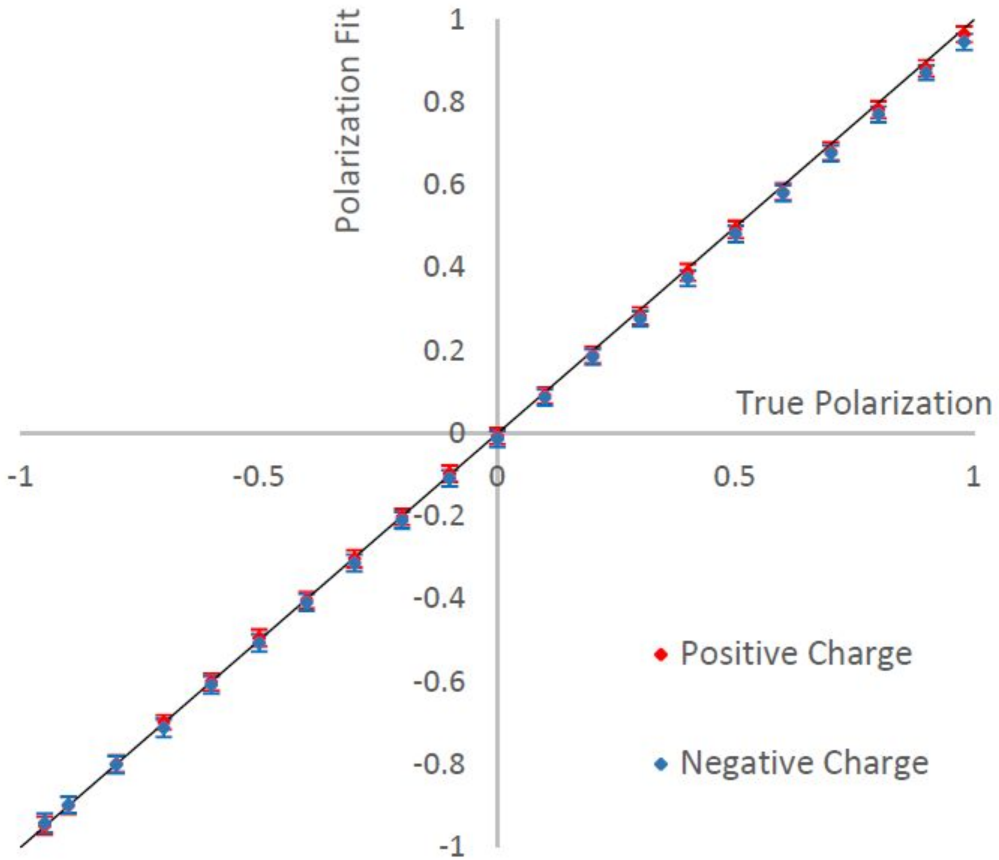
- Identified 21 sources of systematic uncertainty
- Modelling/Understanding of neutral processes dominates the largest systematics
- Tau Polarimetry could be applied at other e^+e^- colliders interested in polarization
- Paper should be on the ArXiV soon

Thank You!

Backup Slides

Beam Polarization MC "Measurement"

- As PEP-II had no beam polarization we performed MC studies of the polarimetry technique for arbitrary beam polarization states for validation of the method
- This is done by splitting each of the polarized tau MC samples in half
- One half of each is used to perform the polarization fit
- The other half is used to mix specific beam polarization states
  - e.g. 70% polarized = 85% left +15% right
- Simulated beam polarization states are produced in steps of 10% beam polarization
- We found the fit responded well and was able to correctly measure any designed beam state



Polarimetry and cross-sections

- If both beams are polarized the cross-section enhancement adds additional complementary information to the polarization knowledge
- Interaction matrix helps to visualize the process:

$e^+\backslash e^-$	L^-	R^-
R^+	R^+L^-	R^+R^-
L^+	L^+L^-	L^+R^-

- Only the L^+R^- and R^+L^- crossing result in a collision, the L^+L^- and R^+R^- crossings continue down the beam pipe
- For unpolarized beams L=R=0.5, and each quadrant represent 25% of crossings
- The average beam polarization, <P>, is $(R^+L^- - L^+R^-)/(R^+L^- + L^+R^-)$
- The cross-section multiplier, σ, is $(R^+L^- + L^+R^-)/(R^+L^-_{\text{unpolarized}} + L^+R^-_{\text{unpolarized}})$

70% polarized e^- beam

$e^+\backslash e^-$	0.85	0.15
0.5	0.425	0.075
0.5	0.425	0.075

$$\langle P \rangle = \frac{0.5 * 0.85 - 0.5 * 0.075}{0.5 * 0.85 + 0.5 * 0.075} = 0.7$$

$$\sigma = \frac{0.425 + 0.075}{0.25 + 0.25} = 1$$

Polarimetry and cross-sections

- <P> is the variable physics is sensitive to, e.g. 10% increase in <P> is a 10% increase in A_{LR}
- Polarizing both beams enhances <P> and cross-section

70% polarized e^- beam

$e^+ \backslash e^-$	0.85	0.15
0.5	0.425	0.075
0.5	0.425	0.075

<P> = 0.7
σ = 1

80% polarized e^- beam
30% polarized e^+ beam

$e^+ \backslash e^-$	0.90	0.10
0.65	0.585	0.065
0.35	0.315	0.035

<P> = 0.887
σ = 1.24

70% polarized e^- beam
70% polarized e^+ beam

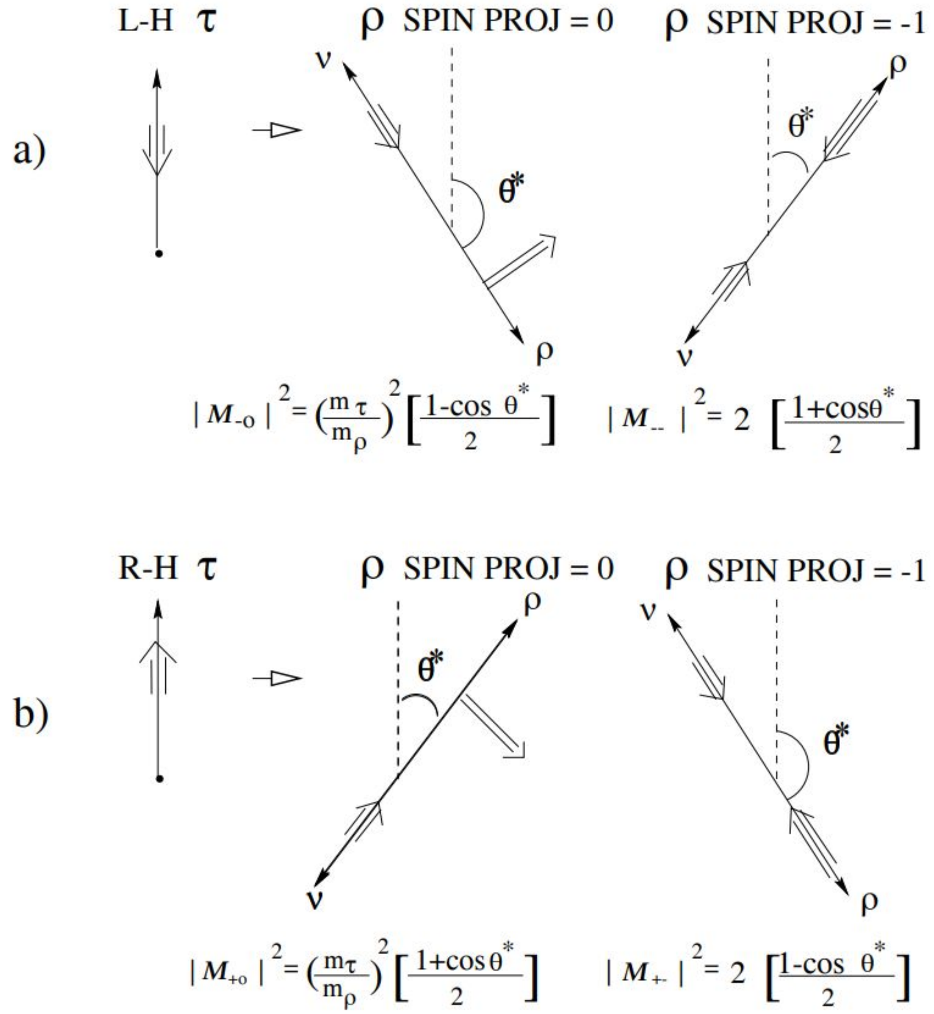
$e^+ \backslash e^-$	0.85	0.15
0.85	0.722	0.128
0.15	0.128	0.022

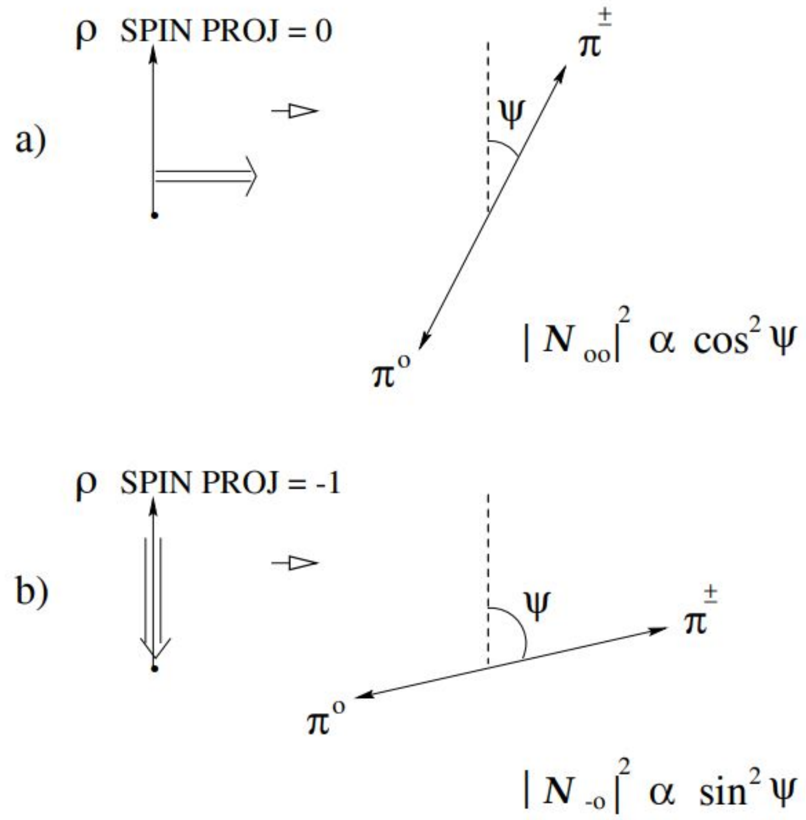
<P> = 0.940
σ = 1.49

- Polarizing both beams significantly improves the physics sensitive <P>
- Also gain additional statistics through cross-section enhancement
- cross-section is not unique to a specific <P> but is highly correlated
  - 75% polarized e^-, 65.3% polarized e^+, results in <P>=0.942, σ=1.49
- Precision measurements of production cross-sections can cross-check Tau Polarimetry technique and vice-versa

Rho Spin Analysis

- The rho complicates the spin projections, which necessitates two variables to extract the polarization





From Dr. Manuella Vincter, PhD thesis, UVIC, 1996