

n-p asymmetry dependence on odd-even staggering in $^{40,48}\text{Ca} + ^{40,48}\text{Ca}$ reactions at 35 MeV/nucleon

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- Effect of LCP on OES
- OES of isotopes of PLF as function of n-p asymmetry.
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introduction

- Odd-even staggering (OES) is an interesting phenomena appearing in different areas in nuclear physics.
- It is attributed to the pairing term of nuclear binding energy
- Bethe-Weizsäcker mass eq.:

$$BE(A,Z) = a_v A - a_s A^{2/3} - a_c Z(Z-1)A^{-1/3} - a_A (A-2Z)^2 A^{-1} + \Delta E_{\text{pair}}$$

with: $\Delta E_{\text{pair}} = +\delta$ for (even-even);

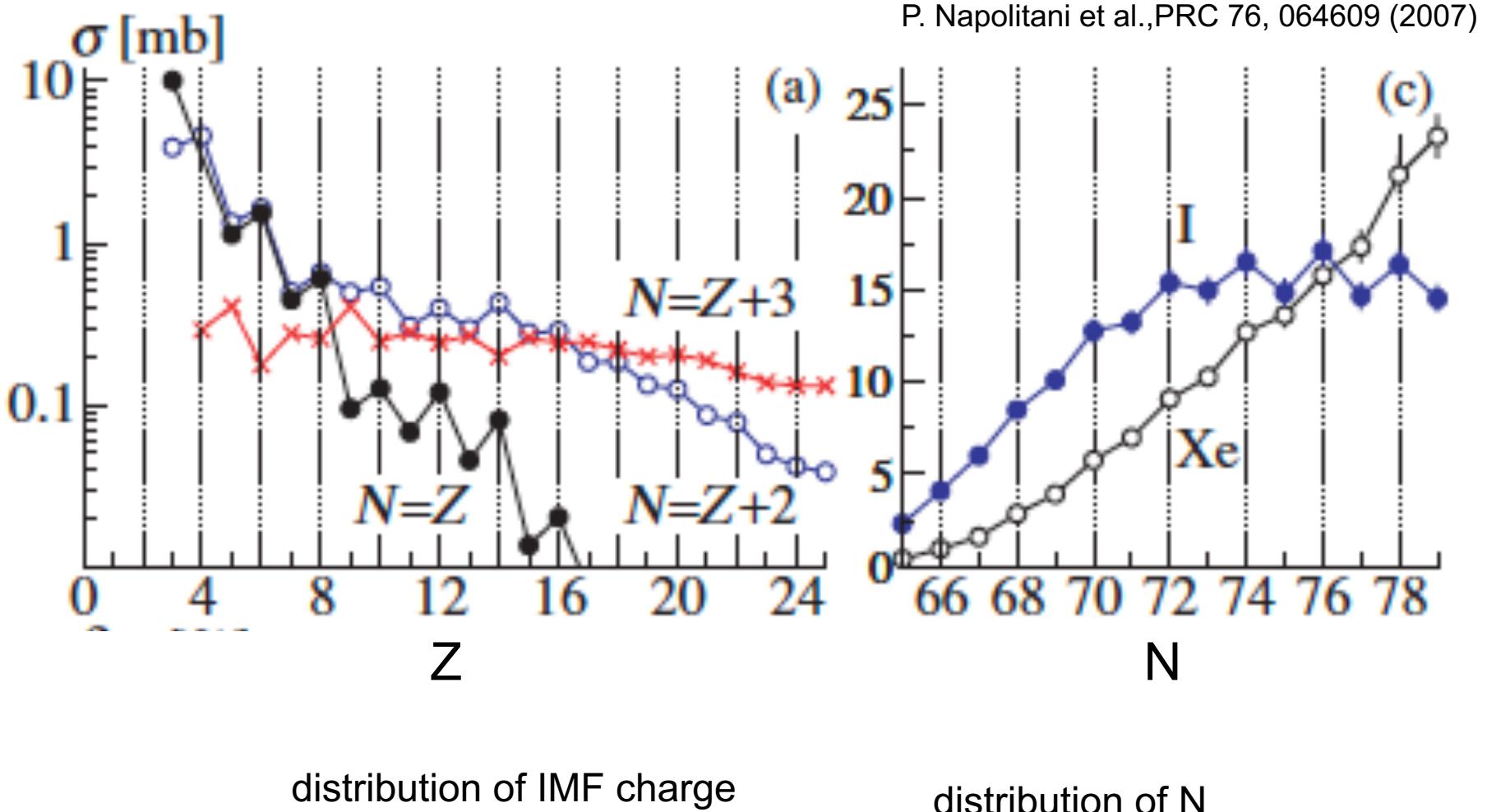
$\Delta E_{\text{pair}} = 0$ for (odd-even);

$\Delta E_{\text{pair}} = -\delta$ for (odd-odd);

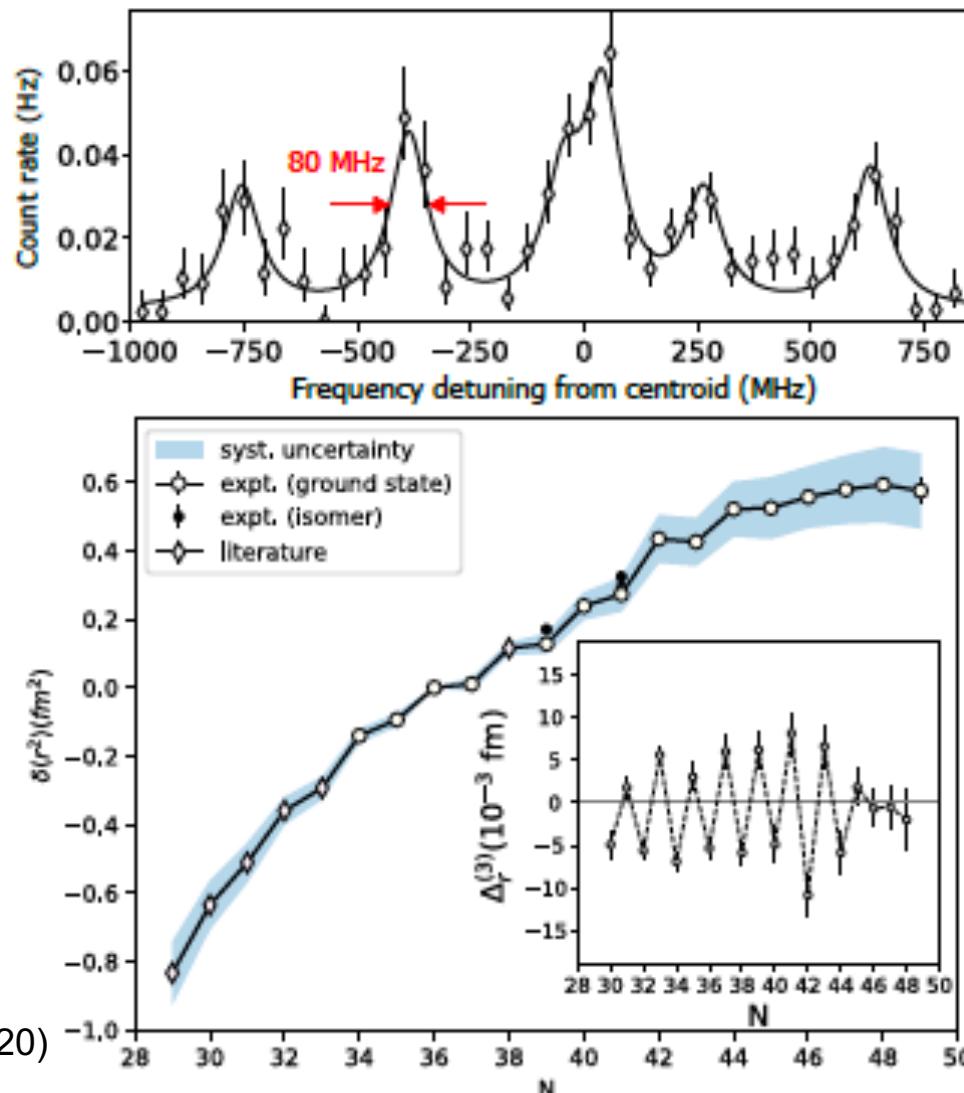
and $\delta = 12 A^{-1/2}$ (MeV)

- OES is observed in different reactions, different projectile-target combinations
- large beam energy range
- In dissipative collisions, the distribution of fragments reveals similar EOS as in the case of low energy

- Example 1: spallation reaction $^{136}\text{Xe} + \text{p}$ @ 1GeV



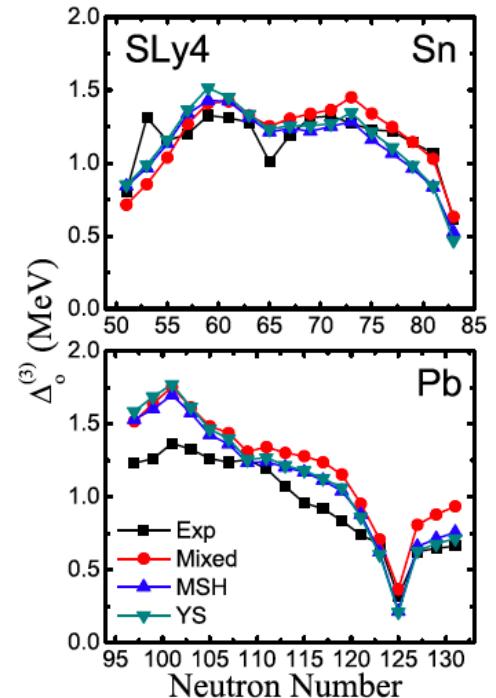
- Example 2: Measurement of OES of charge radii of exotic copper: Collinear Resonance Ionisation Spectroscopy (CRIS) method at ISOLDE CERN



Groote et al., :Nat. Phys, 16, 620 (2020)

Theory

- Microscopic calculations: Hartree Fock + BCS or Hartree Fock-Bogoliubov (HFB) to investigate the relationship between the pairing interaction and OES (see W.J. Chen et al. PRC 91, 047303 (2015)).
- Statistical models, SMM, to study the influence the density of states on fragment charge distribution produced in HIC (N. L. Calleya et al., PRC 90 054616 (2014))
- No OES is predicted in the dynamical theories.



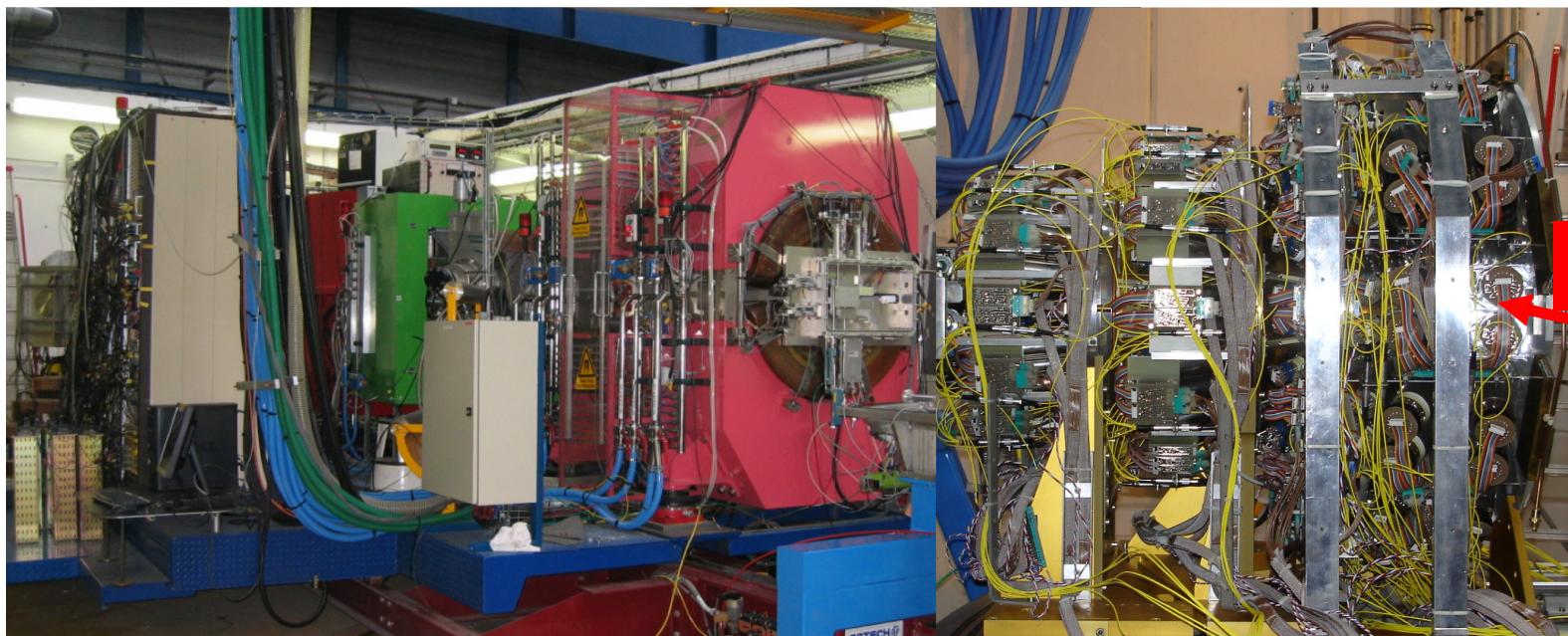
detection

Dipole

Q2

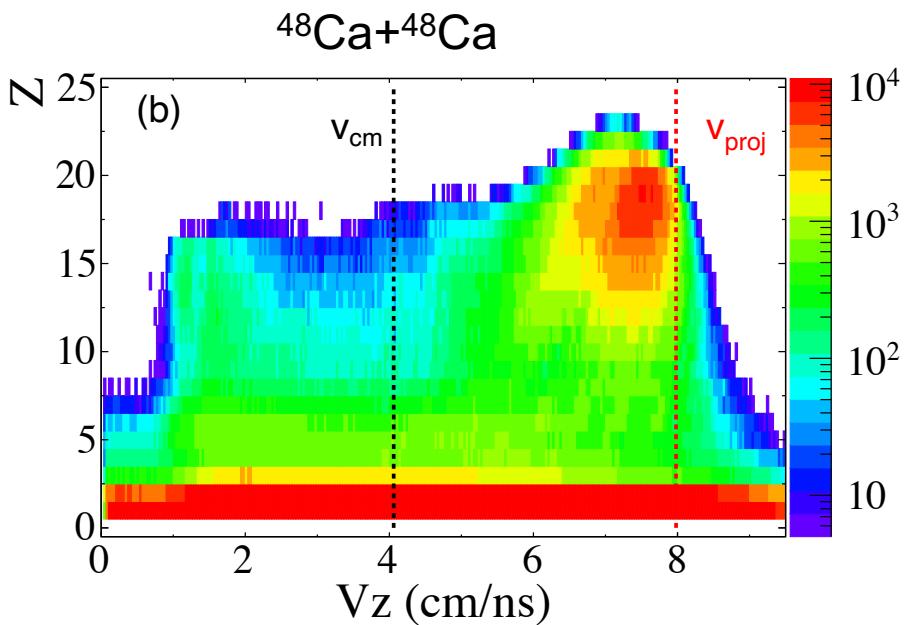
Q1

INDRA



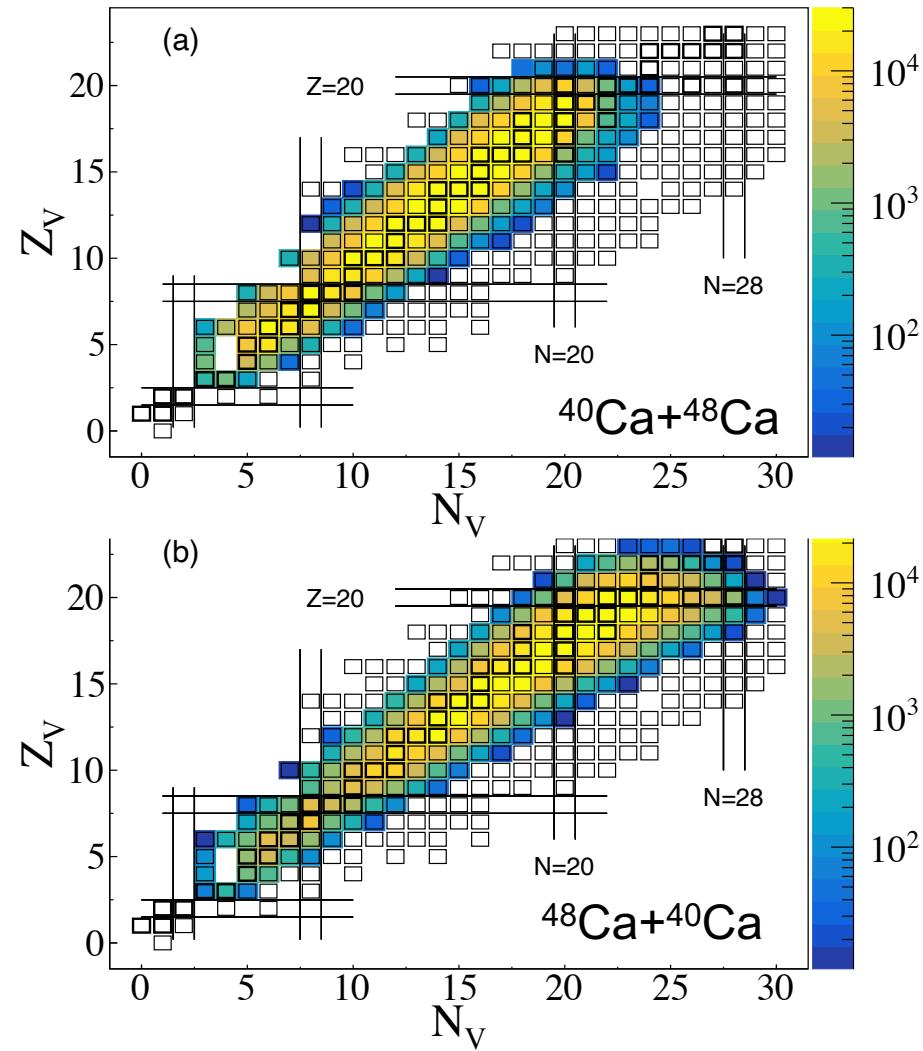
Experiment INDRA-VAMOS provides precise measurement of the isotopic distributions in coincidence with emitted LCP (see Q. Fable contribution)

topology of the events



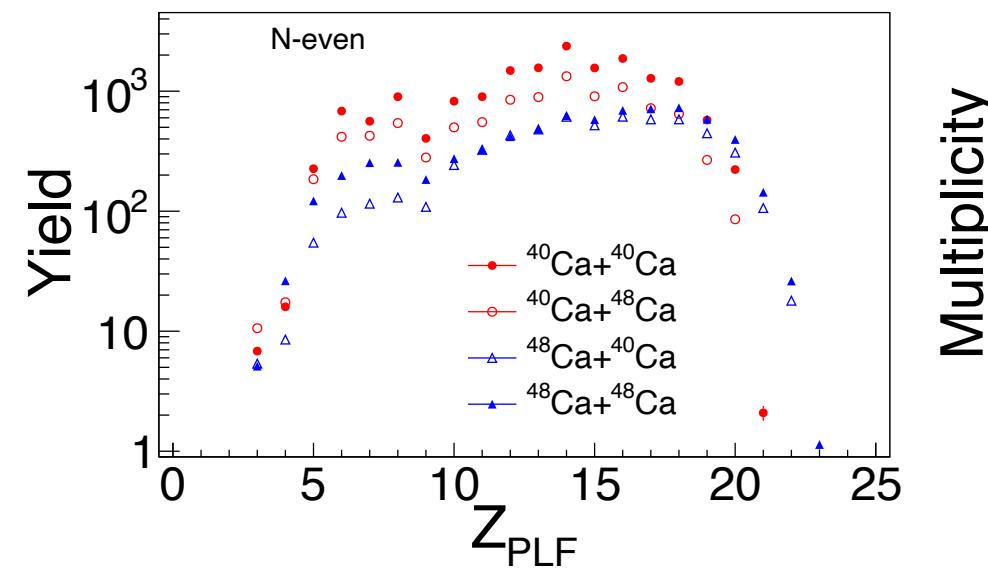
TLF-Indra
LCP-

PLF-VAMOS

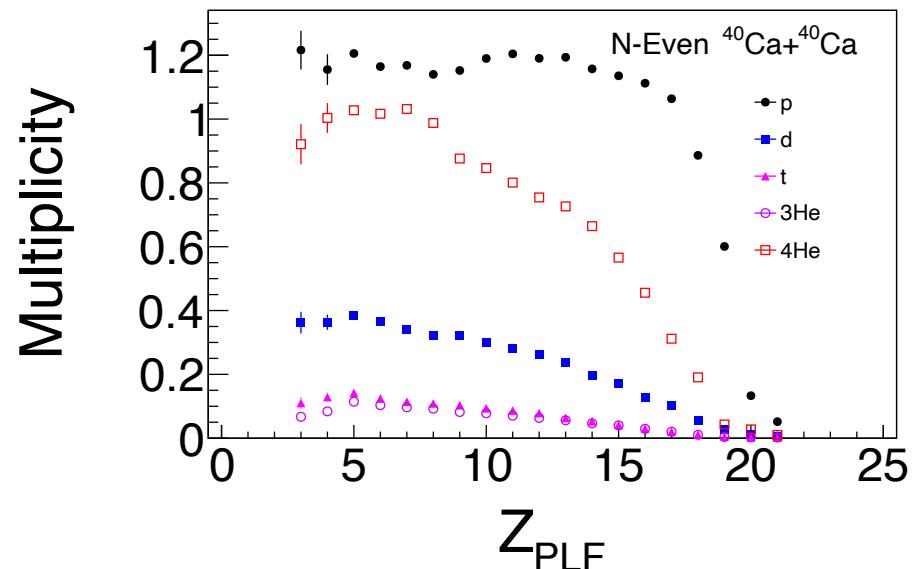


- Identification in charge and mass for a wide range of isotopes for $Z=5-22$
- Proton drip line is populated
- n-rich projectile shows broad isotopic distributions

charge of the PLF and LCP multiplicities



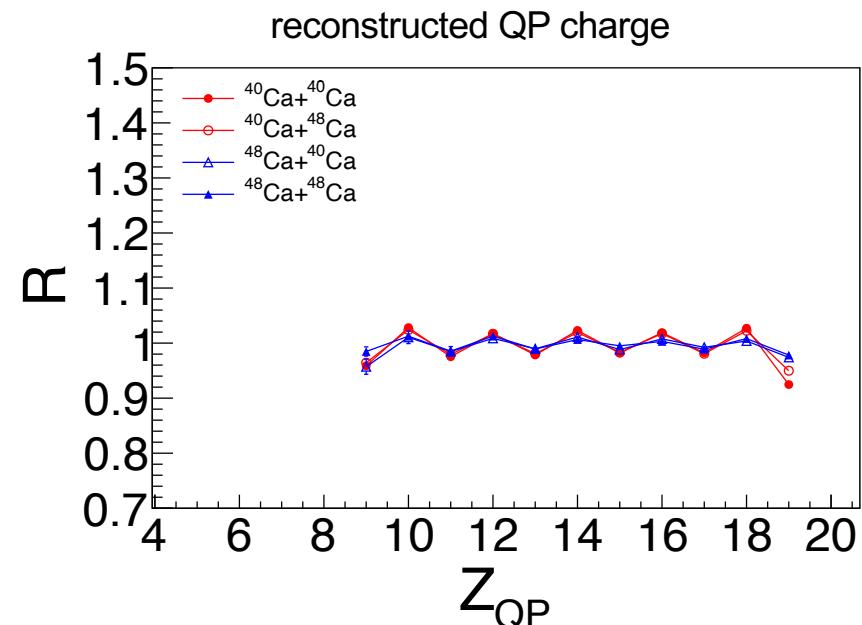
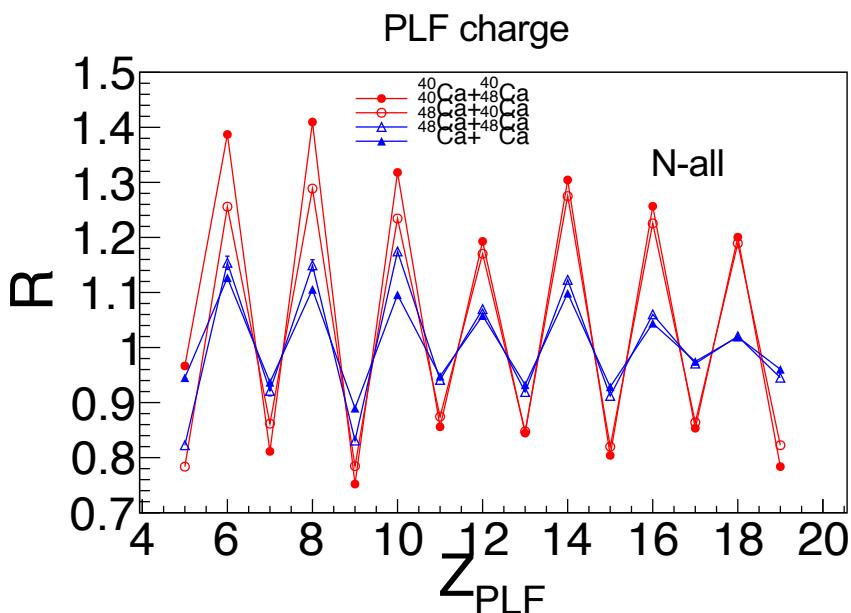
Z_{PLF} shows Odd-Even effect
the effect decreases with n- enrichment



smaller OES is observed for M_{LCP}

Evolution of odd-even of PLF charge and reconstructed QP with N/Z

ratio of data and polynomial fit to 5 successive points amplify the OES



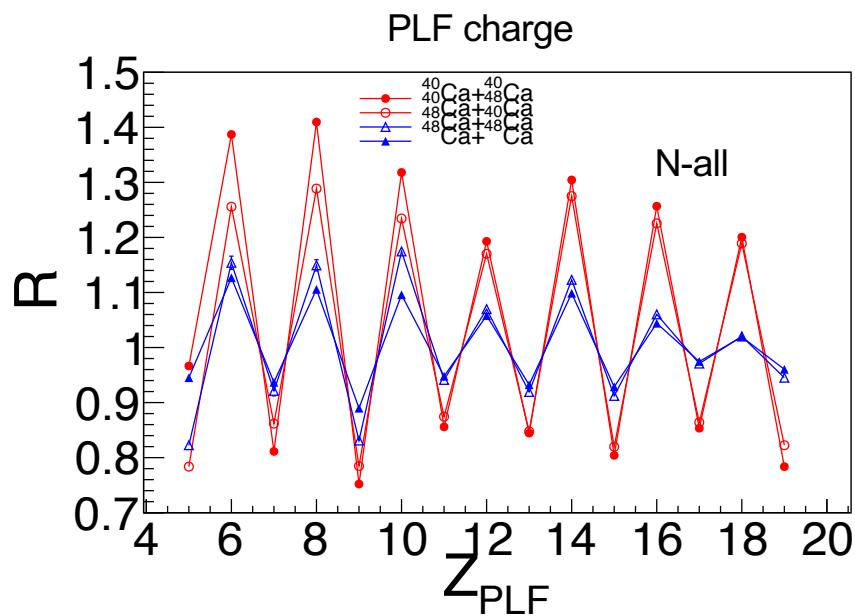
Evolution of the OES with N/Z of the system
OES reduced with increasing n-richness of the sys

$$Z_{QP} = Z_{PLF} + \sum(M_{LCP} * Z)$$

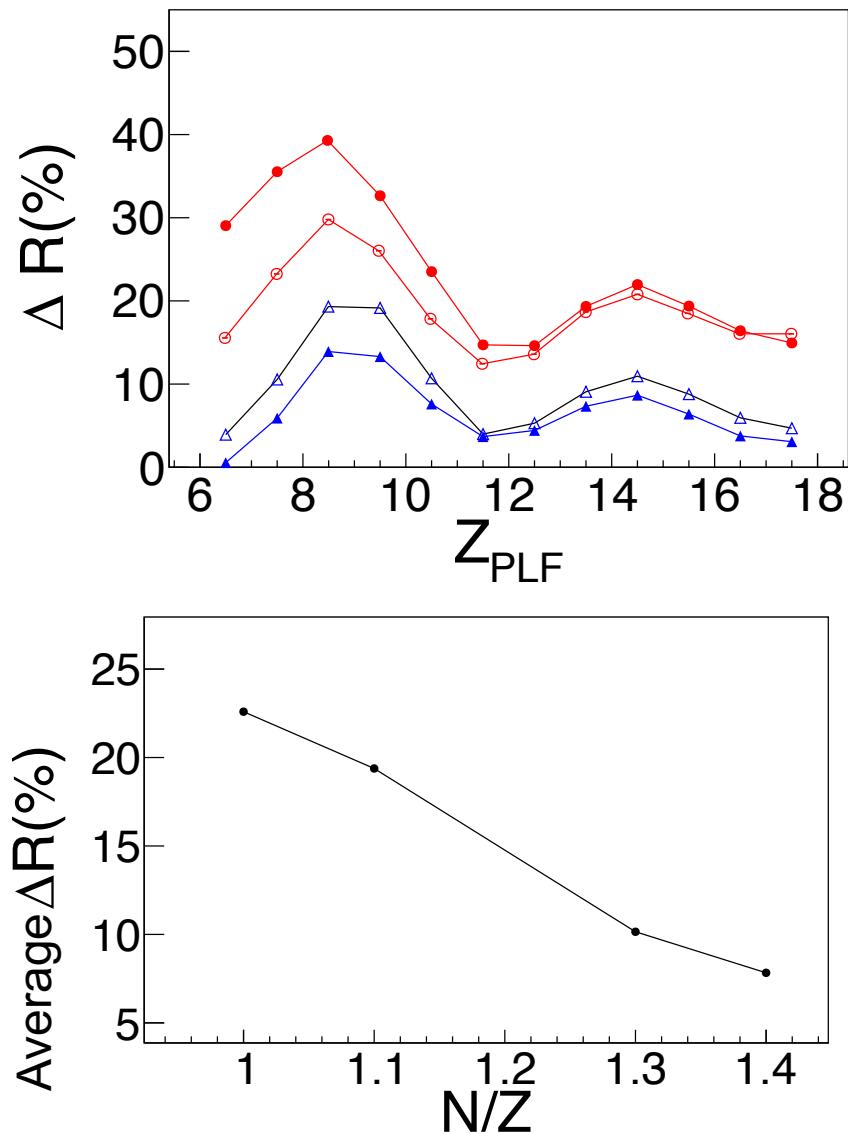
OES effect < 2%

Evolution of odd-even of PLF charge

$$\Delta R(\%) = 100 * \text{abs}(R(Z) - R(Z+1)) / (R(Z) + R(Z+1))$$



Evolution of the OES with N/Z of the system
OES reduced with increasing n-richness of the sys

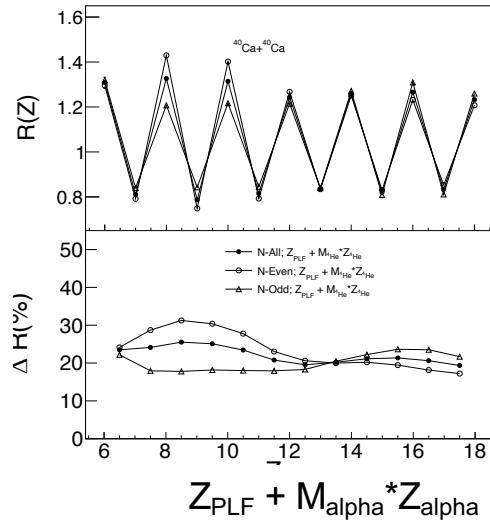
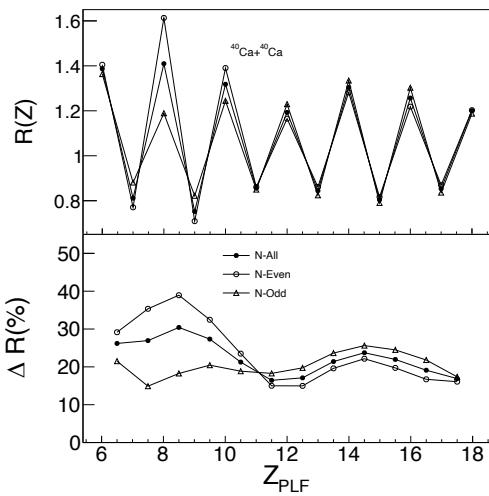


Effect of LCP on OES

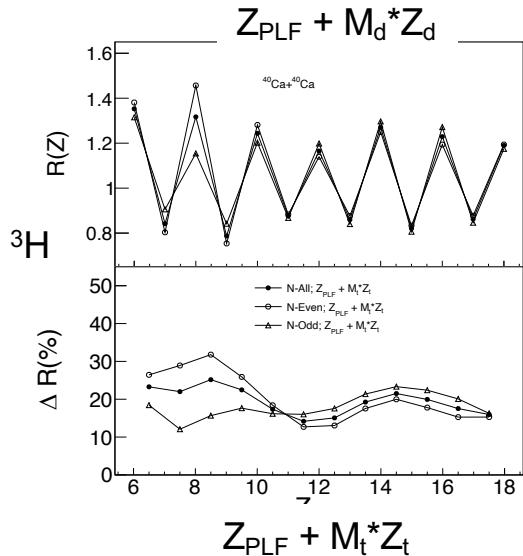
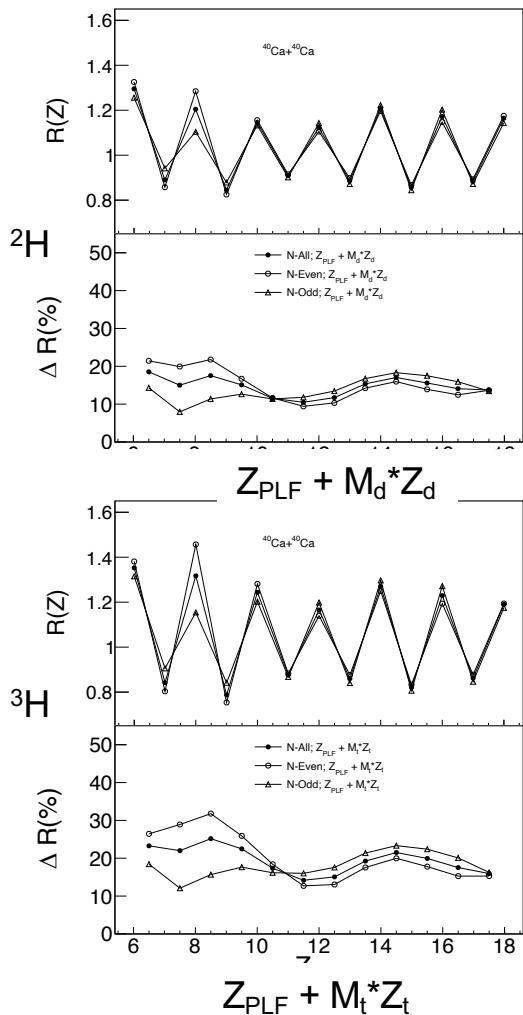
- $Z_{QP} = Z_{PLF} + \Sigma(M_{LCP} * Z)$
- to determine the effect of each LCP
- $Z_{Cont}(i) = Z_{PLF} + \Sigma M_i * Z_i$, with $i = p, d, t, h, \alpha$

Effect of ^2H , ^3H , ^4He on the OES

$$\Delta R(\%) = 100 * \text{abs}(R(Z) - R(Z+1))/(R(Z)+R(Z+1))$$



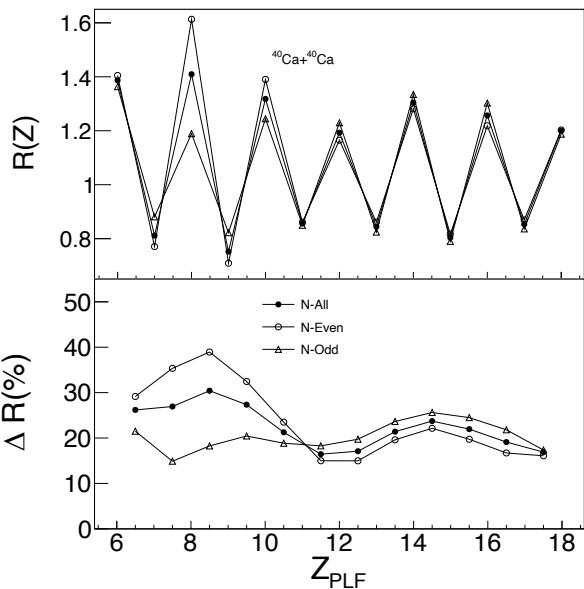
very small effect of the emitted alpha and triton on the OES,
little bit more effect for deuteron



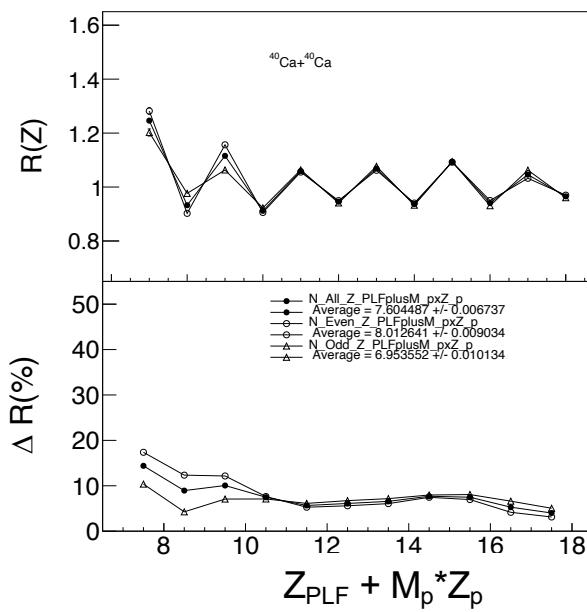
Effect of the proton on the OES

$$\Delta R(\%) = 100 * \text{abs}(R(Z) - R(Z+1))/(R(Z)+R(Z+1))$$

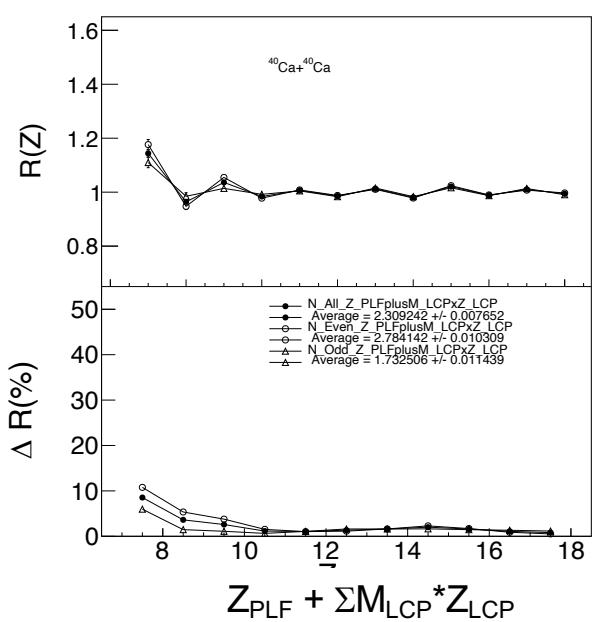
no condition on the emitted particle



$Z_{PLF} + M_{\text{proton}} * (Z=1)$

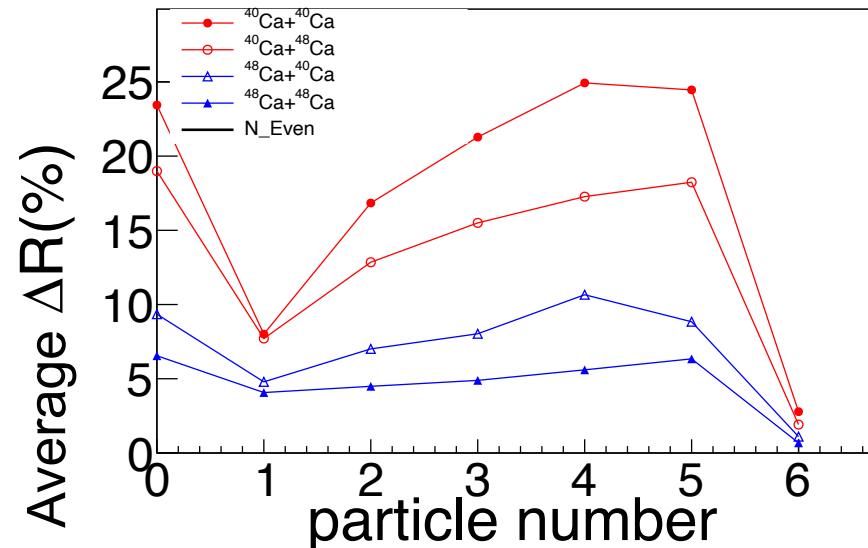
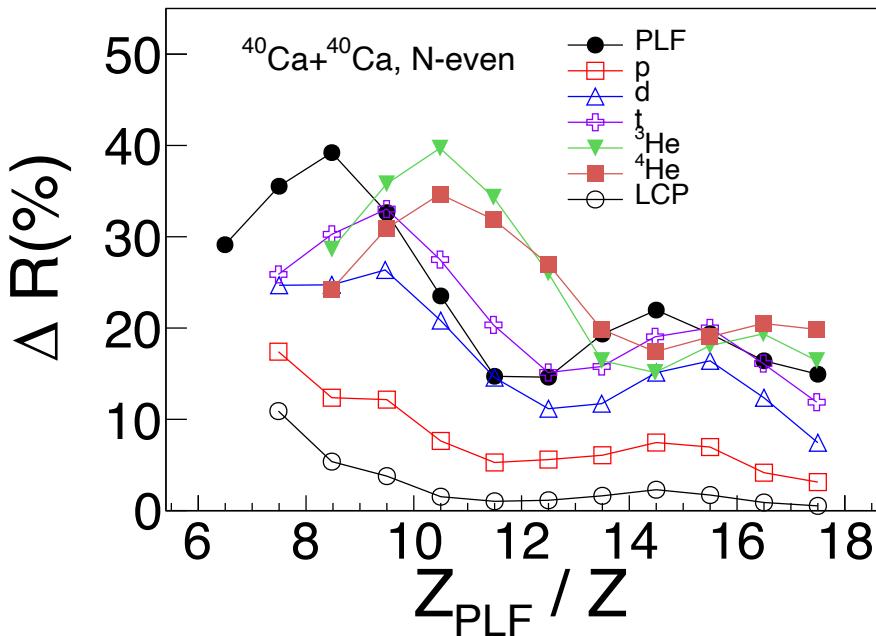


$Z_{PLF} + \sum M_{LCP} * Z_{LCP}$



huge effect of the emitted protons on the OES, it should be the last evaporative particle

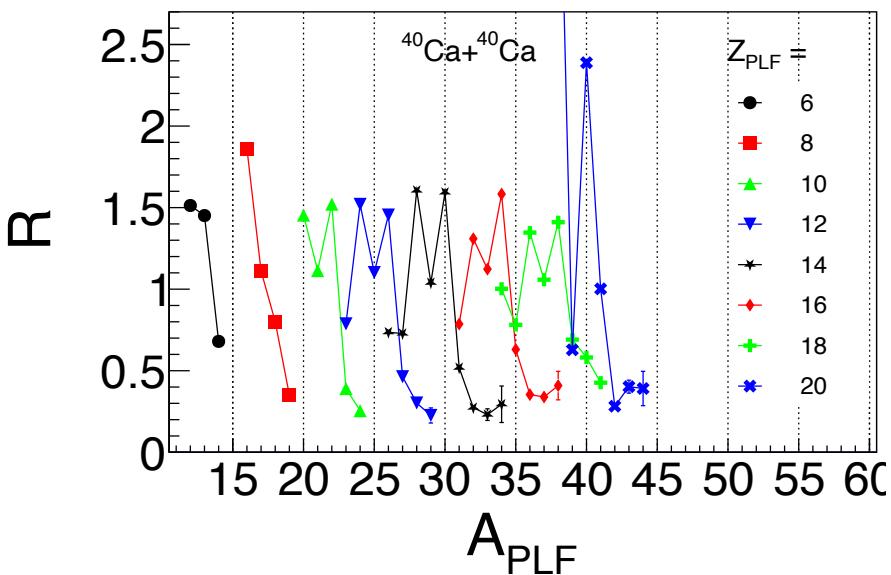
contribution to OES for all particles



- The effect on the OES depends on the particles
- $Z = 2$ no significant effect (just a shift in Z by 2)
- for d and t small effect is observed
- the most significant effect is due to proton
- OES when adding all LCP
- the average OES effect over all charges depends on the system neutron enrichment
- the highest effect is observed for $^{40}40$ system
- vanishes for the 4 system when adding all LCP (bin 6)

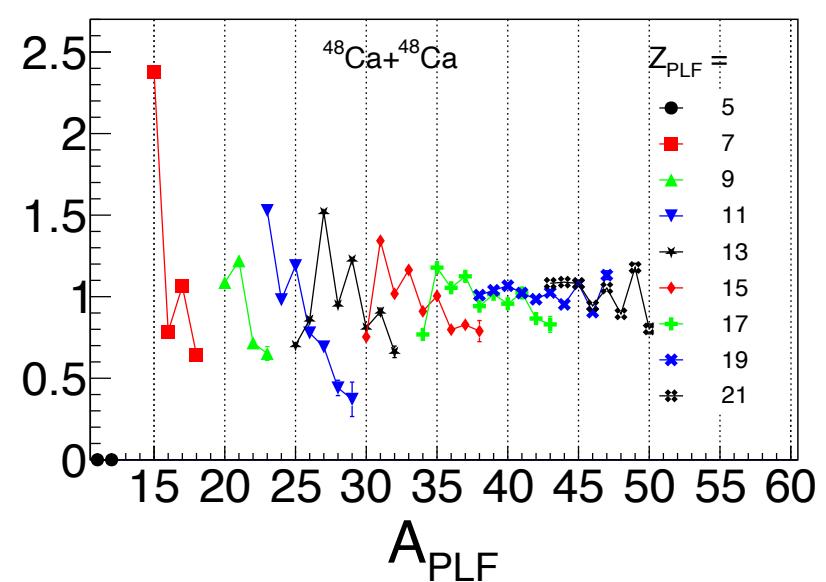
OES applied to the yield of isotopic distributions

EVEN Z n-poor system/ α -conjugate



neutron-rich system

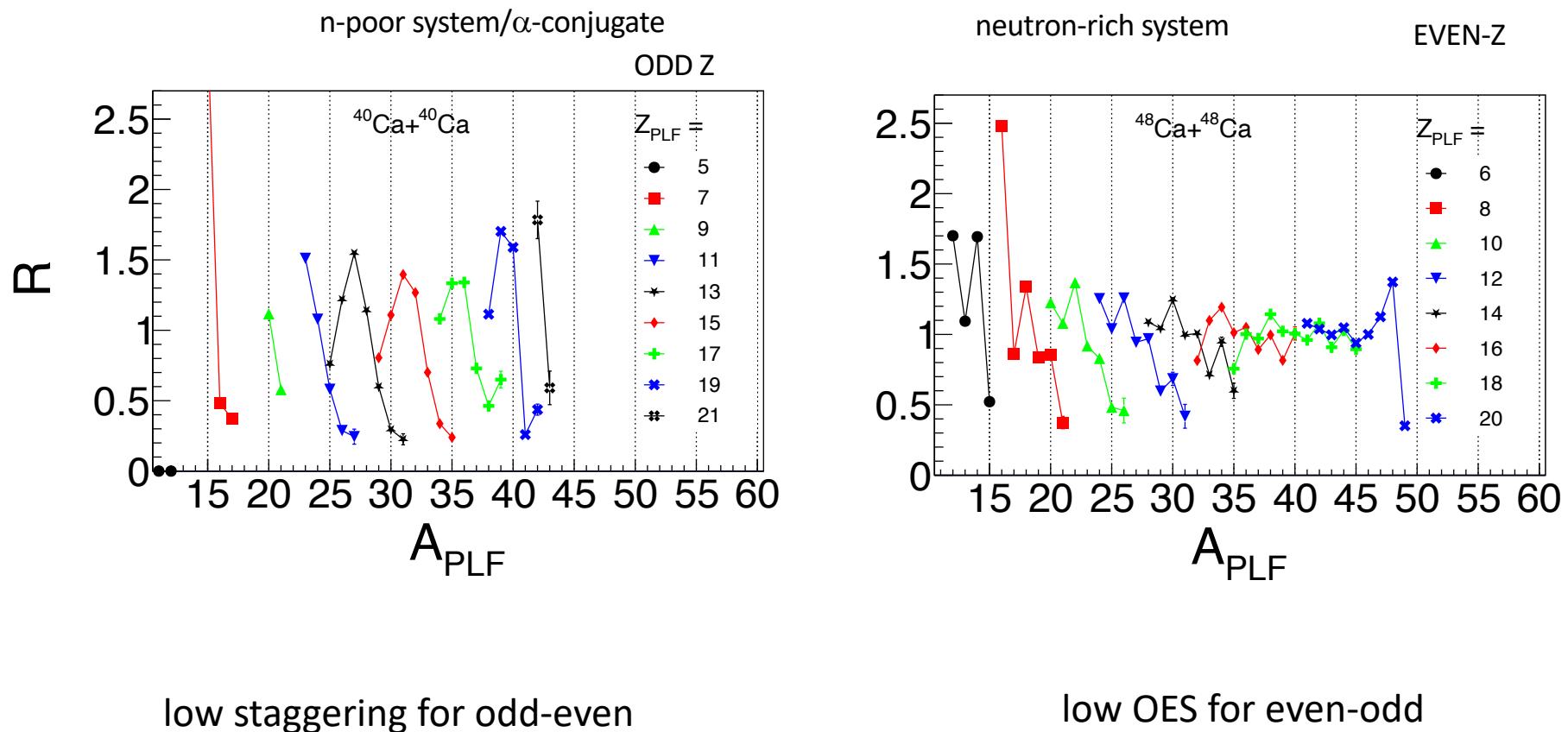
ODD-Z



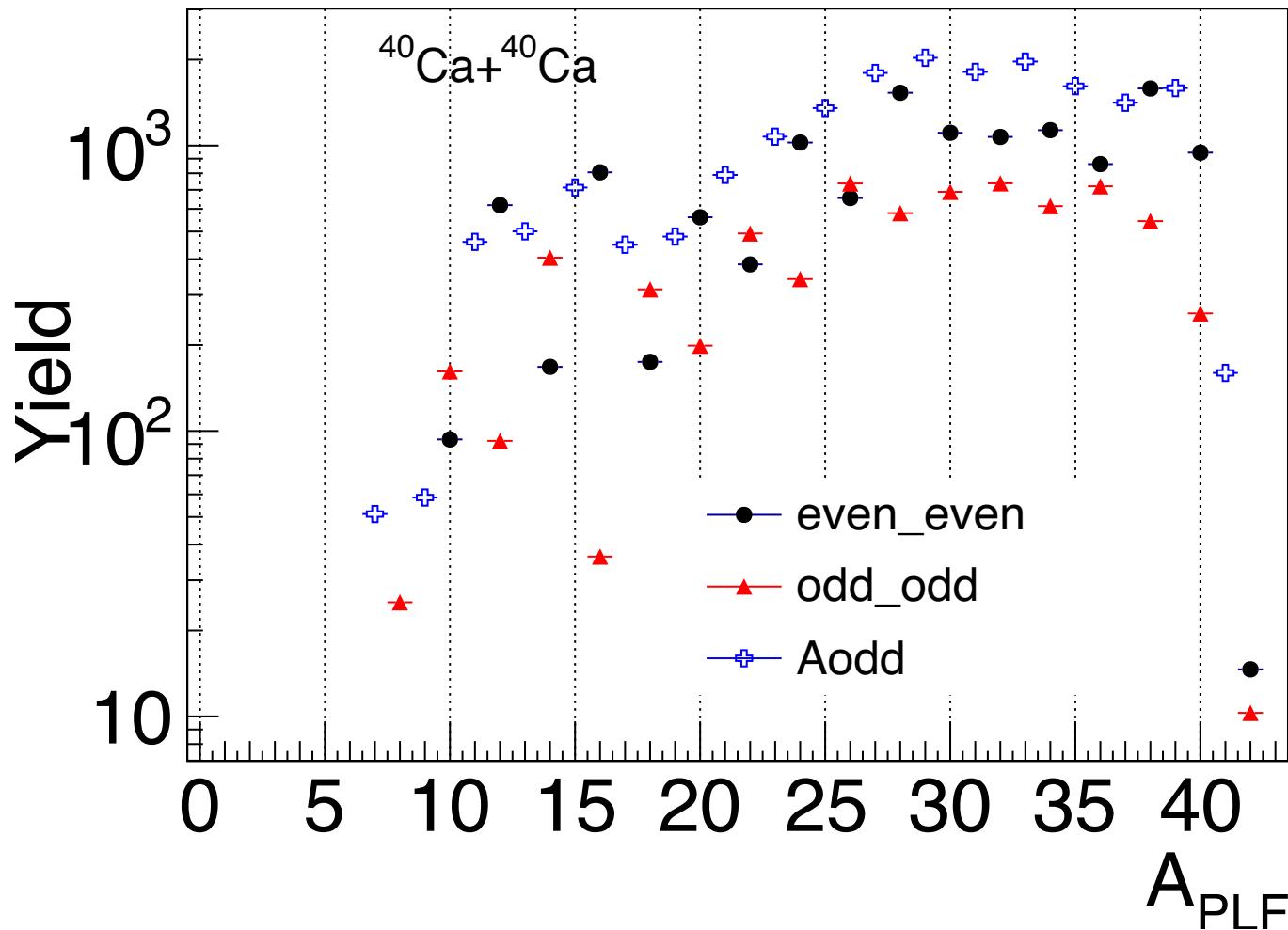
high staggering for even-even
neutron-poor system

high staggering for odd-even
neutron -rich

OES applied to the yield of isotopic distributions

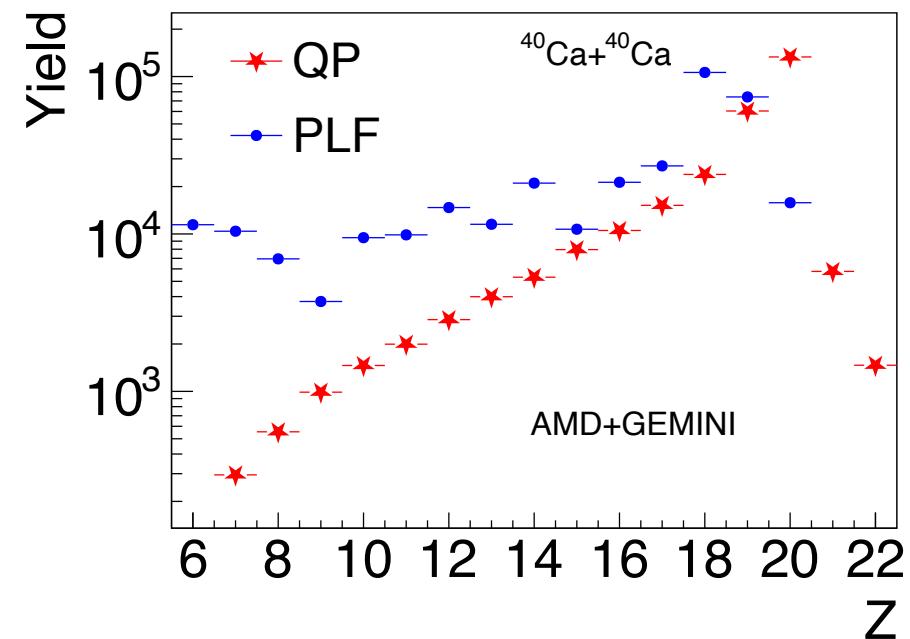


production rate of elements



depends on the parity of N and Z (e-e, o-o or o-e)

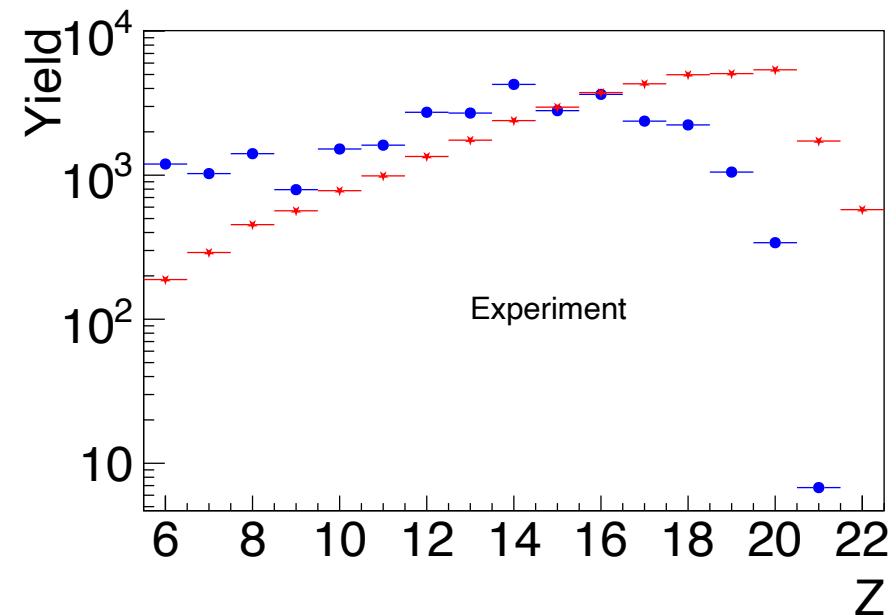
AMD+Gemini calculation



no OES is observed in primary charge produced in AMD

the effect is observed clearly after the PLF decay with Gemini

How well is reproduced?



Conclusion

- EOS more pronounced for the n-poor system and the effect increases with n-enrichment of system.
- The proton evaporation has important contribution to OES however the effect of other evaporative particle is significant.
- The OES depends on the whole evaporation chain.
- A residual OES (<2%) is still present after adding the whole contribution of particles.
- The OES is not trivial effect of evaporation ?
- quantitative comparison to the Statistical calculation is necessary.

- Experiment INDRA-VAMOS provides precise measurement of the isotopic distributions in coincidence with emitted LCP (see Q. Fable contribution)
- OES is observed as function of the N/Z of the 4 systems $^{40,48}\text{Ca} + ^{40,48}\text{Ca}$ @ 35 MeV/nucleon
- OES of PLF charge; of mass; LCP multiplicities distributions
- OES of Q_values
- OES of the Yield of the isotopic distributions for odd-odd, odd-even and even-even

