The Necessity of DUNE Intranuclear $\mathcal{B}-\mathcal{L}$-Violating Searches for a World-Leading, Complementary Physics Program

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THE UNIVERSITY OF TENNESSEE KNOXVILLE

Snowmass 2021 Rare Processes and Precision Frontier
Baryon and Lepton Violation Topical Group

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Please see the associated Letter of Interest, and references therein

DEEP UNDERGROUND NEUTRINO EXPERIMENT

URA UNIVERSITIES RESEARCH ASSOCIATION

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Physics Motivation

Why $\mathcal{B} - \mathcal{L}$ Violation?

How do we understand baryogenesis?
What is the origin of the baryon abundance?

SCIENCE AND TECHNOLOGY

Astrophysicists prove Big Bang was result of gender reveal party gone wrong

1 WEEK AGO *by* MARY GILLIS [@LIVING_MARBLE]

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Can $\Delta B = \Delta L$ Remedy the Baryon Asymmetry?

- Baryon (B) and lepton number (L) are violated ***infinitesimally*** in the SM due to anomalies
- The SM nonperturbatively conserves $B - L$ (t'Hooft 1976)

$$\Longrightarrow \Delta B = \Delta L$$

- It turns out that no theory that operates within the SM has produced a proper baryon abundance ***yet, fully and consistently—EWBG???***
  - **Topological tunneling** is completely ***inadequate***
  - The **sphaleron** mechanism still ***washes out*** any asymmetry we would see today ***if*** when they are generated they conserve $B - L$

A. D. Dolgov, *Baryogenesis, 30 Years Later*
M. E. Shaposhnikov et al 1993 and 1998

Figure 1
correspo

The short answer?

NO!

Proceed by contradiction…

SHOULD

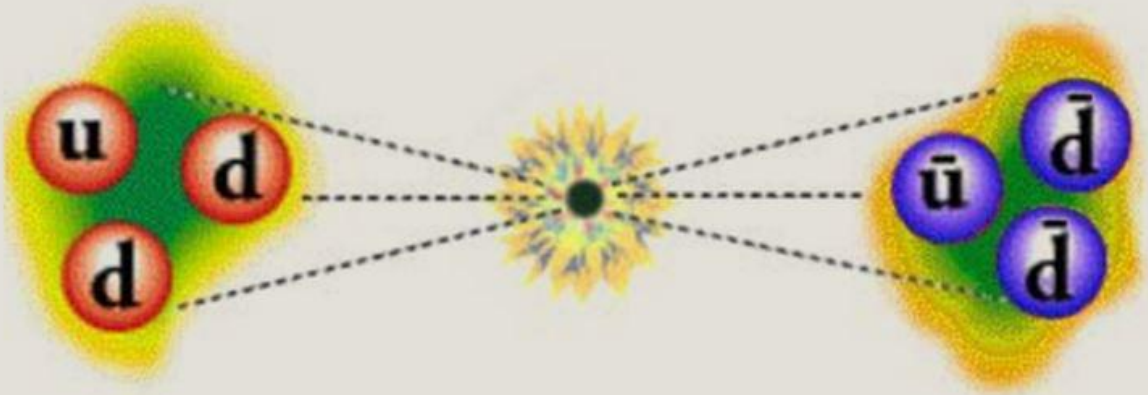
$$B - L$$

BE VIOLATED???

Maybe…

But let's be more *conservative*, and focus on observing processes with

$$\Delta B \neq 0$$



$$n \longrightarrow \overline{n}$$

Work from Now Until Snowmass

Toward the Future

Consider $\mathcal{B} - \mathcal{L}$-violating $n \to \bar{n}$

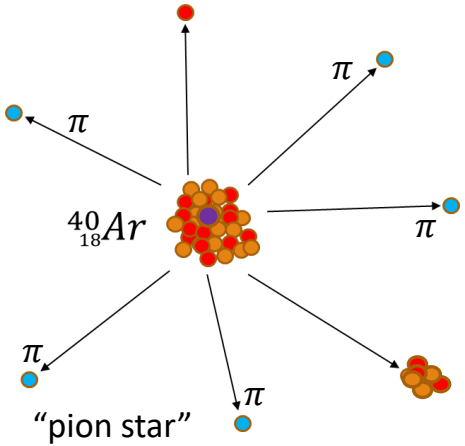
Understanding Modeling Systematics Beyond Previous Ad-hoc Assumptions

$\Delta\mathcal{B} = 2$ Signal Comparison

$n \to \bar{n}$ vs. Backgrounds (ex: Atmospheric Neutrino, ν)

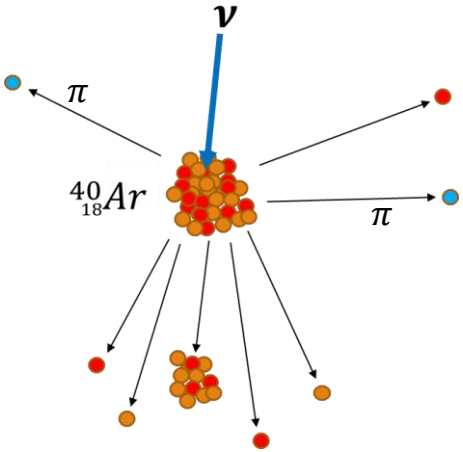
Dover, Gal, and Richard 1983, 1985, ***and*** 1996
~Golubeva and Kondratyuk, 1997
Kopeliovich et al 2018
Golubeva, JB, Ladd 2019
JB, Golubeva, Richard, Paryev 2020

- $\boldsymbol{n \to \bar{n}}$ Annihilation and Knockouts



- ~Noncontinuous energy spectrum
- Generally a ~spherical topology
- ~Low momentum due only to Fermi motion

- Neutral Current Atmospheric $\boldsymbol{\nu}$



- Continuous energy spectrum
- Generally a ~correlated topology
- Large range of total momentum

- Antineutron
- Neutron
- Proton
- Pion

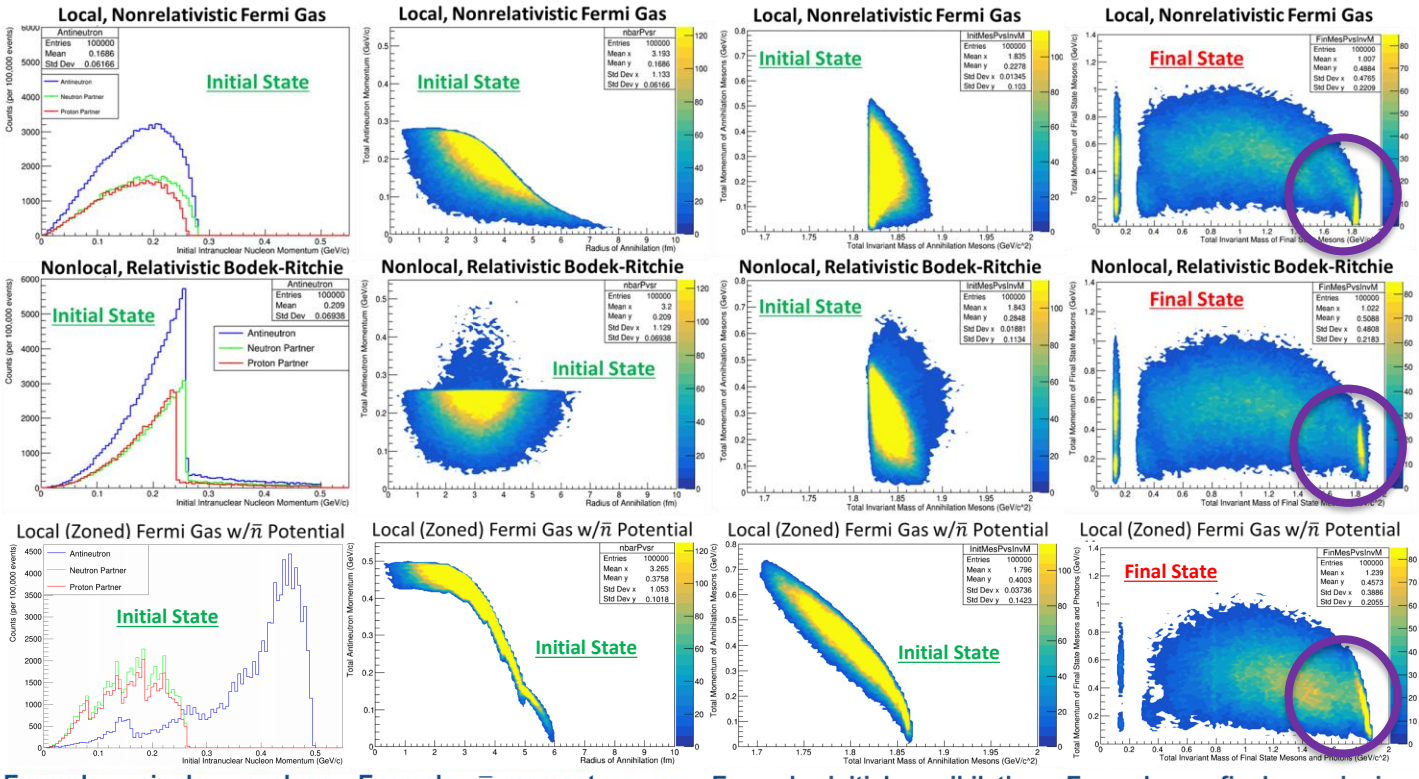
Goals of Ongoing $n \rightarrow \bar{n}$ Studies

- Utilize realistic models of rare process signals and associated backgrounds
  - Integration of the newest ***nuclear model configurations*** available in `GENIE` ***and other $n \rightarrow \bar{n}$ generators from Golubeva et al.*** into full DUNE reconstruction chain underway
  - Fully oscillated atmospheric neutrino fluxes/spectra; expected counts complete
  - Proper ν_τ CC-interactions ***and subsequent τ decays underway*** (issues with GEANT)
- Approximate uncertainties in signal and background topologies
  - Iterate across many nuclear model configurations ***and generators*** as possible
- Automate analysis techniques to extract expected lower limits of many rare processes
  - ***Generate many different samples for many different signals over many different nuclear model configurations, producing outputs from many individually trained CNN/BDTs***

$n \to \bar{n}$ Model Dependencies in Final State Topologies are Being Investigated

First foray into this study detailed in [our recent PRD]

- Compares many `GENIE` models to our generator work with **E. S. Golubeva**



Example single nucleon ($p, n, \bar{n}$) Fermi motion momentum distributions are shown for GENIE & Golubeva. These serve as the starting conditions for all annihilation products.

Example $\bar{n}$ momentum vs. radius distributions are shown for GENIE & Golubeva. Annihilation near the nuclear surface may lead to low momentum products with aspherical topologies.

Example initial annihilation product distributions are shown for GENIE & Golubeva. Different initial conditions, & preservation of radial correlations, may effect the final topology.

Example final pionic parameter spaces are shown for GENIE & Golubeva. Some localization of events might imply more complete signal to background separation in automated analyses.

Summary

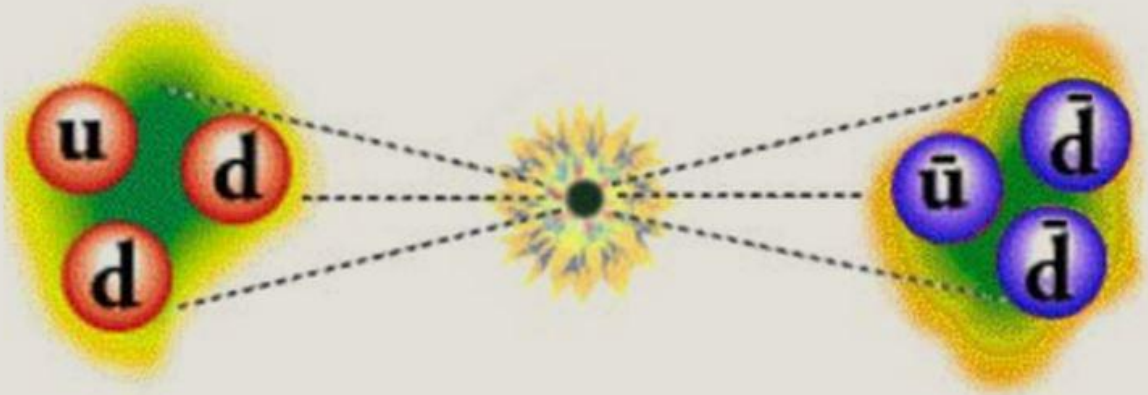
- DUNE shows potential to reach $\tau_{n\bar{n}} \geq 5.58 \times 10^8 s$ lower limit
- Improvements are sought via…
  - Better reconstruction can hopefully lead to better ROI selection
  - BDT input of CNN PID for better cuts against background
- Iteration over nuclear model configurations underway
  - Will allow us to test stability of CNN/BDT response to various topological differences
    - Effectively determine model systematics
  - Will $S:B$ remain the same independent of the nuclear model configuration?

Work to be completed by Summer 2021

- Must finish implementation of detector simulation and reconstruction for signal and background
  - Must integrate these with improved, novel PID automated methods (C. Sarasty, Cincinatti)
- Author DUNE technical notes on atmospheric neutrinos and $n \to \bar{n}\,/p \to K^{+}\bar{\nu}$
  - Possibly also need a technical note on PID improvements
- Write DUNE-official final publication on DUNE sensitivities and associated model uncertainties
  - derived from iteration across model spaces for signal/background

Joint Efforts and Snowmass Outcomes

- DUNE has the power to search for many rare processes and other BSM searches
  - Is understaffed and underfunded for this purpose
  - Simulation studies for these many unknown processes should be prioritized and funded
    - Culture around US students requirements may need to change
  - Encourage interested collaborators to join the HEP Working Group
    - Conveners: Lisa Koerner, Yun-Tse Tsai, Vitaly Kudryavtsev (outgoing)
    - Particularly need motivated graduate students and post-docs to join the group and contribute!



$$n \longrightarrow \overline{n}$$

[Theoretical Innovations for Future Experiments Regarding Baryon Number Violation, Part 1]

ACFI WORKSHOP ON $\Delta\mathcal{B} = 2$

Associated Letter of Interest

[$\Delta\mathcal{B} = 2$: A state of the Field, and Looking Forward]

Backup Slides

For your perusal

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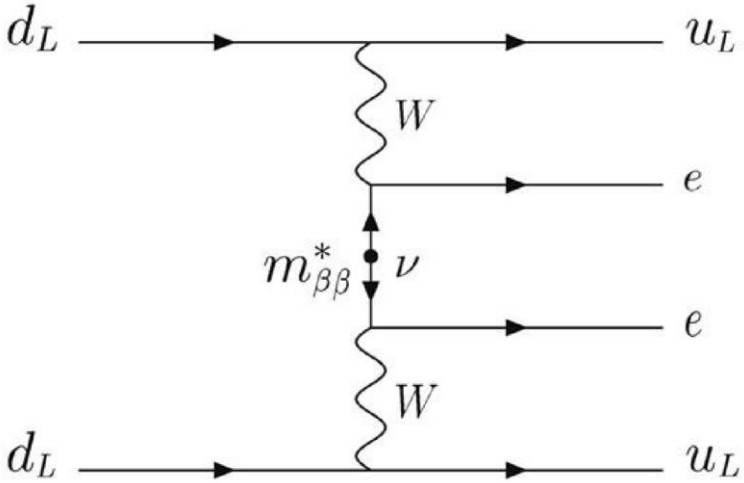
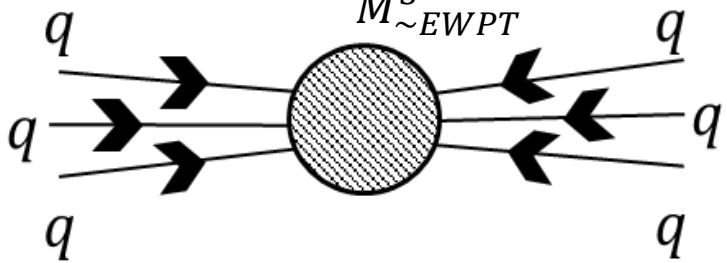
Going Beyond the Standard Model



$$\mathcal{O}^9_{2\mathrm{N}} \sim \lambda \frac{qqq\bar{q}\bar{q}\bar{q}}{M^5_{\sim EWPT}}$$

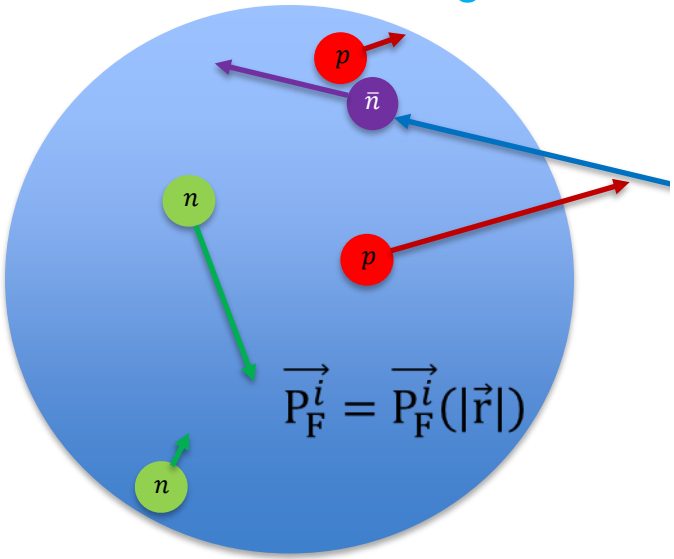


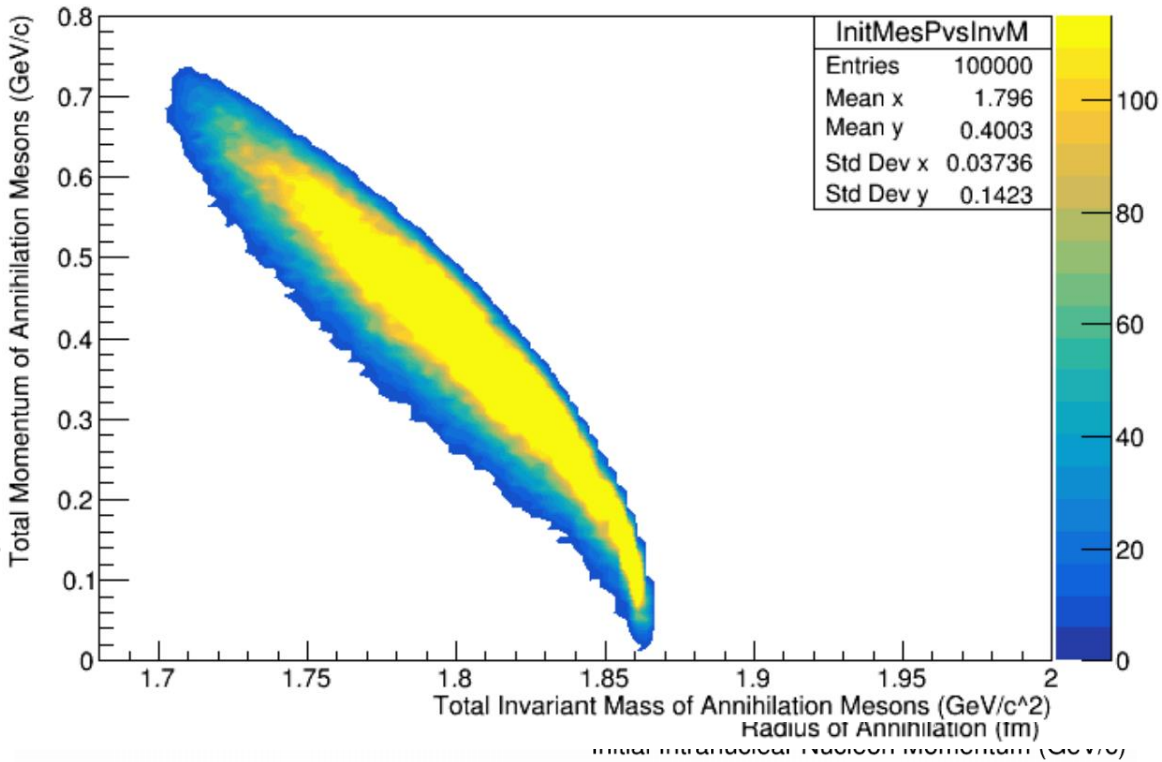
What else do we need to add?

- Proton decay? $\propto qqql \Longrightarrow B - L$ conserving
  - Important to some BSM GUT SUSY theories
  - No experimental evidence in large volume detectors
  - LHC has turned up no persistent signs of SUSY
- Some other kinds of $\Delta B \neq 0$ or $\Delta L \neq 0$?
  - $\boldsymbol{\Delta B = 2}$ operators?
  - $\boldsymbol{\Delta L = 2}$ $\Longrightarrow$leptogenesis?
- Why some over others?
  - ***Can they properly generate the baryon asymmetry of the universe?***
  - ***At what energy scales can these theoretically produce the correct value?***

The Importance of *Some* Initial Physical Correlations

Consider a local Fermi gas nuclear model of Fermi momentum (initial state)



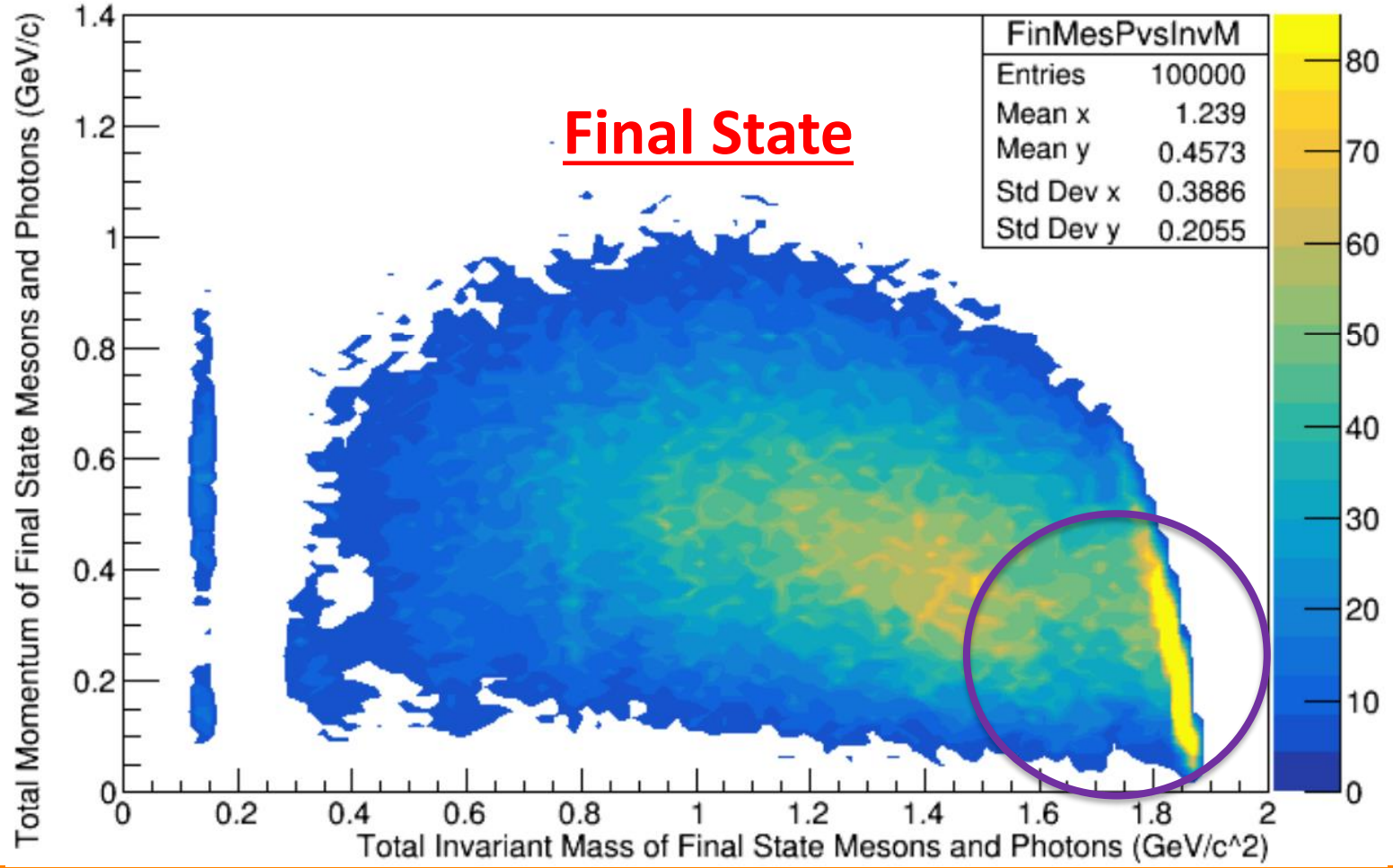


The correlation of radius and momentum has been previously ignored for *all* $n \to \bar{n}$ simulations in *all* experiments

High radii lead to…

- Fewer FSIs, more meson emission
- Lower total momentum (near *ideal case*)

Paryev's distribution


Final State
FinMesPvsInvM
Entries 100000
Mean x 1.239
Mean y 0.4573
Std Dev x 0.3886
Std Dev y 0.2055
Total Momentum of Final State Mesons and Photons (GeV/c)
Total Invariant Mass of Final State Mesons and Photons (GeV/c^2)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
10
20
30
40
50
60
70
80