NA61/SHINE:
Status, Results and Plans

(report to the proposal SPSC-P-330: SPSC-SR-145)

(October 2013 – October 2014)

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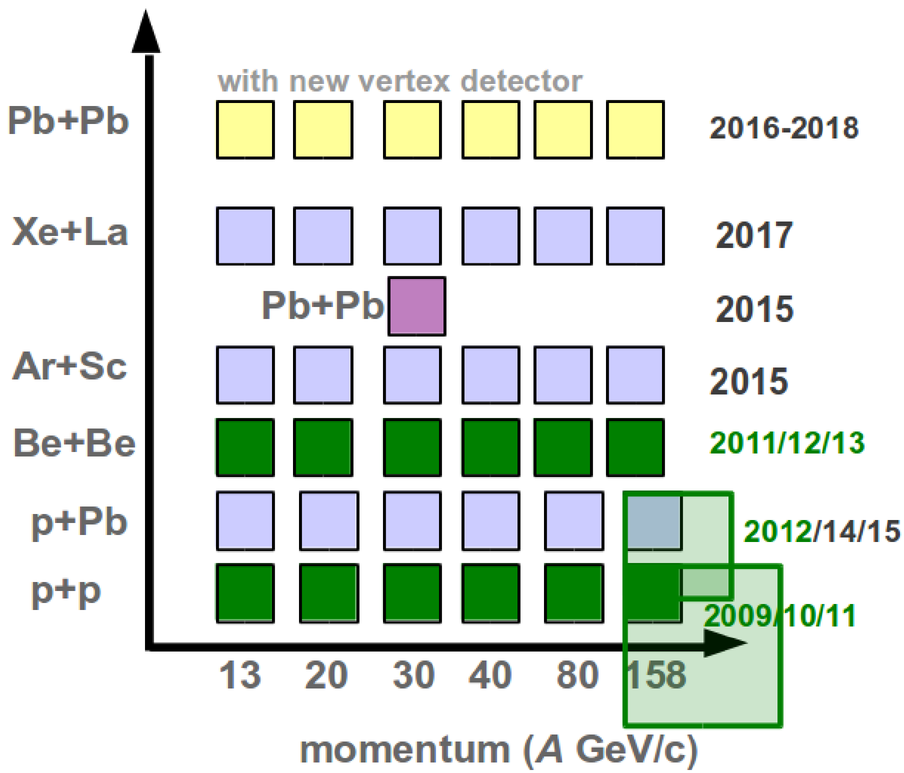
NA61/SHINE (SPS Heavy Ion and Neutrino Experiment)

NA61/SHINE physics program

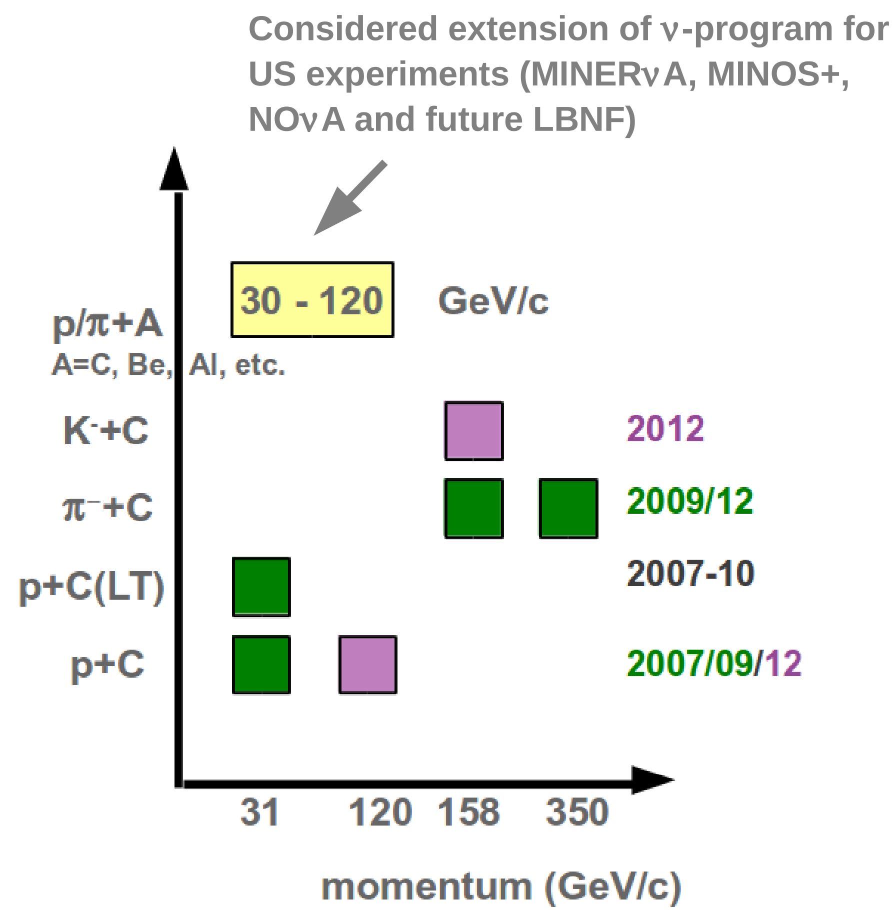
- **Strong interactions program - spectra, fluctuations, correlations**
  - search for the **critical point** of strongly interacting matter
  - study of the **properties of the onset of deconfinement**
  - study **high p_T particles** (energy dependence of nuclear modif. factor)
- **Neutrino and cosmic-ray physics programs - precision data on hadron production (spectra)**
  - **reference measurements** of p+C interactions **for the T2K experiment** for computing initial neutrino fluxes at J-PARC
  - **reference measurements** of p+C, p+p, π+C, and K+C interactions **for cosmic-ray physics** (Pierre-Auger and KASCADE experiments) for improving air shower simulations
- **Planned extensions beyond the approved program**
  - measurements of **Pb+Pb** collisions for the strong interactions program (+ open charm and multi-strange particles, high p_T spectra)
  - measurements for the **Fermilab neutrino program**

Status of data taking

Status of the NA61 data taking within the strong interactions program



Status of the NA61 data taking within the neutrino and CR programs



recorded data

pilot (test) data

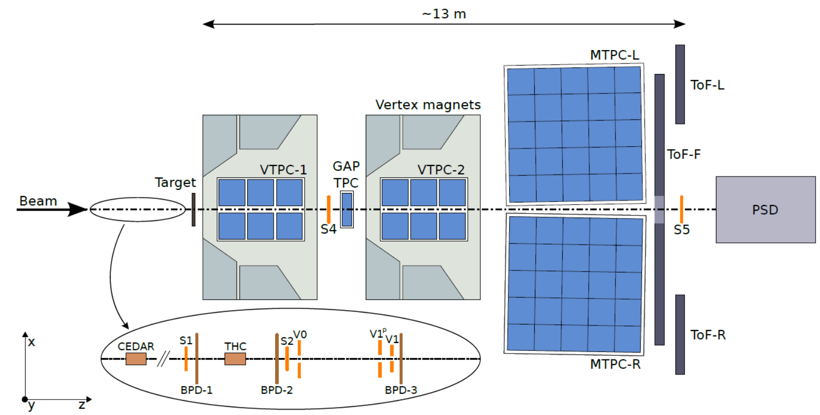
planned data (approved)

beyond the approved program

LT – T2K replica target (90cm)

Facility modifications

- Two completed modifications:
  - **Projectile Spectator Detector upgrade**
    (monitoring, cooling, slow control systems)
  - **ToF-L/R upgrade**
    (ToF-L/R High Voltage distribution system)



- Extension of the TPC drift velocity system will be ready for the 2014 data taking

- Following upgrades are planned to be finished in 2015:
  - upgrade and maintenance of the super-conducting magnets
  - DRS-based read-out upgrade

- R&D work on three new detectors has started:
  - new beam detectors for primary ion beams (S1, S2 counters, new BPDs)
  - Forward TPCs (to close gap between MTPCs; motivated by the Fermilab neutrino program)
  - Vertex Detector (dedicated to open charm and multi-strange hyperon measurements)

- Radiation shielding of the H2 beam line is well advanced and will be finished in January 2015 before data taking with primary Ar beams

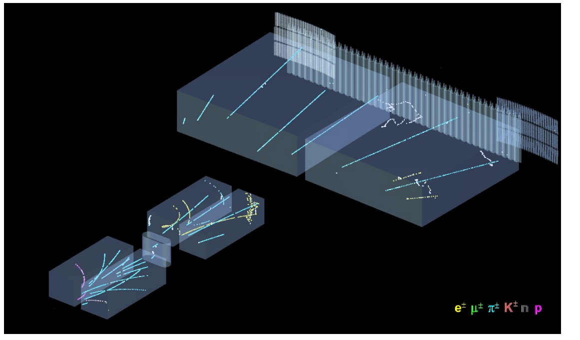
- Performed upgrade and maintenance of the super-conducting magnets (CERN TE department) should assure their stable operation until the end of data taking with primary Ar beams (after that the exchange of vacuum pumps will take place)

Software and calibration modifications

- **Event reconstruction parts of the "legacy" reconstruction chain** has been **ported into SHINE**

- Full validation of the new reconstruction chain within SHINE against "legacy" was demonstrated

π^- + C at 158 GeV/c, GEANT4



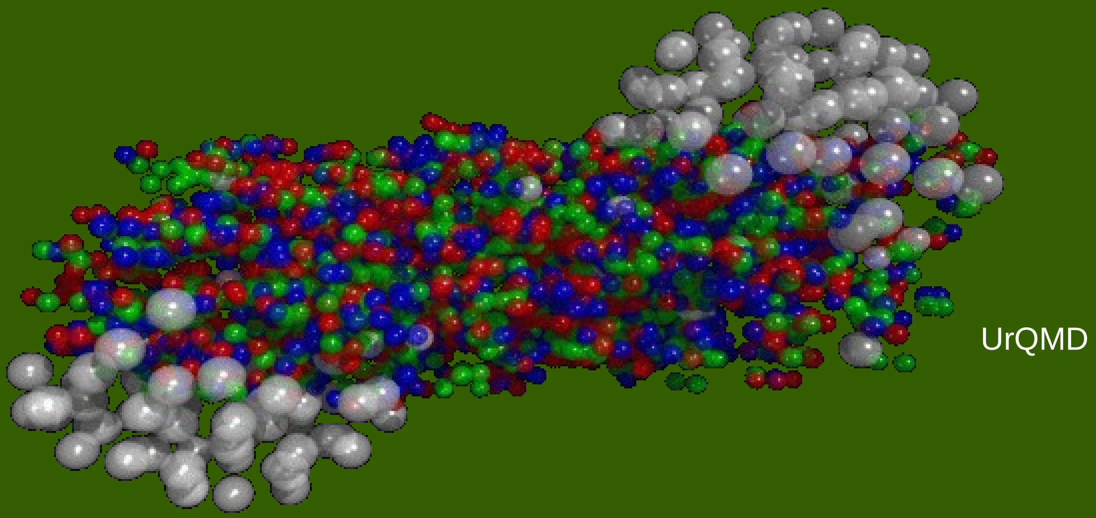
- Decision was made to start full data production using the new software framework and to phase out "legacy" for production as soon as possible

- **Detector description part of the software** was fully implemented **in the SHINE framework** and the important detector parameters in the legacy modules within SHINE are derived from the SHINE Detector

- **New calibration framework** was introduced **in SHINE**, for processing of the recorded physics data stream in order to calculate the event data dependent calibration coefficients such as alignment and drift velocity parameters

- **Deployment of the "legacy" reconstruction chain under CERNVM and CERN OpenStack** infrastructure was finished and the validated against LxBatch productions

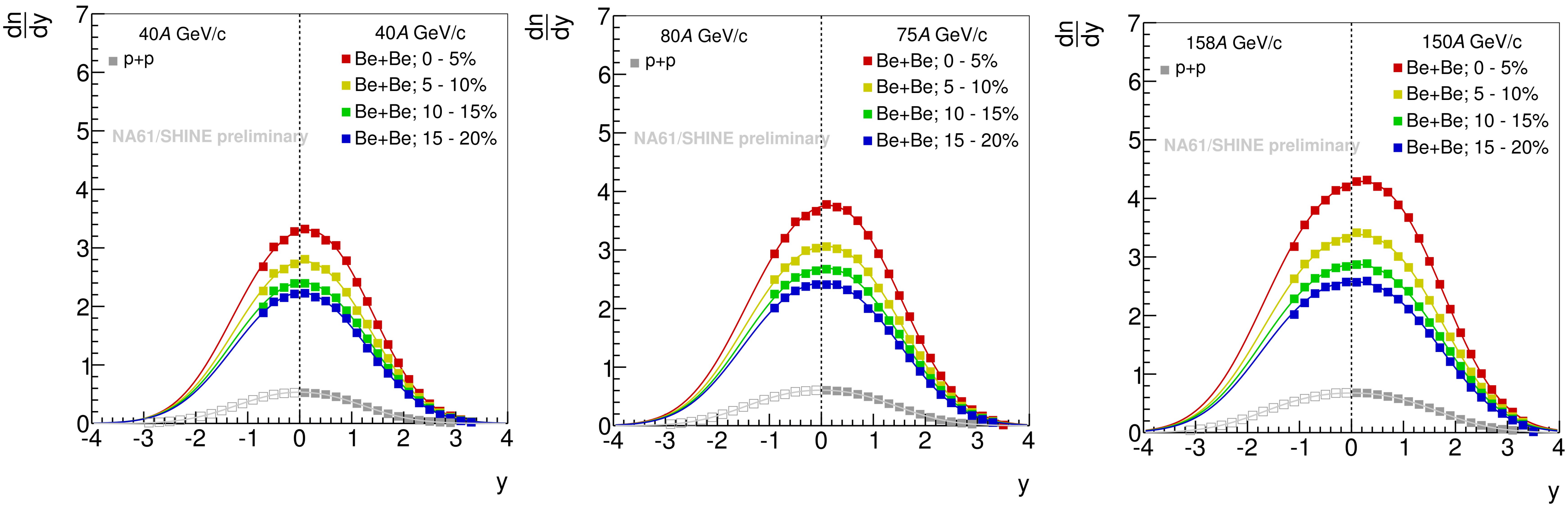
New results for strong interactions physics



- New results from $^{7}Be+^{9}Be$ collisions
  - π^{-} spectra in $^{7}Be+^{9}Be$ (from h^{-} method)
  - p_T fluctuations in $^{7}Be+^{9}Be$
- New results from p+p collisions
  - π, K, p spectra in p+p (from tof-dE/dx analysis)
  - Λ spectra in p+p at 158 GeV/c (see back-up slides)
  - Correlations in $\Delta\eta$, $\Delta\phi$ in p+p
  - Fluctuations of charged pions in p+p (see back-up slides)

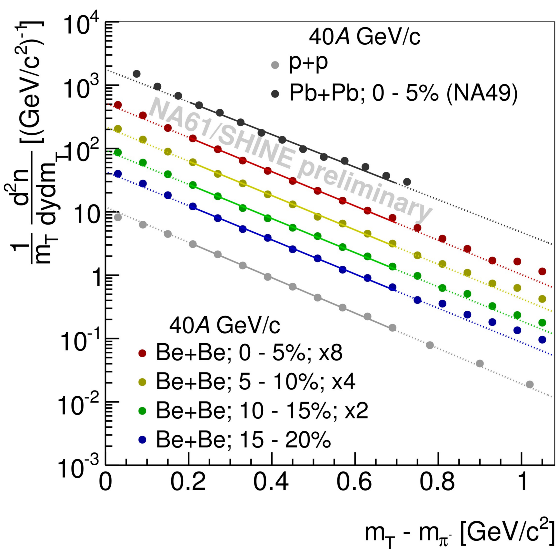
π^- spectra in ^{7}Be+^{9}Be

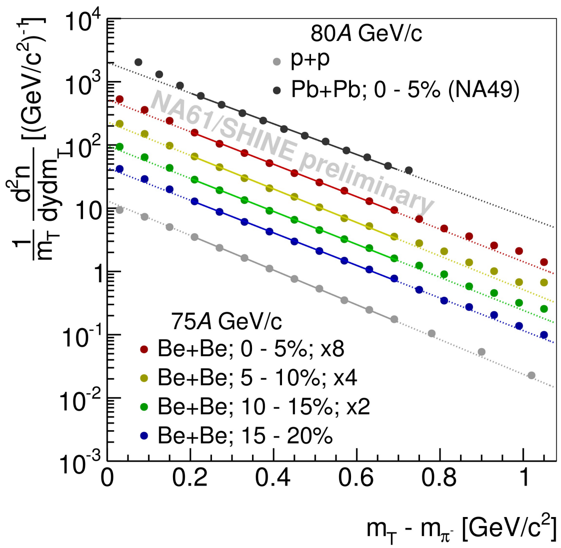
- Since the last Status Report: **spectra extended below mid-rapidity**
- This allows to establish the asymmetry of the rapidity spectrum (double Gaussian functions fitted with the same widths but different amplitudes) and calculate **4π pion multiplicity**
- 4π pion multiplicities can be then used to obtain **kink** plot - $\langle\pi\rangle/\langle N_W\rangle$ vs energy (F) (one of the signals of the onset of deconfinement)

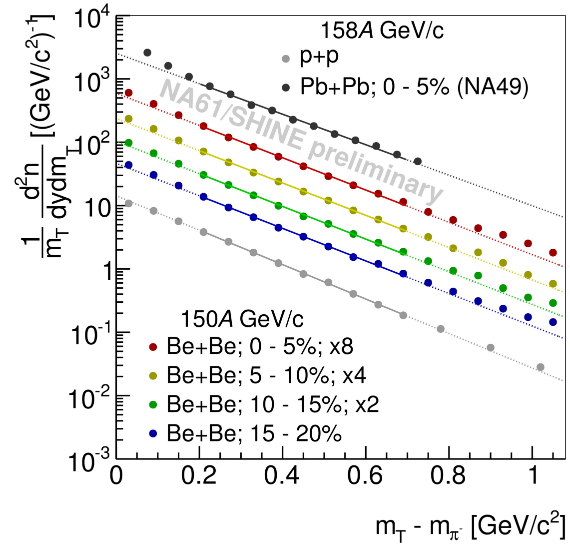


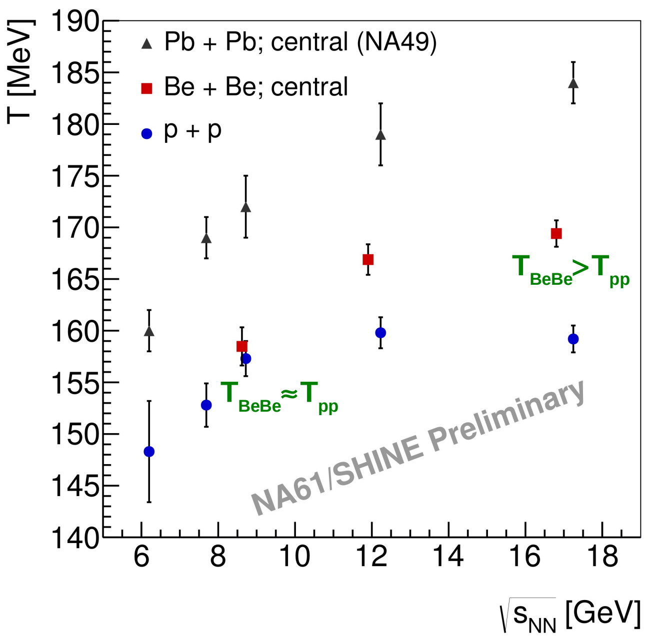
- Asymmetric shapes due to:
  - Asymmetry of colliding system (^{7}Be beam on ^{9}Be target) enhances backward rapidity
  - Centrality selection based on forward energy only enhances forward rapidity

π^- spectra in ^{7}Be+^{9}Be









$$\frac{d^2 n}{dy\, dm_T} = A\, m_T \exp\left(\frac{-m_T}{T}\right)$$

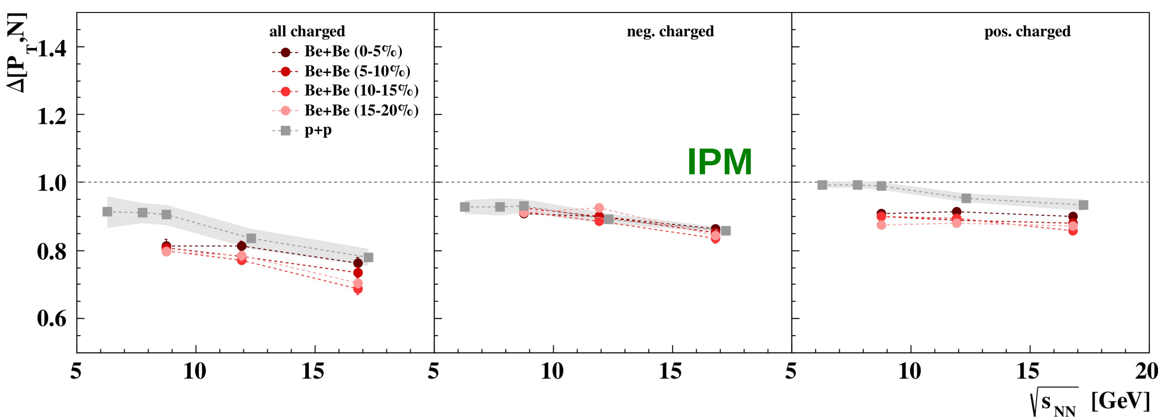
$$0.2 < m_T - m_\pi < 0.7 \quad \mathrm{GeV/c^2}$$

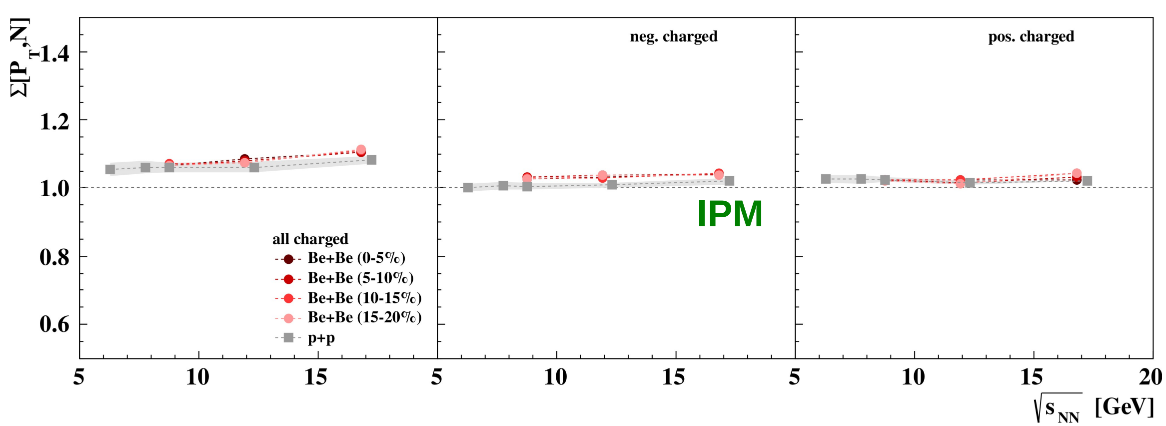
T at 150*A* GeV/c is significantly larger in Be+Be than in p+p → **possible evidence of transverse collective flow in Be+Be collisions at higher SPS energies.**
Beryllium looks “heavy” at 150*A* GeV/c

p_T fluctuations in ^{7}Be+^{9}Be

Search for the critical point (CP) of strongly interacting matter

- **Strongly intensive measures Δ and Σ** PRC 88, 024907 (2013); in Grand Canonical Ensemble they do not depend on volume and volume fluctuations
- No fluctuations → $\Delta = \Sigma = 0$; Independent Particle Model (IMP) → $\Delta = \Sigma = 1$



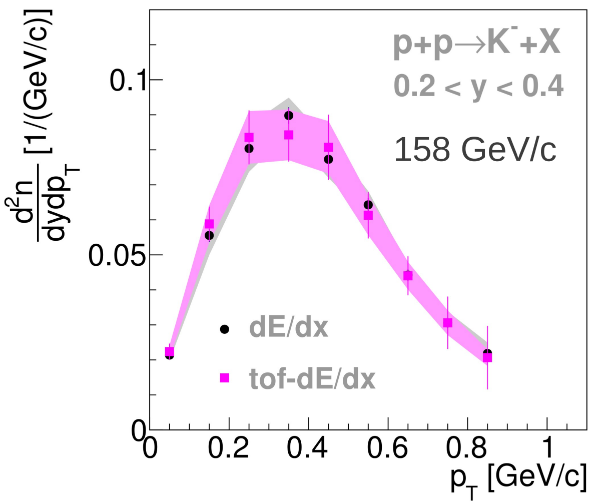


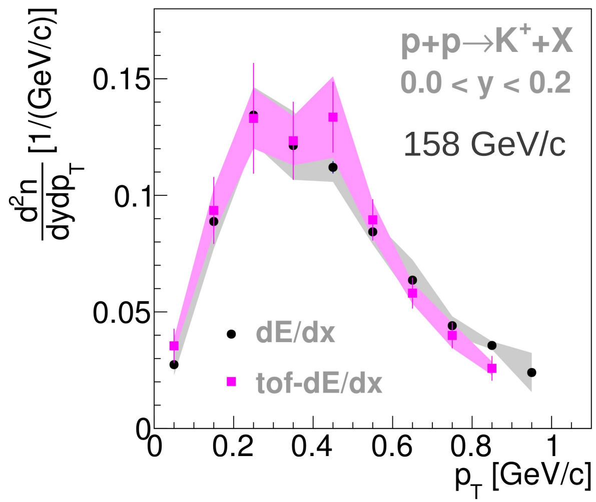
$$P_T = \sum_{i=1}^{N} p_{T,i}$$

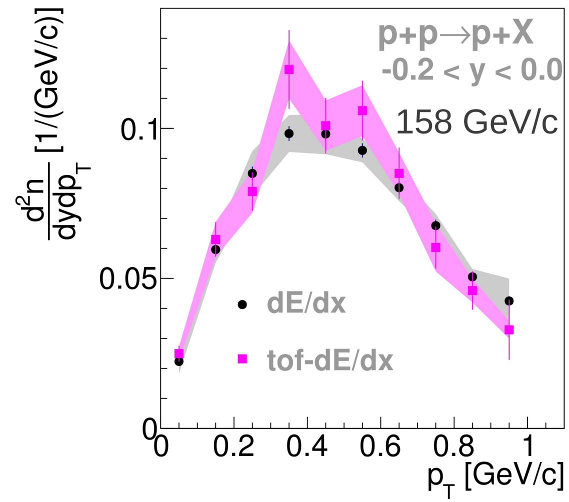
- **No sign of any anomaly that can be attributed to CP** (both in p+p and Be+Be)
- **Σ[P_T, N]** shows fluctuations slightly **above IPM** and **Δ[P_T, N] below IPM.**

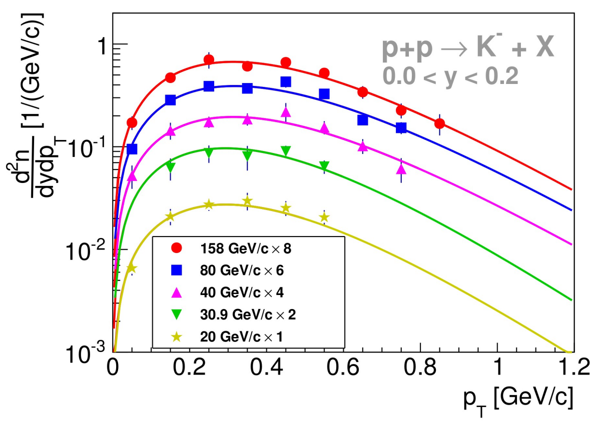
  Possible explanations:
  - ♦ **Bose-Einstein statistics** PLB 730, 70 (2014); PRC 88, 024907 (2013); PLB 439, 6 (1998); PLB 465, 8 (1999)
  - ♦ **P_T/N versus N correlation in p+p** PRC 89, 034903 (2014)

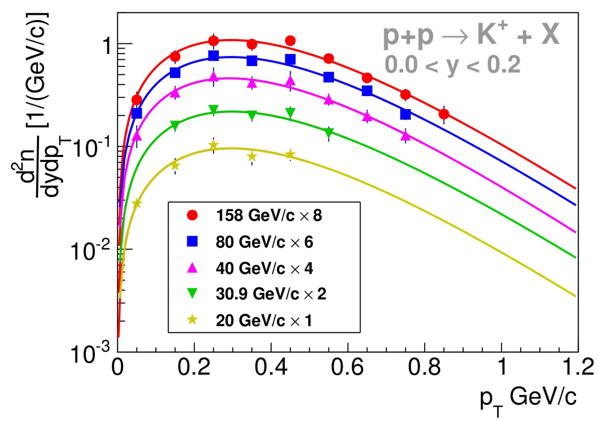
π, K, p spectra in p+p







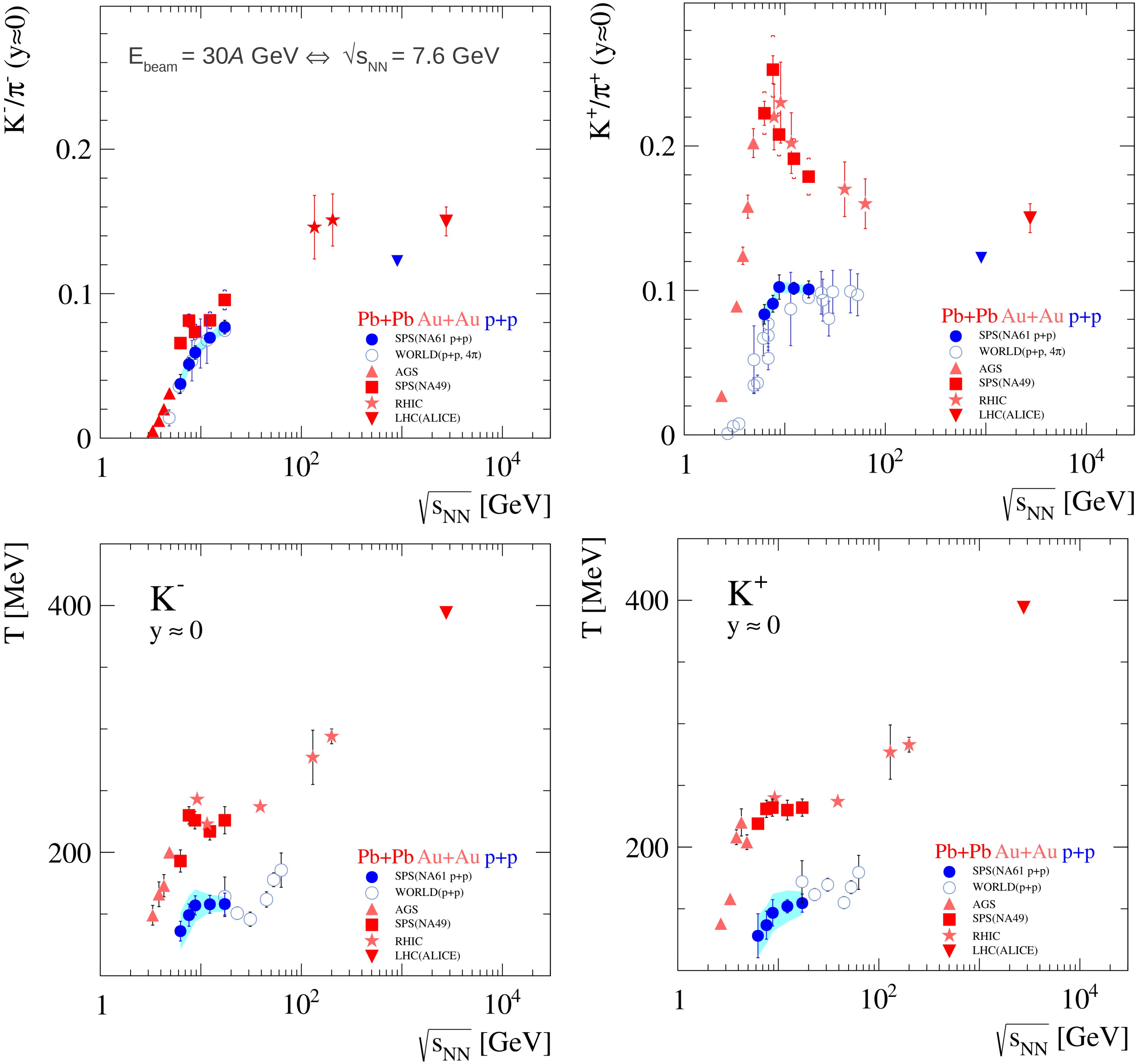




Upper: results from tof-dE/dx (*mass*^{2} vs dE/dx) and dE/dx only are consistent,
example for 158 GeV/c

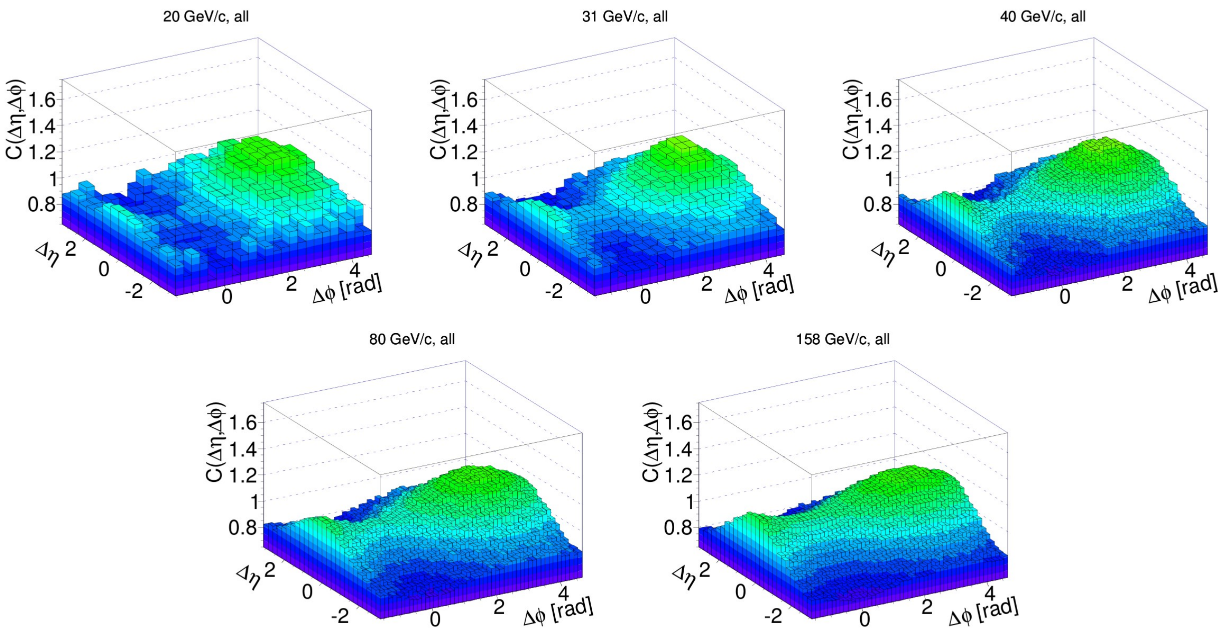
Results from tof-dE/dx allow to obtain **mid-rapidity spectra of kaons**, which are then used for **horn** and **kink** plots

Properties of the onset of deconfinement



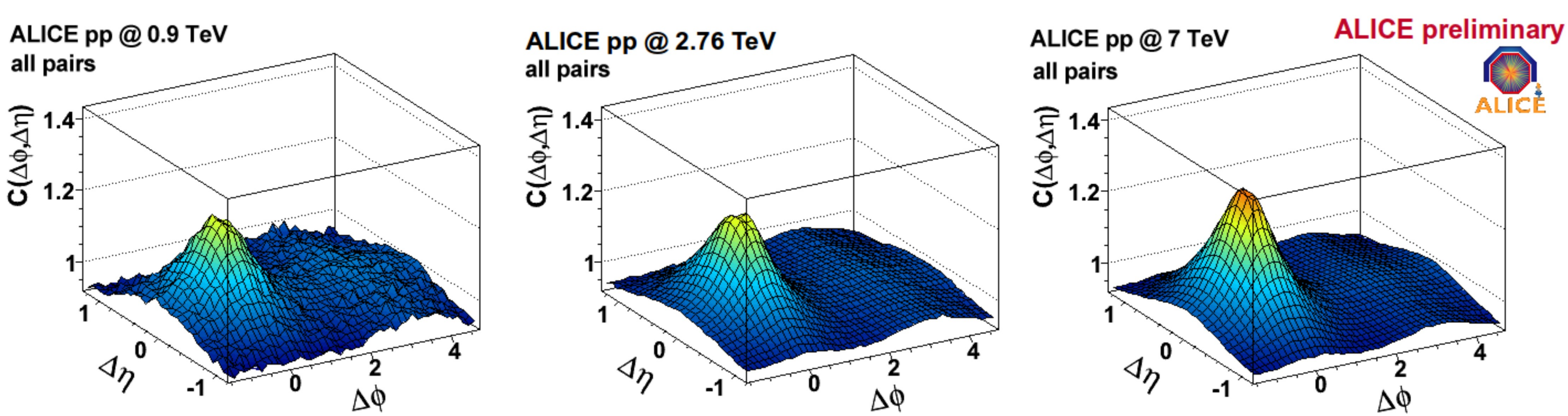
- For Pb+Pb sharp peak (**horn**) in K^+/π^+ ratio due to onset of deconf. (OD)
  (APPB 30, 2705 (1999))
- For Pb+Pb plateau (**step**) in the inverse slope parameter (T) of m_T spectra due to OD (constant T and p in mixed phase)
- Even **in p+p** the energy dependence of K^+/π^+ and T exhibits **rapid changes in the SPS energy range,** but:
- The structures (horn, step) are significantly reduced / modified when compared to Pb+Pb

Correlations in $\Delta\eta$, $\Delta\phi$ in p+p



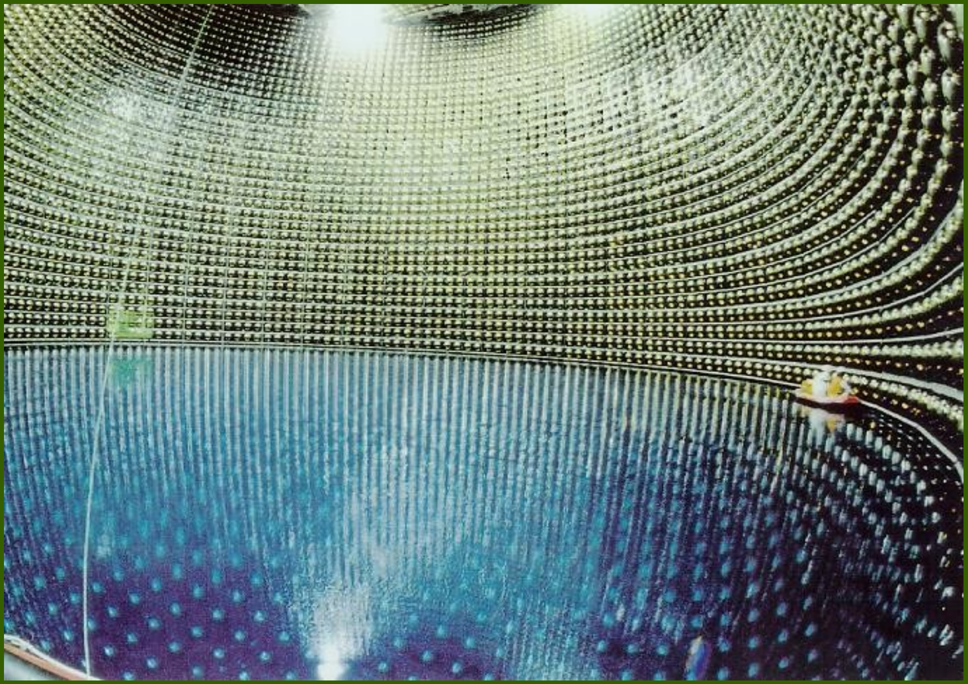
Pairs of **all charged particles** - comparison with ALICE

- NA61: maximum at $(\Delta\eta,\Delta\phi) = (0,\pi)$ probably due to resonance decays and momentum conservation
- NA61 results show stronger enhancement in $\Delta\phi \approx \pi$ and no "jet peak" at $\Delta\phi \approx 0$



PoS (WPCF2011), 026

New results for neutrino physics

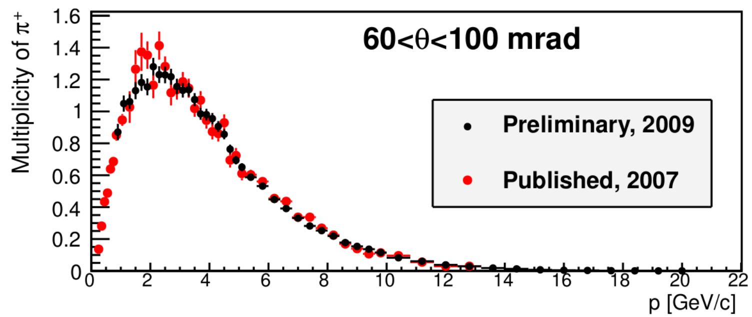


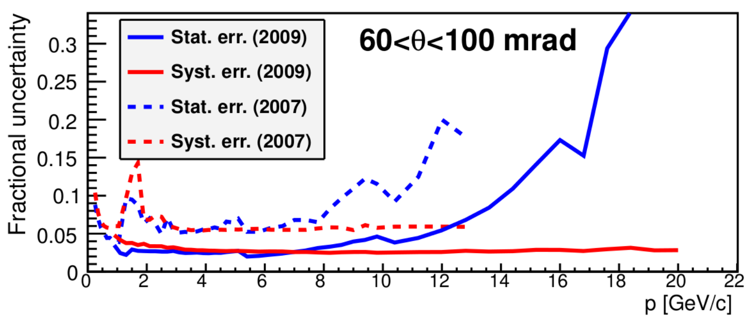
Super Kamiokande

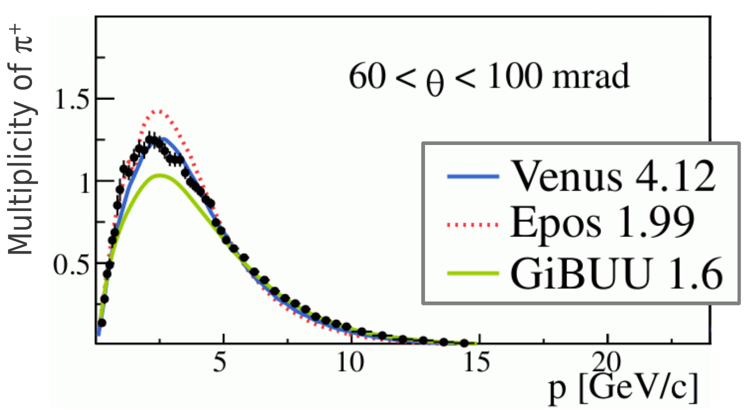
- New results on p+C interactions at 31 GeVc (σ_{inel}, σ_{prod}, π^+, π^-, K^+, K^-, p, K^0_S, Λ; some of not shown are in back-up)
- New results on p+(T2K replica target) collisions at 31 GeVc (charged pions)

Results on p+C at 31 GeV/c

$p+C \rightarrow \pi^+ + X$







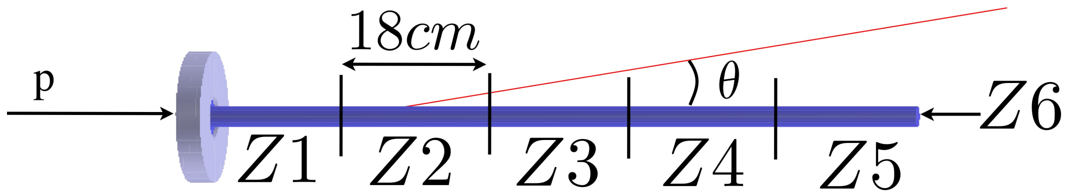
Progress on 2009 p+C at 31GeV/c "thin-target" analysis:

- Analysis of statistic and systematic uncertainties has been finished
- Improvement by a factor 2-3 in precision due to
  - Larger statistics (by a factor 10)
  - Larger acceptance (ToF detector)
  - Better understanding of systematics
- Results of tof-dE/dx analysis for charged hadrons have been released (p>1GeV/c); the rest of the phase space will come soon
- Analysis of K^0_S and Λ is completed (see back-up slides)
- Publication of 2009 results is in preparation

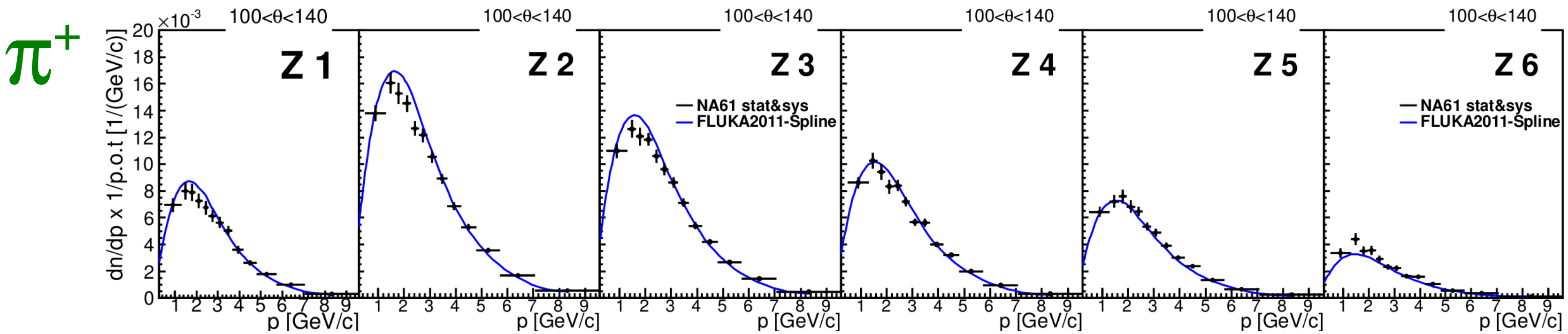
- 2009 results are currently being used for improved prediction of the neutrino beam in the T2K experiment

Results on p+(T2K replica target) at 31 GeV/c

- Preliminary measurements of **fully-corrected charged pion yields** (2009) from the surface of the T2K replica target (“long target”, 90cm)
- Analysis technique based on combined tof-dE/dx approach



Z binning along the target surface, five bins of 18 cm for the target surface plus a sixth bin for the downstream face of the target

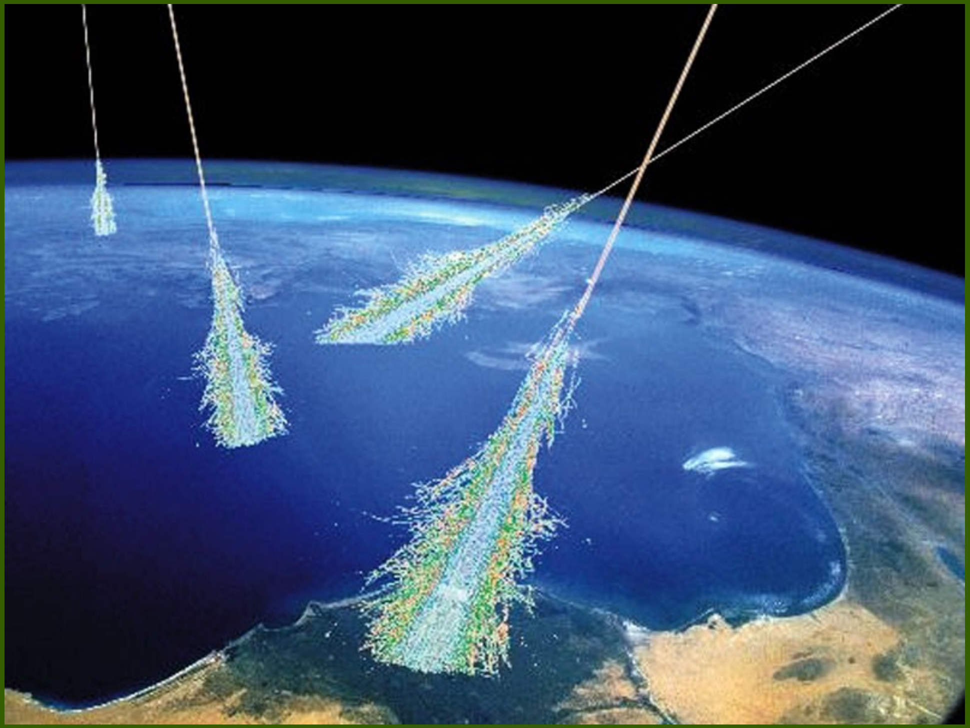


Example for 100 < Θ < 140 [mrad]

- Correction factors due to limited acceptance, decay of particles in flight, re-interaction of particles with detector material were computed bin-by-bin, based on simulations with FLUKA2011 (used by T2K to simulate hadron production in long target)

- Stat. and sys. uncertainties are added in quadrature

New results for cosmic-ray physics



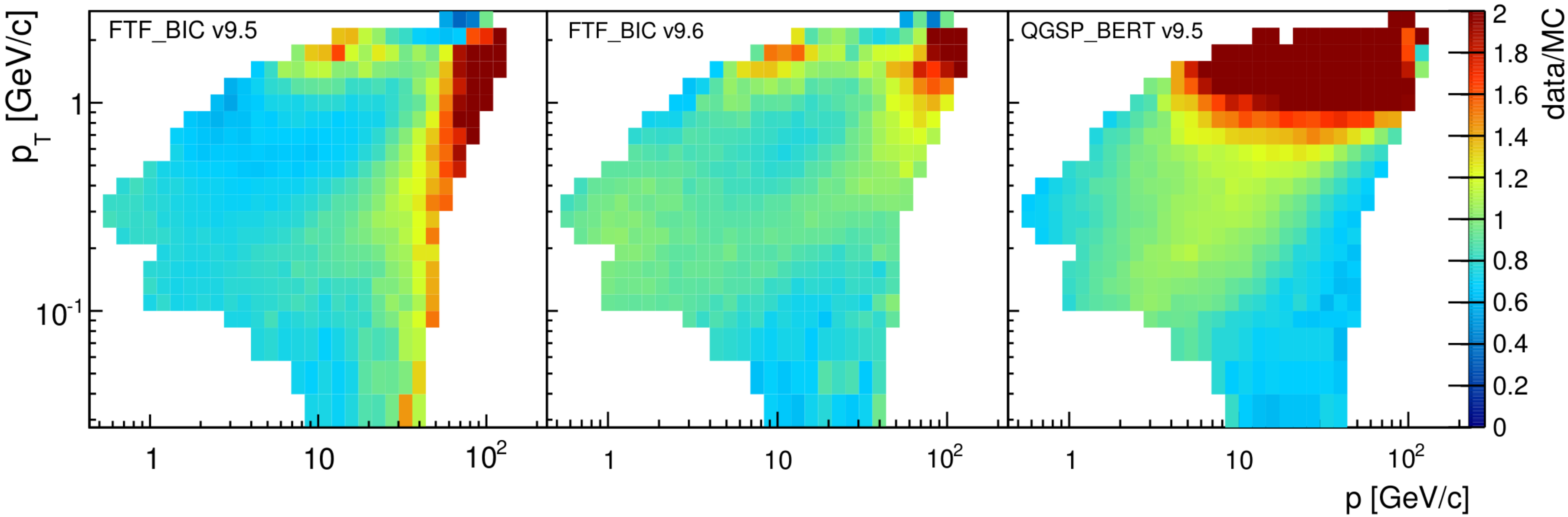
NASA

- Charged and identified hadron spectra in π^-+C at 158 and 350 GeV/c
- Resonances in π^-+C at 158 and 350 GeV/c

$h^{\pm}$ spectra in π^{-}+C at 158 GeV/c

Release of charged hadron spectra from π^{-}+C collisions at 158 and 350 GeV/c (2009) was made in 2012. Currently: finalizing these spectra (improving calibration, corrections, etc.)

$\pi^{-} + C \rightarrow h^{-} + X$ at 158 GeV/c

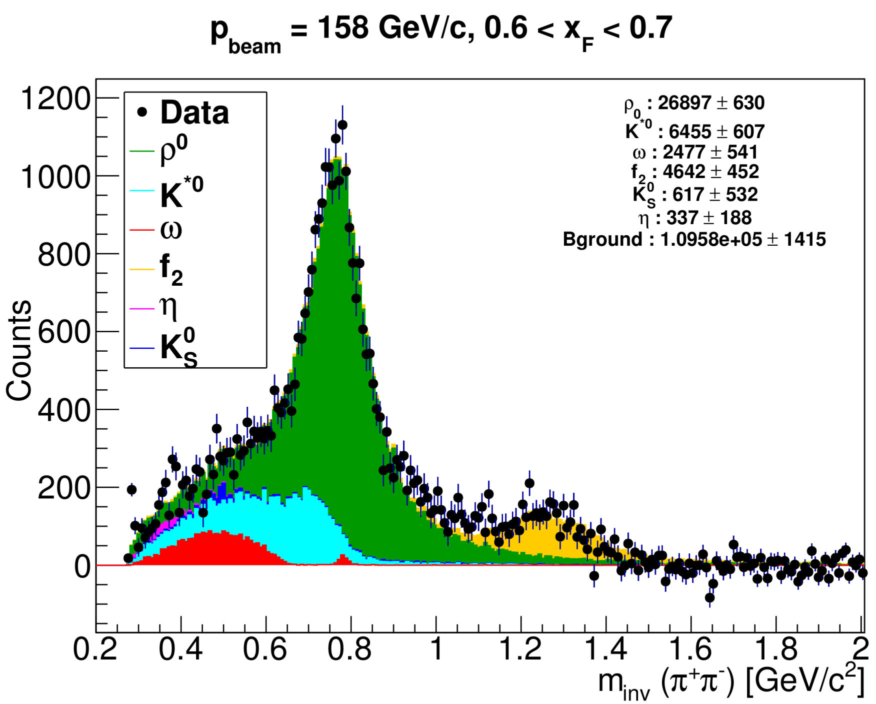


- **Input for validation/tuning of MC generators** for simulation of air showers
- Now also used to validate physics lists available in GEANT4 (QGSP_BERT physics list does not describe data well; the recent update of FTF_BIC list improved agreement at large p when compared to the previous version)

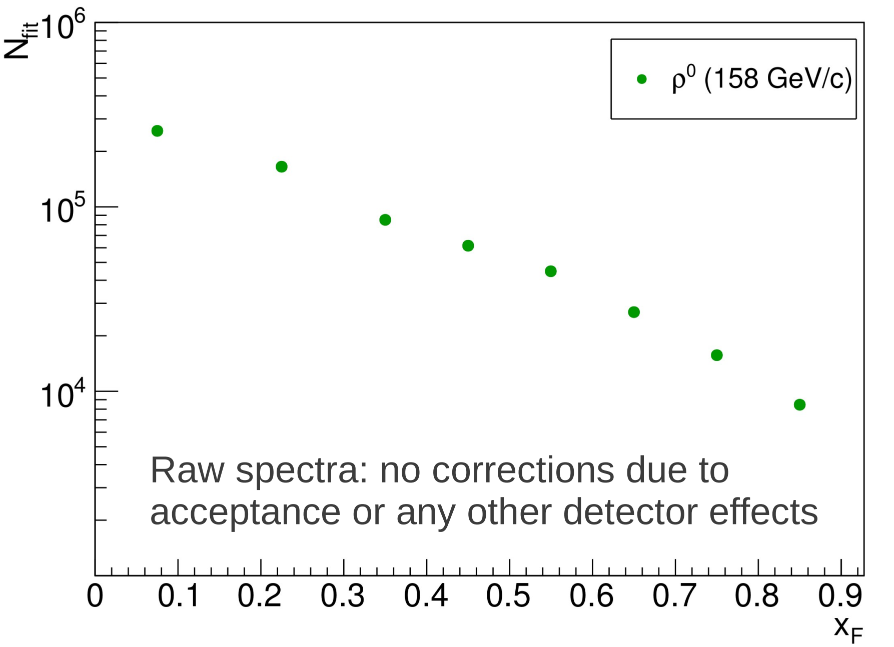
Resonances in π^-+C at 158 GeV/c

New method of extracting resonance production by fitting templates

- $m_{inv}(\pi^+\pi^-)$ distributions in x_f bins
- Using complete simulation and rec. chain of NA61, individual templates of $m_{inv}(\pi^+\pi^-)$ distribution of each generated meson resonance (ρ^0, ω, K^{0*}, f_2) are computed
- These templates are then used to fit $m_{inv}(\pi^+\pi^-)$ distributions
- Charge mixing method used to estimate background



Example of template fit



Results of fit for ρ^0 meson

Data-taking schedule within the approved program

Beam Primary	Beam Secondary	Target	Energy (A GeV)	Year	Days	Physics
p			400			
	p	Pb	158	2014	30 days	CP, OD
Ar		Sc	13, 19, 30, 40, 75, 150	2015	6×8 days	CP, OD
p			400			
	p	Pb	13, 19, 30, 40, 75	2015	5×8 days	CP, OD
Xe		La	13, 19, 30, 40, 75, 150	2017	6×8 days	CP, OD

CP – Critical Point, OD – Onset of Deconfinement

Plans to extend NA61/SHINE physics program

- Measurements of hadron production properties in proton and pion interactions on nuclear and replica targets needed for Fermilab neutrino beams → presented in separate document (**Addendum to NA61/SHINE proposal: SPSC-P-330-ADD7**, see next talk by V. Paolone). Planned 5 weeks of data taking in 2015, to be continued in 2016-17
- Measurements of hadron production properties in Pb+Pb collisions; preparations require 10 days-long test with primary Pb beam in 2015

Publications

- **Published**
  - Measurements of Production Properties of K^0_S mesons and Lambda hyperons in Proton-Carbon Interactions at 31 GeV/c,
    Phys. Rev. C 89, 025205 (2014) [arXiv:1309.1997]
  - Measurement of negatively charged pion spectra in inelastic p+p interactions at p_{lab} = 20, 31, 40, 80 and 158 GeV/c,
    Eur. Phys. J. C 74, 2794 (2014) [arXiv:1310.2417]
  - NA61/SHINE facility at the CERN SPS: beams and detector system,
    JINST 9, P06005 (2014) [arXiv:1401.4699]

- **In preparation**
  - Precise measurements of $\pi^{\pm}$, $K^{\pm}$, K^0_S and (anti)proton production in proton–Carbon interactions at 31 GeV/c (in drafting)
  - Multiplicity and transverse momentum fluctuations in p+p at 20-158 GeV/c (in drafting)
  - First stage of drafting: $\pi^{\pm}$, $K^{\pm}$, and (anti)proton production in p+p; π^- production and centrality determination in Be+Be, Λ production in p+p at 158 GeV/c, chemical fluctuations in p+p, ...

Summary

- **Facility modifications**: completed (PSD, ToF-L/R) and ongoing (TPC drift velocity system, the super-conducting magnets, DRS-based read-out, new beam detectors, Forward TPCs, Vertex Detector, radiation shielding of the H2 beam line)
- **Software modifications**: event reconstruction parts of “legacy” rec. chain ported into SHINE, new calibration framework introduced in SHINE, deployment of “legacy” reconstruction chain under CERNVM and CERN OpenStack infrastructure
- **New results**:
  - π^- spectra and p_T fluctuations in ^{7}Be+^{9}Be at 40*A*-150*A* GeV/c
  - $\pi^\pm$, $K^\pm$ and (anti)proton spectra in inelastic p+p at 20-158 GeV/c
  - Λ spectra in inelastic p+p interactions at 158 GeV/c
  - $\Delta\eta\Delta\phi$ correlations, charged pion multiplicity fluct. in p+p at 20-158 GeV/c
  - identified hadron spectra in p+C at 31 GeV/c from 2009
  - charged pion spectra in p+(T2K replica target) at 31 GeV/c from 2009
- **Data taking plan**: p+Pb at 158 GeV/c (XI-XII 2014), en. scan of Ar+Sc (II-IV 2015), energy scan of p+Pb (end of 2015), en. scan of Xe+La (2017)

- **Plans to extend the NA61/SHINE physics program**:
  - p and π interactions on nuclear and replica targets for Fermilab neutrino beams (SPSC-P-330-ADD7). 5 weeks of data taking in 2015, continuation in 2016/17
  - Pb+Pb collisions (including open charm measurement). Test run with primary Pb beam at 30*A* GeV/c is requested in December 2015

NA49 experiment: Status and Plans

NA49 data on Pb+Pb collisions remain reference for NA61

NA49 continues to provide the heavy nucleus reference and it is therefore necessary to apply physics analysis methods newly developed for NA61 also to the legacy Pb+Pb data

NA49 data and software preservation program is in progress:

- Data summary tapes are being converted to the format of the NA61 analysis framework
- NA49 reconstruction and simulation program chain is maintained in order to allow the computing of the necessary corrections for the new analysis work
- **Request to CERN**: support of computing at present level (afs, CASTOR, LxBatch), space on EOS system, some assistance for migrating NA49 software to CERNVM system

Publications since October 2013:

- Phase-space dependence of particle-ratio fluctuations in Pb+Pb collisions from 20*A* to 158*A* GeV beam energy, **Phys. Rev. C 89, 054902 (2014)** [arXiv:1310.3428v1]

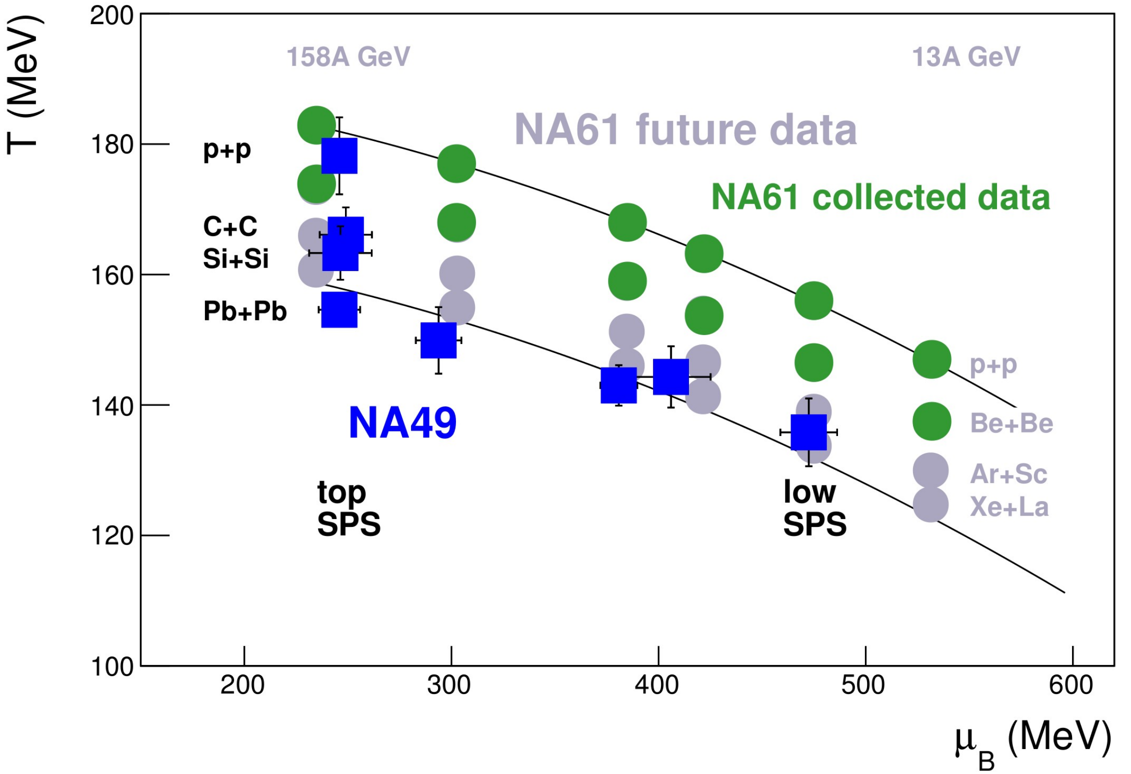
- Two submitted papers (see back-up slides)
- 7 ongoing and further analyses (see back-up slides); 3 papers in drafting

Back-up

Strong interactions program - reminder

The most interesting region of the phase diagram is accessible at the SPS

- Onset of deconfinement at ≅ 30*A* GeV ($\sqrt{s_{NN}}$=7.6 GeV) PRC 77, 024903 (2008)
- Critical point? Example: (T^{CP}, μ_B^{CP}) = (162±2, 360±40) MeV JHEP 0404, 050 (2004)



Estimated (NA49) and expected (NA61) chemical freeze-out points according to PRC 73, 044905 (2006)

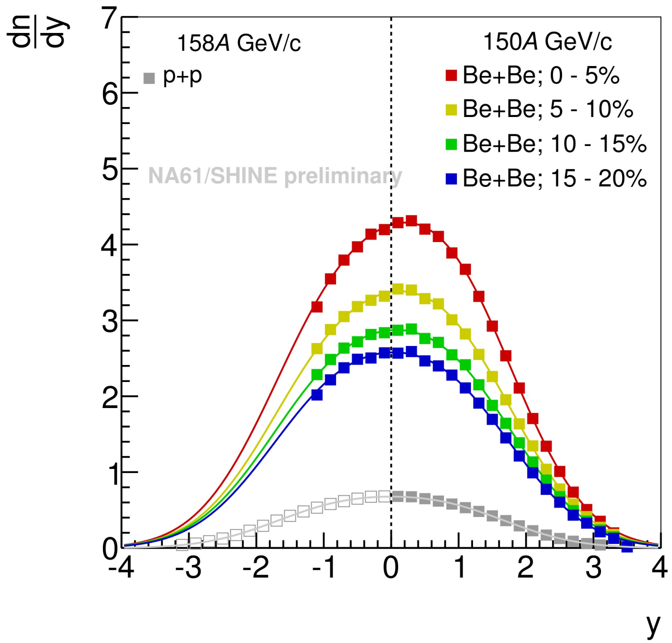
Comprehensive scan in the whole SPS energy range (13A-158A GeV ⇔ $\sqrt{s_{NN}}$=5.1-17.3 GeV) with **light and intermediate mass nuclei**

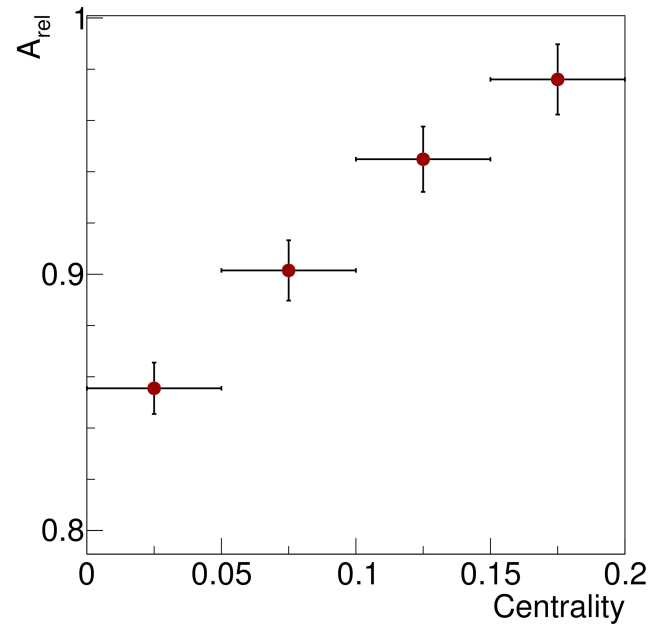
- **Search for the critical point**
  Search for a maximum of CP signatures: fluctuations of N, average p_T, etc., intermittency, when system freezes out close to CP

- **Study of the properties of the onset of deconfinement**
  Search for the onset of horn, kink, step, etc. in collisions of light nuclei

π^- spectra in ^{7}Be+^{9}Be

h⁻ analysis method – majority of negatively charged particles are π^- mesons. Contribution of other particles is subtracted using models (EPOS1.99). The results are corrected for particles from weak decays (feed-down) and the detector effects using simulations (GEANT3 and EPOS1.99).



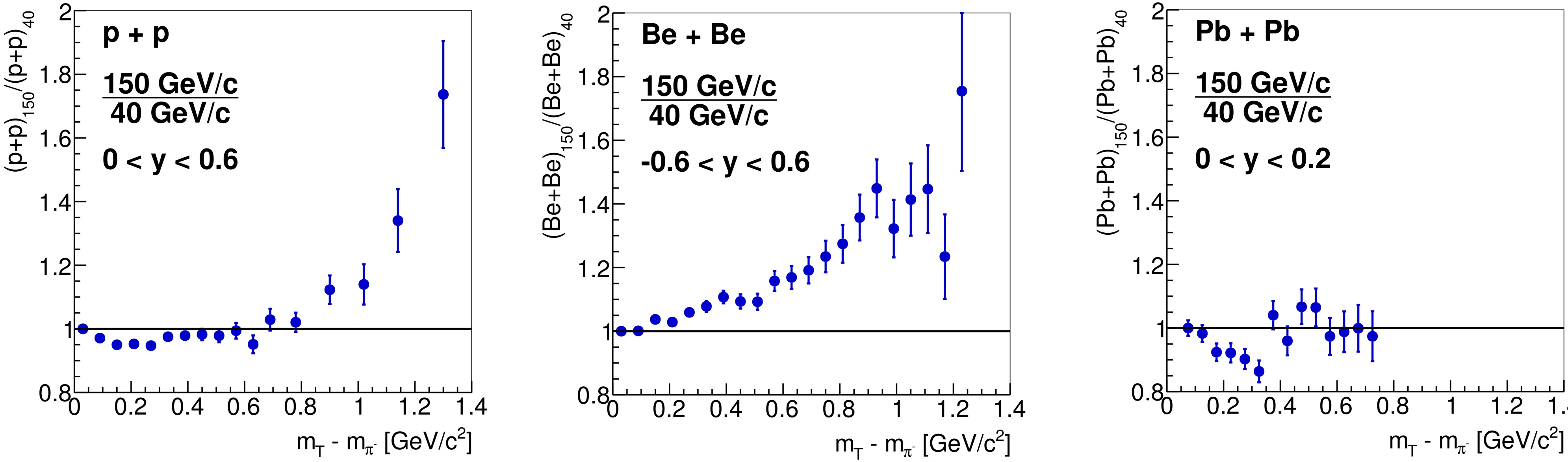


- Fitted: double Gaussian function symmetrically displaced from mid–rapidity (both Gaussians have the same width, but they differ by amplitude)

$$\frac{dn}{dy}(y)=A_o A_{rel}\exp\left(\frac{-(y-y_0)^2}{2\sigma_0}\right)+A_0\exp\left(\frac{-(y+y_0)^2}{2\sigma_0}\right)$$

Asymmetry (relative ampl. of fitted Gaussians) increases from 0.86 (0-5%) to 0.97 (15-20%)

π^- spectra in ^{7}Be+^{9}Be



- Enhancement above 1 GeV/c^2 may be due to energy conservation or jet production threshold

- Enhancement at all values of m_T
- Increase above 1 GeV/c^2 similar to p+p, but increase below 1 GeV/c^2 consistent with onset of collective flow in Be+Be collisions at 150*A* GeV/c

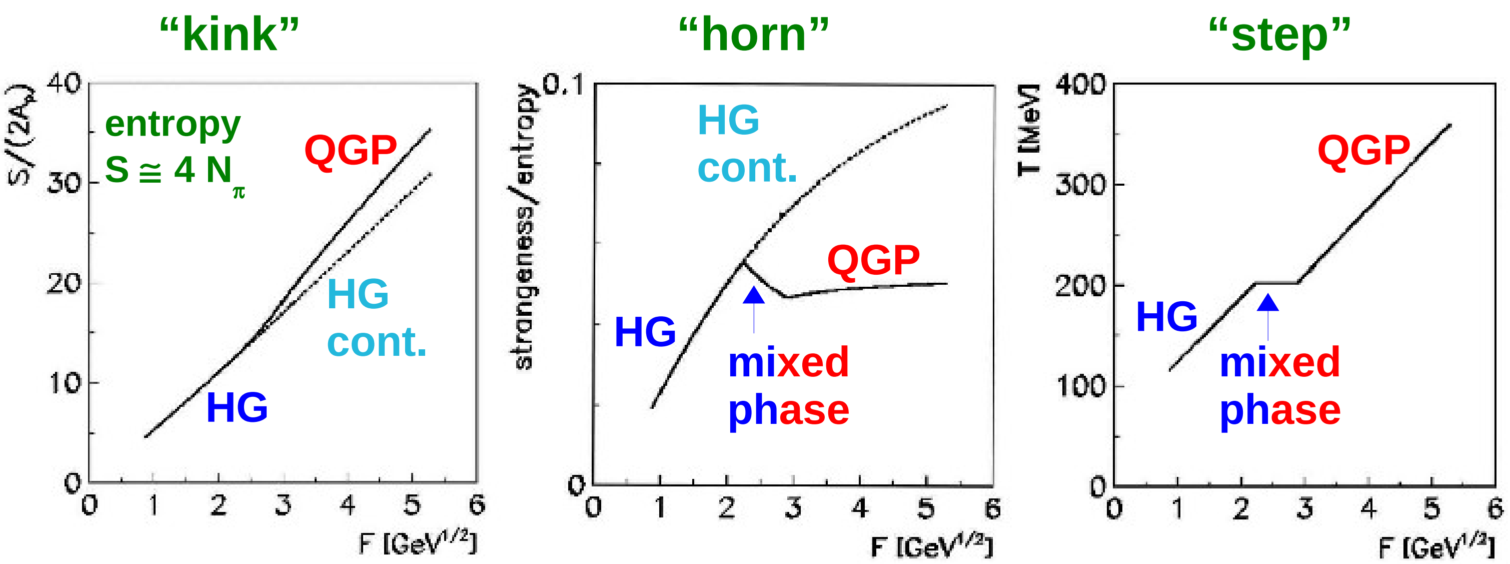
- Flat behavior → presence of radial flow at both energies

Can we estimate the energy threshold for deconfinement precisely ?

(the lowest energy sufficient to create a partonic system)

Motivation: **S**tatistical **M**odel of the **E**arly **S**tage (SMES)

Gaździcki, Gorenstein, Acta Phys. Polon. B30, 2705 (1999)

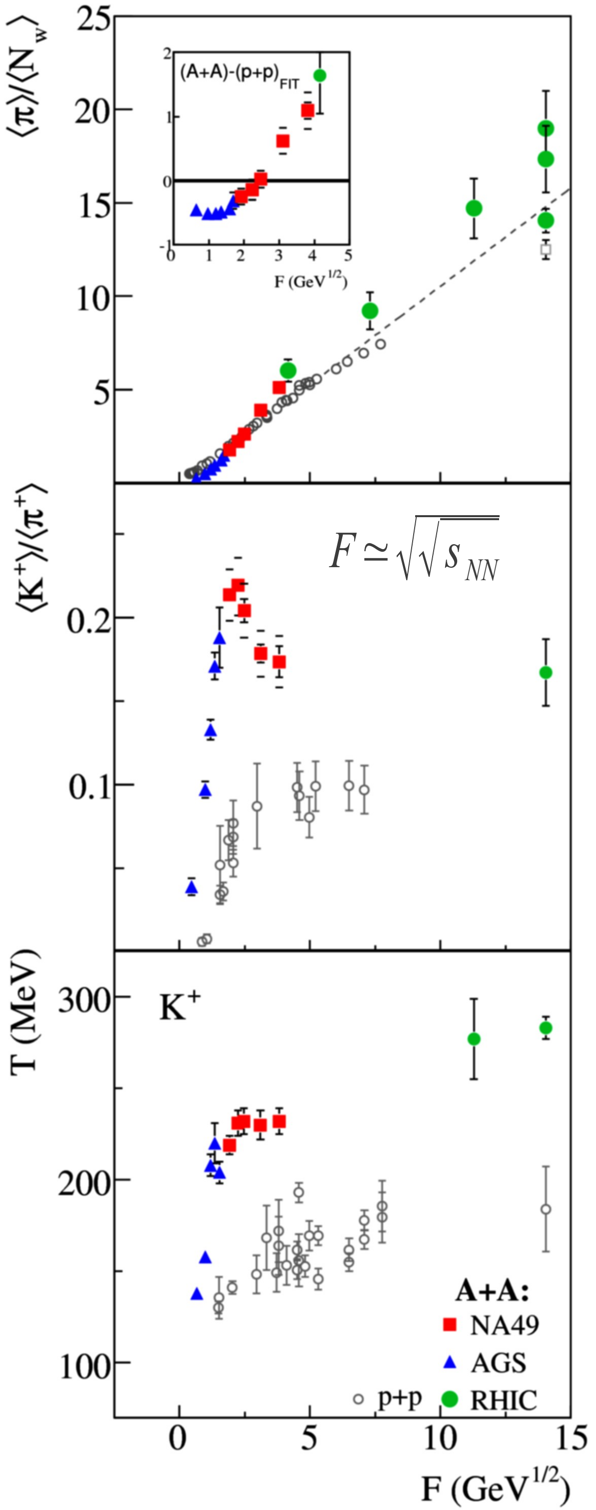


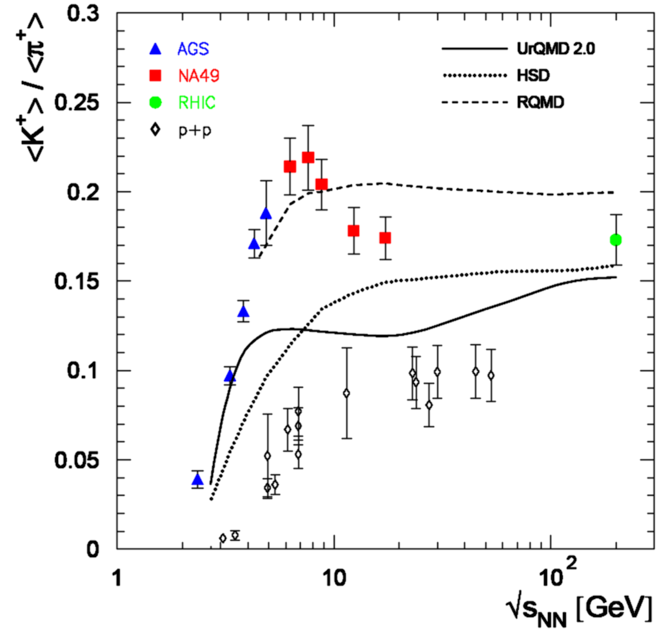
Fermi variable

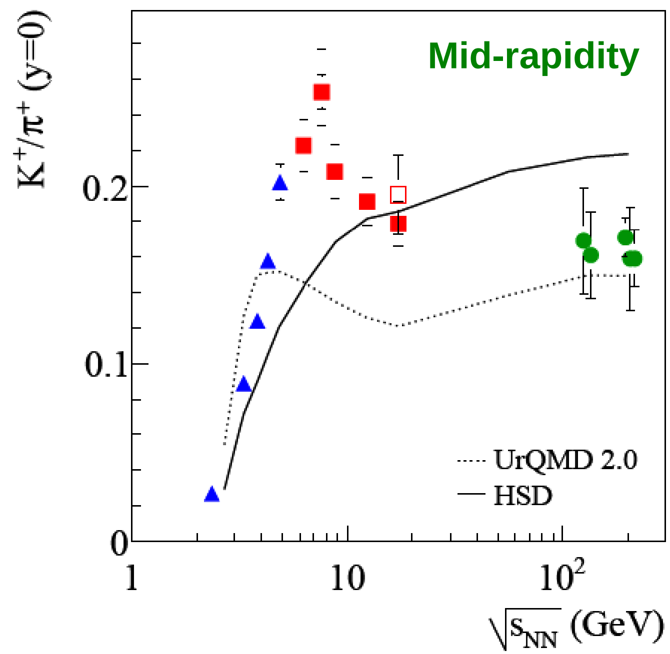
$$F \equiv \left[\frac{\left(\sqrt{s_{NN}} - 2m_N\right)^3}{\sqrt{s_{NN}}} \right]^{1/4}$$

$$F \simeq \sqrt{\sqrt{s_{NN}}}$$

- 1st order phase transition to QGP between top AGS and top SPS energies $\sqrt{s_{NN}} \approx 7$ GeV
- number of internal degrees of freedom (*ndf*) increases HG → QGP (activation of partonic degrees of freedom)
- total entropy and total strangeness are the same before and after hadronization (cannot decrease QGP → HG)
- mass of strangeness carriers decreases HG → QGP ($m_{\Lambda, K, ...} > m_s$)
- constant temperature and pressure in mixed phase

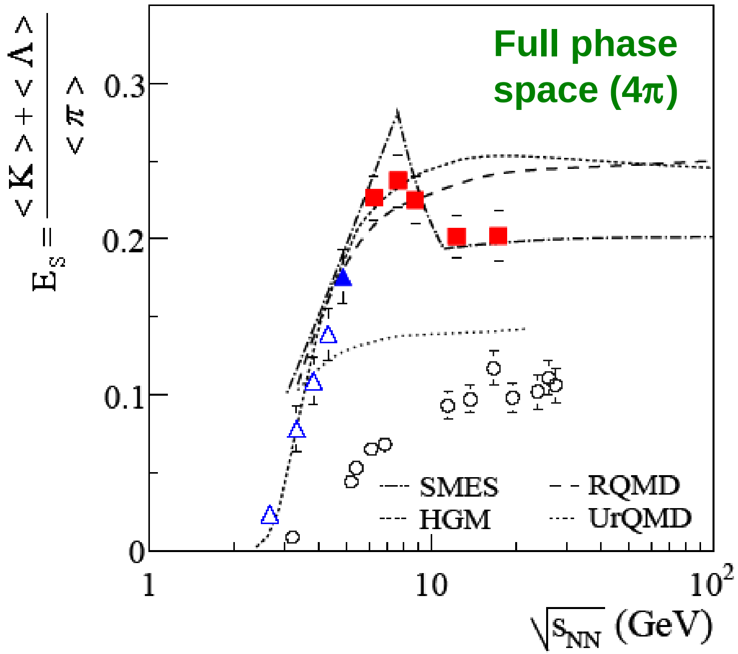






→ Effect on ⟨K⁺⟩/⟨π⁺⟩ even more pronounced at mid-rapidity

E_s - strangeness to entropy

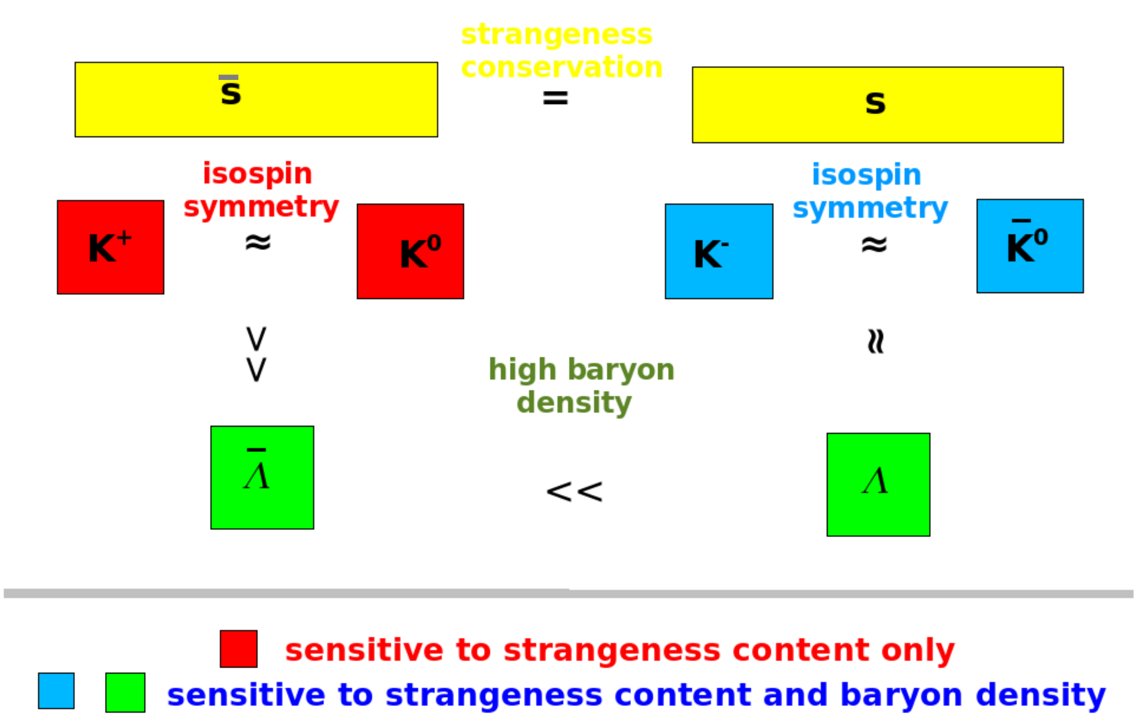


E_S calculated from π, K and Λ yields in 4π. Proposed as a measure of strangeness to entropy ratio (SMES)

→ E_s shows distinct peak at 30*A* GeV

→ Described (predicted) only by model assuming phase transition (SMES)

main strangeness carriers



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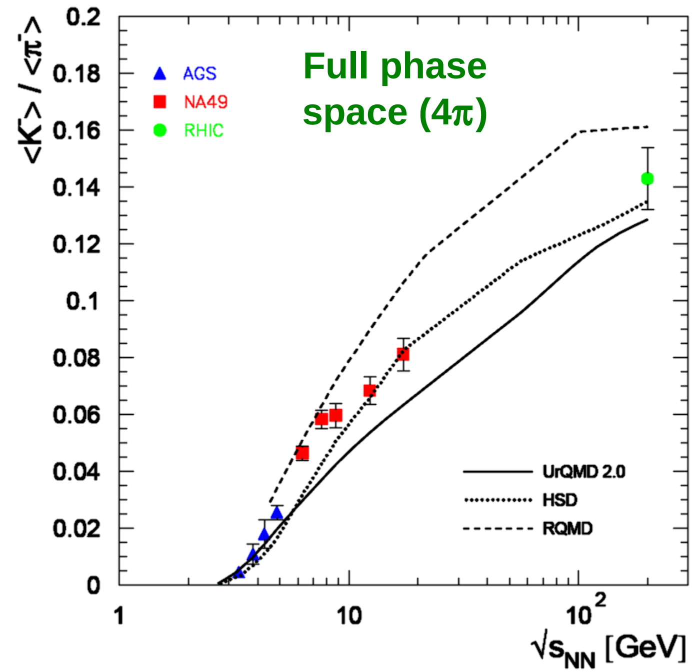
Λ (ud**s**)
K^+ (u **anty-s**)
K^- (anty-u **s**)
K^0 (d **anty-s**)
anty-K^0 (anty-d **s**)



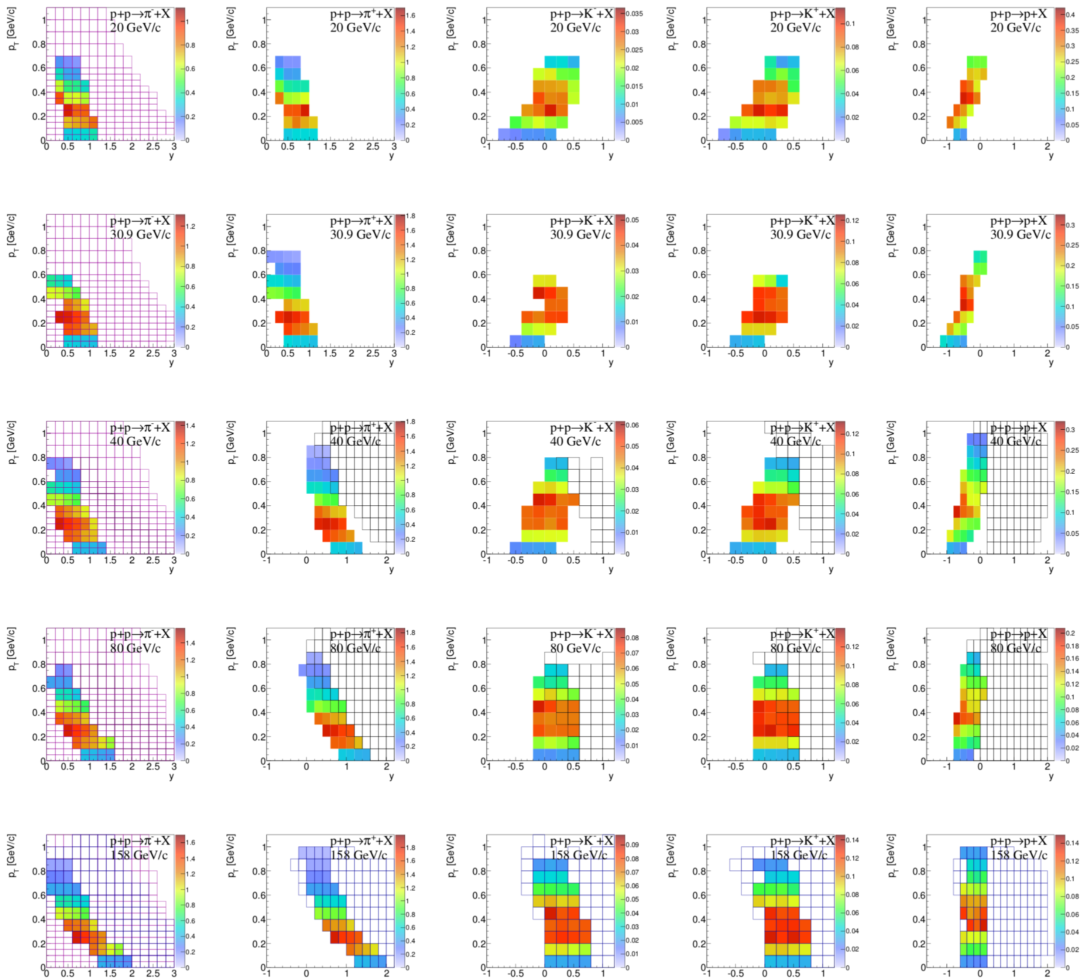
Difference in ⟨K^+⟩ and ⟨K^-⟩ production due to different sensitivity to baryon density. At SPS energies lambdas have significant influence on total strangeness production (anti-lambdas not)

$$\bar{s} \rightarrow K^+, K^0$$
$$s \rightarrow K^-, \bar{K}^0, \Lambda$$

⟨K^+⟩/⟨π^+⟩ proportional to strangeness/entropy

⟨K^-⟩/⟨π^-⟩ additionally sensitive to baryon density

π, K, p spectra in p+p



p_T versus y spectra of identified particles

Color histograms – ToF (*mass*^{2}) vs. dE/dx analysis

Magenta grid – π^- spectra from h^- method NA61, EPJC 74, 2794 (2014)

Black grid – previous preliminary results based on dE/dx only

For p+p interactions at 20 and 31 GeV/c the dE/dx analysis is in progress

M. Kliemant, B. Lungwitz, M. Gazdzicki,
Phys. Rev. C69, 044903 (2004)

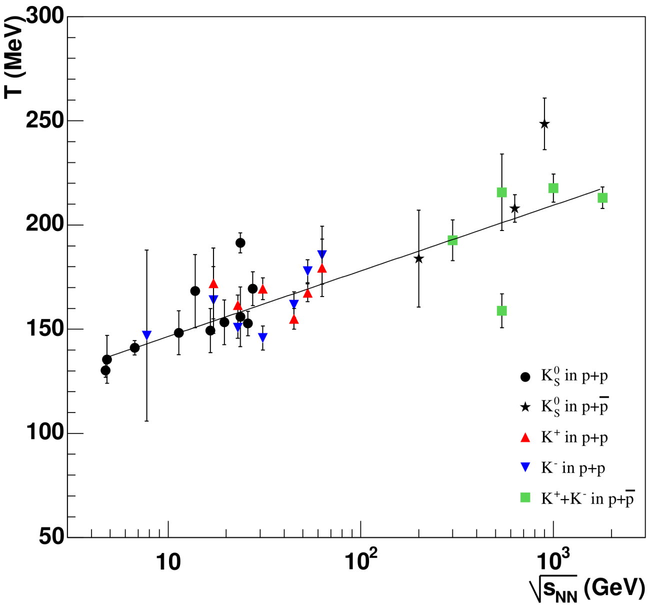
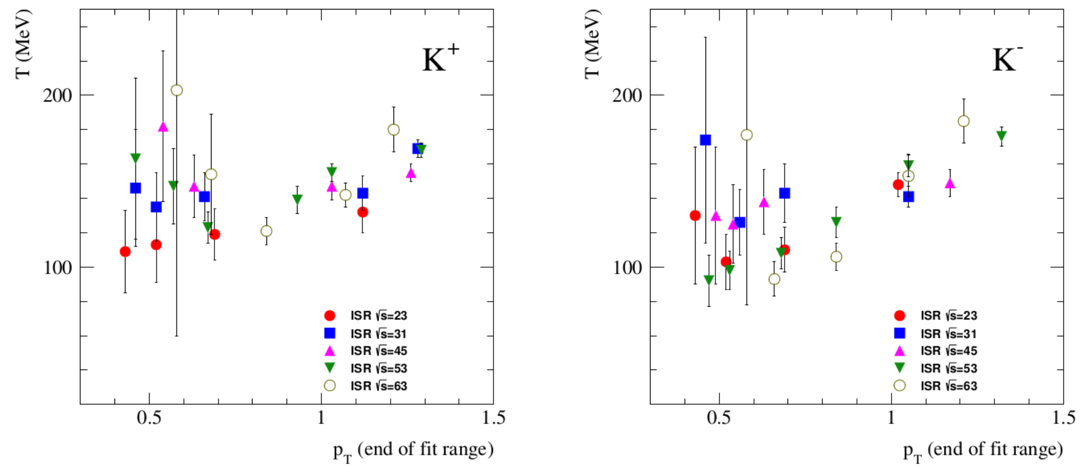
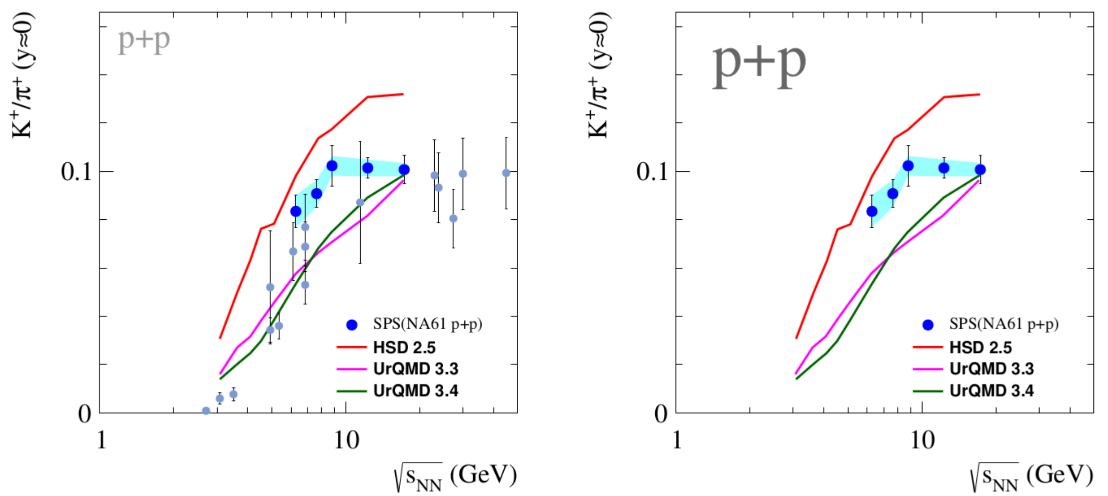


Figure 4: (Color online) Energy dependence of the inverse slope parameter T of transverse mass spectra of K^0_S, K^+ and K^- mesons produced in p+p and p+$\bar{p}$ interactions. The T parameter was determined by fitting the spectra (Eq. 1) in the whole analyzed m_T interval, $m_T - m_0 < 0.25$ GeV/c^2. The logarithmic parameterization is indicated by solid line.

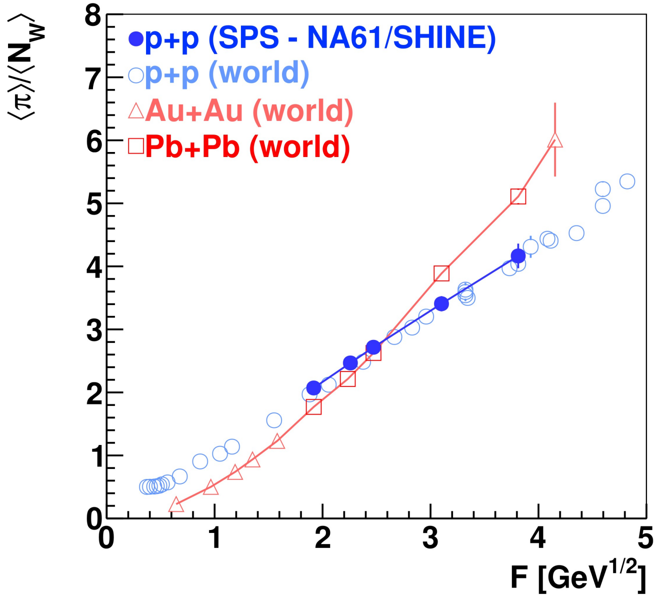
Upper: fits were performed from p_T = 0 GeV/c to values seen on horizontal axis



S. Puławski, unpublished



Properties of the onset of deconfinement



Fermi variable

$$F \equiv \left[\frac{\left(\sqrt{s_{NN}} - 2m_N\right)^3}{\sqrt{s_{NN}}} \right]^{1/4} \qquad F \simeq \sqrt{\sqrt{s_{NN}}}$$

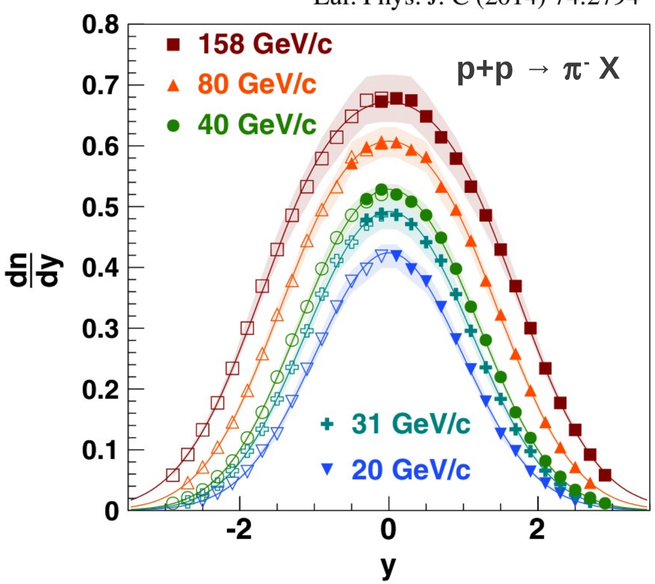
- For A+A change of slope of ⟨π⟩/⟨N_W⟩ vs energy (F) (**kink**) due to onset of deconfinement; not seen in p+p
- High quality of NA61 p+p data

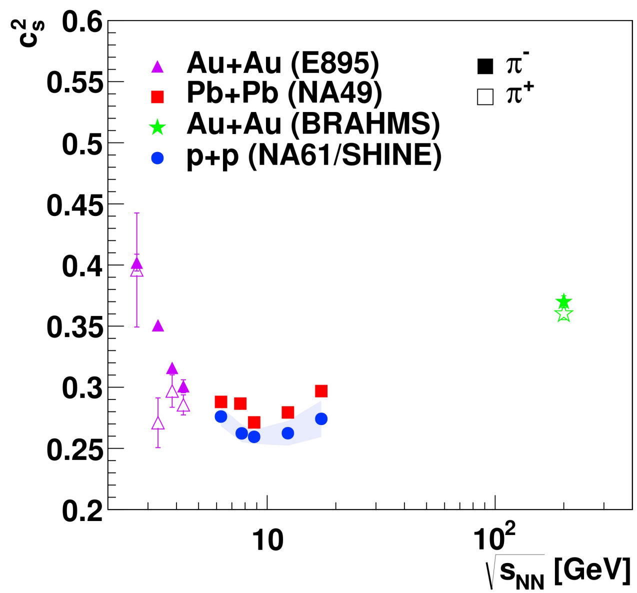
Hydrodynamical Landau model

Shuryak, Yad. Fiz. 16, 395 (1972):

$$\sigma_y^2(\pi^-) = \frac{8}{3} \frac{c_s^2}{1 - c_s^4} \ln\left(\sqrt{s_{NN}}/2m_p\right)$$

Eur. Phys. J. C (2014) 74:2794





- For A+A minimum of sound velocity (**dale**) probably due to onset of deconfinement; **the dale may be present also in p+p reactions!**

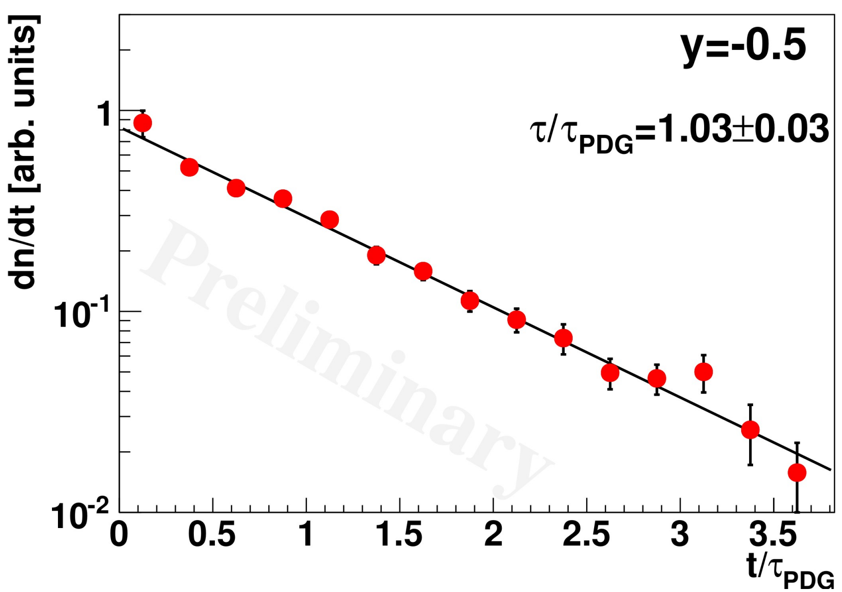
Λ spectra in p+p at 158 GeV/c

Decay chanel: $\Lambda \rightarrow p + \pi^-$

Corrections for geometrical acceptance, inefficiency of the detector and reconstruction, losses due to cuts, other decay channels and feed-down are made with the use of GEANT3 MC simulation based on EPOS1.99

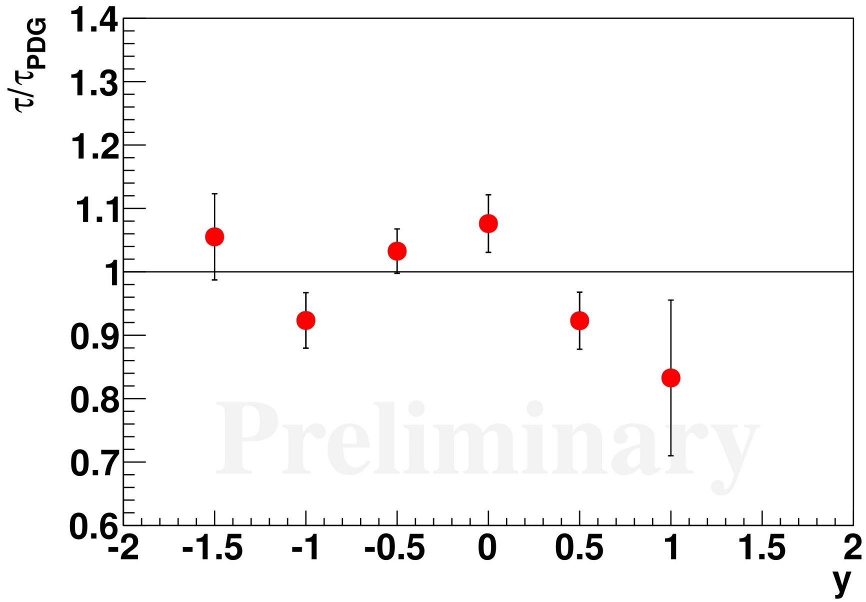
lifetime: $t = \frac{r}{\gamma\beta}$

r - difference between position of the main and the decay vertex



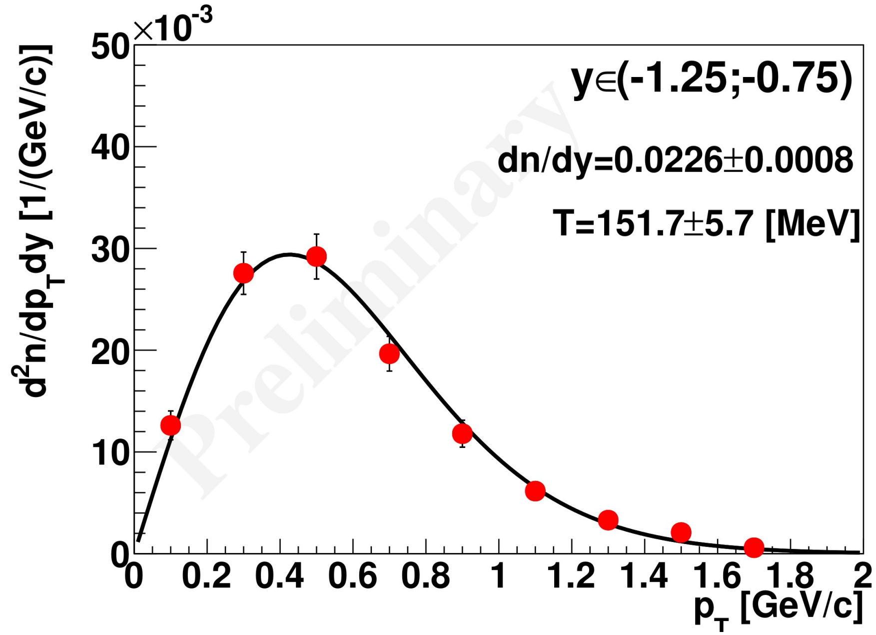
Mean lifetime (τ) ≡ negative inverse slope (from the properties of exponential function)

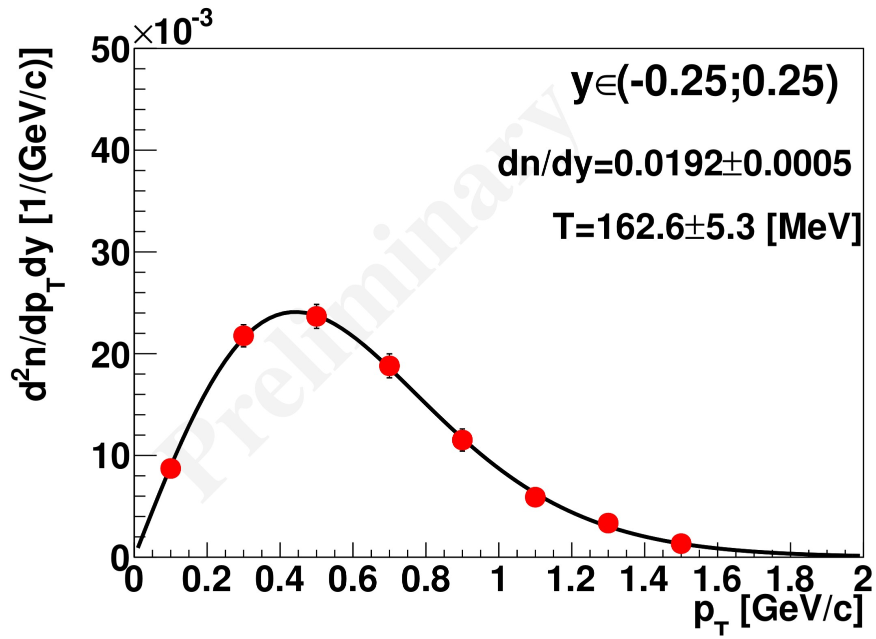
Only statistical errors are shown



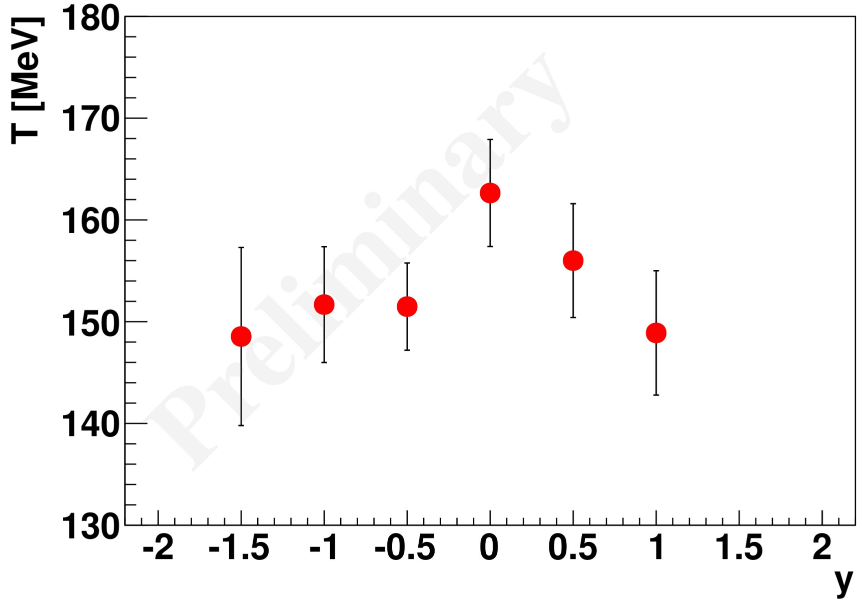
- Results are consistent with PDG value ($c\tau_\Lambda$ = 7.89 cm)

Λ spectra in p+p at 158 GeV/c



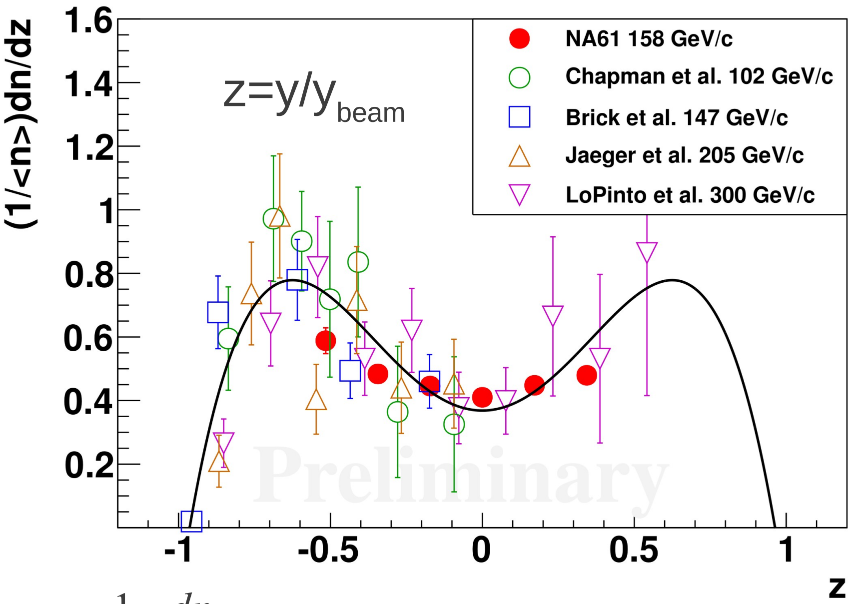


$$\frac{d^2 n}{dp_T\, dy}(p_T)_y = A\, p_T \exp\left(-\frac{\sqrt{p_T^2 + m_\Lambda^2}}{T}\right)$$

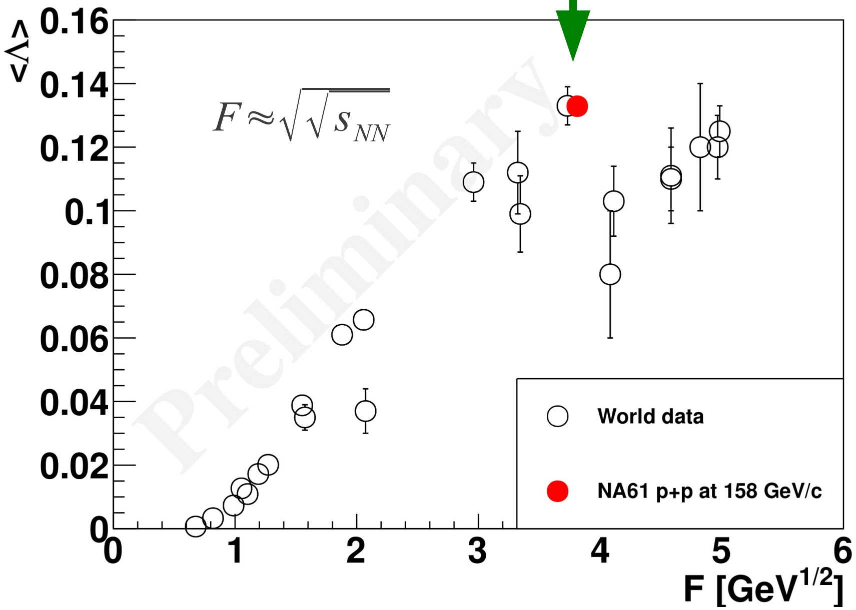


Rapidity dependence of Inverse slope parameters T of p_T spectra

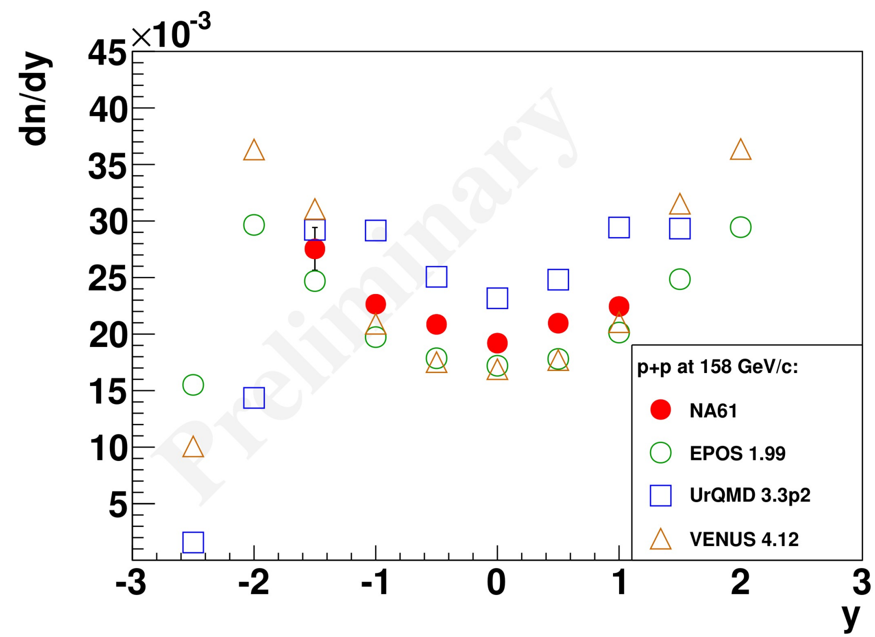
Λ spectra in p+p at 158 GeV/c



$$\frac{1}{\langle n\rangle}\frac{dn}{dz}=0.369+2.10z^2-2.69z^4$$ NP A528, 754 (1991)



Only stat. errors shown; sys. uncertainties are being calculated and are estimated to be about 15%



- NA61 results are consistent with world data; stat. errors show much improved quality
- Rapidity spectrum similar to those ones from EPOS and VENUS

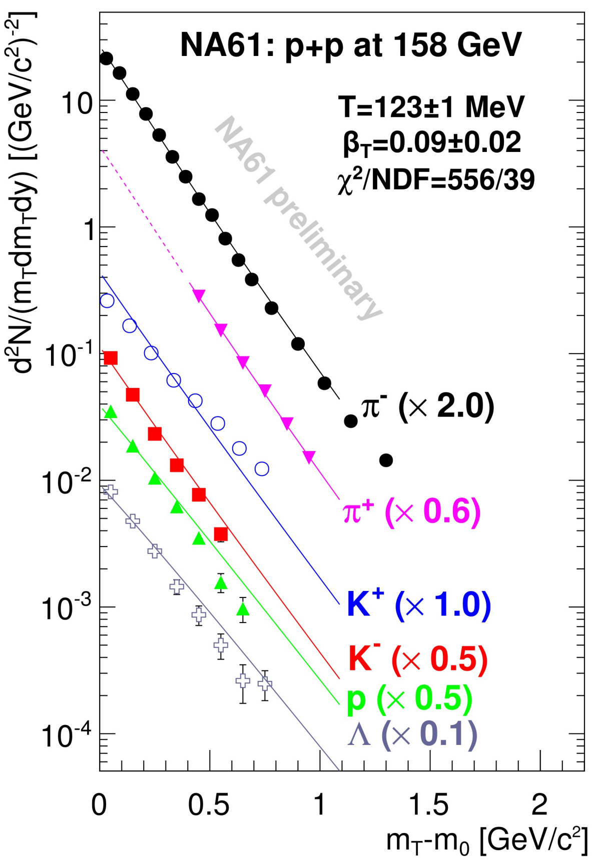
Fits within Blast Wave Model

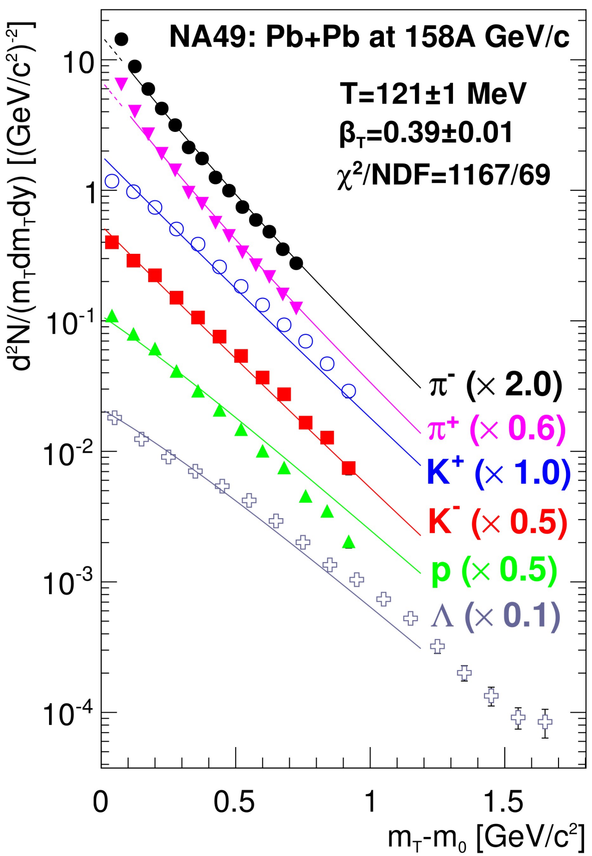
$$\frac{dN_i}{m_T\,dm_T\,dy} = A_i m_T K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right)$$

$$\rho = atanh\,\beta_T$$

Schnedermann, Sollfrank, Heinz, PRC 48, 2462 (1993)

Fits done at mid-rapidity





- Transverse mass spectra are approximately exponential in p+p interactions
- In central Pb+Pb the exponential dependence is modified by the transverse flow (β_T)

$$\frac{1}{p_T}\frac{dN}{dp_T} = \frac{1}{m_T}\frac{dN}{dm_T}$$

Correlations in Δη, Δϕ in p+p

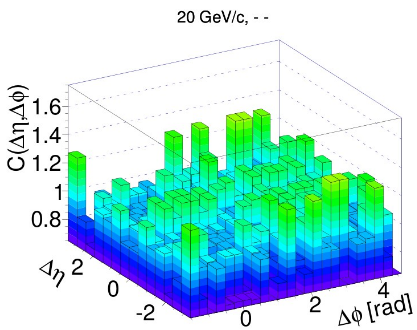
$$\Delta\eta = |\eta_1 - \eta_2| \qquad \Delta\varphi = |\varphi_1 - \varphi_2|$$

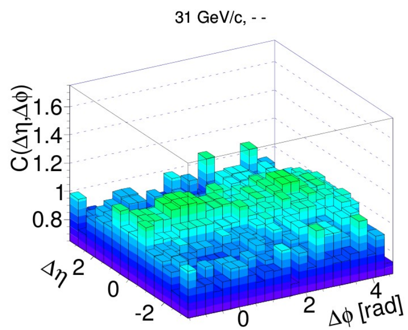
$$C(\Delta\eta,\Delta\varphi) = \frac{N^{pairs}_{mixed}}{N^{pairs}_{data}} \frac{S(\Delta\eta,\Delta\varphi)}{M(\Delta\eta,\Delta\varphi)}$$

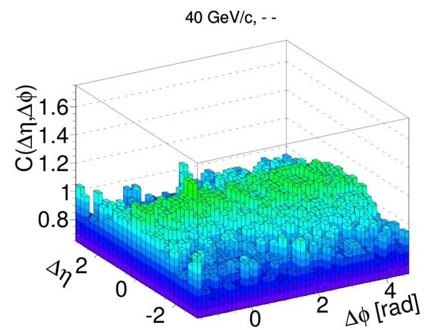
$$S(\Delta\eta,\Delta\varphi) = \frac{d^2 N^{signal}}{d\Delta\eta\ d\Delta\varphi}; \qquad M(\Delta\eta,\Delta\varphi) = \frac{d^2 N^{mixed}}{d\Delta\eta\ d\Delta\varphi}$$

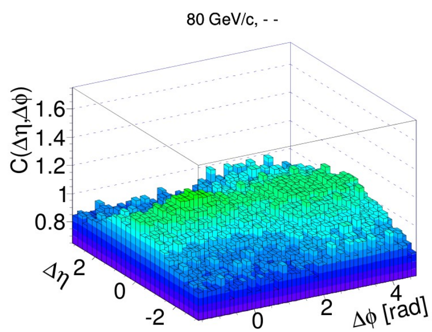
Correlations are corrected for the effects of trigger bias and track reconstruction inefficiencies with the use of GEANT3 MC simulation based on EPOS1.99

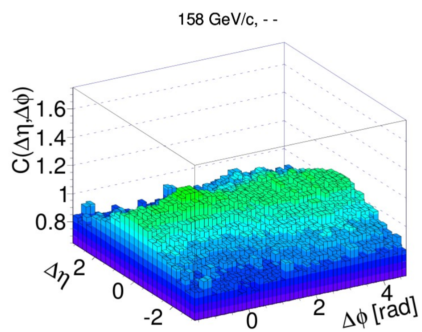
Pairs of **negatively charged particles**







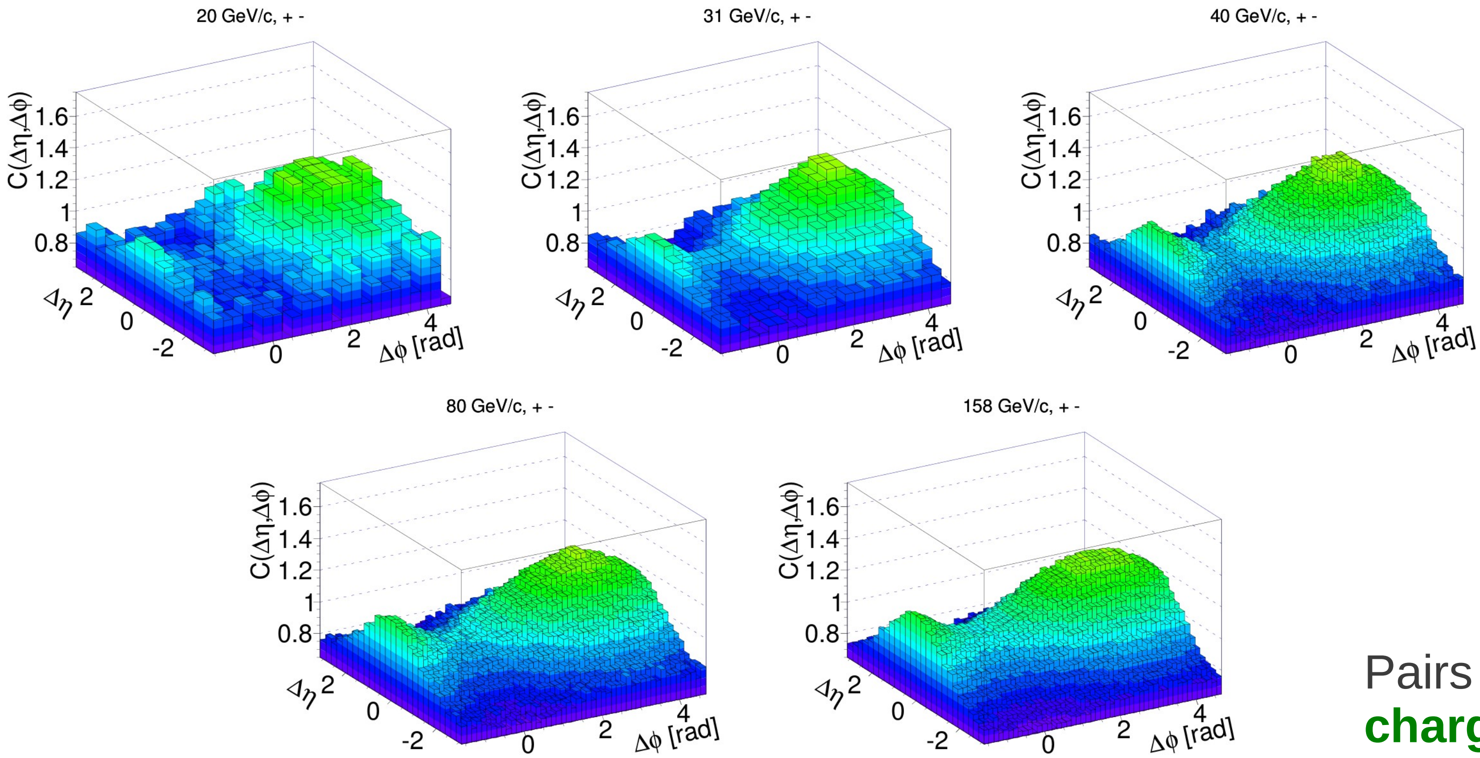




- Quantum effects (B-E) contribute to enhancement at (0,0). Effect stronger for higher energies
- Maximum at (Δη,Δϕ) = (0,π) may be due to momentum conservation

Similar structures in EPOS but without Bose-Einstein

Correlations in $\Delta\eta$, $\Delta\phi$ in p+p



Pairs of **unlike-sign charged particles**

- Maximum at $(\Delta\eta,\Delta\phi) = (0,\pi)$ probably due to resonance decays and momentum conservation
- Coulomb effects contribute to a weak enhancement at (0,0)

Similar structures in EPOS but without SRC (Bose-Einstein + Coulomb)

Transverse momentum fluctuations

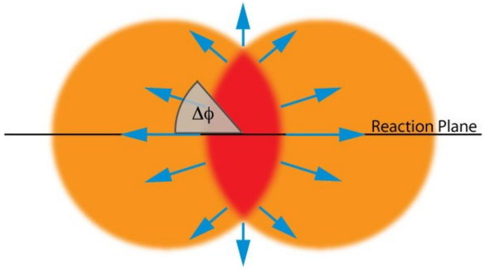
	unit	No fluctuations; N = const. P_T = const.	Independent Particle Model (IPM)	Model of Independent Sources (MIS); for example WNM ($N_S \equiv N_W$)
Φ_{pT}	MeV/c	$\Phi_{p_T} = -\sqrt{\overline{p_T}\,\omega[p_T]}$	$\Phi_{pT} = 0$	**Strongly intensive**: not dependent on N_S and its fluctuations $\Phi_{pT}(N_S \text{ sources}) = \Phi_{pT}(1 \text{ source})$
$\Delta[P_T, N]$	dimensionless	$\Delta[P_T, N] = 0$	$\Delta[P_T, N] = 1$	**Strongly intensive** $\Delta[P_T, N](N_S \text{ sources}) = \Delta[P_T, N](1 \text{ source})$
$\Sigma[P_T, N]$	dimensionless	$\Sigma[P_T, N] = 0$	$\Sigma[P_T, N] = 1$	**Strongly intensive** $\Sigma[P_T, N](N_S \text{ sources}) = \Sigma[P_T, N](1 \text{ source})$

Δ and Σ are dimensionless and have scale which allows for a quantitative comparison of fluctuations of different, in general dimensional, extensive quantities

Multiplicity fluctuations

	unit	No fluct.; N = const.	Poisson N distribution	Model of Independent Sources (MIS); for example WNM ($N_S \equiv N_W$)
ω	dimensionless	$\omega = 0$	$\omega = 1$	**Intensive:** not dependent on N_S but dependent on its fluctuations $\omega(N_S \text{ sources}) = \omega(1 \text{ source}) + \langle n\rangle\omega_{Ns}$ <n> - mean multiplicity from a single source ω_{Ns} - fluctuations in N_S

“Know your reference”



- What does the elliptic flow coefficient v_2=0.1 mean?
- It means that 50% more particles are emitted
“in plane” than “out of plane”. Huge effect!

- What does the Φ_{pT} = 10 MeV/c mean ?
- Nothing! We do not know whether it is a large or a small effect.
Especially when the magnitudes of Φ_{pT} from several “trivial” effects (BE statistics, resonance decays, etc.) are not estimated

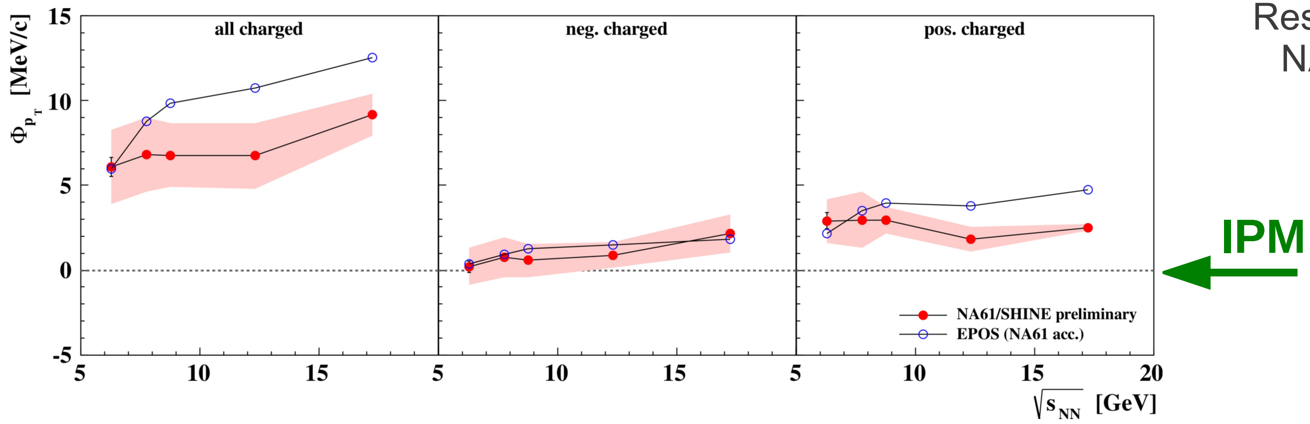
- What does the $\Sigma[P_T, N]$ = 1.1 mean?
- It means that (for this specific combination of moments → Σ quantity) **we measure 10% deviation from IPM** (fluctuations are 10% larger than in IPM)

Similar advantage for ω → here Poisson N distribution (instead of IPM) used as the reference:
ω_N = 0 for N = const. and ω_N = 1 for Poisson N distribution. Thus for *any* P(N) distribution:
ω_N > 1 (or ω_N » 1) corresponds to “large” (or “very large”) fluctuations of N,
ω_N < 1 (or ω_N « 1) corresponds to “small” (or “very small”) fluctuations of N

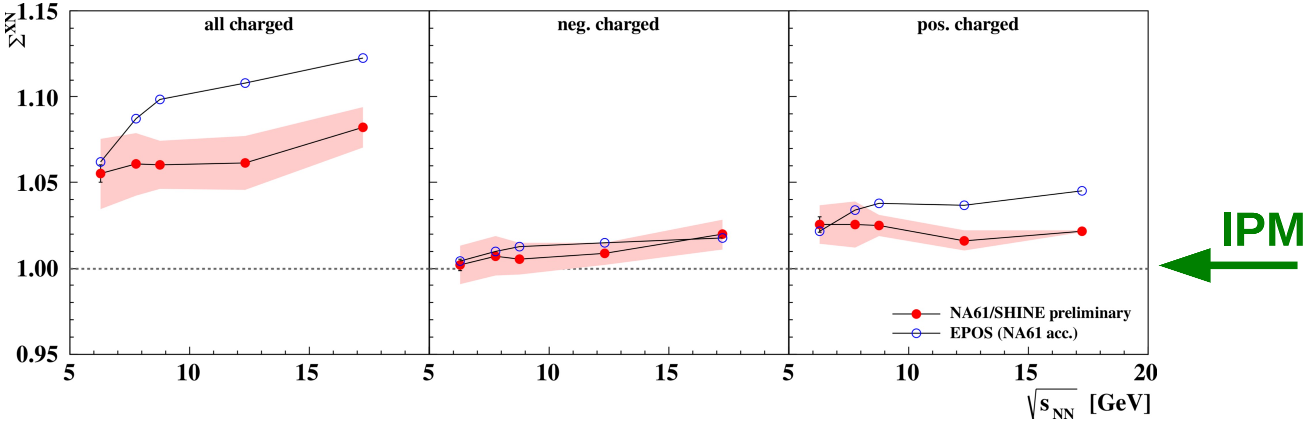
Δ and Σ measures – keep the advantages of both Φ (they are strongly intensive) and ω (they are properly normalized)

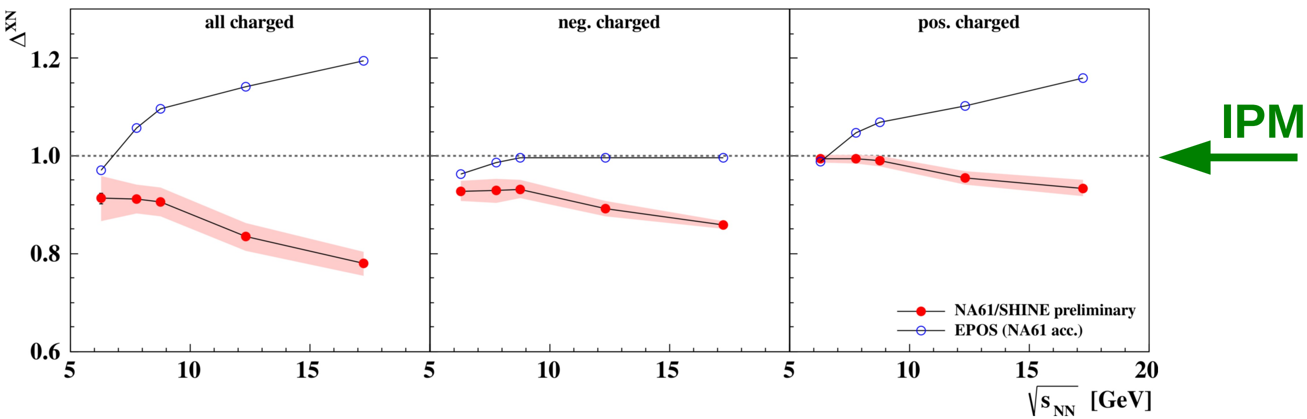
p_T fluctuations in inelastic p+p collisions

Results within the full NA61 acceptance



Φ_{pT} and $\Sigma[P_T, N]$ - the same "family" of strongly intensive measures (the same moments used)





$\Sigma[P_T, N]$ shows fluctuations <u>above</u> IPM predictions and $\Delta[P_T, N]$ <u>below</u> IPM

Possible explanations of $\Sigma[P_T, N] > 1$, $\Delta[P_T, N] < 1$ and $\Phi_{pT} > 0$

- BE statistics → PLB 730, 70 (2014); PRC 88, 024907 (2013); PLB 439, 6 (1998); PLB 465, 8 (1999)
- Average p_T per event P_T/N versus N correlation in pp → PRC 89, 034903 (2014)

p_T fluctuations in Be+Be collisions

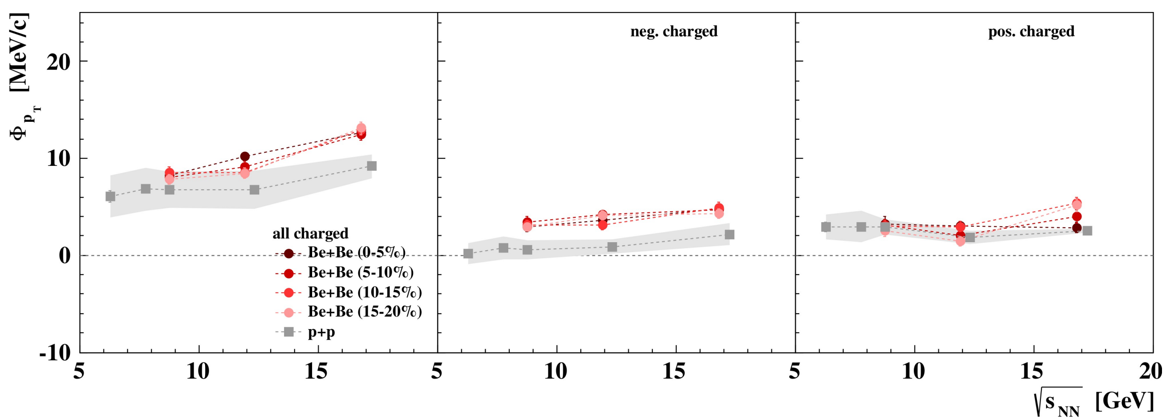
$$\Delta[P_T, N] = \frac{1}{\omega[p_T]\langle N \rangle}\left[\langle N \rangle \omega[P_T] - \langle P_T \rangle \omega[N]\right] \qquad P_T = \sum_{i=1}^{N} p_{T\,i}$$

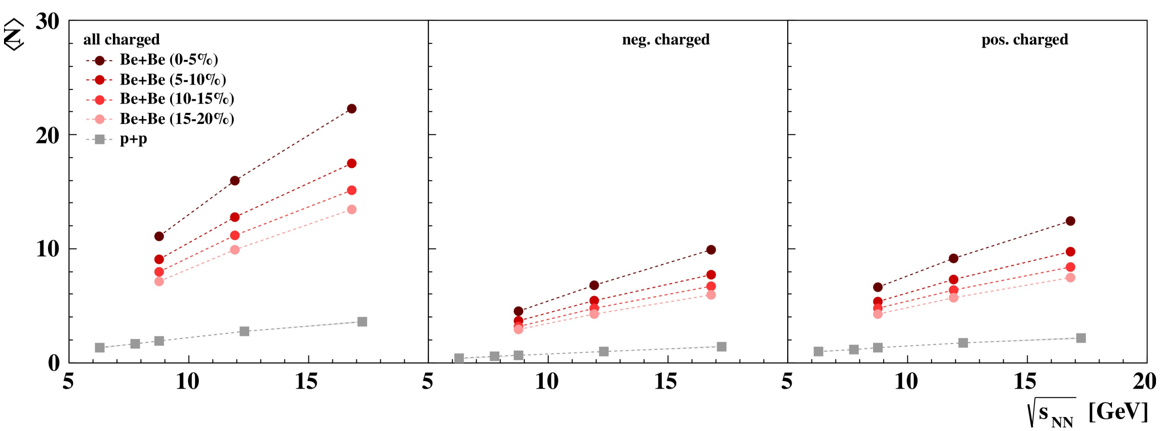
$$\Sigma[P_T, N] = \frac{1}{\omega[p_T]\langle N \rangle}\left[\langle N \rangle \omega[P_T] + \langle P_T \rangle \omega[N] - 2\left(\langle P_T N \rangle - \langle P_T \rangle \langle N \rangle\right)\right]$$

$$\omega[P_T] = \frac{\langle P_T^2 \rangle - \langle P_T \rangle^2}{\langle P_T \rangle} \qquad \omega[N] = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle} \qquad \omega[p_T] = \frac{\overline{p_T^2} - \overline{p_T}^2}{\overline{p_T}}$$

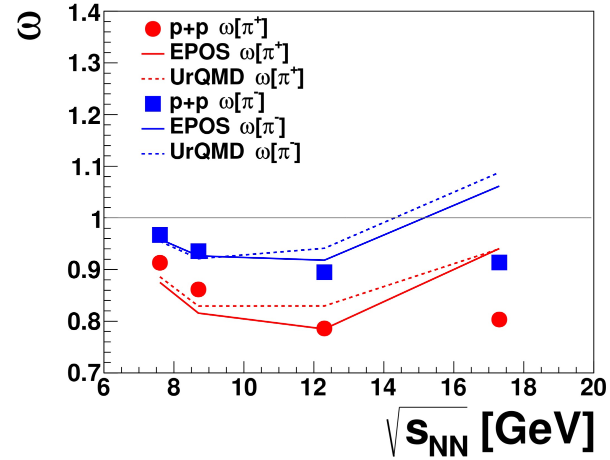
previously used:

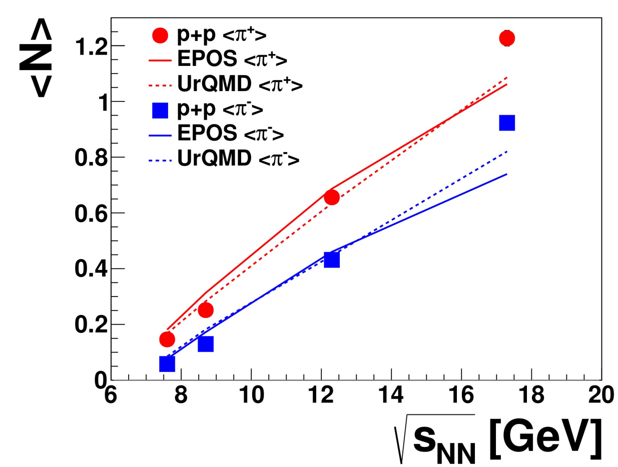
$$\Phi_{p_T} = \sqrt{\overline{p_T}\,\omega[p_T]}\left[\sqrt{\Sigma[P_T, N]} - 1\right]$$





Fluctuations of charged pions in p+p collisions





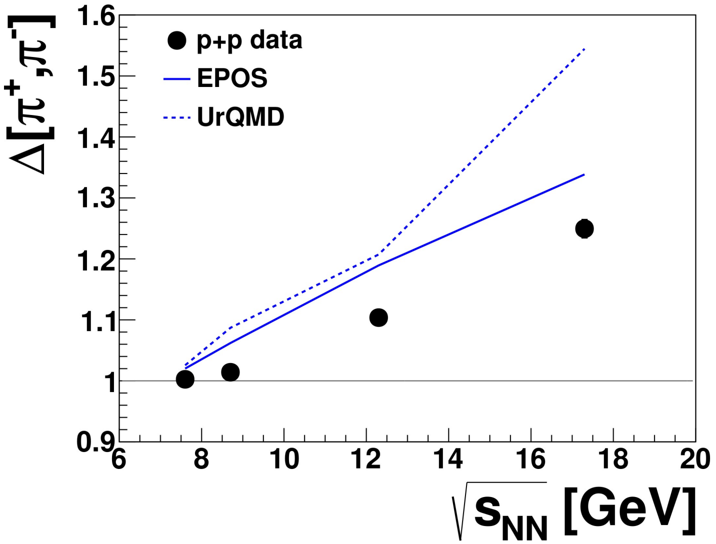
Fluctuations of charged pions in p+p

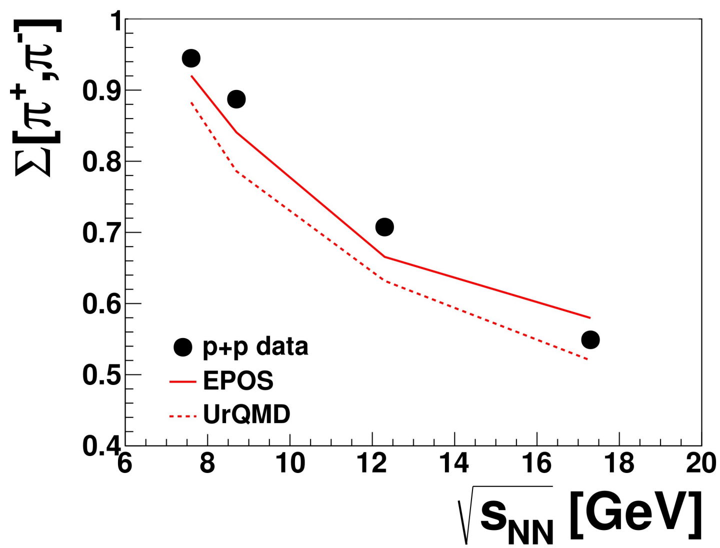
- Fluctuations of charged pions can be sensitive to critical point (long-wavelength fluctuations of the magnitude of the σ-field (PRD 60, 114028; PRL 81, 4816)
- Resonance abundances at chemical freeze-out can be found by measuring fluctuations of π^+ and π^- (arXiv:1409.3023)

$$\Delta[\pi^+,\pi^-]=\frac{1}{\langle\pi^-\rangle-\langle\pi^+\rangle}\left[\langle\pi^-\rangle\omega[\pi^+]-\langle\pi^+\rangle\omega[\pi^-]\right]$$

$$\Sigma[\pi^+,\pi^-]=\frac{1}{\langle\pi^+\rangle+\langle\pi^-\rangle}\left[\langle\pi^+\rangle\omega[\pi^-]+\langle\pi^-\rangle\omega[\pi^+]-2\left(\langle\pi^+\pi^-\rangle-\langle\pi^+\rangle\langle\pi^-\rangle\right)\right]$$

$$\omega[\pi^+]=\frac{\langle\pi^{+2}\rangle-\langle\pi^+\rangle^2}{\langle\pi^+\rangle}\qquad\omega[\pi^-]=\frac{\langle\pi^{-2}\rangle-\langle\pi^-\rangle^2}{\langle\pi^-\rangle}$$





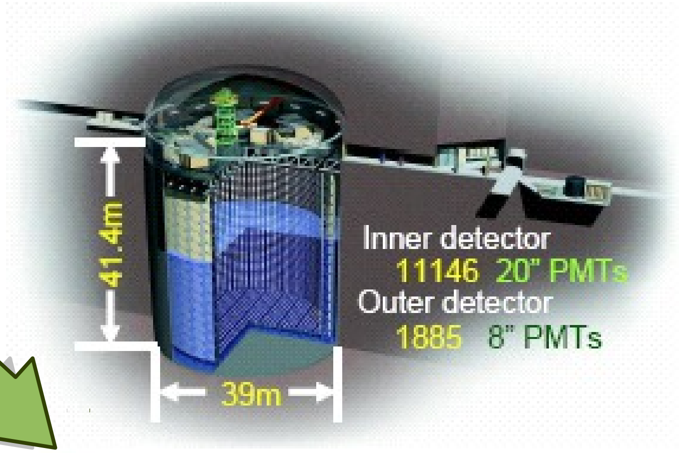
- NA61 results are in rather good agreement with models
- p+p collisions show no effects of critical point

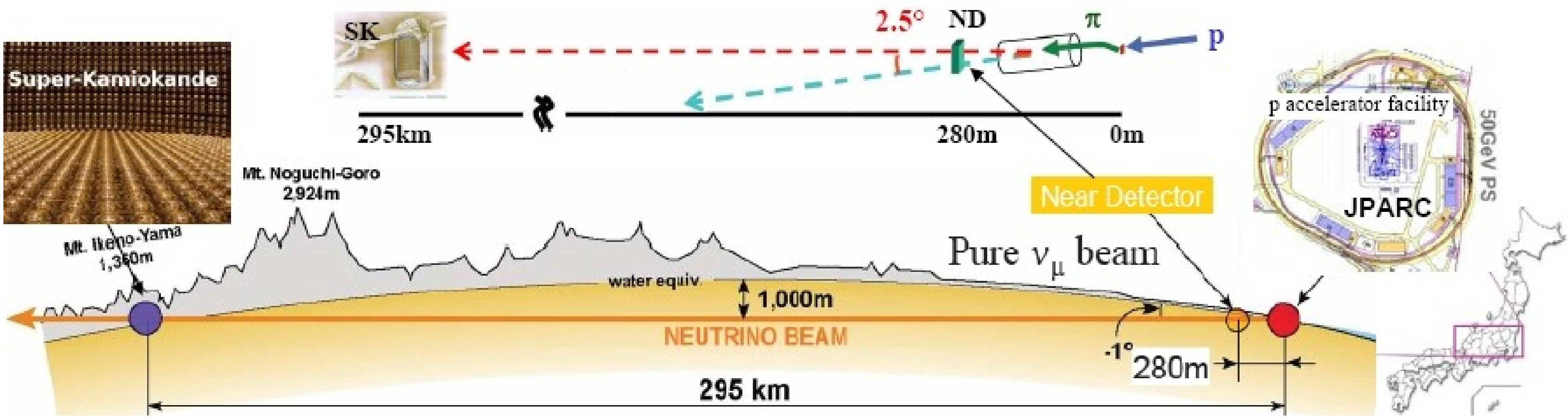
For both π^+ and π^- the same (smaller) acceptance of π^- was used, see: https://edms.cern.ch/document/1237791/1

Neutrino physics - reminder

- Measurements of hadron production to **precisely predict neutrino fluxes at J-PARC.**
- T2K experiment: p+C→π, K,…→ν_μ, …. Interactions of ν observed at Near detectors and Far detector (SK). Looking for ν oscillations: $\nu_\mu \rightarrow \nu_e$ (osc. characterized by Far-to-Near flux ratios). Corrections and sys. error estimate depend on knowledge of **p + C → π^{+-}, K^{+-}, … production**.
- NA61 helps to determine initial ν flux using reactions: p+C at 31 GeV/c and p+C(LT) at 31 GeV/c.

The T2K experiment published a measurement of θ_{13} angle in the neutrino mixing matrix (PRL 107, 041801 (2011))
Systematic error estimate was based on the NA61/SHINE results



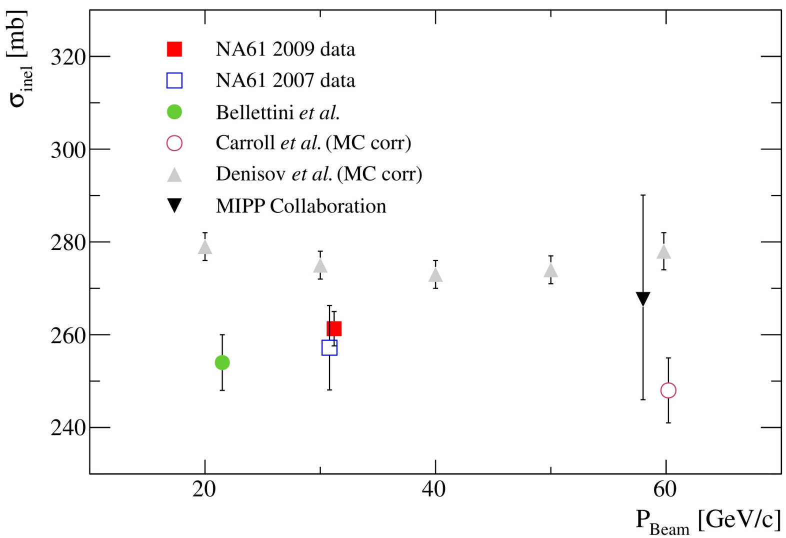


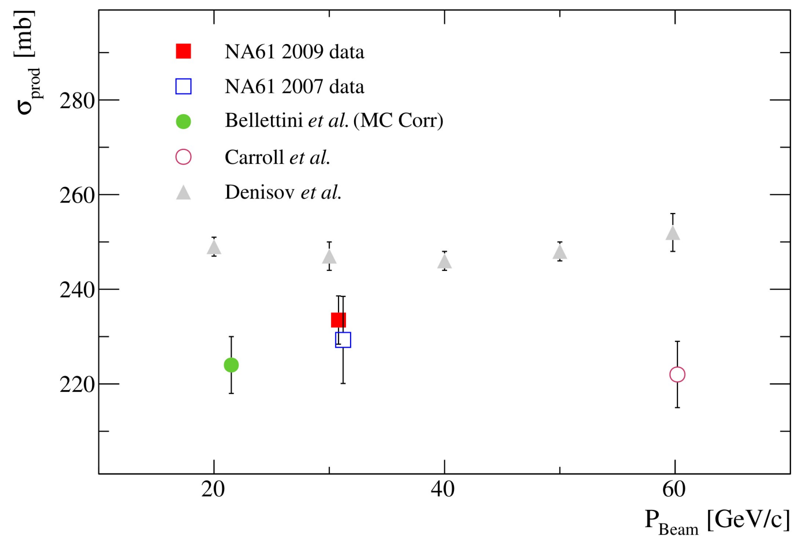
Results on p+C at 31 GeV/c

High statistics 2009 p+C at 31GeV/c "thin-target" dataset

σ_{inel} = 261.3 ± 2.8(stat) ± 2.4(det) ± 0.3(mod) mb

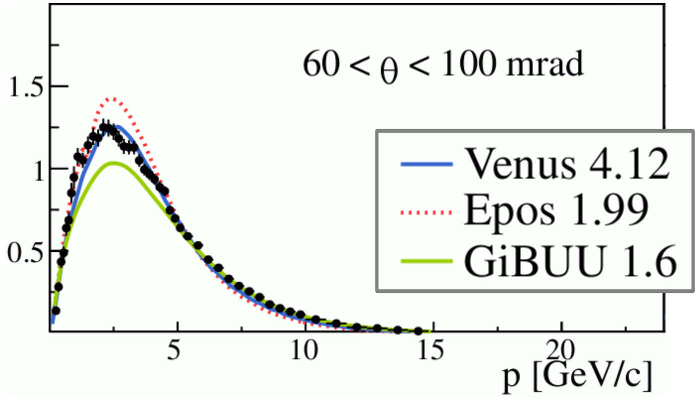
σ_{prod} = 233.5 ± 2.8(stat) ± 2.4(det) ± 3.6(mod) mb



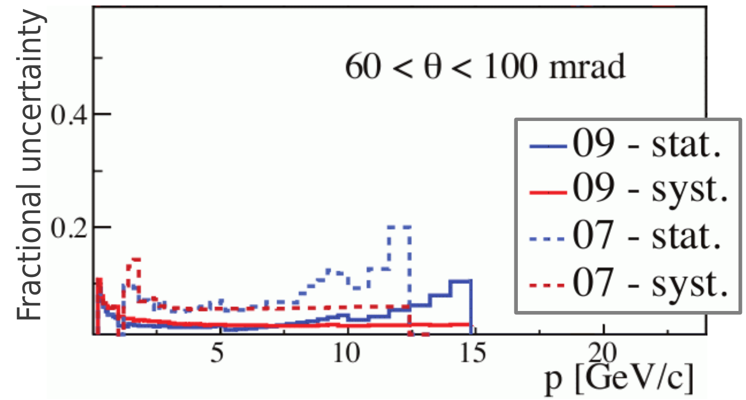


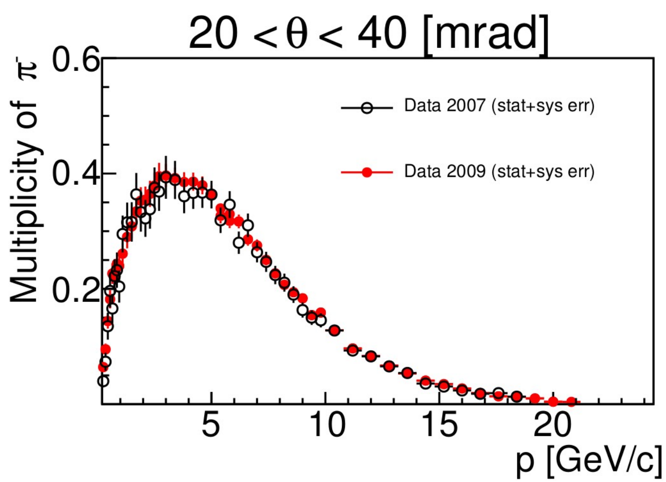
Summary of data collected by NA61 for T2K

beam	target	year	stat.x10^6	Status of analysis	The T2K beam MC
protons at 31 GeV/c	thin target 2cm ($0.04\lambda_I$)	2007	0.7	published: $\pi^\pm$, K^+, K^0_S, Λ	is used
		2009	5.4	prelim: $\pi^\pm$, $K^\pm$, p, K^0_S, Λ	to be used in 2014
	the T2K replica target 90 cm ($1.9\lambda_I$)	2007	0.2	published: $\pi^\pm$	method developed
		2009	2.8	to be released in 2014	-
		2010	~10	calibration	-

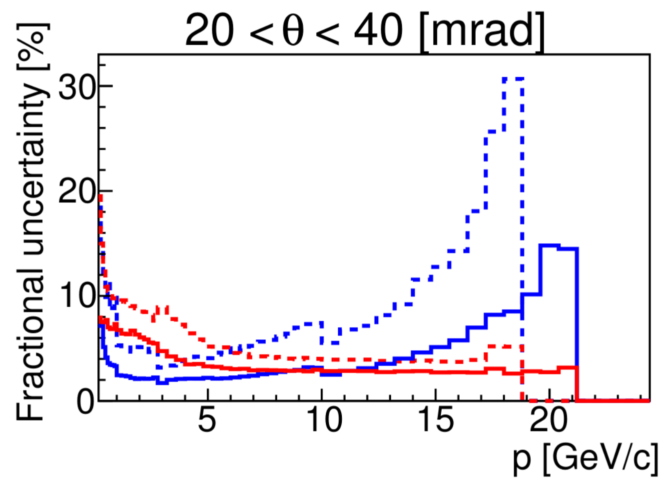


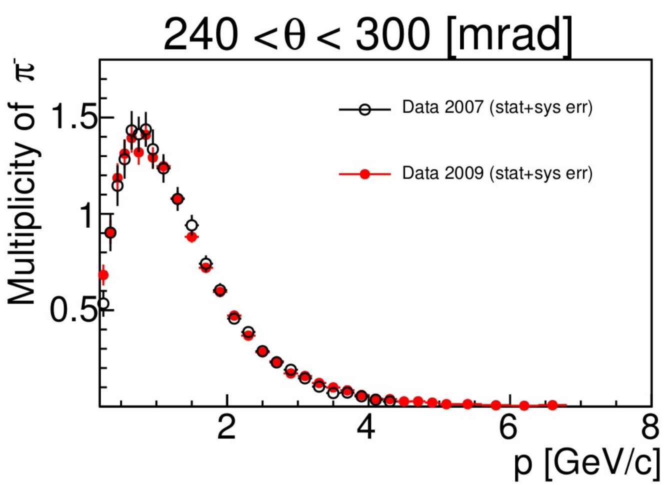
2009 p+C at 31 GeV/c (tof-dE/dx method)

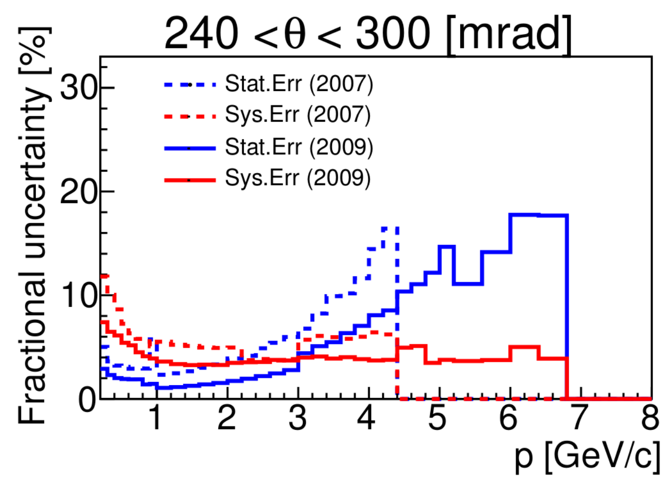




2009 p+C at 31 GeV/c (h^- method)





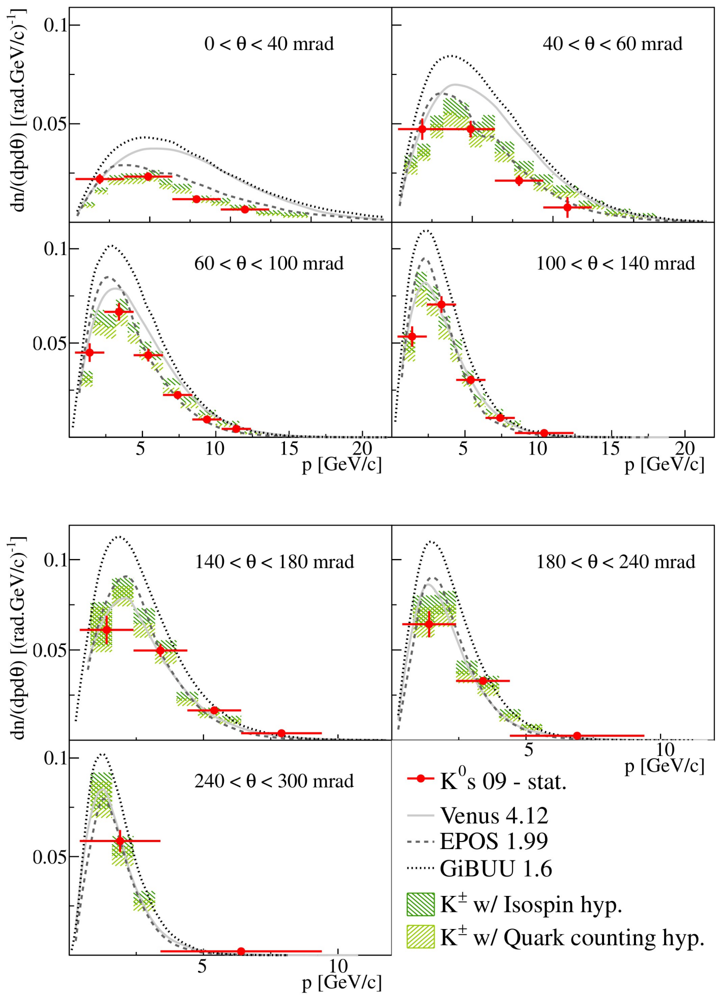


Results on p+C at 31 GeV/c

Analysis of K^0_S and Λ is very important → reduction of the feed-down contribution for the pion and proton spectra

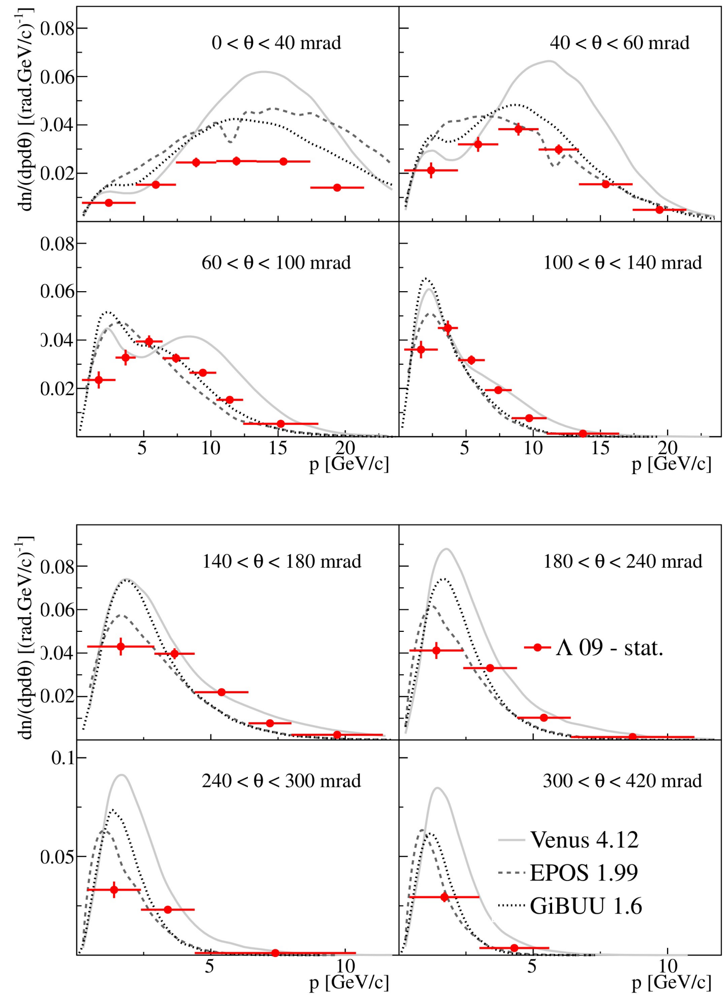
Decay chanel: $K^0_S \rightarrow \pi^+ + \pi^-$

$\Gamma = (69.20 \pm 0.05)\%$



Decay chanel: $\Lambda \rightarrow p + \pi^-$

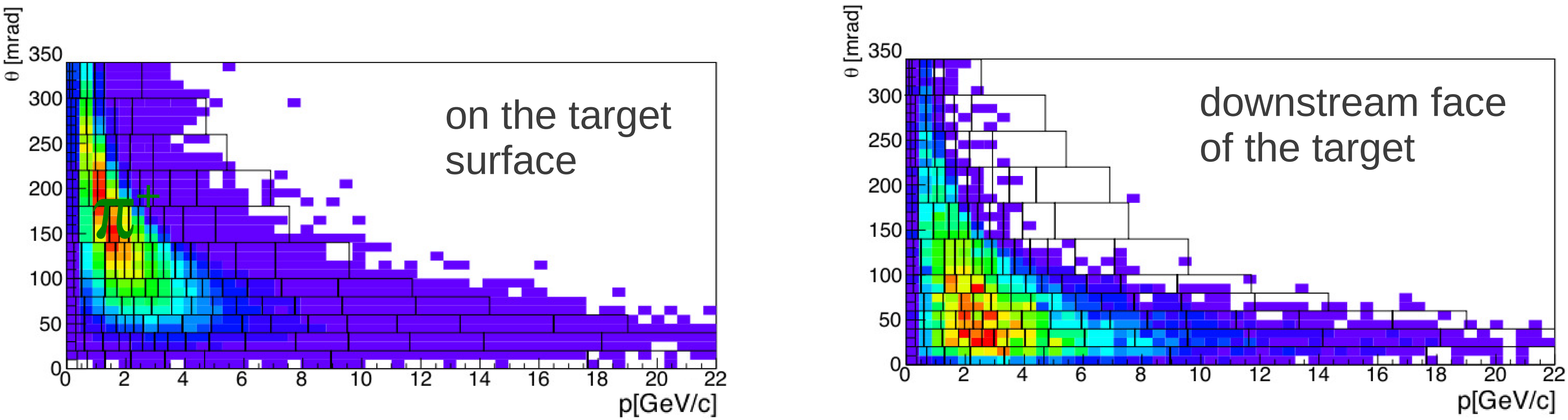
$\Gamma = (63.9 \pm 0.5)\%$



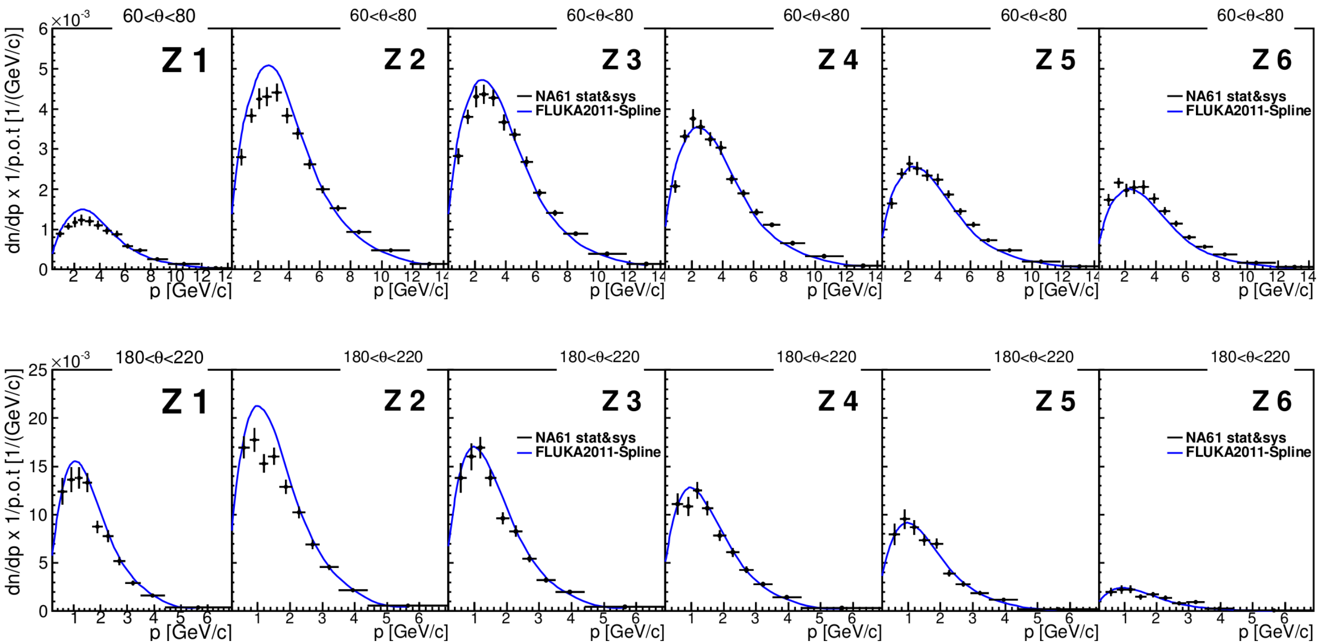
Isospin argument: $\langle K^0_S \rangle = \frac{1}{2}(\langle K^+ \rangle + \langle K^- \rangle)$

Quark-counting rule: $\langle K^0_S \rangle = \frac{1}{8}(3\langle K^+ \rangle + 5\langle K^- \rangle)$

Results on p+(T2K replica target) at 31 GeV/c



Color histograms - distributions of π^+ contributing to ν_μ flux at SK; **Black boxes** – phase space bins considered for T2K replica target analysis (covers most part of the phase space of interest for T2K)



Correction factors due to limited acceptance, decay of particles in flight, re-interaction of particles with detector material were computed bin-by-bin, based on MC simulations with FLUKA2011 (model used by T2K to simulate hadron production in LT)

Stat. and sys. uncertainties are added in quadrature

Cosmic ray physics - reminder

- Particle production spectra for Pierre-Auger and KASCADE experiments to **improve air shower simulations.** Primary cosmic ray is identified by the properties of the produced air shower. Problem: large systematic uncertainties of models used for simulations. Shower evolution strongly depends on the **π^{+-} + air nucleus → π^{+-}, K^{+-}, p, ... production** (SPS energies).
- Special "cosmic runs": π^-+C at 158 and 350 GeV/c, C – close to mass of air nuclei
- Also useful:
  - p+C at 31 GeV/c
  - p+p scan from 13 to 158 GeV/c

KASCADE

Cosmic ray composition of central importance for understanding sources, kink, ankle...

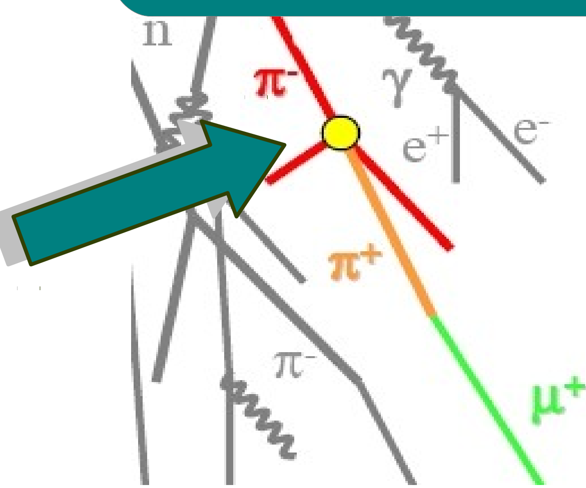
Modern detector installations: high statistics/quality data

Indirect measurement (extensive air showers): simulations needed

Strong model dependence: due mainly to simulation of muon production

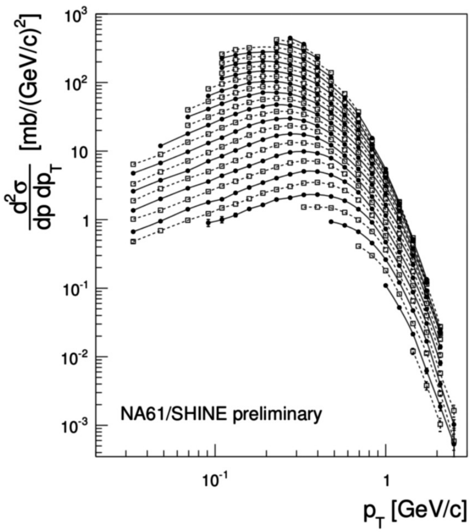
Muon production related to hadronic interactions at fixed-target energies

Study of particle production in last generation of air shower cascade

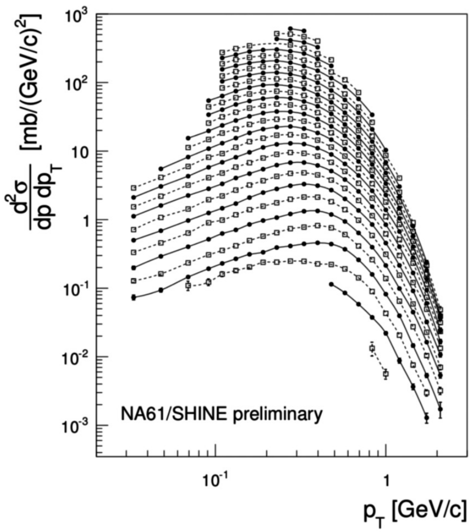


Charged hadrons in π^-+C at 158 and 350 GeV/c

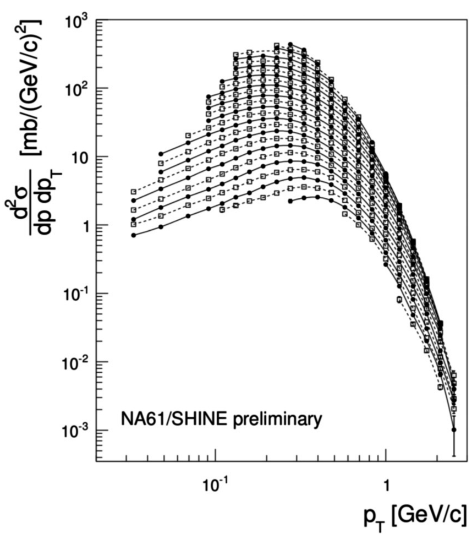
CPOD 2013



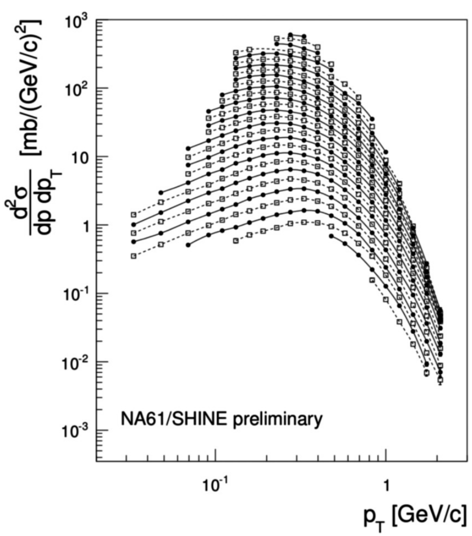
(a) h^- at 158 GeV/c



(b) h^+ at 158 GeV/c



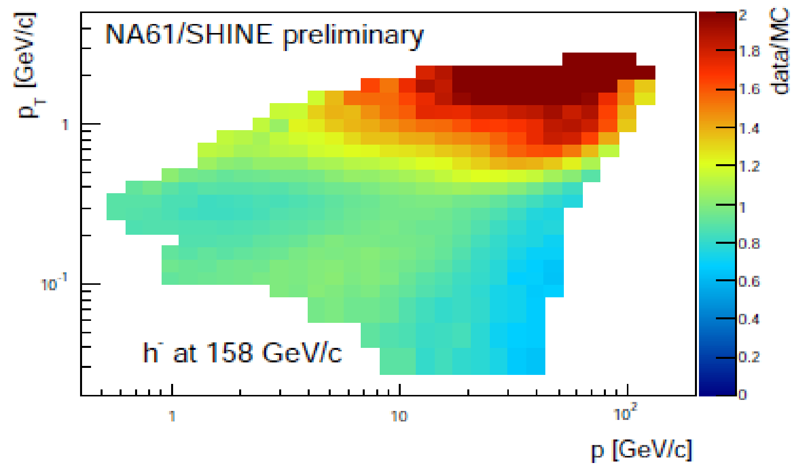
(c) h^- at 350 GeV/c

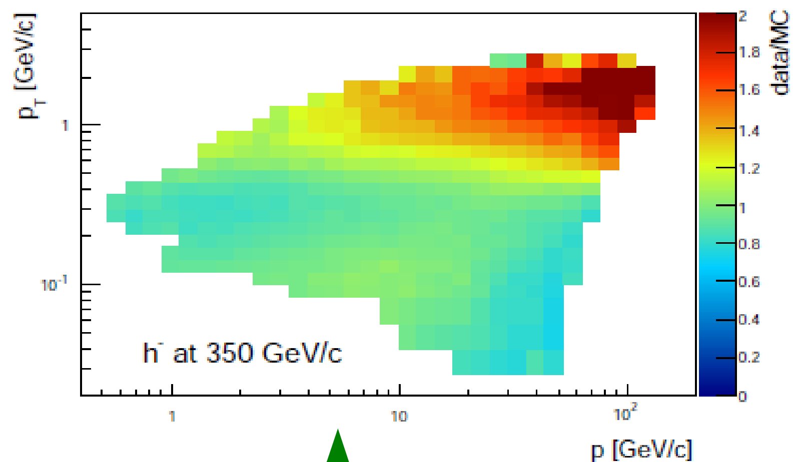


(d) h^+ at 350 GeV/c

p = 0.6, …, 121 GeV/c in steps of lg p/(GeV/c) = 0.08

$\pi^- + C \rightarrow h^- + X$





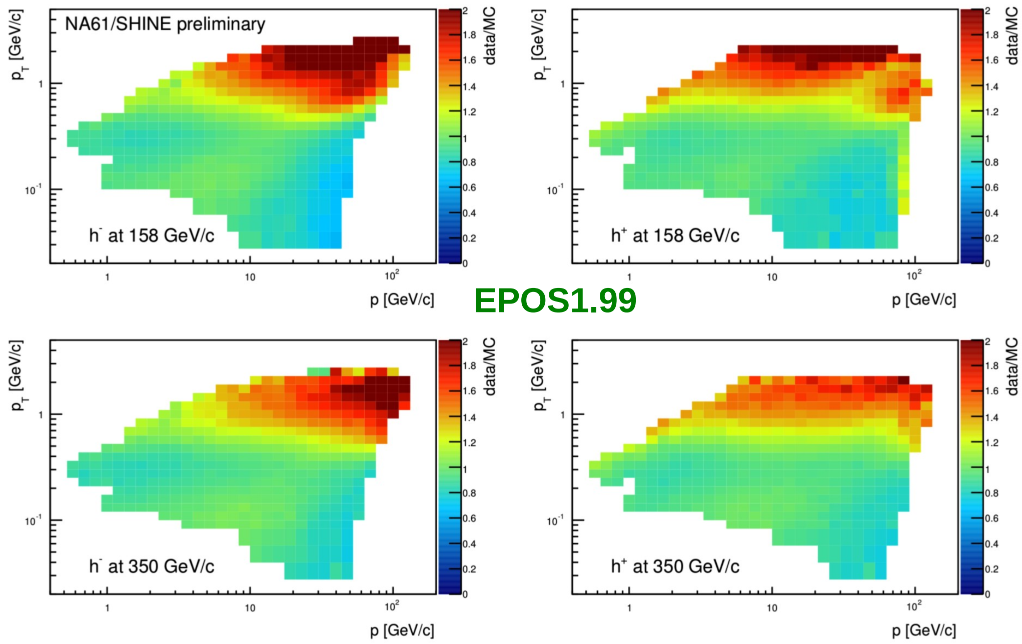
NA61 data/EPOS

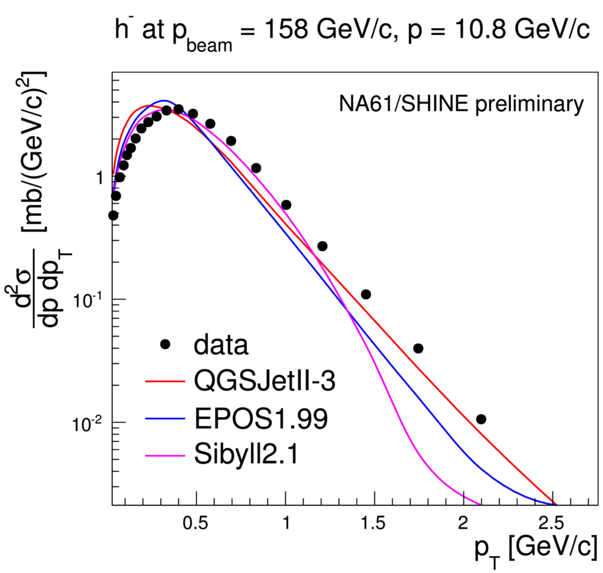
Input for validation/tuning of Monte Carlo generators.

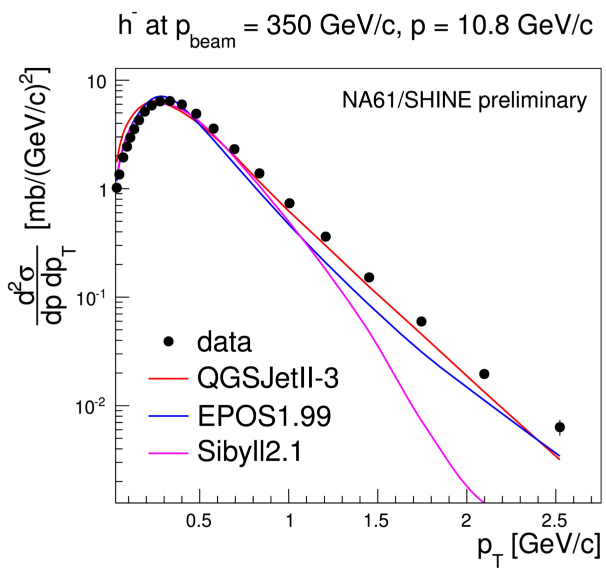
Compared with models: EPOS1.99, UrQMD1.3.1, Fluka2011, QGSJet, etc.

Measuring cosmic-ray composition
Example: cross section and spectra measurements

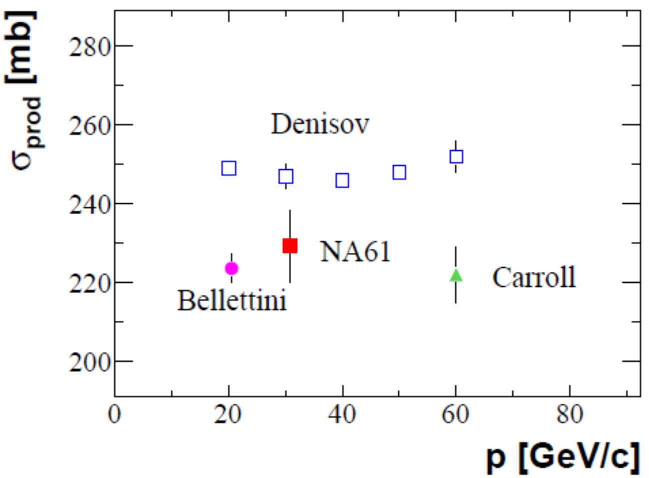
Input for validation/tuning of Monte Carlo generators:



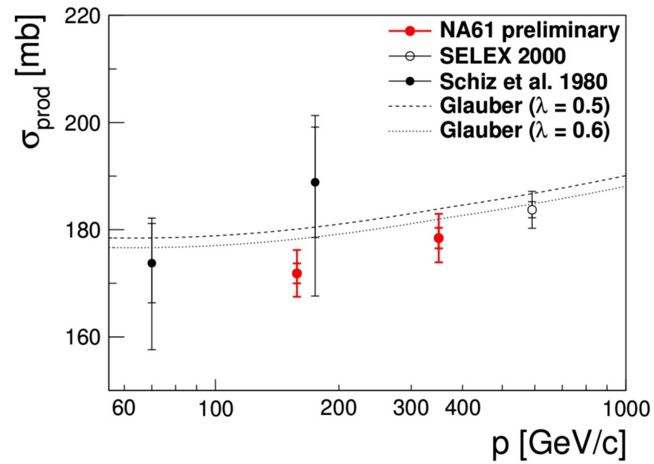




p+C at 31 GeV/c

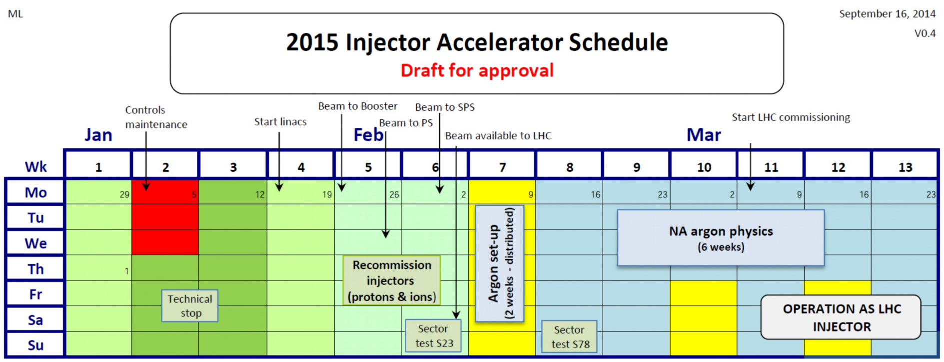


π^-+C at 158 and 350 GeV/c

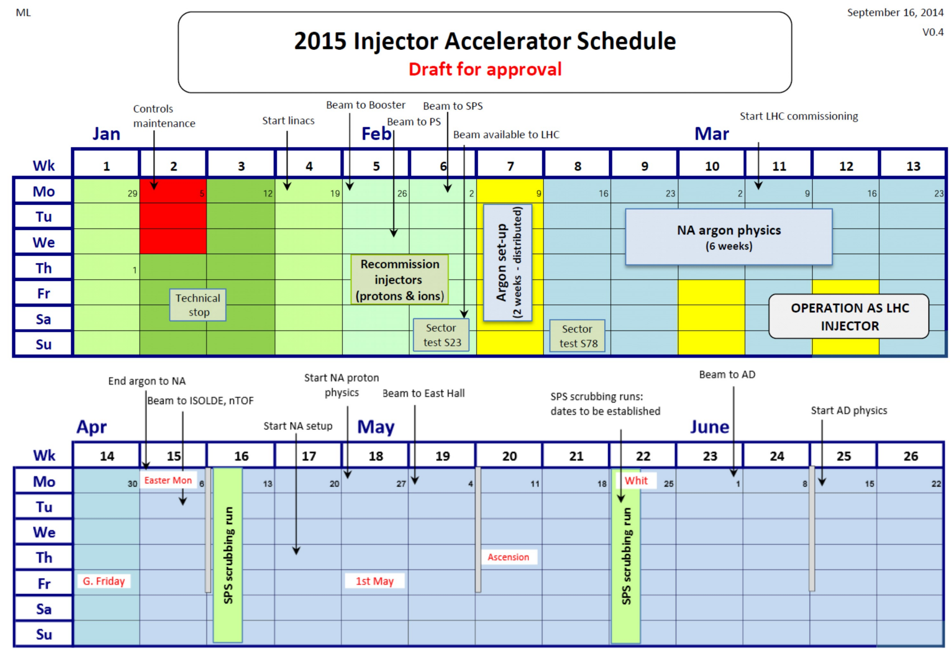


Schedule: Primary Ar run

- Recommissioning entire complex starts 26/1/15
- 8 week Ar run 9/2/15- 6/4/2015
  - Includes 2 weeks setting up (machine extraction + North Area)
  - 6 momenta
  - while operating as LHC proton injector
  - Finishes after Easter



Schedule: Primary Ar run



Tentative planning for Xe run

- Xe cannot be prepared in injectors in 2015
  - Ar run followed by Linac3 maintenance/repair
  - then recommissioning of Pb in all injectors in view of Pb-Pb run in the LHC (currently planned for mid-November 2015)
- No Pb-Pb run in 2017 due to EYETS
- Xe commissioning in Linac3, LEIR, PS & SPS in 2017
- Xe run for North Area at the end of 2017
  - 6 momenta (13, 19, 30, 40, 75, 150 AGeV/c)

5 year plan

- 2014 March-August: Ar commissioning in ECR/RFQ/Linac3/LEIR
- 2014 September-December: Ar commissioning in PS/SPS
- 2015 February 23rd -April 6th: Ar run for NA61 (6 momenta)
- 2015 July-October: Pb recommissioning in injectors
- 2015 November-December:
  Pb-Pb run for LHC (+ early test of primary Pb for NA61?)
- 2016 Pb MDs in injectors
- 2016 November-December:
  Pb-Pb run for LHC (+ Run primary Pb for NA61? x momenta?)
- 2017 January-October:
  Xe commissioning in ECR/RFQ/Linac3/LEIR/PS/SPS
- 2017 November-December:
  Xe run for NA61 (6 momenta in 8 weeks)
- 2018 January: switch to Pb in injectors
- 2018 June: p-Pb (or Pb-Pb?) run for LHC
  (+ Run primary Pb for NA61? x momenta?)

Test run with primary Pb beam (2015)

- **Test of PSD detector** → the performed upgrade of the PSD Front-End-Electronics and the scheduled replacement of the PSD readout with advanced DRS4 electronics in 2015 require a careful test of PSD performance with different ion beams (Pb test beam in 2015 is required in order to study performance of PSD in Pb+Pb reactions). Data recored in the test will allow to study capability and precision of the reaction plane reconstruction by PSD (need for azimuthal flow measurements).

- **Test of scintillator-fiber beam hodoscope** → they will be used to track the incoming heavy ions and will replace aging proportional chambers. At the same time new digitizing readout electronics for NA61/SHINE based on the DRS will be tested.

- **Tests of on-line selection of minimum bias events** → study of anisotropic flow requires on-line selection of minimum bias events (selection should take into account a large probability of Pb beam interactions with detector material). Different trigger detector set-ups will be tested in order to optimize possible future data taking.

NA49 experiment: Status and Plans

Publications in refereed journals since October 2013:

- Phase-space dependence of particle-ratio fluctuations in Pb+Pb collisions from 20A to 158A GeV beam energy, **Phys. Rev. C 89, 054902 (2014)** [arXiv:1310.3428v1]

Submitted papers:

- Energy, system-size and transverse-momentum dependence of two-particle azimuthal correlations of high-p_T charged hadrons in nucleon-nucleon and nucleus-nucleus collisions at the SPS, submitted to Cern review
- Evidence for critical fluctuations of the proton density in A+A collisions at 158A GeV, arXiv:1208.5292v2, resubmitted to Phys. Lett. B

Subjects of ongoing and further analyses:

- Production of hyperons and hyperon resonances in p+p collisions (T. Anticic, K. Kadija, T. Susa)
- Energy dependence of proton and antiproton production in central Pb+Pb collisions from 20A to 158A GeV at the CERN SPS (M. Kowalski)
- Production of light nuclei (^{3}He and t) in Pb+Pb collisions from 20A to 158A GeV at the CERN SPS (V. Kolesnikov)
- Study of identified particle multiplicity fluctuations using strongly intensive observables Φ, Δ, Σ (M. Maćkowiak-Pawłowska, A. Rustamov)
- Study of $\langle p_T \rangle$ fluctuations using the strongly intensive observables Δ and Σ (K. Grebieszkow)
- Correlations of $\langle p_T \rangle$ and charged particle multiplicity (A. Wojtaszek-Szwarc)
- $\Delta\eta\Delta\phi$ correlatins in Pb+Pb collisions (B. Maksiak)