# SIM e NucSYS: attività di ricerca

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INFN - Sezione di Torino

Giornate di Studio sulla Fisica Teorica
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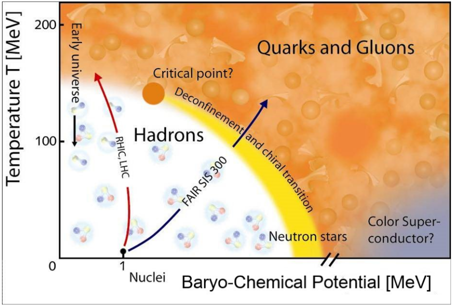
Istituto Nazionale di Fisica Nucleare

# The local SIM group

- INFN staff: Marzia Nardi, Arturo De Pace, Andrea Beraudo, Marco Monteno;
- INFN-Fellini: Daniel Pablos;
- Unito Staff: Wanda Alberico (retired)

# Heavy-ion collisions: exploring the QCD phase-diagram




QCD phases identified through the *order parameters*

- Polyakov loop $\langle L \rangle \sim e^{-\beta \Delta F_Q}$: energy cost to add an isolated color charge
- Chiral condensate $\langle \bar{q} q \rangle \sim$ effective mass of a "dressed" quark in a hadron

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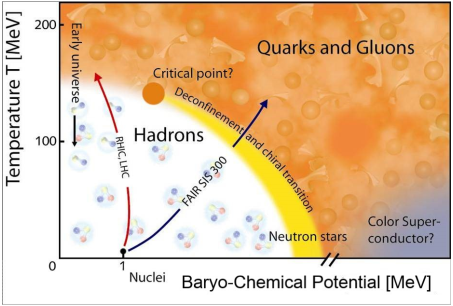


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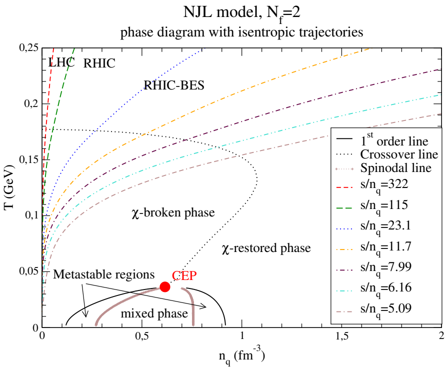
Heavy-Ion Collision (HIC) experiments performed to study the transition

- From QGP (color deconfinement, chiral symmetry restored)
- to hadronic phase (confined, chiral symmetry broken)

NB $\langle \overline{q}q \rangle \neq 0$ responsible for most of the baryonic mass of the universe: *only ∼35 MeV of the proton mass from* $m_{u/d} \neq 0$

# Heavy-ion collisions: exploring the QCD phase-diagram




- Region explored at the LHC ($\sqrt{s_{\rm NN}} \approx 5$ TeV) and highest RHIC energy: *high-T/low-density* (early universe, $n_B/n_\gamma \sim 10^{-9}$)
- Higher baryon-density region accessible at lower $\sqrt{s_{\rm NN}} \approx 10$ GeV (Beam-Energy Scan at RHIC)

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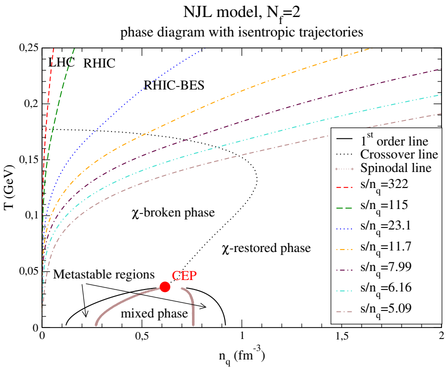


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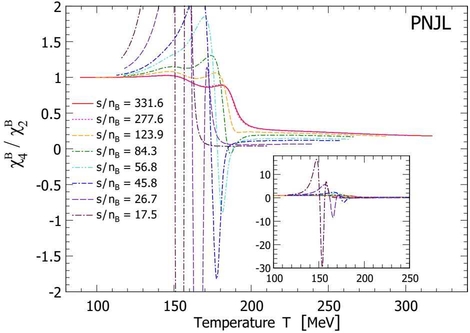
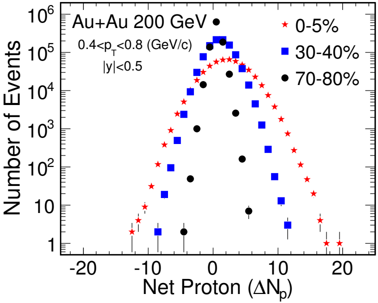
**Is there a Critical End-Point in the QCD phase diagram?**

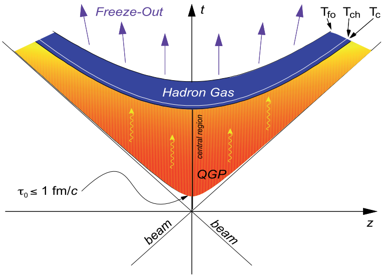
# Looking for signatures of the CEP

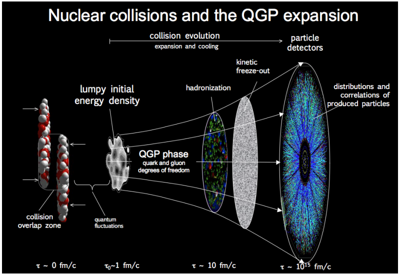



$\xi \to \infty$ at CEP should affect observables, e.g. ratio of cumulants of distributions of conserved charges (Mario Motta PhD thesis)

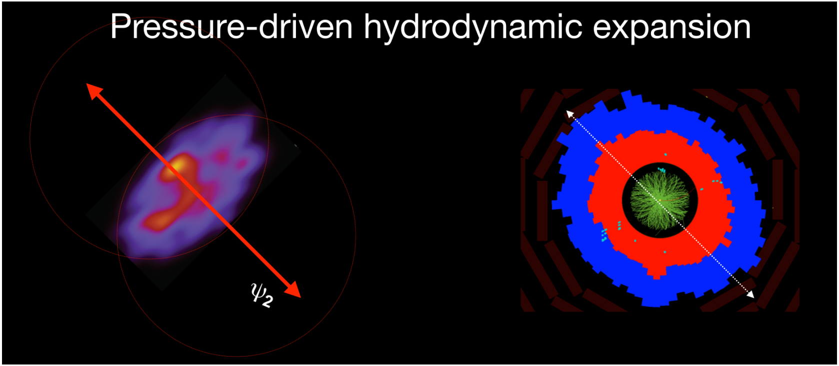
# Heavy-ion collisions: a cartoon of space-time evolution




- Soft probes (low-$p_T$ hadrons): collective behavior of the *medium*;
- Hard probes (high-$p_T$ particles, heavy quarks, quarkonia): produced in *hard pQCD processes* in the initial stage, allow to perform a tomography of the medium.

# A medium displaying a collective behavior

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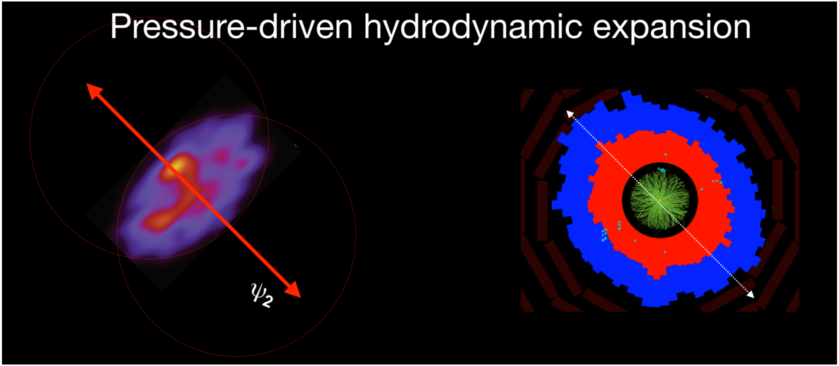


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NB picture relying on the condition $\lambda_{\mathrm{mfp}} \ll L$

# Relativistic hydrodynamics: conceptual setup

When $\lambda_{\mathrm{mfp}} \ll L$ only conservation laws matter:

$$\partial_\mu T^{\mu\nu} = 0 \quad + \quad \mathrm{EoS} \quad P = P(\epsilon)$$

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- Relativistic Navier-Stokes first-order theory (violates causality)

$$\pi^{\mu\nu} = 2\eta \nabla^{<\mu} u^{\nu>}$$

with

$$\nabla^{<\mu} u^{\nu>} \equiv \frac{1}{2}(\nabla^\mu u^\nu + \nabla^\nu u^\mu) - \frac{1}{3}\Delta^{\mu\nu}(\nabla_\alpha u^\alpha)$$

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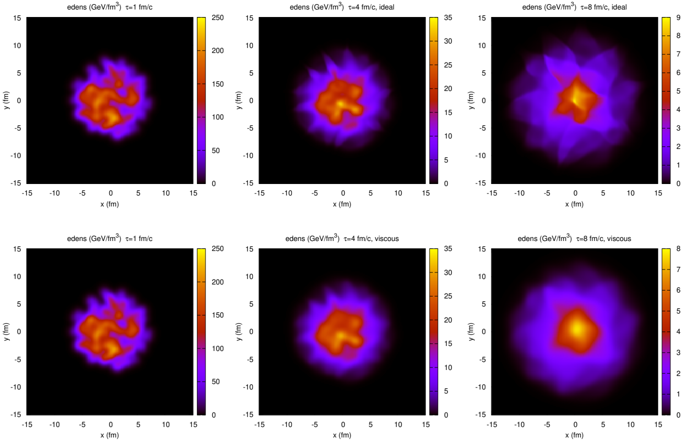
- Israel-Stewart second-order theory and further developments (respect causality): re-discovered and improved by heavy-ion community

  $$\boxed{\dot{\pi}^{\mu\nu} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta \nabla^{<\mu} u^{\nu>})}$$

# ECHO-QGP: a major outcome of the Italian SIM group

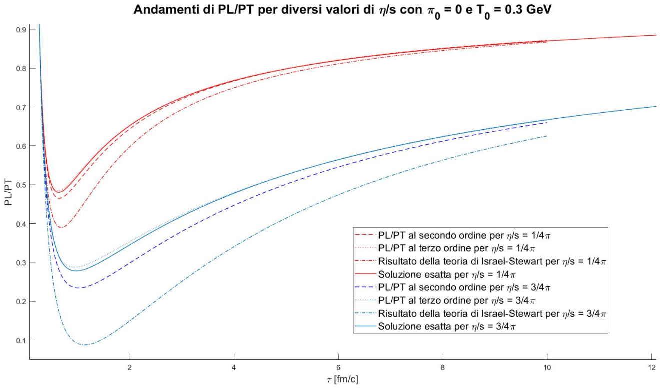
Ideal (upper panels) and viscous (lower panels) evolution [1] starting from the *same initial condition* (central Au-Au collision at $\sqrt{s_{\rm NN}} = 200$ GeV)




**Viscosity damps short-wavelength modes!**

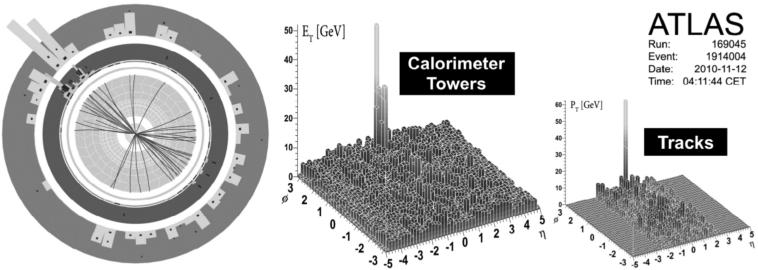
[1] Eur.Phys.J. C73 (2013) 2524

# Beyond the Israel-Stewart theory




One can perform a Chapman-Enskog expansion in powers of $\mathrm{Kn} = \lambda_{\mathrm{mfp}}/L$ and compare the results with the exact solution of the Boltzmann equation (bachelor thesis by Vittorio Larotonda)

# A medium inducing energy-loss to colored probes




Strong unbalance of di-jet events, visible at the level of the event-display itself, without any analysis: jet-quenching

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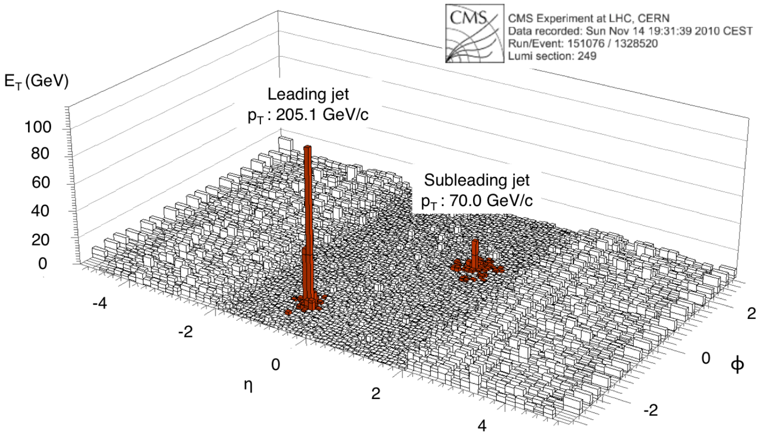


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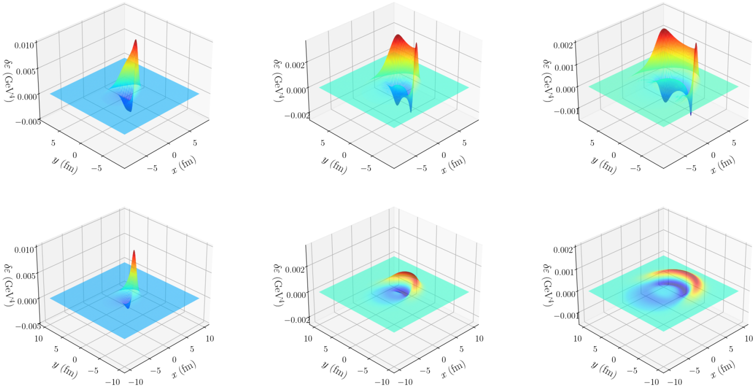
# How the medium responds to jets




Wake arising from jet propagation in an ideal and viscous medium studied in linearized hydrodynamics (Daniel Pablos et al., JHEP 05 (2021) 230)

# HQ dynamics in the fireball

To model the HQ propagation in the hot medium we developed a relativistic Langevin equation, obtained from the soft-scattering limit of the Boltzmann equation (A.B. et al., Nucl.Phys. A831 (2009) 59)

$$\frac{\Delta p^i}{\Delta t} = -\underbrace{\eta_D(p)p^i}_{\text{determ.}} + \underbrace{\xi^i(t)}_{\text{stochastic}} ,$$

with the properties of the noise encoded in

$$\langle\xi^i(\boldsymbol{p}_t)\rangle = 0 \quad \langle\xi^i(\boldsymbol{p}_t)\xi^j(\boldsymbol{p}_{t'})\rangle = b^{ij}(\boldsymbol{p})\frac{\delta_{tt'}}{\Delta t} \quad b^{ij}(\boldsymbol{p}) \equiv \kappa_{\|}(p)\hat{p}^i\hat{p}^j + \kappa_{\perp}(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

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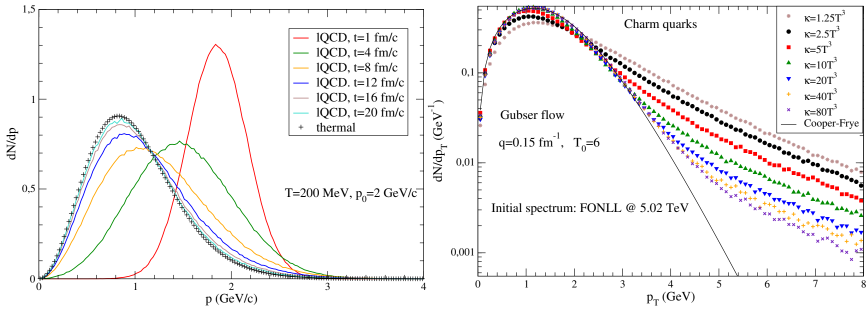
*Transport coefficients* describe the HQ-medium coupling

- *Momentum diffusion* $\kappa_\perp \equiv \frac{1}{2}\frac{\langle \Delta p_\perp^2 \rangle}{\Delta t}$ and $\kappa_\parallel \equiv \frac{\langle \Delta p_\parallel^2 \rangle}{\Delta t}$;
- *Friction* term (dependent on the discretization scheme!)

$$\eta_D{}^{\text{Ito}}(p) = \frac{\kappa_\parallel(p)}{2TE_p} - \frac{1}{E_p^2}\left[(1-v^2)\frac{\partial \kappa_\parallel(p)}{\partial v^2} + \frac{d-1}{2}\frac{\kappa_\parallel(p) - \kappa_\perp(p)}{v^2}\right]$$

fixed in order to assure approach to equilibrium (Einstein relation)

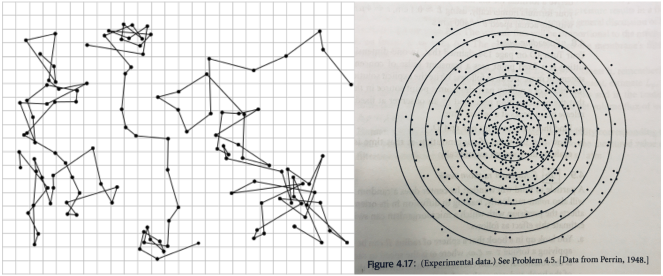



- Left panel: evolution in a static medium
- Right panel: decoupling from expanding medium at $T_{\rm FO} = 160$ MeV

For late times or for very large transport coefficients HQ's approach local kinetic equilibrium with the medium.

Figures adapted from Federica Capellino master thesis, awarded with *Milla Baldo Ceolin* and *Alfredo Molinari* INFN prizes.

# What studying HQ's in the QGP? A bit of history...

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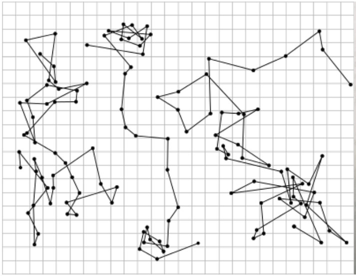

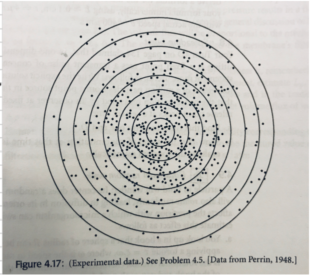


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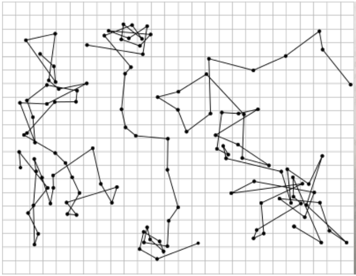

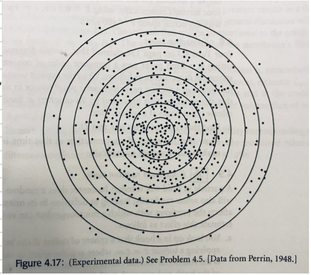


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Perrin obtained the values $\mathcal{N}_A \approx 5.5 - 7.2 \cdot 10^{23}$.

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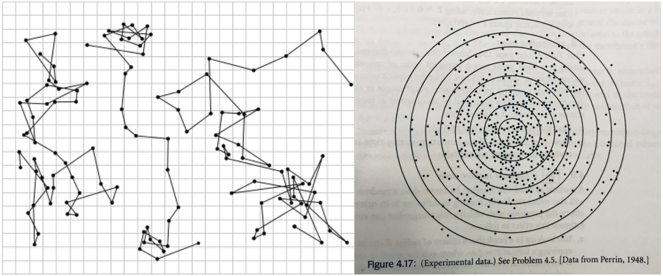


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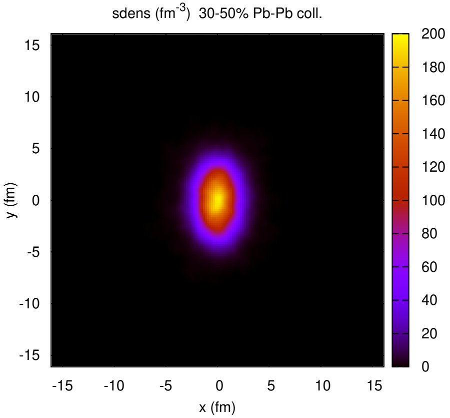
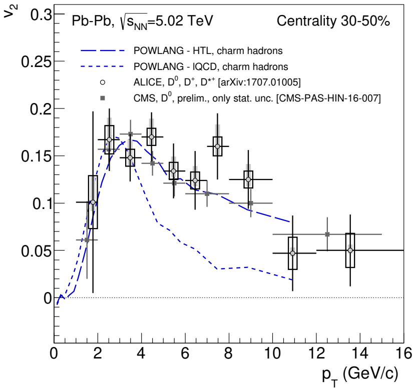
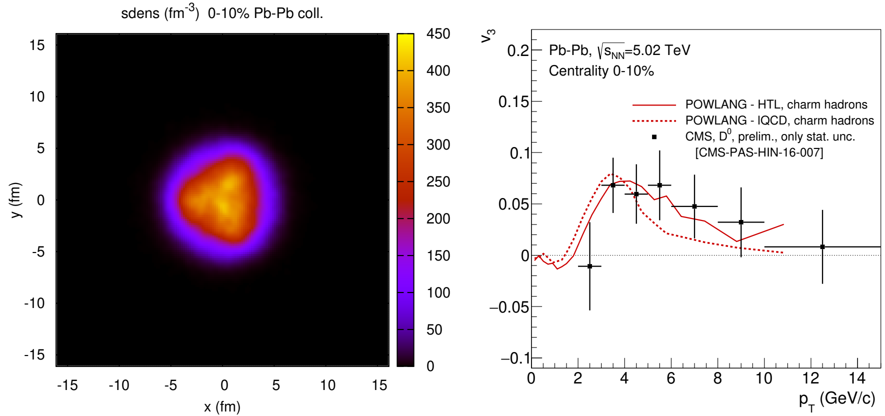
Perrin obtained the values $\mathcal{N}_A \approx 5.5 - 7.2 \cdot 10^{23}$. We would like to derive HQ transport coefficients in the QGP with a comparable precision!

# Some results: *D*-meson $v_2$ and $v_3$ in Pb-Pb




Transport calculations carried out in JHEP 1802 (2018) 043, with hydrodynamic background calculated via the ECHO-QGP code (EPJC 73 (2013) 2524) starting from Glauber Monte-Carlo initial conditions.

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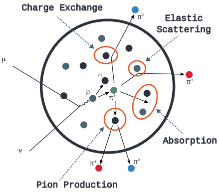
# Iniziativa Specifica NucSys

Staff: Maria Barbaro (UniTo), Arturo De Pace (INFN)
PhD students: Juan Manuel Franco (Seville/Torino), Valerio Belocchi (co-tutor Carlo Giunti)

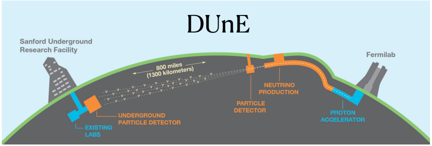
## Nuclear theory, Electroweak interactions in medium/heavy nuclei

We work at developing and improving **nuclear models** to be used in the description of **lepton-nucleus scattering** in the **relativistic regime** (0.5-10 GeV): mean-field models, nucleon-nucleon correlations, final-state interactions, two-body currents, meson production, DIS, etc.




## Main application: theoretical support to long and short baseline neutrino experiments

Ongoing (MicroBooNE, T2K, NOvA) and next-generation (DUnE, HyperK) **neutrino oscillation experiments** seek to answer some fundamental questions on the nature of matter and the evolution of the Universe, such as the existence of **CP violation in the leptonic sector** (could neutrinos be the reason that the Universe is made of matter rather than antimatter?) and the existence of **sterile neutrinos**.

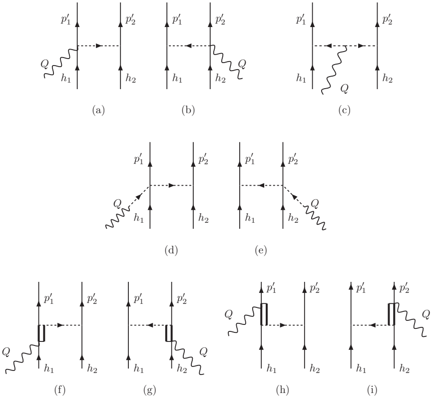


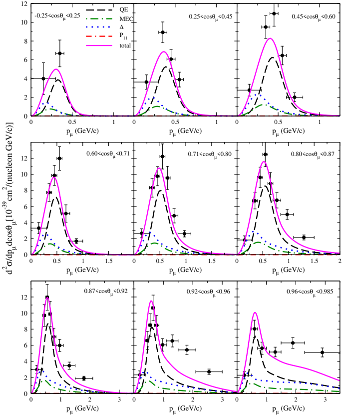

Since detectors are made of complex nuclei (typically argon, carbon, oxygen), the analysis and interpretation of the data relies on **accurate modelling of nuclear effects** to minimise systematic errors.

## Collaborations

Universities of Seville, Granada, Complutense de Madrid (Spain), Paris Univ. (France), M.I.T., ODU/JLab (USA), NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)

# Neutrino-nucleus interaction




Beyond the quasi-elastic peak, processes in which two correlated nucleons (MEC) are extracted have to be included in neutrino-nucleus cross section, together with nucleon-resonance excitations

*Remember that "Lavorare stanca" (C. Pavese), so enjoy this weekend!*