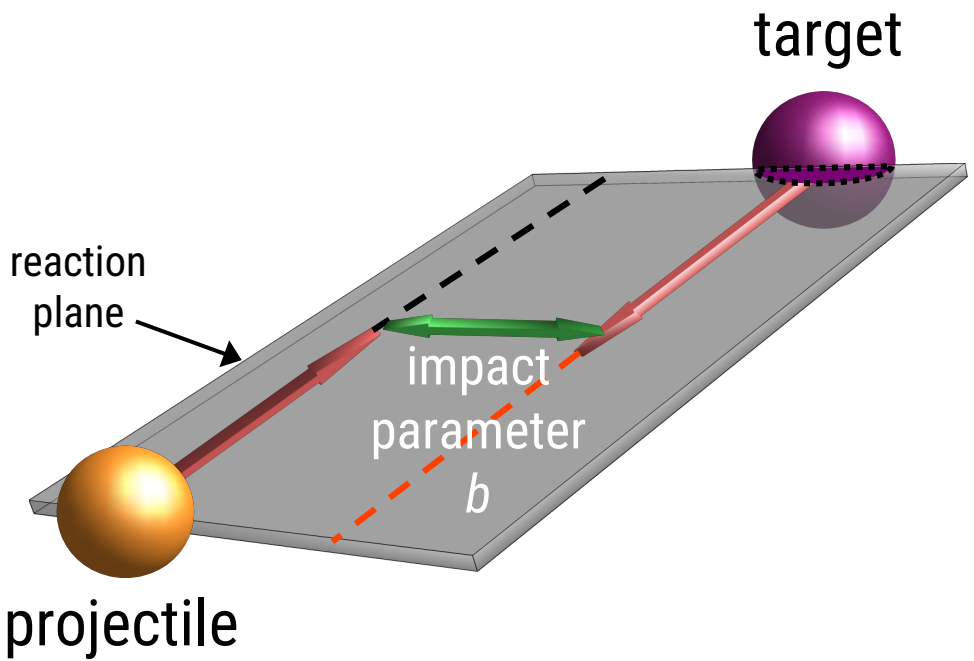
CENTRAL COLLISIONS AT FERMI ENERGIES

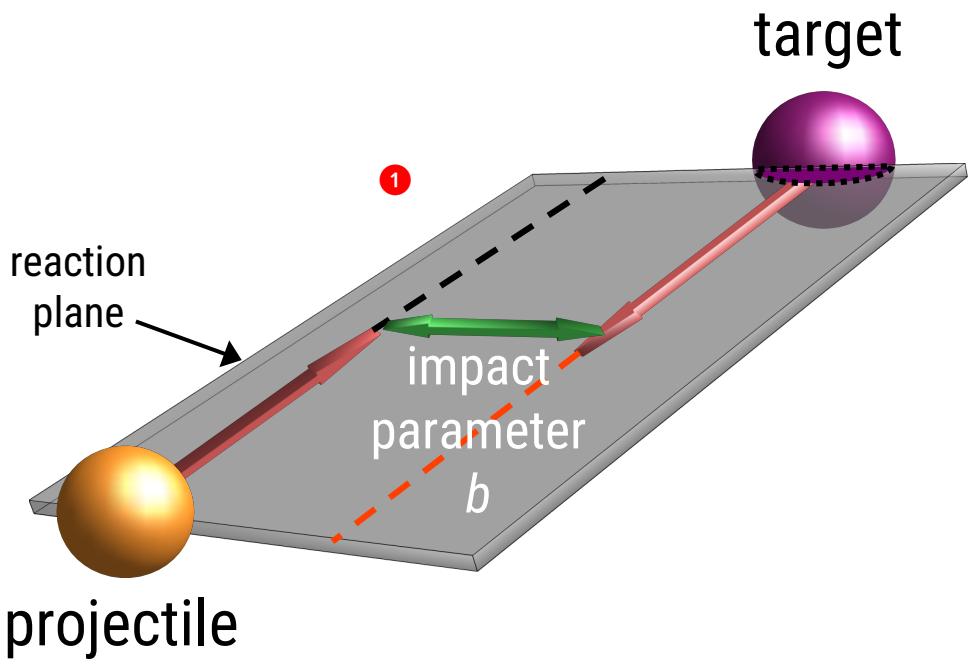
*- What your mother never told you...**

John Frankland
IN2P3/GANIL

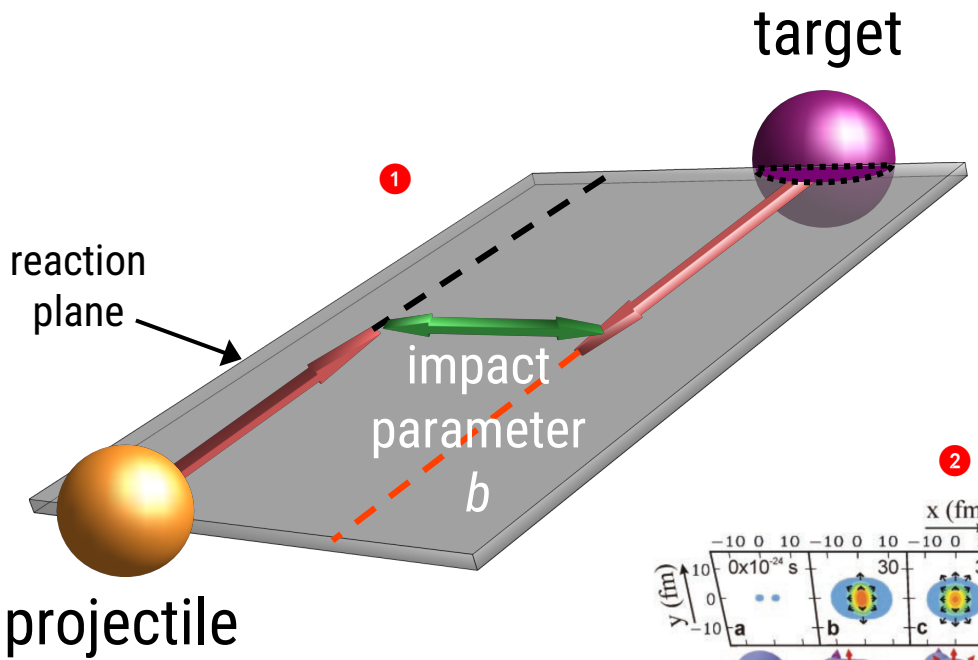
1. Centrality & impact parameter
2. How to recognize central collisions
3. How to find central collisions
4. How to estimate experimental centrality
5. Systematics for central collisions (INDRA)
6. How isotropic are the most isotropic events ?
7. "Oh, momma, can this really be the end ?"

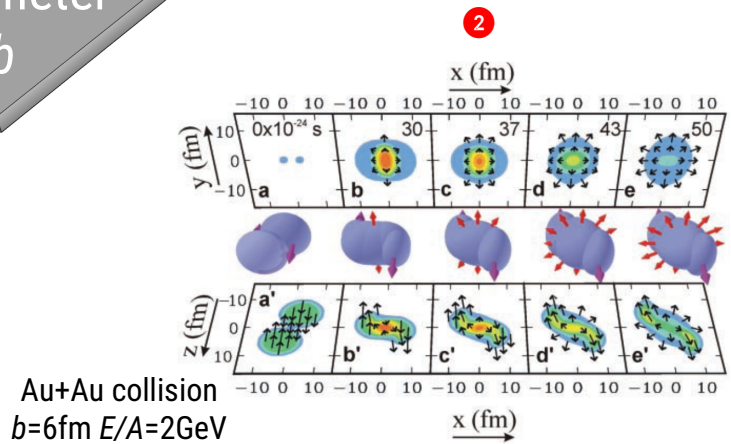
**Inspired by the C++ FAQ chapter "Inheritance – What your mother never told you"*
See isocpp.org/wiki/faq/strange-inheritance


target
reaction
plane
impact
parameter
b
projectile



1. The impact parameter determines the centrality of collisions between two nuclei

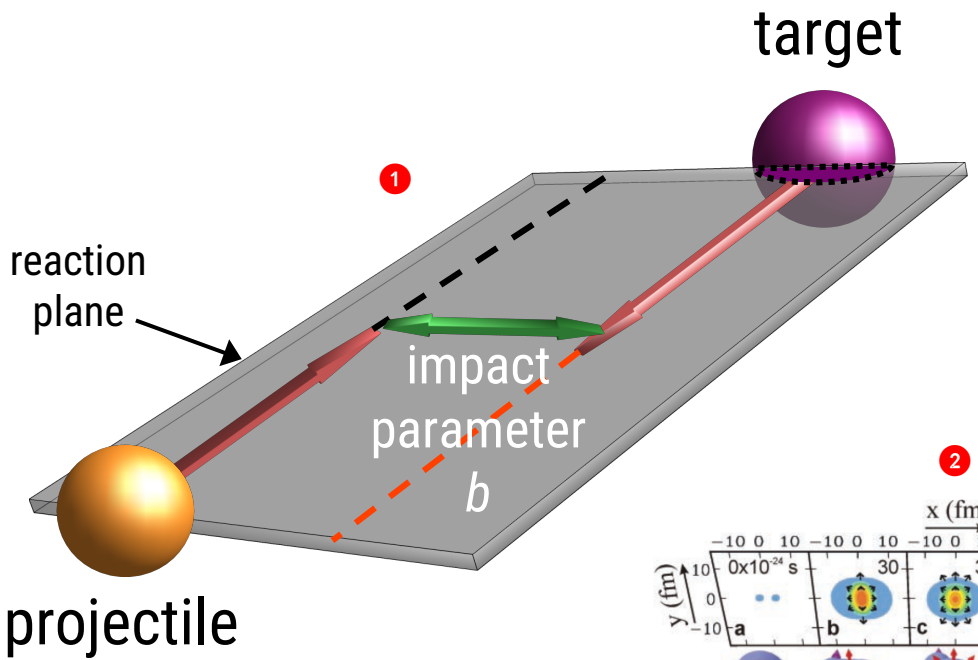


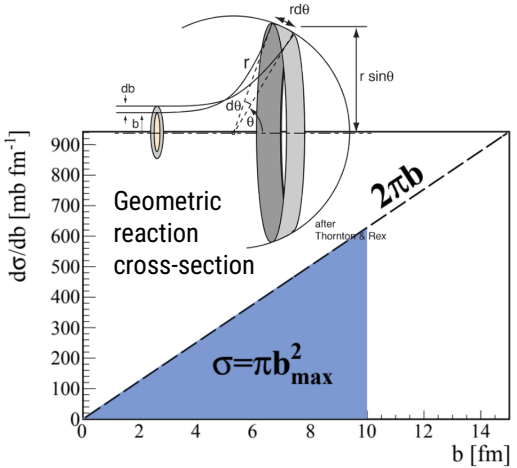


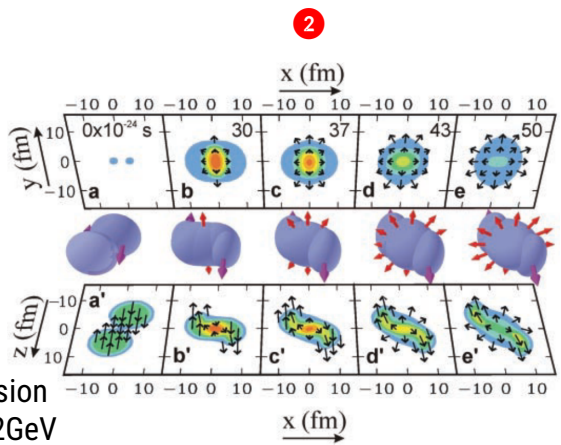
Danielewicz et al. Science 298, 1592 (2002)

1. The impact parameter determines the centrality of collisions between two nuclei

2. Increasing centrality means increasing initial density, pressure and temperature of nuclear matter







Au+Au collision
b=6fm *E/A*=2GeV

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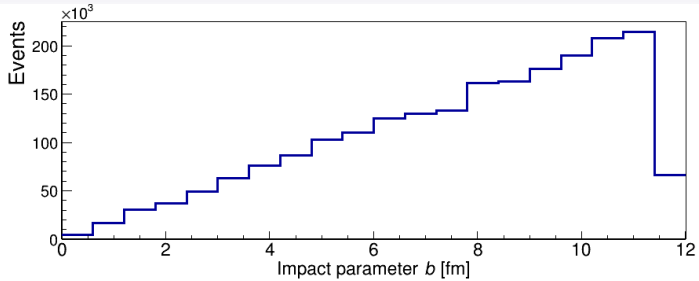
1. The impact parameter determines the centrality of collisions between two nuclei
2. Increasing centrality means increasing initial density, pressure and temperature of nuclear matter
3. From simple geometric considerations, reaction cross-section decreases with centrality:
   - central collisions are rare!

2. How to recognize central collisions

Simulated ^{58}Ni+^{58}Ni collisions 32AMeV
Antisymmetrised molecular dynamics (AMD)

Ono & Horiuchi, Prog. Part. Nucl. Phys. 53, 501 (2004)



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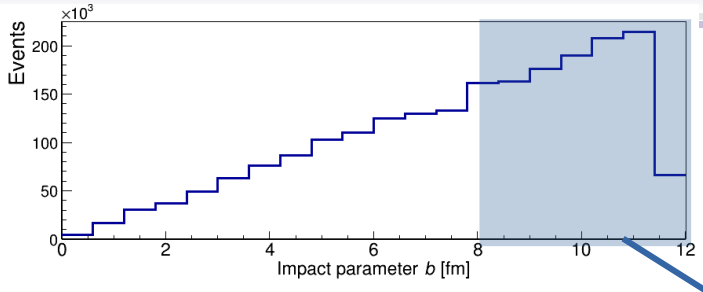

PERIPHERAL COLLISIONS

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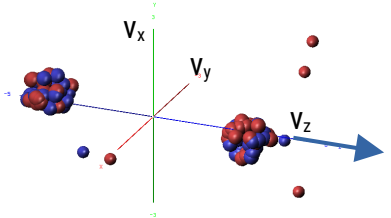

beam direction

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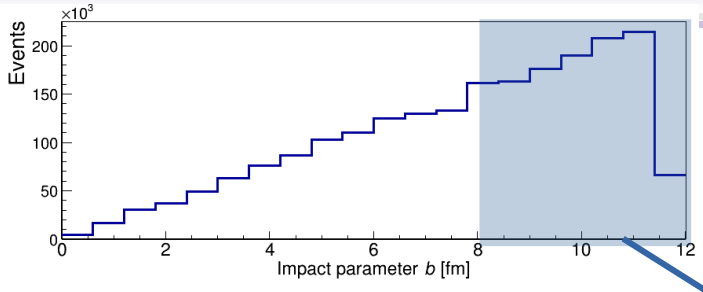

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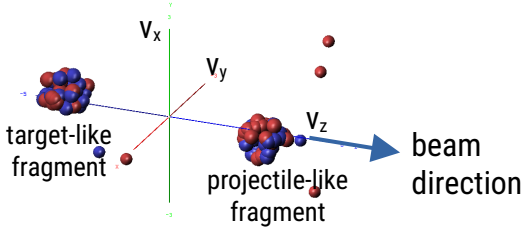

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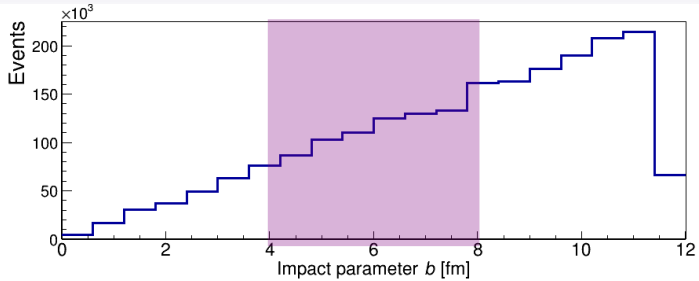

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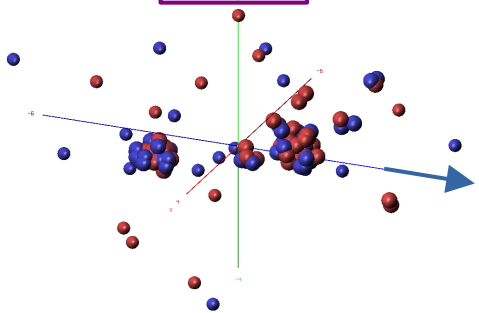
MID-PERIPHERAL COLLISIONS

PERIPHERAL COLLISIONS

b=6.5fm



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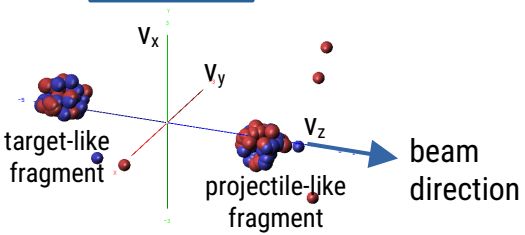

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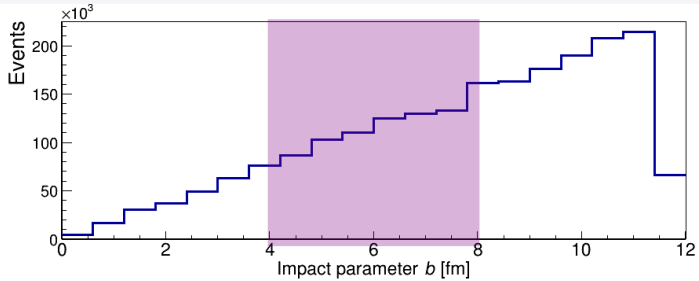

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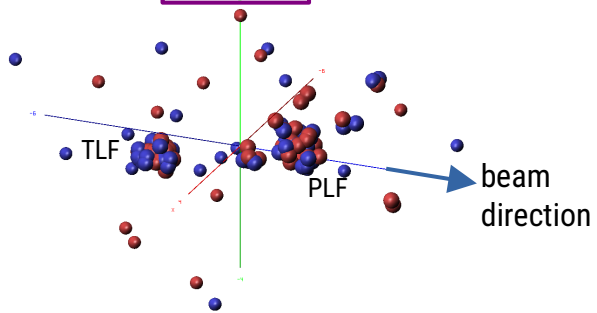

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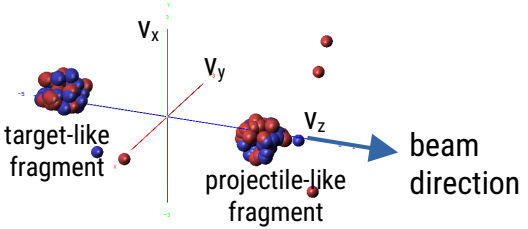

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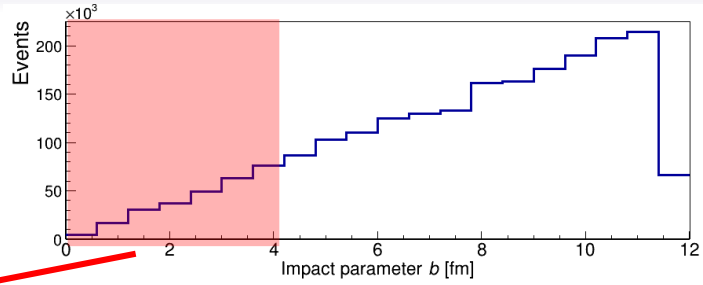

CENTRAL COLLISIONS

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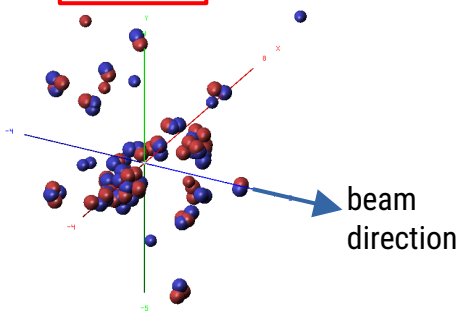

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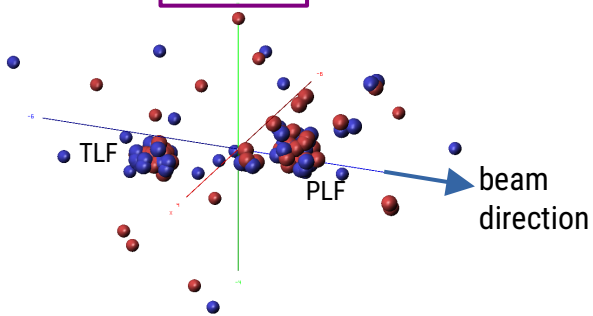

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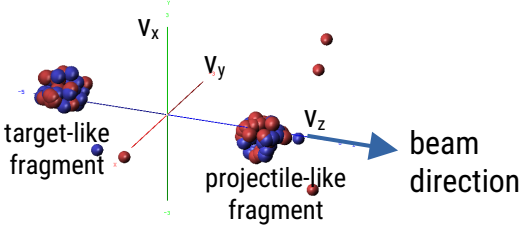

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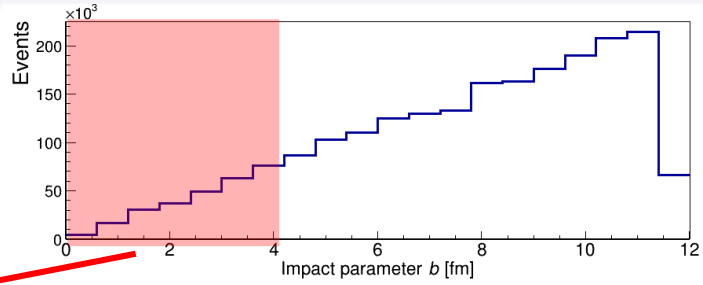

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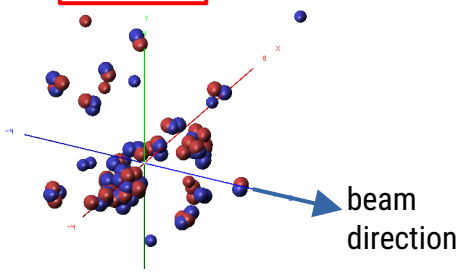

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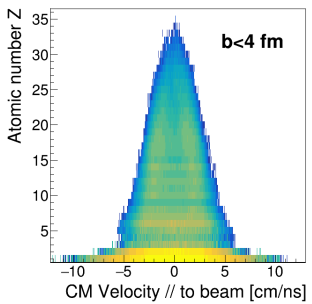

$V_{//}$

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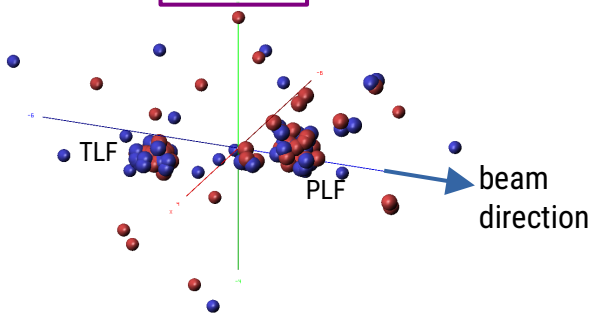

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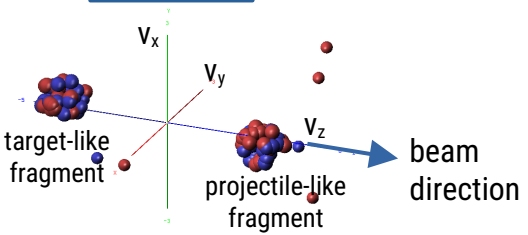

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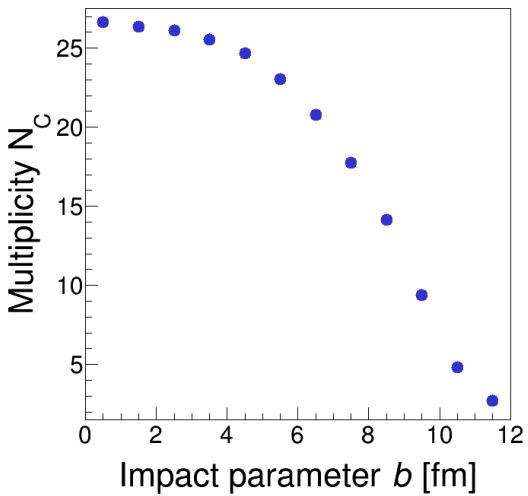

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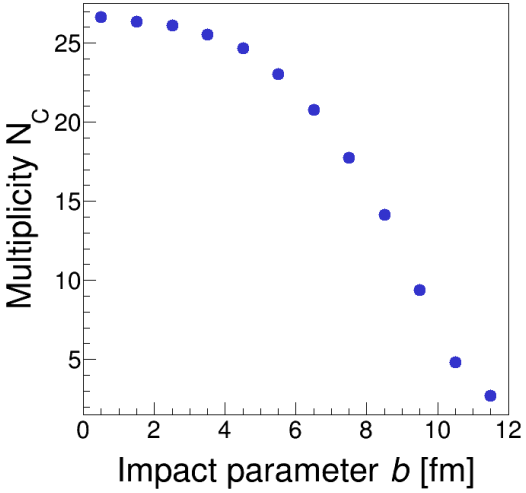

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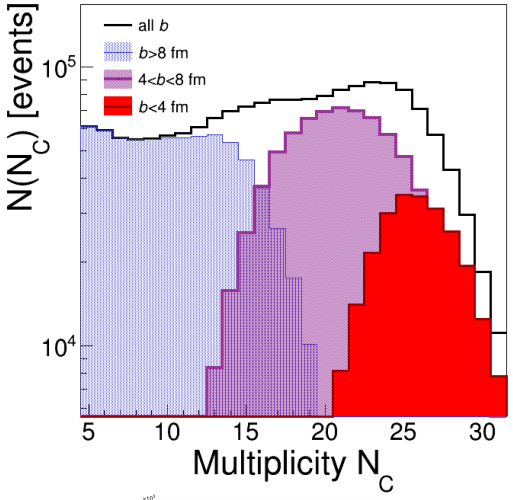

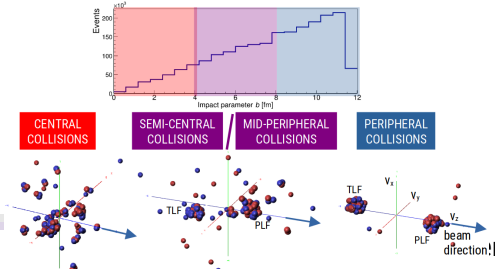

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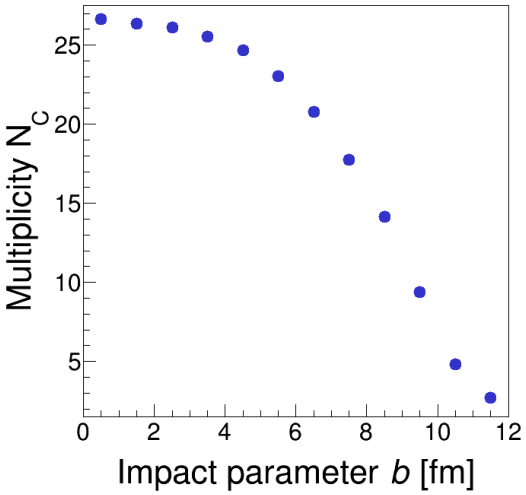

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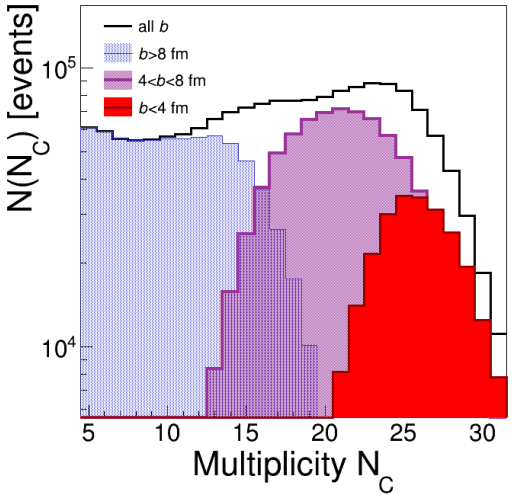

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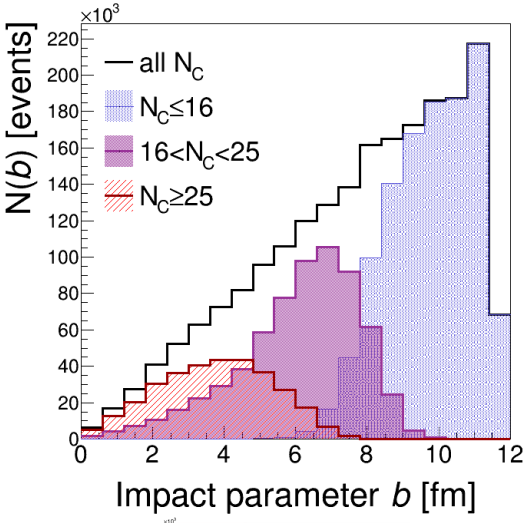

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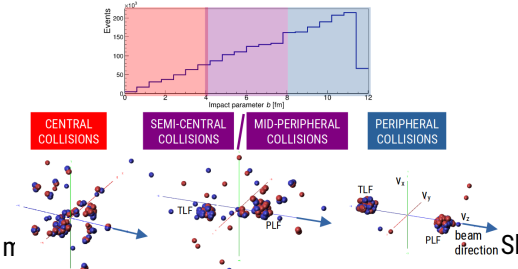
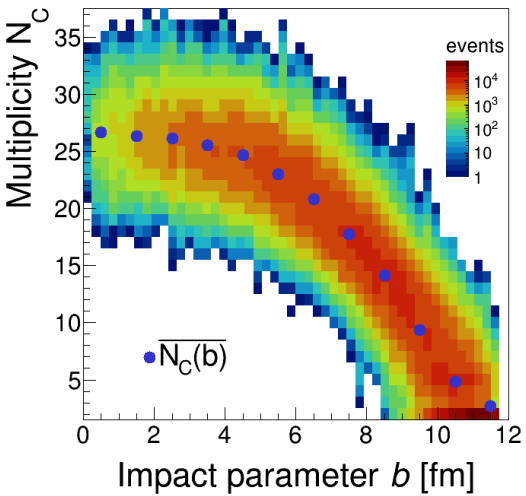


ALL OBSERVABLES FLUCTUATE FROM ONE COLLISION TO THE NEXT



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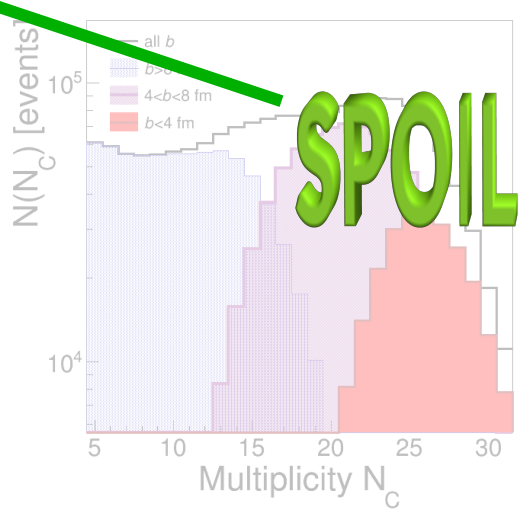

SPOILER ALERT!

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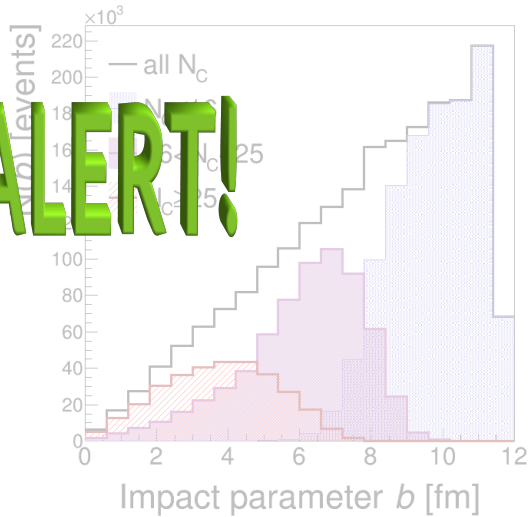

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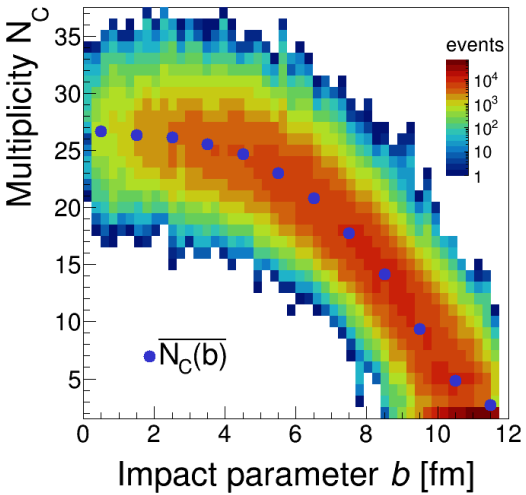

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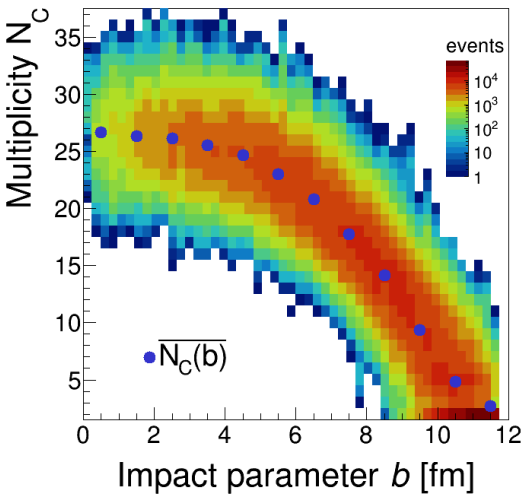

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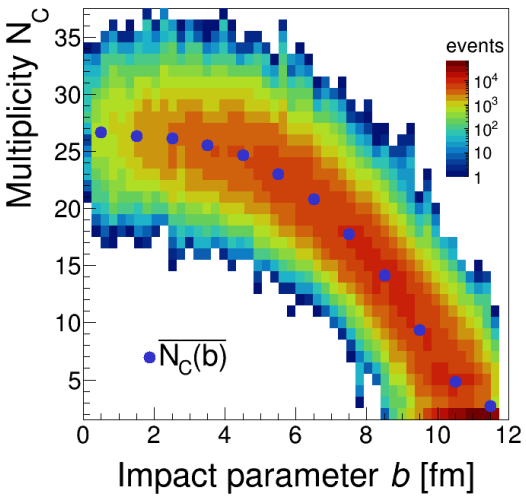

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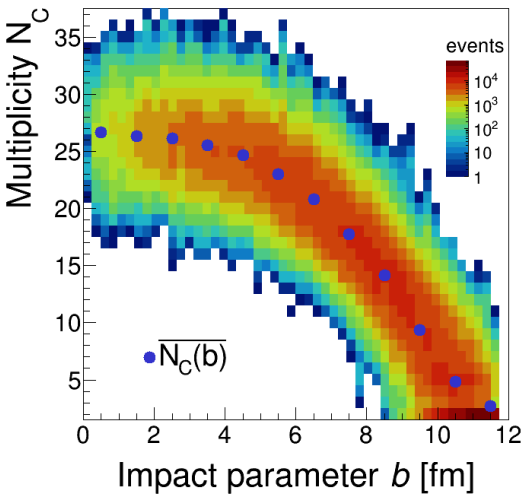

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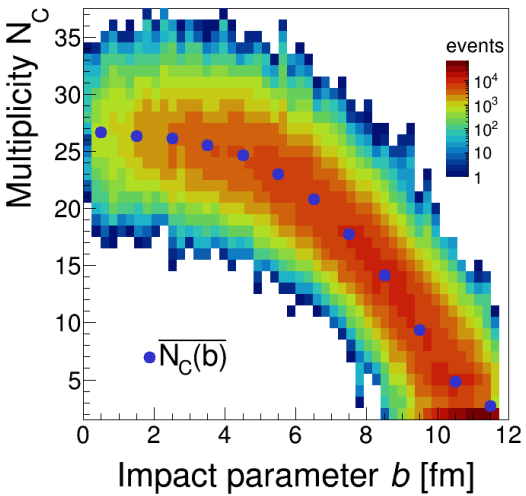

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❺ Not a drawback, as we always work with sets of events (*ensembles*) anyway: for reactions with a huge number of possible final states [phase space]
a single collision/event is not representative and can tell us NOTHING.

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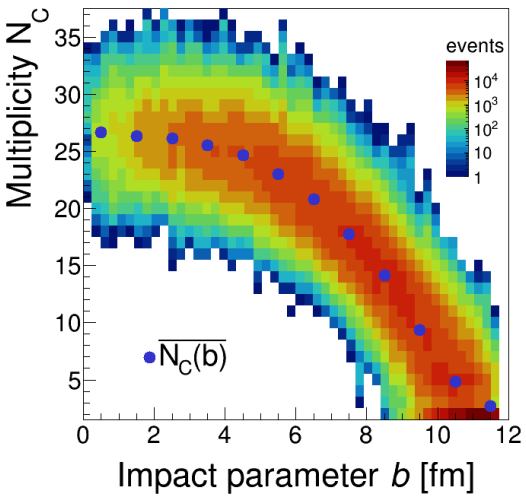

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❶ Fluctuations are due to physics of nuclear collisions
[many-body correlations, nucleon-nucleon collisions, instabilities, etc.]

❷ In each collision information is lost concerning the impact parameter
[entropy, irreversible]

❸ We cannot (should not) associate 1 event with 1 impact parameter
[*even* with Machine Learning, Neural Networks, Quantum Computing...]

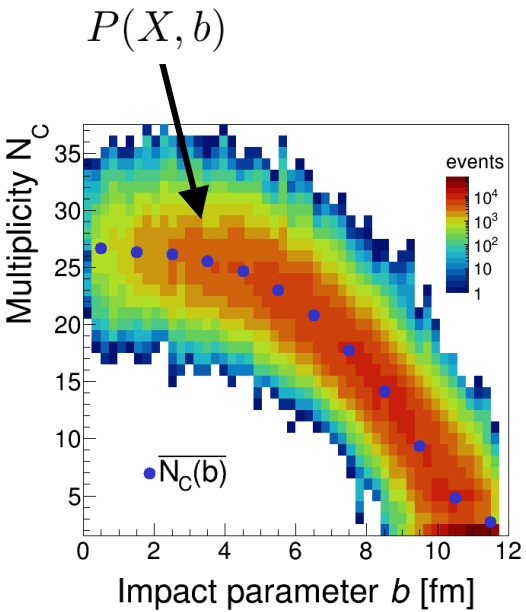
❹ But, for a given *set* of events, we *can* estimate the corresponding impact parameters *probabilistically* ⇨ How?

❺ Not a drawback, as we always work with sets of events (*ensembles*) anyway:
for reactions with a huge number of possible final states [phase space]
a single collision/event is not representative and can tell us NOTHING.

Original idea from ultra-relativistic HI collisions (RHIC, LHC):

S. J. Das, G. Giacalone, P.-A. Monard, and J.-Y. Ollitrault, Physical Review C **97**, 014905 (2018).
R. Rogly, G. Giacalone, and J.-Y. Ollitrault, Physical Review C **98**, 024902 (2018).

Embrace the fluctuations!
Deduce probability distribution *P(X,b)* from experimental data & we know everything



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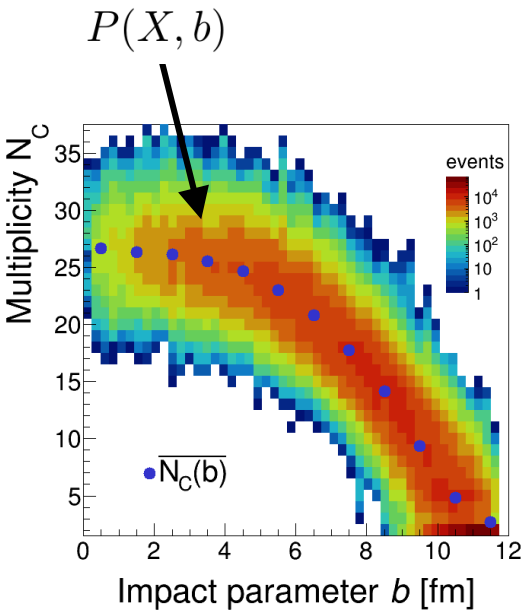

Parameterize *P(X,b)* in terms of mean value evolution + fluctuations

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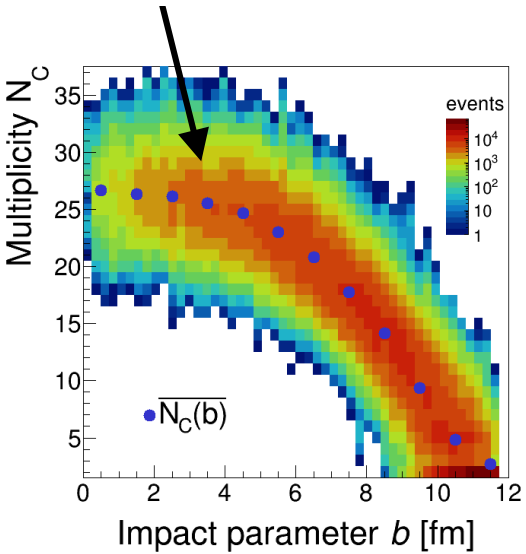
$P(X,b)$



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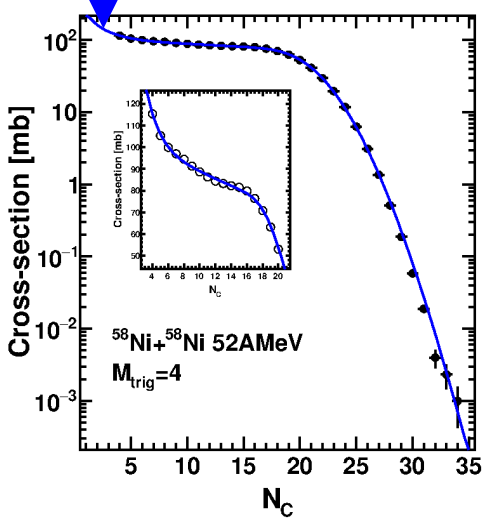
$$P(X) = \int P(X,b)\,\mathrm{d}b$$



Vary parameterization of *P(X,b)* in order to fit measured *P(X)*

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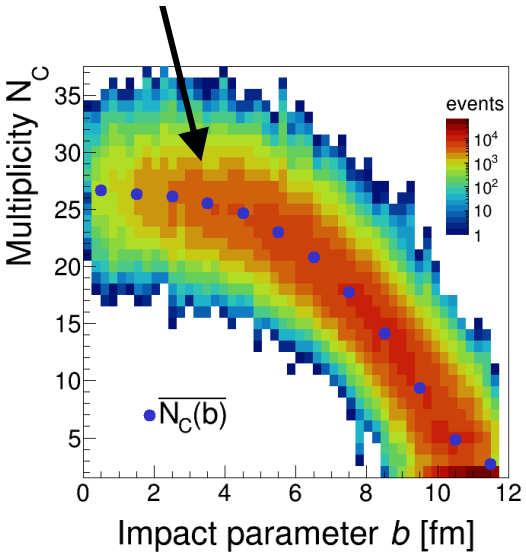
$$P(X,b)$$



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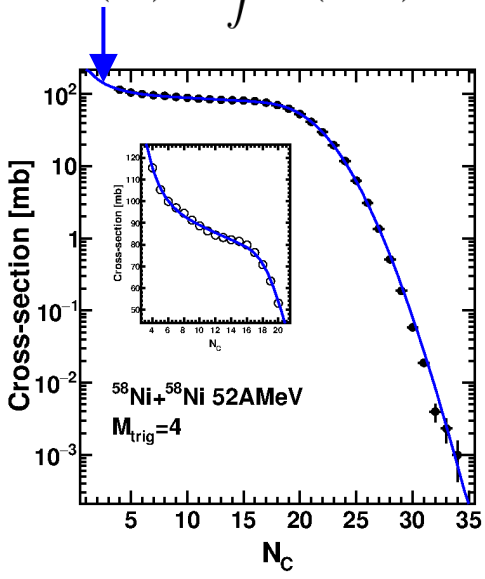
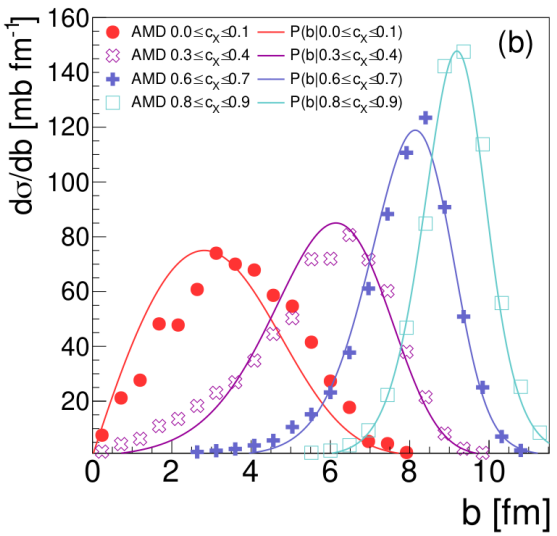


Vary parameterization of *P(X,b)* in order to fit measured *P(X)*

$$P(b|X_1 \le X \le X_2) \sim \int_{X_1}^{X_2} P(X,b)\,\mathrm{d}X$$



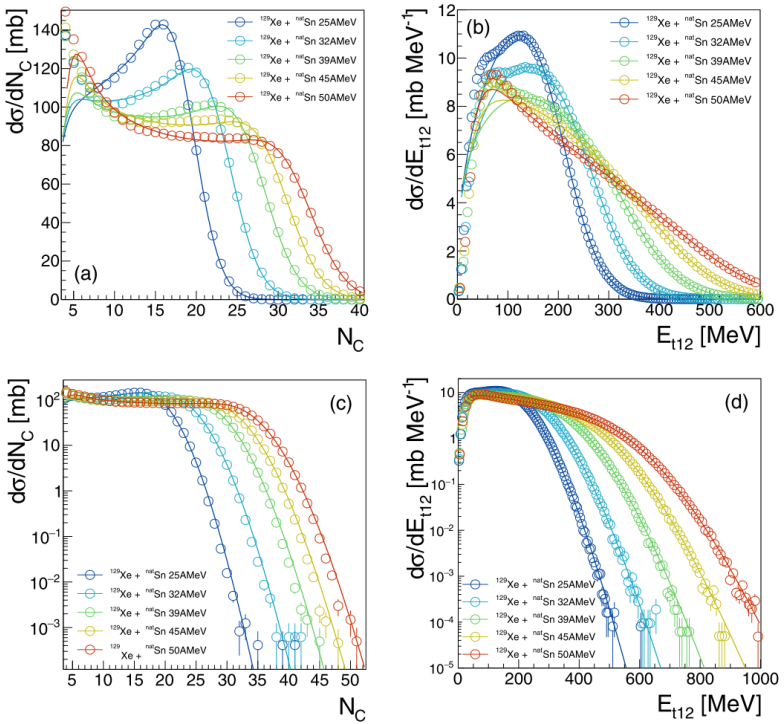
Symbols: AMD *b* distribution for cuts
Curves: reconstructed from fit of *P(X,b)*

Applications to INDRA data

J.D. Frankland, D. Gruyer et al. (INDRA collab.),
Phys. Rev. **C 104**, 034609 (2021) [September 8th]

linear scale

log scale



Fits to multiplicity & LCP transverse energy distributions
INDRA data Xe+Sn 25-50 MeV/nucleon

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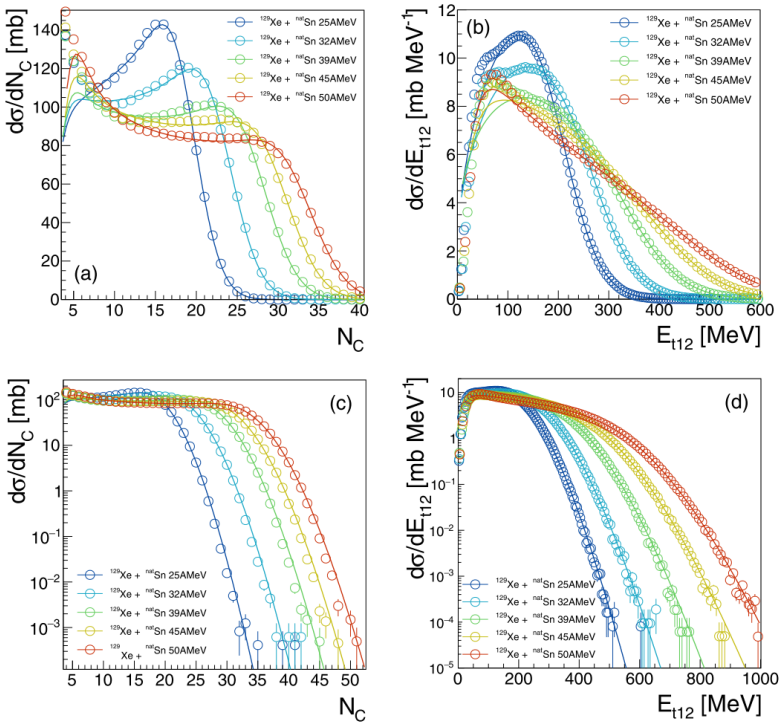

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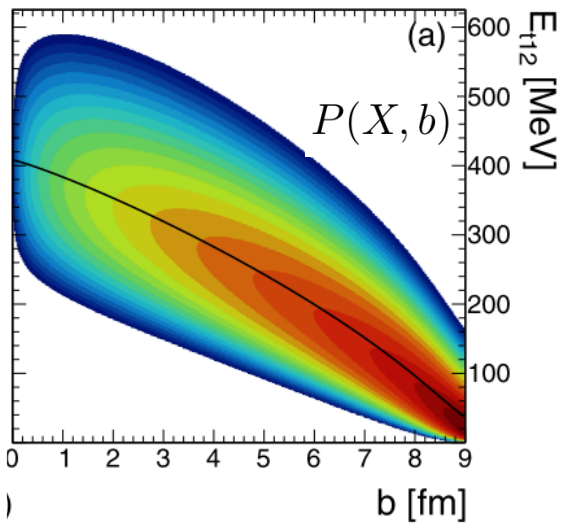

Deduced *P(X,b)* for Xe+Sn 39 MeV/nucleon
INDRA data, total LCP transverse energy

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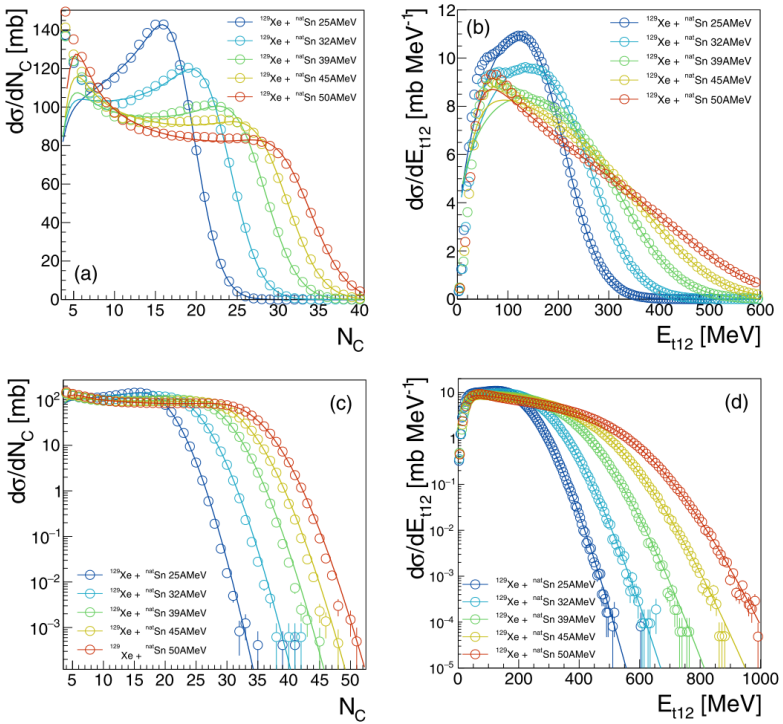

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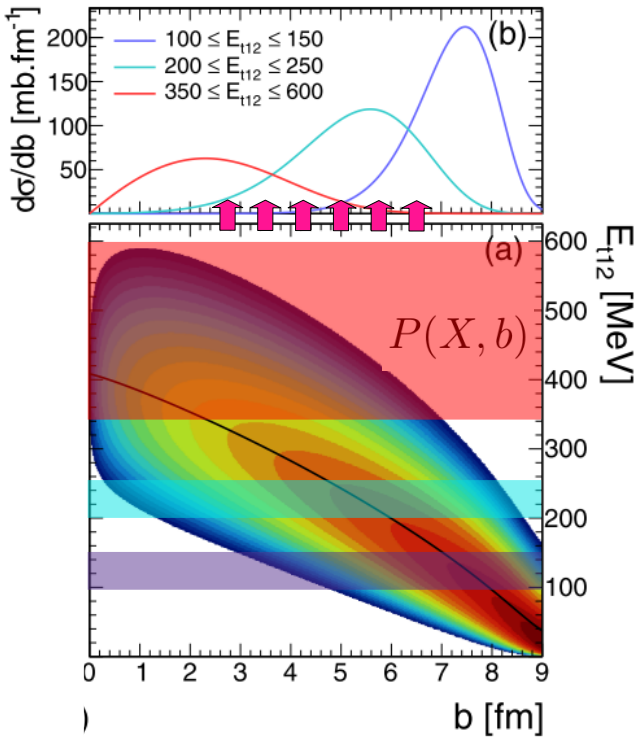

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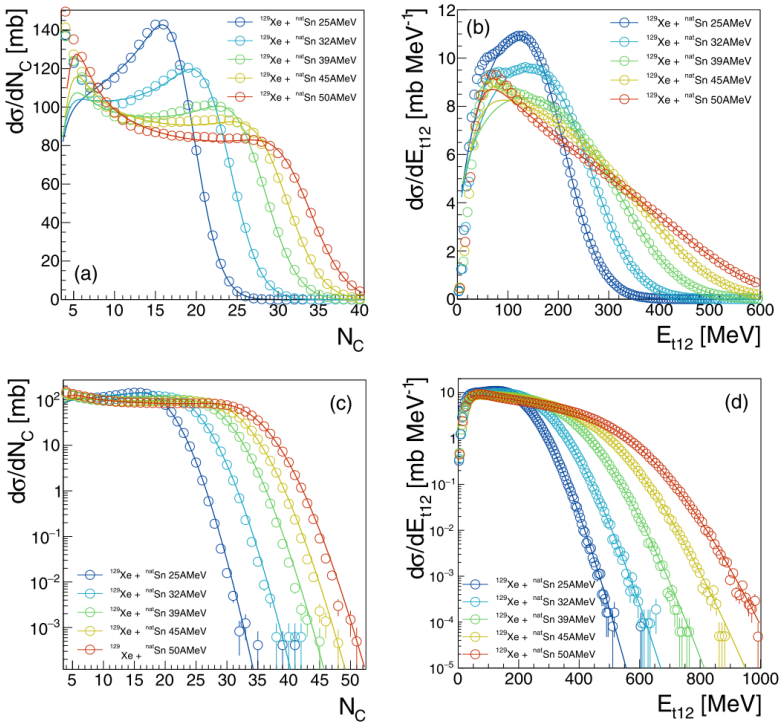

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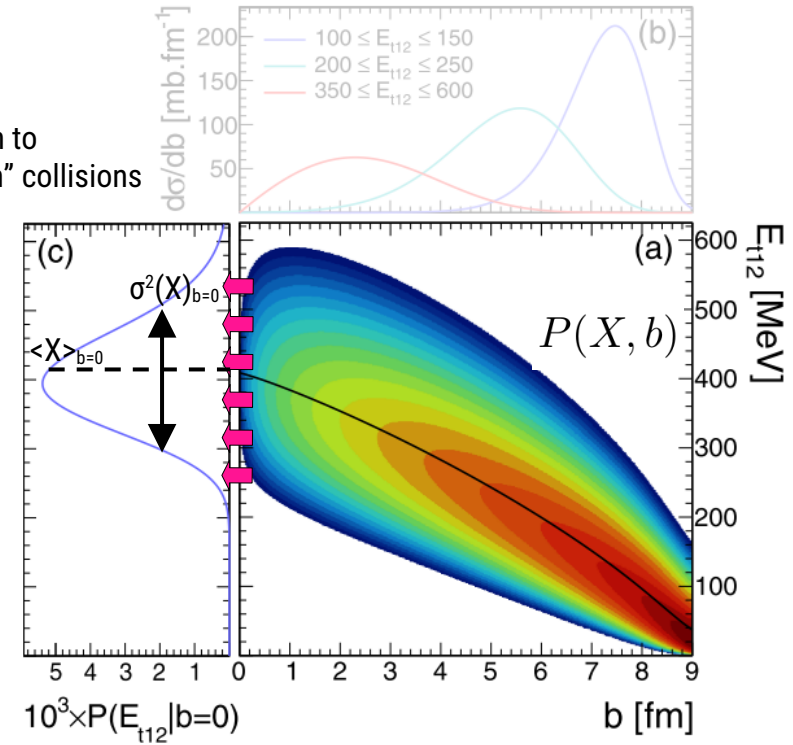

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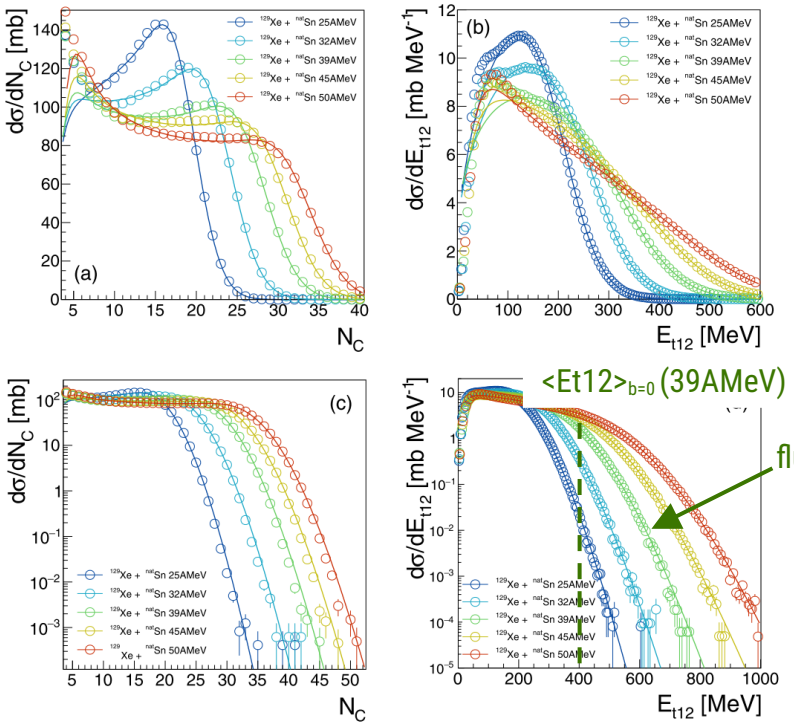

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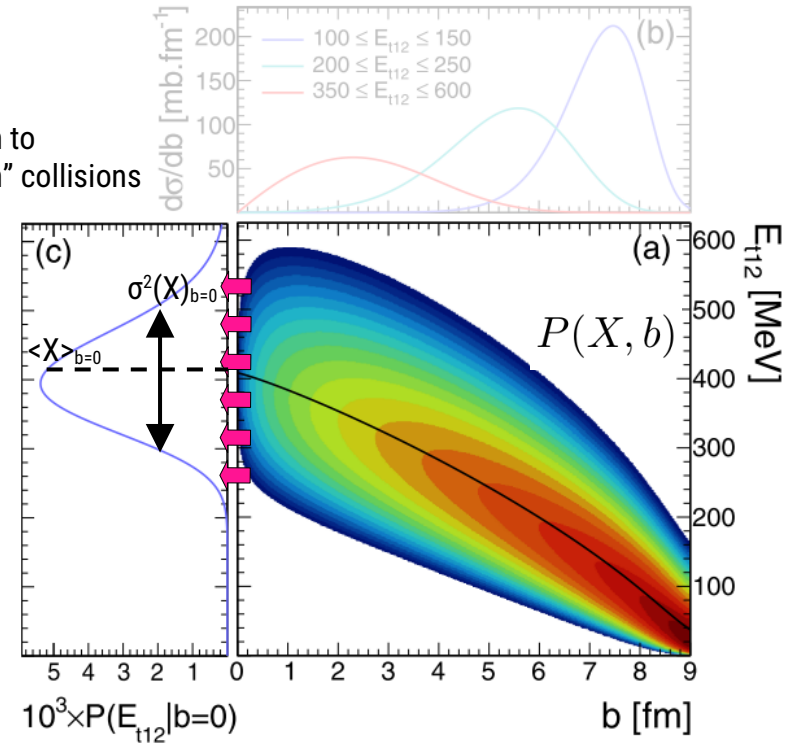

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Systematics for full INDRA dataset

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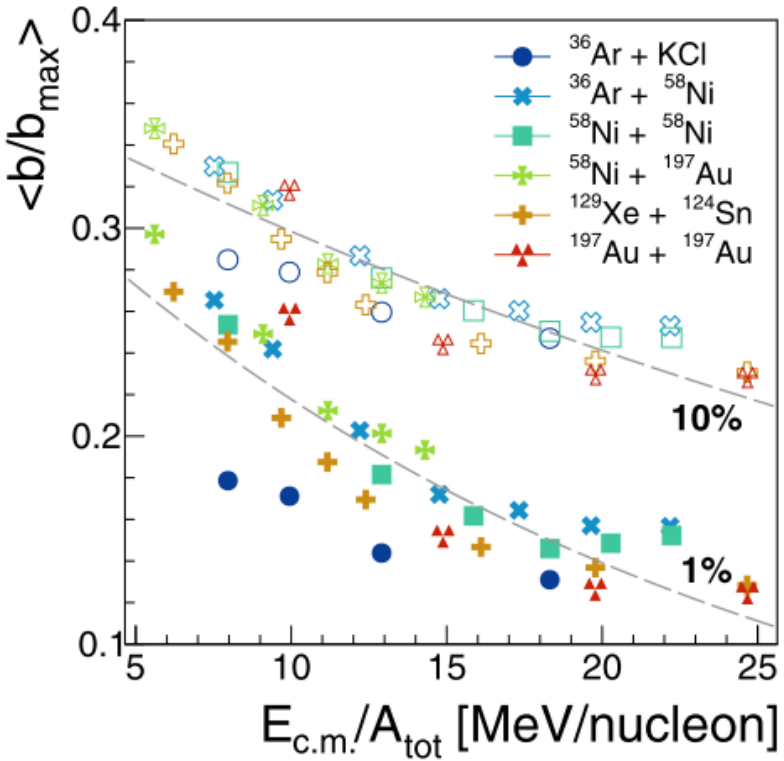

Using *P(X,b)* fitted to data to estimate true centrality for commonly-used experimental selections of “central collisions”

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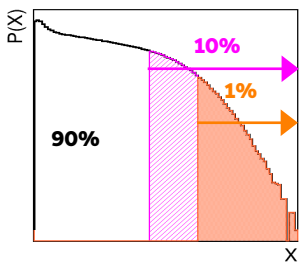
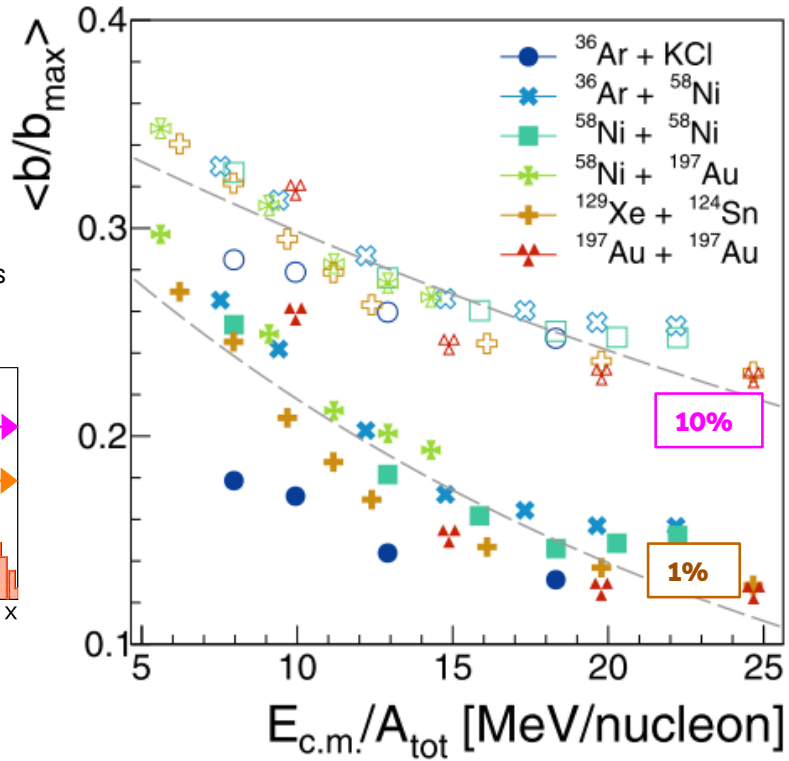
Experimental centrality cuts

$$c_x \equiv \int_x^{\infty} P(X)\,dX$$





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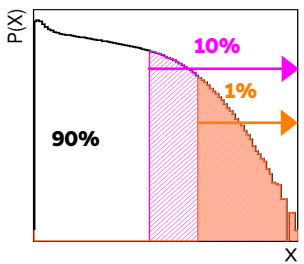

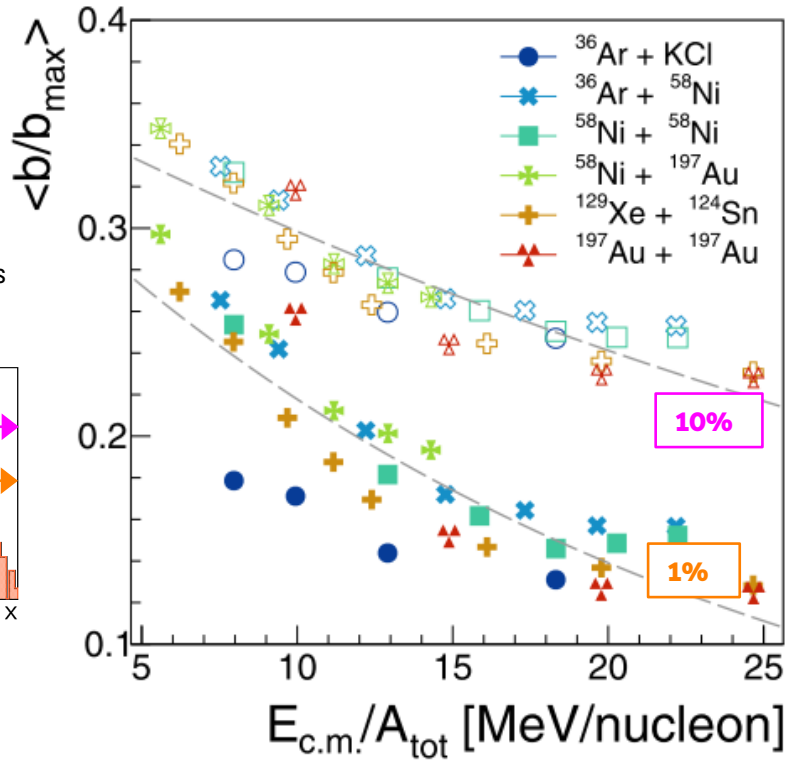

❶ Impact parameter distributions for different experimental selections

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❶ Systematics for different system masses/asymmetries are very similar

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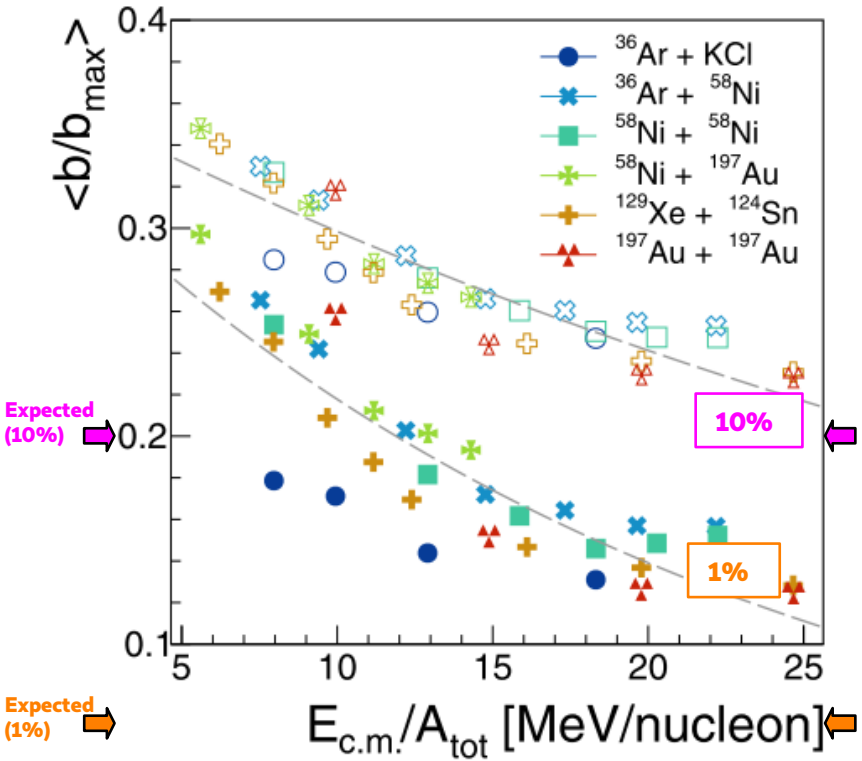

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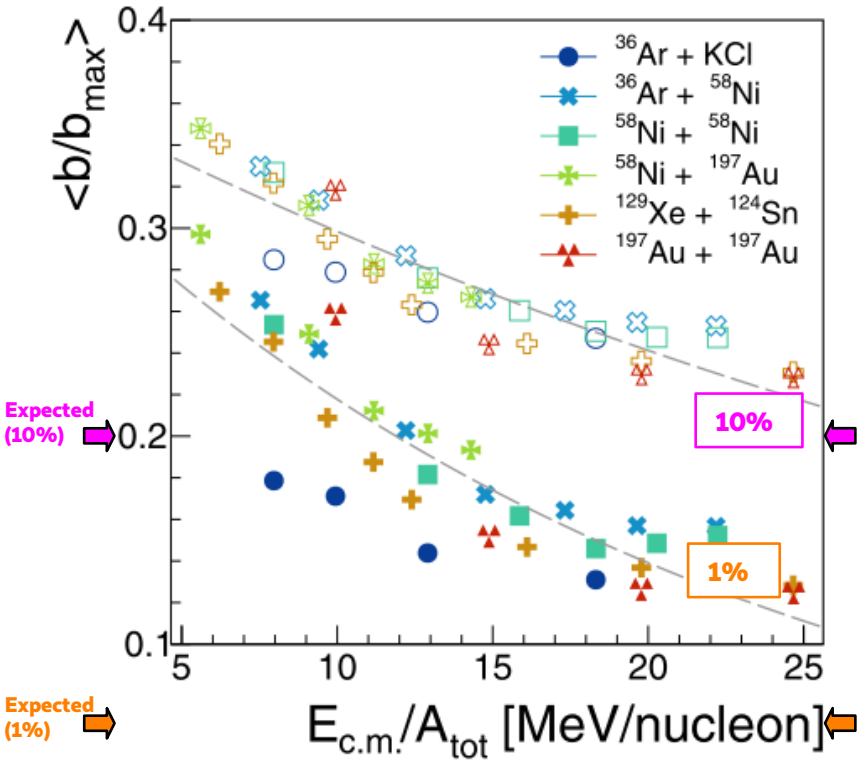

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❶ Systematics for different system masses/asymmetries are very similar

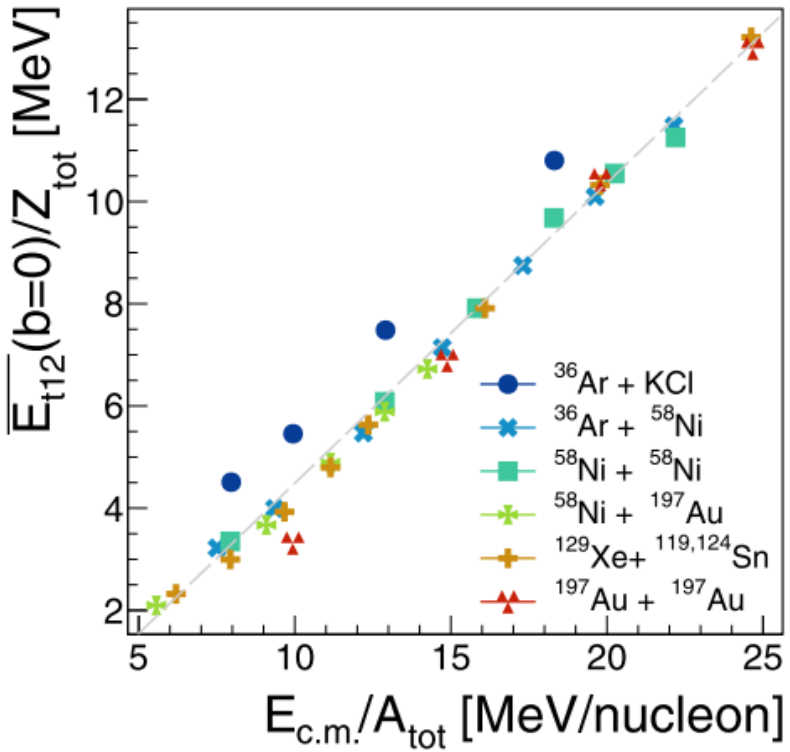
❷ Mean centralities <b/b$_{max}$> are mostly much larger than naïve expectation (sharp cut-off approximation)

❸ Strong energy dependence of true centrality
- beware when making systematic comparisons

Systematics for full INDRA dataset

J.D. Frankland, D. Gruyer et al. (INDRA collab.),
Phys. Rev. **C 104**, 034609 (2021) [September 8th]

2 Extrapolation to
b=0 “head-on” collisions



Using *P(X,b)* fitted to data to extrapolate mean total transverse energy of LCP at *b=0*

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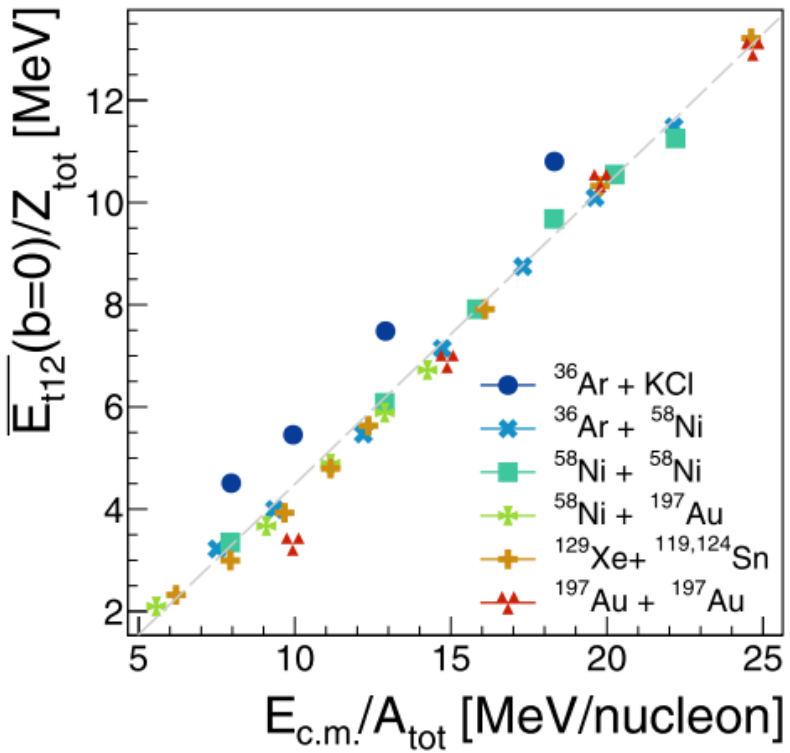

❷ Extrapolation to b=0 “head-on” collisions

Using *P(X,b)* fitted to data to extrapolate mean total transverse energy of LCP at *b=0*

❶ Near-perfect scaling with $Z_{tot}=Z_{proj}+Z_{targ}$ as a function of centre-of-mass energy ?

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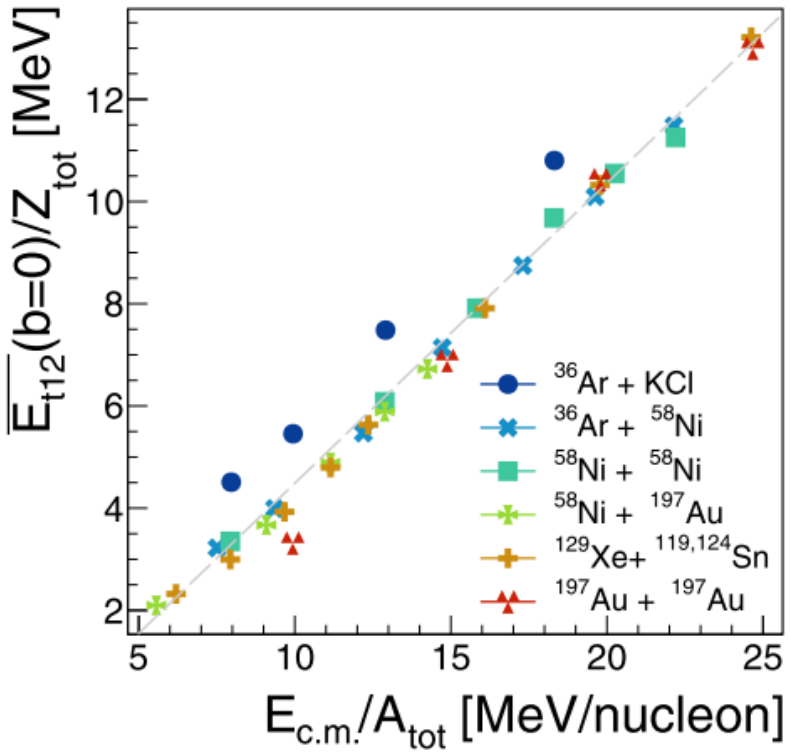
Phys. Rev. **C 104**, 034609 (2021) [September 8th]



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❶ Near-perfect scaling with $Z_{tot}=Z_{proj}+Z_{targ}$ as a function of centre-of-mass energy ?

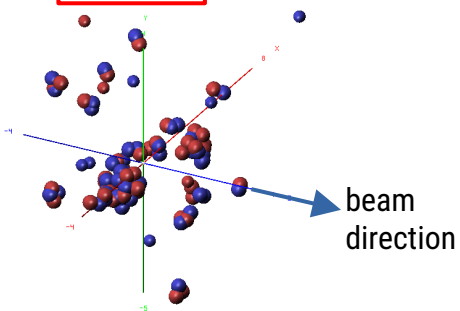
❷ Transverse energy ↔ nuclear stopping/transparency
- mean field vs. NN collisions, in-medium modification of NN cross-sections, …
- benchmark test for transport models? [fast: only need to calculate *b=0*]

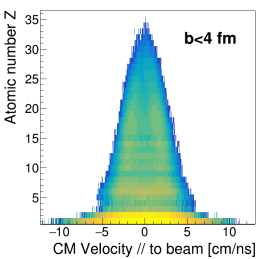
TMEP (Transport Model Evaluation Project)
Xu *et al*., Phys. Rev. **C 93**, 044609 (2016)
Zhang *et al*., Phys. Rev. **C 97**, 034625 (2018)
Colonna *et al*., Phys. Rev. **C 104**, 024603 (2021)

So… “most central collisions” is a rather ambiguous term.
What about “most isotropic” ?

CENTRAL COLLISIONS

b=2.4fm





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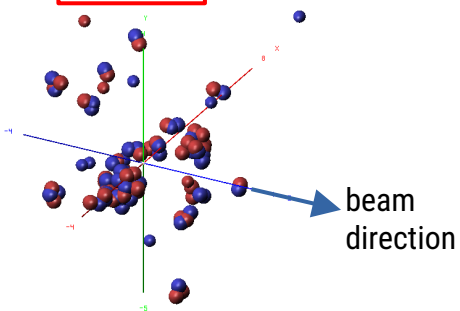
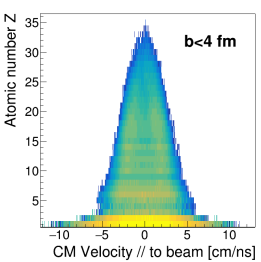
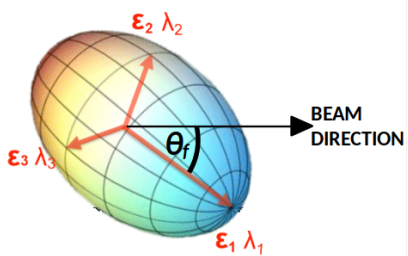




❶ Different ways to measure the apparent isotropy of events (in momentum/energy space)

Momentum/KE Flow Tensor

$$T_{\alpha\beta} = \sum_{i=1} \omega_i p_\alpha(i) p_\beta(i)$$



S: sphericity

Isotropy ratio

$$R_E = \frac{\sum_i E_{i,\perp}}{2\sum_i E_{i,\parallel}} = \frac{\sum_i E_i \sin^2\theta_i}{2\sum_i E_i \cos^2\theta_i}$$

parallel/perpendicular to beam direction

R_E^{ell}: wrt ellipsoid axes

R_E^{fw}: forward-CM only

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CENTRAL COLLISIONS

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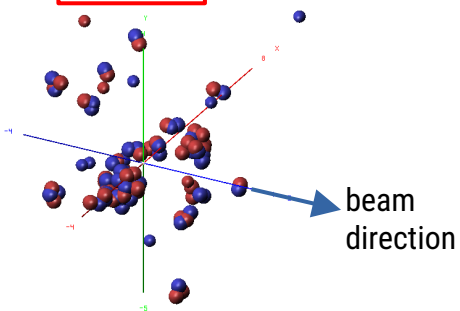

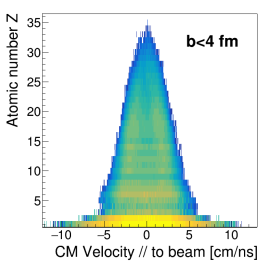

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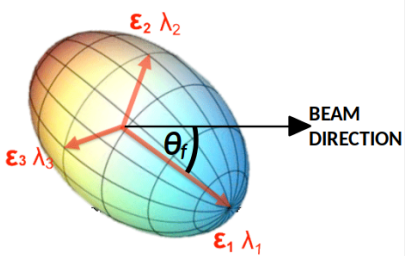

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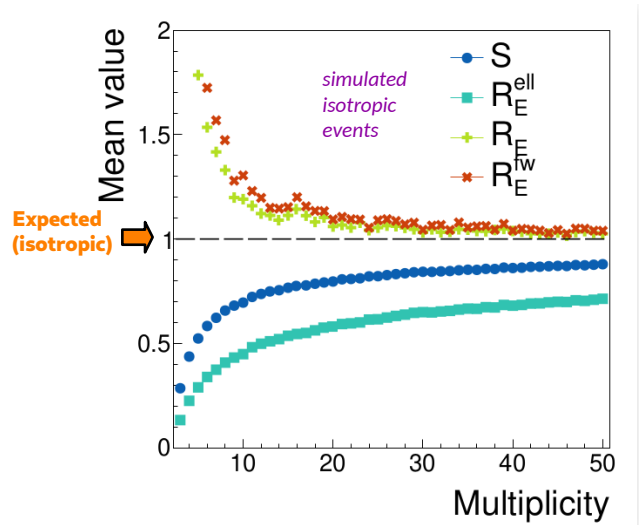
❷ Apparent isotropy is strongly multiplicity-dependent



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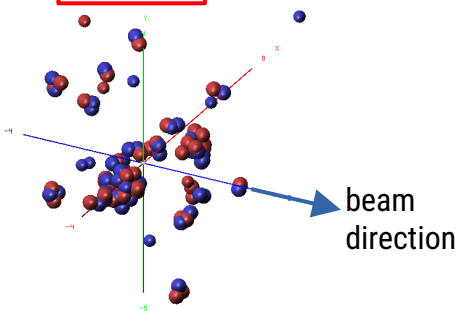

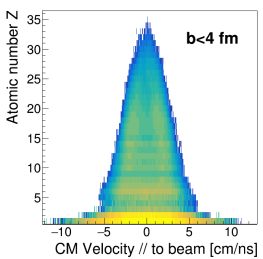

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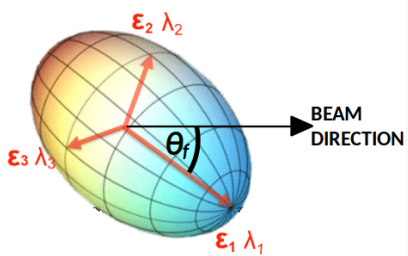
$$T_{\alpha\beta} = \sum_{i=1} \omega_i p_\alpha(i) p_\beta(i)$$

S: sphericity



Isotropy ratio

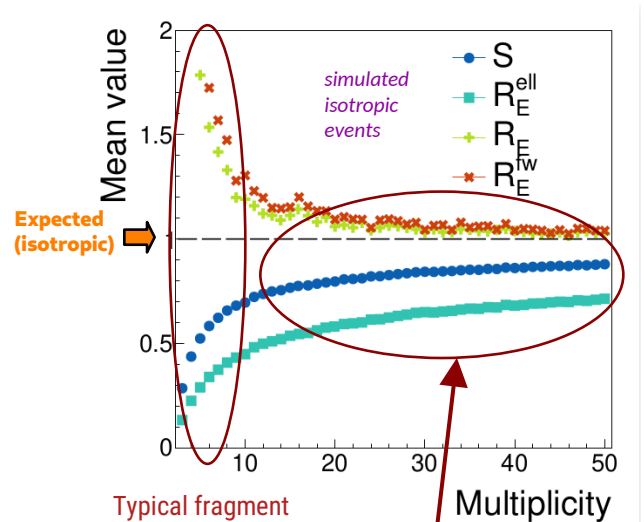
$$R_E = \frac{\sum_i E_{i,\perp}}{2\sum_i E_{i,\parallel}} = \frac{\sum_i E_i \sin^2\theta_i}{2\sum_i E_i \cos^2\theta_i}$$

parallel/perpendicular to beam direction

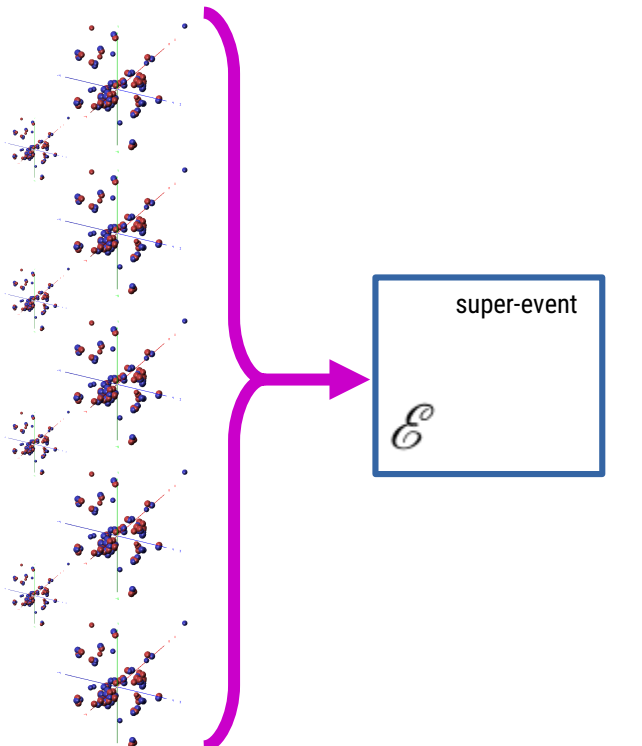
R_E^{ell}: wrt ellipsoid axes

R_E^{fw}: forward-CM only

❷ Apparent isotropy is strongly multiplicity-dependent



Maximizing the isotropy of “infinite” multiplicity super-events



$\mathscr{E}$ sample size: 2000 events

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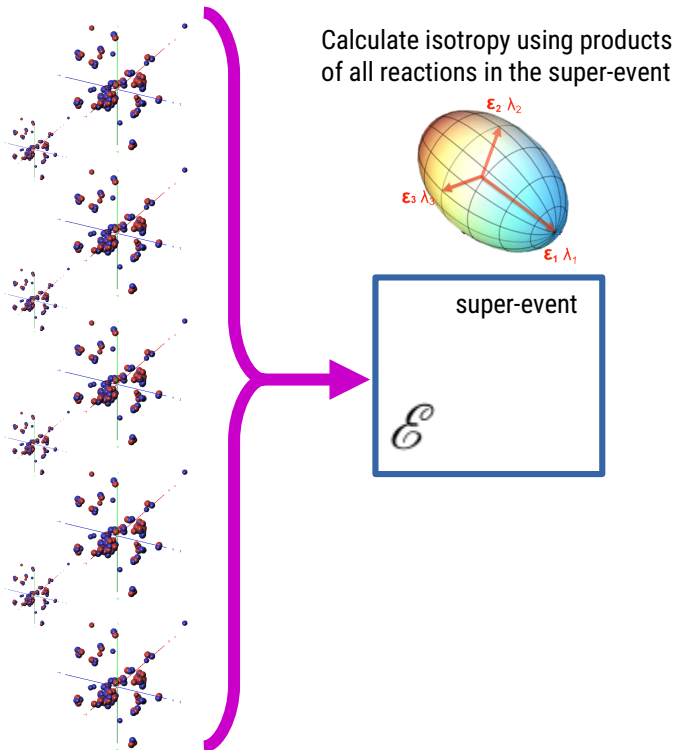
Maximizing the isotropy of “infinite” multiplicity super-events



Calculate isotropy using products of all reactions in the super-event

$\mathscr{E}$ sample size: 2000 events

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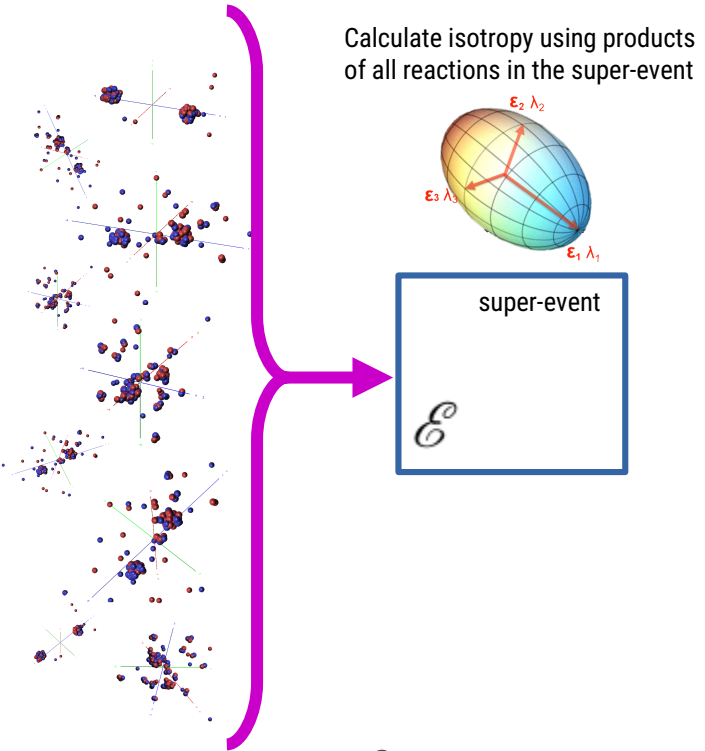
Maximizing the isotropy of “infinite” multiplicity super-events



Calculate isotropy using products of all reactions in the super-event

super-event

$\mathscr{E}$

$\mathscr{E}$ sample size: 2000 events

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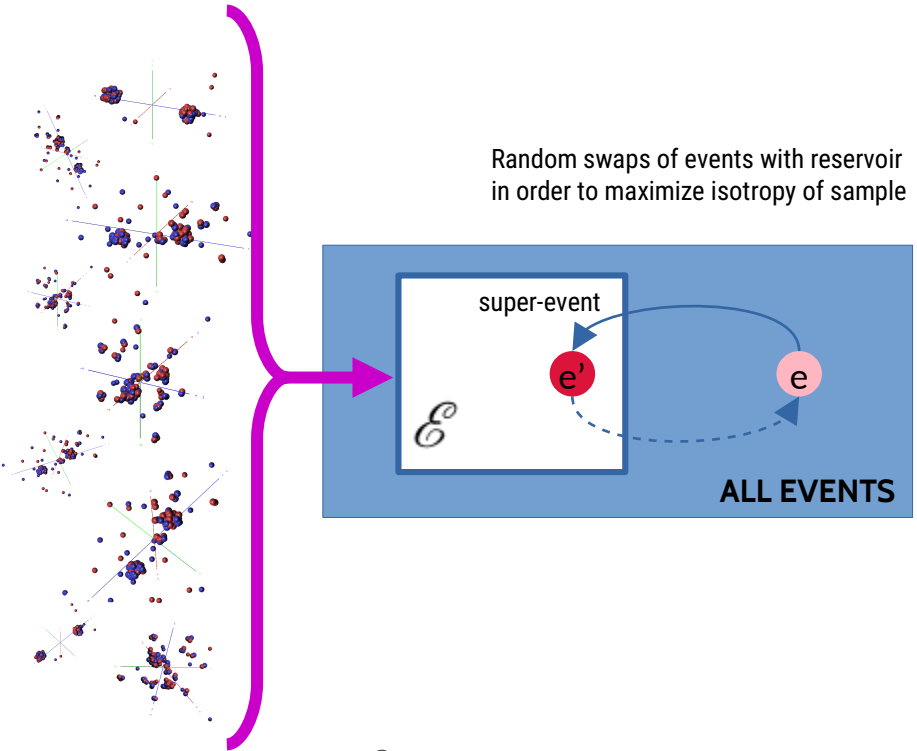
Maximizing the isotropy of “infinite” multiplicity super-events



Random swaps of events with reservoir in order to maximize isotropy of sample

$\mathscr{E}$ sample size: 2000 events

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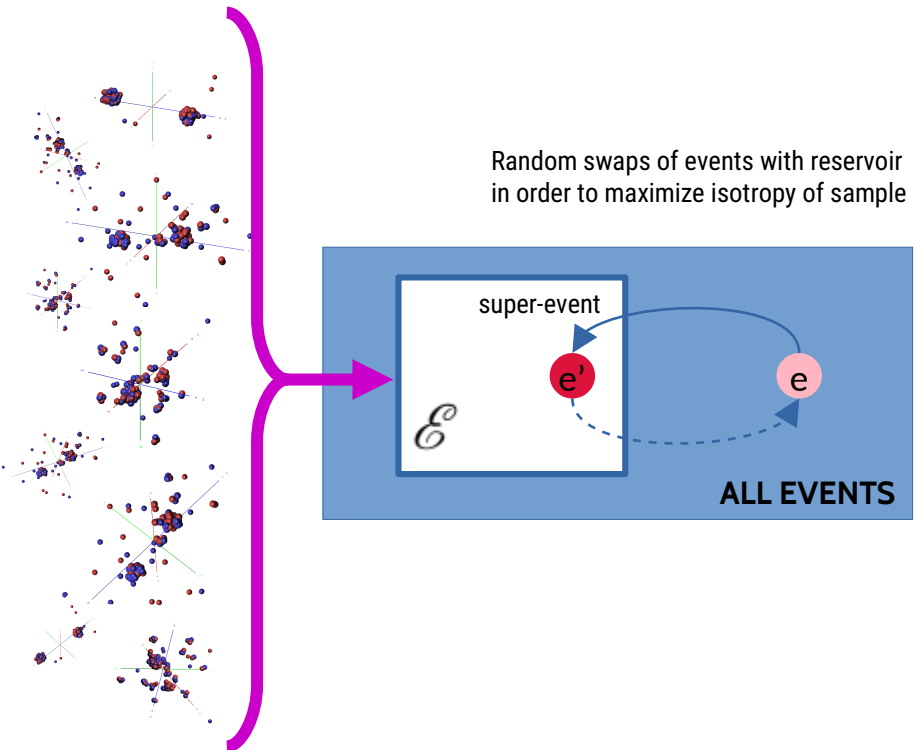
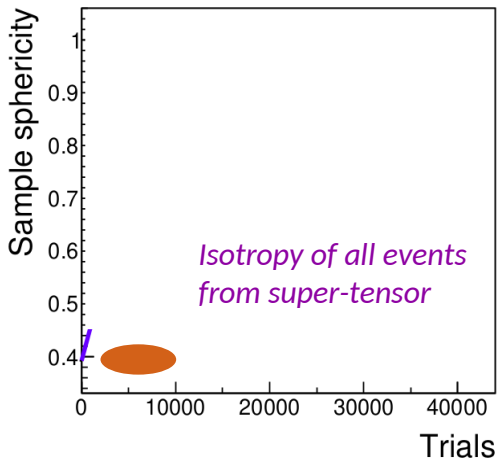
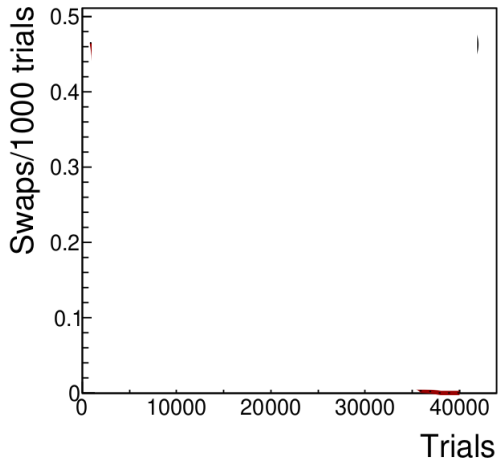
Maximizing the isotropy of “infinite” multiplicity super-events



Random swaps of events with reservoir in order to maximize isotropy of sample

$\mathscr{E}$ sample size: 2000 events





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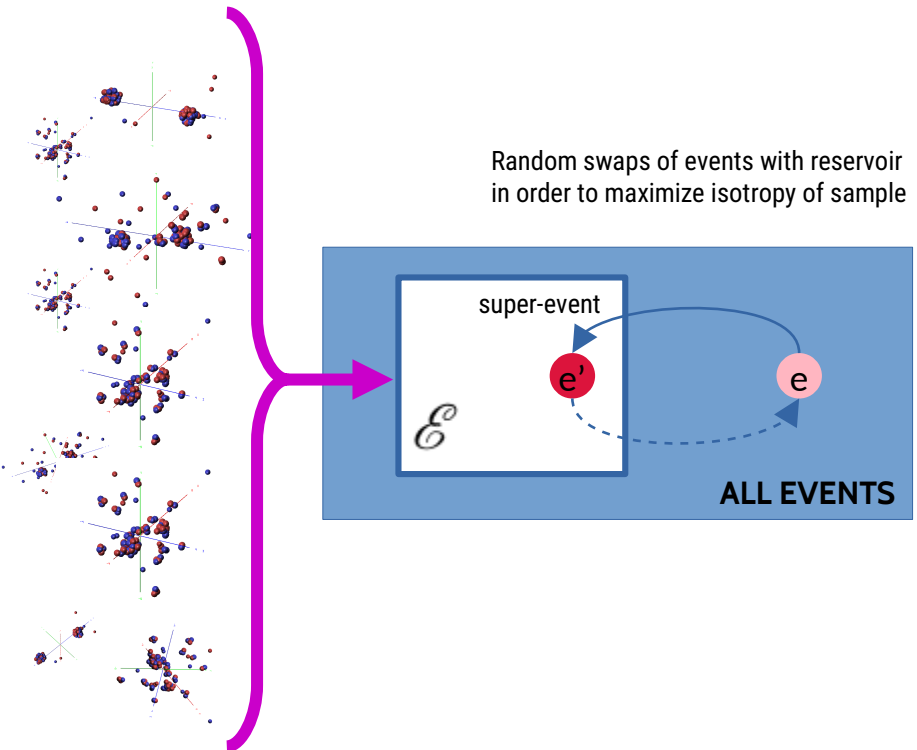
Maximizing the isotropy of “infinite” multiplicity super-events



Random swaps of events with reservoir in order to maximize isotropy of sample

$\mathscr{E}$ sample size: 2000 events

J.D. Frankland, HDR, Université de Caen (2020)
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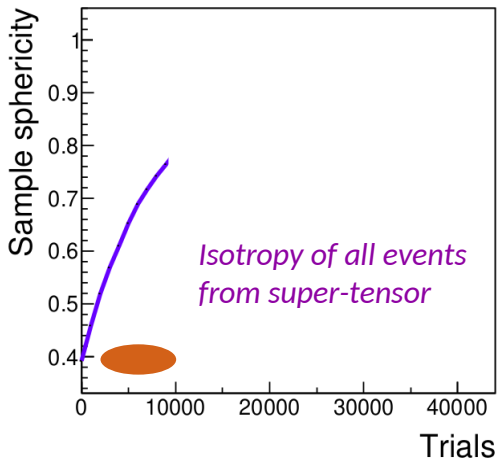
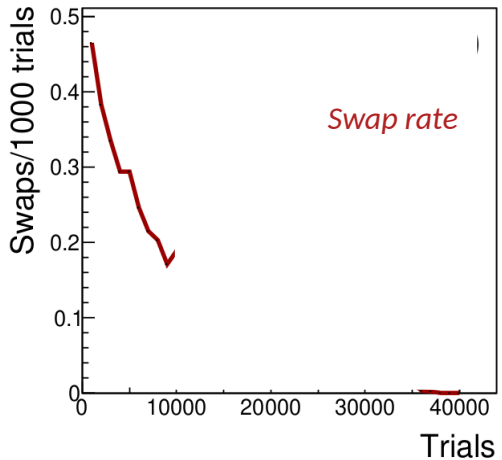
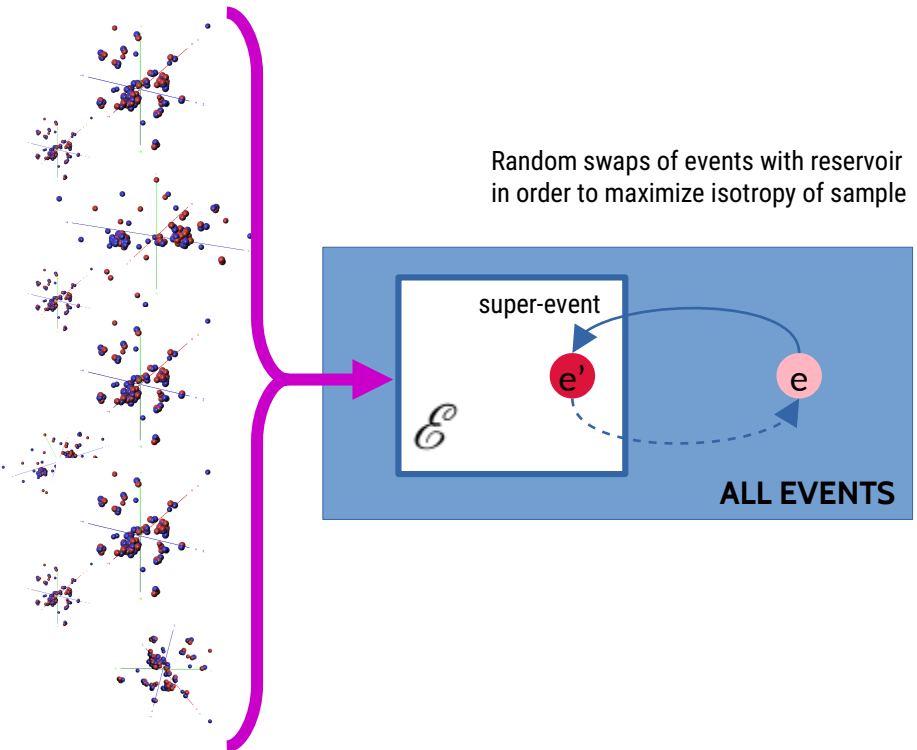


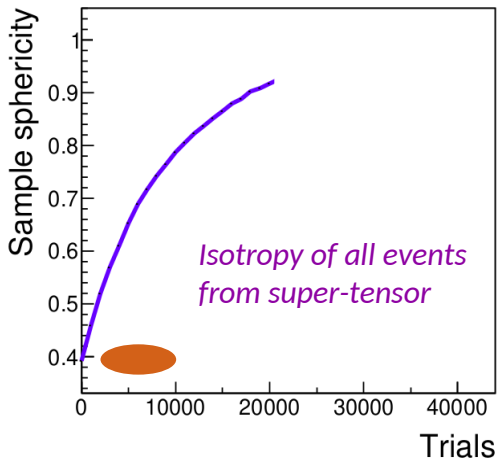


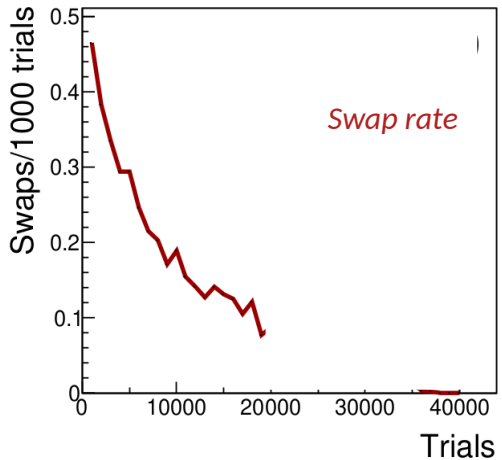
Maximizing the isotropy of “infinite” multiplicity super-events



Random swaps of events with reservoir in order to maximize isotropy of sample

$\mathscr{E}$ sample size: 2000 events





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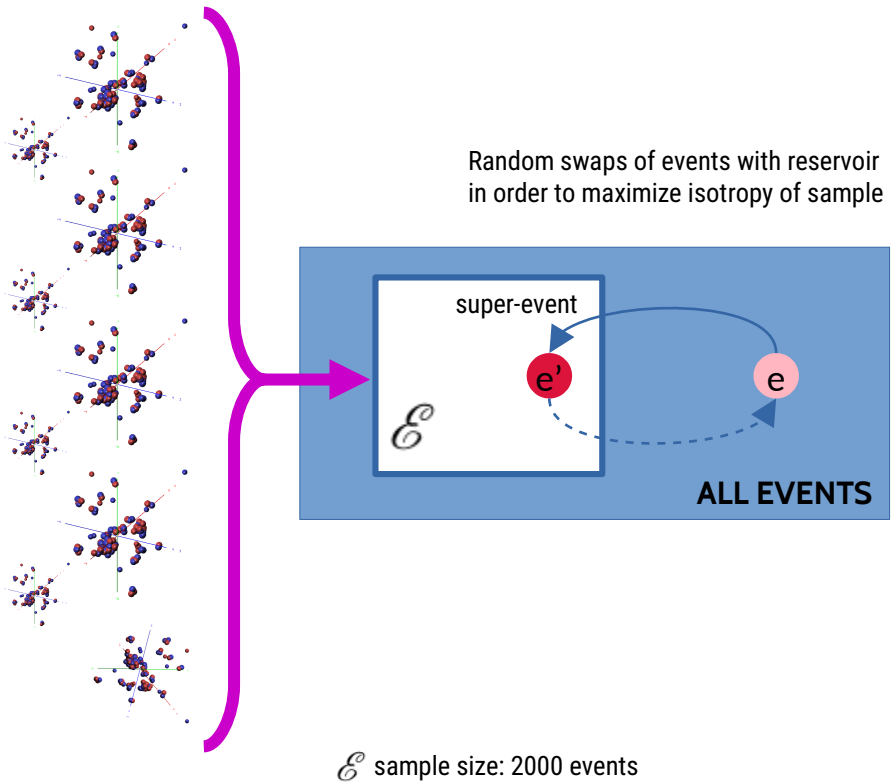
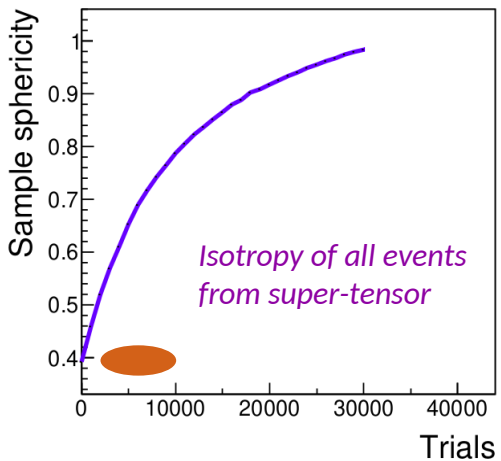
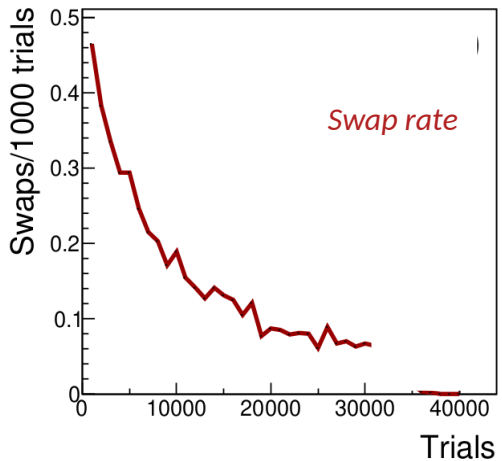
Maximizing the isotropy of “infinite” multiplicity super-events



$\mathscr{E}$ sample size: 2000 events





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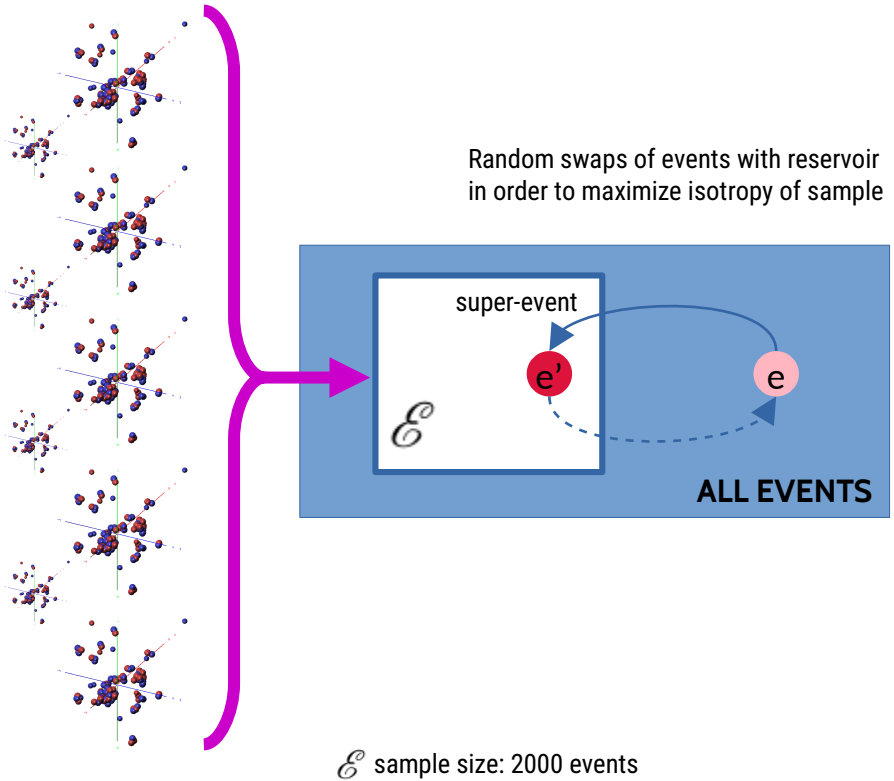
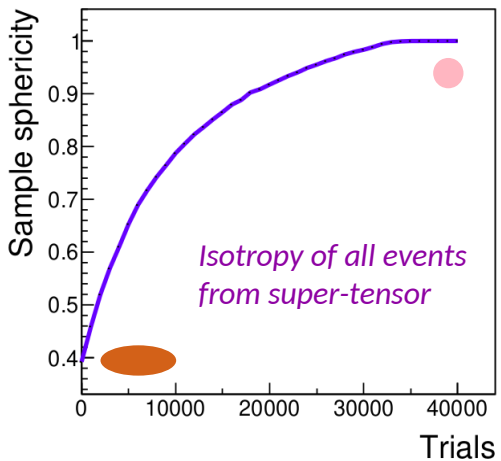
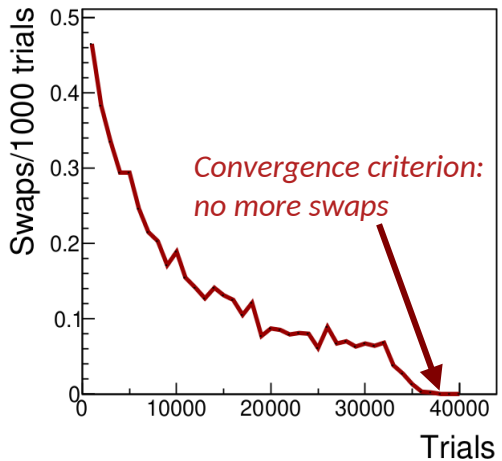
Maximizing the isotropy of “infinite” multiplicity super-events







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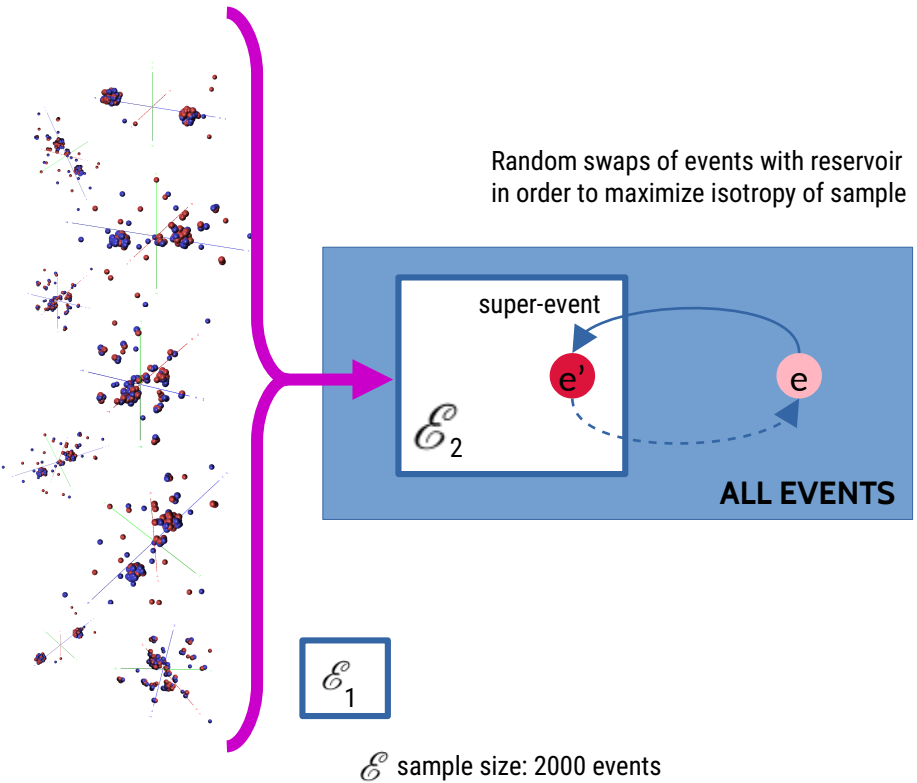
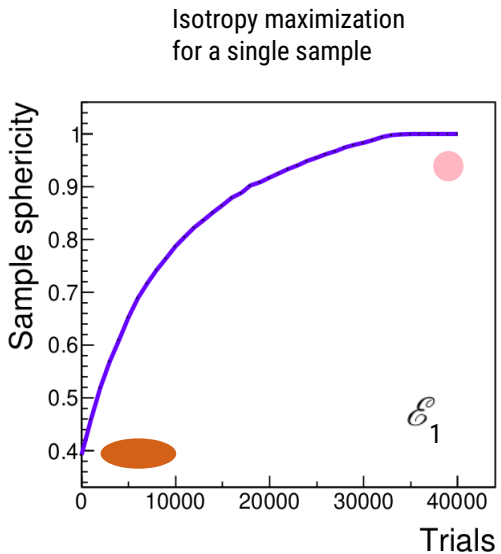
Maximizing the isotropy of “infinite” multiplicity super-events





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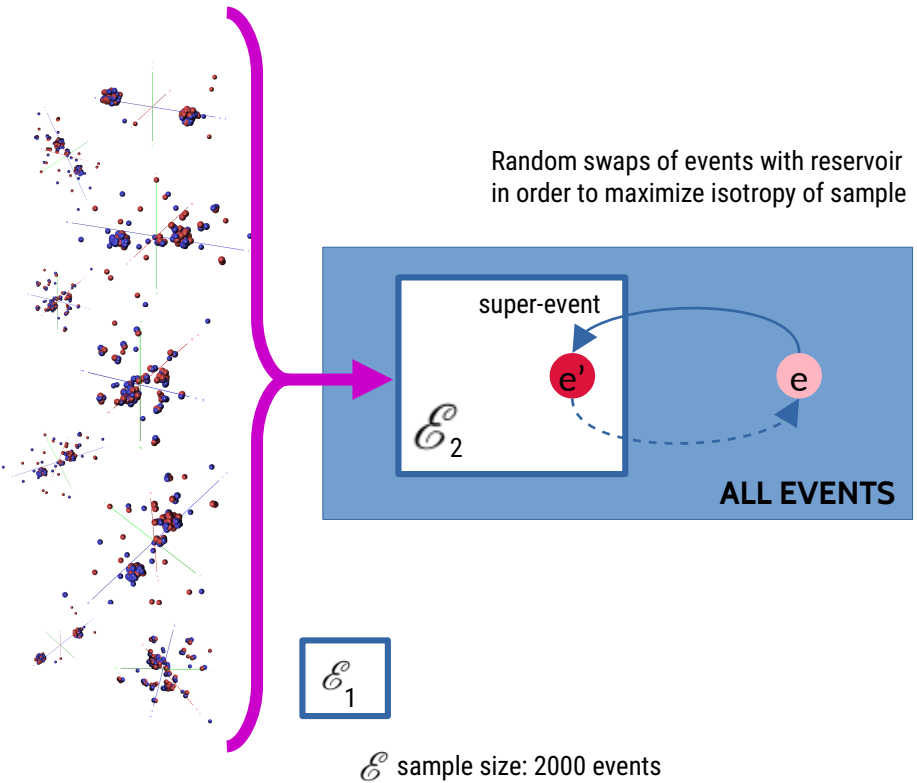
Maximizing the isotropy of “infinite” multiplicity super-events



Random swaps of events with reservoir in order to maximize isotropy of sample

$\mathscr{E}_1$

$\mathscr{E}$ sample size: 2000 events

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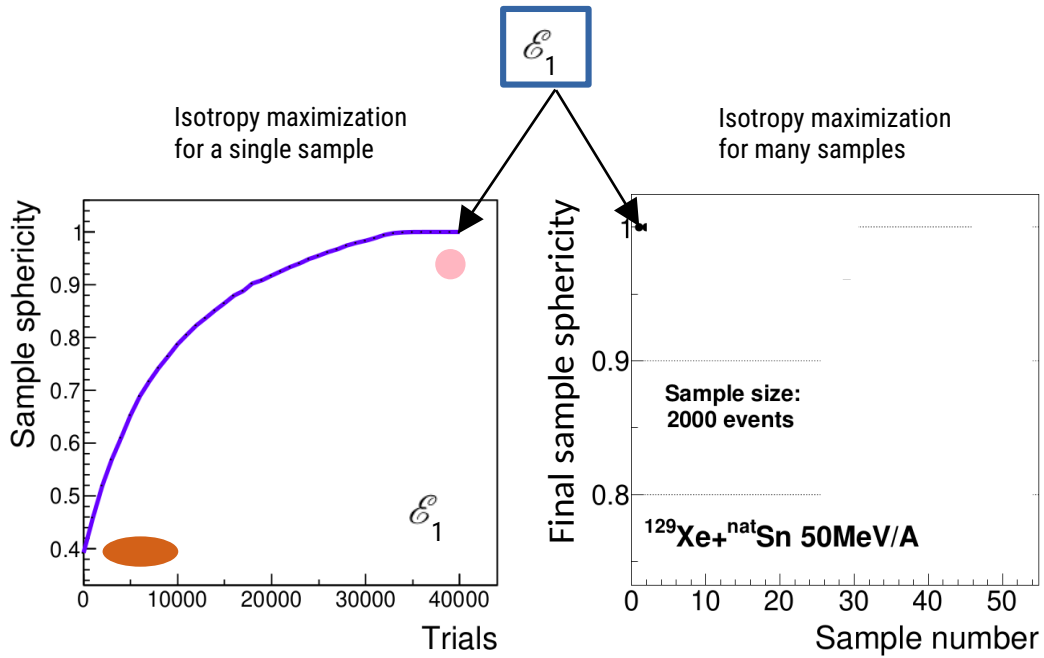
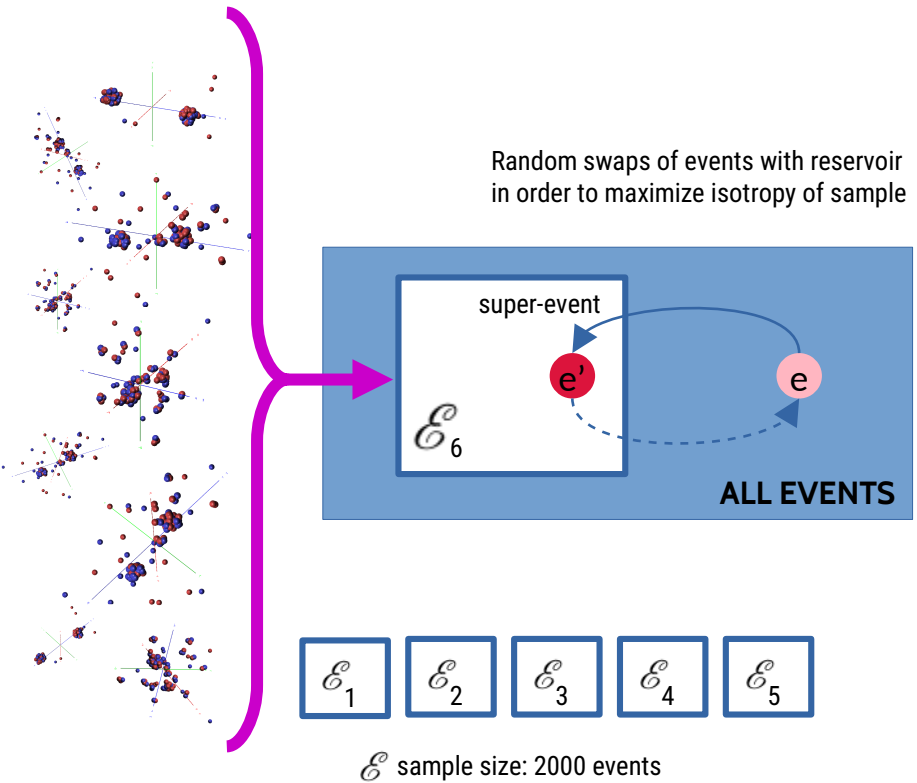
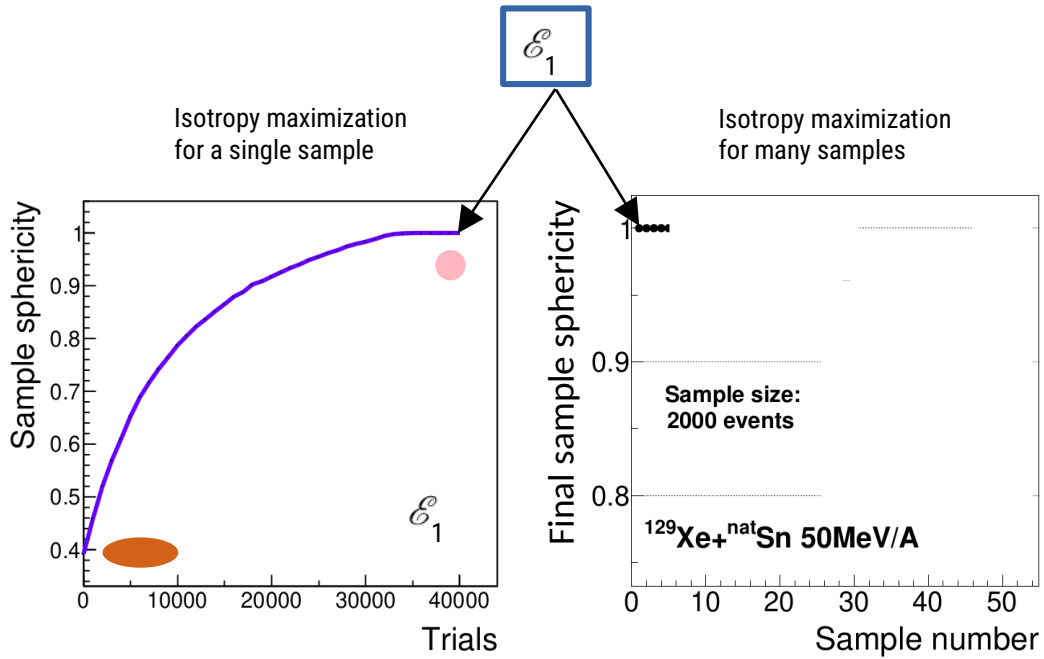


Maximizing the isotropy of “infinite” multiplicity super-events





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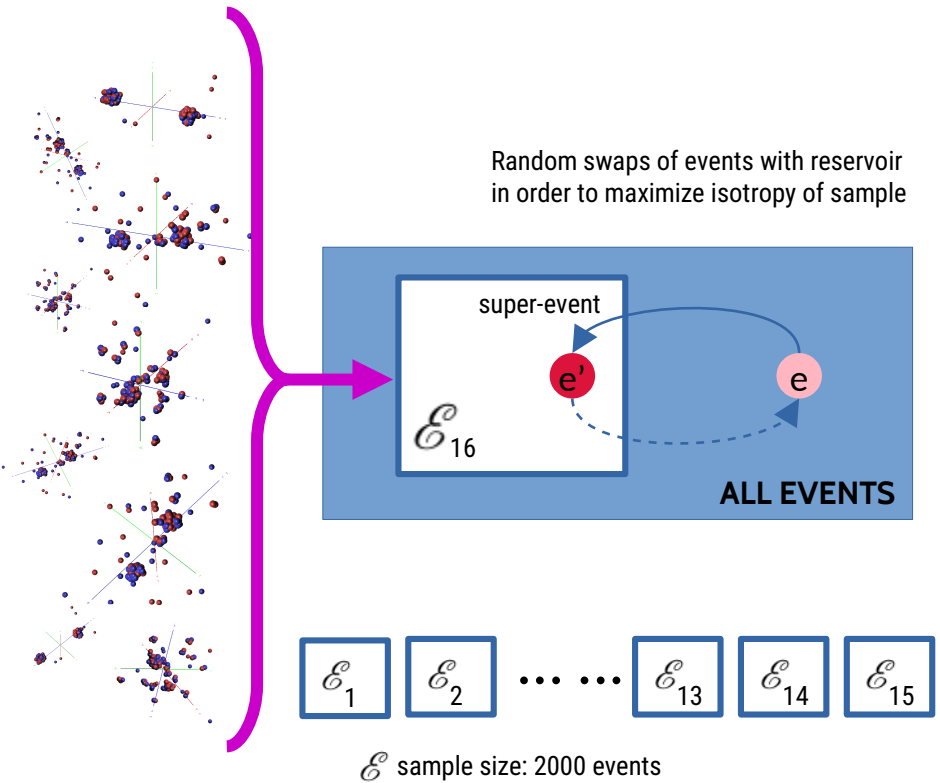
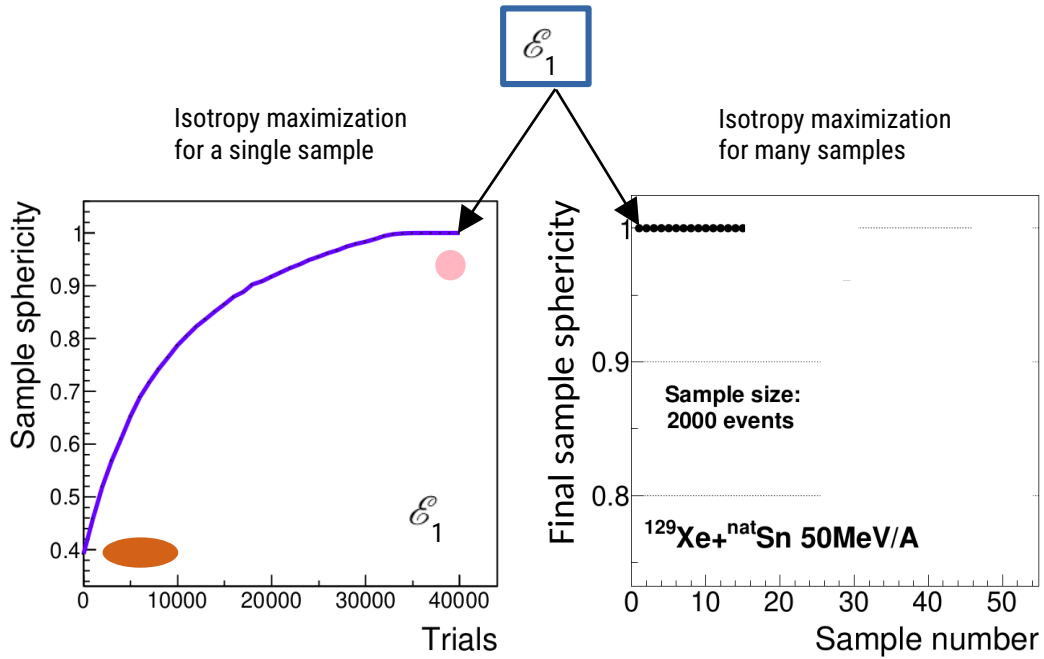
Maximizing the isotropy of “infinite” multiplicity super-events





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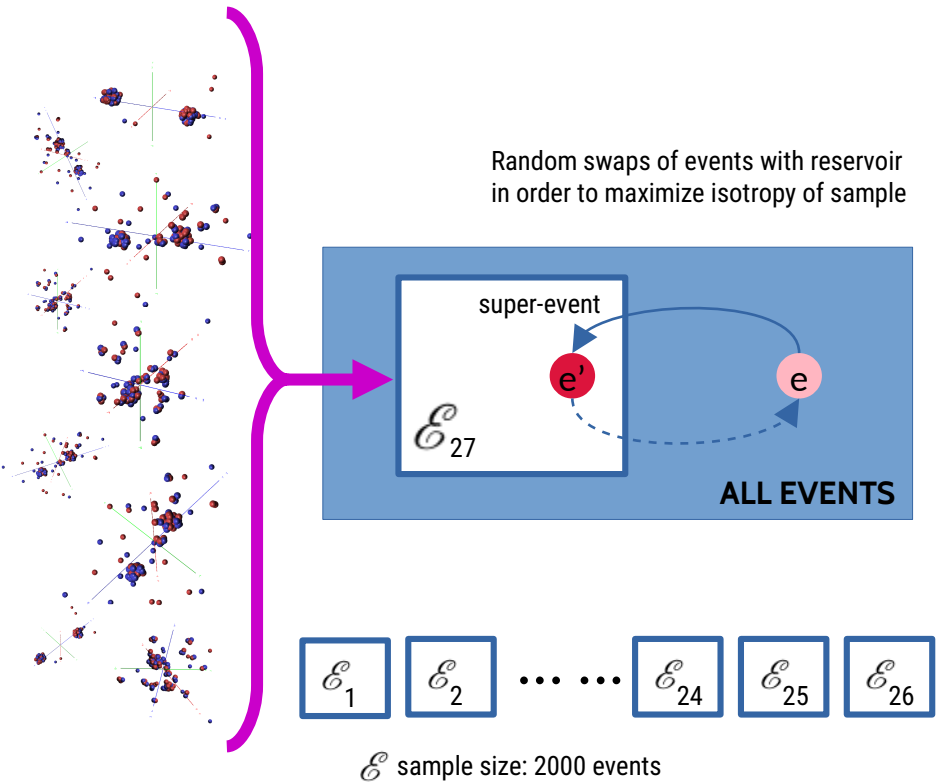
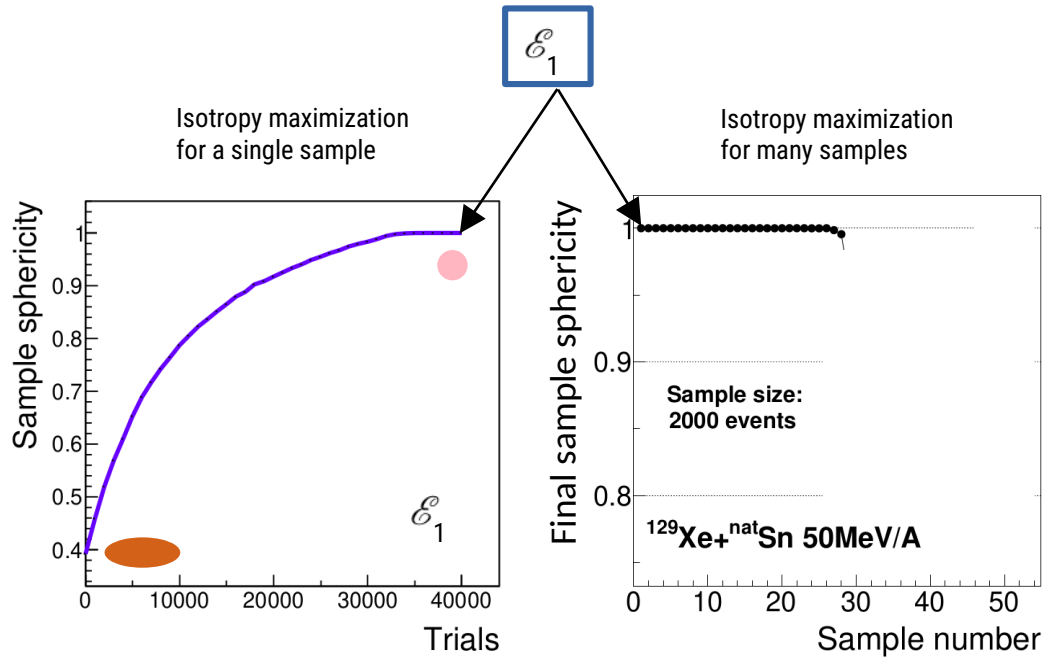
Maximizing the isotropy of “infinite” multiplicity super-events





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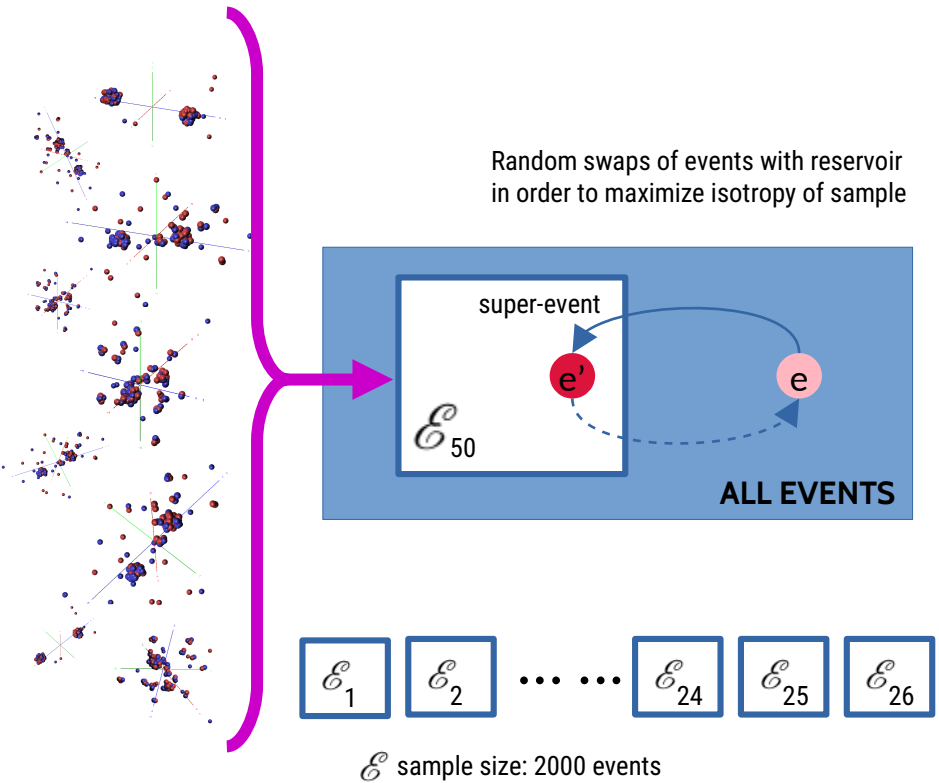
Maximizing the isotropy of “infinite” multiplicity super-events



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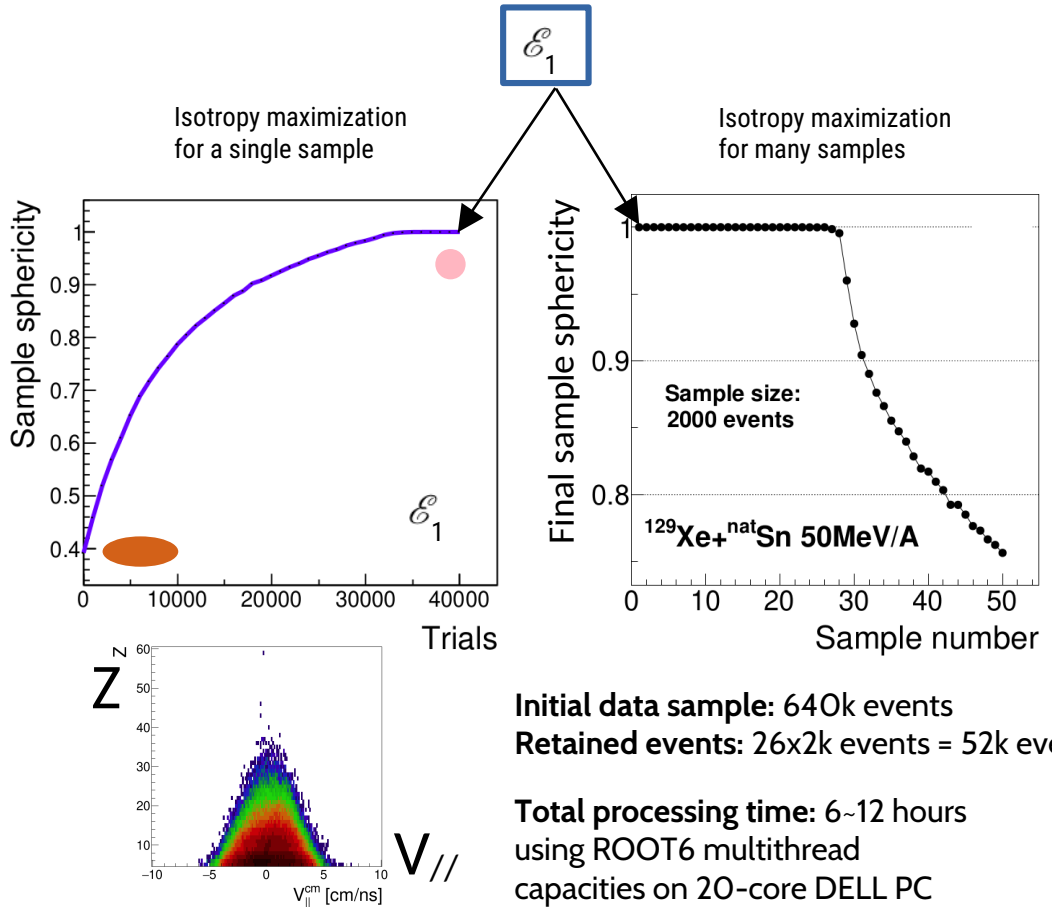
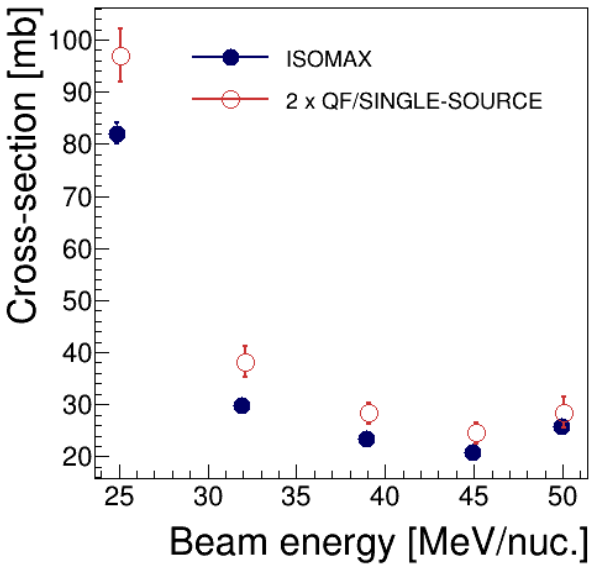


Initial data sample: 640k events
Retained events: 26x2k events = 52k events

Total processing time: 6~12 hours using ROOT6 multithread capacities on 20-core DELL PC

Cross-sections for most isotropic (ISOMAX) events



❶ Cross-sections decrease with bombarding energy

INDRA data Xe+Sn 25-50 MeV/nucleon

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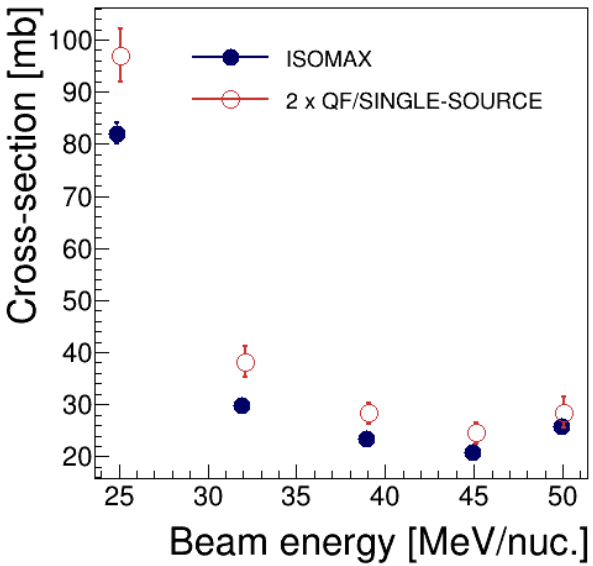
tel-03064998

Cross-sections for most isotropic (ISOMAX) events



INDRA data Xe+Sn 25-50 MeV/nucleon

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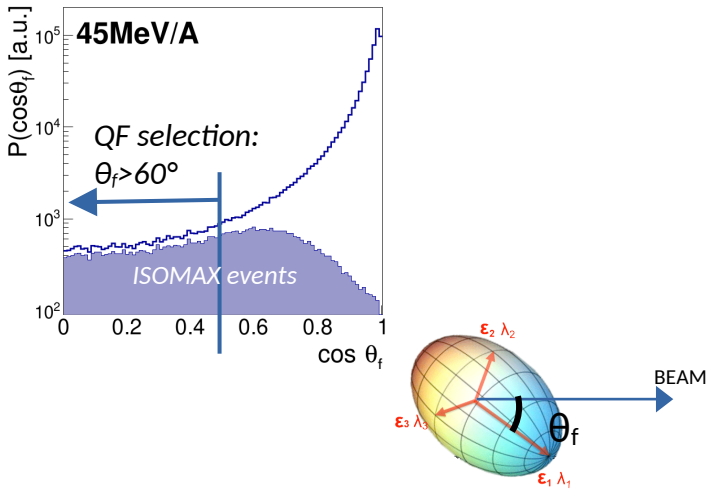
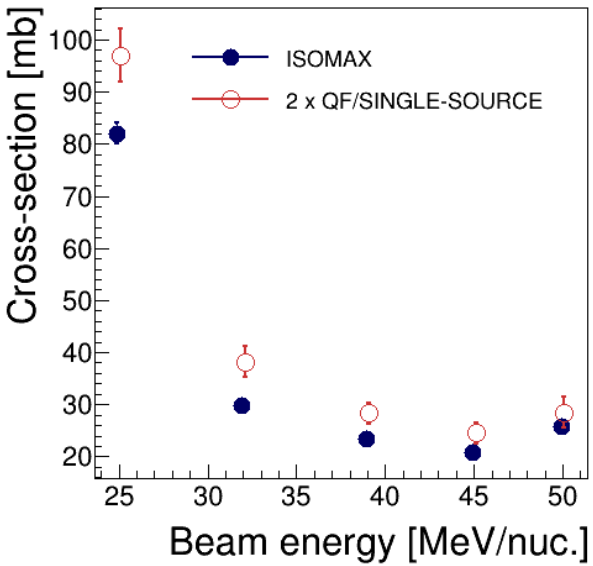
tel-03064998

❶ Cross-sections decrease with bombarding energy

❷ Similar to cross-sections for single-source/quasifusion multifragmentation events
+ fragment multiplicities, partitions etc. same [not shown]



Cross-sections for most isotropic (ISOMAX) events



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❶ Cross-sections decrease with bombarding energy

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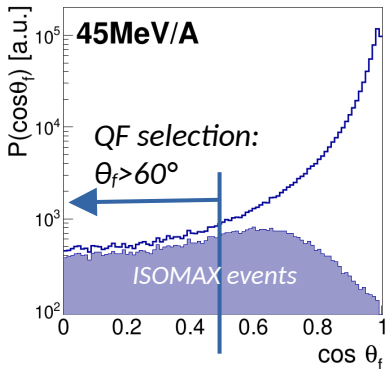
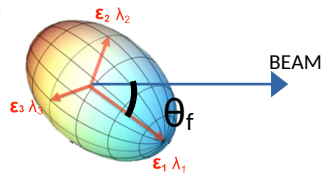
+ fragment multiplicities, partitions etc. same [not shown]

❸ Most of historical QF events included in most isotropic events

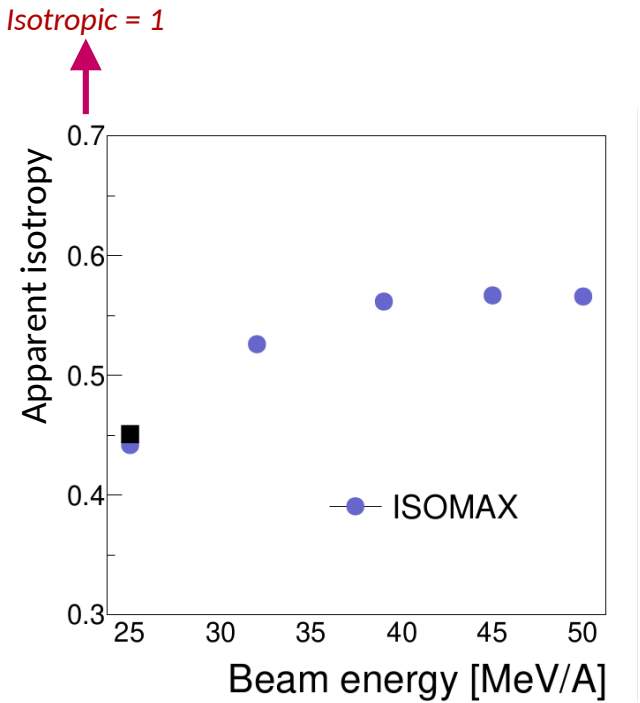


Historical INDRA works using QF events to study LG phase transition in nuclei

Marie et al., PLB (1997)
Frankland et al., NPA (2001)
Botet et al., PRL (2001)
D'Agostino et al., NPA (2002)
Le Neindre et al., NPA (2007)
Piantelli et al., NPA (2008)
Bonnet et al., NPA (2009)
Borderie et al., PLB (2013)
etc. etc.



So just how isotropic *are* the most isotropic events?

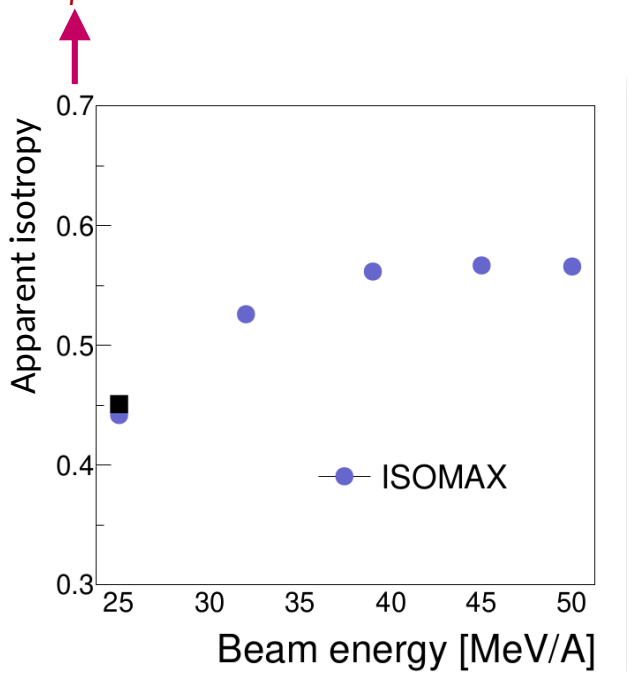


INDRA data Xe+Sn 25-50 MeV/nucleon

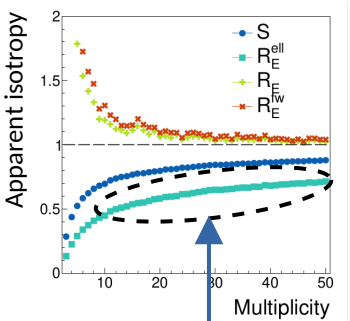
J.D. Frankland, HDR, Université de Caen (2020)
tel-03064998

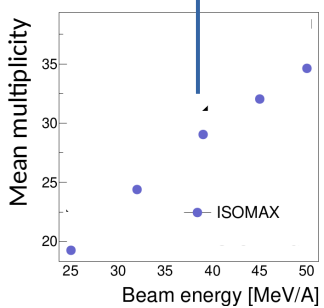
So just how isotropic *are* the most isotropic events?

Isotropic = 1



Beware of effect of multiplicity increase on apparent isotropy





INDRA data Xe+Sn 25-50 MeV/nucleon

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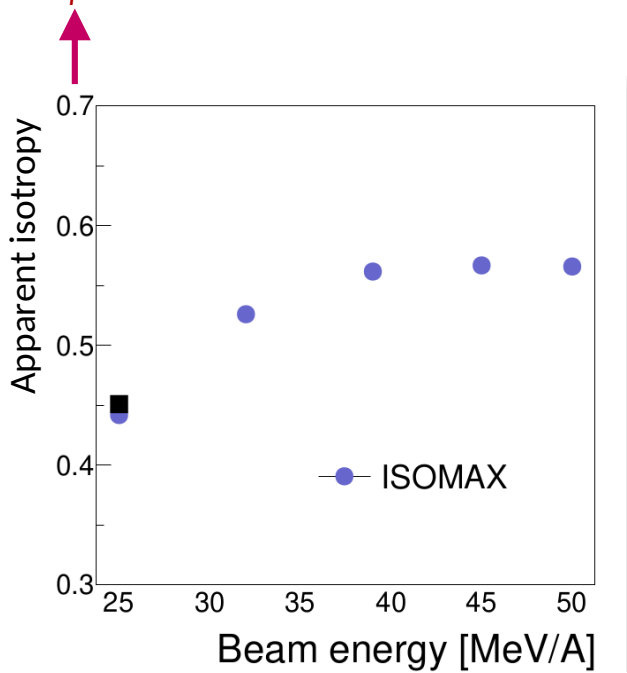
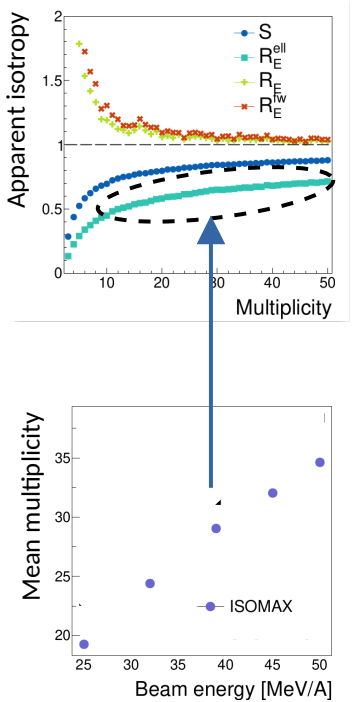
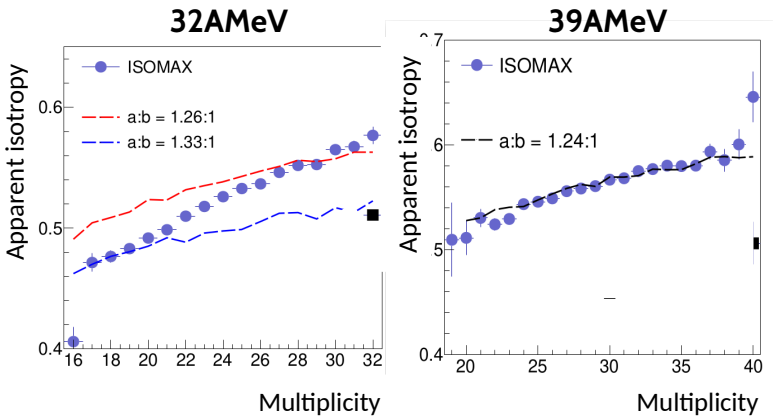


Beware of effect of multiplicity increase on apparent isotropy



Fit multiplicity dependence to simulated anisotropic distributions



INDRA data Xe+Sn 25-50 MeV/nucleon

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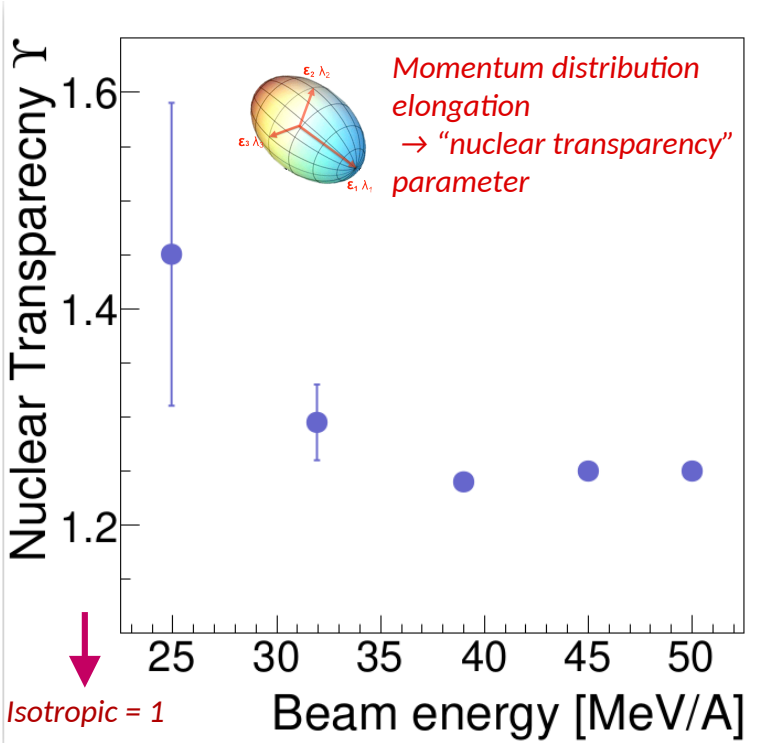
So just how isotropic *are* the most isotropic events?

❶ The most isotropic events are *not* isotropic



INDRA data Xe+Sn 25-50 MeV/nucleon

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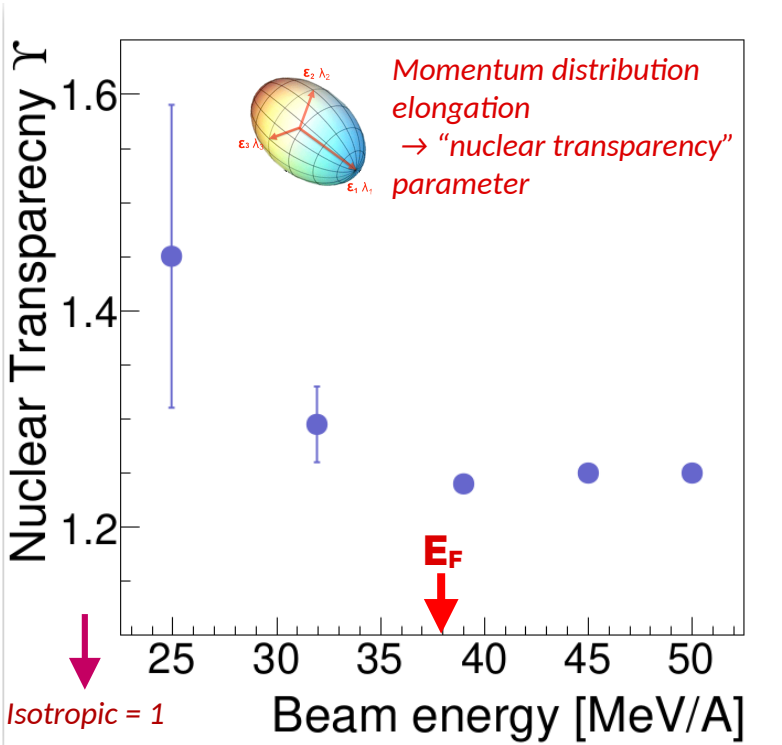
tel-03064998

So just how isotropic *are* the most isotropic events?



INDRA data Xe+Sn 25-50 MeV/nucleon

J.D. Frankland, HDR, Université de Caen (2020)
tel-03064998

❶ The most isotropic events are *not* isotropic
❷ Anisotropy decreases and reaches minimum at Fermi energy
→ to be confirmed with data for other systems/energies

6. How isotropic are the most isotropic events ?

So just how isotropic *are* the most isotropic events?

❶ The most isotropic events are *not* isotropic
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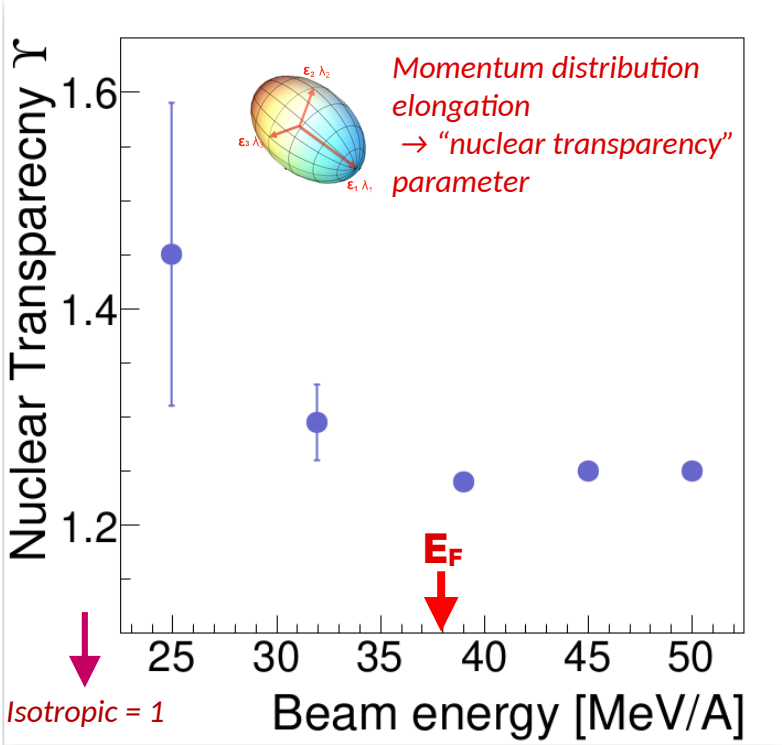


INDRA data Xe+Sn 25-50 MeV/nucleon

J.D. Frankland, HDR, Université de Caen (2020)
tel-03064998

CONTRADICTS PREVIOUS WORK:

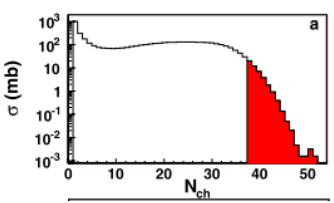
PRL **104,** 232701 (2010) PHYSICAL REVIEW LETTERS week ending 11 JUNE 2010

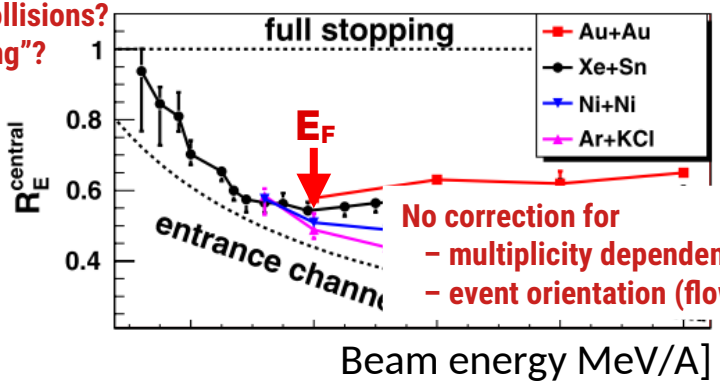
Study of Nuclear Stopping in Central Collisions at Intermediate Energies

G. Lehaut,[1,2] D. Durand,[1] O. Lopez,[1] E. Vient,[1] A. Chbihi,[3] J. D. Frankland,[3] E. Bonnet,[3] B. Borderie,[4] R. Bougault,[1] E. Galichet,[4,5] D. Guinet,[2] Ph. Lautesse,[2] N. Le Neindre,[1] P. Napolitani,[4] M. Parlog,[1] M. F. Rivet,[4] and E. Rosato[6]

(INDRA and ALADIN Collaborations)

Isotropy decreases & reaches minimum at Fermi energy for "central" collisions?
→ Decrease of nuclear "stopping"?





No correction for
– multiplicity dependence
– event orientation (flow)

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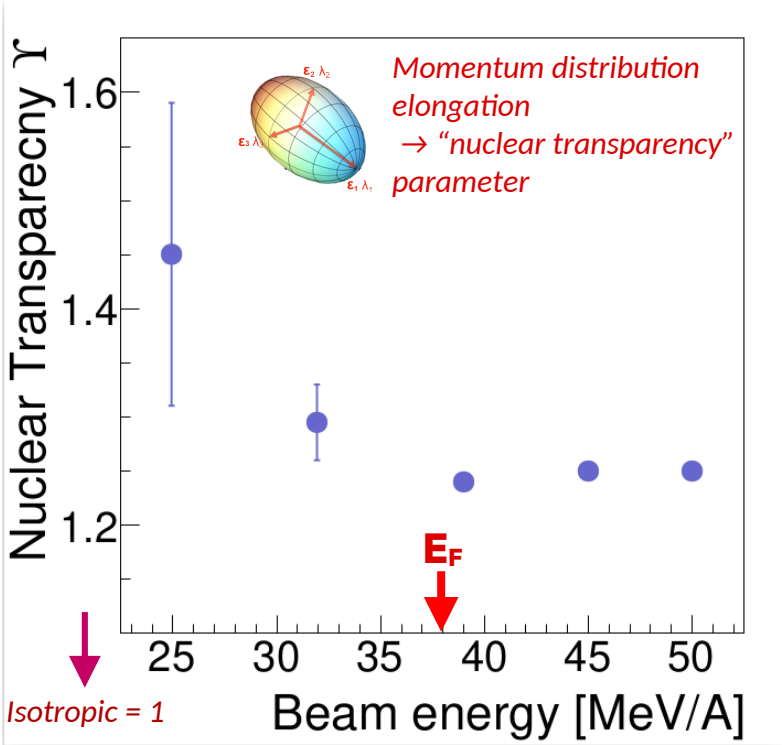
So just how isotropic *are* the most isotropic events?
And how central are the most isotropic events?



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❶ The most isotropic events are *not* isotropic
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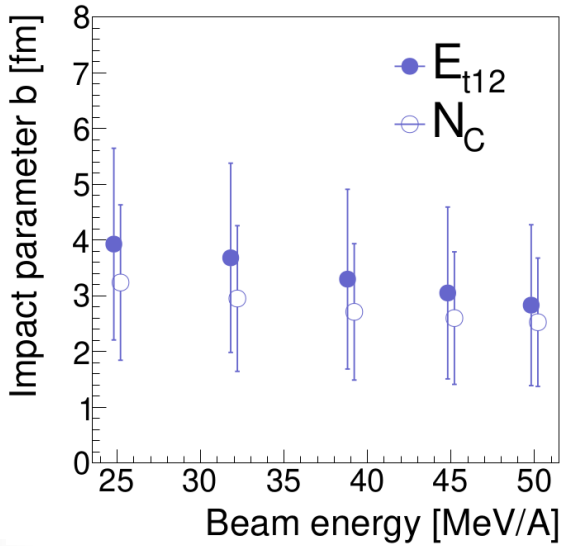
❸ The most isotropic events are *not* the most central collisions:
→ mean impact parameters 3~4 fm



Using method published in

J.D. Frankland, D. Gruyer et al. (INDRA collab.),
Phys. Rev. **C 104**, 034609 (2021) [September 8th]

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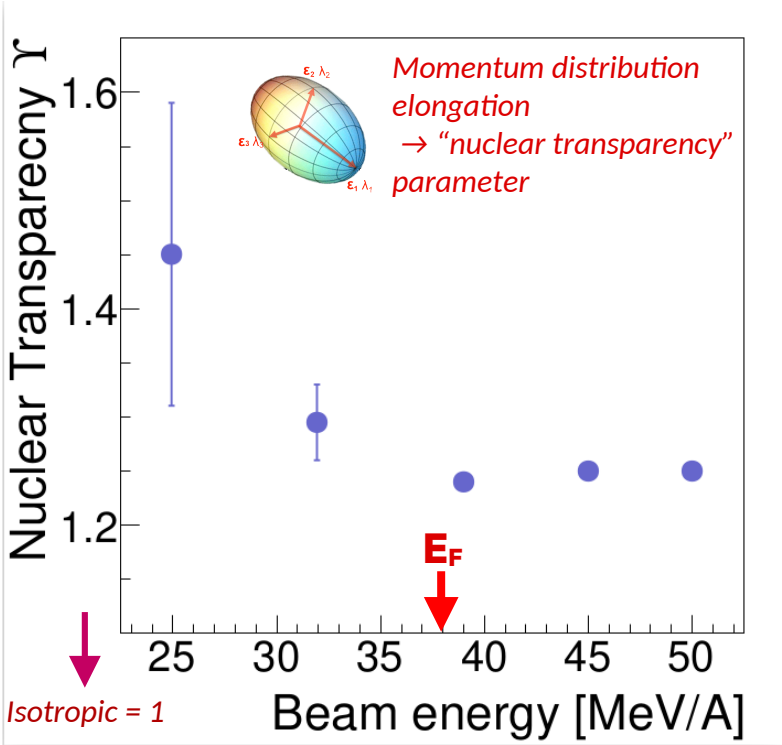

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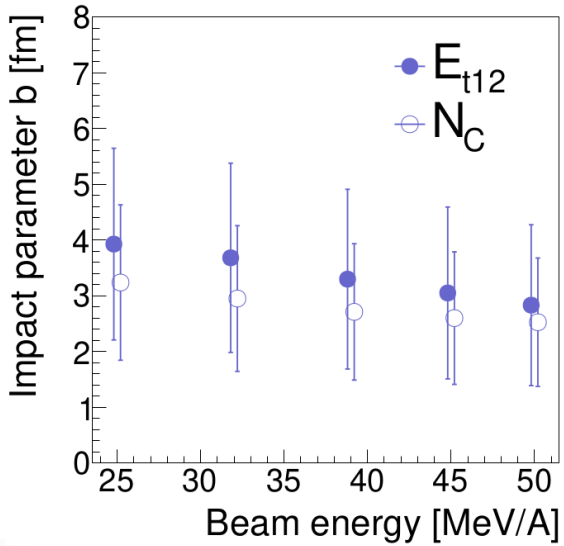

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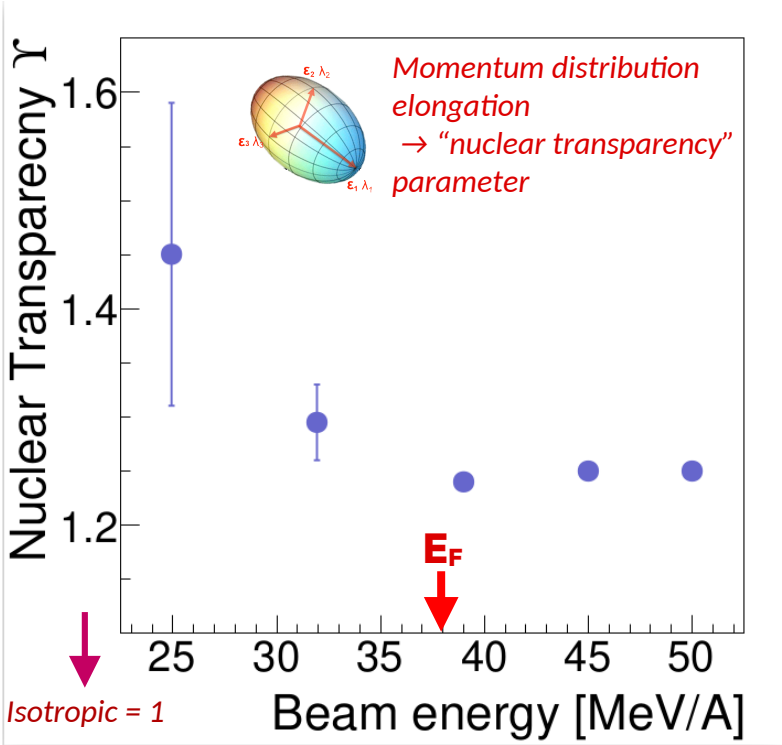

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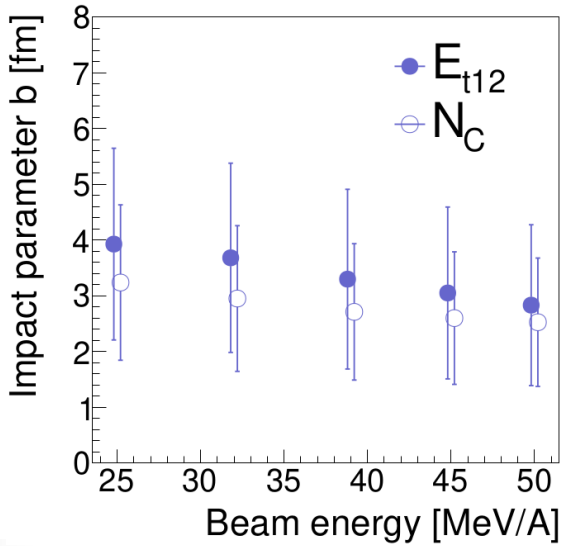
CORRECT IMPACT PARAMETER DISTRIBUTIONS!!



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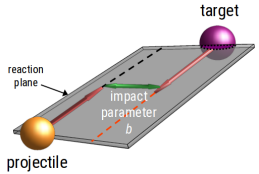
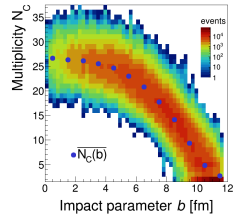
7. Summary

The fluctuations inherent to heavy-ion collisions prevent an event-by-event reconstruction of the impact parameter

→ whether using simple global variables
or more sophisticated tools





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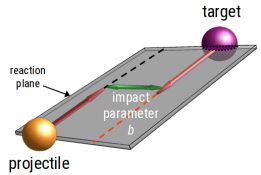
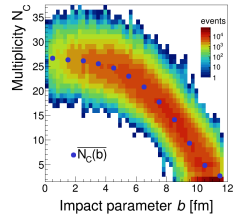
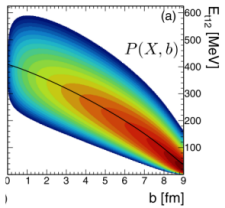




We now have a model-independent method to estimate impact parameter distributions for any sample of experimental events, adapted from the ultra-relativistic (LHC, RHIC) domain



$$P(c_b|\mathbb{S}) = \frac{\int P(X|c_b)\frac{P(X|\mathbb{S})}{P(X)}\,dX}{\int P(X|\mathbb{S})\,dX}$$

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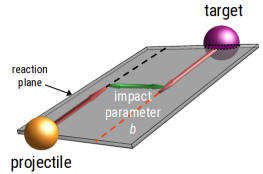

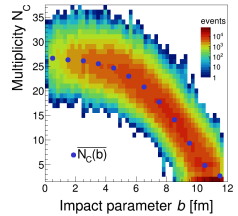

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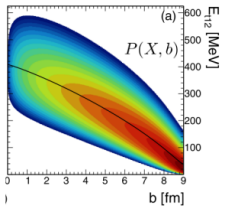

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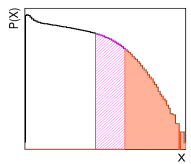

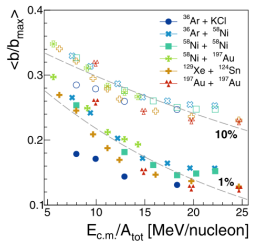

Experimentally, “(most) central collisions” usually means the events with the highest multiplicities, highest transverse energies, etc.
→ the method shows that they are far less central
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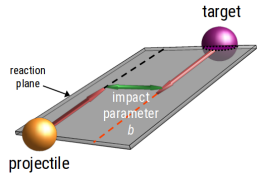

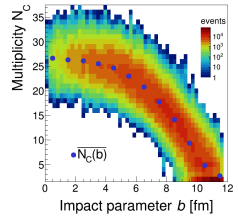

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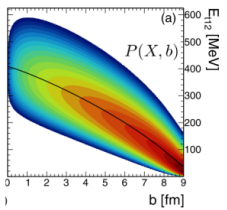

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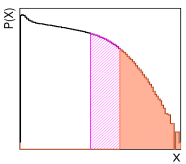
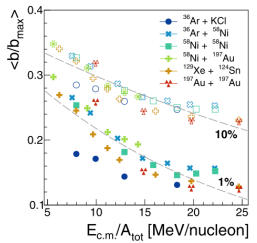
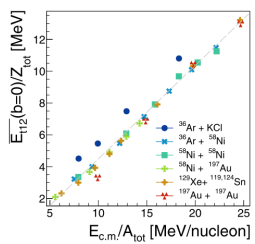
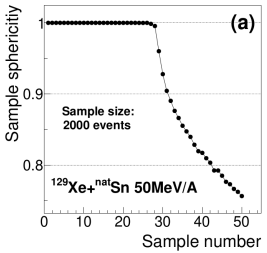


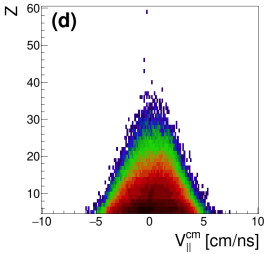


The remarkable scaling of maximum transverse energies E_{t12} extrapolated to b=0 may be a new benchmark test for transport models
→ the uniformity from 25 to 100 MeV/u seems to contradict previous reports of a reduction of nuclear stopping or in-medium cross-sections etc.



Although “most central collisions” is not a well-defined concept, it *is* possible to find sets of events which are the most isotropic at a given beam energy
→ only done for Xe+Sn 25-50 MeV/u, other systems may differ





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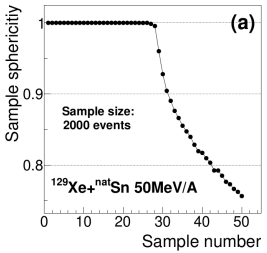
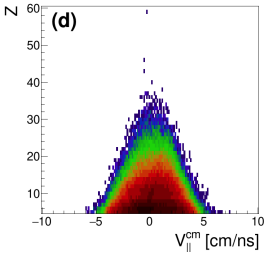
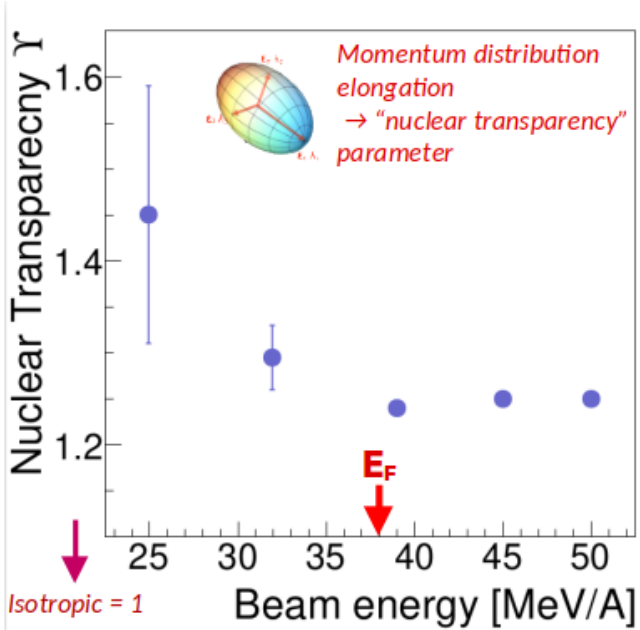




The increasing isotropy of these events approaching the Fermi energy is strongly reminiscent of the expected increase of stopping as phase space opens up for *NN* collisions (decreasing Pauli blocking)
just like mother always said
→ again, this contradicts previous results concerning a decrease of stopping at Fermi energies



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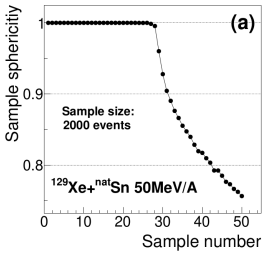

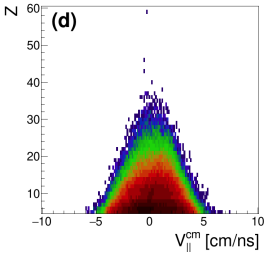

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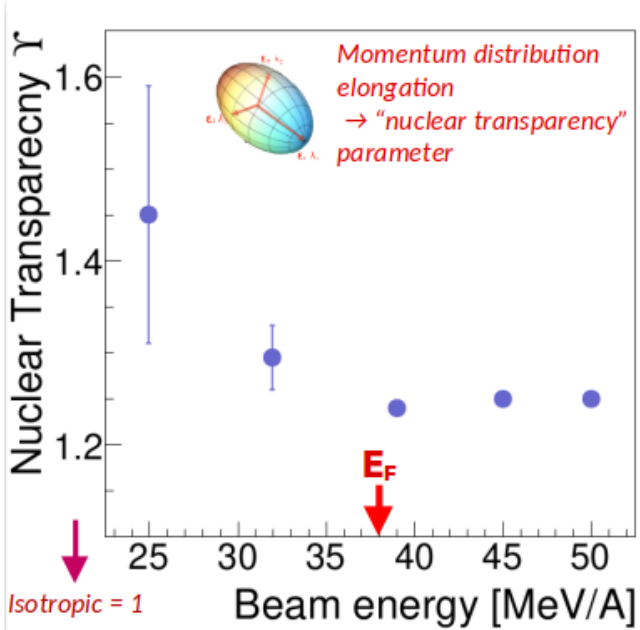

Definitive answers can only come from comparisons to transport models for which one of the essential inputs is an impact parameter distribution which is representative of the data
→ this we now can and must do

Thank you.