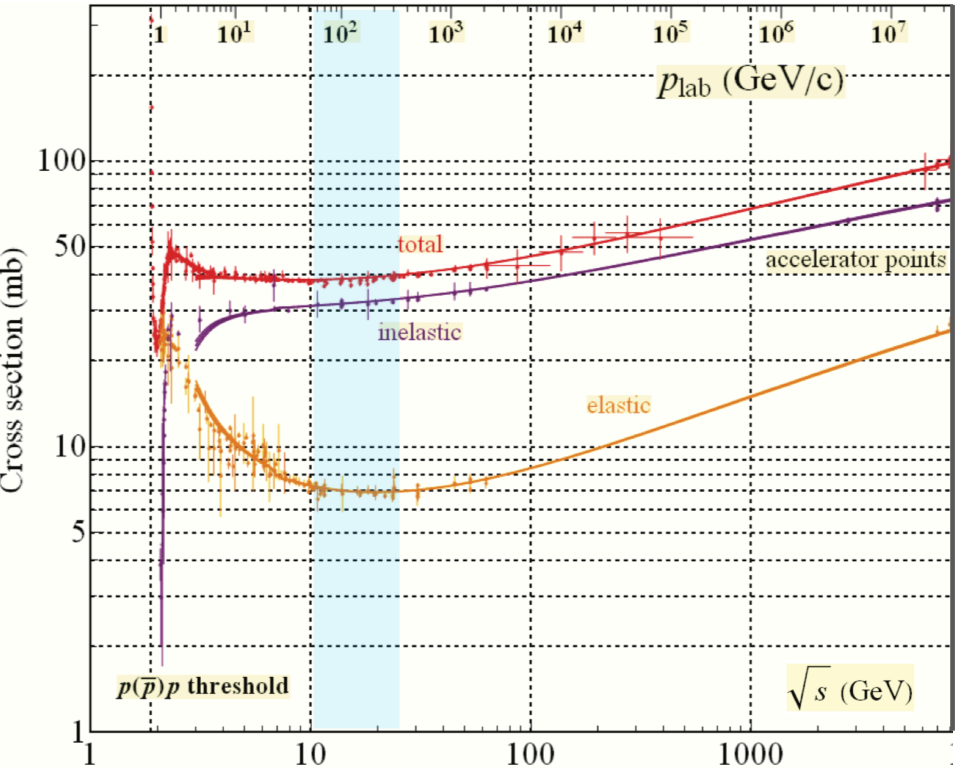
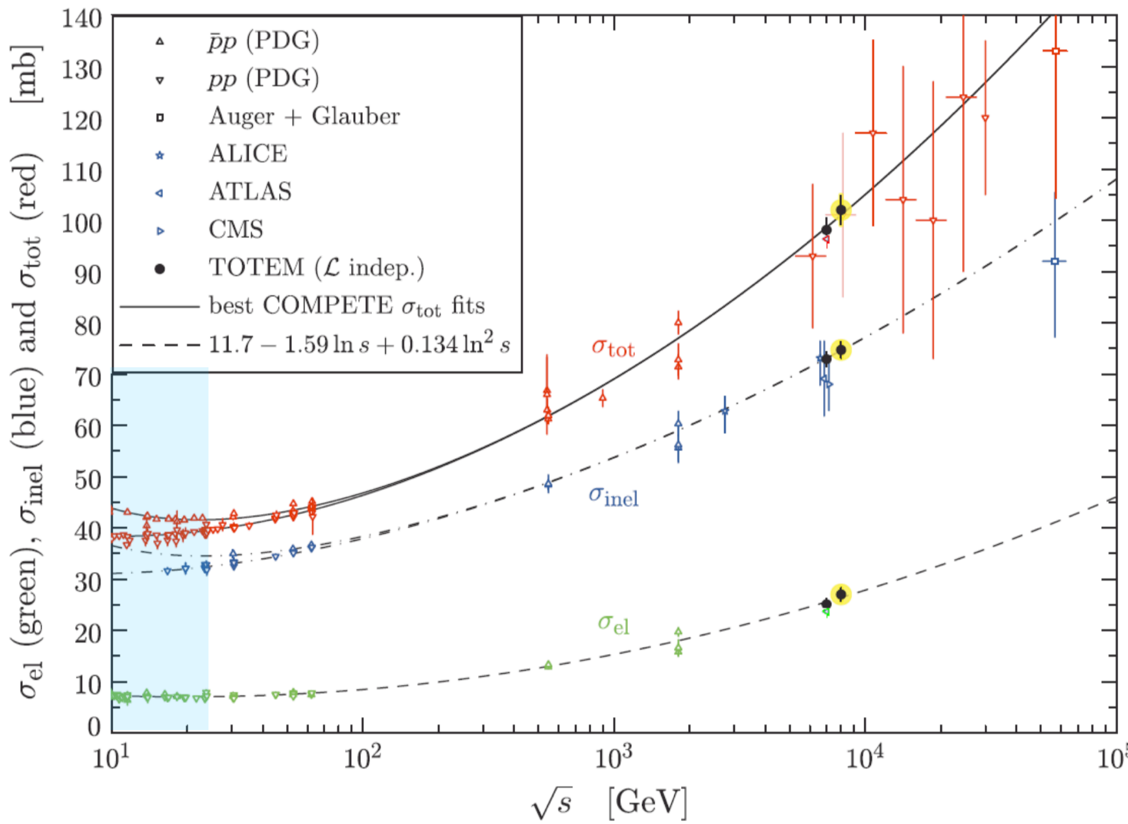
State-of-the art of the experimental data of p+p interactions in the energy range of NICA

Current state of the p+p experimental data at NICA energy range

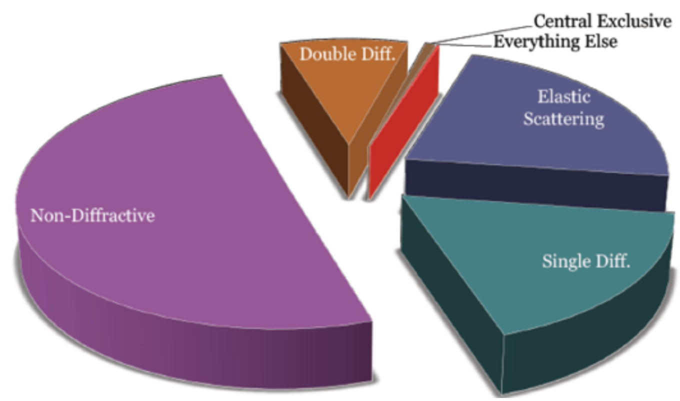
$\sqrt{s} = 10 \div 27$ GeV



M. Tanabashi *et al.* (Particle Data) Phys. Rev. D **98**, 030001 (2018)



$$\sigma_{TOT} = \sigma_{el} + \overbrace{(\sigma_{SD} + \sigma_{DD} + \cdots) + \sigma_{ND}}^{\sigma_{inel}}$$



Inelastic cross section:

Current state of the p+p experimental data at NICA energy range

One common objective of experiments aiming to measure multiparticle final states at $\sqrt{s} < 30$ GeV is to contribute and learn about the non-perturbative QCD sector.

The **inclusive** measurements account for the simplest contribution to the multidimensional phase-space.

But still, the measurements of inclusive cross sections are far from being satisfactory! It has not been possible to obtain sufficiently **precise** and internally **consistent** data sets covering the whole available space phase.

precision → Well defined error limits in the measured data, so that the resulting cross section data sets could be consistent within those limits.

↓

To allow to study the evolution of the inclusive yields from elementary to nuclear interactions.

↓

Most theoretical concepts for the interpretation of nuclear collisions rely on such experimental data as input for their calculations.

The comparison with elementary data is being significantly affected by the scarcity of p+p precise data in this energy region

Current state of the p+p experimental data at NICA energy range

Experiments that have measured inclusive particle yield from proton-proton interactions:

FermiLab (FNAL)

Bubble chambers

- the statistics is restricted to small data samples of about 10^4 events (30 inch bubble chamber).
- the particle identification is mostly absent.

Spectrometers

- small solid angle devices.
- well defined ranges of production angles.
- complete particle identification by means of Cerenkov and Scintillator counters along with proportional chambers inside the spectrometer.

→ measured inelastic pp events at 100 ÷ 400 GeV/c corresponding to $\sqrt{s}$ = 14 ÷ 27 GeV

CERN Intersecting Storage Rings (ISR) 1971 - 1984 → measured elastic and inelastic pp and $p\bar{p}$ events at $\sqrt{s}$ = 23.6 ÷ 62.2 GeV.

CERN SPS NA49 → inelastic pp interactions at p_{beam} = 158 GeV/c (equivalent to $\sqrt{s} = 17.3$ GeV)

CERN SPS NA61/SHINE → inelastic pp interactions:

p_{beam} (GeV/c)	20	31	40	80	158
$\sqrt{s}$ (GeV)	6.27	7.74	8.76	12.32	17.27

Current state of the p+p experimental data at NICA energy range

The largest collection of experimental proton-proton cross sections at energies below 30 GeV was obtained with bubble chambers and spectrometers and with the CERN ISR collider.

However, detailed information about particle production from proton-proton at $\sqrt{s}$ =10 ÷ 30 GeV is not sufficient:

- ✓ sparse
- ✓ mainly refer to basic features of unidentified charged hadron production
- ✓ the results on identified hadron spectra, fluctuations and correlations are mostly missing
- ✓ the tracking is not precise: experiments between 1970 and 1980 measured cross section without any correction for feed-down products from strange weak decays.

CERN SPS NA49 (http://cern.ch/spshadrons)

✓ Before SPS/NA61, only the NA49 experiment performed a detailed measurement of inelastic pp interactions at p_{beam} = 158 GeV/c (equivalent to $\sqrt{s} = 17.3$ GeV)

Inclusive **cross sections** for particle production (particle densities per inelastic event)

- $p + p \to \pi^{\pm} + X$ — *Eur. Phys. J. C45 (2006) 343*
- $p + p \to p + X$, $p + p \to \overline{p} + X$, $p + p \to n + X$ — *Eur. Phys. J. C65 (2006) 9*
- $p + p \to K^{\pm} + X$ — *Eur. Phys. J. C68 (2006) 1-73*

p+p measurements:

- Double differential cross section of identified particles in the x_F, p_T phase-space:

$$f(x_F, p_T) = \frac{d^2\sigma}{dx_F dp_T^2} = E(x_F, p_T) \cdot \frac{d^3\sigma}{dp^3}(x_F, p_T) \quad [\text{mb}/(\text{GeV}^2/\text{c}^3)]$$

$$x_F = \frac{p_z}{\sqrt{s}/2}$$

- Integrated invariant **cross section** *vs* x_F: $F = \int f dp_T^2$

- Density distributions *vs* x_F: $\frac{dn}{dy} = \frac{\pi}{\sigma_{inel}} \int f dp_T^2 \qquad \frac{dn}{dx_F} = \frac{\pi}{\sigma_{inel}} \frac{\sqrt{s}}{2} \int \frac{f}{E} dp_T^2$

- Mean multiplicity from dn/dx_F integration: $\langle n \rangle$

Current state of the p+p experimental data at NICA energy range

CERN SPS NA61/SHINE Large acceptance hadron spectrometer at the CERN **S**uper **P**roton **S**ynchrotron

Aim: to perform a two dimensional scan in $\sqrt{s}$ and colliding nuclei to perform a systematic study of the phase diagram of the strongly interacting matter.

Measurement of inclusive **spectra** and mean multiplicity of **charged** particles produced in inelastic p+p interactions

p_{beam} (GeV/c)	20	31	40	80	158
$\sqrt{s}$ (GeV)	6.27	7.74	8.76	12.32	17.27

$$\boldsymbol{p} + \boldsymbol{p} \to \boldsymbol{\pi}^{\pm} + \boldsymbol{X}$$
$$\boldsymbol{p} + \boldsymbol{p} \to \boldsymbol{p} + \boldsymbol{X}$$
$$\boldsymbol{p} + \boldsymbol{p} \to \overline{\boldsymbol{p}} + \boldsymbol{X}$$
$$\boldsymbol{p} + \boldsymbol{p} \to \boldsymbol{K}^{\pm} + \boldsymbol{X}$$

Eur. Phys. J. C77 (2017) 671

Lambda hyperon measurement from inelastic p+p interactions

p_{beam} (GeV/c)	158
$\sqrt{s}$ (GeV)	17.27

$$\boldsymbol{p} + \boldsymbol{p} \to \boldsymbol{\Lambda}^{0}$$

Eur. Phys. J. C76 (2016) 198

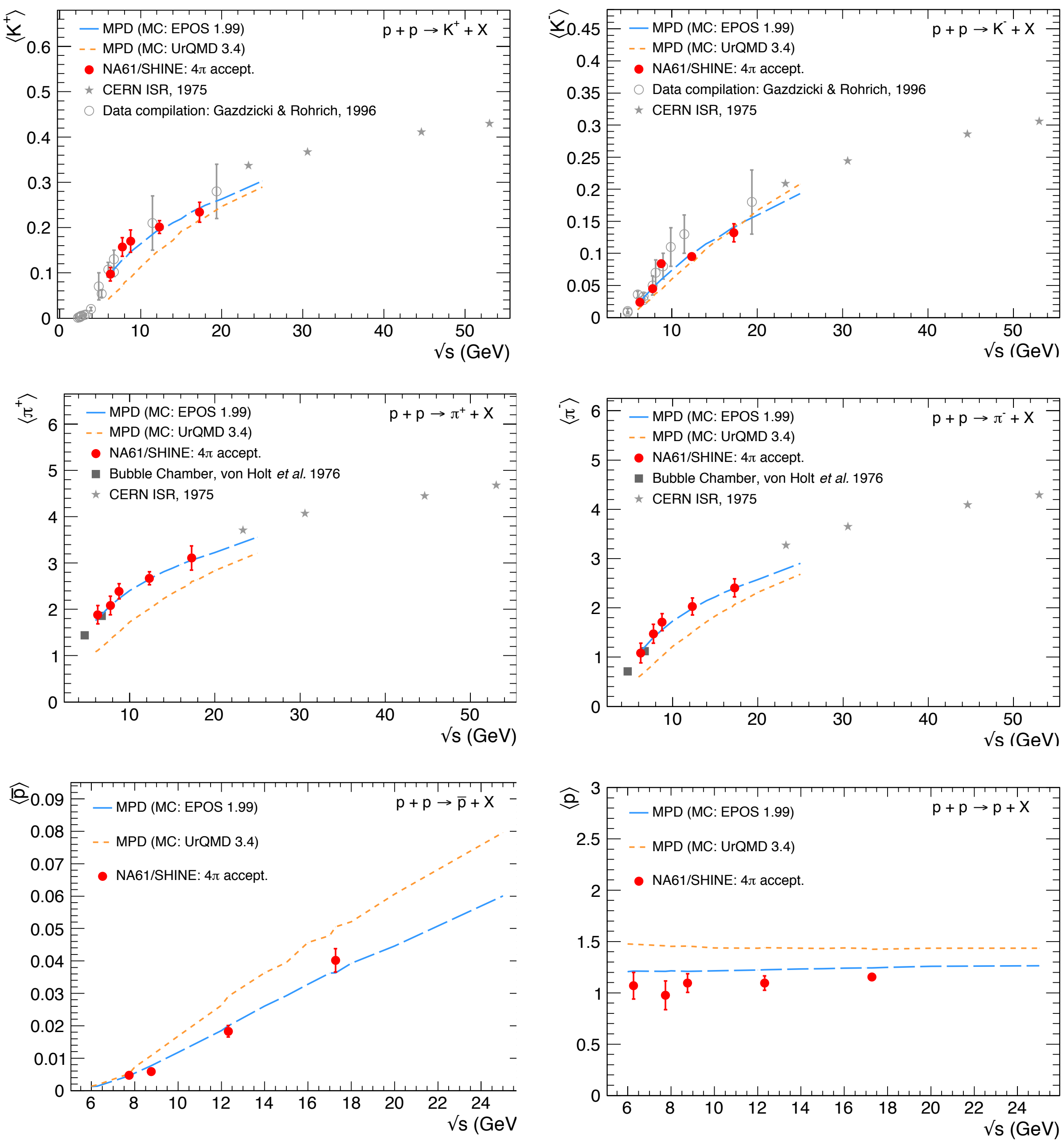
p+p measurements:

- Double differential spectra of identified particles in the p_T, y phase-space: $\frac{d^2n}{dy dp_T}\ vs.\ p_T$
- A parametrization was proposed: $\frac{d^2n}{dy dp_T} = \frac{S \cdot c^2 \cdot p_T}{T^2 + m \cdot T} \exp(-(m_T - m)/T)$ m: particle mass, S: yield integral, T: inverse slope parameter
- Energy dependence of the mean multiplicity from dn/dy integration: $\langle n \rangle\ vs.\ \sqrt{s}$

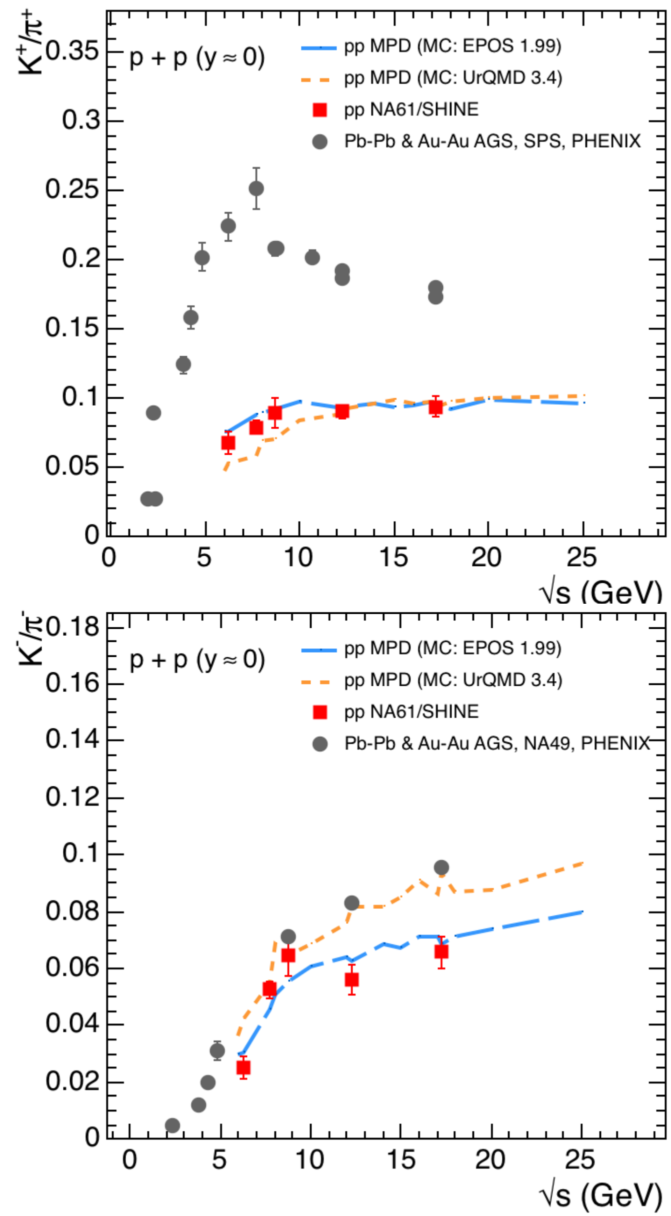
CERN SPS NA61/SHINE

$p,\ \bar{p},\ \pi^{\pm},.K^{\pm}$ from pp inelastic interactions

Energy dependence of the mean multiplicity distribution

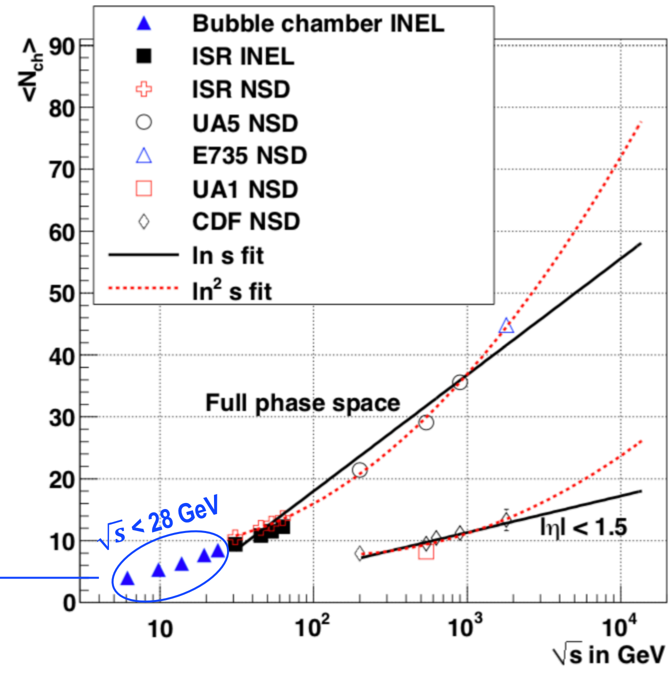


Horn effect



Current state of the p+p experimental data at NICA energy range

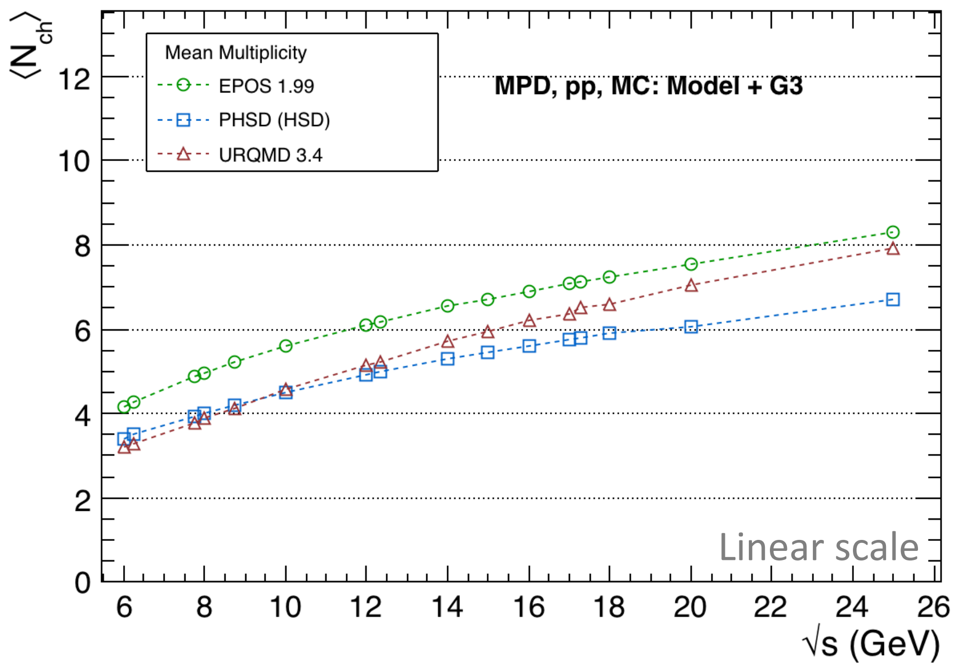
Average charged multiplicity as function of the collision energy ⇒

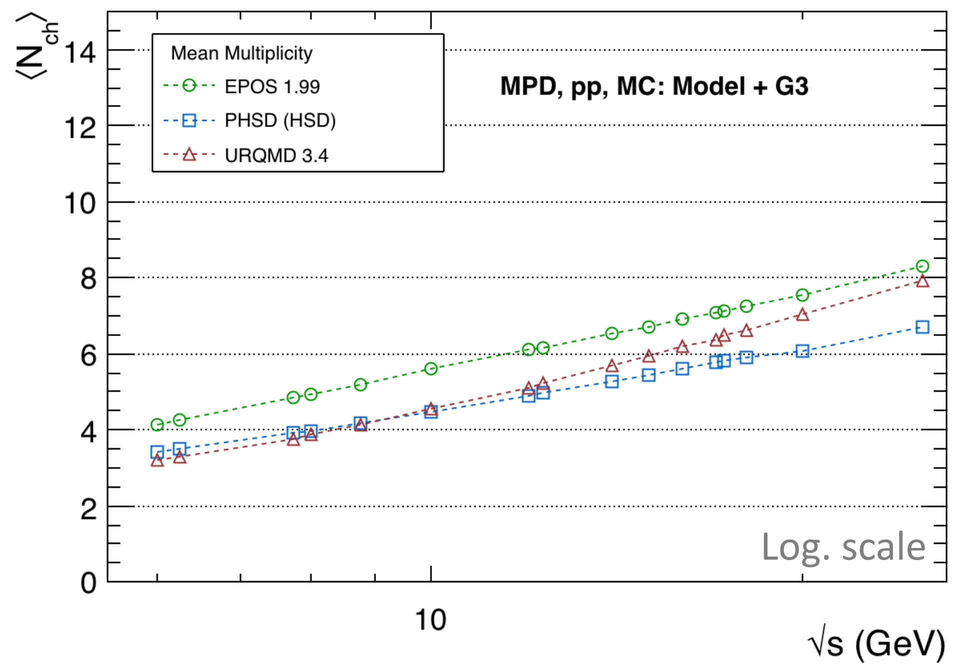


Inelastic pp measurements with bubble chambers

- 50 ÷ 300 GeV/c ($\sqrt{s}$= 9.7 ÷ 24 GeV), Mirabelle chamber, Serpukhov , Russia, 1972. *Phys. Rev. Lett. 29 (1972) 1624*
- 100 ÷ 400 GeV/c ($\sqrt{s}$= 14 ÷ 27.4 GeV), FNAL bubble chambers. *Phys. Rep. 10 (1974) 273, Phys. Rept. 29 (1976) 187*

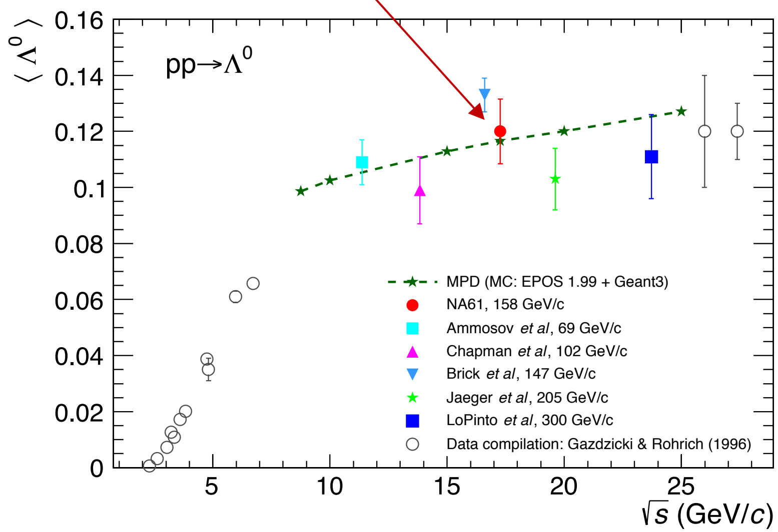
Energy range of NICA: $\sqrt{s}$ < 27 GeV





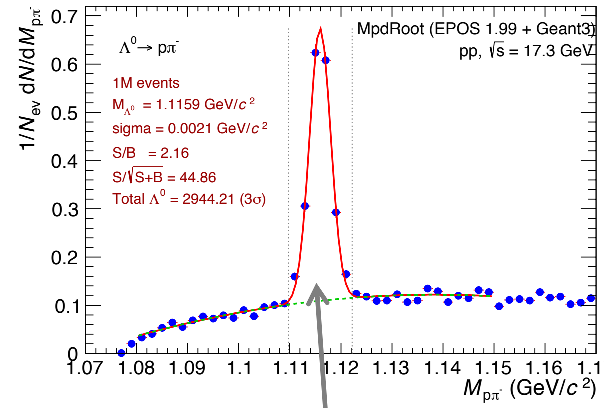
CERN SPS NA61/SHINE

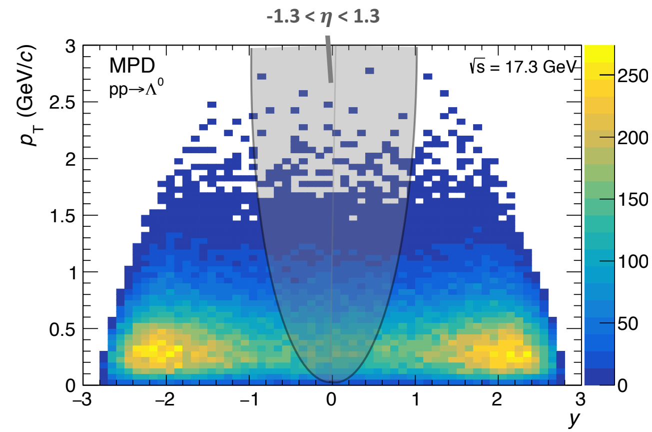
Λ^0 from pp inelastic interactions



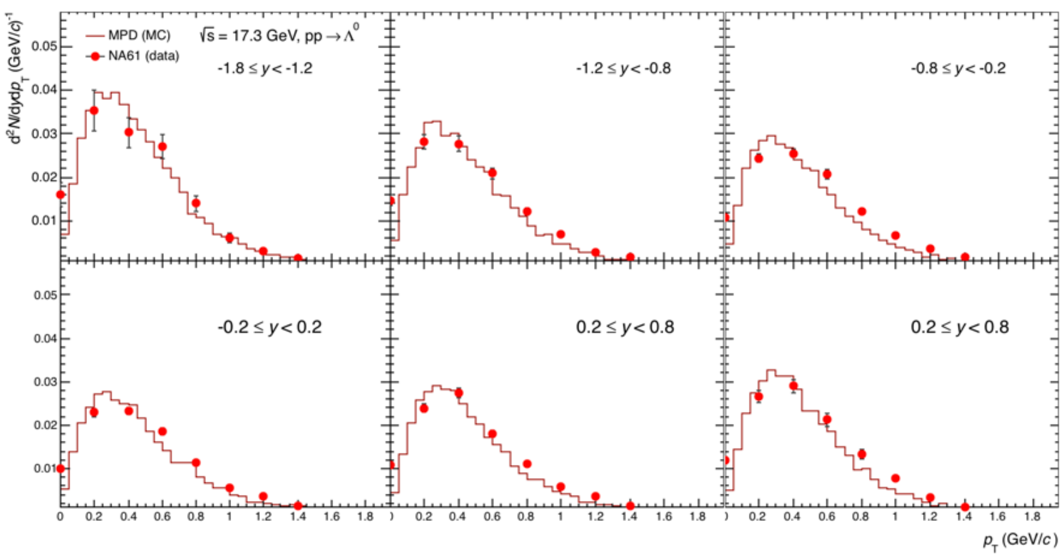
$$\Lambda^0 \to p + \pi^-$$

MC simulation of $pp \to \Lambda^0$ with EPOS-1.99 generator, very close to the experimental data (in the NICA energy range)

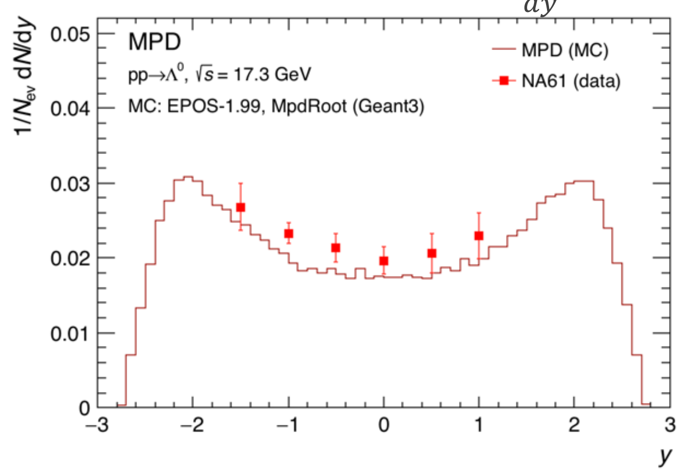




Double-differential distribution of Λ^0 from pp @ $\sqrt{s}$ = 17.3 GeV



Rapidity density distribution $\frac{dN}{dy}$ of Λ^0



$\phi(1020)$ meson production at NA61/SHINE

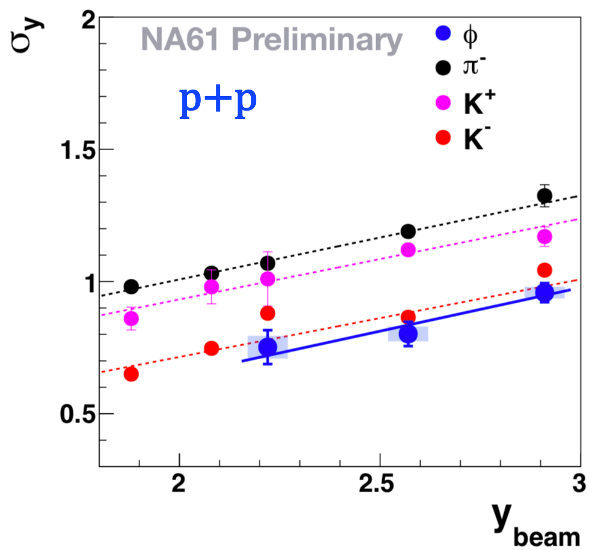
$\phi \rightarrow K^+ + K^-$ (49.2%)

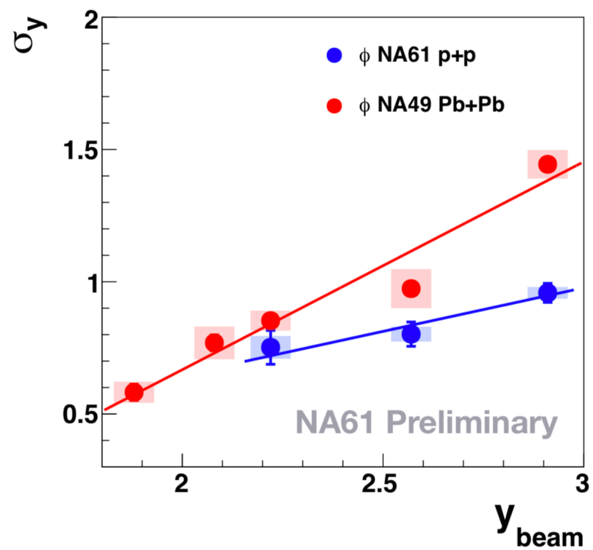
p_{beam} (GeV/c)	40	80	158
$\sqrt{s}$ (GeV)	8.76	12.32	17.27

$\{p + p \rightarrow \phi(1020)\}$ *T. Susa, Talk in SQM-2017*
EPJ Web of Conferences 199 (2019) 02020 "MESON 2018"

- $\phi(1020)$ meson production
  - As constraint of hadron production models
  - As reference for heavier systems (strangeness studies)

Widths of ***y*** distributions (Gaussian fitted)





In pp collisions ϕ follows the trends of other hadrons.

Different slopes in pp and Pb-Pb.

For Pb-Pb the behavior of σ_y is qualitatively consistent with the rescattering of kaons from the ϕ mesons decaying in the fireball

It was also measured by NA49 in central collisions of pp, p-Pb and Pb-Pb at **158 GeV/c** (Phys. Lett. B 491 (2000) 59)

CERN SPS NA61/SHINE

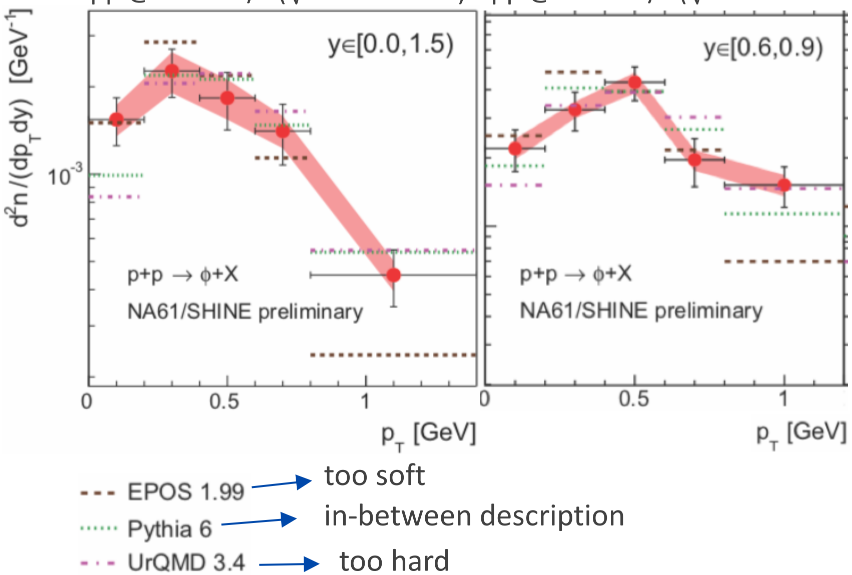
ϕ(1020) meson production at NA61/SHINE

$\phi \rightarrow K^+ + K^-$ (49.2%)

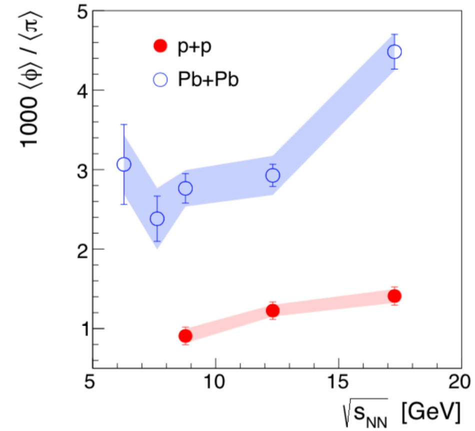
First differential measurements of ϕ(1020) meson production at $\sqrt{s}$ = 8.76 and 12.3 GeV

- Transverse momentum spectra in rapidity bins *(EPJ Web of Conferences 199 (2019) 020209)*

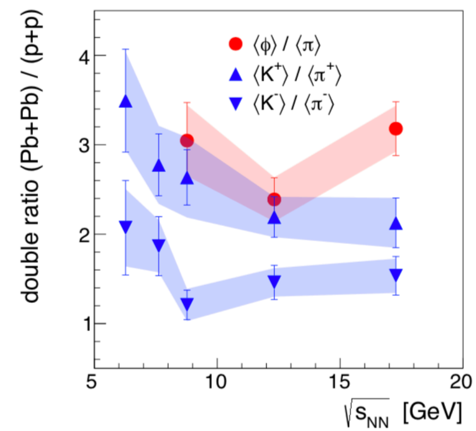
pp @ 40 GeV/c ($\sqrt{s}$ = 8.76 GeV) pp @ 80 GeV/c ($\sqrt{s}$ = 12.3 GeV)



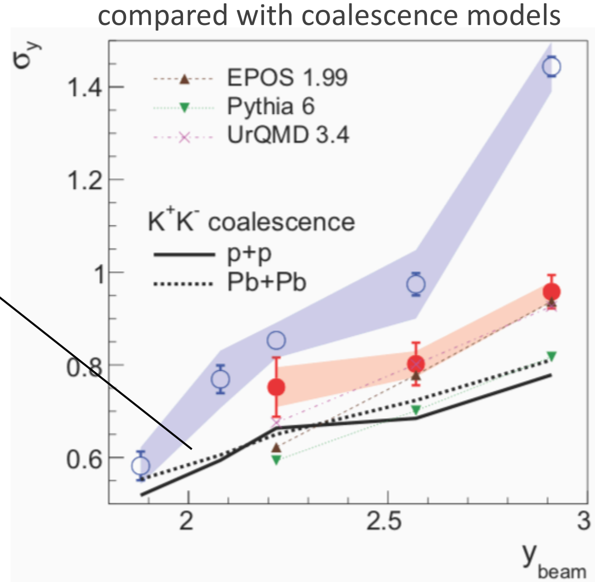
Ratio of total yield of ϕ mesons to the mean total yield of pions



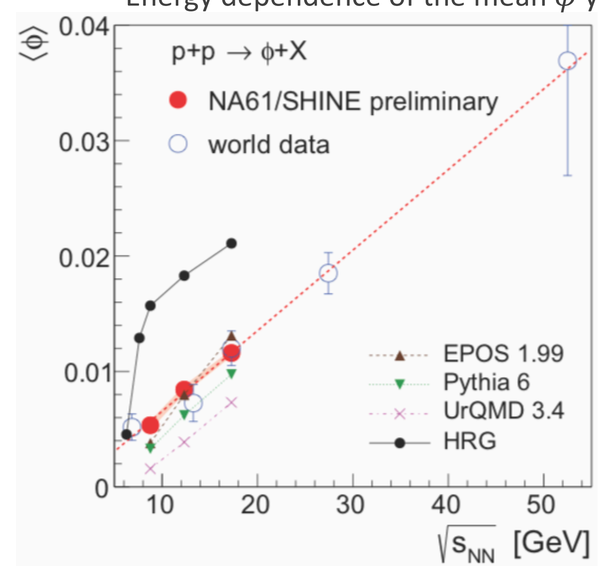
$$(\langle\phi\rangle / \langle\pi\rangle) = \frac{(\langle\phi\rangle / \langle\pi\rangle)_{Pb+Pb}}{(\langle\phi\rangle / \langle\pi\rangle)_{p+p}}$$



- Widths of y distributions of ϕ mesons compared with coalescence models



- Energy dependence of the mean ϕ yield



Enhancement strangeness of ϕ in Pb-Pb w.r.t. pp collisions with increasing SPS energies.

Coalescence scenario investigated assuming:

$$\frac{1}{\sigma_\phi^2} = \frac{1}{\sigma_{K+}^2} + \frac{1}{\sigma_{K-}^2}$$

Experimental results are not compatible with the picture of ϕ production through the K^+K^-coalescence.

EPOS 1.99

Energy conserving quantum mechanical multiple scattering approach, based on **P**artons (partons ladders), **O**ff-shell remnants, and **S**plitting of parton ladders.

Unified formalism based on a combination of:

- Gribov – Regge theory
  - Focusses on the **soft** aspects of the particle collisions.
  - Describes multiple interactions using "Pomerons" representing an elementary interaction.
- Parton model
  - Introduces quarks and gluons giving a more precise description of interactions.
  - Uses QCD and QED descriptions to calculate cross sections of parton jets.
  - Parton production represented by Lund model strings.

Strengths:

- Consistent treatment of soft and hard scattering.
- Hard processes are introduced in a natural way without arbitrary assumptions (no artificial cuts)
- Energy conservation is considered in both, particle production and cross section calculation.
- Hydrodynamical evolution is done event by event.
- Treatment of participants and remnants ensures the energy conservation.

- **Data used to constrain parameters (~100) :**
  - string fragmentation : e+e- data,
  - hard Pomeron : DIS data,
  - soft Pomeron and vertices : pp,πp,Kp, pA cross sections
  - diffraction : pp low energy diffraction and multiplicity distributions
  - excitation functions : multiplicity in pp from SPS to LHC,
  - string ends and remnants : NA49 data
  - collective and screening effects : RHIC and LHC

EPOS designed to be used for particle physics experiment analysis (SPS, RHIC, LHC) for pp or Heavy Ion

Consistent treatment for all kind of systems: different contributions of particle production at different energies and rapidities (includes both: diffractive and inelastic scattering)!!!

Final state depends on the energy used for each event (multiplicity), not only on the energy available (collective hadronization when density of particles is high)

EPOS 1.99 can be used for minimum bias hadronic interaction generation from 100 GeV (lab) 1000 TeV (cms)

↓ $\sqrt{s} = 13.6$ GeV ↓ Air showers

- **One set of parameters for all energies and system**
  - not designed to be tuned by users

UrQMD 3.4

Ultra Relativistic Quantum Molecular Dynamics

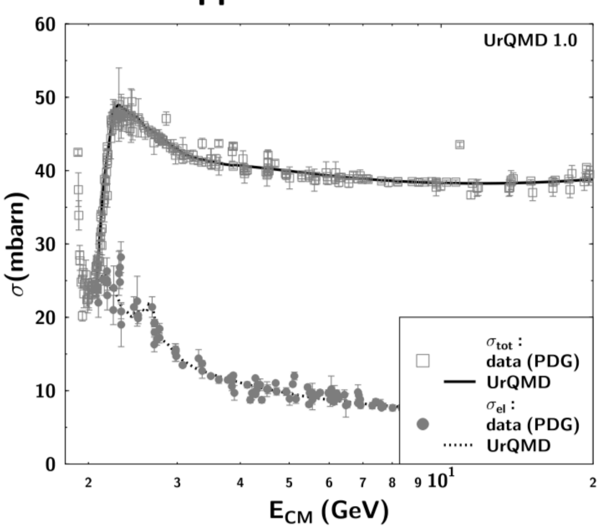
It is a non-equilibrium microscopic transport model for heavy ion collisions.

The underlying degrees of freedom are hadrons and strings

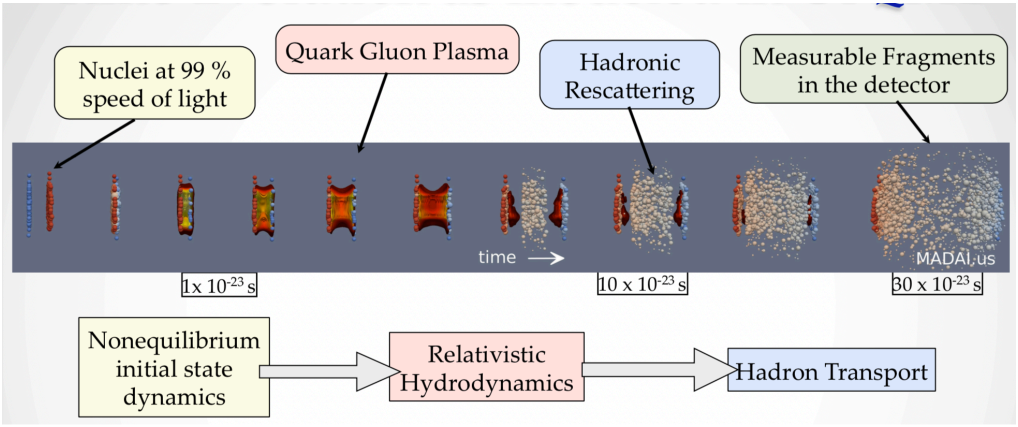
55 baryon and 32 meson species, ground state particles and all resonance with masses up to 2.25 GeV/c^2. Full particle-antiparticle, isospin and flavour SU(3) symetries are applied

Uses tables at low energies to properly describe data.

pp cross sections



Time evolution in UrQMD



Hybrid approach is added for low energies and includes an ideal fluid-dynamic evolution for the hot and dense stage.

Time evolution of the distribution functions for particle species is described by a non-equilibrium approach based on an effective solution of the relativistic Boltzmann equation.

PHSD

Parton **H**adron **S**tring **D**ynamics

The Parton-Hadron-String Dynamics (PHSD) is a microscopic off-shell transport approach that consistently describes the full evolution of a relativistic heavy-ion collision from the initial hard scatterings and string formation through the dynamical deconfinement phase transition to the quark-gluon plasma as well as hadronization and to the subsequent interactions in the hadronic phase. It has been developed by the Giessen/Frankfurt groups on the basis of the **Hadron-String Dynamics transport approach (HSD)** and in the hadronic sector, PHSD is equivalent to HSD.

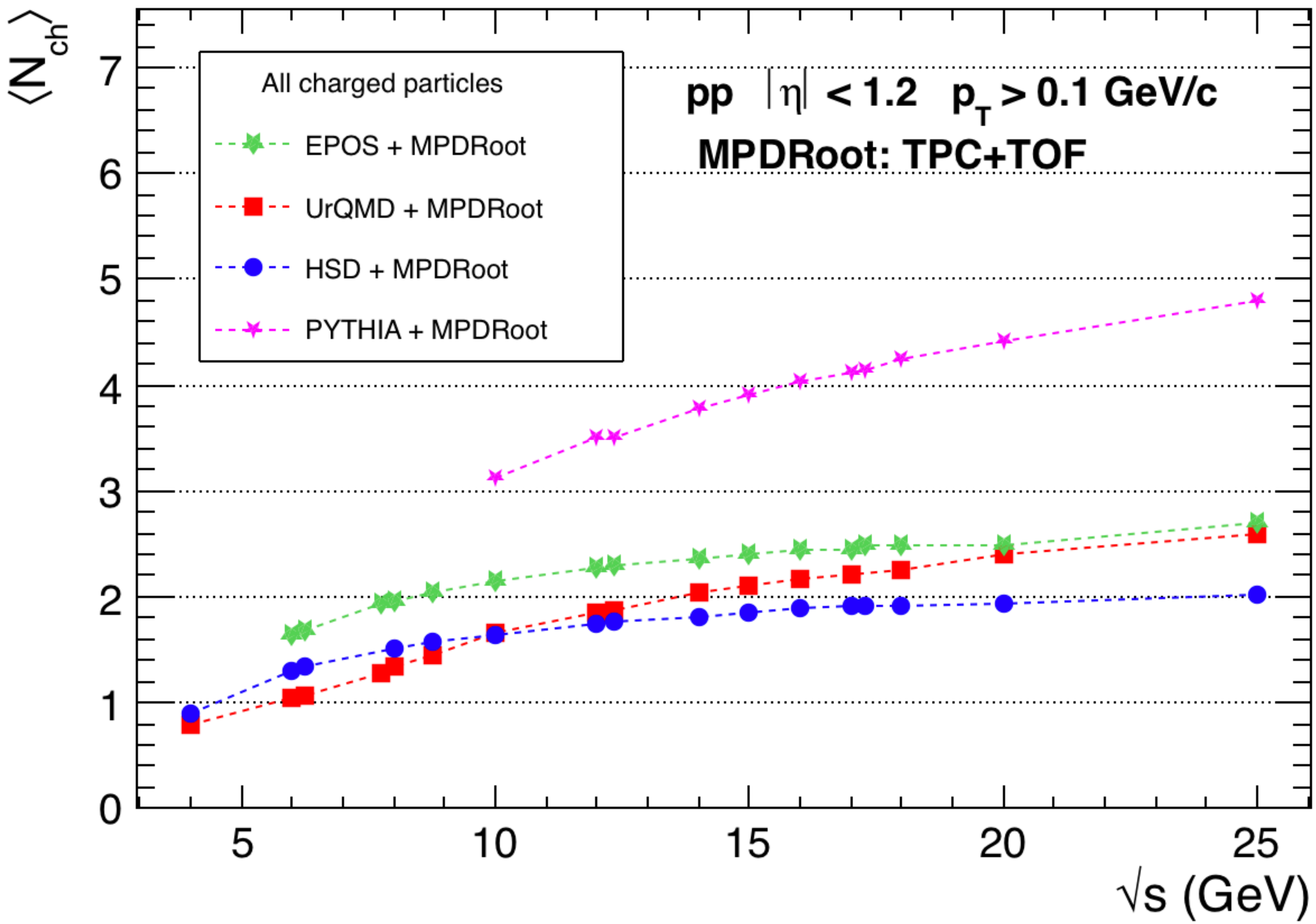
It is a non-equilibrium microscopic transport model for heavy ion collisions.

The underlying degrees of freedom are hadrons and strings

p+p collisions is used as an input based on the LUND string model via subroutines of FRITIOF string model.

Available models to study pp collisions are currently under investigation to define its possibilities as particle generator at the energies available in NICA.

Mean multiplicity of all charged particles in MPD (TPC+TOF).
Here the models EPOS, UrQMD, HSD and PYTHIA were used as generators.



- EPOS-1.99
- HSD-4.0
- UrQMD-3.4
- Pythia-8.215