Bell inequality violation detection with flavor entanglement of B^0-B^0 pairs at ATLAS experiment in LHC Run-3

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@Physics in LHC and Beyond

Hidden variable theory

- Einstein's consideration on quantum mechanics
  - Quantum Mechanics (QM) is approximation of a complete theory.
  - In the complete theory, each element of the physical reality (e.g. spin, flavor) is a function of hidden variable λ

↓

Hidden Variable Theory (HVT)

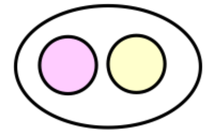
- Premise in HVT
  - **Locality condition** : A measurement on one particle does not influence the other.
  - **"Free will"** : An experimenter has freedom to choose a measurement condition.

Bell developed a formula that HVT must satisfy.

Bell inequality

- $A(t_a)$, $B(t_b)$: eigenvalues of two particles (e.g. meson flavors)

  measured in certain conditions (e.g. measured time t_a, t_b).

$A(t_a) \longleftarrow$  $\longrightarrow B(t_b)$

- Expectation value of $A(t_a)B(t_b)$: $C(t_a, t_b) = \sum_{A,B} AB\,P_{t_a t_b}(A,B)$

  ↑ PDF (Probability Density Function) of $A(t_a)B(t_b)$

- In HVT, (A, B) are functions of hidden variable λ :

$$P_{t_a t_b}(A,B) = \int P_{t_a}(A,\lambda)P_{t_b}(B,\lambda)P(\lambda)d\lambda$$

$$\Rightarrow C(t_a,t_b) = \int \sum_A A P_{t_a}(A,\lambda) \sum_B B P_{t_b}(B,\lambda)P(\lambda)\,d\lambda$$

Free will

Locality condition

- **Bell inequality**

$$|S| = |C(t_a,t_b) + C(t'_a,t_b) + C(t_a,t'_b) - C(t'_a,t'_b)| \leqq 2$$

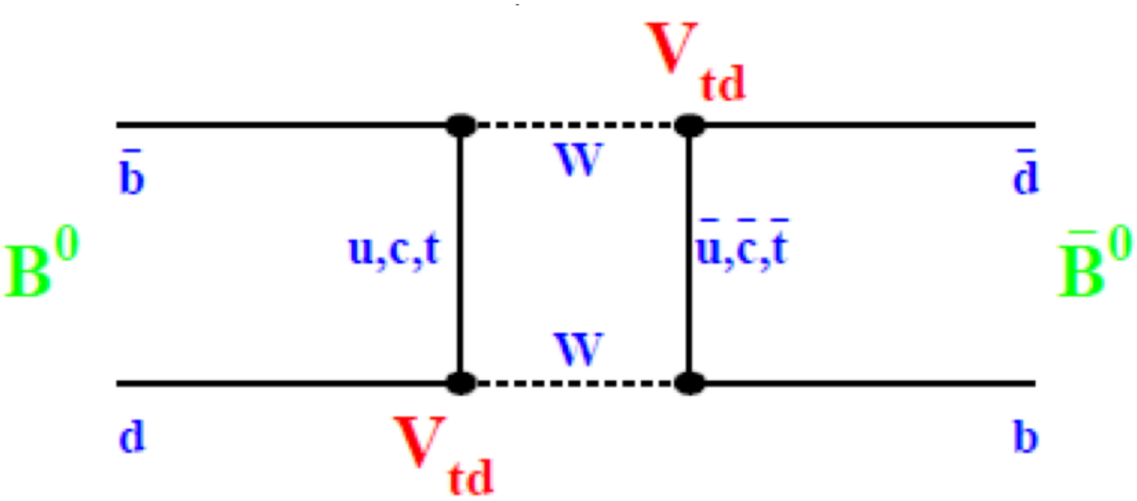
If HVT is correct, $|S| \leqq 2$.

Flavor mixing in B meson

- B^0 mesons are flavor eigenstates (B^0, $\bar{B}^0$) and make CP eigenstates with different mass (B_H, B_L). (B^0, $\bar{B}^0$) are expressed by the CP eigenstates :

$$|B^0\rangle = \frac{|B_H\rangle + |B_L\rangle}{\sqrt{2}}, \ |\bar{B}^0\rangle = \frac{|B_H\rangle - |B_L\rangle}{\sqrt{2}}$$

(Assuming CP conservation)

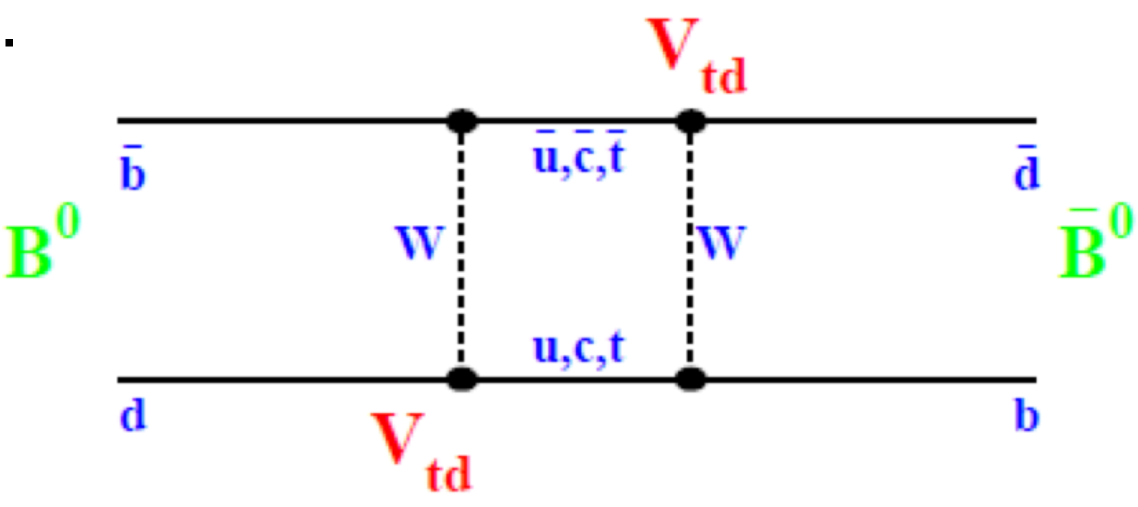


- B^0 and $\bar{B}^0$ are mixed during time evolution.

($\Delta M = M_H - M_L$, $\Gamma = \Gamma_H - \Gamma_L$)

$$P(B^0 \rightarrow B^0, t) = \frac{e^{-\Gamma t}}{2}(1 + \cos \Delta M t)$$

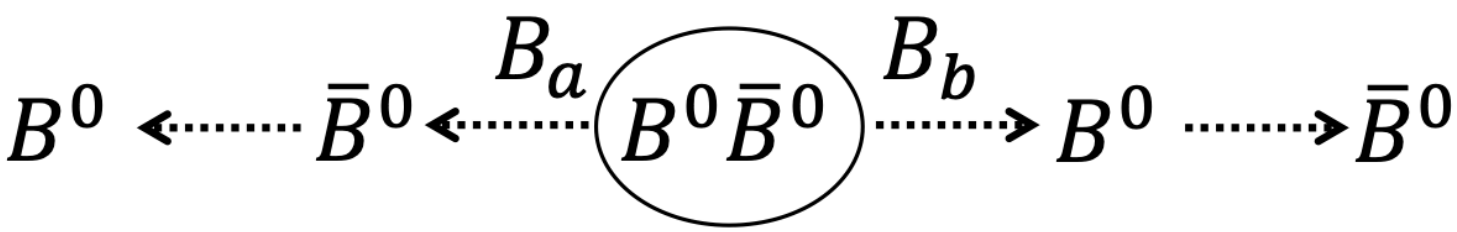
$$P(B^0 \rightarrow \bar{B}^0, t) = \frac{e^{-\Gamma t}}{2}(1 - \cos \Delta M t)$$



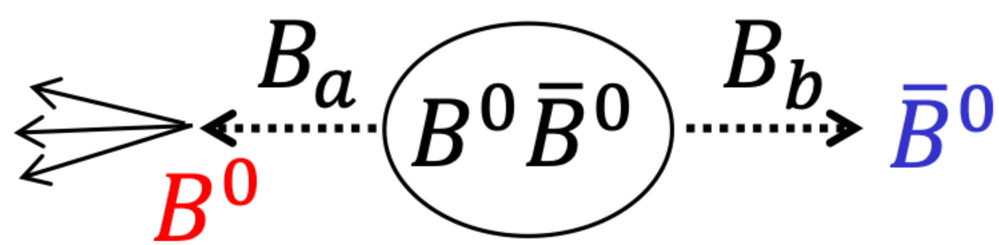
Flavor mixing in entangled state

- In QM, a $B^0\bar{B}^0$ pair (e.g. created from Υ(4S) or gluon) is in entangled state
  → If one is B^0, the other is $\bar{B}^0$.

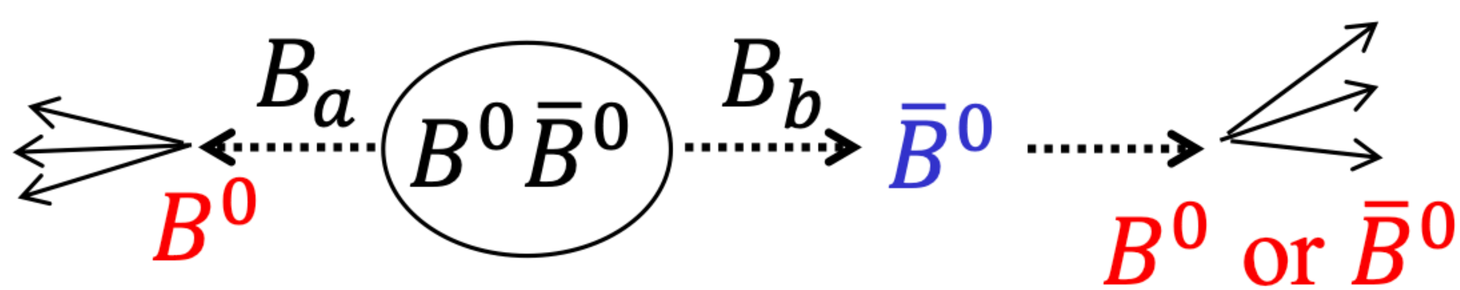
$$\psi(t_a, t_b) = \frac{1}{\sqrt{2}}(|B^0(t_a)\rangle|\bar{B}^0(t_b)\rangle - |\bar{B}^0(t_a)\rangle|B^0(t_b)\rangle)$$



- If B_a decays into B^0 eigenstate, the state of B_b at that timing is $\bar{B}^0$ (vice versa).



- The flavor of B_a, B_b is mixed during its travel and the flavor is determined at the timing of its decay.



Bell inequality in flavor correlation

- Flavor correlation at decay times ($t_{a/b}$)

$$C^Q(t_a, t_b) = \sum_{A,B} AB P^Q_{t_b\, t_b}(A, B)$$

$$P^Q_{t_a, t_b}(A,B) = \frac{N^{AB}_{(t_a,t_b)}}{N^{B^0B^0}_{(t_a,t_b)} + N^{\bar{B}^0\bar{B}^0}_{(t_a,t_b)} + N^{B^0\bar{B}^0}_{(t_a,t_b)} + N^{\bar{B}^0B^0}_{(t_a,t_b)}}$$

\# of events with flavor (A, B) at the decay time of $B_{a/b}(t_a, t_b)$

$$= \frac{N^{B^0B^0}_{(t_a,t_b)} + N^{\bar{B}^0\bar{B}^0}_{(t_a,t_b)} - N^{B^0\bar{B}^0}_{(t_a,t_b)} - N^{\bar{B}^0B^0}_{(t_a,t_b)}}{N^{B^0B^0}_{(t_a,t_b)} + N^{\bar{B}^0\bar{B}^0}_{(t_a,t_b)} + N^{B^0\bar{B}^0}_{(t_a,t_b)} + N^{\bar{B}^0B^0}_{(t_a,t_b)}}$$

$$= -\cos(\Delta M \Delta t)$$

- Defining $t_2 - t'_1 = t_1 - t_2 = t'_2 - t_1 = \Delta t$,

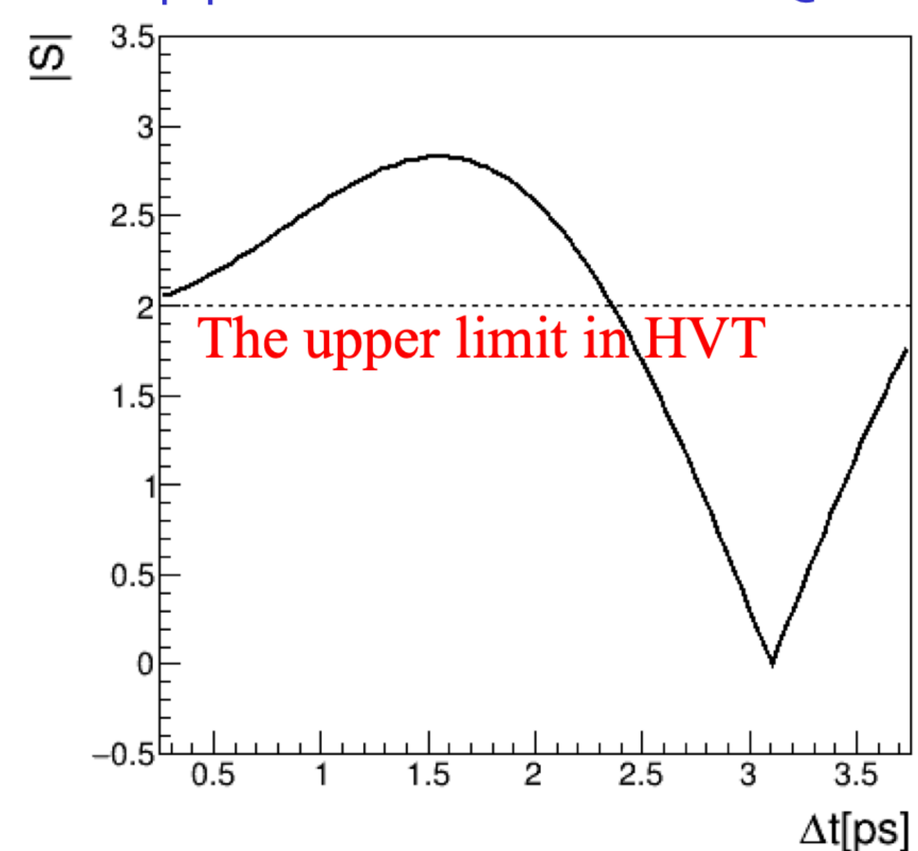
$$|S^Q(\Delta t)| = |C^Q(t_1, t_2) + C^Q(t'_1, t_2) + C^Q(t_1, t'_2) - C^Q(t'_1, t'_2)|$$

$-\cos(\Delta M\Delta t)$ $-\cos(\Delta M\Delta t)$ $-\cos(\Delta M\Delta t)$ $-\cos(3\Delta M\Delta t)$

$$= |-3\cos(\Delta M\Delta t) + \cos(3\Delta M\Delta t)|$$

- In QM, |S| has the maximum value of $2\sqrt{2}$ at $\Delta t = 1.55$ ps.
  → **QM violates Bell inequality**

|S| as a function of Δt in QM

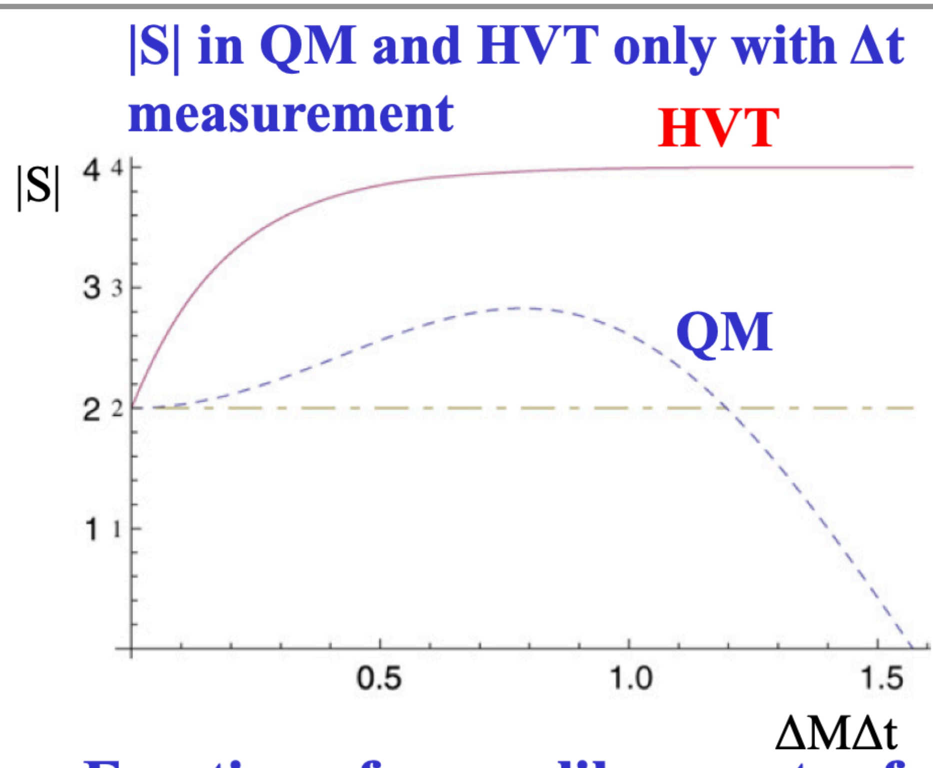


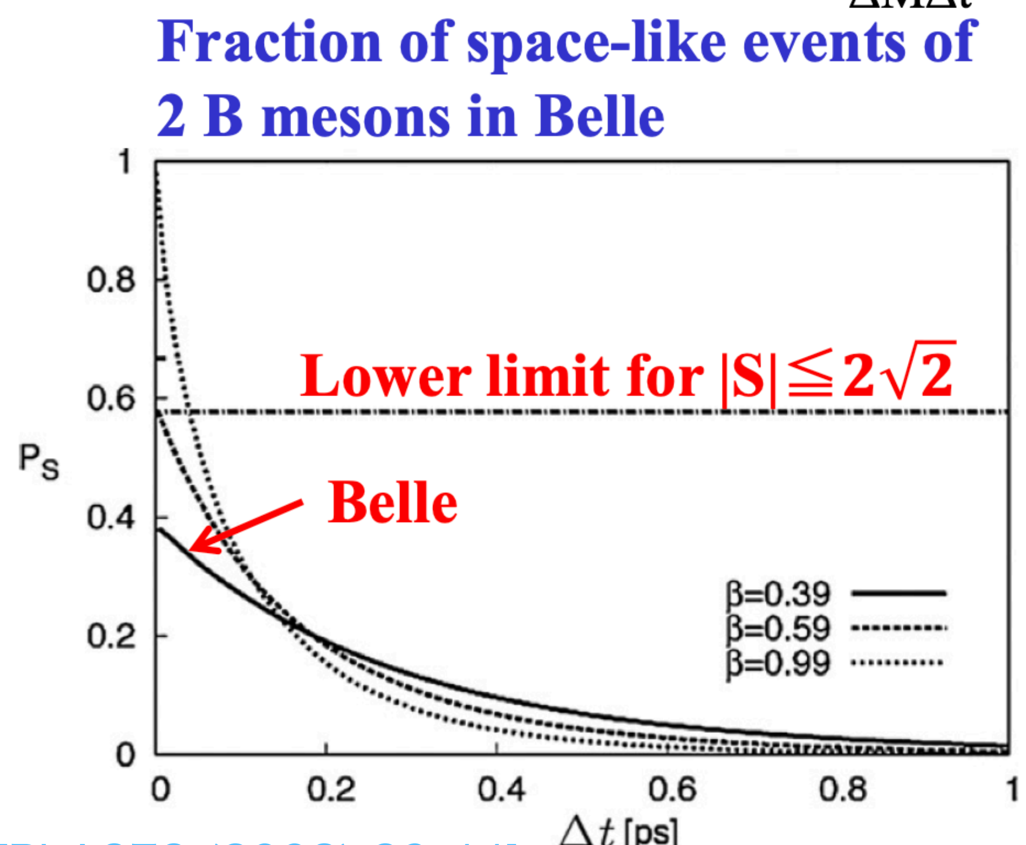
Previous experiments

- B meson (Belle) [arXiv:030192(2003)]
  - A measurement only for Δt, where (t_a, t_b) were not measured separately.
  - |S| has the maximum value of 4 and includes that of QM.
- K meson (CPLEAR) [PLB422, 339-348]
  - A measurement only for $C^Q(t_a, t_b)$ so is not a Bell test.

  - Most of 2 mesons are not space-like and the locality is not ensured in both experiments

The previous experiments were not enough for Bell test on the flavor entanglement

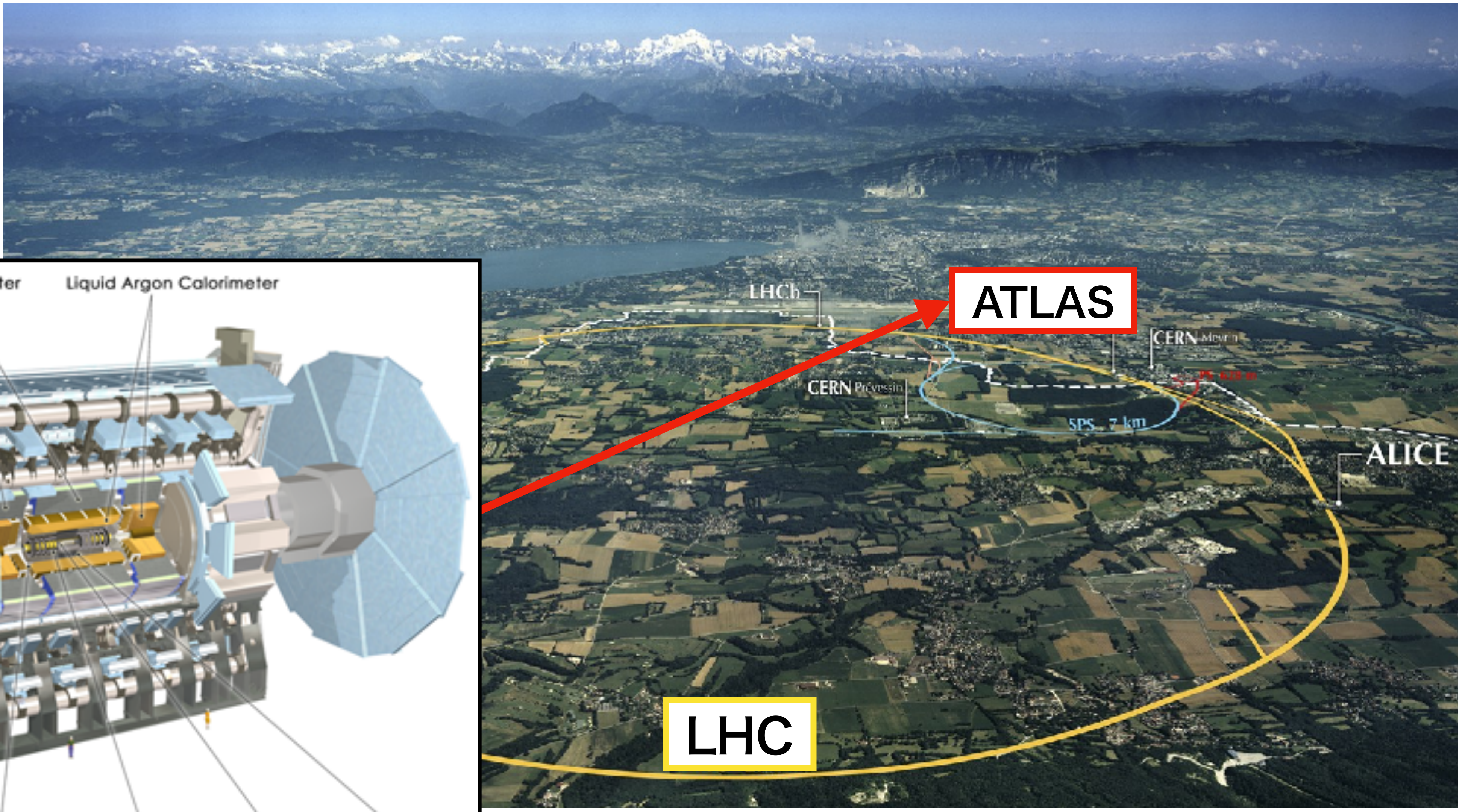


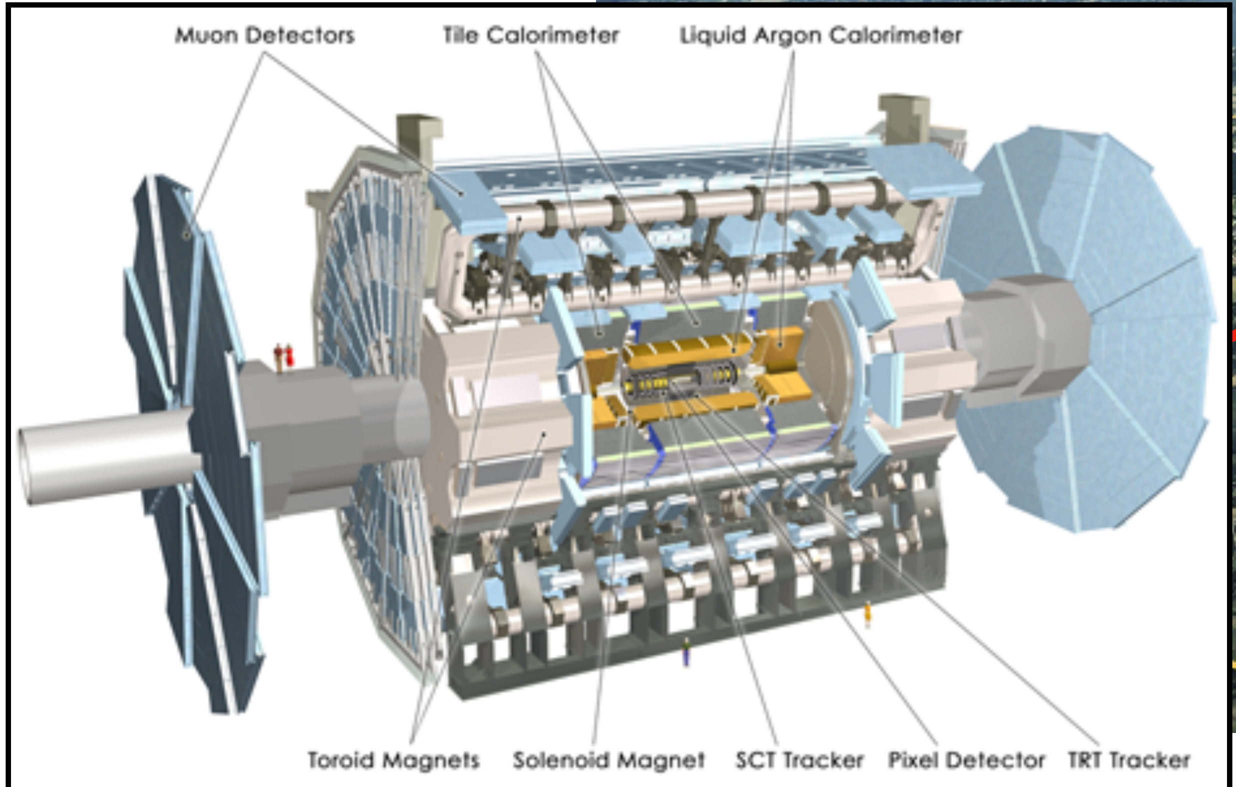


[PLA373 (2008) 39-44]

LHC and ATLAS detector

- LHC-ATLAS experiment
  - Experiment for discovery of new particles and new physics
  - Planning **the low-luminosity run** this year in addition to usual high luminosity run
    - **The number of p-p collisions when bunches of proton cross (“pile-up”) is about 1** in low-luminosity run.

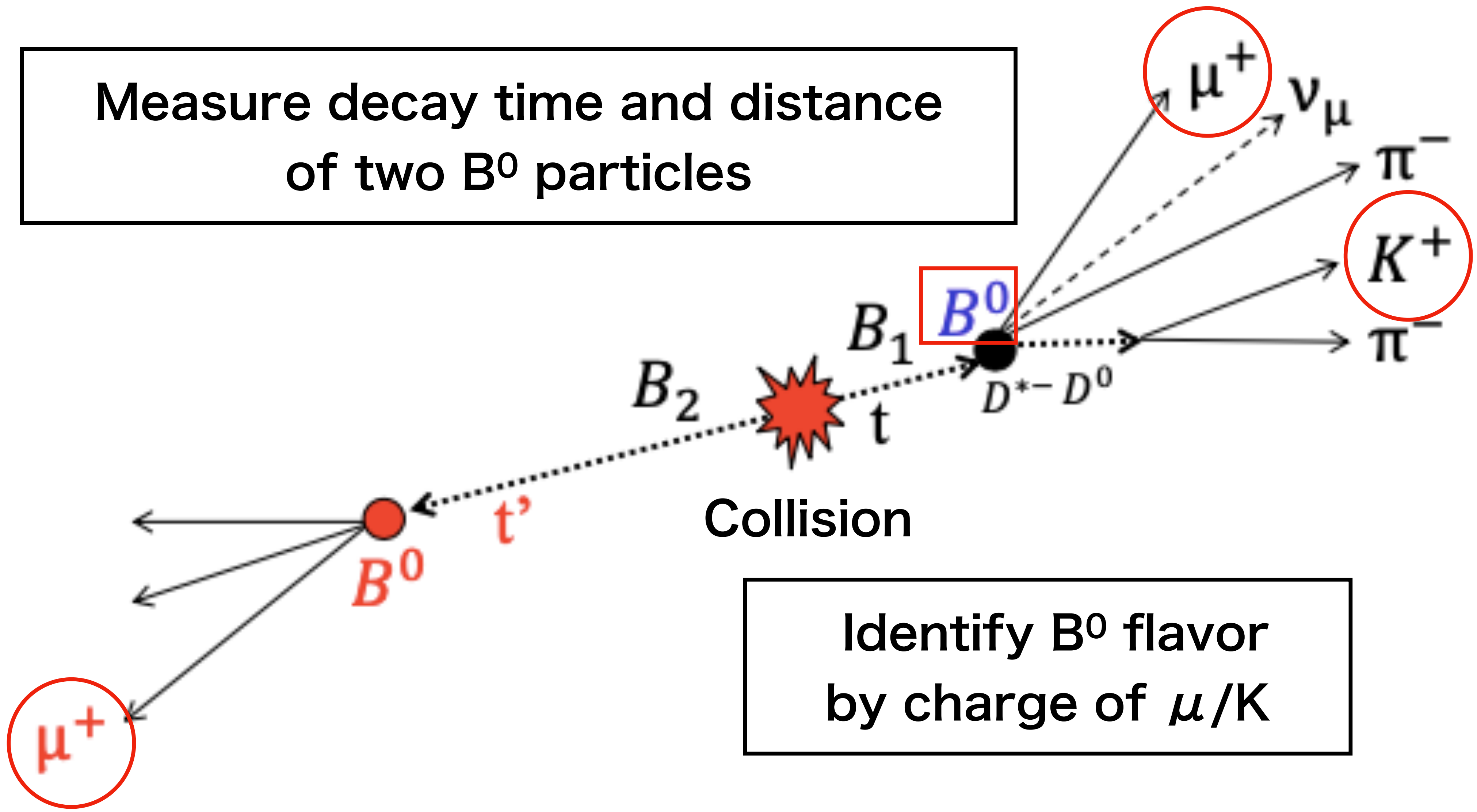




ATLAS detector

Validation of Bell inequality violation

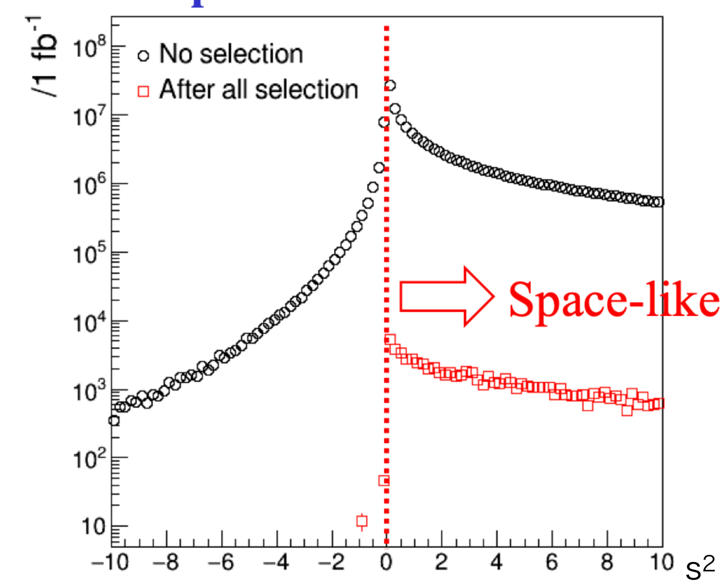
- Validation in LHC-ATLAS experiment
  - Correlation of B^0 flavor in events with gg/qq → bb → B^0B^0, $B^0 \to D^* \mu\ \nu$
    - Measure the decay time, reconstructing vertex with μ and π $(\sigma_t \sim 0.11\ \text{ps})$
    - Identify the flavor of B^0 by the charge sign of μ and K particles in the events
    - Count the events in which two B^0 particles with same(different) flavor is identified



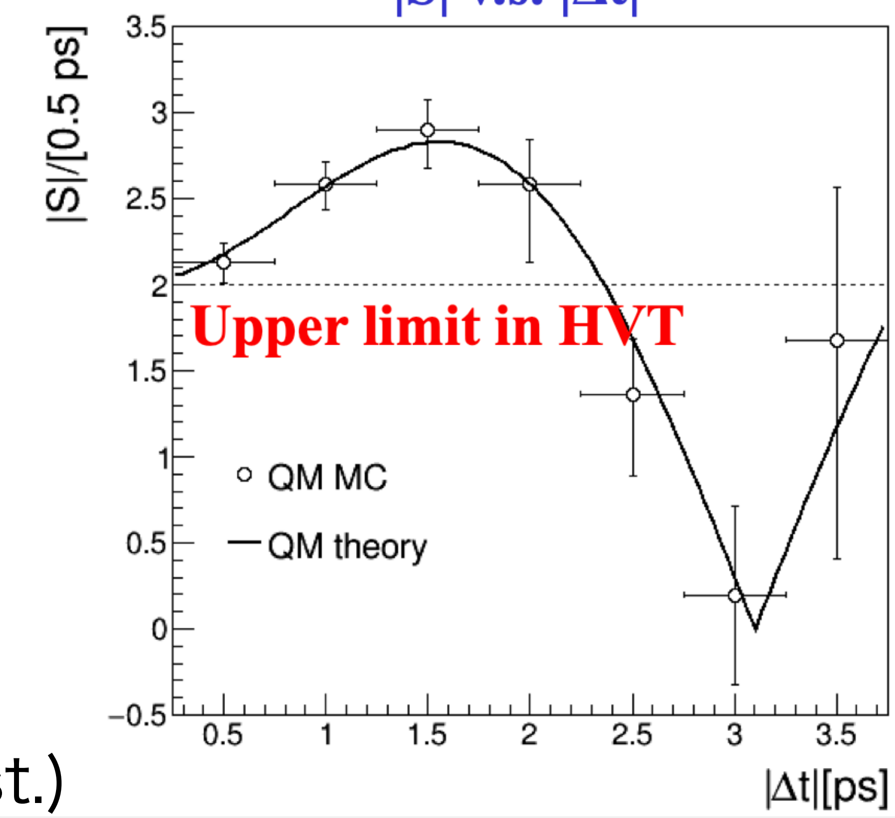
Simulation study in ATLAS

- Simulation in the truth level was performed based on the ATLAS experiment with PYTHIA8.245
- **The low-luminosity ("pile-up"~1) operation** with 1 fb^{-1} of data was assumed for background rejection.
- The sensitivity to Bell inequality violation was evaluated with $B^0\bar{B}^0$ events from "gg/qq→bb"(69 μb) and "gg/qq→ jj" (319 μb).
- Selection criteria used in "D*μX" analysis at ATLAS was assumed. [Nucl. Pays. B 864 (2012) 341-381]
  - "$p_T(\mu)$ > 6 GeV" was modified to "$p_T(\mu)$ > 4 GeV".
    (→ **Development of new muon trigger to get low-p_T μ)**
  - "$p_T(K\pi\pi)$ > 4.5 GeV" was modified to "$p_T(\mu)$ > 3 GeV"

Proper distance distribution



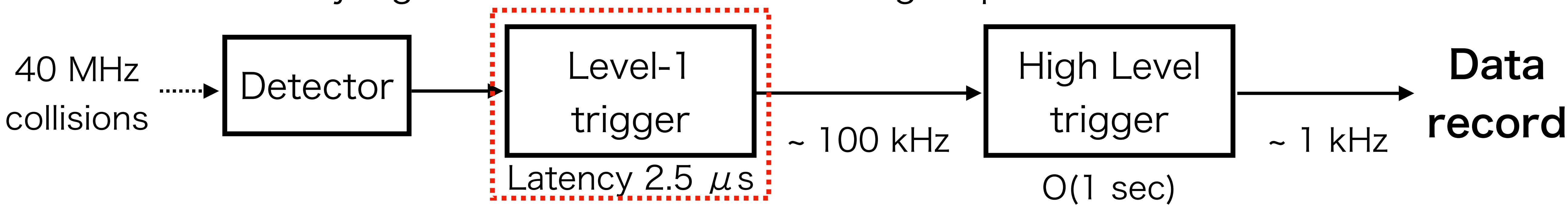
|S| v.s. |Δt|



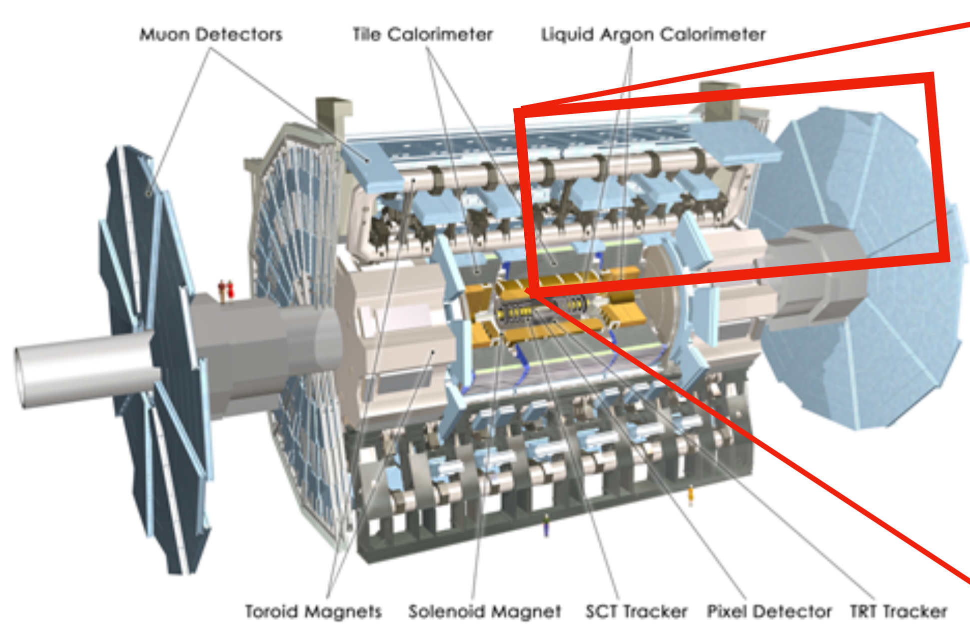
- Results : [Phys.Rev. D 104, 056004]
  - More than 99% B meson pairs are space-like in ATLAS
  - |S(1.5±0.25 ps)| = 2.89 ± 0.17 (stat.) ± -0.13 (syst.)
    - **Deviation from |S| = 2 can be detected with 4.2 σ significance at 1.55 ps.**

Trigger system in ATLAS

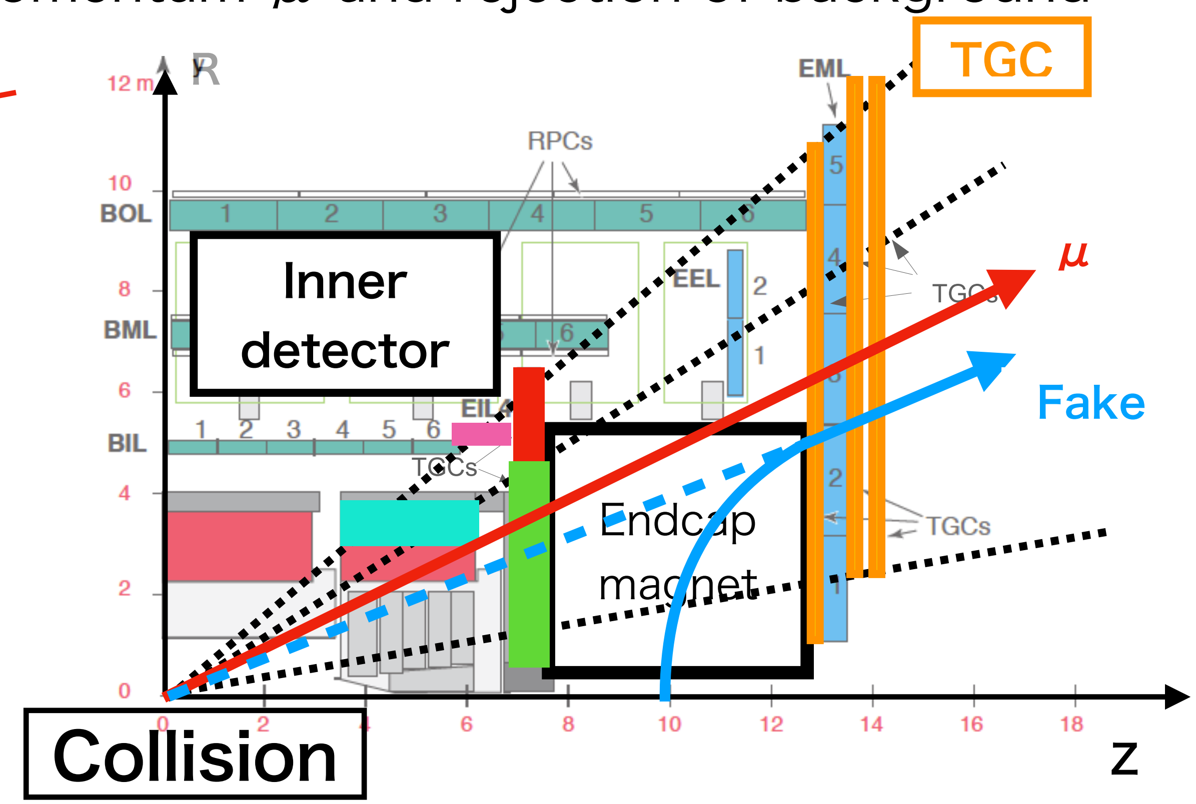
- Structure
  - Frequency of collision is 40 MHz, but maximum rate for data recording is about 1 kHz.
  - Select as many significant events for recording as possible



- Upgrade for LHC Run-3
  - LHC Run-3 will start in June, 2022. We upgraded the muon trigger system.
    - For improvement of sensitivity of low-momentum μ and rejection of background

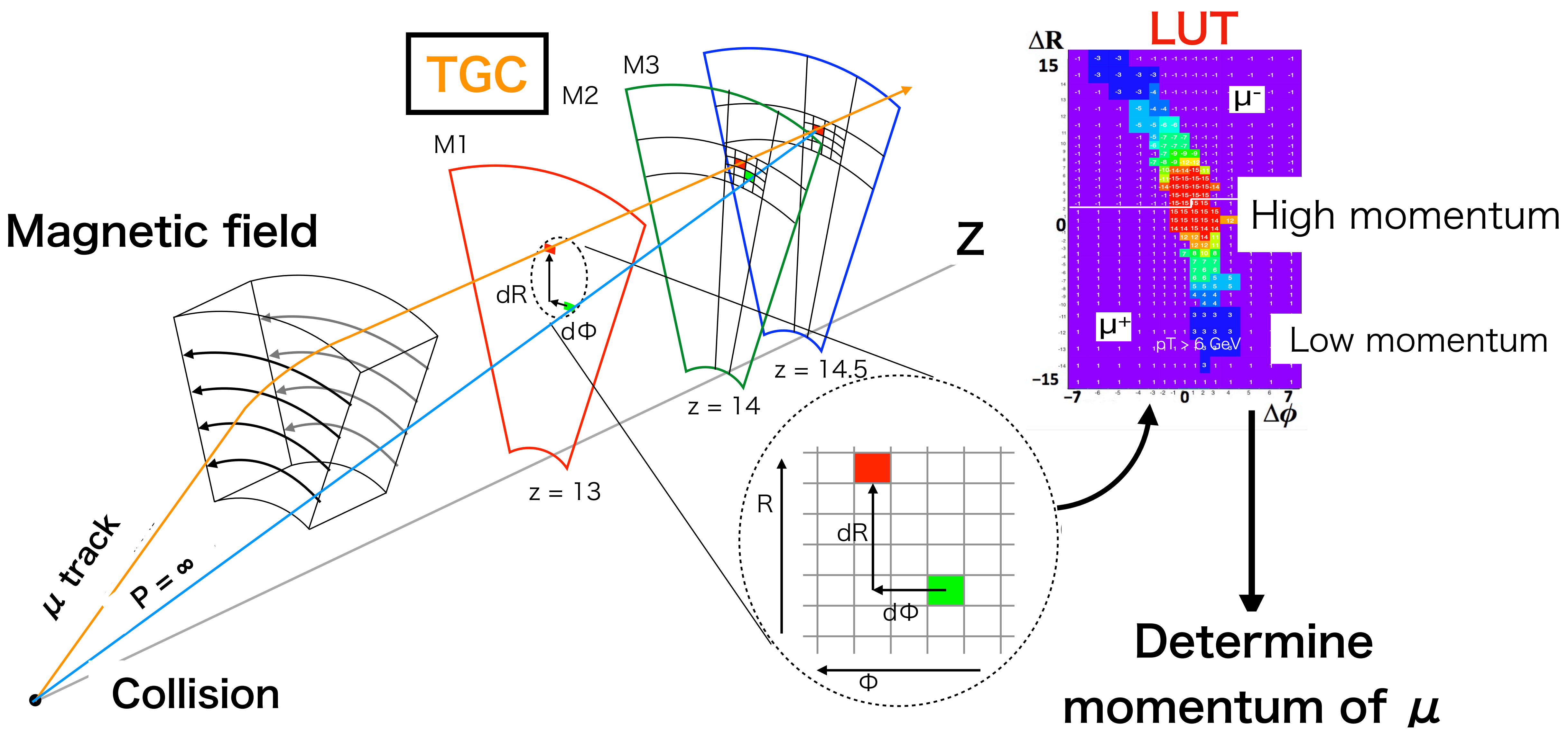


ATLAS detector



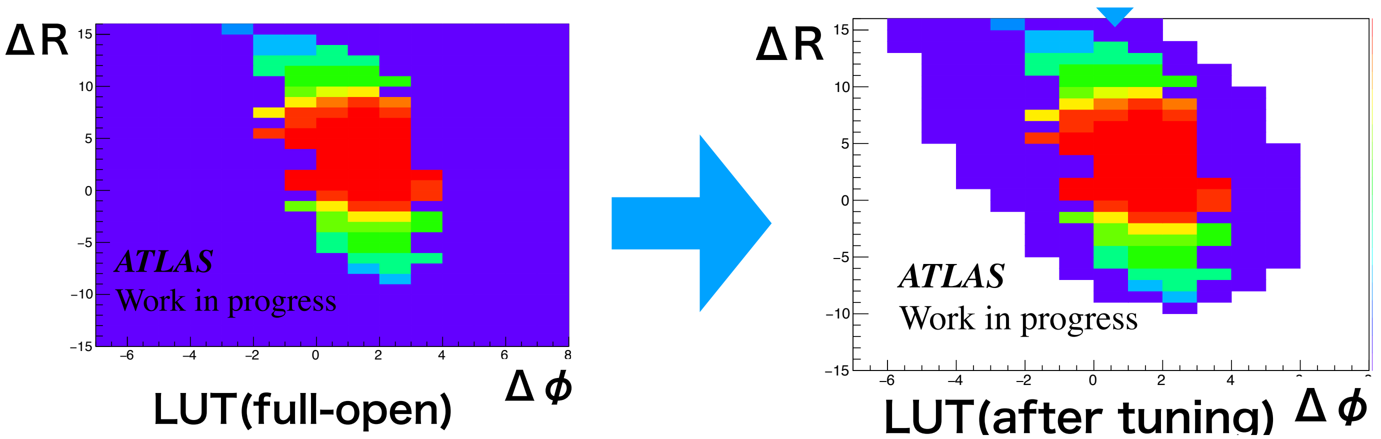
Muon trigger decision with TGC detector

- Identification of muon candidate with transverse momentum (p_T)
  - Using deference of hit position (ΔR:$\Delta \phi$) between three stations
  - Defined by hit maps generated by simulation samples
    - Setting 15 thresholds using predefined look-up tables (LUT)

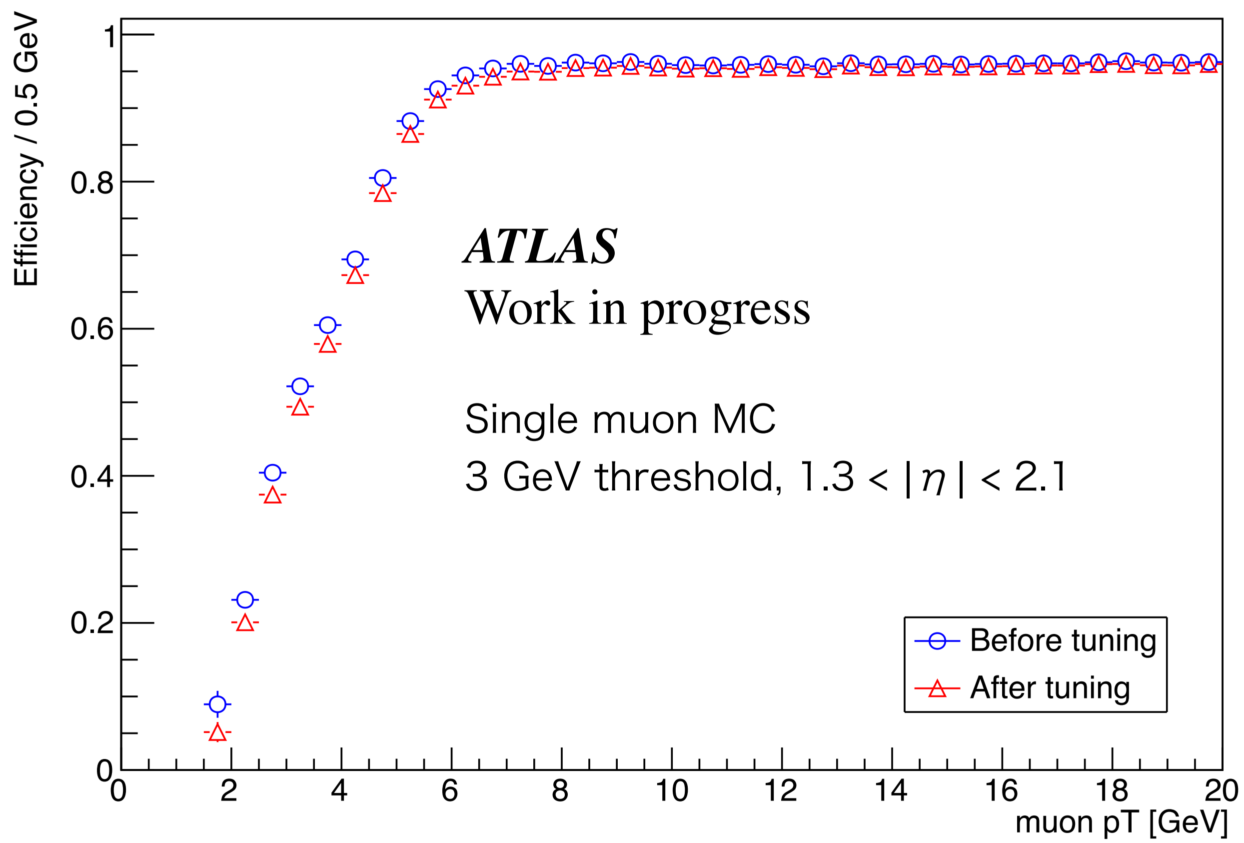


Development of low-p_T muon trigger

- Tuning of look-up tables for background rejection
  - Restrict the “full-open” area of look-up tables



- Expected performance for trigger with p_T > 3 GeV threshold
  - Evaluated with MC samples and Run-2 data.
  - **50% reduction of “fake-muon”-oriented events** in the endcap region (|η|>1)
  - **~ 30% trigger rate reduction** expected for 3GeV threshold (in whole region)
  - High efficiency in the plateau



Trigger efficiency of 3 GeV threshold

Summary & conclusions

- Bell inequality provides upper limit of correlation between two particles that HVT should satisfy.
- Entangled state with two meson flavors in QM violates Bell inequality.
- The previous experiments on meson flavor entanglement were inconclusive for Bell inequality violation
  - Only with Δt measurement without satisfying the locality condition
- Simulation study concluded that Bell test on B meson flavor is possible at the ATLAS experiment.
  - Bell inequality violation can be tested with **4.2 σ precision**.
- We organized analysis group in ATLAS and aim the measurement during Run-3(2022-24)
- We developed and evaluated the new low-p_T muon trigger in Run-3
  - **~ 30% trigger rate reduction** expected for 3 GeV threshold in whole region
  - High efficiency in the plateau

Back up slides

Q&A in Bell test with meson flavor

Q1 |S| has the maximum value at 1.55 ps. Is the oscillation frequency is too long with respect to lifetime of B_d^0 (1.5 ps)?

A1 No problem since $C^Q(t_a, t_b)$ is normalized by # of events at (t_a, t_b).

Q2 HVT assumes free will of experimenter in a measurement but decay of B_d^0 is determined by nature. Can it be assumed as free will?

A2 We assumed that B_d^0 decay randomly and it corresponds to free will of the particle. Also in Aspect experiment, a random generator is used to operate the detector and it is assumed as free will.

Possible loophole in Bell test

- Free will loophole

  This study is assumed that the decay of a particle happened randomly with particle's will.

- Efficiency loophole

  About 82.8% ($2\sqrt{2} - 2$) of efficiency is necessary to close the efficiency loophole. Since the efficiency in this study is only 2%, fair sampling assumption is assumed.

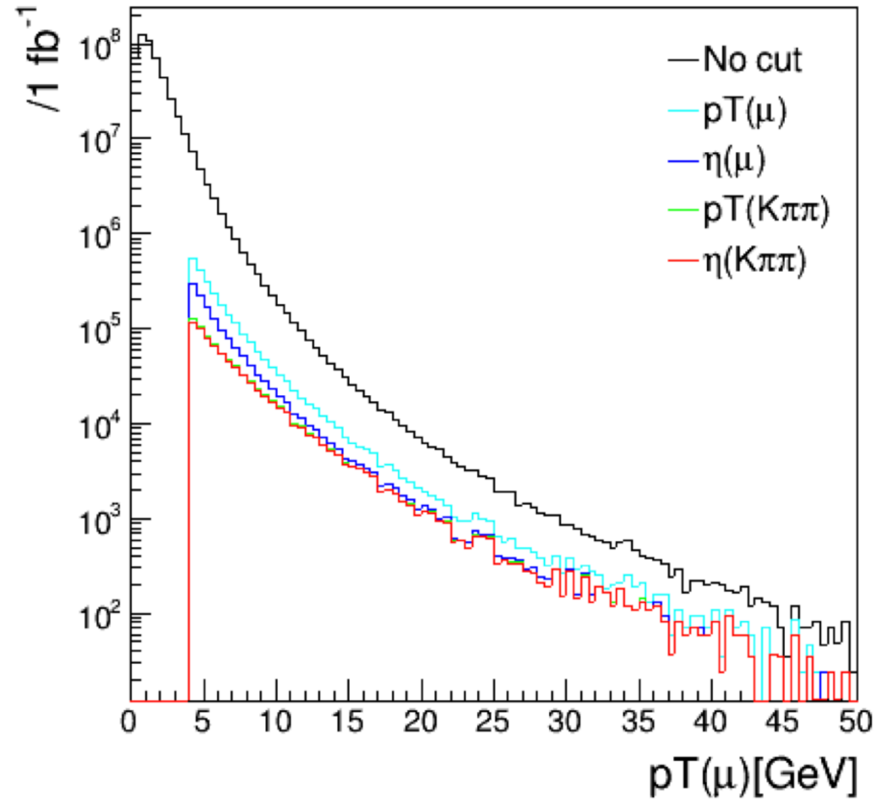
- Locality loophole

  2 particles decay randomly and they are space-like, therefore, locality loop hole is closed successfully.

Acceptance cut of simulation study

- Selection criteria used in 「$D^{*+}\mu^{-}X$」 analysis at ATLAS was assumed [Nucl. Phys. B 864 (2012) 341-381].
- 「pT(μ)>6 GeV」 was modified to 「> 4 GeV」
- 「pT($K^{\pm}\pi^{\mp}\pi^{\mp}$) > 4.5 GeV」 was modified to 「>3 GeV」

μ-pT distribution in 「$B^0 \to D^{*-}\mu^+\nu$」



Cut	Total acceptance (A)	$\sigma \times A$ (pb)
No cut	1.0	247,611
pT(μ) > 4 GeV	5.03×10^{-3}	1,246
$\|\eta(\mu)\| < 2.4$	2.79×10^{-3}	690
pT($K^{\pm}\pi^{\mp}\pi^{\mp}$) > 3 GeV	1.56×10^{-3}	385
$\|\eta(K^{-}\pi^{+}\pi^{+})\| < 2.5$	1.49×10^{-3}	369

Event selection of simulation study

	Efficiency	Comment
Track reconstruction (ε_{reco})	0.483	From「$D^{*+}\mu^{-}X$」analysis
Trigger ($\varepsilon_{trigger}$)	0.429	$(0.819 \times 0.8)^2$ was assumed. • 0.819 is efficiency for single-μ trigger with pT>6GeV.

Selection criteria ($\varepsilon_{selection}$)	Total eff.	Comment
pT > 1 GeV for π^+/K^- in D^0 candidates	0.510	
pT > 250 MeV for π^+ from D^{*+}	0.452	
• $\lvert m(K^-\pi^+) - m(D^0)\rvert < 64$ MeV (pT($K^-\pi^+\pi^+$) > 12 GeV, $\lvert\eta(K^-\pi^+\pi^+)\rvert > 1.3$) • $\lvert m(K^-\pi^+) - m(D^0)\rvert < 40$ MeV elsewhere	0.209	Assume σ^2 cut (0.46)
2.5 GeV < $m(D^{*+}\mu^-)$ < 5.4 GeV	0.097	Assume σ^2 cut (0.46)

$$\varepsilon_{total}\ (\varepsilon_{reco} \times \varepsilon_{trigger} \times \varepsilon_{selection}) = 0.020$$

$(\sigma \times A) \times \varepsilon_{total} \times L(pb^{-1}) = 7.4L(pb^{-1})$ events → 7.4k events with 1fb^{-1}.

Background & systematic errors

Background

- Contamination of $B^0\bar{B}^0$ originated from different gluons is less than 0.1% (negligible)
- BG contamination in 「$D^{*+}\mu^-$X」 analysis was 「6.8±0.26%」, which is taken into account in this study.
  - 6.2% is combinatorial BG (e.g.:「c → D^{*+}X」 and 「$\bar{c}$ → μ^-X'」)

Systematic errors on |S|

- BG contamination
  - Shifting the entries in one Δt bin by 0.26%, the maximum shift in |S| was adopted as the systematic error of BG contamination (most conservative evaluation).
  - BG should be smaller for μ~1 since 「$D^{*+}\mu^-$X」 analysis used data with μ>2.
- Δt resolution
  - Evaluated by fluctuating Δt with the resolution ($0.11\sqrt{2}$ps) 1000 times.