Testing quantum mechanics in Collider Experiments

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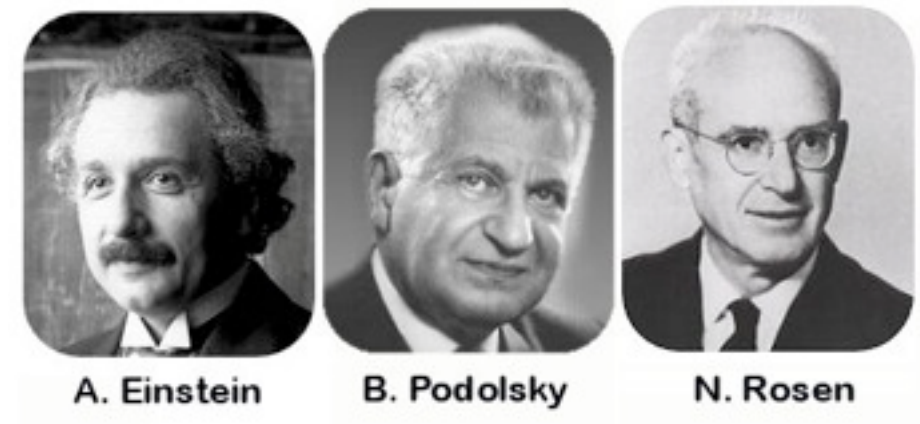
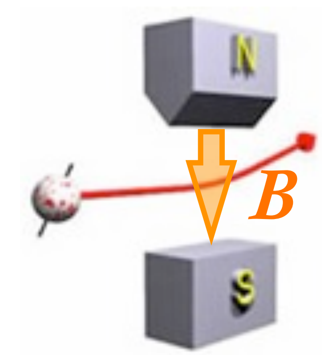
Introduction

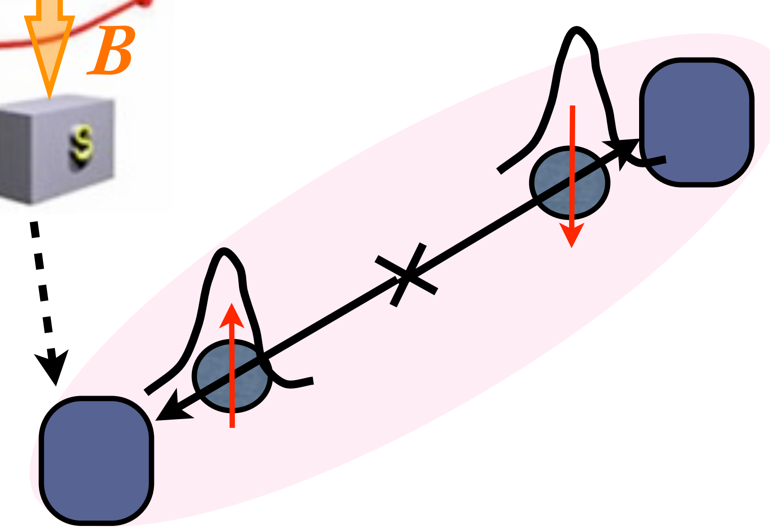


Open questions of quantum mechanics

- Interpretation of undeterministicity
- Description of measurement
- Non-locality



e.g. SG instrument



Einstein-Podolsky-Rosen (EPR, 1930)

- Consider an entangled state
  where two spin 1/2 particles run back-to-back
- Spin measurement on particle 1
- Particle-2's state reduces in accordance with that
  of particle-1 with no timing delay
- even if they are specially localized

$$\frac{|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle}{\sqrt{2}} \rightarrow \frac{|\uparrow\rangle|\downarrow\rangle}{\sqrt{2}} \text{ or } \frac{|\downarrow\rangle|\uparrow\rangle}{\sqrt{2}}$$

Analysis through Bell's inequality

(~1960)

- Can classical theory have an equivalent description as QM?

  e.g. Introduce "hidden variables" → recover local & deterministic physics

No

Bell's theorem (1964)

Any local & deterministic theory must follow

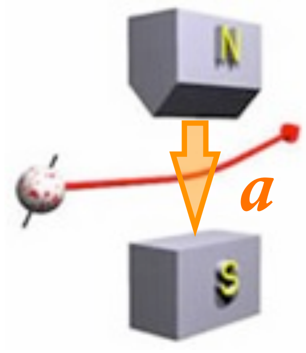
$$S = |E(\boldsymbol{a}, \boldsymbol{b}) + E(\boldsymbol{a}, \boldsymbol{d}) + E(\boldsymbol{c}, \boldsymbol{b}) - E(\boldsymbol{c}, \boldsymbol{d})| \leq 2$$ (CHSH-1974 type.)

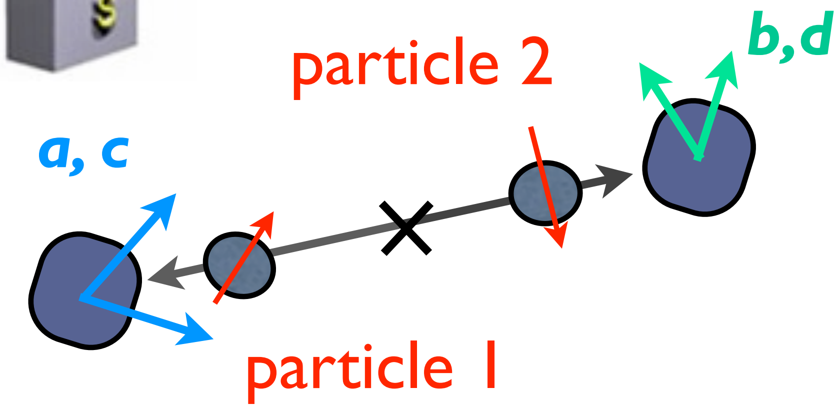
$E(\boldsymbol{a}, \boldsymbol{b}) := \langle AB \rangle$

A, (B): measured value of spin 1 (2)

with the measurement axis being $\boldsymbol{a}$ ($\boldsymbol{b}$)

when 2 meas. are in a space-like timing





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(CHSH-1974 type.)

Classical limit: $S_C <= 2$

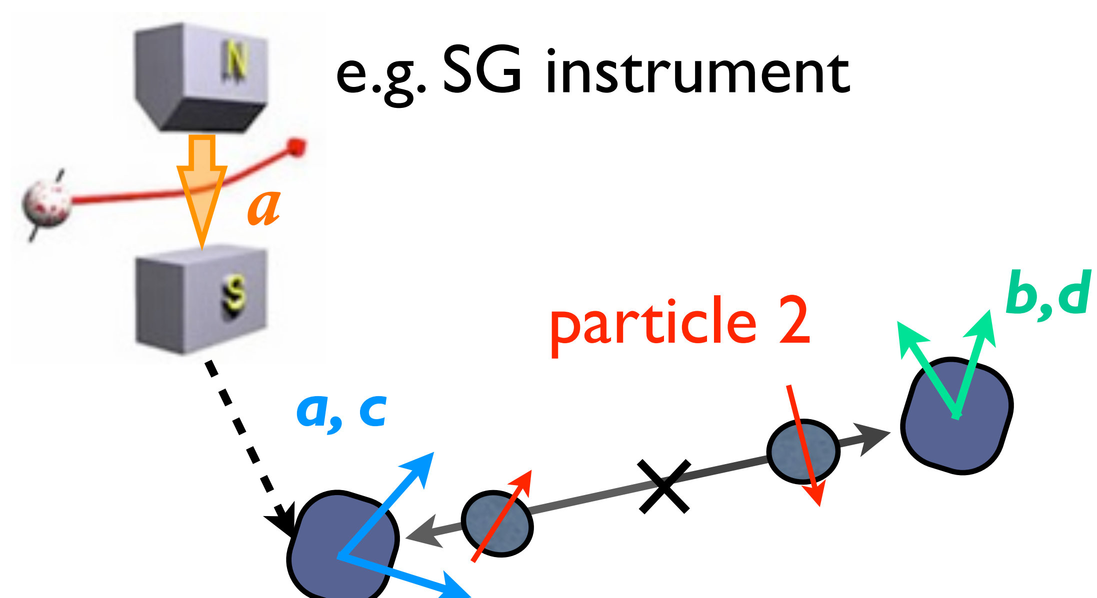
S>2 ⇒ exclusion of local reality

Quantum limit: $S_Q <= 2\sqrt{2}$

- local QM: S<=2

⇒ Inclusive non-locality test

e.g. SG instrument



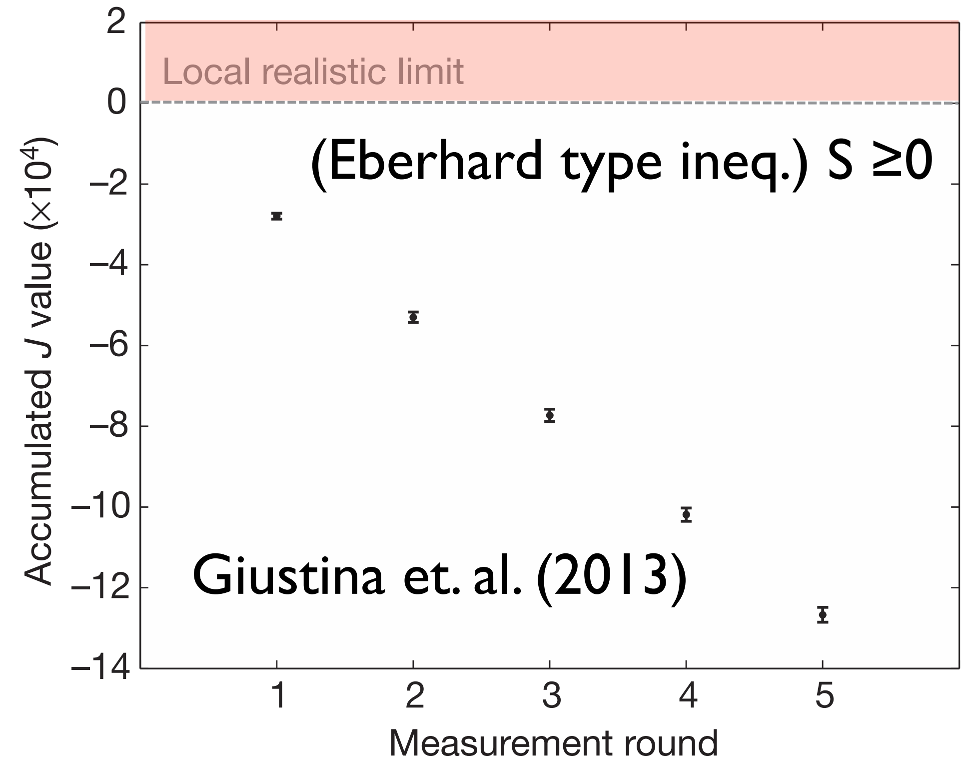
Analysis through Bell's inequality

Optical experiments （1969~today）

- Entangled photon pair + polarimeter

  Consistent with QM less assumptions

- Huge statistics, sensitivity (10σ ~ 279σ)



What's still interesting?

▪ Test in more general regime / diverse systems

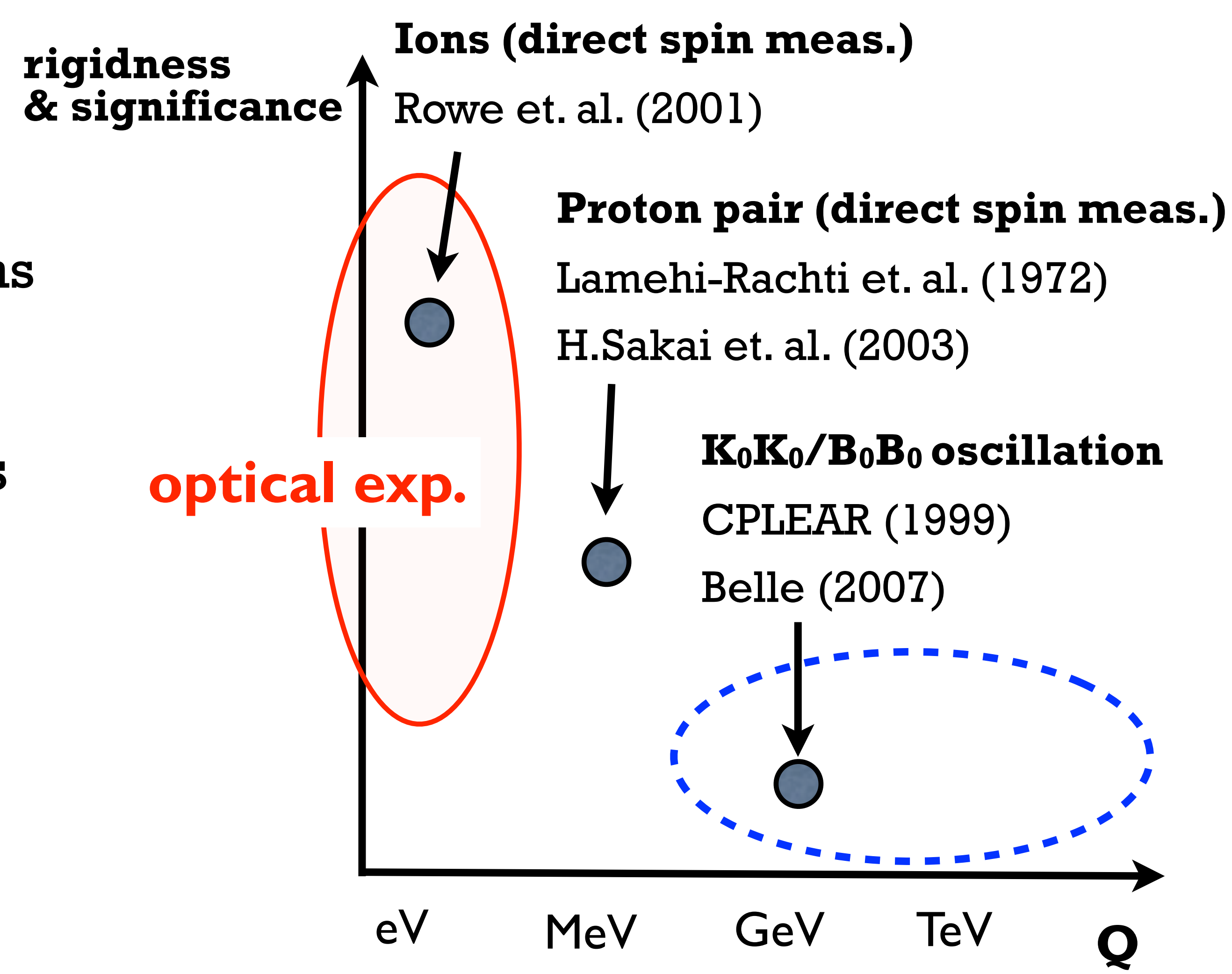
check if the features are universal

e.g. high energy scale, relativistic systems

⇒ high E collier exp.!

▪ Non-optical experiment: $O(10^0)$

⇒ more adaptable method

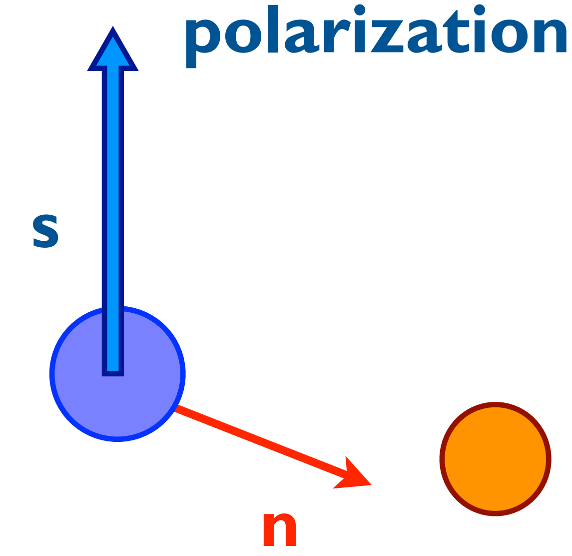


Necessary components for the test

- Spin analyser
- Entangled state
- Bell’s inequality

Spin analyser

N.Törnqvist (1981, 1986)



"polarimeter decay"

Weak decay gives rise asymmetry w.r.t the parent particle polarization

⇒ measure the spins though angular distribution of final state particles

$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha \boldsymbol{s} \cdot \boldsymbol{n}$$

"asymmetric parameter"
performance as a polarimeter

- Considering available statistics, Λ, τ decays are promising

	α
$\Lambda \to p\pi$	-0.642±0.013
$\Lambda \to n\pi_0$	-0.648±0.045
$\Sigma^+ \to p\pi_0$	-0.98±0.016
$\tau \to l\nu\nu$	0.33
$\tau \to \pi\nu$	1
$\tau \to \rho\nu$	0.46

Source of entanglement state

- (pseudo-) scalar → 2×fermion

Maximally entangled

$\Lambda\Lambda$, $\tau\tau$ helicity

$$|\psi\rangle = \frac{|++\rangle + |--\rangle}{\sqrt{2}}$$ (χ_{c0}, H: scalar)

$$|\psi\rangle = \frac{|++\rangle - |--\rangle}{\sqrt{2}}$$ (η_c: pseudo-scalar)

- vector → 2×fermion

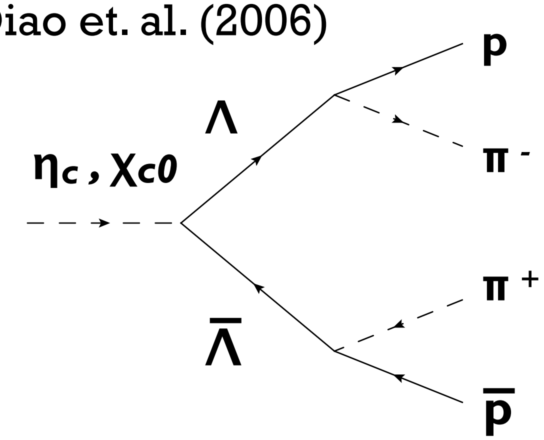
No entanglement in non-relativistic limit

(spin conservation)

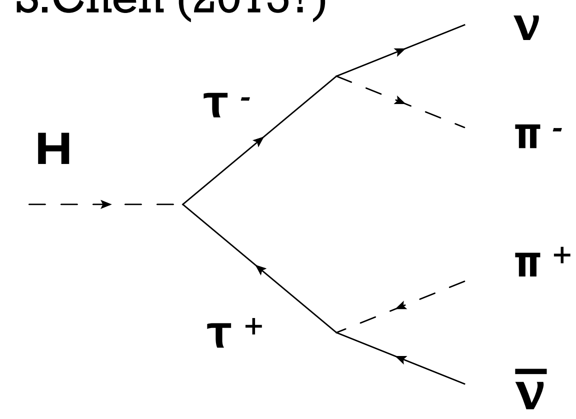
But relativistic spin-orbital angular momentum mixing can cause entanglement even if not maximally

Candidates

Qiao et. al. (2006)

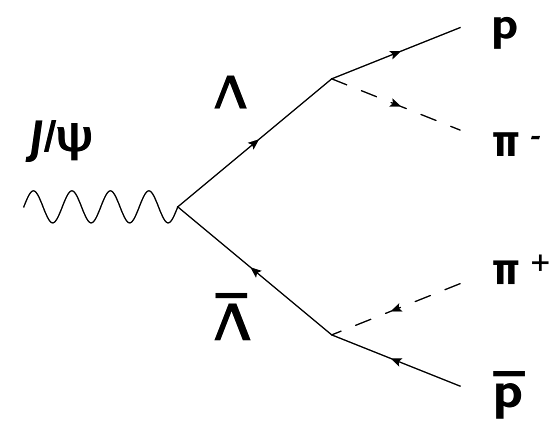


S.Chen (2015?)

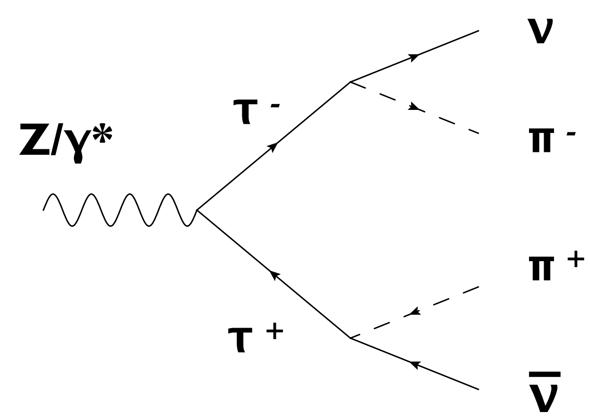


N.Törnqvist (1981)

Qiao et. al. (2006)



P.Privitera (1992)



Bell's inequality for our setup

Chen et. al. (2013)

s, s': polarization vector of $\Lambda\bar{\Lambda}$
n, n': direction of π-, π+ @Λ rest frame
n_a: projection onto ***a***

e.g. cc→$\Lambda\bar{\Lambda}$→pπpπ

$\Lambda\bar{\Lambda}$ polarization

$$|\langle s_a s'_b \rangle + \langle s_a s'_d \rangle + \langle s_c s'_b \rangle - \langle s_c s'_d \rangle| \leq 2$$

$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha \boldsymbol{s} \cdot \boldsymbol{n}$$

π+ π- direction

$$Q = |\langle n_a n'_b \rangle + \langle n_a n'_d \rangle + \langle n_c n'_b \rangle - \langle n_c n'_d \rangle| \leq \frac{2\alpha_\Lambda^2}{9}$$

Fix a-d s.t. Q is maximized

$$Q_{\max} = 2\sqrt{\lambda_1 + \lambda_2}$$

$\lambda_{1,2}$: largest 2 eigen values of $C^T C$

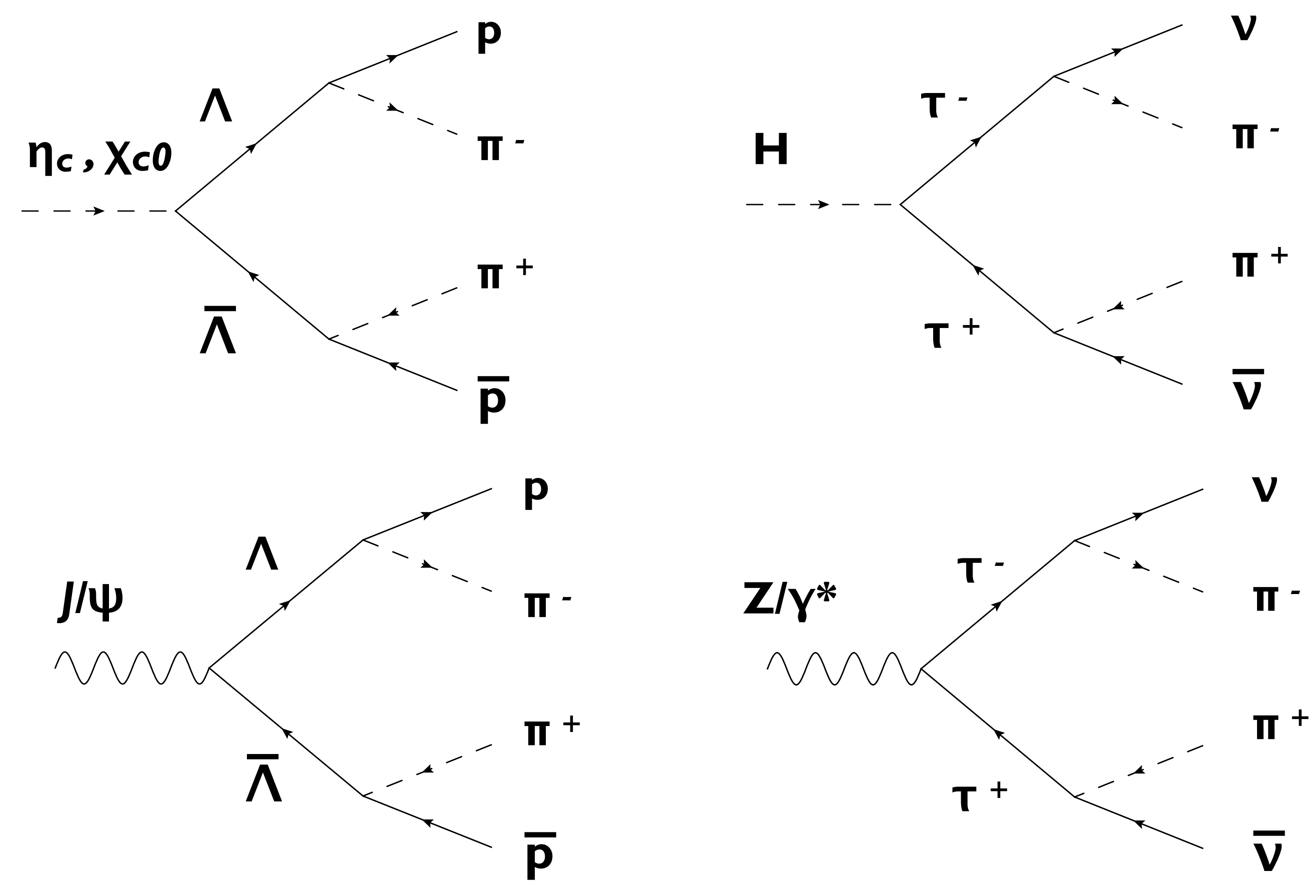
$$C = \frac{9}{2\alpha^2} \begin{pmatrix} \langle n_x n'_x \rangle & \langle n_x n'_y \rangle & \langle n_x n'_z \rangle \\ \langle n_y n'_x \rangle & \langle n_y n'_y \rangle & \langle n_y n'_z \rangle \\ \langle n_z n'_x \rangle & \langle n_z n'_y \rangle & \langle n_z n'_z \rangle \end{pmatrix}$$

Bell inequality $Q_{\max} \leq 1$ (Quantum limit: $\sqrt{2}$)

QM prediction

- LO matrix element
  + measured form factors

Bell’s inequality: Qmax ≤ 1



channel	χc0→ΛΛ	ηc→ΛΛ	J/ψ→ΛΛ	ee→γ*→ττ	ee→Z→ττ	H→ττ
Qmax	√2	√2	0.976±0.048	$\frac{\sqrt{5-2\Gamma+2\Gamma^2}}{2+\Gamma}$ $\Gamma := (2m_\tau/\sqrt{s})^2$	√5/2	√2
violation	○	○	×?		○	○

○ with √s>8.6 GeV, max: √5/2

Experimental feasibility

<u>Requirements</u>

- Λ, τ rest frame can be reconstructed

  Since observables are all defined in the frame

- Low BG level

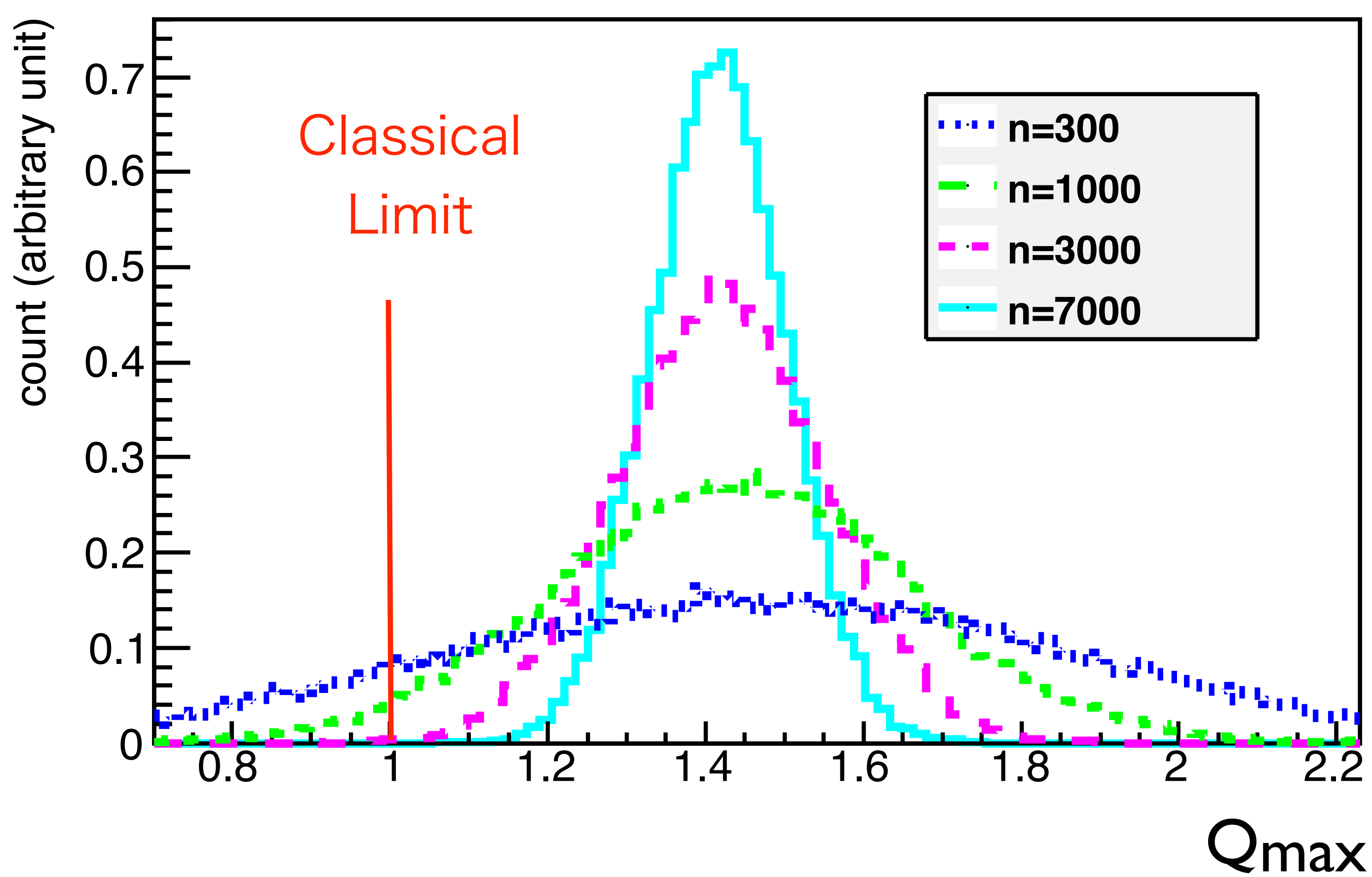
  e+e- colliders: ◎

  hadron coll.: ×?

- Statistics is needed

  for confirmation of violation

<u>Qmax ($\eta_c \to \Lambda\Lambda \to p\pi p\pi$)</u>



η_c, $\chi_{c0} \to \Lambda\Lambda \to p\pi p\pi$

Expected events @BES3

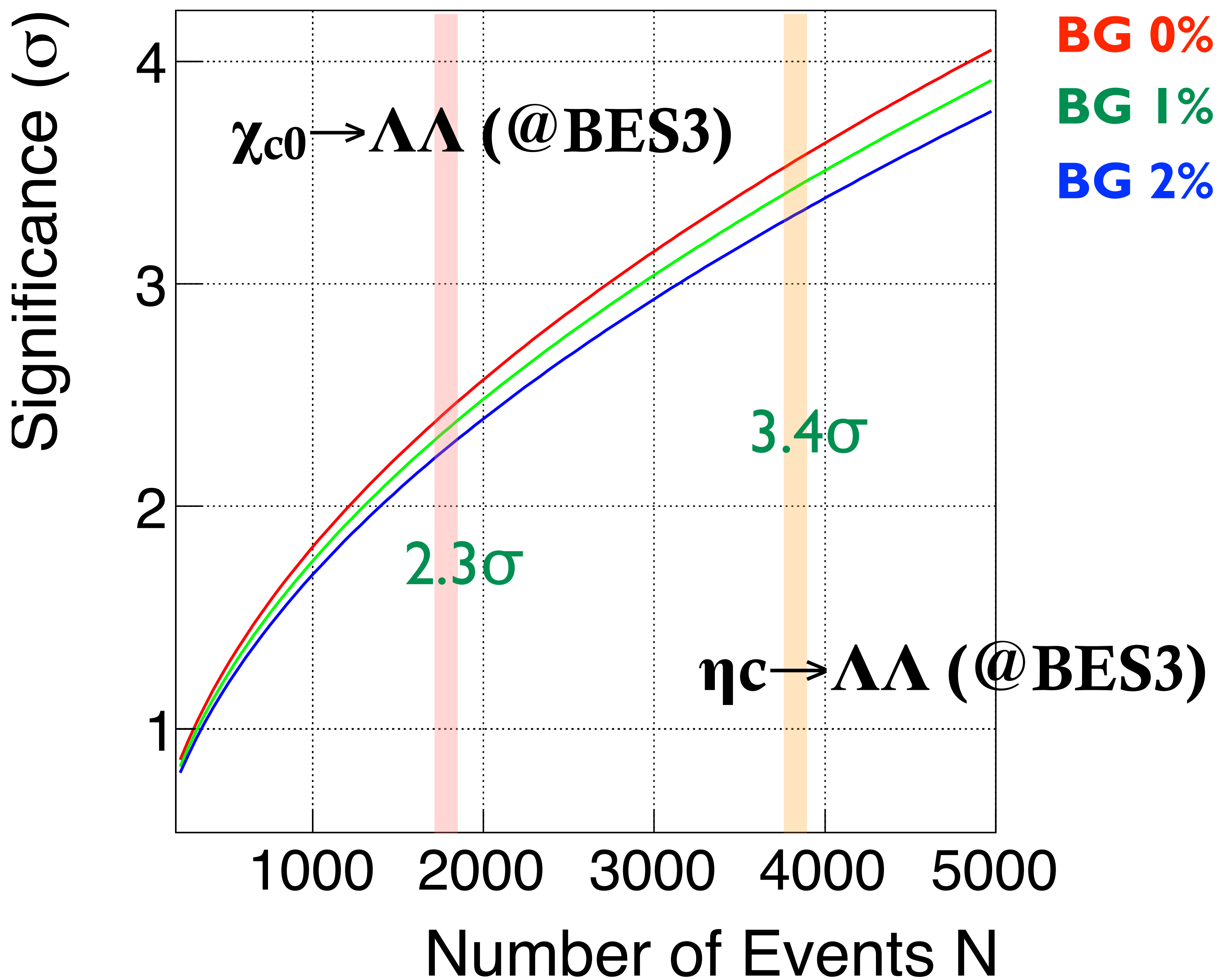
12000evt × eff (η_c channel)
4000evt × eff (χ_{co} channel)

Candidates: BES3, CLEO

Assuming Eff. ~ 20-30%, BG <0.5%

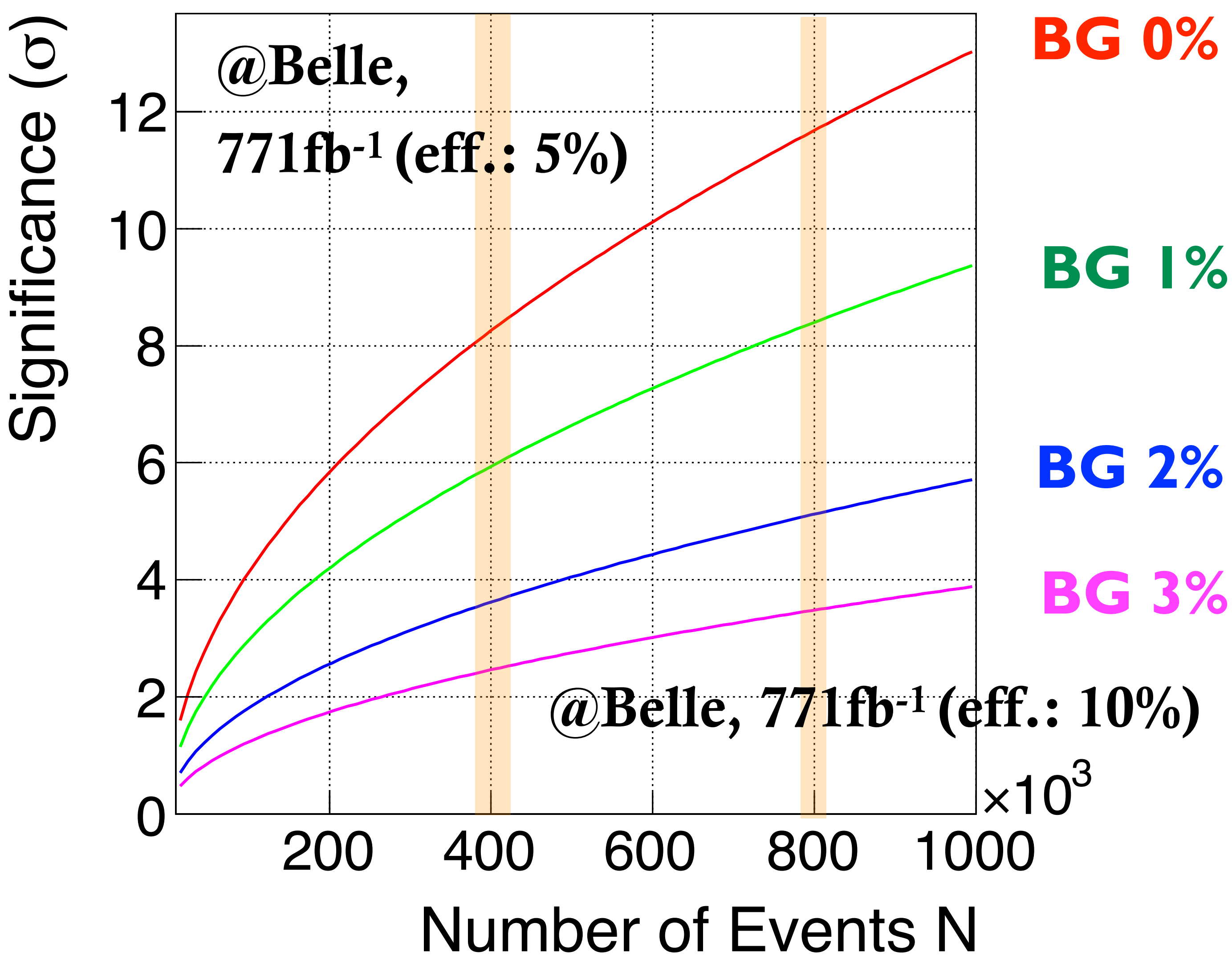
(→backup)

2-3.5σ significance
is already feasible!

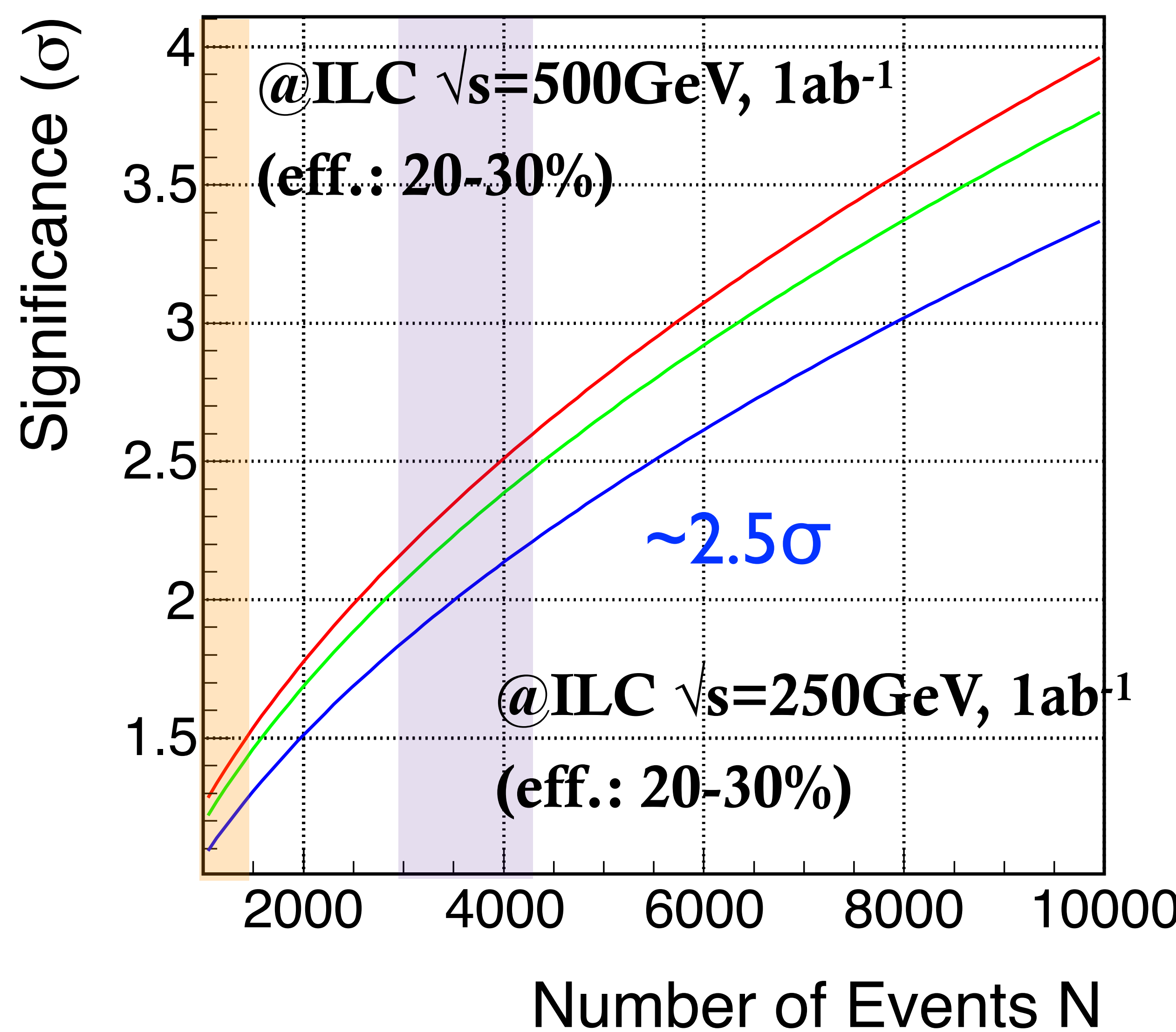


ee→γ*→ττ→πνπν **Candidates:** Belle, Babar, LEP, ILC?

Belle: √s=10.58 GeV (Qmax=1.03; LO)



ILC: √s=250-500 GeV (Qmax~1.11; LO)

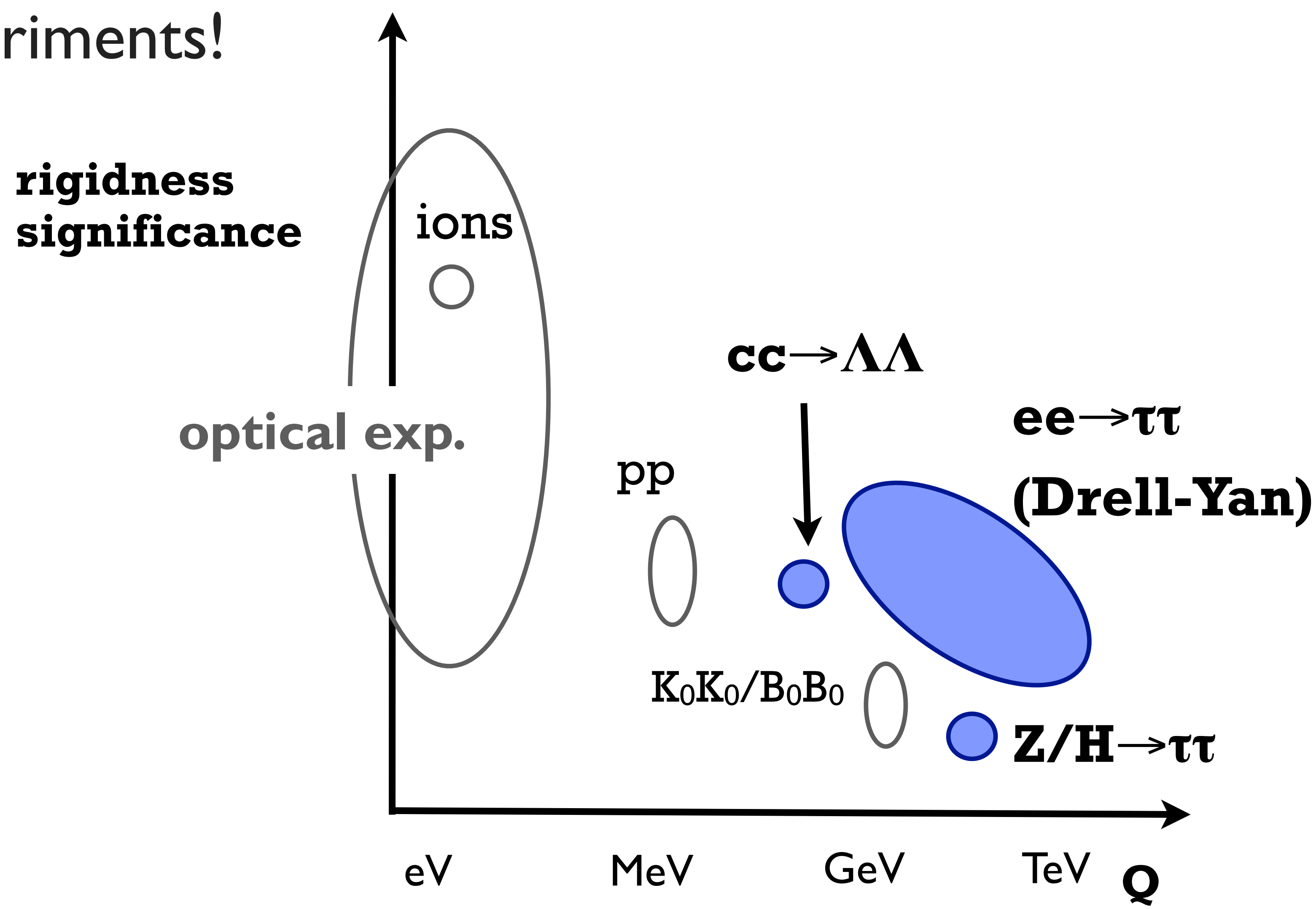


Belle: need to update calculation (Qmax=1.03)

ILC: 2-3σ ok

Summary

- Test quantum locality in high energy colliders in untested method & systems
- through Bell's inequality
- Looking forward to experiments!



Thanks for the attention!

Backup

Rigidness of LHVT test

c.f. I. Tsutsui (Kinchakai@KEK, 2010)

Optical exp.		**Efficiency LH**	**Locality LH**	**significance**
A. Aspect et. al. (1981)	photon	×	×	5σ
Weihs et. al. (1998)	photon (400m)	×	○	>10σ
Rowe et. al. (2001)	ions	○	×	>10σ
Particle exp.				
CPLEAR@CERN (1999)	K_0-$\overline{K}_0$	×	△	~3σ
Sakai et.al @RHIC (2006)	p-p	○	△	~3σ
Belle@KEK (2007)	B_0-$\overline{B}_0$	×	×	3-4σ
Tornqvist, Baranov, Chen	ΛΛ, ττ	×	△	2~3σ

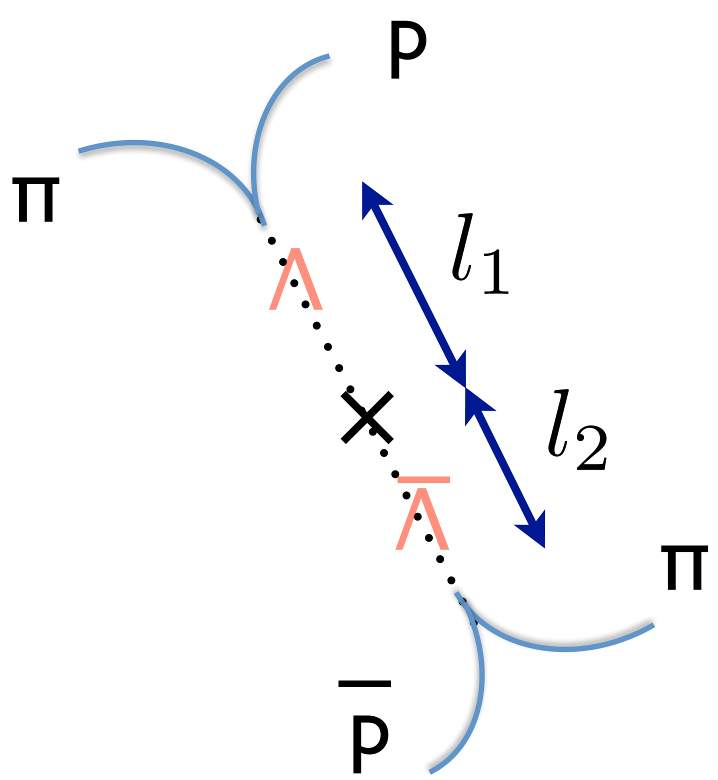
Space-time Separation of $\Lambda\bar{\Lambda}$

- $\Lambda(\bar{\Lambda})$ decay ~ spin measurement

- Fraction of events with space-like separated decays events:

$$\omega = 2\int_0^\infty dt_1 \int_{t_1}^{\frac{1+\beta}{1-\beta}t_1} dt_2 \; \frac{1}{\tau}e^{-\frac{t_1}{\tau}}\,\frac{1}{\tau}\,e^{-\frac{t_2}{\tau}} = \beta.$$

(Λ, Λbar decay time : t_1, t_2)



	η_c	χ_{c0}	J/ψ
β	0.663	0.757	0.693

space-time separation condition:

$$l_1 + l_2 > c\,|t_1 - t_2| = \frac{1}{\beta}|l_1 - l_2|$$