

# Semiparametric robust mean estimations based on the orderliness of quantile averages

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## Weighted Inequalities and Binomial Mean

Analogous to the  $\gamma$ -orderliness, the  $\gamma$ -trimming inequality for a right-skewed distribution is defined as  $\forall 0 \leq \epsilon_1 \leq \epsilon_2 \leq \frac{1}{1+\gamma}$ ,  $TM_{\epsilon_1, \gamma} \geq TM_{\epsilon_2, \gamma}$ .  $\gamma$ -orderliness is a sufficient condition for the  $\gamma$ -trimming inequality, as proven in the SI Text. The next theorem shows a relation between the  $\epsilon, \gamma$ -quantile average and the  $\epsilon, \gamma$ -trimmed mean under the  $\gamma$ -trimming inequality, suggesting the  $\gamma$ -orderliness is not a necessary condition for the  $\gamma$ -trimming inequality.

**Theorem .1.** *For a distribution that is right-skewed and follows the  $\gamma$ -trimming inequality, it is asymptotically true that the quantile average is always greater or equal to the corresponding trimmed mean with the same  $\epsilon$  and  $\gamma$ , for all  $0 \leq \epsilon \leq \frac{1}{1+\gamma}$ .*

*Proof.* According to the definition of the  $\gamma$ -trimming inequality:  $\forall 0 \leq \epsilon \leq \frac{1}{1+\gamma}$ ,  $\frac{1}{1-\epsilon-\gamma\epsilon} \int_{\gamma\epsilon}^{1-\epsilon+\delta} Q(u) du \geq \frac{1}{1-\epsilon-\gamma\epsilon} \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du$ , where  $\delta$  is an infinitesimal positive quantity. Subsequently, rewriting the inequality gives  $\int_{\gamma\epsilon}^{1-\epsilon+\delta} Q(u) du - \frac{1-\epsilon-\gamma\epsilon+2\delta}{1-\epsilon-\gamma\epsilon} \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du \geq 0 \Leftrightarrow \int_{1-\epsilon}^{1-\epsilon+\delta} Q(u) du + \int_{\gamma\epsilon}^{\gamma\epsilon} Q(u) du - \frac{2\delta}{1-\epsilon-\gamma\epsilon} \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du \geq 0$ . Since  $\delta \rightarrow 0^+$ ,  $\frac{1}{2\delta} \left( \int_{1-\epsilon}^{1-\epsilon+\delta} Q(u) du + \int_{\gamma\epsilon}^{\gamma\epsilon} Q(u) du \right) = \frac{Q(\gamma\epsilon)+Q(1-\epsilon)}{2} \geq \frac{1}{1-\epsilon-\gamma\epsilon} \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du$ , the proof is complete.  $\square$

An analogous result about the relation between the  $\epsilon, \gamma$ -trimmed mean and the  $\epsilon, \gamma$ -Winsorized mean can be obtained in the following theorem.

**Theorem .2.** *For a right-skewed distribution following the  $\gamma$ -trimming inequality, asymptotically, the Winsorized mean is always greater or equal to the corresponding trimmed mean with the same  $\epsilon$  and  $\gamma$ , for all  $0 \leq \epsilon \leq \frac{1}{1+\gamma}$ , provided that  $0 \leq \gamma \leq 1$ . If assuming  $\gamma$ -orderliness, the inequality is valid for any non-negative  $\gamma$ .*

*Proof.* According to Theorem .1,  $\frac{Q(\gamma\epsilon)+Q(1-\epsilon)}{2} \geq \frac{1}{1-\epsilon-\gamma\epsilon} \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du \Leftrightarrow \gamma\epsilon(Q(\gamma\epsilon)+Q(1-\epsilon)) \geq \left( \frac{2\gamma\epsilon}{1-\epsilon-\gamma\epsilon} \right) \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du$ . Then, if  $0 \leq \gamma \leq 1$ ,  $1, \left( 1 - \frac{1}{1-\epsilon-\gamma\epsilon} \right) \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du + \gamma\epsilon(Q(\gamma\epsilon)+Q(1-\epsilon)) \geq 0 \Rightarrow \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du + \gamma\epsilon Q(\gamma\epsilon) + \epsilon Q(1-\epsilon) \geq \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du + \gamma\epsilon(Q(\gamma\epsilon)+Q(1-\epsilon)) \geq \frac{1}{1-\epsilon-\gamma\epsilon} \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du$ , the proof of the first assertion is complete. The second assertion is established in Theorem 0.3. in the SI Text.  $\square$

Replacing the TM in the  $\gamma$ -trimming inequality with WA forms the definition of the  $\gamma$ -weighted inequality. The  $\gamma$ -orderliness also implies the  $\gamma$ -Winsorization inequality when  $0 \leq \gamma \leq 1$ , as proven in the SI Text. The same rationale as presented in Theorem ??, for a location-scale distribution characterized by a location parameter  $\mu$  and a scale parameter  $\lambda$ , asymptotically, any  $WA(\epsilon, \gamma)$  can be expressed as  $\lambda WA_0(\epsilon, \gamma) + \mu$ , where  $WA_0(\epsilon, \gamma)$  is a function of  $Q_0(p)$  according to the definition of the weighted average. Adhering to the rationale present in Theorem ??, for any probability distribution within a location-scale family, a necessary and sufficient condition for whether it follows the  $\gamma$ -weighted inequality is whether the family of probability distributions also adheres to the  $\gamma$ -weighted inequality.

To construct weighted averages based on the  $\nu$ th  $\gamma$ -orderliness and satisfying the corresponding weighted inequality, when  $0 \leq \gamma \leq 1$ , let  $\mathcal{B}_i = \int_{i\epsilon}^{(i+1)\epsilon} QA(u, \gamma) du$ ,  $ka = k\epsilon + c$ . From the  $\gamma$ -orderliness for a right-skewed distribution, it follows that,  $-\frac{\partial QA}{\partial \epsilon} \geq 0 \Leftrightarrow \forall 0 \leq a \leq 2a \leq \frac{1}{1+\gamma}$ ,  $-\frac{(QA(2a, \gamma) - QA(a, \gamma))}{a} \geq 0 \Rightarrow \mathcal{B}_i - \mathcal{B}_{i+1} \geq 0$ , if  $0 \leq \gamma \leq 1$ . Suppose that  $\mathcal{B}_i = \mathcal{B}_0$ . Then, the  $\epsilon, \gamma$ -block Winsorized mean, is defined as

$$BWM_{\epsilon, \gamma, n} := \frac{1}{n} \left( \sum_{i=n\gamma\epsilon+1}^{(1-\epsilon)n} X_i + \sum_{i=n\gamma\epsilon+1}^{2n\gamma\epsilon+1} X_i + \sum_{i=(1-2\epsilon)n}^{(1-\epsilon)n} X_i \right),$$

which is double weighting the leftest and rightest blocks having sizes of  $\gamma\epsilon n$  and  $\epsilon n$ , respectively. As a consequence of  $\mathcal{B}_i - \mathcal{B}_{i+1} \geq 0$ , the  $\gamma$ -block Winsorization inequality is valid, provided that  $0 \leq \gamma \leq 1$ . The block Winsorized mean uses two blocks to replace the trimmed parts, not two single quantiles. The subsequent theorem provides an explanation for this difference.

**Theorem .3.** *Asymptotically, for a right-skewed distribution following the  $\gamma$ -orderliness, the Winsorized mean is always greater than or equal to the corresponding block Winsorized mean with the same  $\epsilon$  and  $\gamma$ , for all  $0 \leq \epsilon \leq \frac{1}{1+\gamma}$ , provided that  $0 \leq \gamma \leq 1$ .*

*Proof.* From the definitions of BWM and WM, the statement necessitates  $\int_{\gamma\epsilon}^{1-\epsilon} Q(u) du + \gamma\epsilon Q(\gamma\epsilon) + \epsilon Q(1-\epsilon) \geq \int_{\gamma\epsilon}^{1-\epsilon} Q(u) du + \int_{\gamma\epsilon}^{2\gamma\epsilon} Q(u) du + \int_{1-2\epsilon}^{1-\epsilon} Q(u) du \Leftrightarrow \gamma\epsilon Q(\gamma\epsilon) + \epsilon Q(1-\epsilon) \geq \int_{\gamma\epsilon}^{2\gamma\epsilon} Q(u) du + \int_{1-2\epsilon}^{1-\epsilon} Q(u) du$ . Define  $WML(x) = Q(\gamma\epsilon)$  and  $BWML(x) = Q(x)$ . In both functions, the interval for  $x$  is specified as  $[\gamma\epsilon, 2\gamma\epsilon]$ . Then, define  $WMu(y) = Q(1-\epsilon)$  and  $BWMu(y) = Q(y)$ . In both

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functions, the interval for  $y$  is specified as  $[1 - 2\epsilon, 1 - \epsilon]$ . The function  $y : [\gamma\epsilon, 2\gamma\epsilon] \rightarrow [1 - 2\epsilon, 1 - \epsilon]$  defined by  $y(x) = 1 - \frac{x}{\gamma}$  is a bijection.  $WML(x) + WMu(y(x)) = Q(\gamma\epsilon) + Q(1 - \epsilon) \geq BWML(x) + BWMu(y(x)) = Q(x) + Q(1 - \frac{x}{\gamma})$  is valid for all  $x \in [\gamma\epsilon, 2\gamma\epsilon]$ , according to the definition of  $\gamma$ -orderliness. Integration of the left side yields,  $\int_{\gamma\epsilon}^{2\gamma\epsilon} (WML(u) + WMu(y(u))) du = \int_{\gamma\epsilon}^{2\gamma\epsilon} Q(\gamma\epsilon) du + \int_{\gamma\epsilon}^{2\gamma\epsilon} Q(1 - \epsilon) du = \int_{\gamma\epsilon}^{2\gamma\epsilon} Q(\gamma\epsilon) du + \int_{1-2\epsilon}^{1-\epsilon} Q(1 - \epsilon) du = \gamma\epsilon Q(\gamma\epsilon) + \epsilon Q(1 - \epsilon)$ , while integration of the right side yields  $\int_{\gamma\epsilon}^{2\gamma\epsilon} (BWML(x) + BWMu(y(x))) dx = \int_{\gamma\epsilon}^{2\gamma\epsilon} Q(u) du + \int_{\gamma\epsilon}^{2\gamma\epsilon} Q(1 - \frac{x}{\gamma}) dx = \int_{\gamma\epsilon}^{2\gamma\epsilon} Q(u) du + \int_{1-2\epsilon}^{1-\epsilon} Q(u) du$ , which are the left and right sides of the desired inequality. Given that the upper limits and lower limits of the integrations are different for each term, the condition  $0 \leq \gamma \leq 1$  is necessary for the desired inequality to be valid.

## Hodges–Lehmann inequality and $\gamma$ - $U$ -orderliness

The Hodges–Lehmann estimator stands out as a unique robust location estimator due to its definition being substantially dissimilar from conventional  $L$ -estimators,  $R$ -estimators, and  $M$ -estimators. In their landmark paper, *Estimates of location based on rank tests*, Hodges and Lehmann (1) proposed two methods for computing the H-L estimator: the Wilcoxon score  $R$ -estimator and the median of pairwise means. The Wilcoxon score  $R$ -estimator is a location estimator based on signed-rank test, or  $R$ -estimator, (1) and was later independently discovered by Sen (1963) (2, 3). However, the median of pairwise means is a generalized  $L$ -statistic and a trimmed  $U$ -statistic, as classified by Serfling in his novel conceptualized study in 1984 (4). Serfling further advanced the understanding by generalizing the H-L kernel as  $hl_k(x_1, \dots, x_k) = \frac{1}{k} \sum_{i=1}^k x_i$ , where  $k \in \mathbb{N}$  (4). Here, the weighted H-L kernel is defined as  $whl_k(x_1, \dots, x_k) = \frac{\sum_{i=1}^k x_i w_i}{\sum_{i=1}^k w_i}$ , where  $w_i$ s are the weights applied to each element.

By using the weighted H-L kernel and the  $L$ -estimator, it is now clear that the Hodges–Lehmann estimator is an  $LL$ -statistic, the definition of which is provided as follows:

$$LL_{k,\epsilon,\gamma,n} := L_{\epsilon_0,\gamma,n} \left( \text{sort} \left( (whl_k(X_{N_1}, \dots, X_{N_k}))_{N=1}^{\binom{n}{k}} \right) \right),$$

where  $L_{\epsilon_0,\gamma,n}(Y)$  represents the  $\epsilon_0, \gamma$ - $L$ -estimator that uses the sorted sequence,  $\text{sort} \left( (whl_k(X_{N_1}, \dots, X_{N_k}))_{N=1}^{\binom{n}{k}} \right)$ , as input. The upper asymptotic breakdown point of  $LL_{k,\epsilon,\gamma}$  is  $\epsilon = 1 - (1 - \epsilon_0)^{\frac{1}{k}}$ , as proven in DSSM II. There are two ways to adjust the breakdown point: either by setting  $k$  as a constant and adjusting  $\epsilon_0$ , or by setting  $\epsilon_0$  as a constant and adjusting  $k$ . In the above definition,  $k$  is discrete, but the bootstrap method can be applied to ensure the continuity of  $k$ , also making the breakdown point continuous. Specifically, if  $k \in \mathbb{R}$ , let the bootstrap size be denoted by  $b$ , then first sampling the original sample  $(1 - k + \lceil k \rceil)b$  times with each sample size of  $\lceil k \rceil$ , and then subsequently sampling  $(1 - \lceil k \rceil + k)b$  times with each sample size of  $\lceil k \rceil$ ,  $(1 - k + \lceil k \rceil)b \in \mathbb{N}$ ,  $(1 - \lceil k \rceil + k)b \in \mathbb{N}$ . The corresponding kernels are computed separately, and the pooled sorted sequence is used as the input for the  $L$ -estimator. Let  $\mathbf{S}_k$  represent the sorted sequence. Indeed, for any finite sample,  $X$ , when  $k = n$ ,  $\mathbf{S}_k$  becomes a single point,

$whl_{k=n}(X_1, \dots, X_n)$ . When  $w_i = 1$ , the minimum of  $\mathbf{S}_k$  is  $\frac{1}{k} \sum_{i=1}^k X_i$ , due to the property of order statistics. The maximum of  $\mathbf{S}_k$  is  $\frac{1}{k} \sum_{i=1}^k X_{n-i+1}$ . The monotonicity of the order statistics implies the monotonicity of the extrema with respect to  $k$ , i.e., the support of  $\mathbf{S}_k$  shrinks monotonically. For unequal  $w_i$ s, the shrinkage of the support of  $\mathbf{S}_k$  might not be strictly monotonic, but the general trend remains, since all  $LL$ -statistics converge to the same point, as  $k \rightarrow n$ . Therefore, if  $\sum_{i=1}^n \frac{X_i w_i}{w_i}$  approaches the population mean when  $n \rightarrow \infty$ , all  $LL$ -statistics based on such consistent kernel function approach the population mean as  $k \rightarrow \infty$ . For example, if  $whl_k = BM_{\nu,\epsilon_k,n=k}$ ,  $\nu \ll \epsilon_k^{-1}$ ,  $\epsilon_k \rightarrow 0$ , such kernel function is consistent. These cases are termed the  $LL$ -mean ( $LLM_{k,\epsilon,\gamma,n}$ ). By substituting the  $WA_{\epsilon_0,\gamma,n}$  for the  $L_{\epsilon_0,\gamma,n}$  in  $LL$ -statistic, the resulting statistic is referred to as the weighted  $L$ -statistic ( $WL_{k,\epsilon,\gamma,n}$ ). The case having a consistent kernel function is termed as the weighted  $L$ -mean ( $WLM_{k,\epsilon,\gamma,n}$ ). The  $w_i = 1$  case of  $WLM_{k,\epsilon,\gamma,n}$  is termed the weighted Hodges–Lehmann mean ( $WHLM_{k,\epsilon,\gamma,n}$ ). The  $WHLM_{k=1,\epsilon,\gamma,n}$  is the weighted average. If  $k \geq 2$  and the  $WA$  in  $WHLM$  is set as  $TM_{\epsilon_0}$ , it is called the trimmed H-L mean (Figure ??,  $k = 2$ ,  $\epsilon_0 = \frac{15}{64}$ ). The  $THLM_{k=2,\epsilon,\gamma=1,n}$  appears similar to the Wilcoxon's one-sample statistic investigated by Saleh in 1976 (5), which involves first censoring the sample, and then computing the mean of the number of events that the pairwise mean is greater than zero. The  $THLM_{k=2,\epsilon=1-(1-\frac{1}{2})^{\frac{1}{2}},\gamma=1,n}$  is the Hodges–Lehmann estimator, or more generally, a special case of the median Hodges–Lehmann mean ( $mHLM_{k,n}$ ).  $mHLM_{k,n}$  is asymptotically equivalent to the  $MoM_{k,b=\frac{n}{k}}$  as discussed previously. Therefore, it is possible to define a series of location estimators, analogous to the  $WHLM$ , based on  $MoM$ . For example, the  $\gamma$ -median of means,  $\gamma moM_{k,b=\frac{n}{k},n}$ , is defined by replacing the median in  $MoM_{k,b=\frac{n}{k},n}$  with the  $\gamma$ -median.

The  $hl_k$  kernel distribution, denoted as  $F_{hl_k}$ , can be defined as the probability distribution of the sorted sequence  $\text{sort} \left( (hl_k(X_{N_1}, \dots, X_{N_k}))_{N=1}^{\binom{n}{k}} \right)$ . For any real value  $y$ , the cdf of the  $hl_k$  kernel distribution is given by:  $F_{h_k}(y) = \Pr(Y_i \leq y)$ , where  $Y_i$  represents an individual element from the sorted sequence. The overall  $hl_k$  kernel distributions possess a two-dimensional structure, encompassing  $n$  kernel distributions with varying  $k$  values, from 1 to  $n$ , where one dimension is inherent to each individual kernel distribution, while the other is formed by the alignment of the same percentiles across all kernel distributions. As  $k$  increases, all percentiles converge to  $\bar{X}$ , leading to the concept of  $\gamma$ - $U$ -orderliness:

$$(\forall k_2 \geq k_1 \geq 1, \gamma mHLM_{k_2, \epsilon=1-(\frac{\gamma}{1+\gamma})^{\frac{1}{k_2}}, \gamma} \geq \gamma mHLM_{k_1, \epsilon=1-(\frac{\gamma}{1+\gamma})^{\frac{1}{k_1}}, \gamma}) \vee$$

$$(\forall k_2 \geq k_1 \geq 1, \gamma mHLM_{k_2, \epsilon=1-(\frac{\gamma}{1+\gamma})^{\frac{1}{k_2}}, \gamma} \leq \gamma mHLM_{k_1, \epsilon=1-(\frac{\gamma}{1+\gamma})^{\frac{1}{k_1}}, \gamma}),$$

where  $\gamma mHLM_k$  sets the  $WA$  in  $WHLM$  as  $\gamma$ -median, with  $\gamma$  being constant. The direction of the inequality depends on the relative magnitudes of  $\gamma mHLM_{k=1,\epsilon,\gamma} = \gamma m$  and  $\gamma mHLM_{k=\infty,\epsilon,\gamma} = \mu$ . The Hodges–Lehmann inequality can be defined as a special case of the  $\gamma$ - $U$ -orderliness when  $\gamma = 1$ . When  $\gamma \in \{0, \infty\}$ , the  $\gamma$ - $U$ -orderliness is valid for any distribution as previously shown. If  $\gamma \notin \{0, \infty\}$ , analytically proving the validity of the  $\gamma$ - $U$ -orderliness for a parametric distribution is pretty challenging. As an example, the

166  $hl_2$  kernel distribution has a probability density function  
 167  $f_{hl_2}(x) = \int_0^{2x} 2f(t)f(2x-t)dt$  (a result after the transfor-  
 168 mation of variables); the support of the original distribution is  
 169 assumed to be  $[0, \infty)$  for simplicity. The expected value of the  
 170 H-L estimator is the positive solution of  $\int_0^{H-L}(f_{hl_2}(s))ds = \frac{1}{2}$ .  
 171 For the exponential distribution,  $f_{hl_2,exp}(x) = 4\lambda^{-2}xe^{-2\lambda^{-1}x}$ ,  
 172  $\lambda$  is a scale parameter,  $E[H-L] = \frac{-W_{-1}(-\frac{1}{2e})-1}{2}\lambda \approx 0.839\lambda$ ,  
 173 where  $W_{-1}$  is a branch of the Lambert  $W$  function which can-  
 174 not be expressed in terms of elementary functions. However,  
 175 the violation of the  $\gamma$ - $U$ -orderliness is bounded under certain  
 176 assumptions, as shown below.

**Theorem .4.** *For any distribution with a finite second central moment,  $\sigma^2$ , the following concentration bound can be established for the  $\gamma$ -median of means,*

$$\mathbb{P}\left(\gamma \text{moM}_{k,b=\frac{n}{k},n} - \mu > \frac{t\sigma}{\sqrt{k}}\right) \leq e^{-\frac{2n}{k}\left(\frac{1}{1+\gamma} - \frac{1}{k+t^2}\right)^2}.$$

177 *Proof.* Denote the mean of each block as  $\hat{\mu}_i$ ,  $1 \leq i \leq b$ . Ob-  
 178 serve that the event  $\left\{\gamma \text{moM}_{k,b=\frac{n}{k},n} - \mu > \frac{t\sigma}{\sqrt{k}}\right\}$  necessitates  
 179 the condition that there are at least  $b(1 - \frac{\gamma}{1+\gamma})$  of  $\hat{\mu}_i$ s larger  
 180 than  $\mu$  by more than  $\frac{t\sigma}{\sqrt{k}}$ , i.e.,  $\left\{\gamma \text{moM}_{k,b=\frac{n}{k},n} - \mu > \frac{t\sigma}{\sqrt{k}}\right\} \subset$   
 181  $\left\{\sum_{i=1}^b \mathbf{1}_{(\hat{\mu}_i - \mu) > \frac{t\sigma}{\sqrt{k}}} \geq b(1 - \frac{\gamma}{1+\gamma})\right\}$ , where  $\mathbf{1}_A$  is the indica-  
 182 tor of event  $A$ . Assuming a finite second central moment,  
 183  $\sigma^2$ , it follows from one-sided Chebeshev's inequality that  
 184  $\mathbb{E}\left(\mathbf{1}_{(\hat{\mu}_i - \mu) > \frac{t\sigma}{\sqrt{k}}}\right) = \mathbb{P}\left((\hat{\mu}_i - \mu) > \frac{t\sigma}{\sqrt{k}}\right) \leq \frac{\sigma^2}{k\sigma^2 + t^2\sigma^2}.$

185 Given that  $\mathbf{1}_{(\hat{\mu}_i - \mu) > \frac{t\sigma}{\sqrt{k}}} \in [0, 1]$  are independent  
 186 and identically distributed random variables, accord-  
 187 ing to the aforementioned inclusion relation, the one-  
 188 sided Chebeshev's inequality and the one-sided Ho-  
 189 effding's inequality,  $\mathbb{P}\left(\gamma \text{moM}_{k,b=\frac{n}{k},n} - \mu > \frac{t\sigma}{\sqrt{k}}\right) \leq$   
 190  $\mathbb{P}\left(\sum_{i=1}^b \mathbf{1}_{(\hat{\mu}_i - \mu) > \frac{t\sigma}{\sqrt{k}}} \geq b(1 - \frac{\gamma}{1+\gamma})\right) =$   
 191  $\mathbb{P}\left(\frac{1}{b} \sum_{i=1}^b \left(\mathbf{1}_{(\hat{\mu}_i - \mu) > \frac{t\sigma}{\sqrt{k}}} - \mathbb{E}\left(\mathbf{1}_{(\hat{\mu}_i - \mu) > \frac{t\sigma}{\sqrt{k}}}\right)\right) \geq$   
 192  $\left(1 - \frac{\gamma}{1+\gamma}\right) - \mathbb{E}\left(\mathbf{1}_{(\hat{\mu}_i - \mu) > \frac{t\sigma}{\sqrt{k}}}\right)\right) \leq$   
 193  $e^{-2b\left(\left(1 - \frac{\gamma}{1+\gamma}\right) - \mathbb{E}\left(\mathbf{1}_{(\hat{\mu}_i - \mu) > \frac{t\sigma}{\sqrt{k}}}\right)\right)^2} \leq$   
 194  $e^{-2b\left(1 - \frac{\gamma}{1+\gamma} - \frac{\sigma^2}{k\sigma^2 + t^2\sigma^2}\right)^2} = e^{-2b\left(\frac{1}{1+\gamma} - \frac{1}{k+t^2}\right)^2}. \quad \square$

195 **Theorem .5.** *Let  $B(k, \gamma, t, n) = e^{-\frac{2n}{k}\left(\frac{1}{1+\gamma} - \frac{1}{k+t^2}\right)^2}$ . If*  
 196  *$n \in \mathbb{N}$ ,  $\gamma \geq 0$ ,  $0 \leq t^2 < \gamma + 1$ , and  $\gamma - t^2 + 1 \leq k \leq$*   
 197  *$\frac{1}{2}\sqrt{9\gamma^2 + 18\gamma - 8\gamma t^2 - 8t^2 + 9} + \frac{1}{2}(3\gamma - 2t^2 + 3)$ ,  $B$  is mono-*  
 198 *tonic decreasing with respect to  $k$ .*

199 *Proof.* Since  $\frac{\partial B}{\partial k} = \left(\frac{2n\left(\frac{1}{\gamma+1} - \frac{1}{k+t^2}\right)^2}{k^2} - \frac{4n\left(\frac{1}{\gamma+1} - \frac{1}{k+t^2}\right)}{k(k+t^2)^2}\right)$   
 200  $e^{-\frac{2n\left(\frac{1}{\gamma+1} - \frac{1}{k+t^2}\right)^2}{k}}$  and  $n \in \mathbb{N}$ ,  $\frac{\partial B}{\partial k} \leq 0 \Leftrightarrow$   
 201  $\frac{2n\left(\frac{1}{\gamma+1} - \frac{1}{k+t^2}\right)^2}{k^2} - \frac{4n\left(\frac{1}{\gamma+1} - \frac{1}{k+t^2}\right)}{k(k+t^2)^2} \leq 0 \Leftrightarrow$

$$\frac{2n(-\gamma+k+t^2-1)(k^2-3(\gamma+1)k+2kt^2+t^2(-\gamma+t^2-1))}{(\gamma+1)^2k^2(k+t^2)^3} \leq 0 \Leftrightarrow$$

$$(-\gamma+k+t^2-1)(k^2-3(\gamma+1)k+2kt^2+t^2(-\gamma+t^2-1)) \leq 0.$$

When the factors are expanded, it yields a cubic inequality in terms of  $k$ :  $k^3 + k^2(3t^2 - 4(\gamma + 1)) + 3k(\gamma - t^2 + 1)^2 + t^2(\gamma - t^2 + 1)^2 \leq 0$ . Assuming  $0 \leq t^2 < \gamma + 1$  and  $\gamma \geq 0$ , using the factored form and subsequently applying the quadratic formula, the inequality is valid if  $\gamma - t^2 + 1 \leq k \leq \frac{1}{2}\sqrt{9\gamma^2 + 18\gamma - 8\gamma t^2 - 8t^2 + 9} + \frac{1}{2}(3\gamma - 2t^2 + 3)$ .  $\square$

Let  $X$  be a random variable and  $\bar{Y} = \frac{1}{k}(Y_1 + \dots + Y_k)$  be the average of  $k$  independent, identically distributed copies of  $X$ . Applying the variance operation gives:  $\text{Var}(\bar{Y}) = \text{Var}\left(\frac{1}{k}(Y_1 + \dots + Y_k)\right) = \frac{1}{k^2}(\text{Var}(Y_1) + \dots + \text{Var}(Y_k)) = \frac{1}{k^2}(k\sigma^2) = \frac{\sigma^2}{k}$ , since the variance operation is a linear operator for independent variables, and the variance of a scaled random variable is the square of the scale times the variance of the variable, i.e.,  $\text{Var}(cX) = E[(cX - E[cX])^2] = E[(cX - cE[X])^2] = E[c^2(X - E[X])^2] = c^2E[(X - E[X])^2] = c^2\text{Var}(X)$ . Thus, the standard deviation of the  $hl_k$  kernel distribution, asymptotically, is  $\frac{\sigma}{\sqrt{k}}$ . By utilizing the asymptotic bias bound of any quantile for any continuous distribution with a finite second central moment,  $\sigma^2$ , (6), a conservative asymptotic bias bound of  $\gamma \text{moM}_{k,b=\frac{n}{k}}$  can be estab-

lished as  $\gamma \text{moM}_{k,b=\frac{n}{k}} - \mu \leq \sqrt{\frac{\gamma}{1-\frac{\gamma}{1+\gamma}}} \sigma_{hl_k} = \sqrt{\frac{\gamma}{k}} \sigma$ . That implies in Theorem .4,  $t < \sqrt{\gamma}$ , so when  $\gamma = 1$ , the upper bound of  $k$ , subject to the monotonic decreasing constraint, is  $2 + \sqrt{5} < \frac{1}{2}\sqrt{9 + 18 - 8t^2 - 8t^2 + 9} + \frac{1}{2}(3 - 2t^2 + 3) \leq 6$ , the lower bound is  $1 < 2 - t^2 \leq 2$ . These analyses elucidate a surprising result: although the conservative asymptotic bound of  $\text{MoM}_{k,b=\frac{n}{k}}$  is monotonic with respect to  $k$ , its concentration bound is optimal when  $k \in (2 + \sqrt{5}, 6]$ .

Then consider the structure within each individual  $hl_k$  kernel distribution. The sorted sequence  $\mathbf{S}_k$ , when  $k = n - 1$ , has  $n$  elements and the corresponding  $hl_k$  kernel distribution can be seen as a location-scale transformation of the original distribution, so the corresponding  $hl_k$  kernel distribution is  $\nu$ th  $\gamma$ -ordered if and only if the original distribution is  $\nu$ th  $\gamma$ -ordered according to Theorem ?? . Analytically proving other cases is challenging. For example,  $f'_{hl_2}(x) = 4f(2x)f(0) + \int_0^{2x} 4f(t)f'(2x-t)dt$ , the strict negative of  $f'_{hl_2}(x)$  is not guaranteed if just assuming  $f'(x) < 0$ , so, even if the original distribution is monotonic decreasing, the  $hl_2$  kernel distribution might be non-monotonic. Also, unlike the pairwise difference distribution, if the original distribution is unimodal, the pairwise mean distribution might be non-unimodal, as demonstrated by a counterexample given by Chung in 1953 and mentioned by Hodges and Lehmann in 1954 (7, 8). Theorem ?? implies that the violation of  $\nu$ th  $\gamma$ -orderliness within the  $hl_k$  kernel distribution is also bounded, and the bound monotonically shrinks as  $k$  increases because the bound is in unit of the standard deviation of the  $hl_k$  kernel distribution. If all  $hl_k$  kernel distributions are  $\nu$ th  $\gamma$ -ordered and the distribution itself is  $\nu$ th  $\gamma$ -ordered and  $\gamma$ - $U$ -ordered, then the distribution is called  $\nu$ th  $\gamma$ - $U$ -ordered. The following theorems highlight the significance of  $\gamma$ -symmetric distributions.

**Theorem .6.** *Any  $\gamma$ -symmetric distribution is  $\nu$ th  $\gamma$ - $U$ -ordered, provided that the  $\gamma$  is the same.*

The succeeding theorem shows that the  $whl_k$  kernel distribution is invariably a location-scale distribution if the original distribution belongs to a location-scale family with the same location and scale parameters.

**Theorem .7.**  $whl_k(x_1 = \lambda x_1 + \mu, \dots, x_k = \lambda x_k + \mu) = \lambda whl_k(x_1, \dots, x_k) + \mu$ .

*Proof.*  $whl_k(x_1 = \lambda x_1 + \mu, \dots, x_k = \lambda x_k + \mu) = \frac{\sum_{i=1}^k (\lambda x_i + \mu) w_i}{\sum_{i=1}^k w_i} = \frac{\sum_{i=1}^k \lambda x_i w_i + \sum_{i=1}^k \mu w_i}{\sum_{i=1}^k w_i} = \lambda \frac{\sum_{i=1}^k x_i w_i}{\sum_{i=1}^k w_i} + \frac{\sum_{i=1}^k \mu w_i}{\sum_{i=1}^k w_i} = \lambda \frac{\sum_{i=1}^k x_i w_i}{\sum_{i=1}^k w_i} + \mu = \lambda whl_k(x_1, \dots, x_k) + \mu$ .  $\square$

According to Theorem .7, the  $\gamma$ -weighted inequality for a right-skewed distribution can be modified as  $\forall 0 \leq \epsilon_{01} \leq \epsilon_{02} \leq \frac{1}{1+\gamma}$ ,  $WLM_{k, \epsilon=1-(1-\epsilon_{01})^{\frac{1}{k}, \gamma}} \geq WLM_{k, \epsilon=1-(1-\epsilon_{02})^{\frac{1}{k}, \gamma}}$ , which holds the same rationale as the  $\gamma$ -weighted inequality defined in the last section. If the  $\nu$ th  $\gamma$ -orderliness is valid for the  $whl_k$  kernel distribution, then all results in the last section can be directly implemented. From that, the binomial H-L mean (set the WA as BM) can be constructed (Figure ??), while its maximum breakdown point is  $\approx 0.065$  if  $\nu = 3$ . A comparison of the biases of  $BM_{\nu=3, \epsilon=\frac{1}{8}}$ ,  $SQM_{\epsilon=\frac{1}{8}}$ ,  $THLM_{k=2, \epsilon=\frac{1}{8}}$ ,  $WHLM_{k=2, \epsilon=\frac{1}{8}}$ ,  $MHLM_{k=\frac{2 \ln(2) - \ln(3)}{3 \ln(2) - \ln(7)}, \epsilon=\frac{1}{8}}$  (midhinge H-L mean),  $mHLM_{k=\frac{\ln(2)}{3 \ln(2) - \ln(7)}, \epsilon=\frac{1}{8}}$ ,  $THLM_{k=5, \epsilon=\frac{1}{8}}$ , and  $WHLM_{k=5, \epsilon=\frac{1}{8}}$  is appropriate (Figure ??, SI Dataset S1), given their same breakdown points, with  $mHLM_{k=\frac{\ln(2)}{3 \ln(2) - \ln(7)}, \epsilon=\frac{1}{8}}$  exhibiting the smallest biases. Another comparison among the H-L estimator, the trimmed mean, and the Winsorized mean, all with the same breakdown point, yields the same result that the H-L estimator has the smallest biases (SI Dataset S1). This aligns with Devroye et al.(2016)'s seminal work that MoM is nearly optimal with regards to concentration bounds for heavy-tailed distributions (9).

In 1958, Richtmyer introduced the concept of quasi-Monte Carlo simulation that utilizes low-discrepancy sequences, resulting in a significant reduction in computational expenses for large sample simulation (10). Among various low-discrepancy sequences, Sobol sequences are often favored in quasi-Monte Carlo methods (11). Building upon this principle, in 1991, Do and Hall extended it to bootstrap and found that the quasi-random approach resulted in lower variance compared to other bootstrap Monte Carlo procedures (12). By using a deterministic approach, the variance of  $mHLM_{k,n}$  is much lower than that of  $MoM_{k, b=\frac{n}{k}}$  (SI Dataset S1), when  $k$  is small. This highlights the superiority of the median Hodges-Lehmann mean over the median of means, as it not only can provide an accurate estimate for moderate sample sizes, but also allows the use of quasi-bootstrap, where the bootstrap size can be adjusted as needed.

**Data Availability.** Data for Figure ?? are given in SI Dataset S1. All codes have been deposited in [GitHub](#).

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