Entanglement on demand: Time reordering

Bisker, Gershoni, Lindner,
Meirom, Warburton

Bell states

$$|0\rangle_A \otimes |1\rangle_B \pm |1\rangle_A \otimes |0\rangle_B$$

$$|0\rangle_A \otimes |0\rangle_B \pm |1\rangle_A \otimes |1\rangle_B$$

Maximally entangled
Good for Quantum information

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Qubits

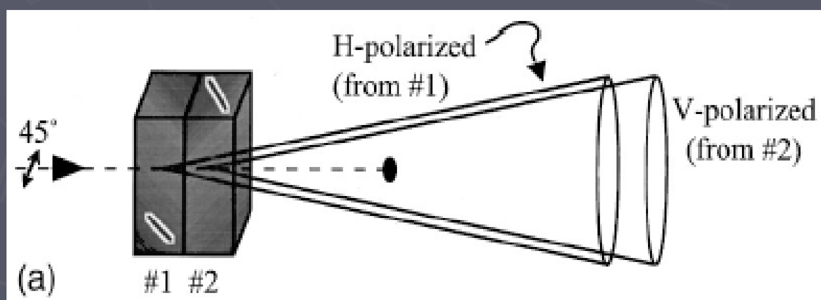
Flying quabits: Photons
Storage qubits: Nuclear spin
Working qubits: Electronic states

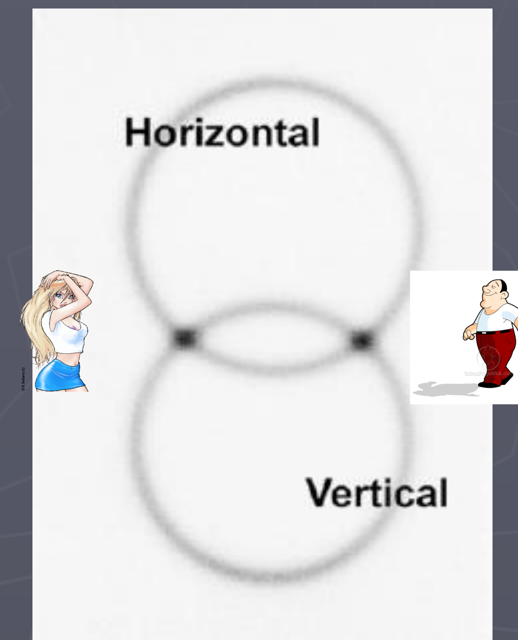
Photons: encode qubit in polarization

$$|0\rangle = |H\rangle\,, \quad |1\rangle = |V\rangle$$

Down conversion

Nonlinear optics: $a^\dagger_{2k,D}\,|0\rangle \longrightarrow a^\dagger_{k,H}a^\dagger_{k,V}\,|0\rangle$





$$|V\rangle_A \otimes |H\rangle_B + |H\rangle_A \otimes |V\rangle_B$$

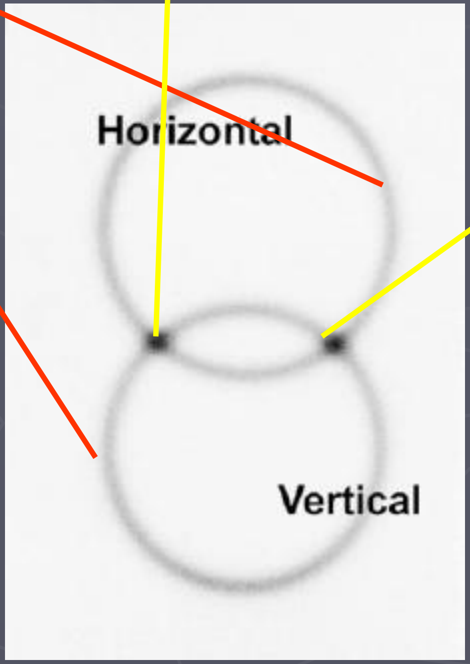
Which path ambiguity

On demand

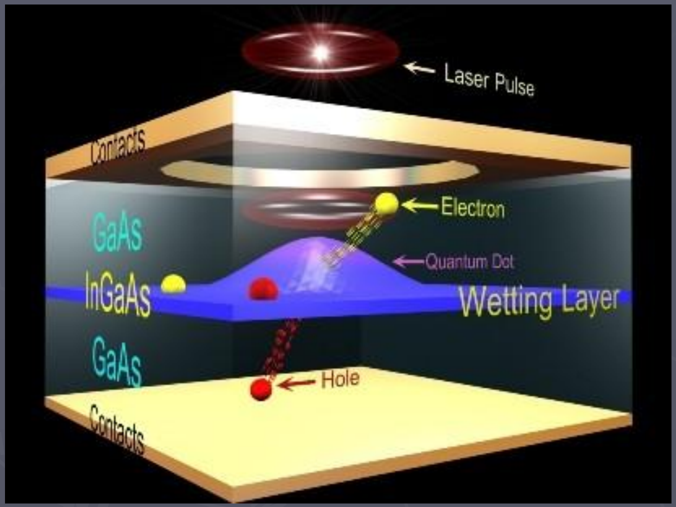
$$|0\rangle \otimes |0\rangle + \varepsilon(\,|V\rangle \otimes |H\rangle + |H\rangle \otimes |V\rangle\,)$$

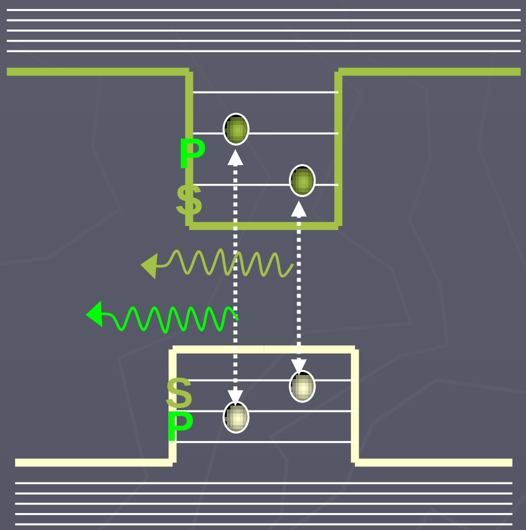
junk

Entangled piece



Quantum dots



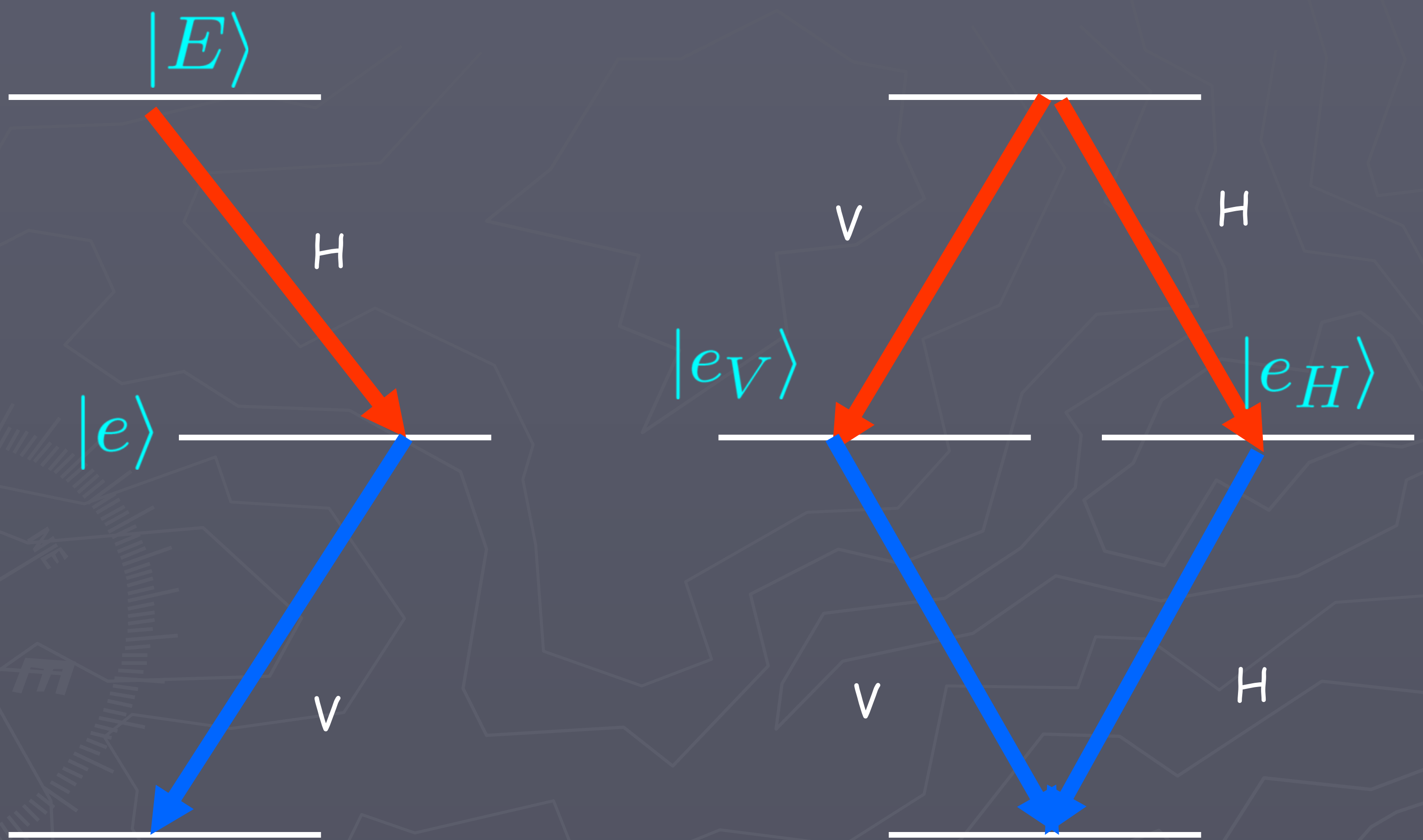


$$|e\rangle = |eh\rangle \,, \qquad |E\rangle = \left|(eh)^2\right\rangle$$

$$photon\ \ zap \rightarrow \left|(eh)^2\right\rangle \rightarrow |photon\ \ pair\rangle$$

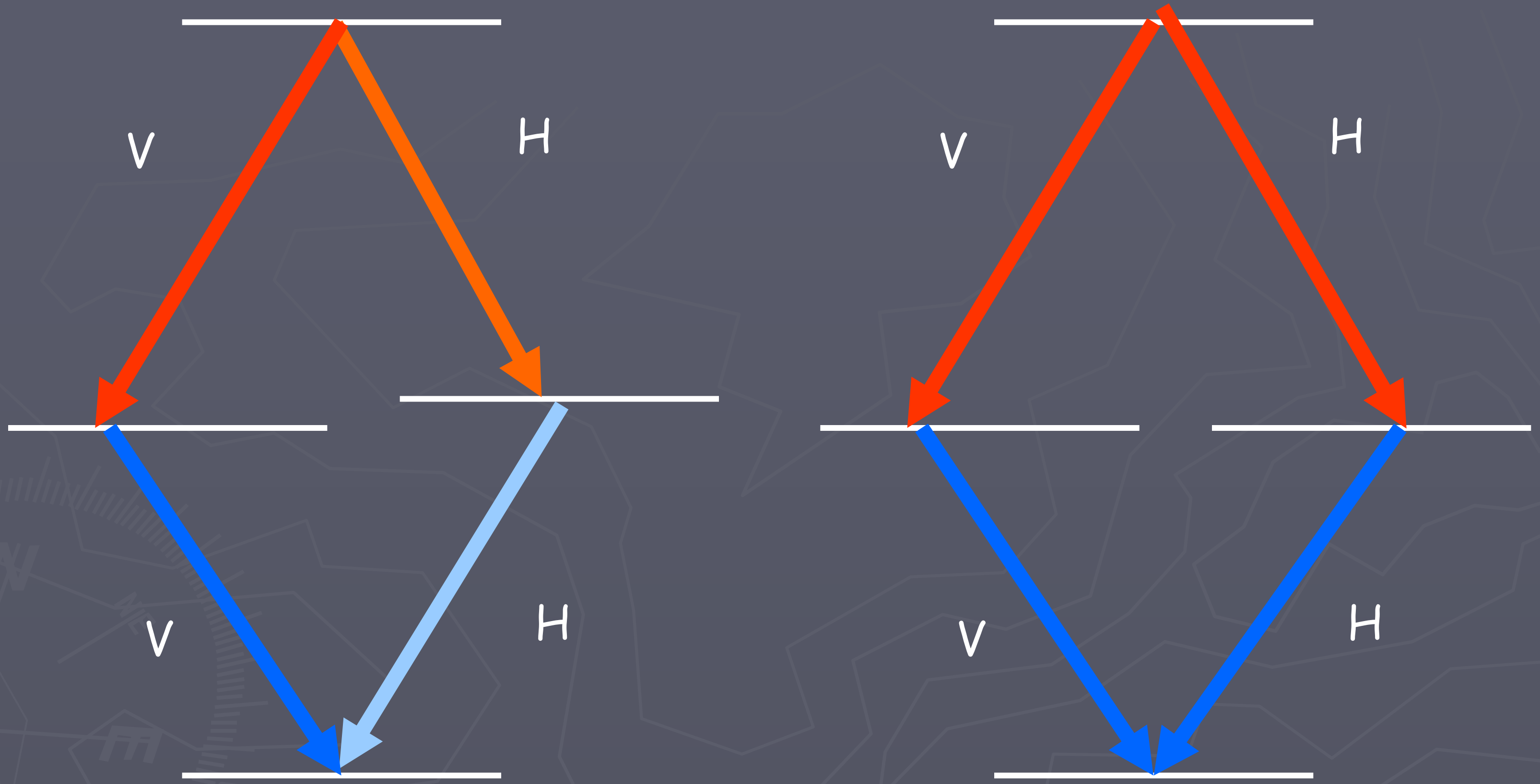
Can one entangle the pair?

Which path and entanglement



Entanglement: A 2 photon analog of interference

Color monitors the cascade



Monitored by color

Un-monitored

Monitoring: Kills ambiguity and entanglement

What is entanglement?

Classical vs quantum probabilities

independence $$P_{ab}(j,k) = P_a(j)P_b(k)$$





Correlations due to common preparation

$$P_{ab}(j,k) = \sum_\alpha p_\alpha \, P_a^\alpha(j) P_b^\alpha(k)$$

Classical probabilities

Any probability distribution is a weighted sum of independent

$$P(j,k) = \sum_{\alpha\beta} P(\alpha,\beta)\,\delta_{j,\alpha}\delta_{k,\beta}, \qquad P(\alpha,\beta) > 0$$

Independent (sure) events

Common preparation

Quantum probabilities

Quantum independence

$$\rho_A \otimes \rho_B \longrightarrow Prob(j,k) = Tr_A(\rho_A P_j) Tr_B(\rho_B P_k)$$

Correlations due to common preparation

$$\rho = \sum_i p_i \, \rho_A^i \otimes \rho_B^i, \;\; p_i > 0$$

Separable states

States that are not separable are entangled

Entangled states

Separable states

$$\rho = \sum_i p_i \, \rho_A^i \otimes \rho_B^i, \;\; p_i > 0$$

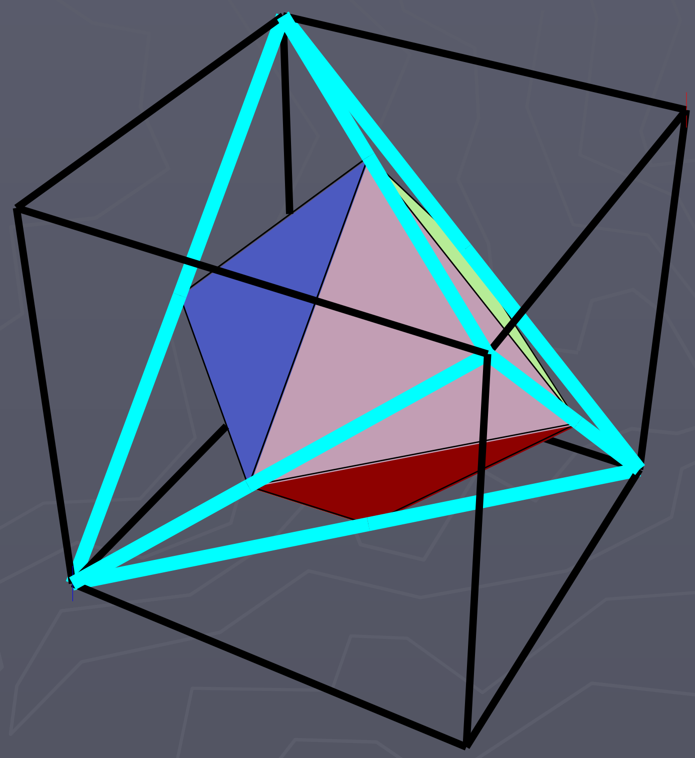
Independent up to common preparation

There are states, $\rho > 0$, that are not separable!

Definition: States that are not separable are entangled

Separable and entangled states

Octahedron=separable
Tetrahedron=all states



Horodecki's,Leinaas Myrheim Uvrom, Kenneth Avron, Bisker

Entanglement (Peres) test

$$\rho = \begin{pmatrix} A & B \\ D & C \end{pmatrix}, \qquad \rho^P = \begin{pmatrix} A & D \\ B & C \end{pmatrix}$$

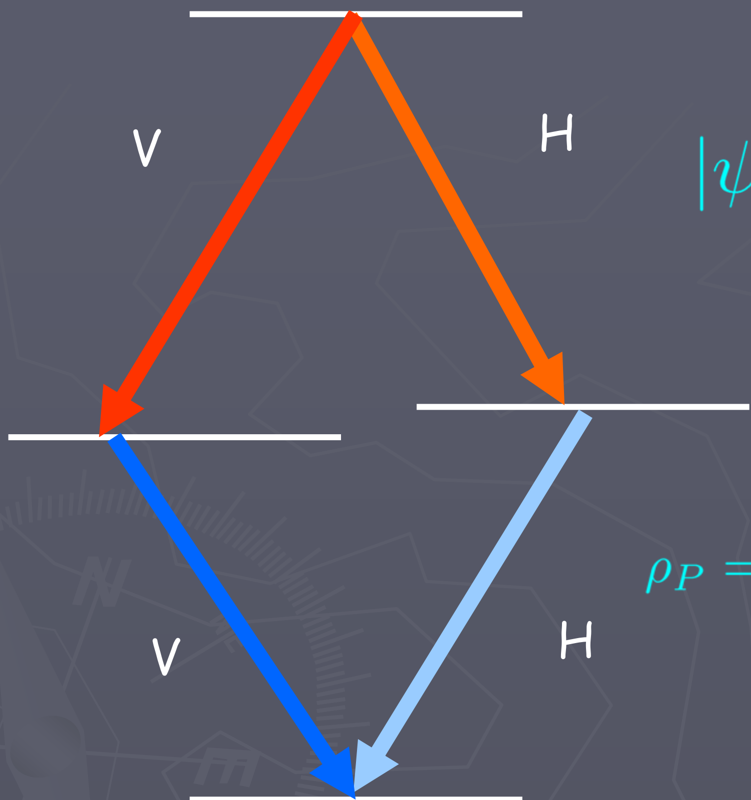
If transform has negative eigenvalue state is entangled

Example: Bell state

$$\rho = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \rho^P = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

Negative eigenvalue is a measure of entanglement

How monitoring kills entanglement

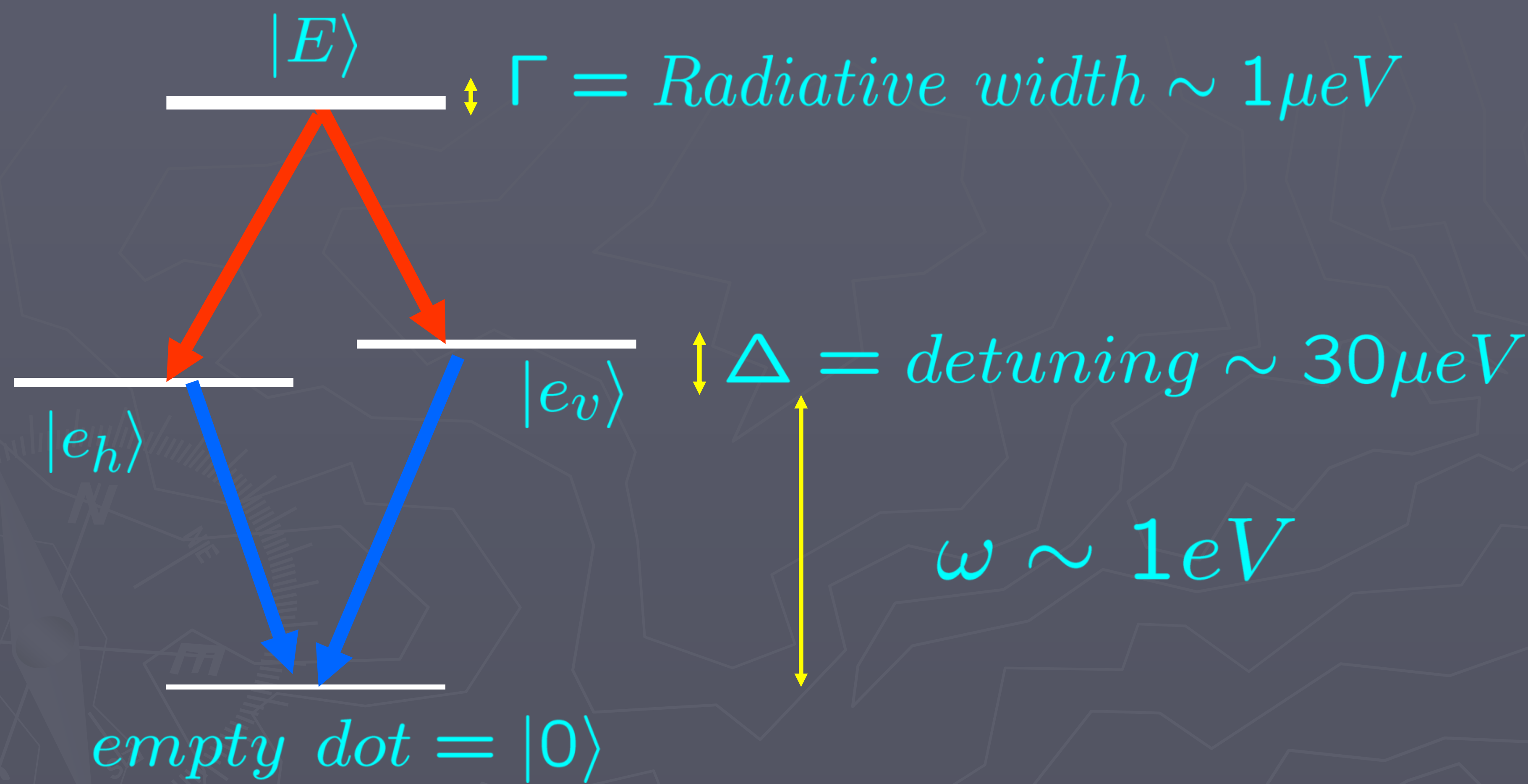


$$|\psi\rangle = |f\rangle_C |HH\rangle_P + |g\rangle_C |VV\rangle_P$$

$$\rho_P = Tr_C\left(|\psi\rangle\langle\psi|\right) = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 & \langle f|g\rangle \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \langle g|f\rangle & 0 & 0 & 1 \end{pmatrix}$$

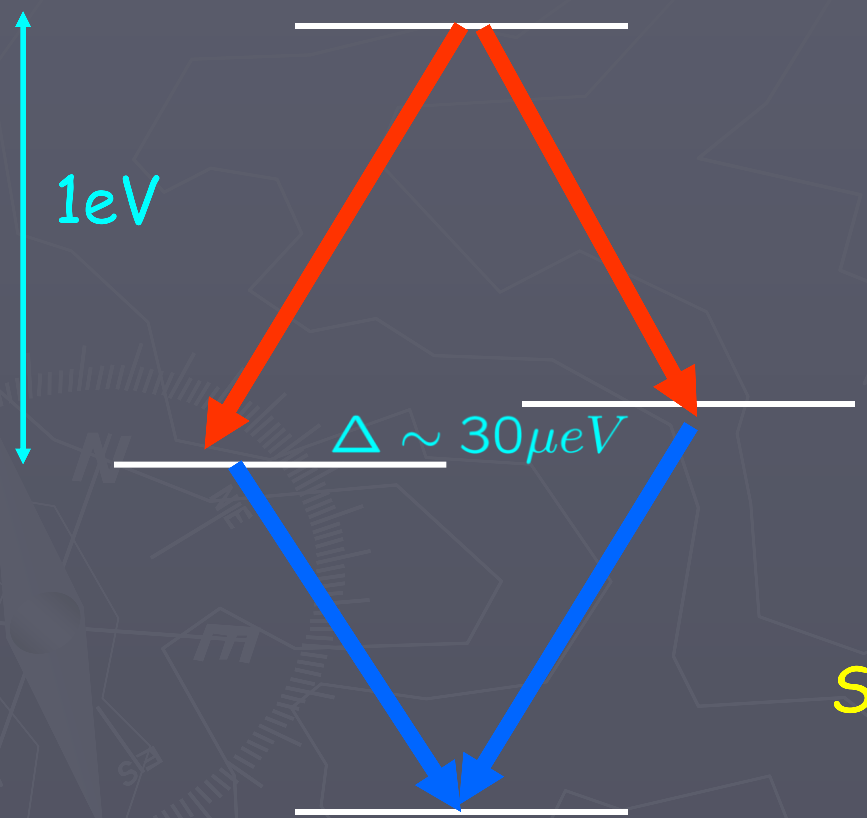
$|\langle f|g\rangle|$ is a measure of entanglment

Monitoring: Energy scales

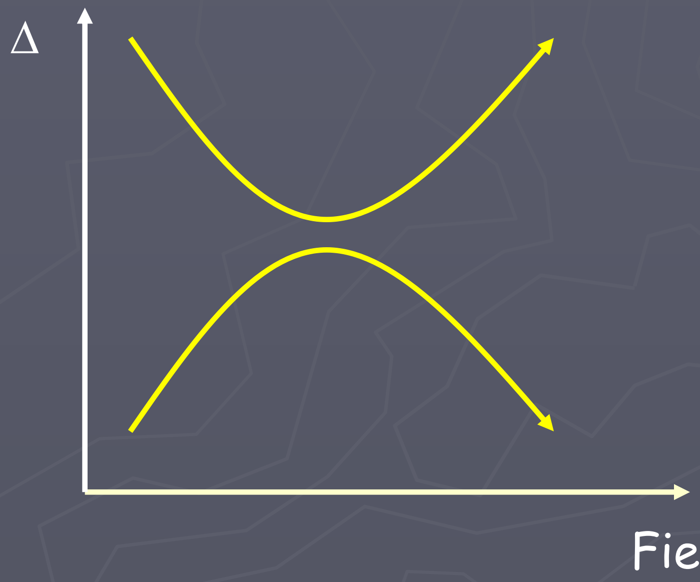


Entanglement needs $\Gamma > \Delta$

Why making Δ small is hard



Principle of level repulsion

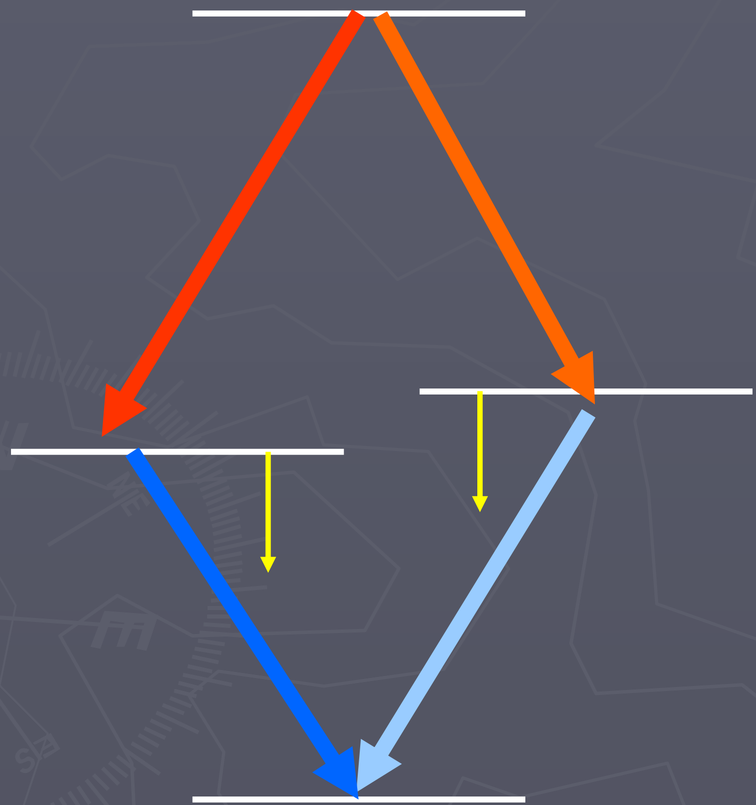


Spin-Orbit: Protected subspace

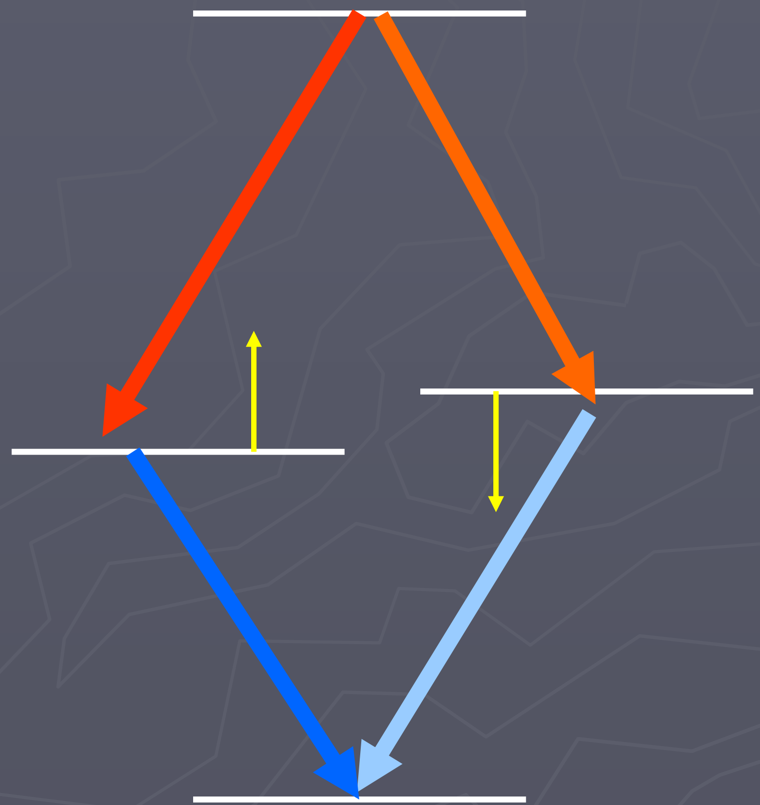
Forcing degeneracy: Stevenson et. al. , Hafenbrak et. al.

Life in protected subspace

Δ is due to spin orbit interaction - Relativistic effect



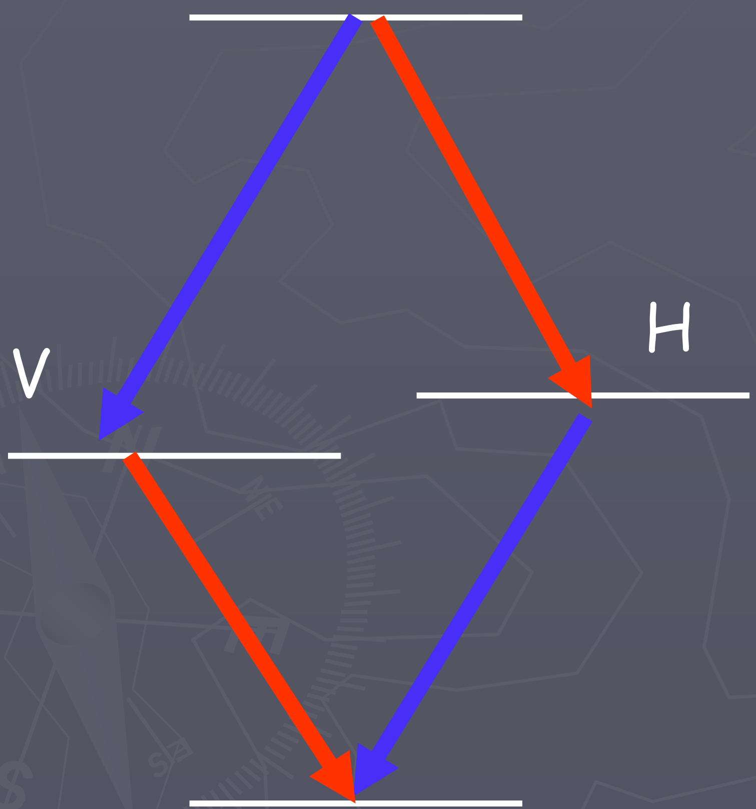
In principle easy

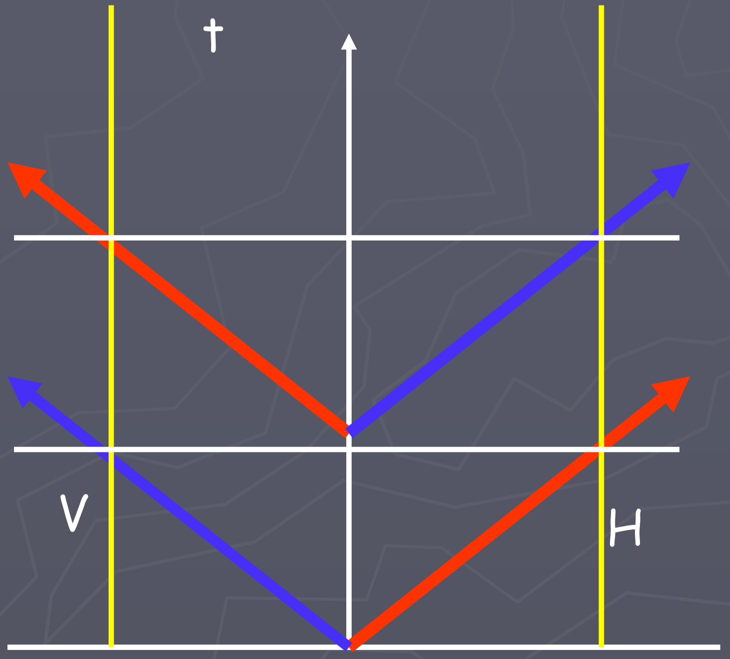


In principle hard

Ambiguity up to order

Space time diagrams: Lindenr



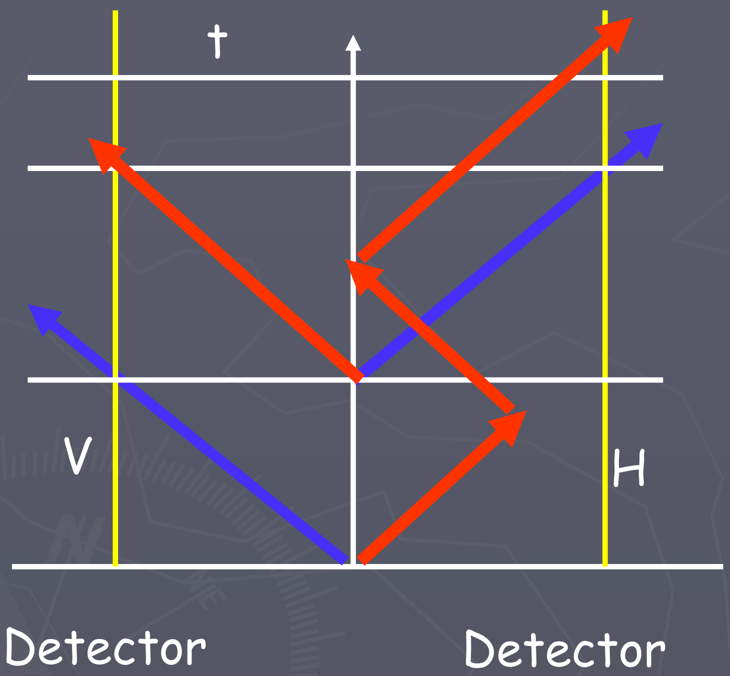


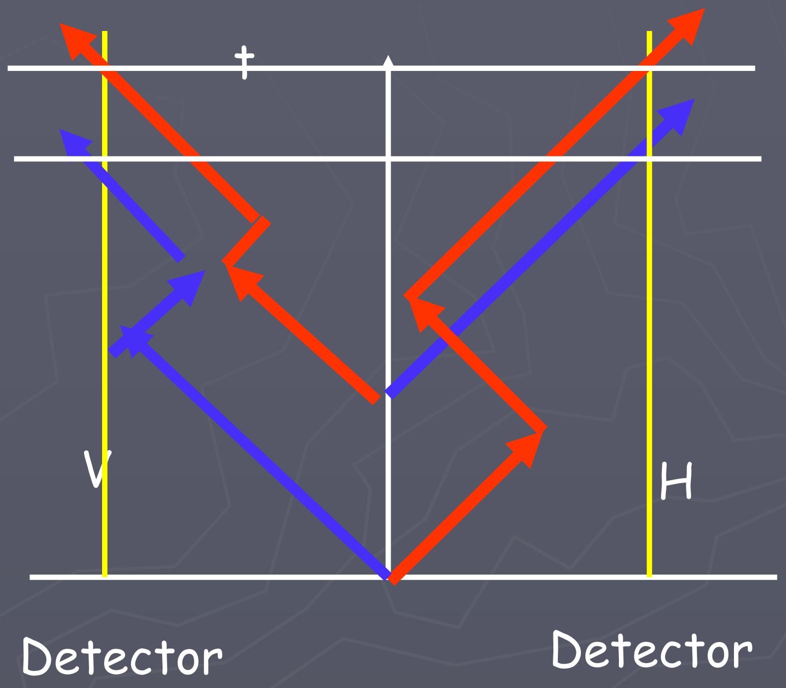
J. Finley

Order Monitors the path

Reordering

Reimer et. al.





Fixing the order

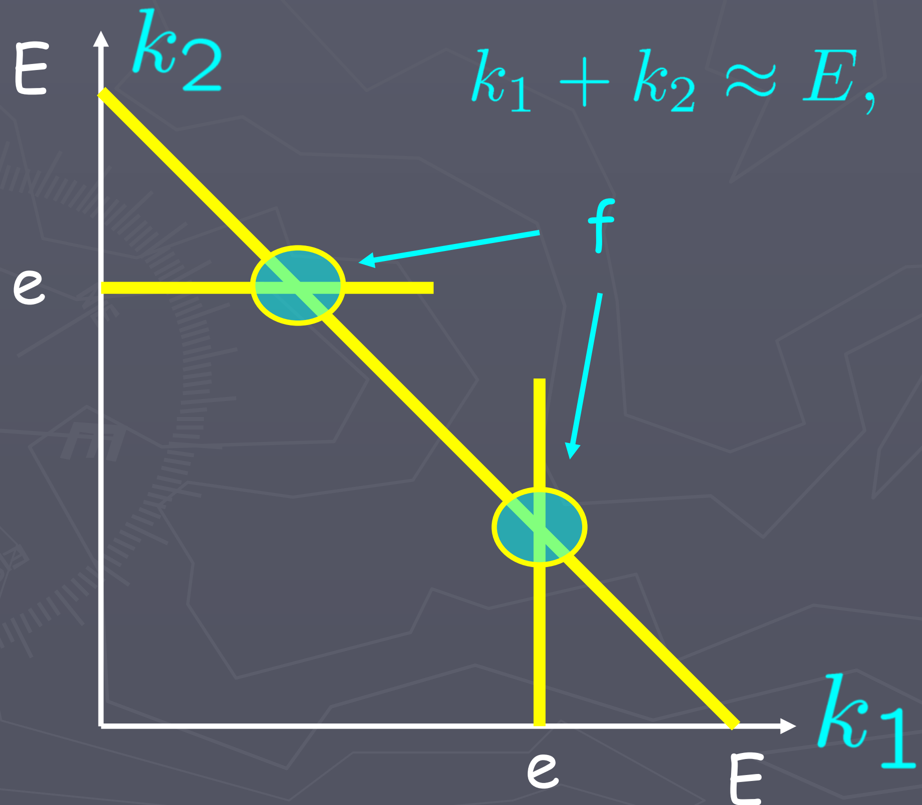
Forcing ambiguity

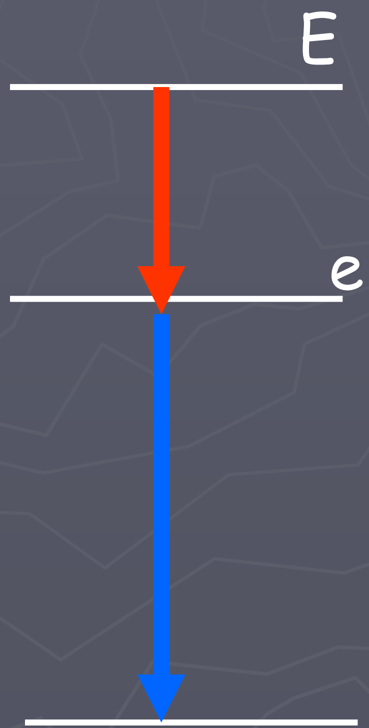
How much entanglement?
Can reordering be done on demand,i.e. unitary?

Photon field from cascade

$$|E, e\rangle = \sum f(k_1, k_2; E, e) a^\dagger(k_1) a^\dagger(k_2) |0\rangle$$

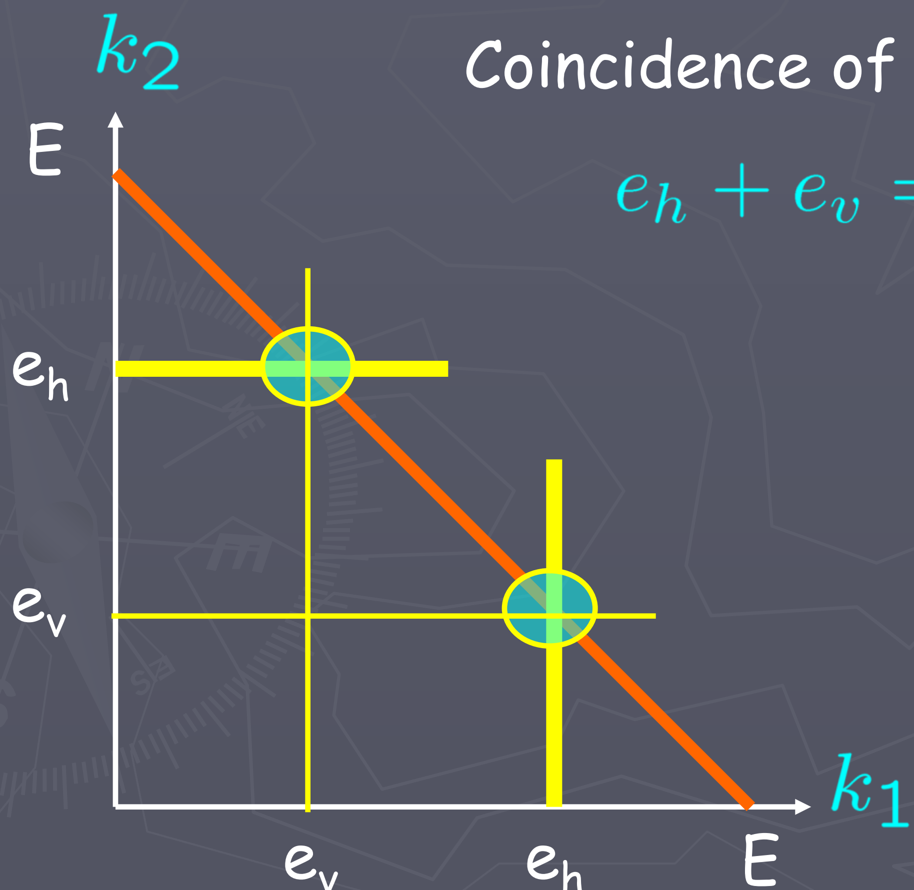
$$k_1 + k_2 \approx E, \quad k_{1,2} \approx e$$





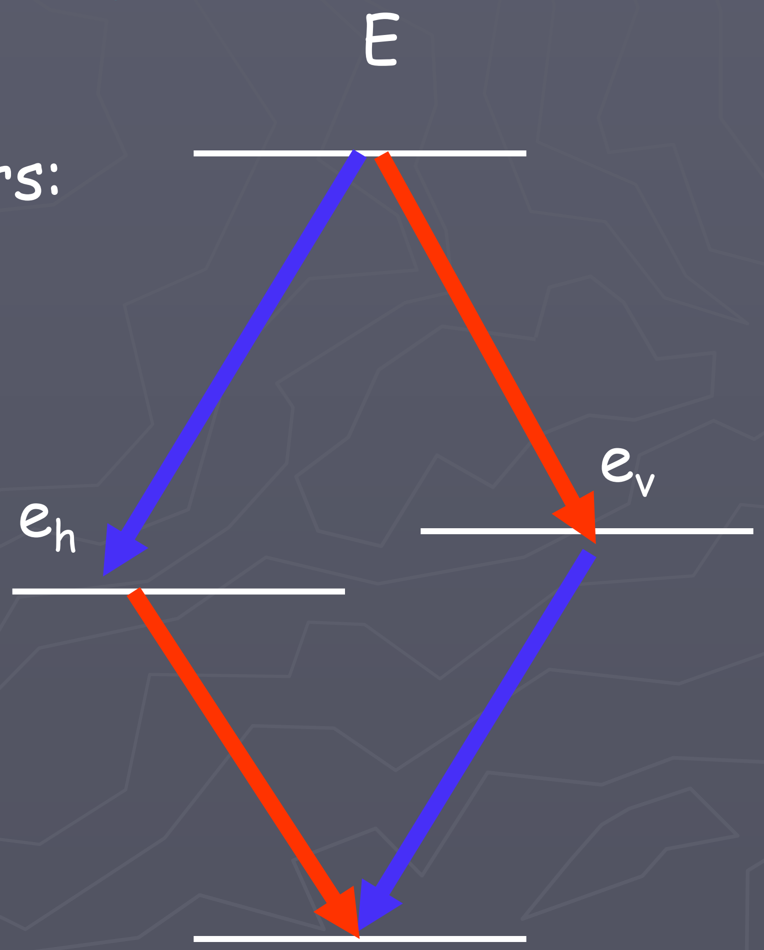
Photon field for 2 paths

$$|E, e_h\rangle \rightarrow h(k_1, k_2), \quad |E, e_v\rangle \rightarrow v(k_1, k_2)$$



Coincidence of colors:

$$e_h + e_v = E$$



How much entanglement?

Entanglment small $\langle h|v\rangle \approx 0$

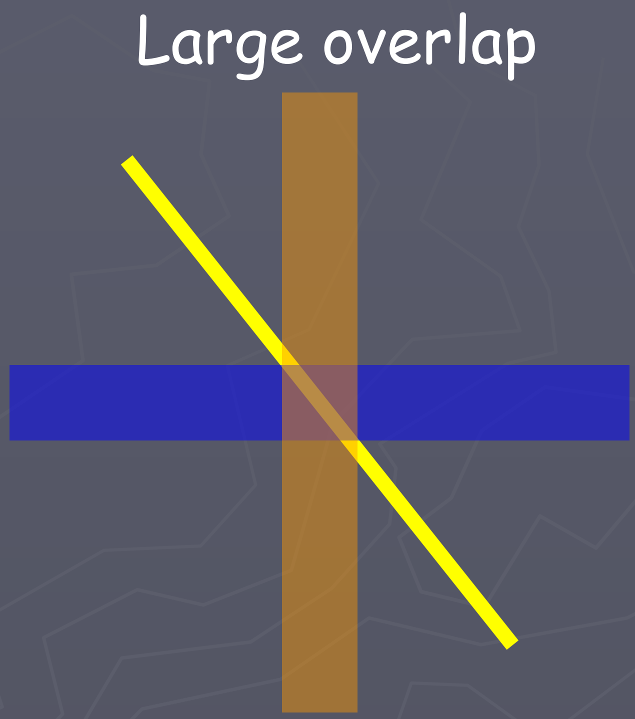
By phase cancellation not by lack of overlap

$W = e^{i(\gamma_h - \gamma_v)}, \quad \gamma_{h,v}(k_1, k_2)$ manifestly unitary

$$h = |h|e^{i\gamma_h}, \quad v = |v|e^{i\gamma_v}$$

$\langle E, e_h|\, W \,|E, e_v\rangle = \langle |h||v|\rangle$ Not small

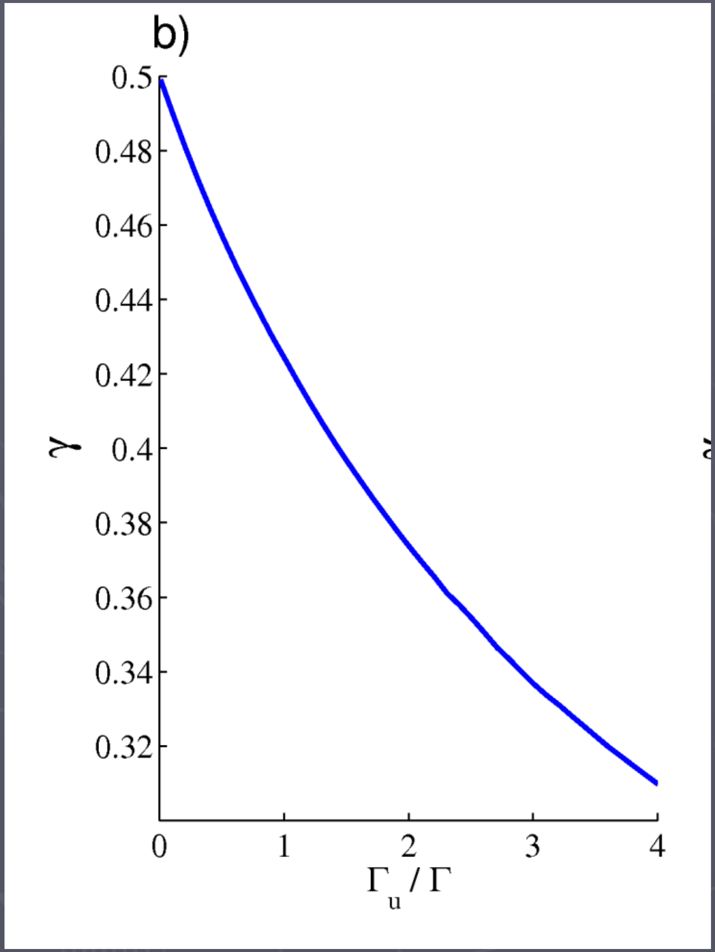
How much overlap ?



$$\Gamma_E > \Gamma_e$$

$$\Gamma_E < \Gamma_e$$

Setup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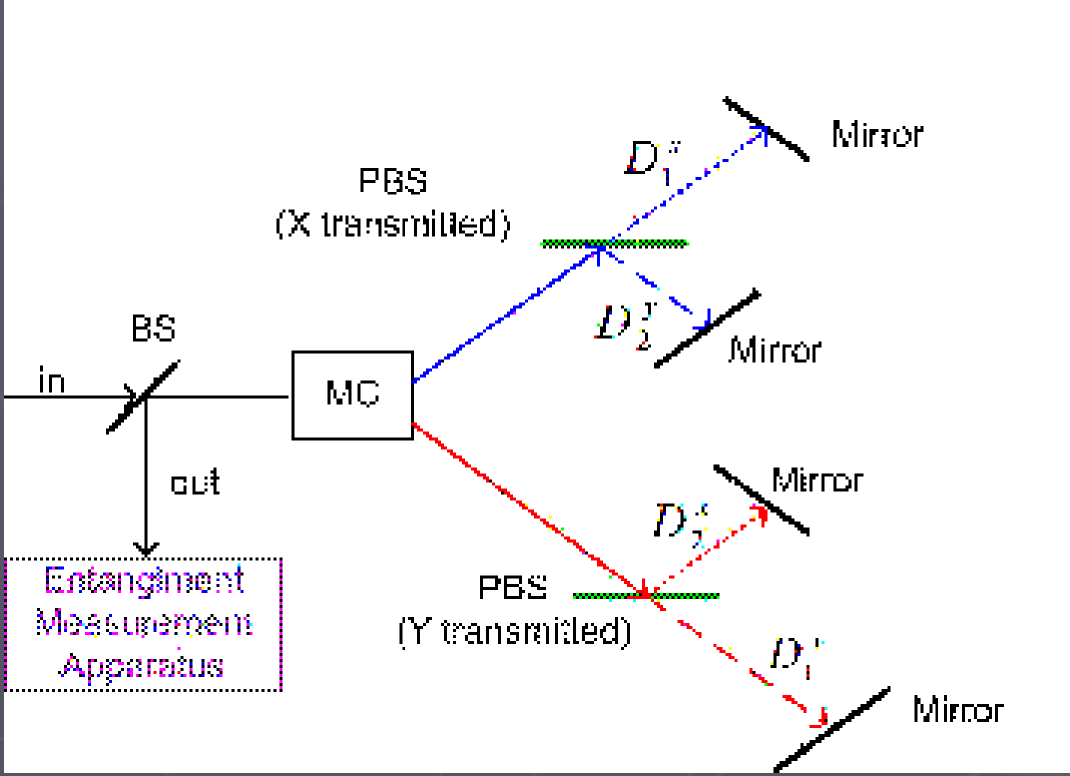
Mirror
PBS
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Mirror
BS
in
MC
out
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PBS
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Mirror
Entangment
Measurement
Apparatus

Concluding remarks

- Test: Make the experiment
- Dephasing
- Fight Wigner von Neuman

Special thanks to Jonathan Finely