Open and hidden heavy flavor measurements at RHIC

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Outline

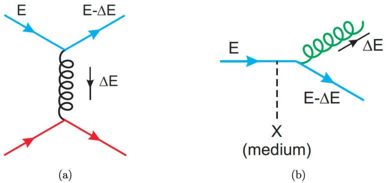
Motivation

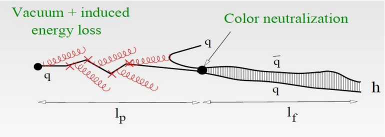
Open Heavy Flavor:

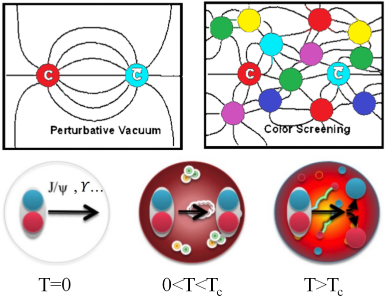
- Heavy quarks are good probes of medium properties
  - produced very early in the collision and then propagate the medium
  - loose energy due to collisions(a) or medium-induced gluon radiation(b)
- Hadronization via fragmentation or coalescence
  - Which is dominant?

Quarkonium:

- Quarkonia dissociate at high temperature due to Debye-like screening of color charges
- Complications:
  - Cold nuclear matter(CNM) effects:
    - shadowing/antishadowing
    - break-up due to comover interactions
  - regeneration/recombination
  - feed-down
  - energy loss?

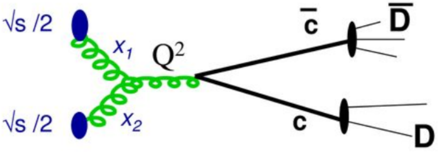






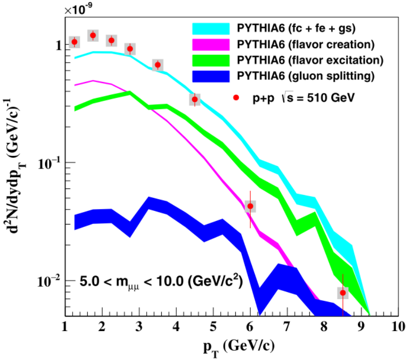
[A. Rothkopf, Hard Probes 2012]

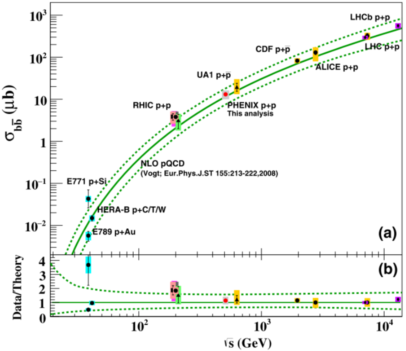
Heavy flavor production in $p + p$



$b\bar{b}$ cross section

- PHENIX measured $b\bar{b}$ cross section at forward rapidity ($1.2 < |y| < 2.2$) by:
  - selecting like-sign dimuons originating from $B^0 \leftrightarrow \bar{B}^0$ oscillations

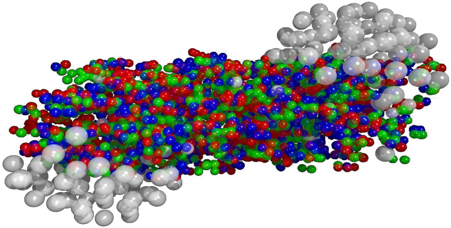


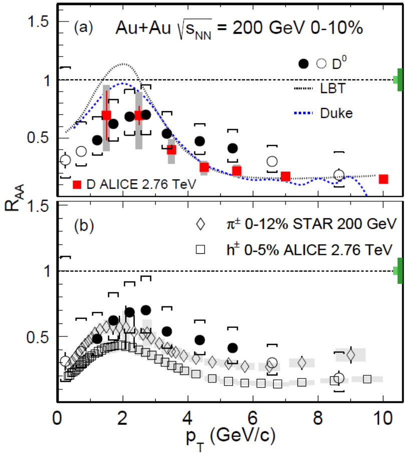


[Phys. Rev. D 102, 092002]

- Results favor $b\bar{b}$ production via flavor creation and excitation over gluon splitting
- Cross section consistent with NLO pQCD calculation *[Eur. Phys. J. Spec. Top. 155, 213–222]*

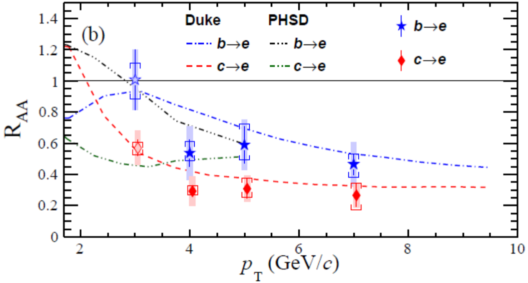
Heavy flavor suppression in $Au + Au$

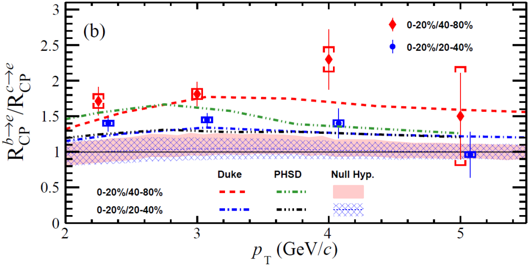




[Phys. Rev. C 99, 034908]

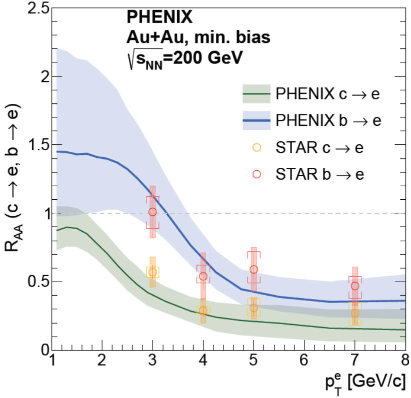
- D^0 mesons are strongly suppressed in central $Au + Au$ collisions
  - Similar level to light flavor hadrons
  - D^0 measured by ALICE suppressed at the same level
  - reproduced by models including collisional and radiative energy loss
- Charm quarks interact strongly with medium created at RHIC energy

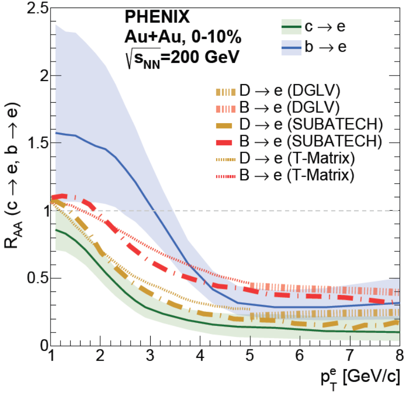




- R_{AA} is lower for $c \to e$ than $b \to e$
- Mass ordering of energy loss:
  - smaller energy loss for b quarks than for c
  - related to the "Dead cone effect" *[Nature v605, p440–446 (2022)]*
- Reproduced by models including:
  - heavy quark diffusion
  - coalescence
  - fragmentation
  - mass-dependent energy loss

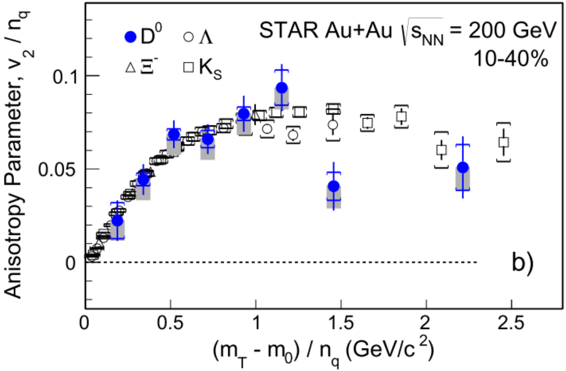
[arXiv:2111.14615]





[arXiv:2203.17058]

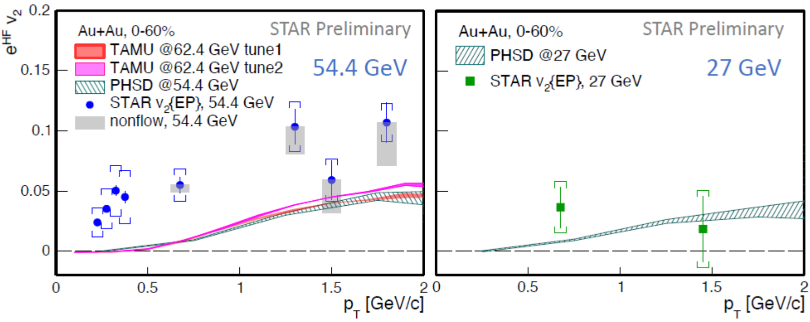
- Good agreement with STAR
- Charm results are well described by the models
- Bottom R_{AA} well described for $p_T > 4\,\mathrm{GeV/c}$



[Phys. Rev. Lett. 118, 212301]

- Significant v_2 for D^0 mesons measured by STAR
- Similar magnitude to lighter hadrons
    - Follows NCQ scaling
    - indication of charm thermalization at RHIC
    - charm quarks strongly interact with QGP

Elliptic flow of $c, b \to e$ at 54.4 GeV and 27 GeV



[Yuanjing Ji, RHIC&AGS Users Meeting 2021]

[Phys. Rev. C 91, 024904 (2015)]

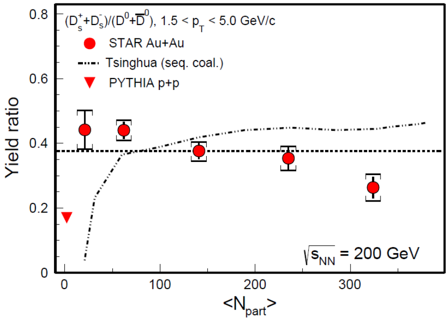
[Phys. Rev. C 92, 014910 (2015)]

[Phys. Rev. C 96, 014905 (2017)]

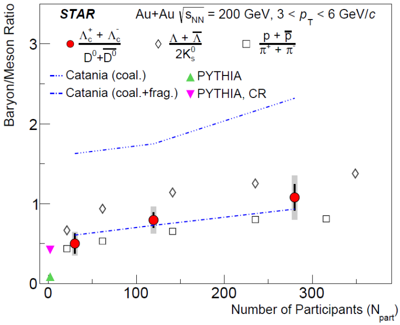
- Strong charm interactions still present at 54.4 GeV
- TAMU and PHSD calculations underestimate $v_2\{EP\}$ at 54.4 GeV for $p_T < 1.4\ \mathrm{GeV/c}$
  - Consistent above $p_T > 1.4\ \mathrm{GeV/c}$ including upper limit of estimated non-flow and uncertainties

Charm hadrochemistry

Ratios of D_s and λ_c to D^0 measured by STAR



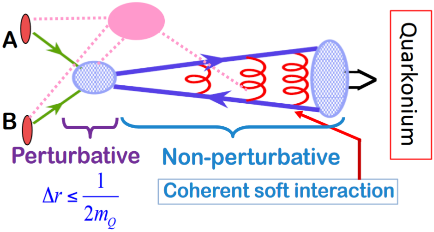
[Phys. Rev. Lett. 127, 092301]



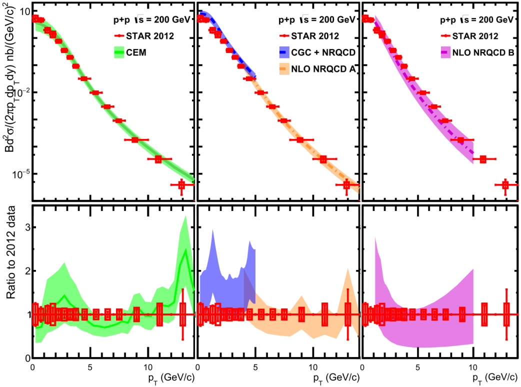
[Phys. Rev. Lett. 124, 172301]

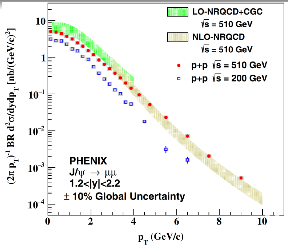
- D_s and λ_c are enhanced compared to D^0 compared to PYTHIA
  - Data indicate coalescence of charm quarks
  - Are charm quarks redistributed in $A + A$ collisions?
- More likely to produce strange open charm due to strangeness enhancement in $A + A$ *[Phys. Rev. Lett. 108, 072301]*

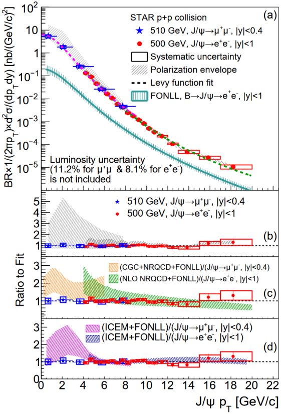
Quarkonium production in p+p



J/ψ spectra at RHIC

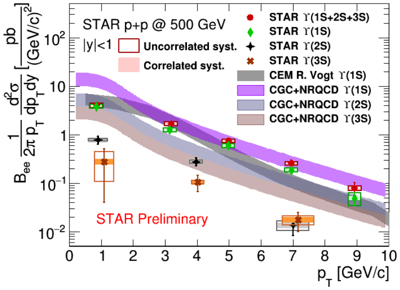




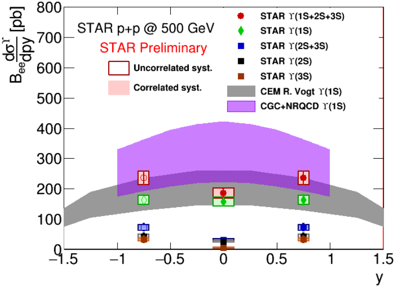


[Phys. Lett. B, 786, 87–93], [Phys. Rev. D, 101(5), 052006],
[Physical Review D, 100(5), 052009]

- Precise measurements performed by STAR at mid-rapidity and PHENIX at forward rapidity
- Data are well described by CEM, ICEM, CGC+NRQCD and NLO+NRQCD models including $B \to J/\psi$ contribution calculated using FONLL



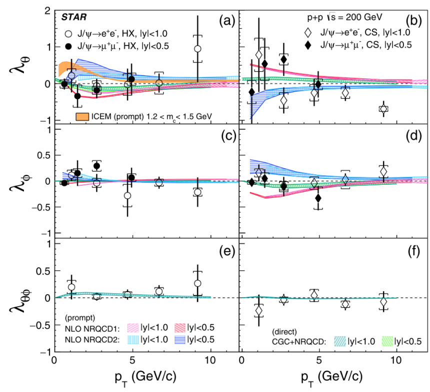
[L. Kosarzewski, QM2022]



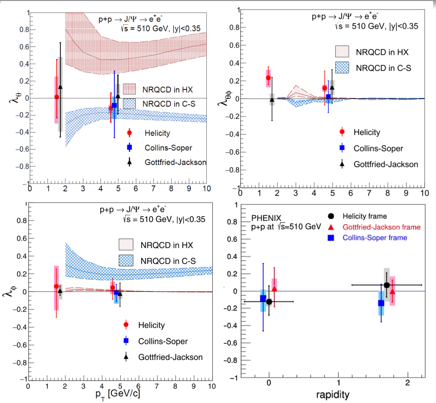
[L. Kosarzewski, 20th Conference of Czech and Slovak Physicists]

- STAR measured separated p_T and y spectra of $\Upsilon(nS)$ states
- $\Upsilon(1S)$ data are:
  - Well described by inclusive CEM calculation
  - Overestimated by direct CGC+NRQCD calculation

J/ψ polarization at RHIC



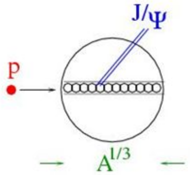
[Phys. Rev. D 102, 092009]

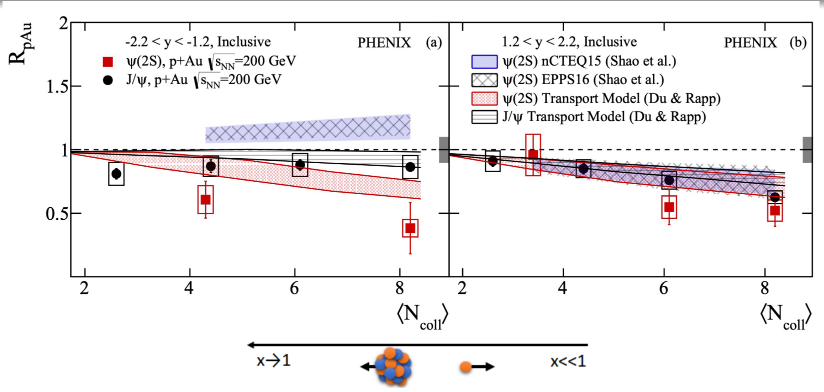


[Phys. Rev. D 102, 072008]

- All polarization coefficients measured by STAR and PHENIX in (almost) all frames
    - Consistent results in different frames
    - Consistent with no J/ψ polarization (except λ_θ at high-p_T in $|y| < 0.5$)
- Data best described by CGC+NRQCD calculation
    - Other models hard to rule out due to large uncertainties
- No difference between forward $1.2 < y < 2.2$ and mid-rapidity $|y| < 0.35$ measured by PHENIX

Cold nuclear matter effects in $p + Au$

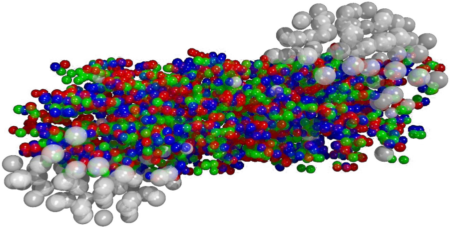


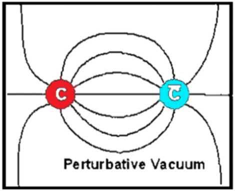


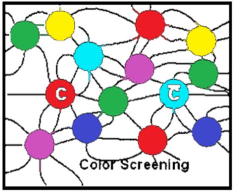
[Phys. Rev. C 105, 064912]

- Similar suppression observed in p(d)-going direction(forward)
  - initial state effects dominate in this region
- Only $\psi(2S)$ suppressed in Au-going side
  - final state effects dominate here
  - $\psi(2S)$ seems to be affected by final state effects
- Relative modification well described by transport model, but R_{pA} $\psi(2S)$ is underpredicted

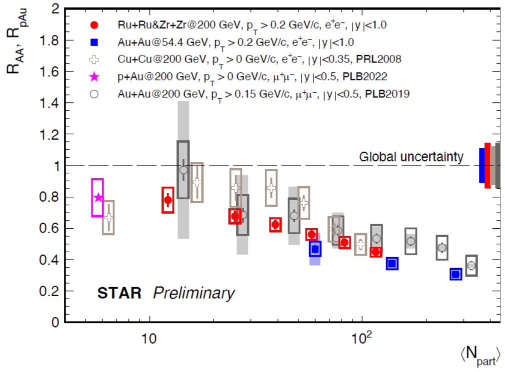
Quarkonium studies in $Au + Au$

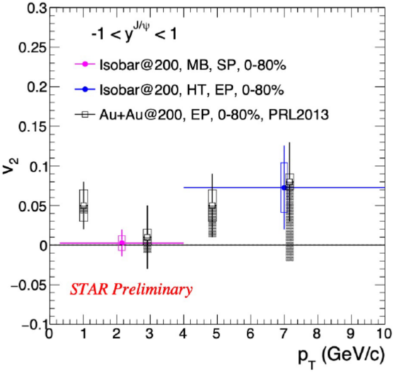






J/ψ R_{AA} and v_2 in isobar

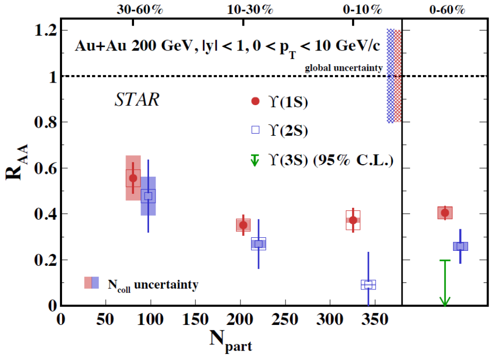




[Rongrong Ma, RBRC, 2022]

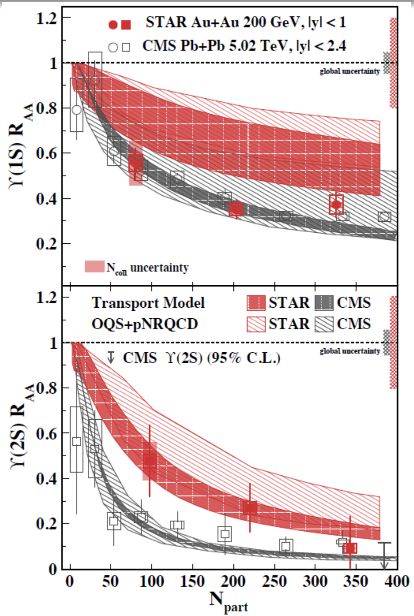
- R_{AA} vs. $< N_{part} >$ consistent across different systems and collision energies
  - Indication of a global trend
  - Interplay of dissociation, regeneration and cold nuclear matter effects
- v_2 consistent with zero for $p_T < 4\,\mathrm{GeV/c}$
  - Small regeneration or small charm flow

Υ states R_{AA} from STAR



[arXiv:2207.06568]

- R_{AA} of each of Υ states shows suppression of each $\Upsilon(nS)$
- Observation of sequential suppression of Υ states at RHIC energy
  - 3σ difference between R_{AA} of $\Upsilon(1S)$ and $\Upsilon(3S)$
- Indication of increasing suppression from peripheral to central collisions



[arXiv:2207.06568]

- Similar suppression level for $\Upsilon(1S)$ at RHIC and LHC
  - due to suppression of excited states contribution and cold nuclear matter effects
  - primordial $\Upsilon(1S)$ not significantly suppressed
- Indication of smaller suppression for $\Upsilon(2S)$ at RHIC
- Models show larger separation between RHIC and LHC than data

Models:
Transport: *[PRC 96 (2017) 054901]*
OQS+pQCD: *[arXiv:2205.10289]*

Summary

Open heavy flavor

- Data suggest strong interaction of heavy quarks with the medium down to 54.4 GeV
  - Suppression and v_2 similar for charm and light flavors
  - Bottom quarks show smaller energy loss than charm
- Significant contribution of coalescence in charm hadronization
  - Charm is redistributed among charmed mesons and baryons compared to $p+p$

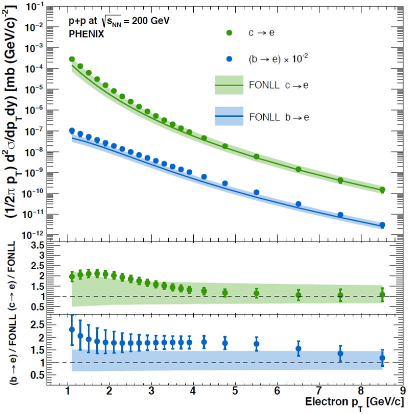
Quarkonia

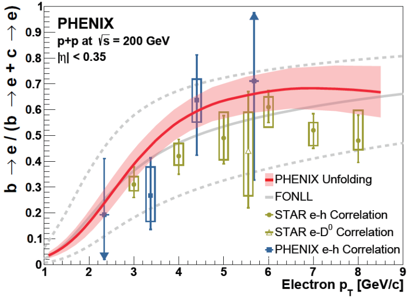
- Production overall well described by models, with only a few exceptions
- Polarization of J/ψ favors CGC+NRQCD
- $\psi(2S)$ in $p+A$ suppressed due to final state effects
- J/ψ suppression in $A+A$ similar across different systems and RHIC energies
  - Interplay of dissociation and CNM effects
- Small flow of J/ψ for $p_T < 4\,\mathrm{GeV/c}$
  - Regeneration is small
- Sequential suppression of Υ states observed at RHIC
  - Indication of stronger suppression towards central collisions
  - $\Upsilon(1S)$ suppressed at the same level at RHIC and LHC
    - Mostly due to suppression of excited states contribution

Thank you for your attention!

BACKUP

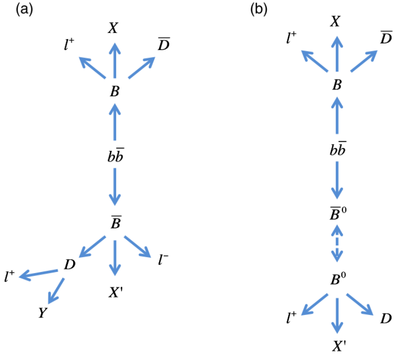
- Measured by PHENIX with silicon vertex tracker





[Phys. Rev. D 99, 092003]

- Consistent with STAR and FONLL calculations



[Phys. Rev. D 102, 092002]