Efficient Extraction of Polarization-entanglement in ultrafast type-II SPDC

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Polarization-entangled two-photon states (Bell-states)

$$|\psi^{(\pm)}\rangle = \frac{1}{\sqrt{2}}(|X\rangle_1|Y\rangle_2 \pm |Y\rangle_1|X\rangle_2)$$

$$|\phi^{(\pm)}\rangle = \frac{1}{\sqrt{2}}(|X\rangle_1|X\rangle_2 \pm |Y\rangle_1|Y\rangle_2)$$

$|X\rangle \perp |Y\rangle$

$$|\psi\rangle \neq |\chi\rangle_1 \otimes |\chi\rangle_2$$

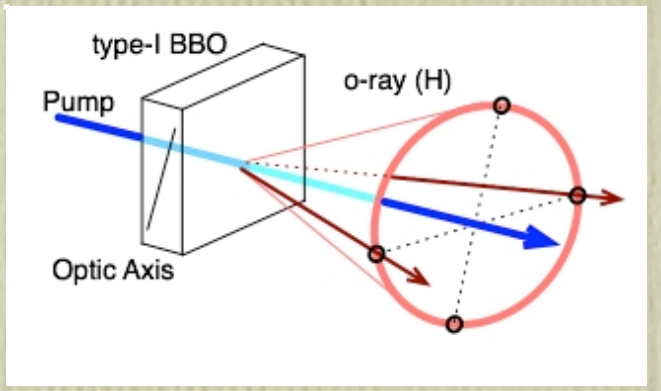
Important for ...

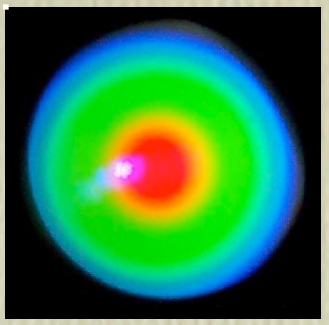
- ☑ Optical quantum computing
- ☑ Quantum cryptography
- ☑ Test of foundations of quantum physics
- ☑ As a building block for multi-photon entanglement
- ☑ and more ...

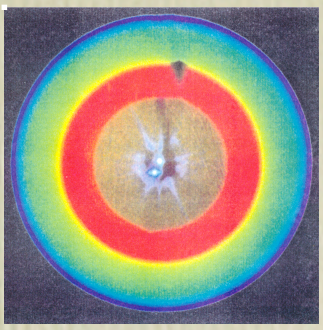
Spontaneous Parametric Down-Conversion (SPDC) is often used to generate polarization-entangled photon pairs.

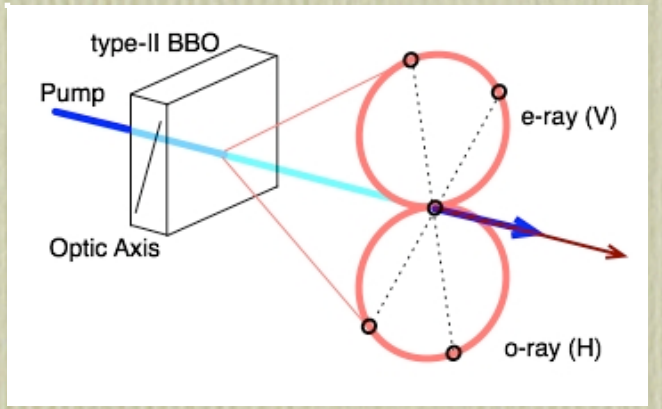
Spontaneous Parametric Down-Conversion (SPDC)

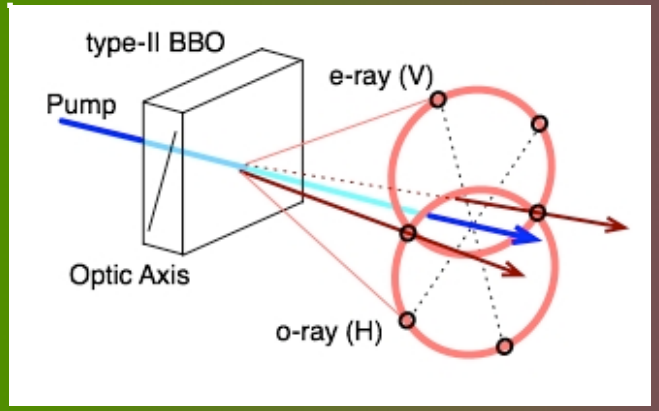
Phase Matching

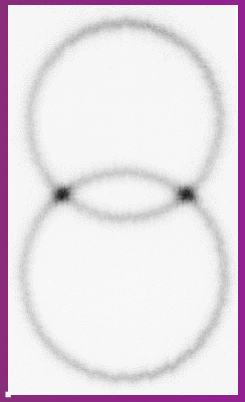










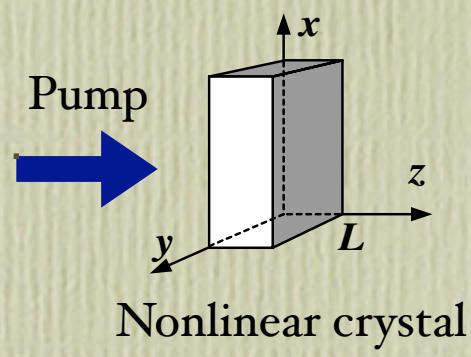


Most popular choice

Pump Source

Pump Source	Good	Bad
CW Laser	Good polarization entanglement	Huge emission time uncertainty
Ultrafast Pulsed Laser	Emission time uncertainty can be less than 100 fsec	Poor polarization entanglement ==> *Spectral postselection required*

Quantum state of type-II SPDC



$$|\psi\rangle = -\frac{i}{\hbar}\int_{\infty}^{\infty} dt\, \mathcal{H}|0\rangle$$

$$\mathcal{H} = \epsilon_0 \int d^3\mathbf{r}\, E_p(z,t) E_s^{(-)} E_i^{(-)}$$

$$\Delta \equiv k_p(\omega_p) - k_s(\omega_s) - k_i(\omega_i)$$

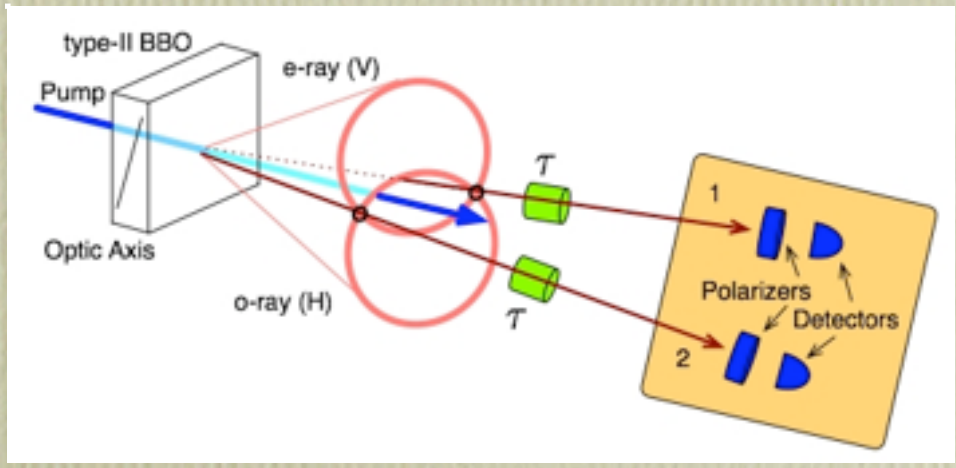
$$\mathcal{E}_p(\omega_s + \omega_i) = e^{[-(\omega_s+\omega_i-\Omega_p)^2/\sigma_p^2]}$$

Ω_p = Pump central frequency

σ_p = Pump bandwidth

$$|\psi\rangle = C \iint d\omega_s d\omega_i\, \mathrm{sinc}(\Delta L/2)\mathcal{E}_p(\omega_s+\omega_i)\, e^{-i\Delta L/2} a_s^\dagger(\omega_s) a_i^\dagger(\omega_i)|0\rangle$$

Joint Spectrum Function



The joint detection rate is given by

$$R_c \propto \int dt_+ \int dt_- |\mathcal{A}(t_+, t_-)|^2$$

$(t_+ = (t_1+t_2)/2 \text{ and } t_- = t_1 - t_2)$

Biphoton Wavepacket

$$\mathcal{A}(t_+, t_-) = \cos\theta_1 \sin\theta_2\, \Pi(t_+, t_- + \tau) - \sin\theta_1 \cos\theta_2\, \Pi(t_+, -t_- + \tau)$$

CW vs. Ultrafast type-II SPDC: temporal picture

Biphoton wavepacket:

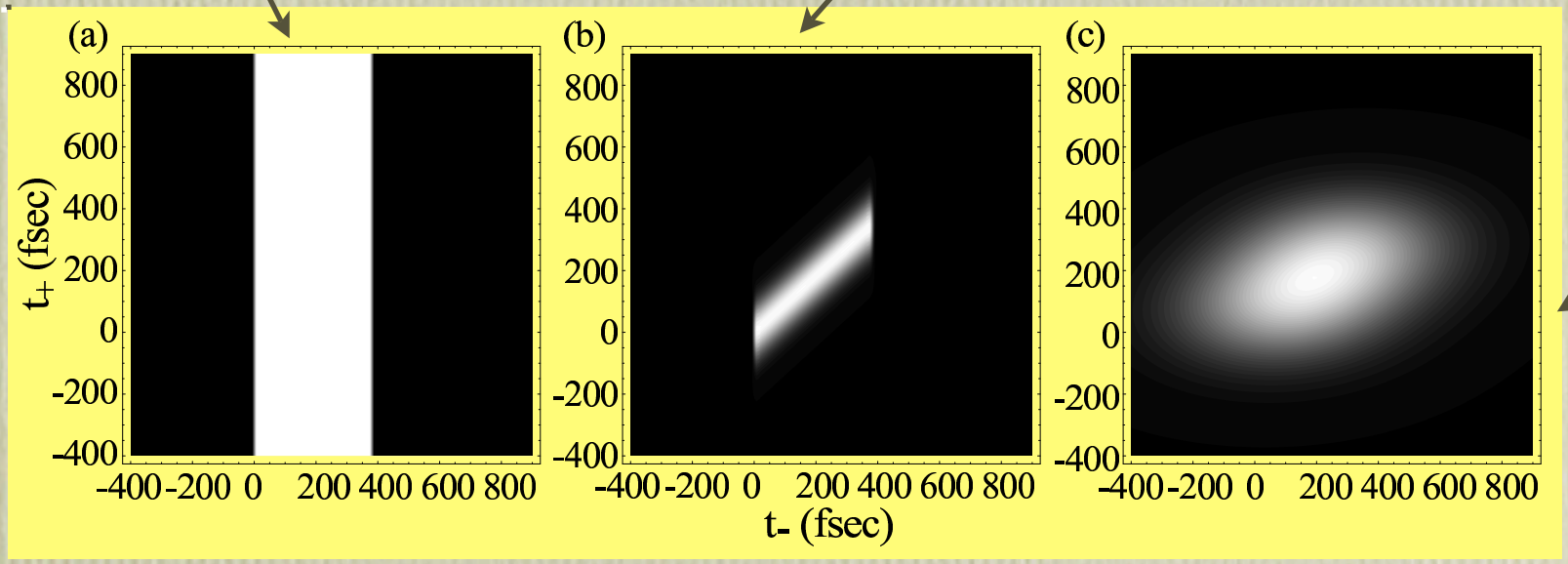
$$\Pi(t_+, t_-) = \begin{cases} e^{-i\Omega_p t_+} e^{-\sigma_p^2 \{t_+ - [D_+/D] t_-\}^2} & \text{for } 0 < t_- < DL \\ 0 & \text{otherwise.} \end{cases}$$

where $D_+ = \frac{1}{2}\left(\frac{1}{u_o(\Omega_o)} + \frac{1}{u_e(\Omega_e)}\right) - \frac{1}{u_p(\Omega_p)}$

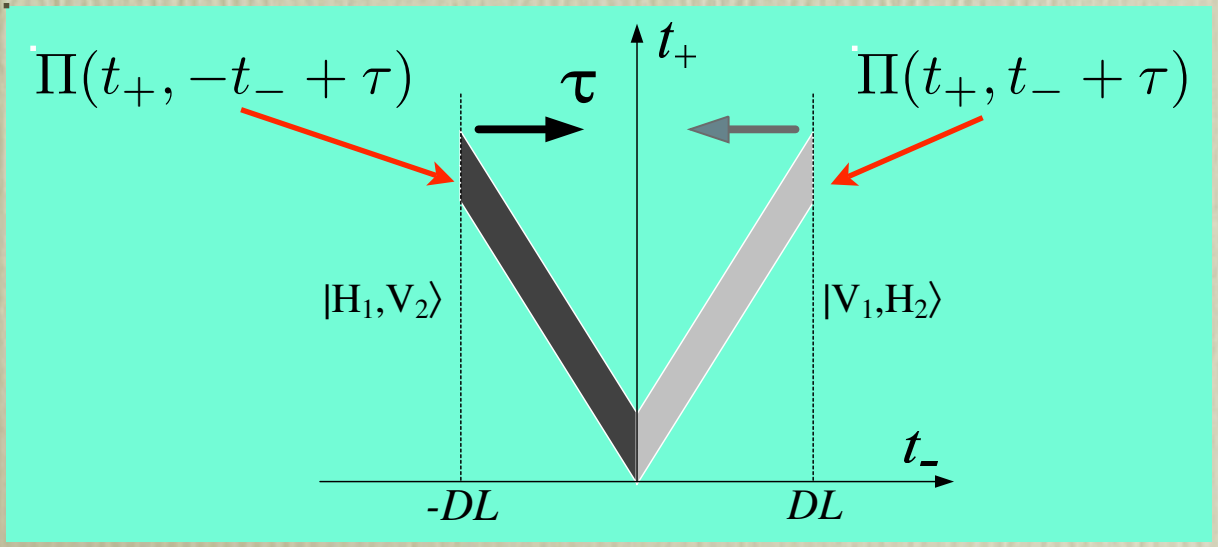
$D = \frac{1}{u_o(\Omega_o)} - \frac{1}{u_e(\Omega_e)}$

CW UV pump

Ultrafast UV pump



Ultrafast UV pump with narrowband filters

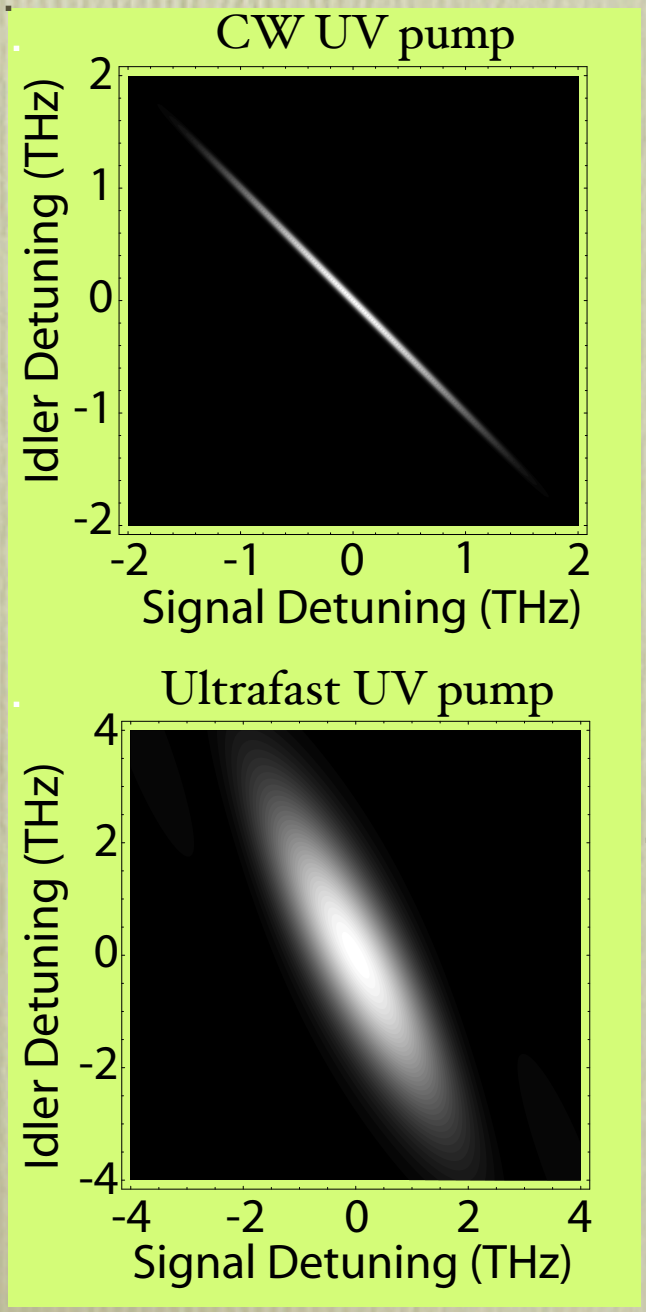


With ultrafast UV pump, type-II SPDC biphoton wavepackets do not completely overlap !

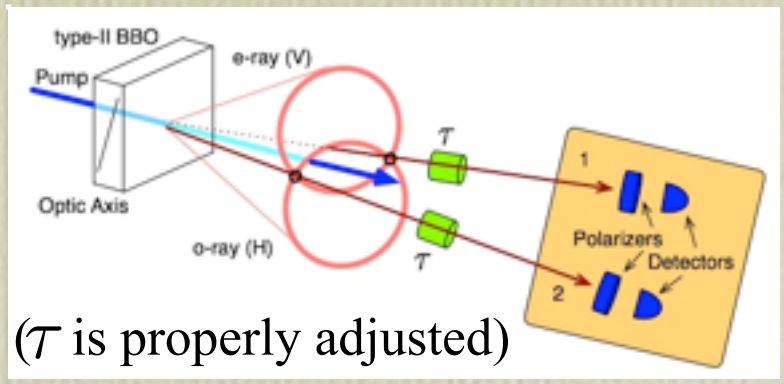
Poor Polarization-entanglement!

CW vs. Ultrafast type-II SPDC: spectral picture

Joint spectrum function: $|\mathcal{S}(\omega_s,\omega_i)|^2 = |\mathrm{sinc}(\Delta L/2)\mathcal{E}_p(\omega_s+\omega_i)|^2$



Consider



(τ is properly adjusted)

$$|\psi\rangle_{1,2} = C\iint d\omega_s d\omega_i \left\{\mathcal{S}(\omega_s,\omega_i)a_1^\dagger(\omega_s)a_2^\dagger(\omega_i) - \mathcal{S}(\omega_i,\omega_s)a_1^\dagger(\omega_i)a_2^\dagger(\omega_s)\right\}|0\rangle$$

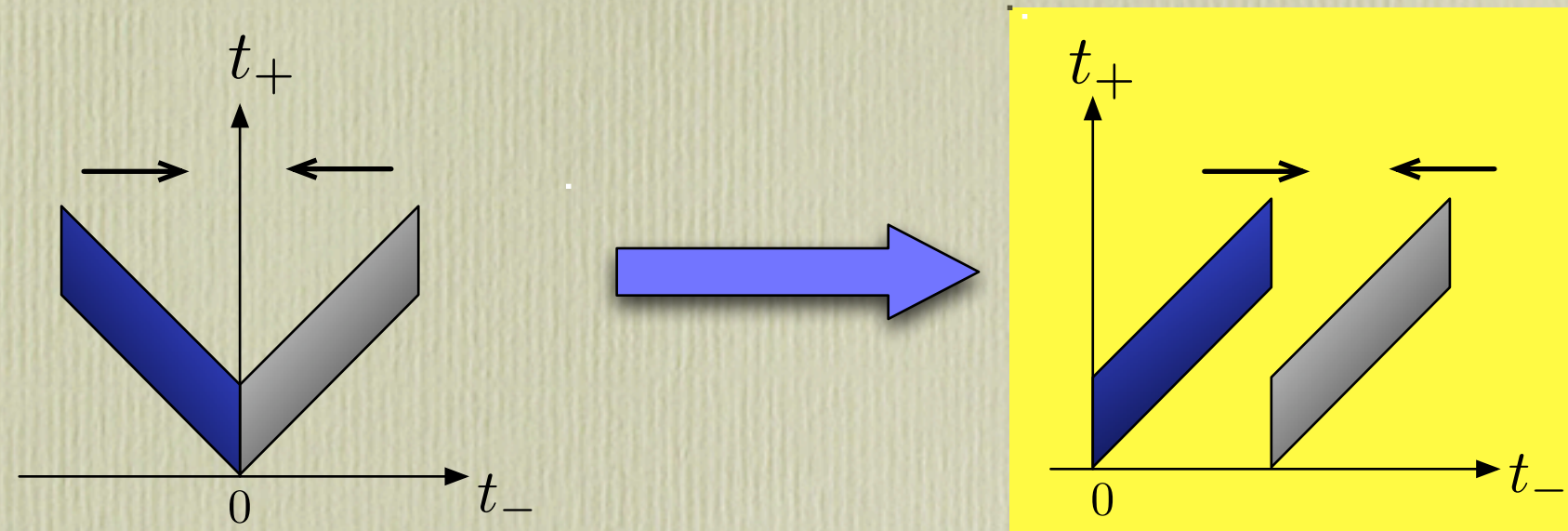
Only if $\mathcal{S}(\omega_i,\omega_s) = \mathcal{S}(\omega_s,\omega_i)$

$$\longrightarrow \quad |\psi\rangle_{1,2} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)$$

Ultrafast UV pump → Asymmetric $|\mathcal{S}(\omega_s,\omega_i)|^2$ → Poor polarization-entanglement

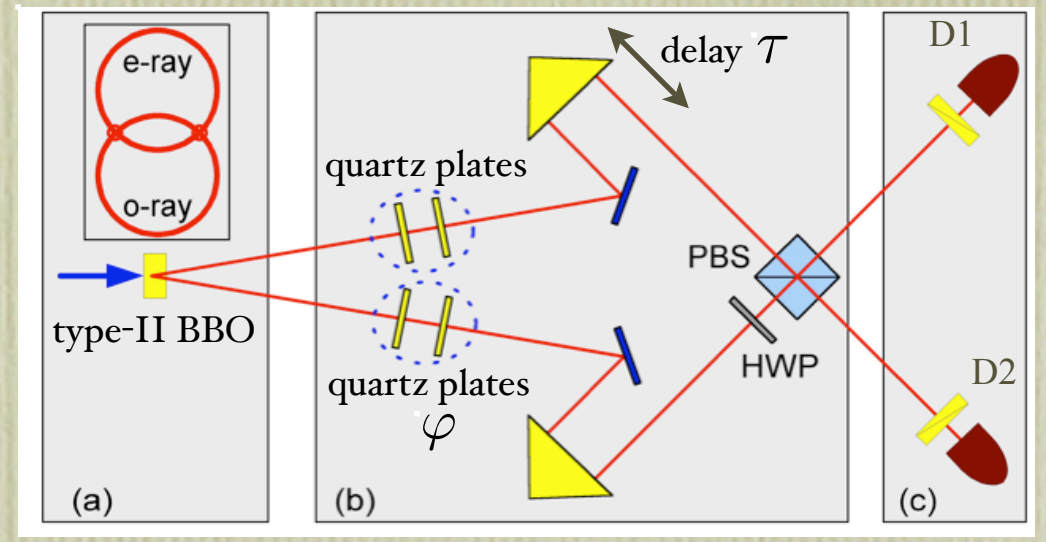
Interferometric Entanglement Extraction: idea

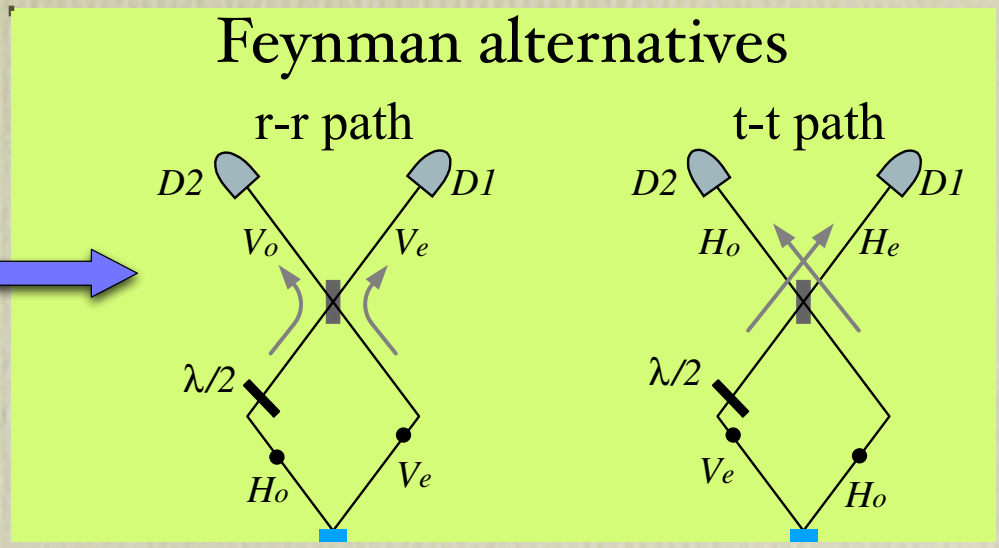
Modify the way in which the biphoton wavepackets overlap !



- Biphoton wavepackets may overlap regardless of their shape which is determined by the pump pulse as well as crystal parameters.
- Interference visibility is therefore irrelevant to the crystal parameters, spectral filtering, and most importantly, the choice of the pump source.

Interferometric Entanglement Extraction: experiment





(a) two-photon polarization state: $\rho_{mix} = \frac{1}{2}\left(|H_1\rangle|V_2\rangle\langle V_2|\langle H_1| + |V_1\rangle|H_2\rangle\langle H_2|\langle V_1|\right)$

(b) interferometric entanglement extraction: $|\psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 + e^{i\varphi}|V\rangle_1|V\rangle_2)$

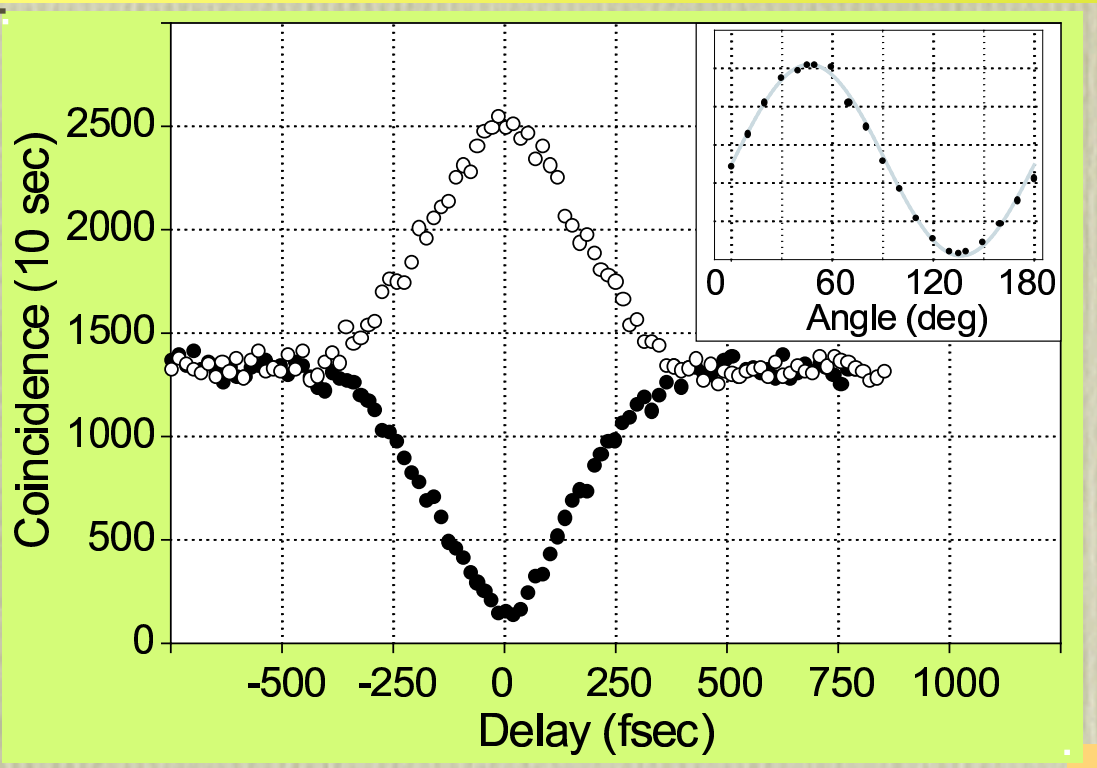
The joint count rate has the form,

(assuming quartz plates are adjusted for zero net phase difference: $\varphi = 0$)

$$R_c \propto \int dt_+ dt_- |\cos\theta_1 \cos\theta_2\, \Pi(t_+ + \tau/2, t_- + \tau) + \sin\theta_1 \sin\theta_2\, \Pi(t_+ + \tau/2, t_- - \tau)|^2$$

Complete overlap of biphoton wavepackets when $\tau = 0$

Interferometric Entanglement Extraction: data



CW 351.1nm pump and 3mm BBO

* open circle : $\varphi = 0 \rightarrow |\psi\rangle = |\phi^{(+)}\rangle$

* solid circle : $\varphi = \pi \rightarrow |\psi\rangle = |\phi^{(-)}\rangle$

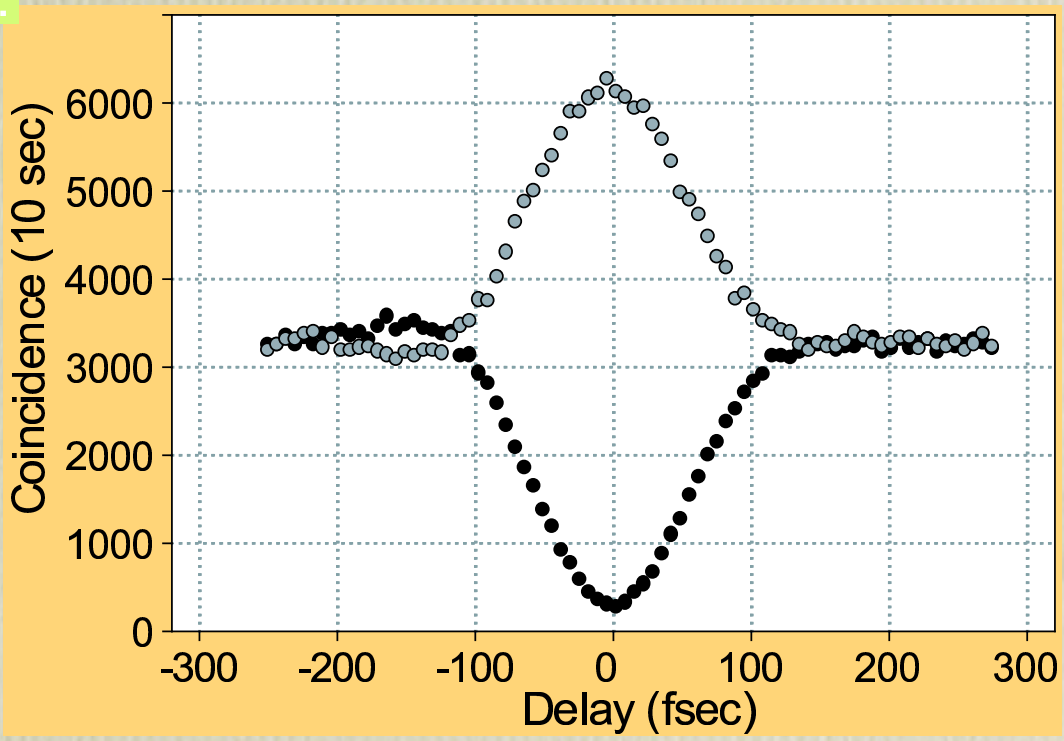
* inset: polarization correlation measurement for $|\phi^{(+)}\rangle$.

Ultrafast 390nm pump and 3mm BBO

$$(\varphi = 0 \rightarrow |\psi\rangle = |\phi^{(+)}\rangle)$$

* peak : both polarizers at 45 deg.

* dip : polarizers are 45/-45 deg.



Summary

- Designed and implemented a new Bell-state generation scheme (using type-II SPDC) in which the quality of polarization entanglement does not depend on the crystal parameters, spectral filters, and most importantly, the choice of pump source.

- If $\tau \neq 0$, a more general state can be generated:

$$\rho = \epsilon|\phi^{(+)}\rangle\langle\phi^{(+)}| + (1-\epsilon)\rho_{mix} \qquad (0 \leq \epsilon \leq 1)$$

- Switching to other Bell-states can be done easily with a half-wave plate.

- Y.-H. Kim *et al.*, Phys. Rev. A **67**, 010301(R) (2003).