Response to reviewers' comments

I thank the reviewers for their generally positive assessment of the paper and for their insightful and detailed comments on the manuscript.

Each point raised in the reports has been addressed individually below. As requested by the Editor, the manuscript has been revised with an emphasis on improving clarity of expression and argumentative precision, rather than on substantive expansion.

Following the journal's guidelines, I have uploaded both a clean version of the manuscript and a version with tracked changes, in which all revisions are clearly indicated. Changes made solely to ensure conformity with the journal's stylistic guidelines have not been marked, in order to avoid unnecessary clutter.

Reviewer 1

Reviewer (1A) — The distinction between predictive and non-predictive measurements is introduced without really specifying what these terms mean precisely. Moreover, near the end of the paper there is also talk of non-prognostic measurements, which seem to mean the same thing as non-predictive, but this is not specified.

Reply: The terms 'non-prognostic' and 'non-predictive' are indeed intended to denote the same notion. The former reflects an early translation choice, corresponding to the German 'nichtprognostisch,' which I inadvertently failed to update consistently in the final version. I have now standardized the terminology throughout the paper, using exclusively 'predictive' and 'non-predictive,' which are clearer and more idiomatic in English.

I have therefore sought to clarify Popper's usage of the terms 'measurement,' 'physical selection,' 'predictive measurement,' and 'non-predictive measurement.' Some confusion may nevertheless arise from the fact that Popper sometimes uses the term 'measurement' to describe, for example, von Weizsäcker 's momentum determination via the Doppler effect. This counts as a 'measurement' insofar as it disturbs the momentum, yet it is 'predictive' in the sense that it can be used as an initial condition. By contrast, Popper proposes to use 'physical selection,' such as a velocity filter that allows only particles with the appropriate momentum to pass through (see also 1B). In modern terms, both procedures would be regarded as functioning as 'preparations'; see the added footnotes q and y. I think that this is an instance Popper's notion of 'selection' does not align with Margenau's notion of 'preparation.' See also 1B.

Reviewer (1B) — The paper argues that both the claims by Jammer and by Margenau "fail to withstand critical scrutiny". In the case of Jammer, I see why this is the case: the chronology does not allow for Popper's thought experiments to have inspired EPR. In Margenau's case, however, it is not completely clear to me why Popper's distinction between physical selections and measurements could not have anticipated Margenau's distinction between preparation and measurement. While it is indeed the case, as the author shows, that there are some differences and that Popper's views were confused, there are also similarities, as the author points out (p. 10). Hence, one could very well claim, as Margenau did, that Popper's distinction did anticipate (aspects of) Margenau's.

Reply: I agree with Reviewer #1 that there are indeed some similarities between Popper's distinction and Margenau's later distinction between preparation and measurement, and I explicitly acknowledge these on p. 10. My claim, however, is not that Popper's views bear *no* resemblance to Margenau's, but that this similarity is *more superficial* than it is usually claimed in the literature (including by Margenau). The difference is reflected in the choice of terminology itself: Popper's 'selections' are

intended to *filter* an ensemble of particles already possessing a pre-assigned state, whereas Margenau's 'preparations' aim to actively *produce* an ensemble in a specific new state. If Popper had realized that his selections were akin to Margenau's preparations, he would have realized that his thought experiment was a non-starter. Indeed, Popper's successive revisions of the experimental set-up were meant to show that momentum selection does not *prepare* the system in a new momentum eigenstate, but merely *reveals* a preexisting momentum. See also 1A

Reviewer (1C) — At the start of section 3 (p. 9), the author writes "Popper starts from the well-known fact" without stating explicitly where Popper does so. It would be good to specify this, given that there are quite a few texts by Popper discussed.

Reply: I have now clarified the formulation to make explicit that this feature is shared by all of Popper's presentations of quantum mechanics discussed in the paper, with particular reference to the more extensive treatment in the *Logik*. The revised wording removes the ambiguity about the textual basis of the claim and avoids singling out an unspecified passage.

Reviewer (1D) — - The discussion on pages 9-10 of Popper's views on the indeterminacy-relations is not completely lear. The main reason for this is that the author introduces several ways to distinguish different interpretations of these relations.

Reply: I thank the referee for this helpful suggestion, which coincides with a concern I had myself. I have now reorganized the system of labels to improve readability.

Reviewer (1E) — - On p. 11, the author argues that Heisenberg claimed that while the indeterminacy relations forbid predictive measurements of a particle's future position-momentum trajectory, they do allow nonpredictive measurements of position and momentum by combining two predictive measurements. Given that it is left unspecified how we are to understand predictive and non-predictive measurements precisely, it is not completely clear how Heisenberg arrived at this second claim (regarding the possibility of non-predictive measurements by combining two predictive measurements).

Reply: I agree that speaking of two predictive measurements was ambiguous, for the reasons explained in 1A, I have rephrased the passage to state that past trajectories can be reconstructed from the combined data of a physical selection and a measurement, taken over the time interval between these two operations. In Section 1.1, I used Heisenberg's experimental set-up as an example, involving the Doppler effect, which determines the particle's momentum and can serve as an initial condition for future predictions. Indeed, Popper sometimes refers to this procedure as a 'measurement' since contrary to a 'selection' by a filter, it does disturb the system, although is not a mere registration (see 1A and 1B).

Reviewer (1F) — - On p. 11, the author suggests in passing that Popper's interest in retrodictive measurements was connected to his more general philosophical views: "for Popper [...] the point is that if sharp past trajectory reconstructions were not possible, the frequency predictions of quantum mechanics could not be falsified, and the theory would therefore belong to the realm of 'metaphysics'. Without the possibility of reconstructing the past paths of particles, one could not subject the theory to empirical control". This is a very interesting point, especially given that, as the author points out, up until now Popper's thought experiment has been barely discussed in the literature about Young Popper. I would therefore like to ask the author to highlight this point more in the introduction of the paper. In that way, it will be clear that the paper's audience is not merely historians of quantum physics, but equally well historians of philosophy of science.

Reply: Indeed, the paper is also intended to address historians of the philosophy of science, not only historians of quantum physics. Following the referee's suggestion, I have presented the connection between Popper's interest in retrodictive measurements and his broader philosophical concerns about falsifiability and empirical control already in the Introduction.

Reviewer (1G) — - On p. 17, the author states that von Weiszacker argued that Popper did not see how non-predictive measurements "escape the indeterminacy relations since they are not physical measurements at all". This point has not been made before, and it would be good to include this in an explanation of how we are to see non-predictive (non-prognostic?) measurements.

Reply: I thank the referee for this suggestion. I have added clarificatory remarks to better define 'physical measurements' in that context. Von Weizsäcker understands a 'proper' physical measurement as one that can serve as an initial condition to plug into dynamical laws for future predictions. By contrast for Popper seems to see 'measurement' as in itself terminal.

Reviewer (1H) — - On p. 26, the author writes that "Popper was not misled by Heisenberg's notion of 'measurement', but by the notion of 'physical selection' he adopted". The 'he' here in this sentence is ambiguous, and could refer to both Popper or Heisenberg. Also, if the 'he' used here refers to Popper, the term 'adopted' seems quite ambiguous as well, given that it was Popper who, according to the author, introduced the term (whereas 'adopted' suggests that he took it over from someone else). I would like to ask the author to clarify this sentence.

Reply: I have rephrased the sentence to eliminate any possible ambiguity in the pronoun reference and to clarify that the notion of 'physical selection' was introduced and employed by Popper himself. I originally used the term 'adopted' in the qualified sense that Popper *committed himself* to this particular conception of 'physical selection'; had he instead employed a notion closer to Margenau's concept of 'preparation,' the difficulty under discussion would not have arisen (see 1B).

Reviewer 2

Reviewer (2A) — As a matter of presentation, the reader and the analysis could benefit from more clarity and information on the distinction between predictive and non-predictive measurements adopted by Heisenberg and, after him, Popper and the distinction between measurement and preparation, of physical selection, proposed by Margenau in the immediate aftermath of the episode.

Reply: Reviewer #1 raised the same concern, and I therefore refer Reviewer #2 to my reply to 1A and 1B.

Reviewer (2B) — One relative weakness of the paper, despite its considerable length, is the missed opportunity to present in more detail (in a page or two) how the different interpretive positions relate to the actors' more philosophical interests and commitments (sometimes evolving) implicitly or explicitly noted in the more technical debate, especially Schlick's, Heisenberg's, Einstein's and above all Popper's. About Popper's, the paper mentions in passing on p.11 the metaphysical status of past trajectories, or rather of the concept, in reaction to Heisenberg's reference to matters of taste and Schlick's to their meaninglessness due to the impossibility of their verification. But no reference is made to Heisenberg's positivist epistemological program, noted for instance in Cassidy's biography, contrary to Popper's.

Reply: I thank the referee for this thoughtful suggestion. I was cautious about expanding this discussion further because the secondary literature itself is divided. Heisenberg, in particular, is often portrayed as a straightforward positivist but other interpreters have argued for a more nuanced reading,[1] suggesting that Heisenberg's positivist rhetoric was at least partly strategic rather than programmatic. A similar situation holds for Schlick in the 1930s, although in this case the attribution of a more strictly verificationist stance with respect to the issues under discussion appears less contentious.[2] Given these historiographical uncertainties, I judged it preferable to describe Popper's portrayals of these philosophical positions rather than to assess in detail how accurately they reflect what their proponents themselves maintained. For the latter, I have added some references to the secondary literature.

I agree that a more extended discussion of the broader philosophical commitments of the actors involved would be of genuine interest. However, given the already considerable length of the paper, and in light of the editor's request to focus revisions on clarity and argumentative precision rather than substantive expansion, I have not added a separate section devoted to broader philosophical contextualization. Instead, I have sought to make the relevant philosophical commitments more explicit at strategic points in the text where they bear directly on the technical discussion. I hope that these clarifications go some way toward addressing the referee's concern while keeping the paper within reasonable bounds.

Reviewer (2C) — The paper describes the exchanges with Heisenberg et al as 'series of experimental conjectures and refutations'. But there's no explicit discussion of the use of thought experiments within the framework of Popper's realism and falsificationism in LSD. Nor is there any consideration of the place within Poppe's philosophy of science of his philosophy of physics and engagement of physicists. Not does the paper take notice of the epistemological response to Heisenberg, Schlick and Bohr in chap IX, sect. 73, of failing to carry out their programs and assuming an inconsistent dual interpretation and, in the new, 1959, appendix XI, adopting a Kantian metaphysical epistemology.

Reply:

I thank the referee for this thoughtful and challenging remark. I have strengthened the connection between Popper's critique of QM and his falsificationist framework by adding a paragraph to the Introduction, as also suggested by Reviewer #1. With regard to a broader philosophical commitment to *realism*, I am not convinced that it can be straightforwardly attributed to Popper in the period 1934–35. At this stage, his attack on QM seems primarily motivated by concerns about *determinism* and the status of statistical laws (cf. §78), rather than by a mature realist program in the later sense of quantum mechanics without the observer. This latter emphasis, in my view, becomes prominent only after the war.

I agree with the referee that Appendix XI of the 1959 edition is highly relevant for understanding Popper's retrospective reassessment of these issues, and I therefore discuss it explicitly in the conclusion. I now draw more extensively on Popper's own distinction between *apologetic* and genuinely *critical* uses of thought experiments. While some commentators have described the epistemological stance articulated in Appendix XI as Kantian, my analysis focuses more narrowly on Popper's explicit attempt to attribute his 'mistake' to Heisenberg's asymmetrical treatment of position and momentum measurement in his γ-ray thought experiment. The point I wish to emphasize is that this reconstruction is contradicted by the unpublished sources discussed in the paper. I hope this strikes an appropriate balance between acknowledging the broader philosophical context and keeping the paper focused on the specific historical and conceptual problem under investigation.

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Notes

[1]Mara Beller. Pascual Jordan's Influence on the Discovery of Heisenberg's Indeterminacy Principle. *Archive for History of Exact Sciences* 33 (1985), pp. 337–349; Kristian Camilleri. *Heisenberg and the Interpretation of Quantum Mechanics. The Physicist As Philosopher*. Cambridge: Cambridge Univerity Press, 2009

[2]Michael Stöltzner. "Can meaning criteria account for indeterminism? Moritz Schlick on causality and verificationism in quantum mechanics." In: ed. by Fynn Ole Engler and Matthias Iven. Berlin, Parerga, 2008, pp. 215–245