Fabbrichesi, GGI, Firenze, Novembre 2023

Bell locality

$$P(A,B|a,b) = \int d\lambda\, \eta(\lambda) P_\lambda(A|a) P_\lambda(B|b)$$

shared resources

Bell inequality

loophole: inequality violated but Bell locality true

Detection loophole [edit]

A common problem in optical Bell tests is that only a small fraction of the emitted photons are detected. It is then possible that the correlations of the detected photons are unrepresentative: although they show a violation of a Bell inequality, if all photons were detected the Bell inequality would actually be respected. This was first noted by Pearle in 1970,[50] who devised a local hidden variable model that faked a Bell violation by letting the photon be detected only if the measurement setting was favourable. The assumption that this does not happen, i.e., that the small sample is actually representative of the whole is called the *fair sampling* assumption.

To do away with this assumption it is necessary to detect a sufficiently large fraction of the photons. This is usually characterized in terms of the detection efficiency η, defined as the probability that a photodetector detects a photon that arrives at it. Garg and Mermin showed that when using a maximally entangled state and the CHSH inequality an efficiency of $\eta > 2\sqrt{2} - 2 \approx 0.83$ is required for a loophole-free violation.[51] Later Eberhard showed that when using a *partially* entangled state a loophole-free violation is possible for $\eta > 2/3 \approx 0.67$,[52] which is the optimal bound for the CHSH inequality.[53] Other Bell inequalities allow for even lower bounds. For example, there exists a four-setting inequality which is violated for $\eta > (\sqrt{5} - 1)/2 \approx 0.62$.[54]

Historically, only experiments with non-optical systems have been able to reach high enough efficiencies to close this loophole, such as trapped ions,[55] superconducting qubits,[56] and nitrogen-vacancy centers.[57] These experiments were not able to close the locality loophole, which is easy to do with photons. More recently, however, optical setups have managed to reach sufficiently high detection efficiencies by using superconducting photodetectors,[30][31] and hybrid setups have managed to combine the high detection efficiency typical of matter systems with the ease of distributing entanglement at a distance typical of photonic systems.[10]

Locality loophole [edit]

One of the assumptions of Bell's theorem is the one of locality, namely that the choice of setting at a measurement site does not influence the result of the other. The motivation for this assumption is the theory of relativity, that prohibits communication faster than light. For this motivation to apply to an experiment, it needs to have space-like separation between its measurements events. That is, the time that passes between the choice of measurement setting and the production of an outcome must be shorter than the time it takes for a light signal to travel between the measurement sites.[58]

The first experiment that strived to respect this condition was Alain Aspect's 1982 experiment.[15] In it the settings were changed fast enough, but deterministically. The first experiment to change the settings randomly, with the choices made by a quantum random number generator, was Weihs et al.'s 1998 experiment.[18] Scheidl et al. improved on this further in 2010 by conducting an experiment between locations separated by a distance of 144 km (89 mi).[59]

Coincidence loophole [edit]

In many experiments, especially those based on photon polarization, pairs of events in the two wings of the experiment are only identified as belonging to a single pair after the experiment is performed, by judging whether or not their detection times are close enough to one another. This generates a new possibility for a local hidden variables theory to "fake" quantum correlations: delay the detection time of each of the two particles by a larger or smaller amount depending on some relationship between hidden variables carried by the particles and the detector settings encountered at the measurement station.[60]

The coincidence loophole can be ruled out entirely simply by working with a pre-fixed lattice of detection windows which are short enough that most pairs of events occurring in the same window do originate with the same emission and long enough that a true pair is not separated by a window boundary.[60]

Memory loophole [edit]

In most experiments, measurements are repeatedly made at the same two locations. A local hidden variable theory could exploit the memory of past measurement settings and outcomes in order to increase the violation of a Bell inequality. Moreover, physical parameters might be varying in time. It has been shown that, provided each new pair of measurements is done with a new random pair of measurement settings, that neither memory nor time inhomogeneity have a serious effect on the experiment.[61][62][63]

Superdeterminism [edit]

Main article: Superdeterminism

A necessary assumption to derive Bell's theorem is that the hidden variables are not correlated with the measurement settings. This assumption has been justified on the grounds that the experimenter has "free will" to choose the settings, and that such is necessary to do science in the first place. A (hypothetical) theory where the choice of measurement is determined by the system being measured is known as *superdeterministic*.[45]

Many-worlds loophole [edit]

The many-worlds interpretation, also known as the Everett interpretation, is deterministic and has local dynamics, consisting of the unitary part of quantum mechanics without collapse. Bell's theorem does not apply because of an implicit assumption that measurements have a single outcome.[64]

loophole free test in atomic and solid-state physics

M. Giustina, *et al.* Phys. Rev. Lett. **115**, no.25, 250401 (2015) [arXiv:1511.03190 [quant-ph]];
L. K. Shalm *et al.*, Phys. Rev. Lett. **115**, 250402 (2015).
B. Hensen, H. Bernien, A. E. Dreau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten and C. Abellan, *et al.* Nature **526**, 682-686 (2015) [arXiv:1508.05949 [quant-ph]].
W. Rosenfeld *et al.*, Phys. Rev. Lett. **119** 010402 (2017).

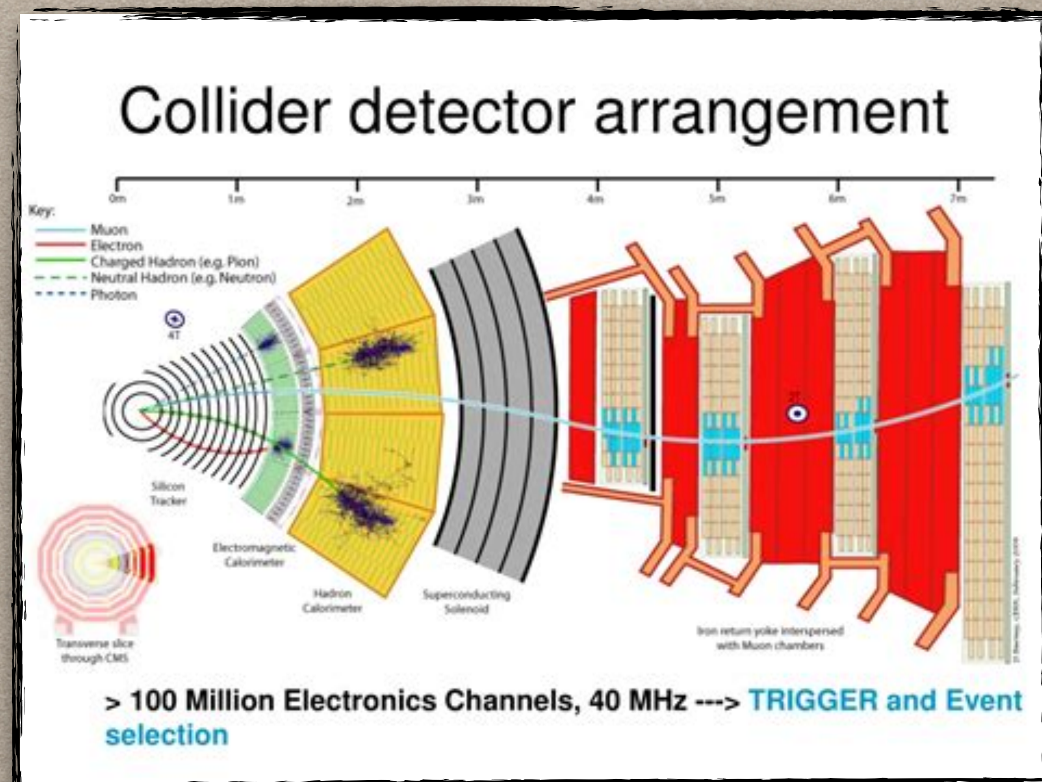
w/ photons

w/ atoms

S. Storz, *et al.* Nature **617**, 265-270 (2023) ← *w/ superconductors*

how about at colliders?

not designed for

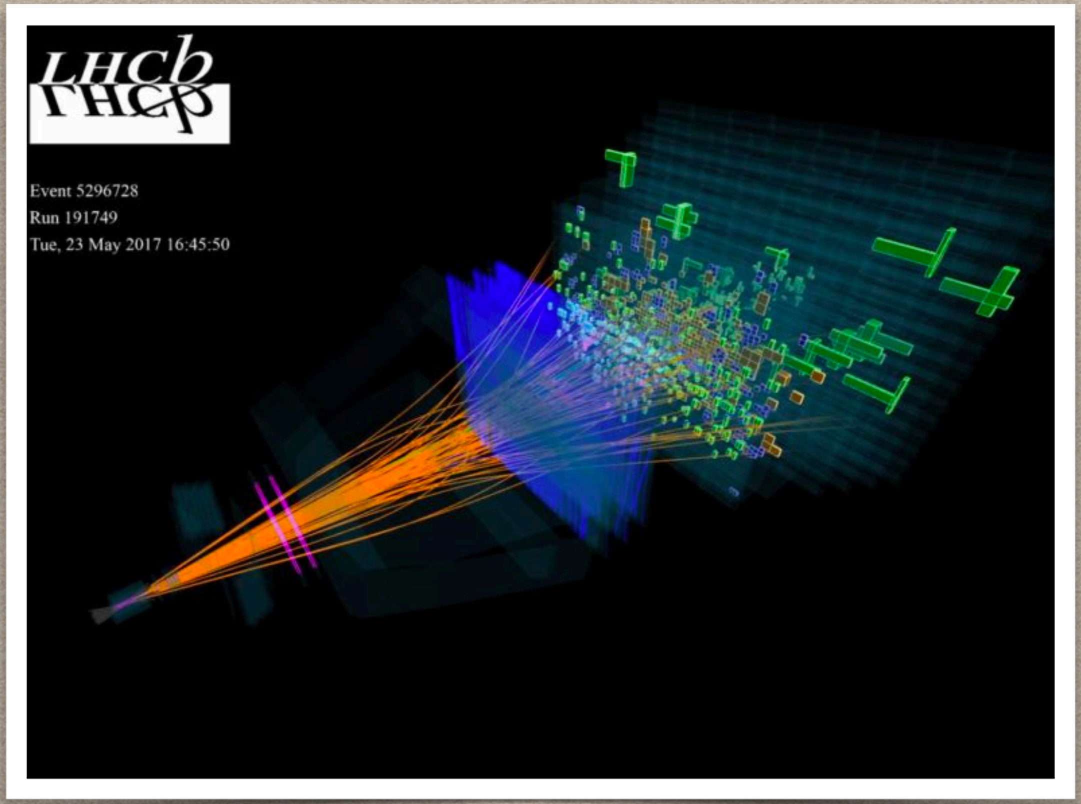


testing Bell inequality

short answer: surprisingly good

Detection loophole

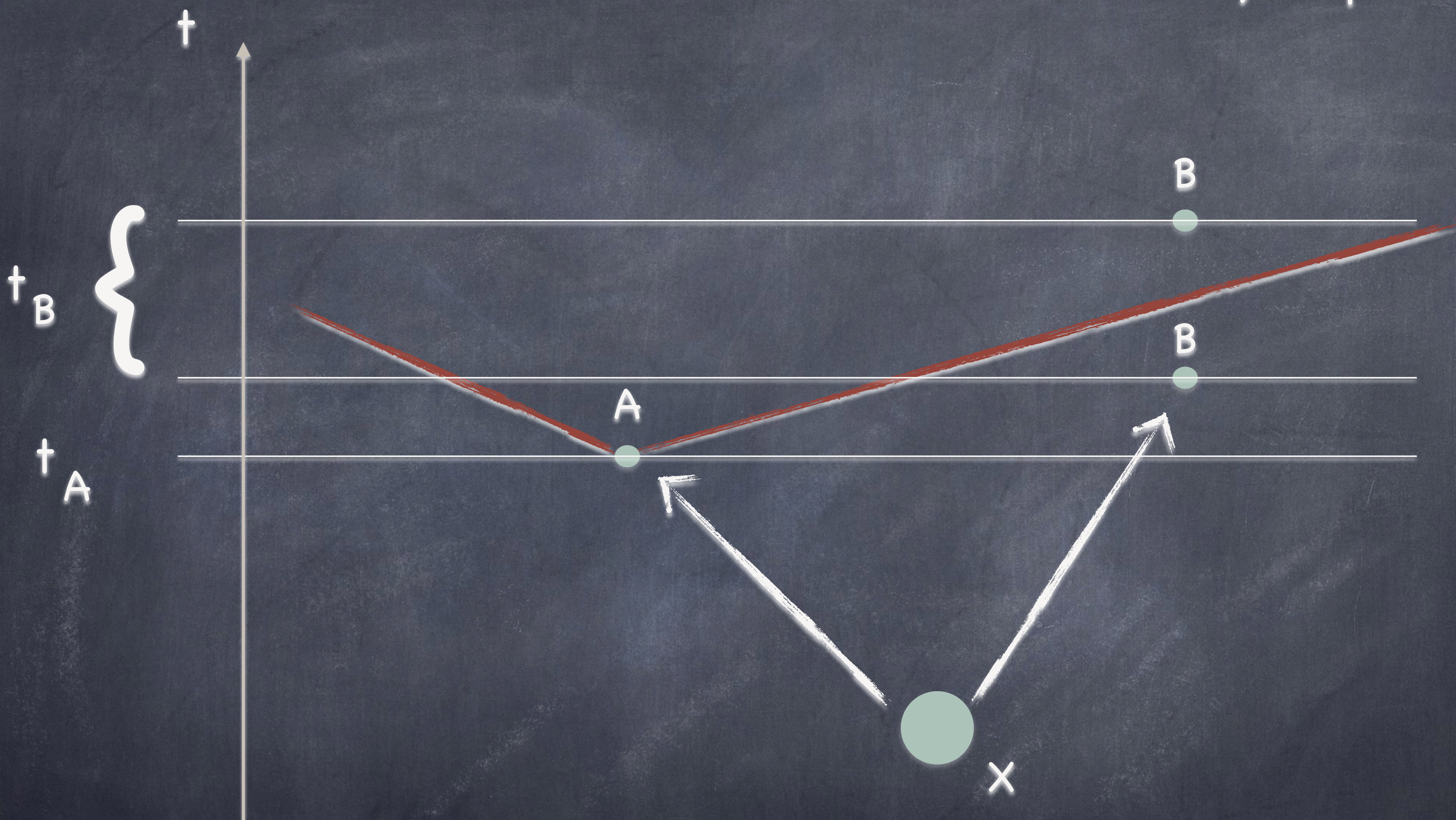
J. F. Clauser, M. A. Horne, A. Shimony and R. A. Holt, Phys. Rev. Lett. **23**, 880-884 (1969).
T. Vèrtesi, S. Pironio and N. Brunne, Phys. Rev. Lett. **104** 060401 (2010).



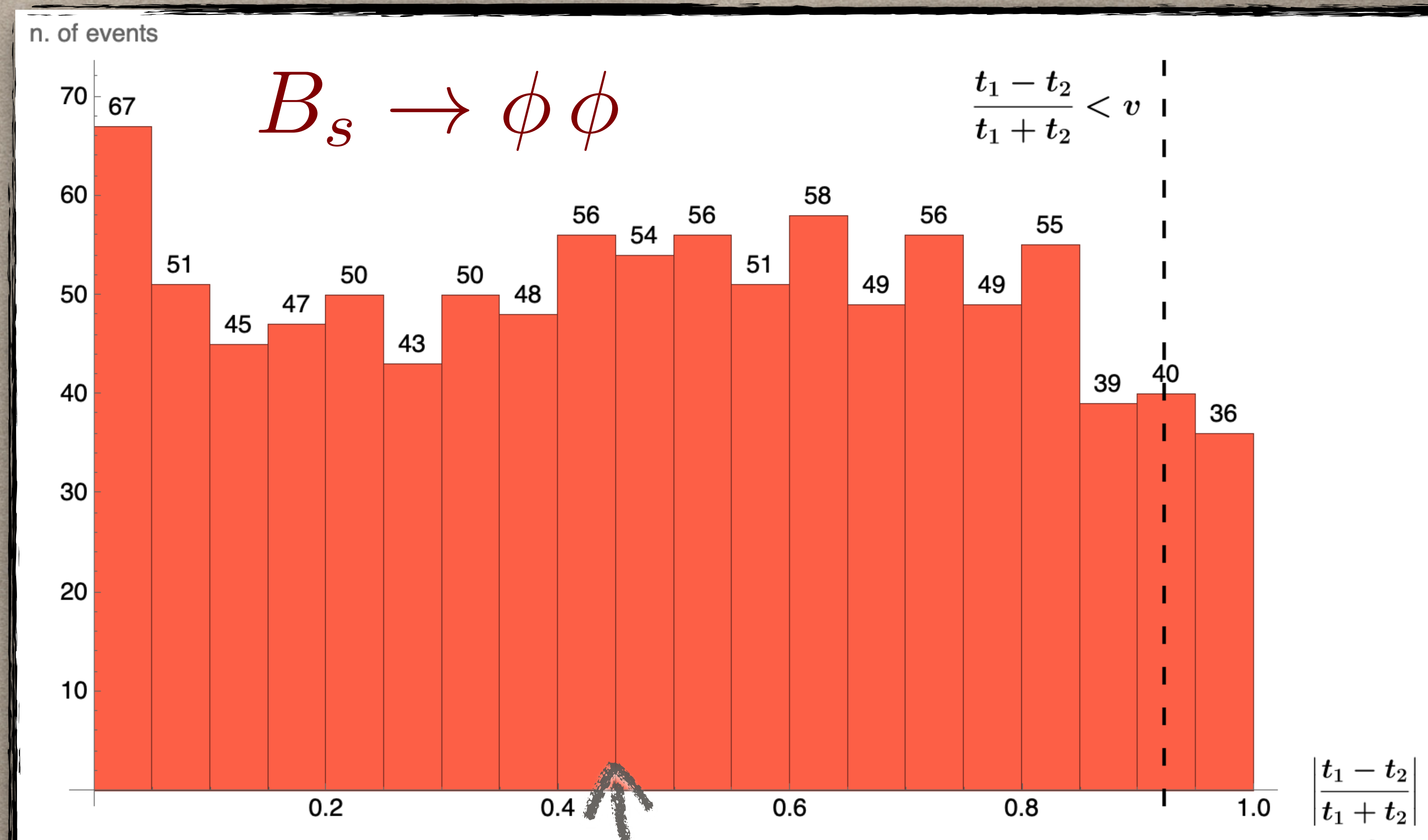
remember: we only need efficiency of detecting charged pions or leptons

more than 80%

Locality loophole



```
v = Sqrt[1 - 4. M_A,B ^2 / M_X ^2];
γ = 1 / Sqrt[1 - v ^2];
t1 = RandomVariate[ExponentialDistribution[Γ_A / γ], 1000];
t2 = RandomVariate[ExponentialDistribution[Γ_B / γ], 1000];
ratio = Abs[t1 - t2] / (t1 + t2) (* < v/c --> condition for space-like interval *)
```



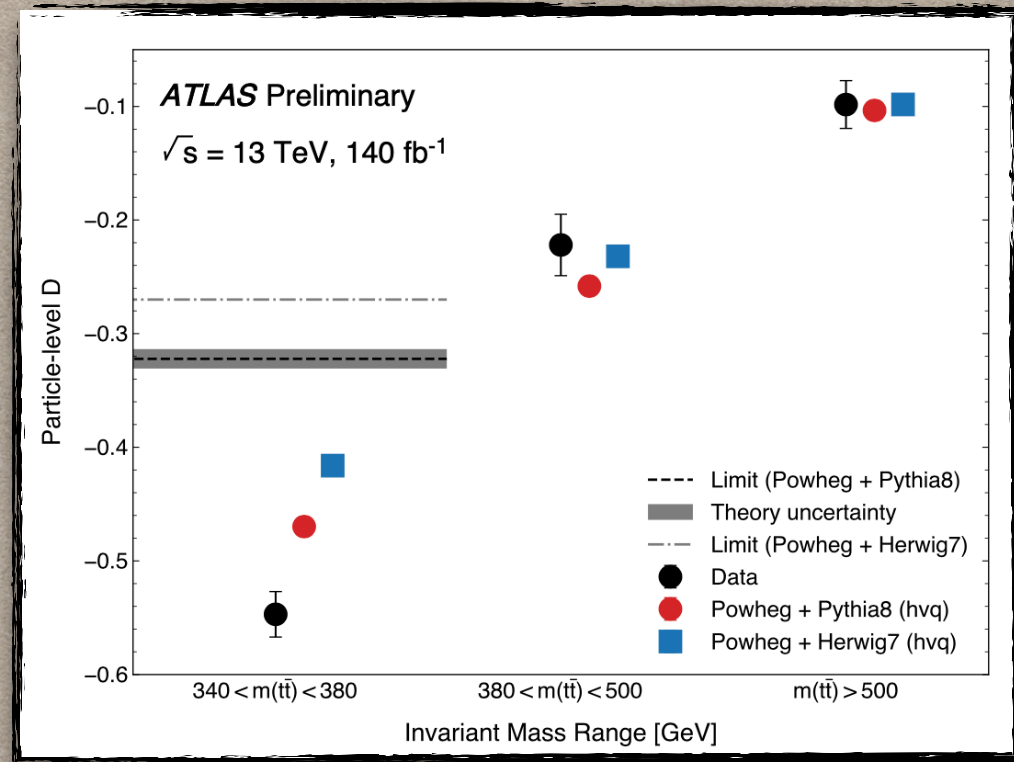
more than 90 %

cluster decomposition vs. entanglement

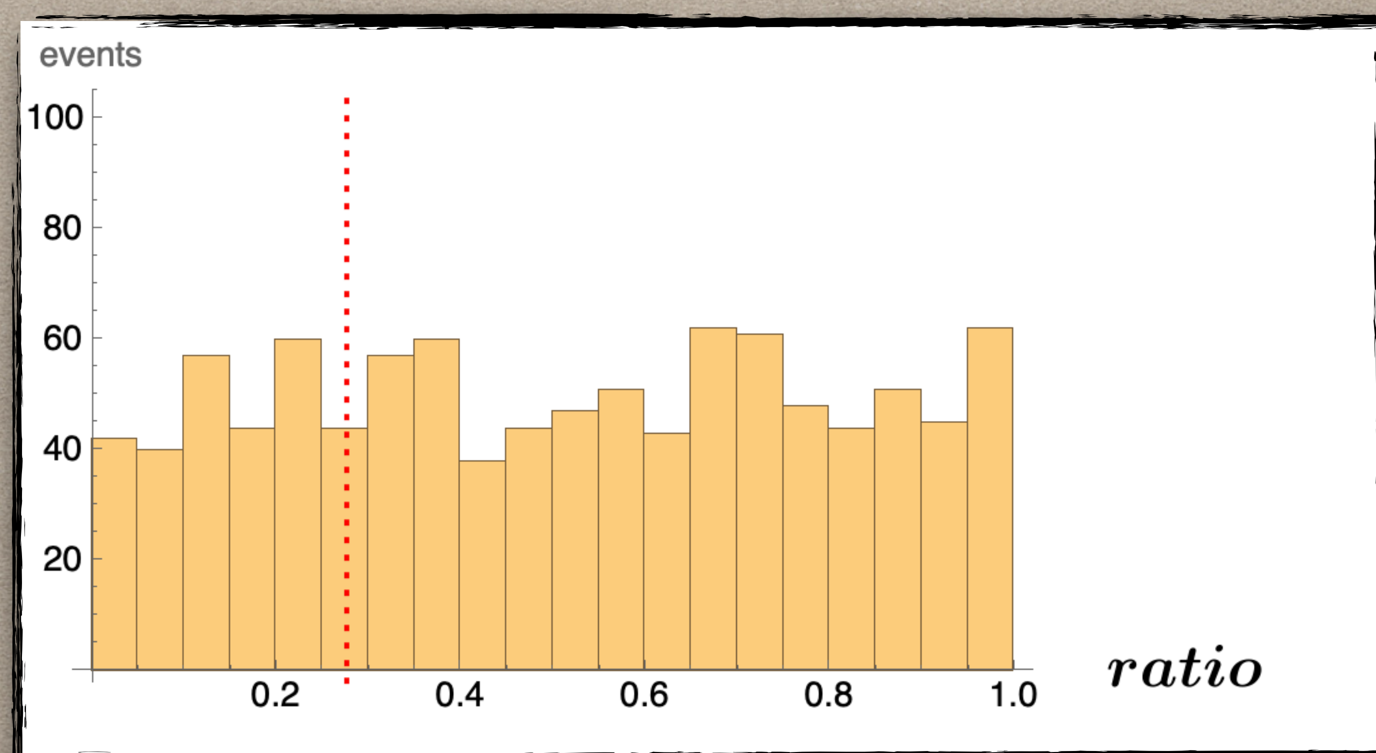
it seems OK at colliders

I don't know in other settings

ATLAS-CONF-2023-069



Sommerfeld?



less than 30 %