The Old New Frontier: Studying the CERN SPS Energy Range with NA61/SHINE

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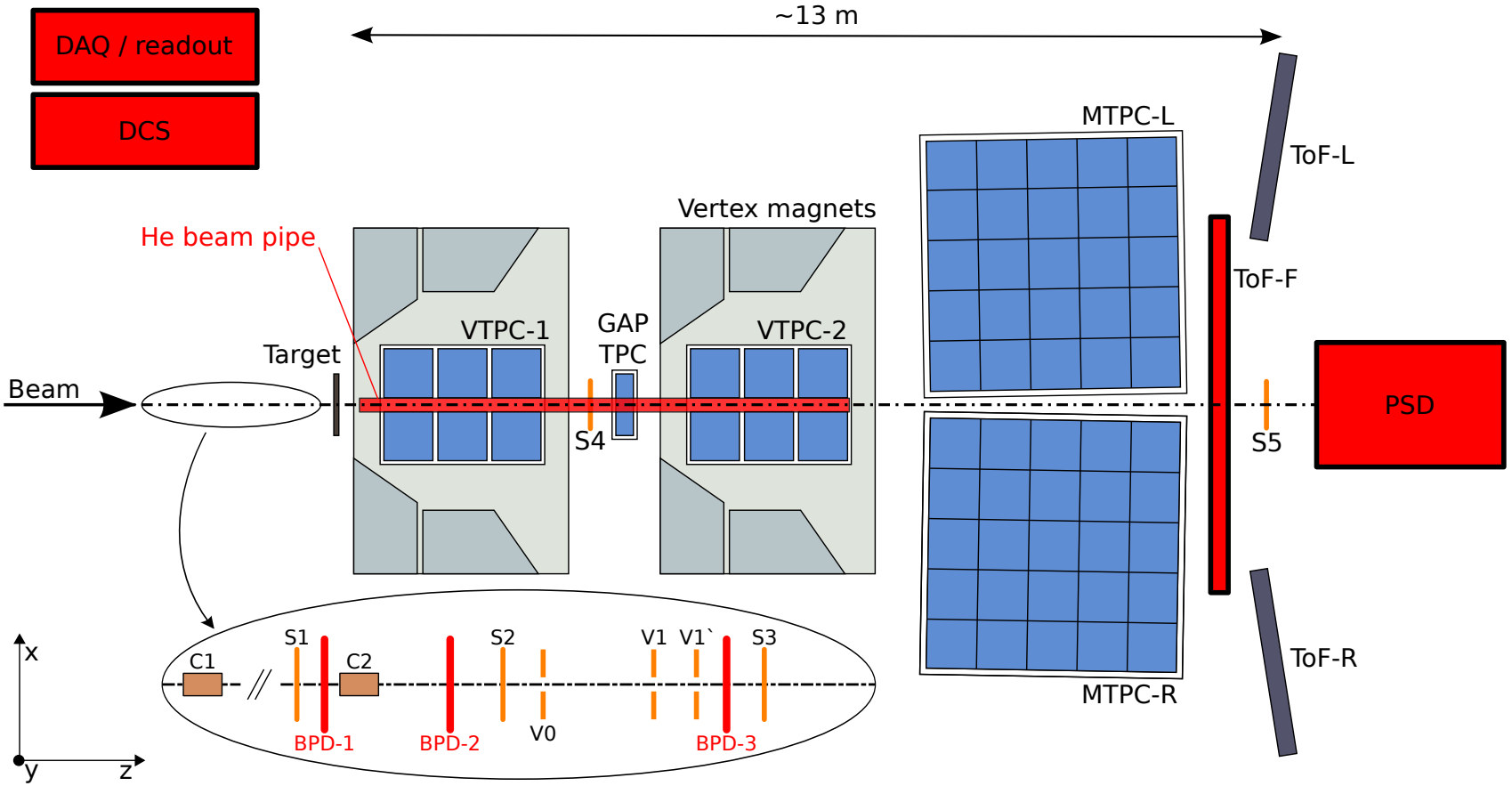
Outline

The NA61/SHINE Experiment

- A fixed-target experiment at the CERN SPS
- One of the largest non-LHC experiments at CERN
- Successor of NA49
- Taking data since 2007
- h+N, h+A and A+A collisions over a wide energy range
- Physics goals:
  - search for the **critical point** and study of the **onset of deconfinement** of QCD matter
  - reference hadroproduction measurements for **neutrino** and **cosmic-ray** experiments
  - study of **high-p_T phenomena** in p+p and p+A collisions

Detector Set-up



Also: LMPD, A and Z detectors, software upgrade, ...

Our Main Assets

We can meet such varied physics goals thanks to:

- large acceptance: ≈ 50 %
- high momentum resolution: $\sigma(p)/p^2 \approx 10^{-4}\ (GeV/c)^{-1}$
- good particle identification:
  - $\sigma(\mathrm{d}E/\mathrm{d}x)/ < \mathrm{d}E/\mathrm{d}x > \approx 0.04$
  - $\sigma(t_{flight}^{ToF-L/R}) \approx 60\ ps$
  - $\sigma(t_{flight}^{ToF-F}) \approx 120\ ps$
  - $\sigma(m_{inv}) \approx 5\ MeV$
- high detector efficiency: over 95 %
- high data rate: 70 events/s

Data Taking

2007 pilot run

- 850 thousand events recorded
- neutrino physics:
  - p+C at 31 GeV/c
  - p+(T2K replica target) at 31 GeV/c

2009 run

- 40 million events recorded
- neutrino physics:
  - p+C at 31 GeV/c
  - p+(T2K replica target) at 31 GeV/c
- cosmic-ray physics:
  - π^-+C at 158 GeV/c
  - π^-+C at 350 GeV/c
- critical point and the onset of deconfinement:
  - p+p at 20 GeV/c
  - p+p at 31 GeV/c
  - p+p at 40 GeV/c
  - p+p at 80 GeV/c
  - p+p at 158 GeV/c

Data Taking

2010 run

- 75 million events recorded
- neutrino physics:
  - p+(T2K replica target) at 31 GeV/c
- high p_T:
  - p+p at 158 GeV/c

2011 run

- 27 million events recorded
- high p_T:
  - p+p at 158 GeV/c
- critical point and the onset of deconfinement:
  - p+p at 13 GeV/c
  - Be+Be at 40A GeV/c
  - Be+Be at 75A GeV/c
  - Be+Be at 150A GeV/c

Data Taking

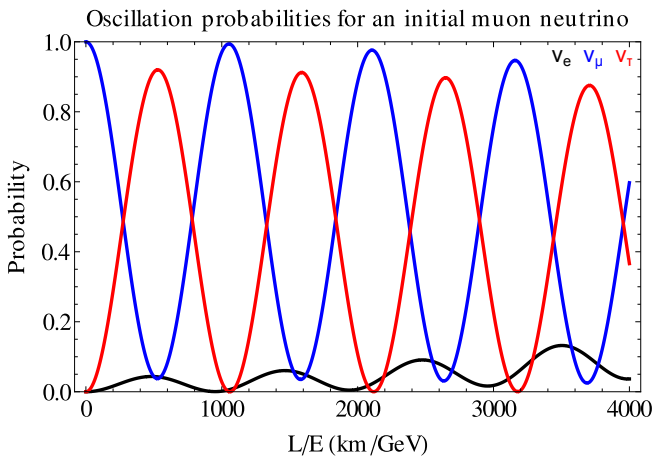
2012 run (plans)

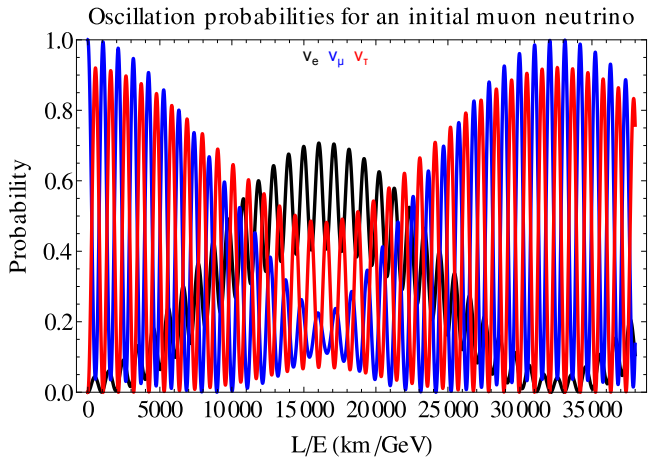
- neutrino physics:
  - p+C at 120 GeV/c
- high p_T:
  - p+Pb at 158 GeV/c
- cosmic-ray physics:
  - π+C at 158 GeV/c
- critical point and the onset of deconfinement:
  - Be+Be at 13A GeV/c
  - Be+Be at 20A GeV/c
  - Be+Be at 30A GeV/c

Outline

Neutrino Oscillation

- Predicted by Pontecorvo in 1957
  - each ν is a mixture of three definite states
  - different masses $\Rightarrow$ different propagation
  - periodic changes of composition
  - upshot: $m_\nu \neq 0$





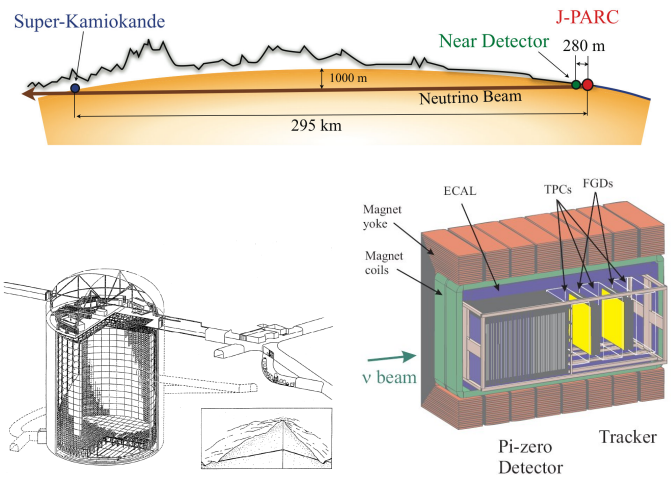
The PMNS Matrix

- Pontecorvo–Maki–Nakagawa–Sakata
- Neutrino mixing matrix
- Similar to CKM matrix for quarks
- Typically parametrised by three Euler angles (θ_{13}, θ_{23}, θ_{12}) and single CP-violation phase (δ):

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

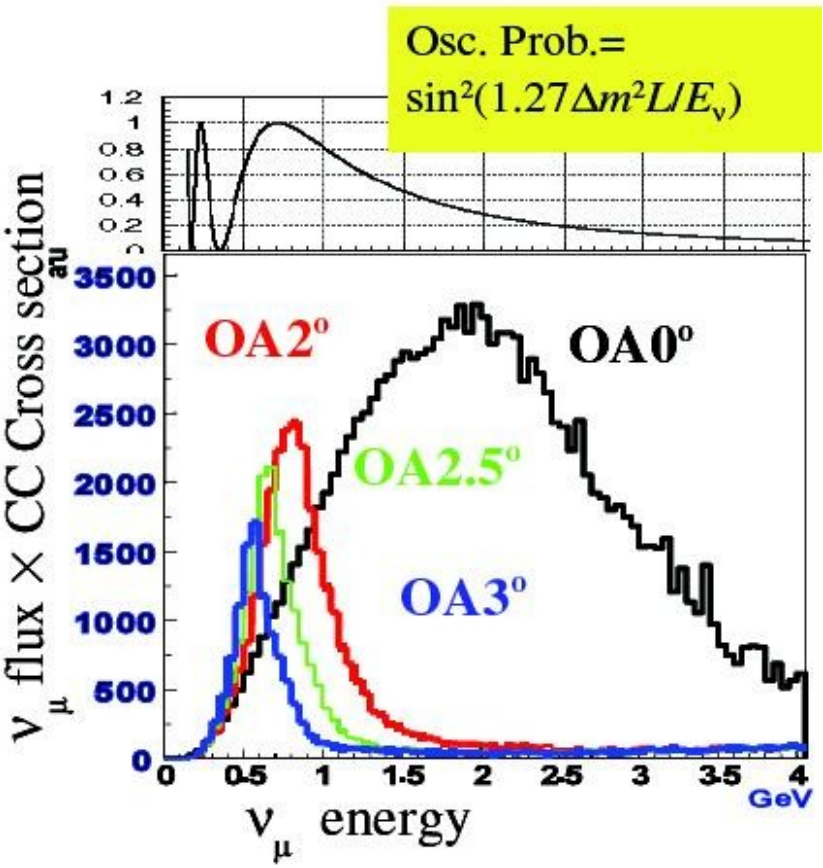
  where $s_{ij} = sin(\theta_{ij})$, $c_{ij} = cos(\theta_{ij})$.
- From observations:
  - θ_{23}, θ_{12} — large
  - θ_{13} — very small

Introducing T2K

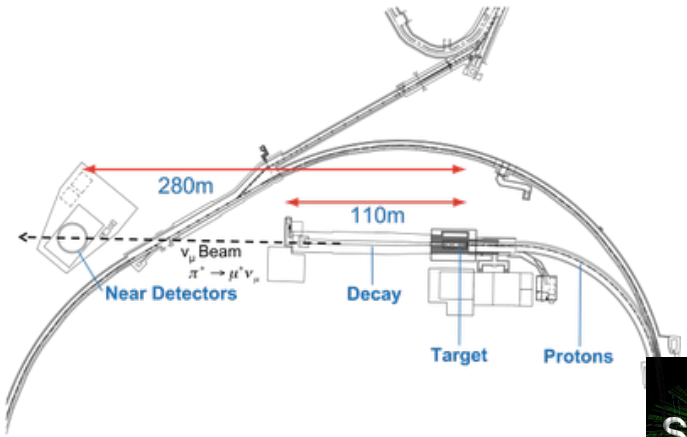


- Tokai-to-Kamioka: a long-baseline neutrino experiment
- search for and measure $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\tau$ oscillations
- improve measurement of θ_{23}, Δm^2_{23}
- one of the first measurements of θ_{13}
- in the future: search for ν CP violation

T2K Neutrino Beam



- J-PARC accelerator complex: proton beams at 31 GeV
- Muon neutrinos produced in a 90-cm carbon target
- Off-axis neutrino beam



The Task for NA61

- Problem: ν emission from target complicated
- Good knowledge of hadron production is a must
- Simulations are model-dependent
- NA61: large acceptance, matching energy
- Our goal: measure inclusive hadron spectra in p+C collisions at 31 GeV
  - thin (2 cm) target
  - replica T2K target

Results So Far

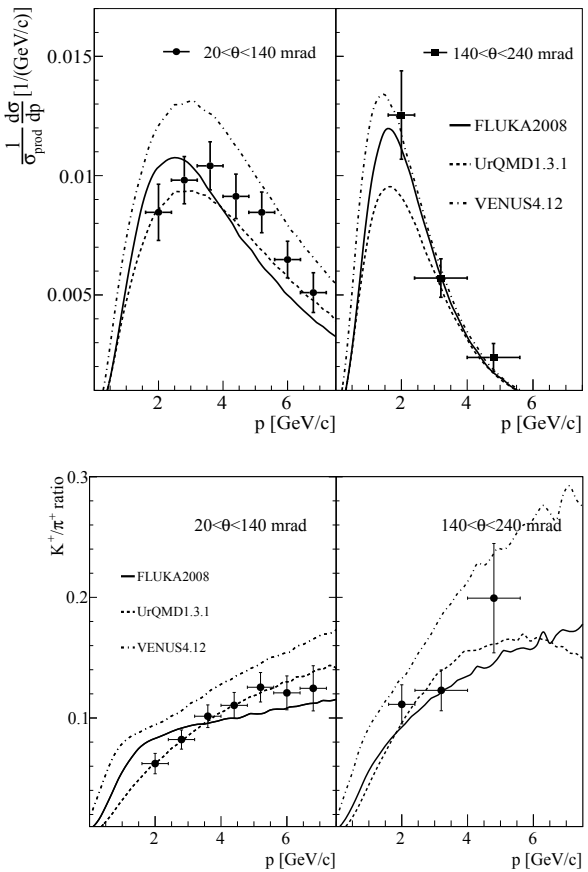
Comparison to FLUKA2002

Comparison to UrQMD 1.3.1

Comparison to Gheisha2008

- Published $\pi^{\pm}$ spectra from 2007 pilot run:
  - Phys.Rev. C84 (2011) 034604
- Published K^{+} spectra from 2007 pilot run:
  - Phys.Rev. C85 (2012) 035210
- Finalising 2009 results

Results So Far



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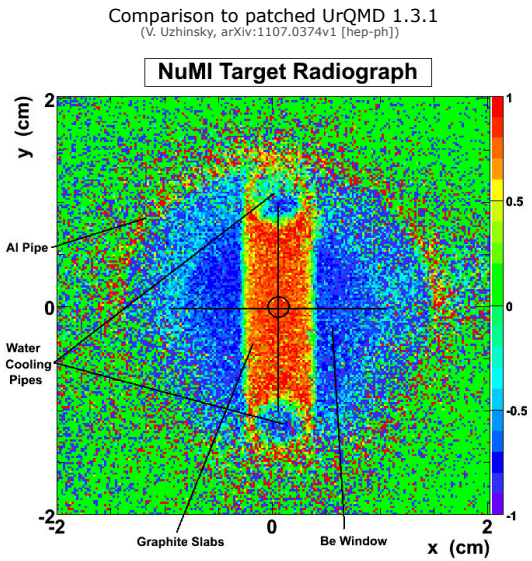
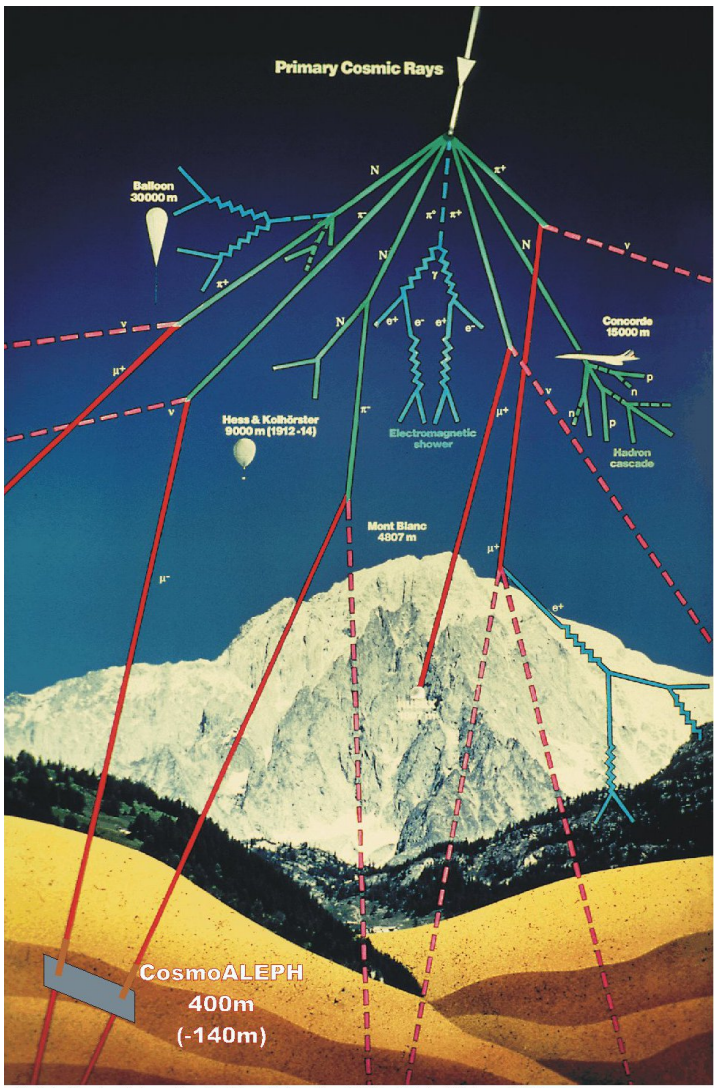
Follow-up



- First published T2K results: systematic-error estimate based on NA61 results
  - Phys.Rev.Lett. 107 (2011) 041801
- First model improvements
  - UrQMD: arXiv:1107.0374 [hep-ph]
  - Geant4 FRITIOF: arXiv:1109.6768 [hep-ph]
- Near future: reference measurements for the NuMI ν source at Fermilab
  - p beams at 120 GeV/c

Outline

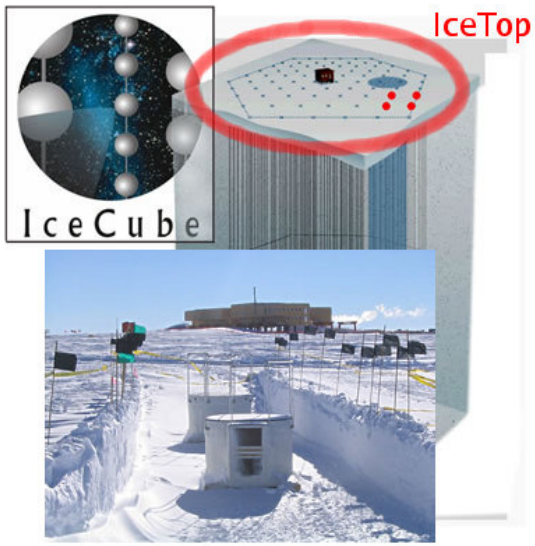
What Are Cosmic Rays?

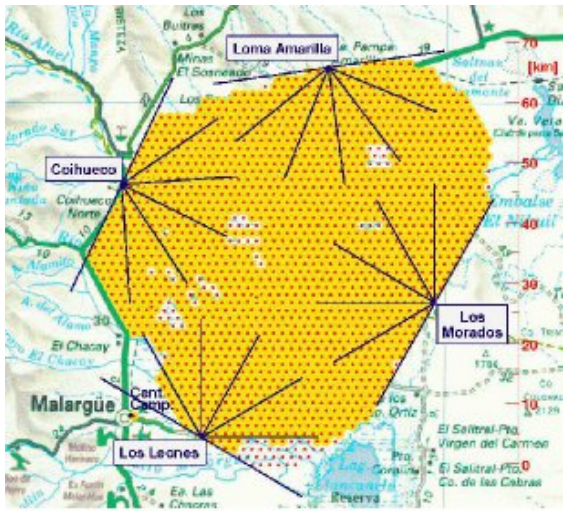


Particle Physics Slides • Sascha Marc Schmeling 1999 • Original Picture: CERN

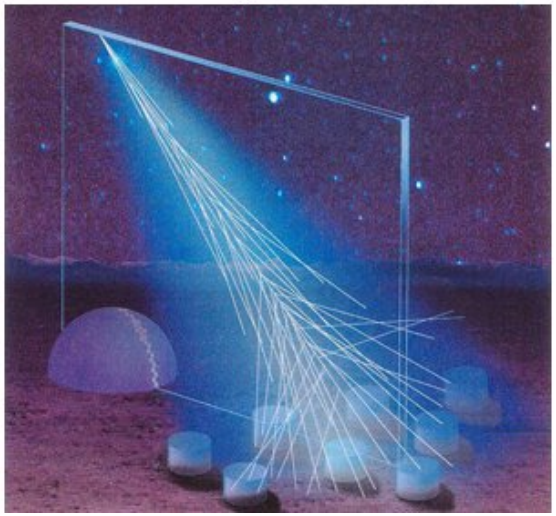
- Particle from astrophysical sources
- Interactions in Earth's atmosphere
- Two measurement methods:
  - direct (with satellites)
  - extensive air showers

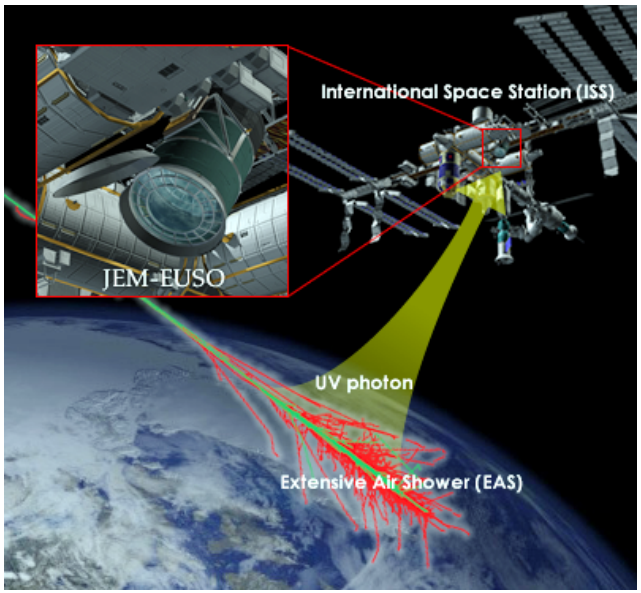
Air-shower Detectors





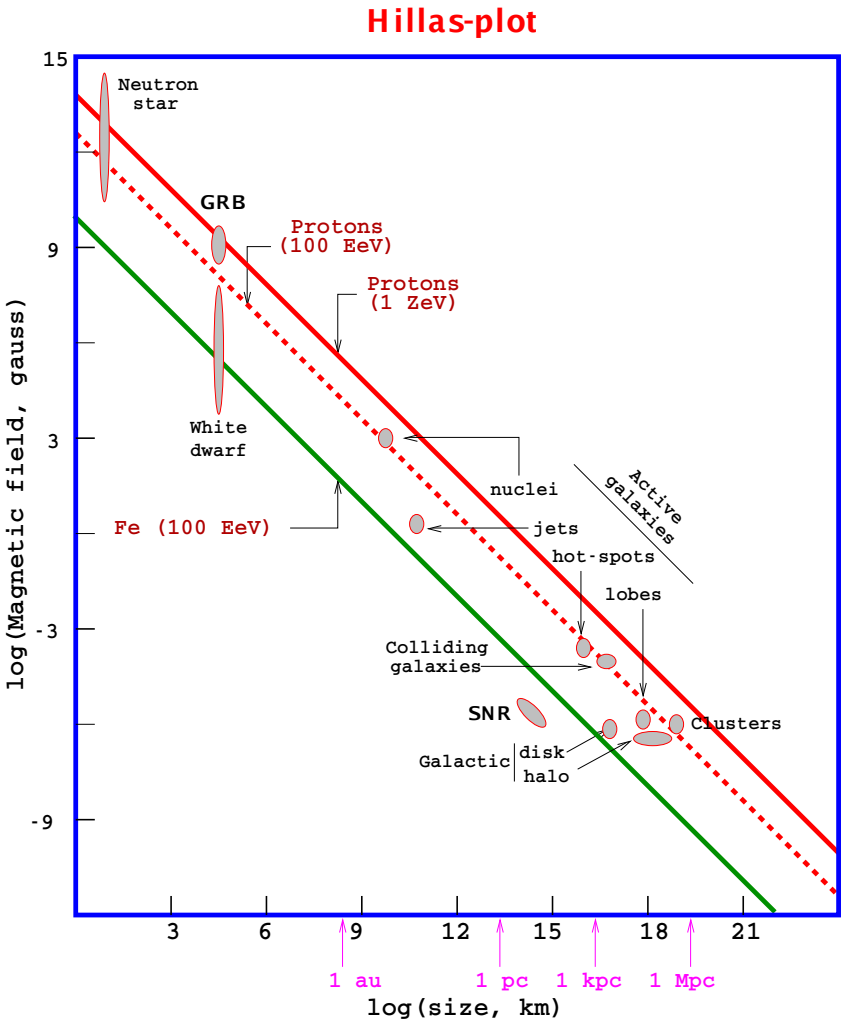
Pierre Auger Observatory





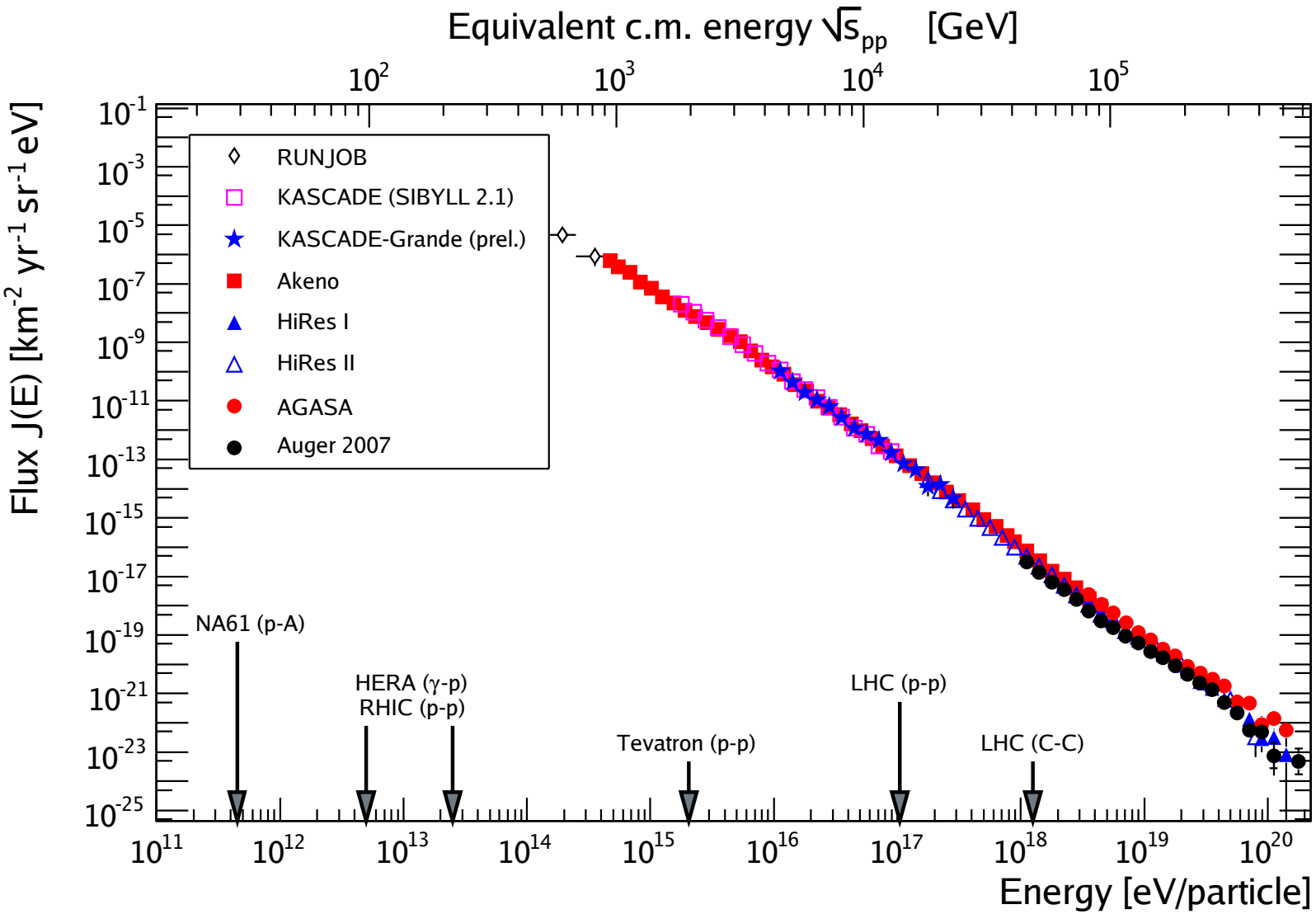
SHINE

What We Look For

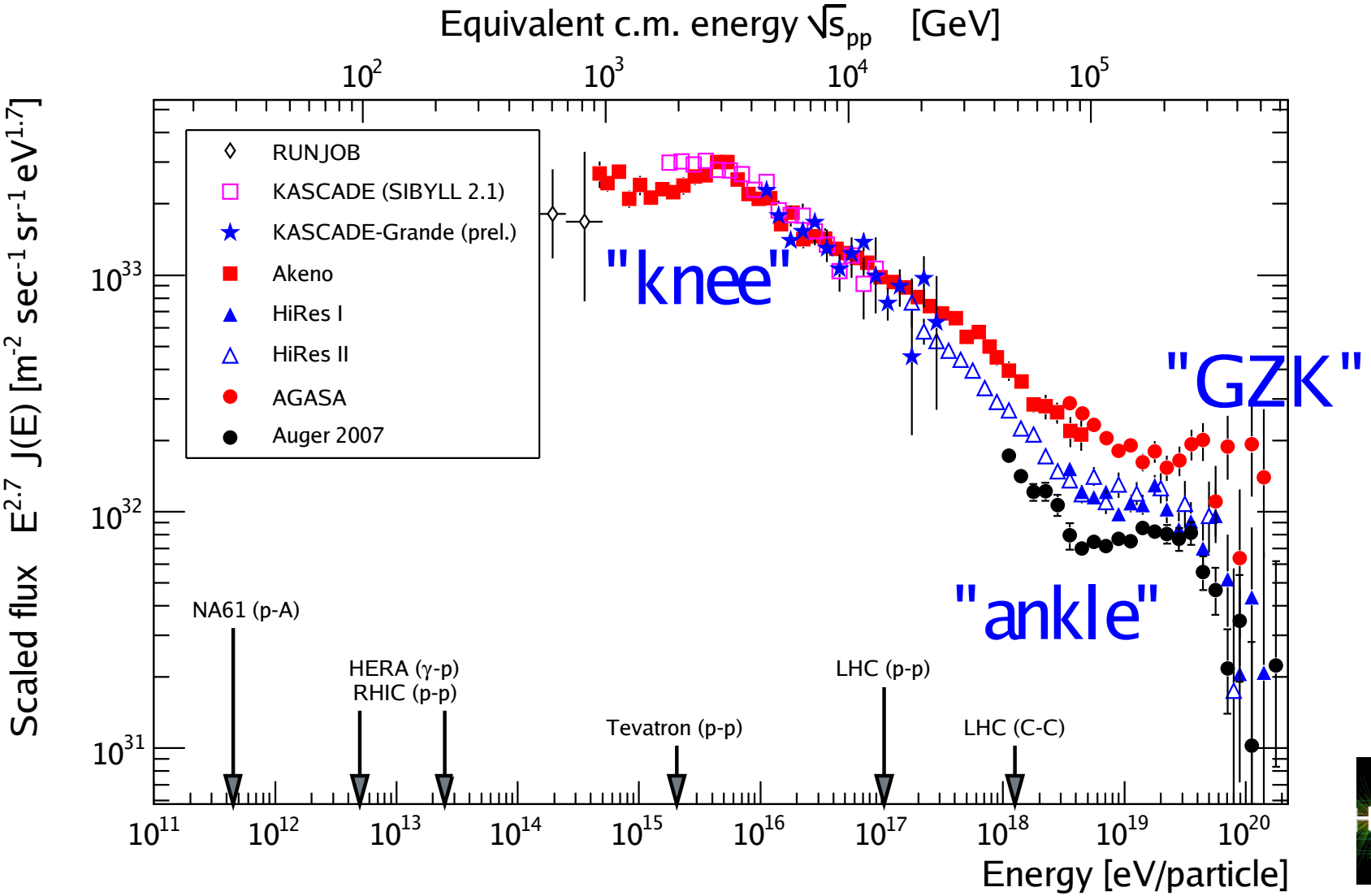


- energy spectrum
- particle species
- *sources!*

Cosmic-ray Energy Spectrum

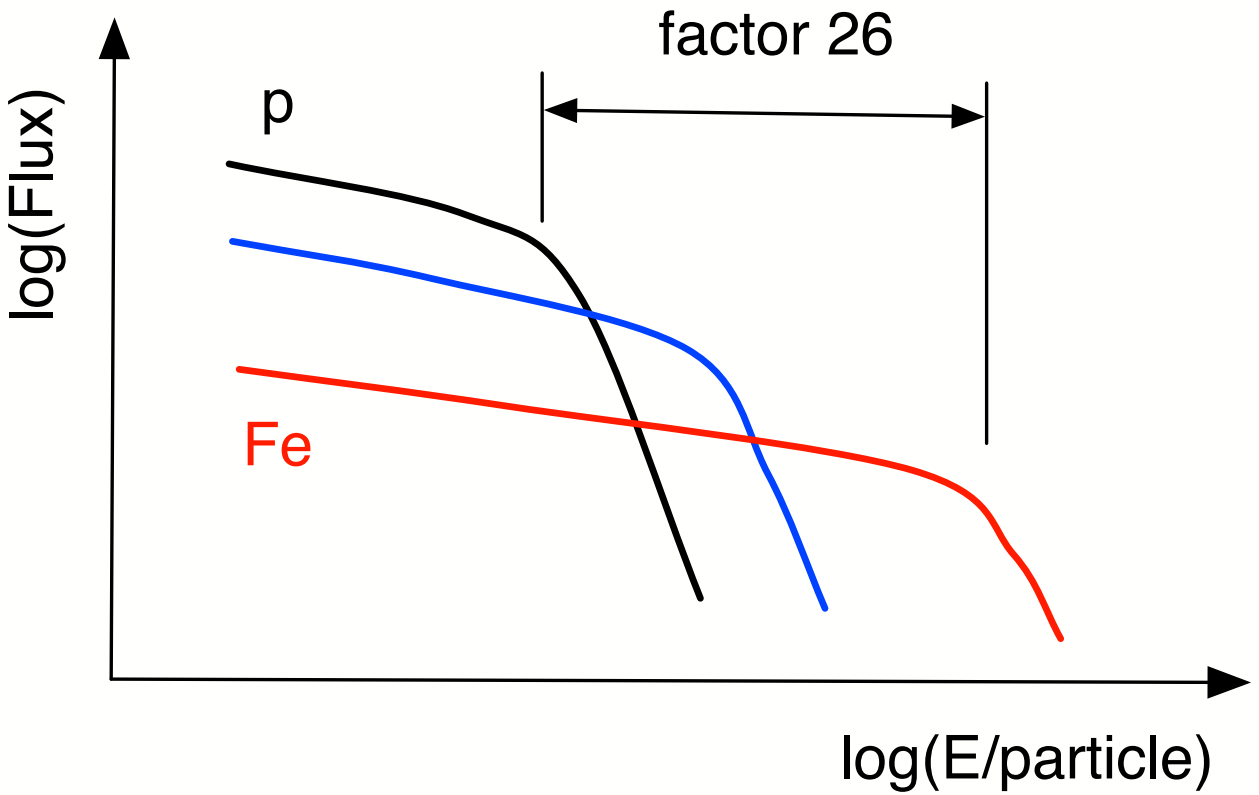


Cosmic-ray Energy Spectrum



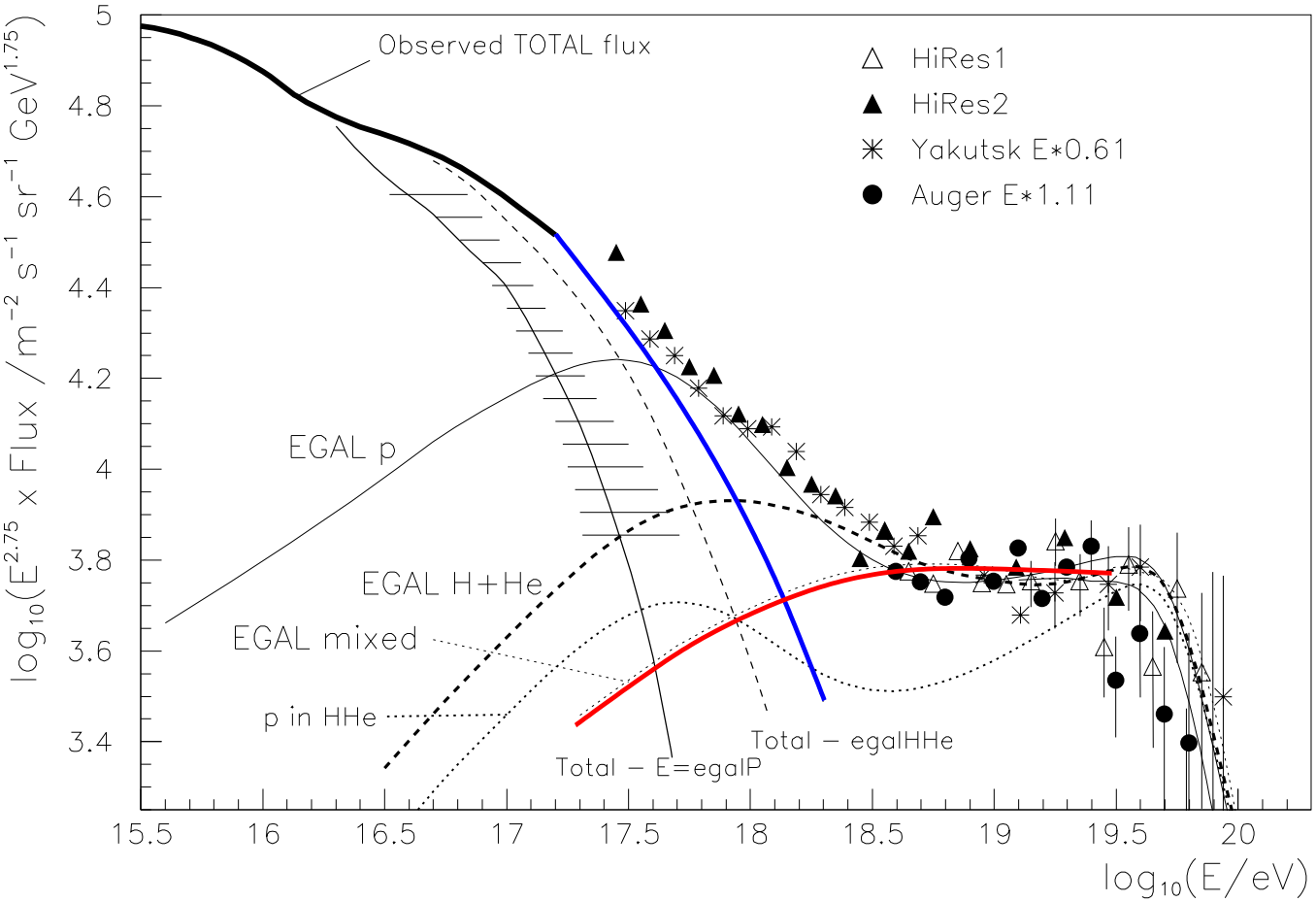
The Knee

Propagation, max. energy of cosmic Pevatrons?



The Ankle

Galactic–extragalactic transition or energy loss?



The Ankle

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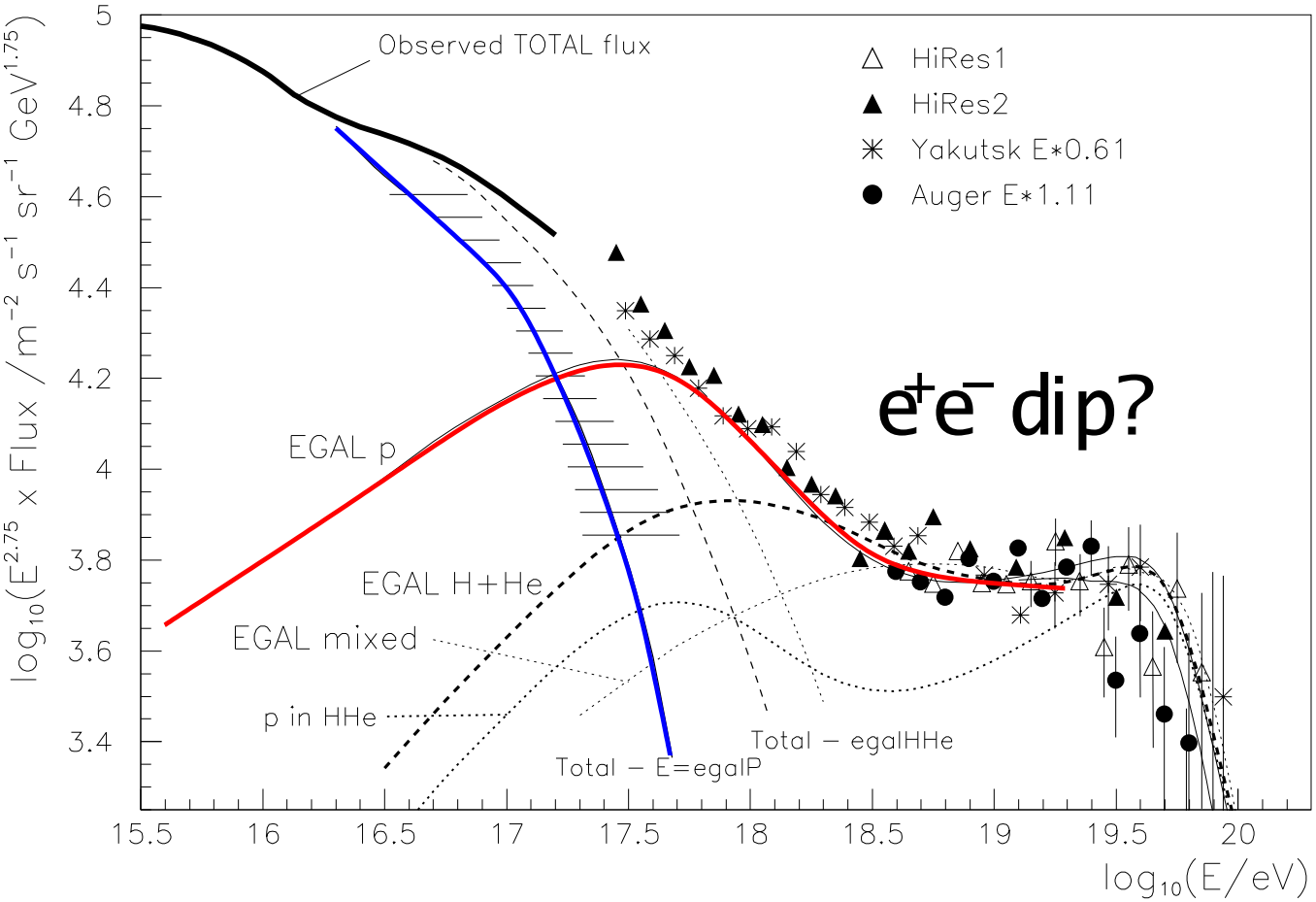
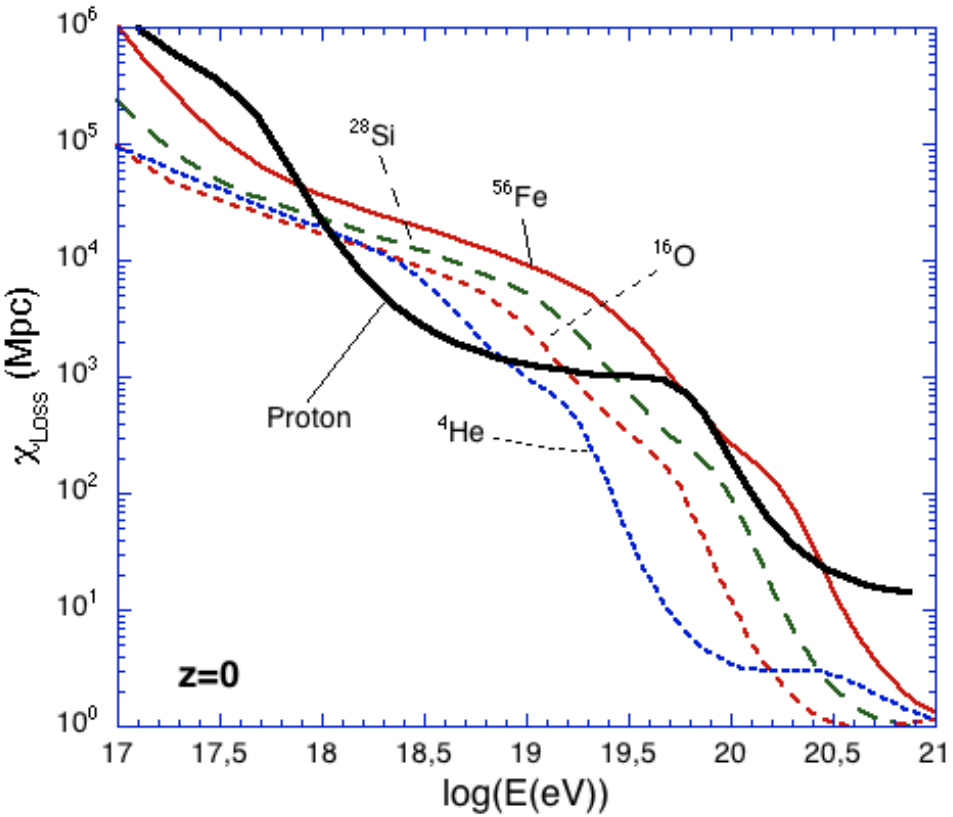


GZK Suppression



D. Allard et al. JCAP, 2006

Cosmic-ray interaction with the microwave background

- energy loss of protons via
  - $p + \gamma_{2.7K} \rightarrow p + \pi^0$
  - $p + \gamma_{2.7K} \rightarrow n + \pi^+$
- photodisintegration of nuclei:
  - $A + \gamma_{2.7K} \rightarrow (A - k) + N_k$

How We Measure It

Ways of measuring air showers:

- Fluorescence telescopes
  - longitudinal development
  - calorimetric
  - require moonless nights ($\tau \approx 13$ %)
- Surface arrays
  - lateral distributions
  - particle densities
  - ($\tau \approx 100$ %)
- Surface calorimeters
  - shower-core energy
- Digital radiotelescopes
  - radio-wave emissions from air showers
  - in (re-)development

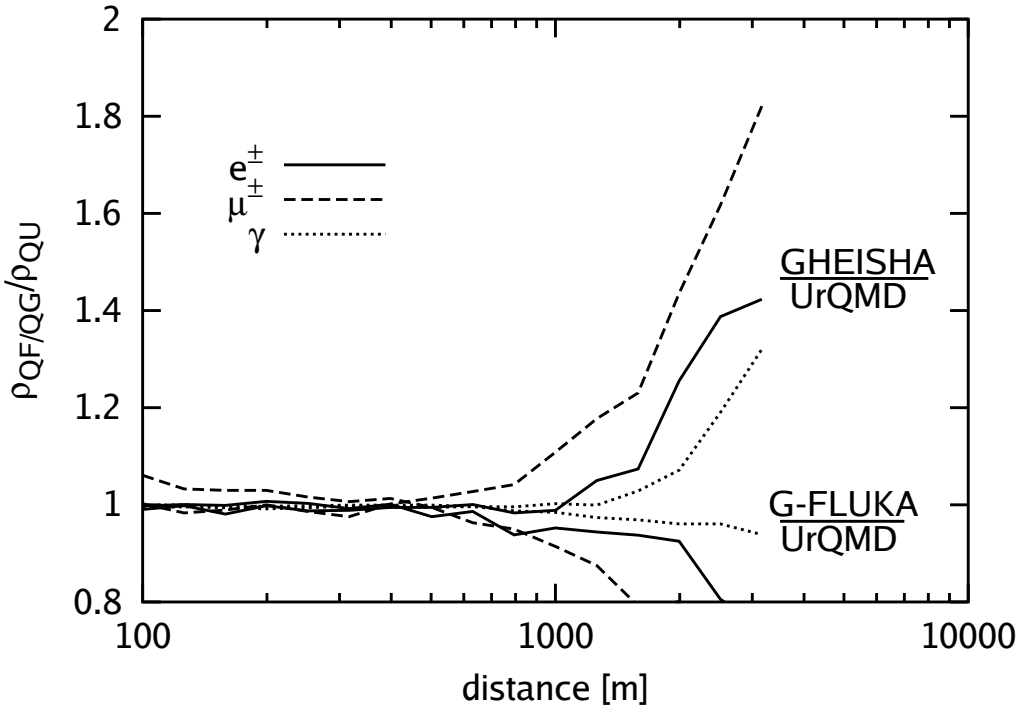
How We Measure It

Example detectors:

- KASCADE — surface array + calorimeter
- KASCADE-Grande — surface array
- LOPES — radiotelescopes
- JEM-EUSO — fluorescence telescope
- Auger — surface array + fluorescence telescopes

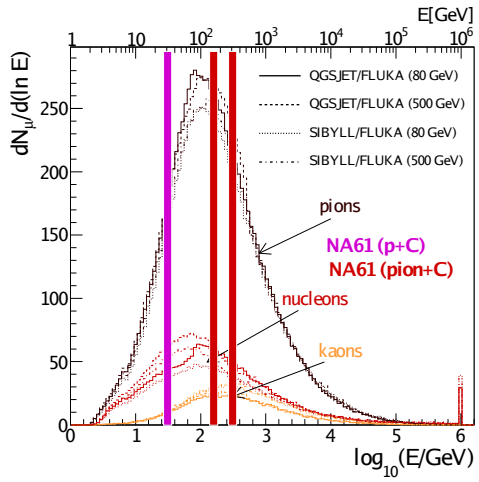
Caveats

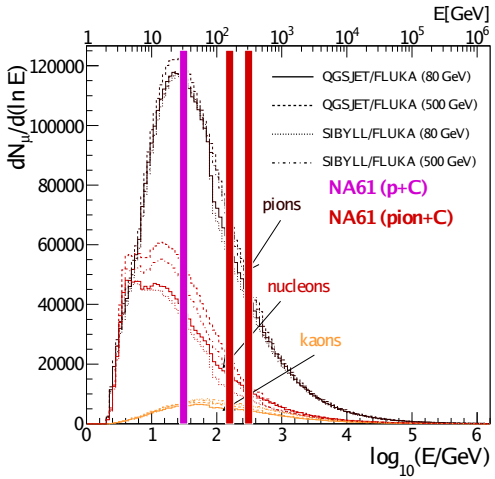
Drescher et al., Astropart. Phys. (2003)



- Hadron production in showers not entirely understood
- Model dependence of muon density!
- Transition between low- and high-energy interaction models
- Need phenomenological calibration!

The Task for NA61





- Primary-level energies not attainable...
- ...but maximum of "grandfather" hadron energy — in the SPS energy range
- Relevant runs:

Projectile	Target	E_{beam} [GeV]	Year
p	C	31	2007
p	C	31	2009
π^-	C	158, 350	2009

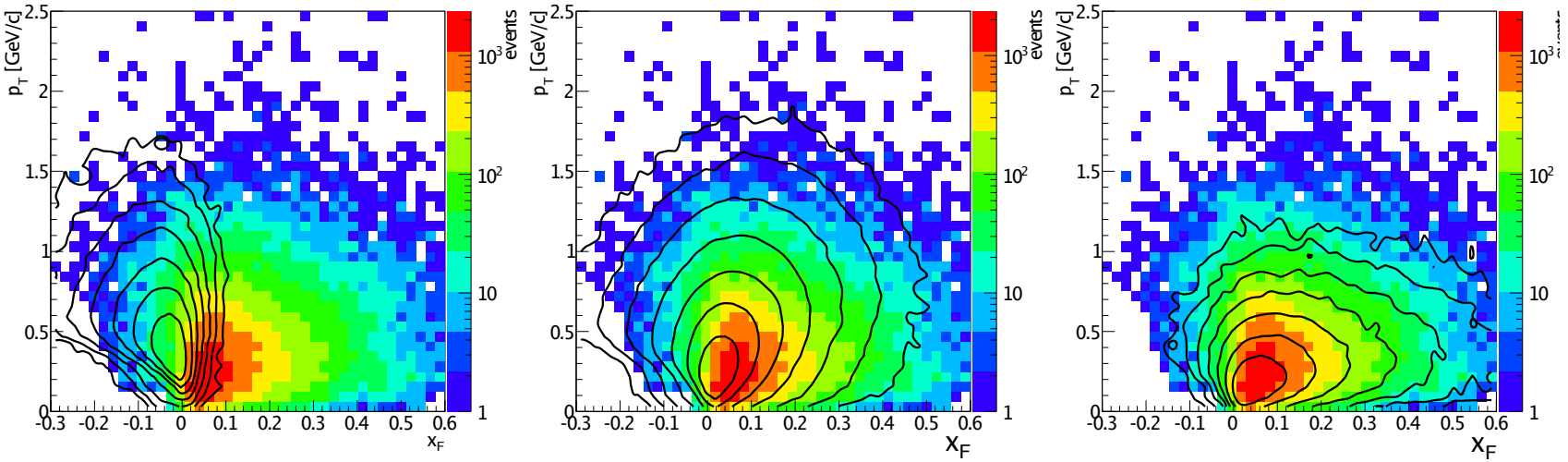
The Task for NA61

158 GeV/c distributions compared with CR-experiment ranges

Auger ($5\ 10^{18}$eV)

KASCADE-Grande ($5\ 10^{17}$eV)

KASCADE (10^{15}eV)

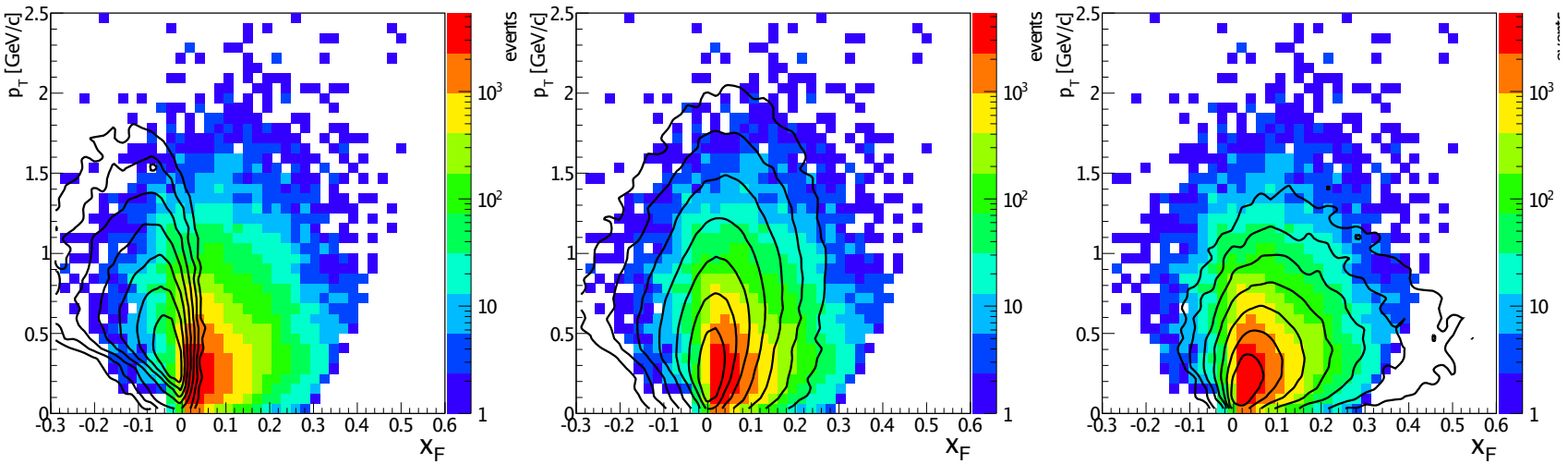


p_T *vs* x_F Colour maps: 2009 data. Black contours: simulations.

The Task for NA61

350 GeV/c distributions compared with CR-experiment ranges

Auger ($5\ 10^{18}$eV) KASCADE-Grande ($5\ 10^{17}$eV) KASCADE (10^{15}eV)



p_T *vs* x_F Colour maps: 2009 data. Black contours: simulations.

The Task for NA61

350 GeV/c distributions compared with CR-experiment ranges

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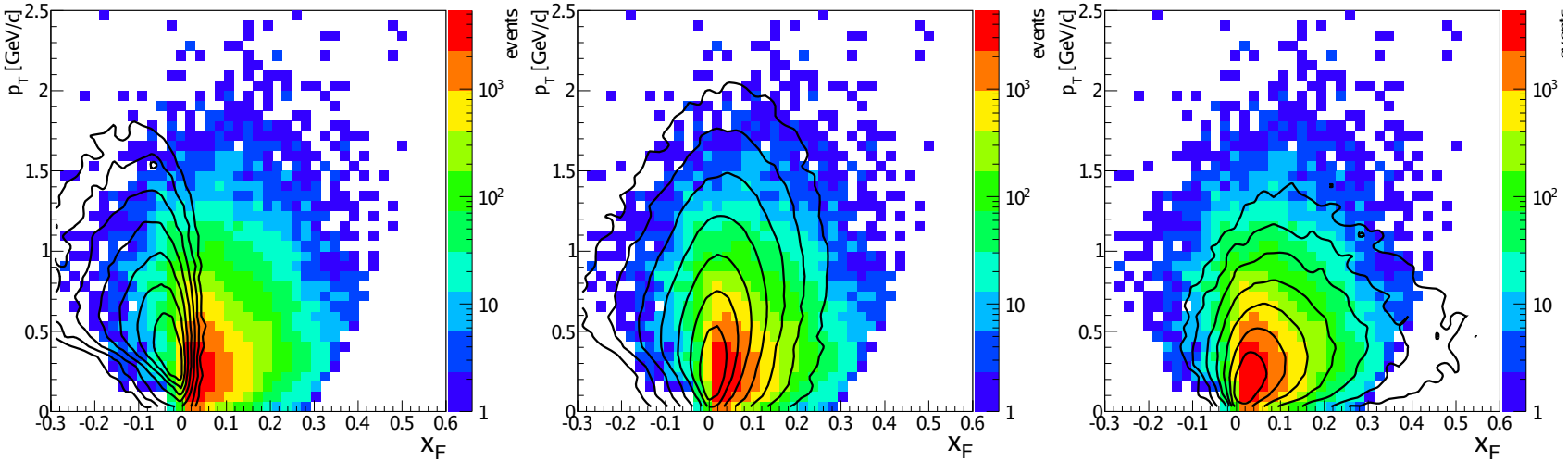


p_T *vs* x_F Colour maps: 2009 data. Black contours: simulations.

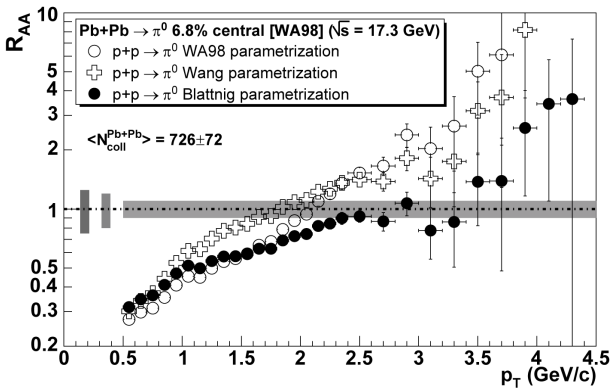
NA61 offers good coverage of the region of interest

The Task for NA61

- Our goal: measure inclusive hadron spectra in p+C and π+C collisions
  - only the latter is cosmic ray-specific
- Status:
  - obtained $h^{\pm}$ spectra for both energies
  - to be released soon, pending final cross-checks and model comparison

Outline

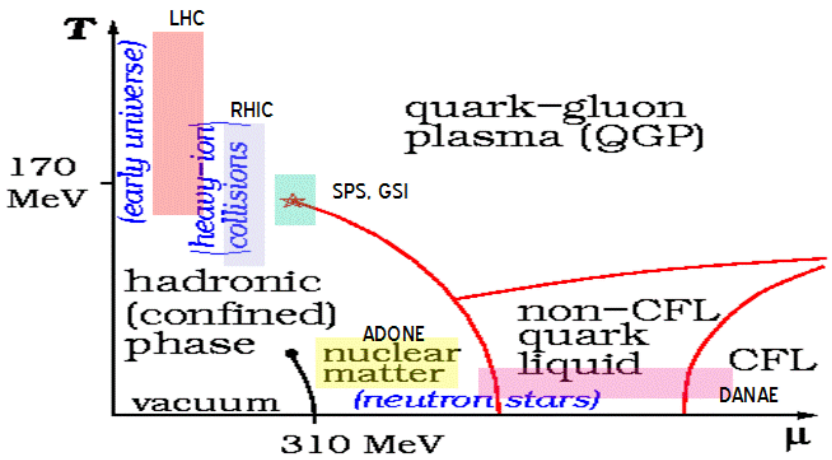
High-p_T, p+p and p+A



- p+p and p+A collisions are important reference systems
  - spectra, N_{coll}, R_{AA}, Cronin effect, ...
- High p_T: insight into the pQCD regime
- Problem: little available data!
  - only 2 % hard scattering at top SPS energy
  - parametrisations introduce model dependency
- Our task: take advantage of our high event rate
  - *e.g.* p+p at 158 GeV — 50 million events!

Outline

QCD Phase Diagram

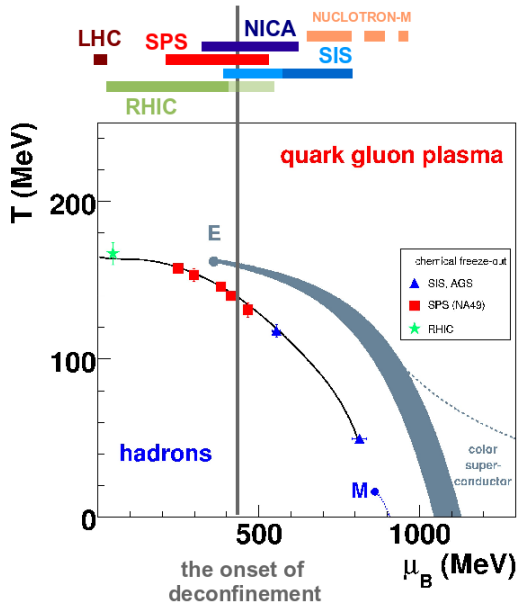


- The critical point of the hadronic–deconfined phase transition is now believed to occur at mid SPS energies
- Onset of deconfinement visible in NA49 data
- More detailed scans:
  - NA61/SHINE
  - Beam Energy Scan at the RHIC
  - Upcoming programmes at FAIR GSI and JINR

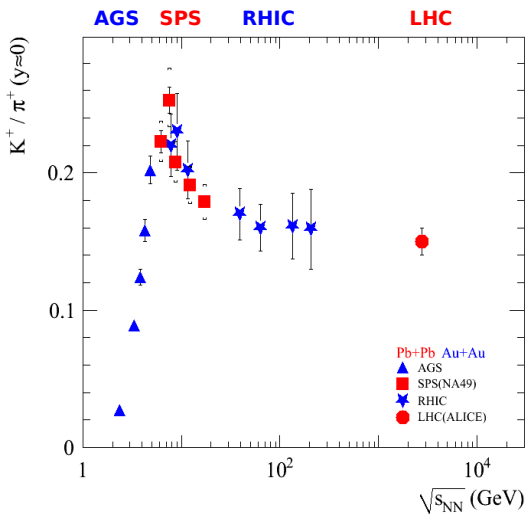
Phase-diagram Scan — Other Experiments

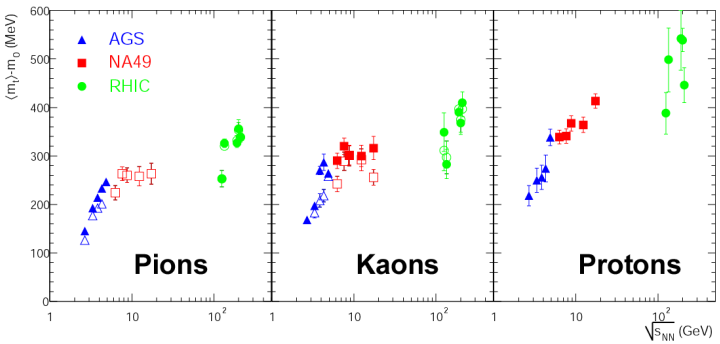
Facility	SPS	RHIC	Nuclotron-M	NICA	SIS-100	SIS-300	LHC
Laboratory	CERN Geneva	BNL Brookhaven	JINR Dubna	JINR Dubna	FAIR GSI Darmstadt	FAIR GSI Darmstadt	CERN Geneva
Experiment	NA61/SHINE	STAR PHENIX	MB@N	MPD	HADES	CBM	ALICE ATLAS CMS
Start	2009(11)	2010	2015	2017	2017/18	2019/20	2009
$\sqrt{s_{NN}}$ [GeV]	5.1–17.3	7.5 (5?)–200	$<\sim$3.5	4–11	2.3–$\sim$5	$\sim$4.5–8.5	up to 5500 p+p: 900–14000
Physics	CP & OD	CP & OD	HDM	HDM & OD	HDM	CP & OD	PDM

CP — critical point; OD — onset of deconfinement, mixed phase, first-order phase transition; HDM — hadrons in dense matter; PDM — propertiess of deconfined matter



Results from NA49



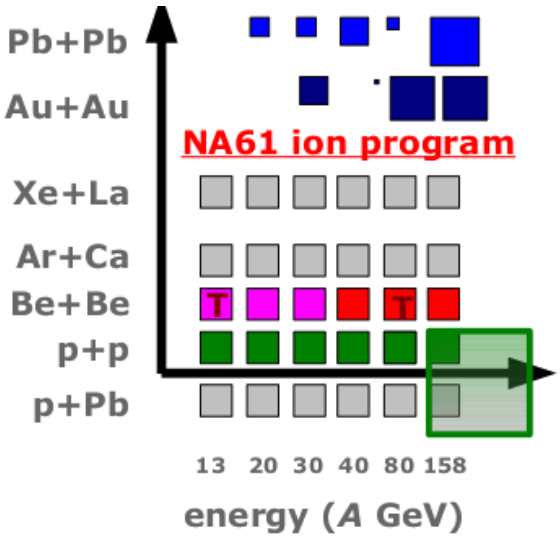


Evidence for the onset of deconfinement:

- Phys.Rev. C77 (2008) 024903
- characteristic spectra properties: horn, kink, step
- result of a one-dimensional (energy) scan
- certain other results inconclusive

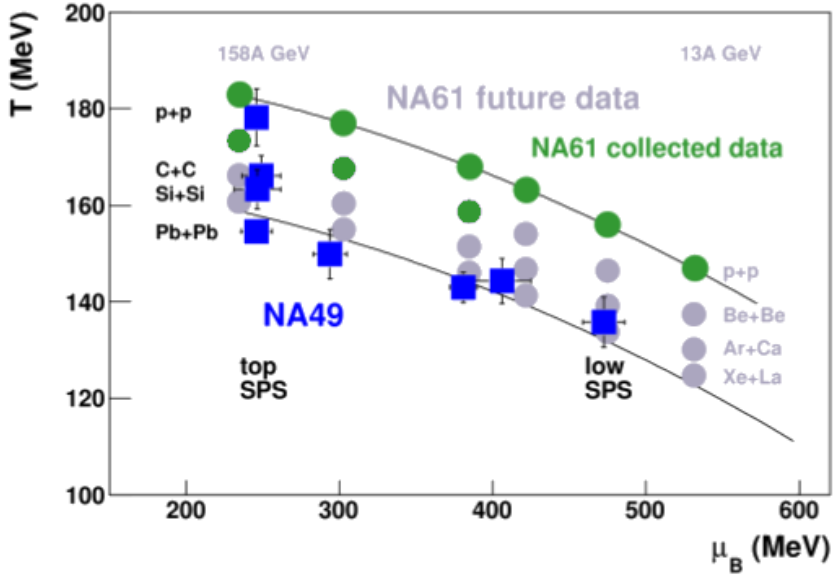
Plans of NA61: extend this scan to two dimensions (energy + system size), with high statistics.

The Two-dimensional Scan



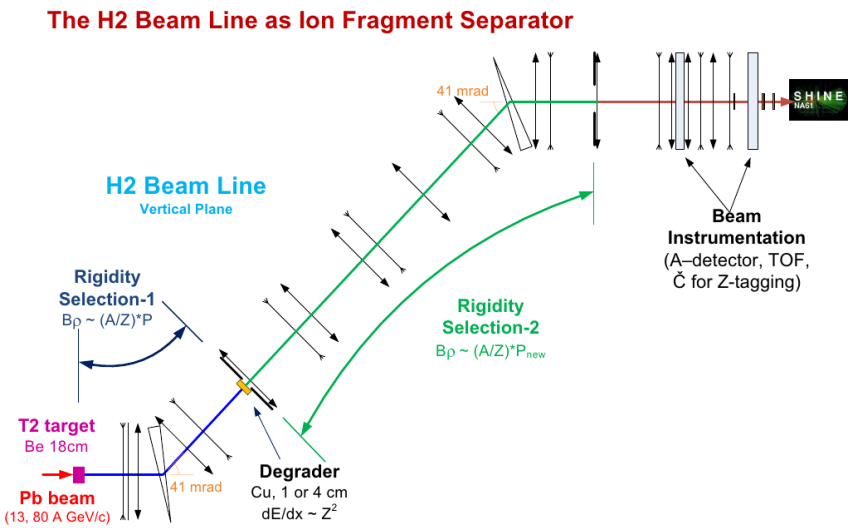
NA49 (1996-2002)
STAR (2008-11)
2015
2014
2010/11/12
2009/10/11
2012/14

T - test of secondary ion beams



Estimated (squares [NA49]) and extrapolated (circles) chemical freeze-out points

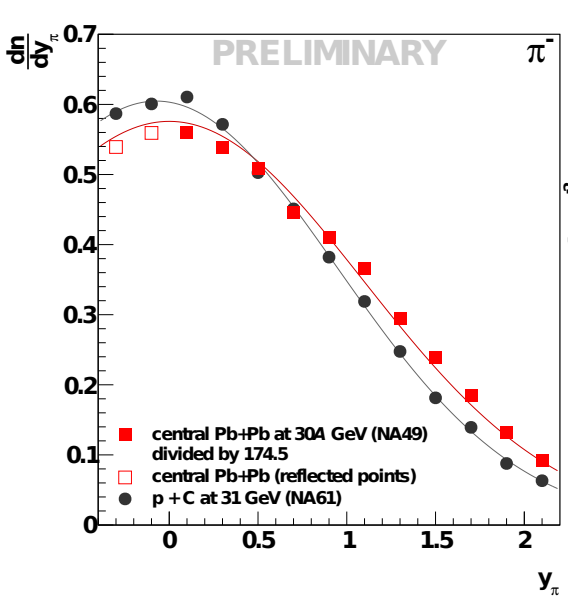
Secondary Ion Beams

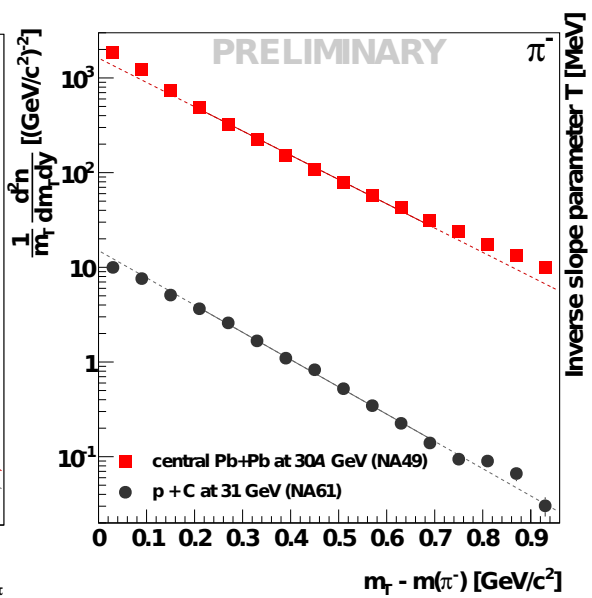


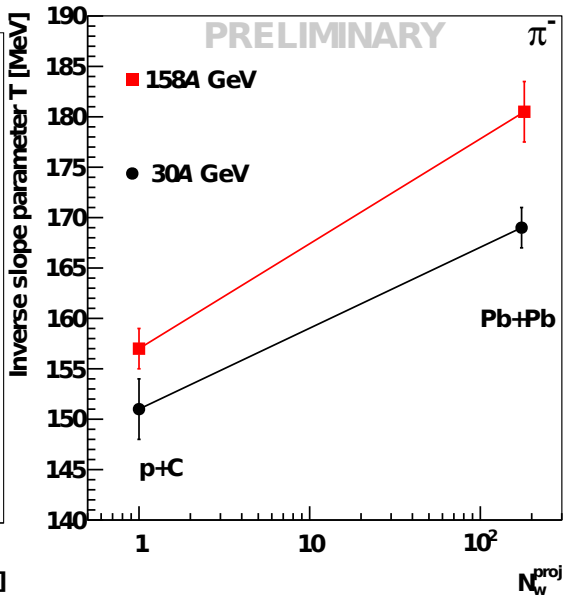
- SPS beams: p and Pb only
  - Ar and Xe to be added soon
- adding new species complicated
- solution for light ions: fragmentation-ion beam line
- 2011 test runs: achieved highly pure, stable ^{7}Be beams at 40A, 75A and 158A GeV/c

Preliminary Results

Additional π^- Spectra from p+C Collisions at 31 GeV

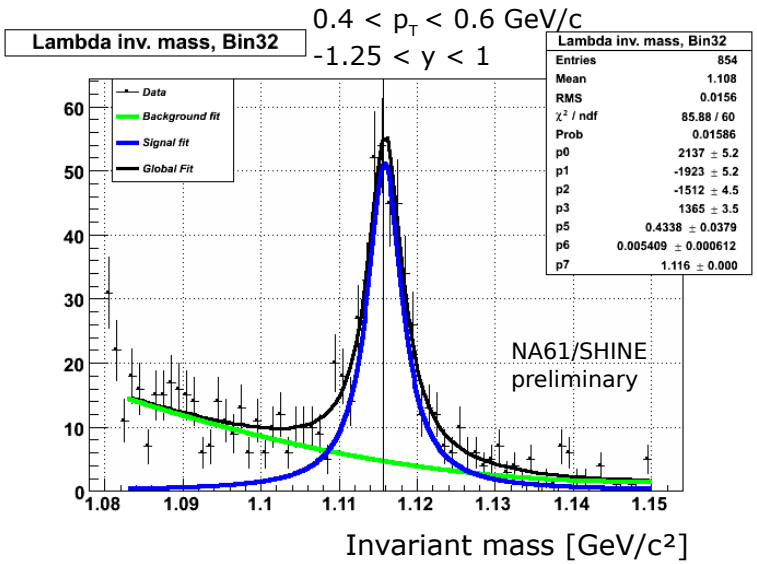


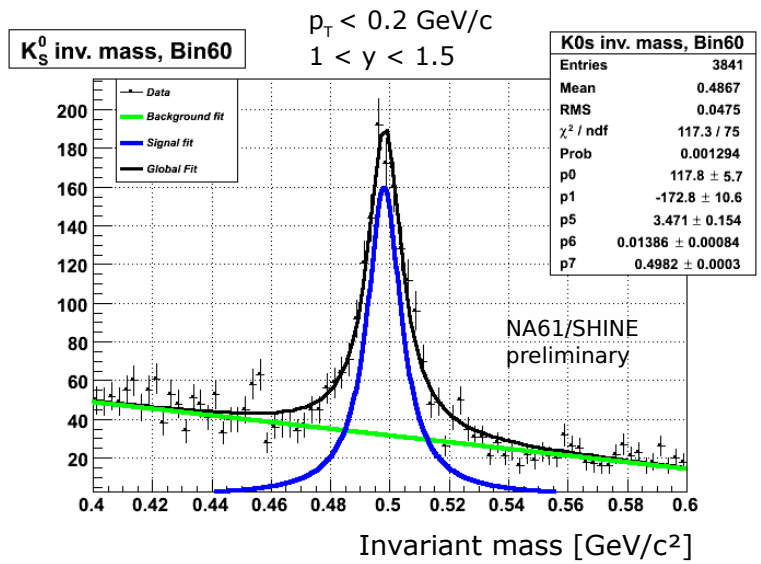


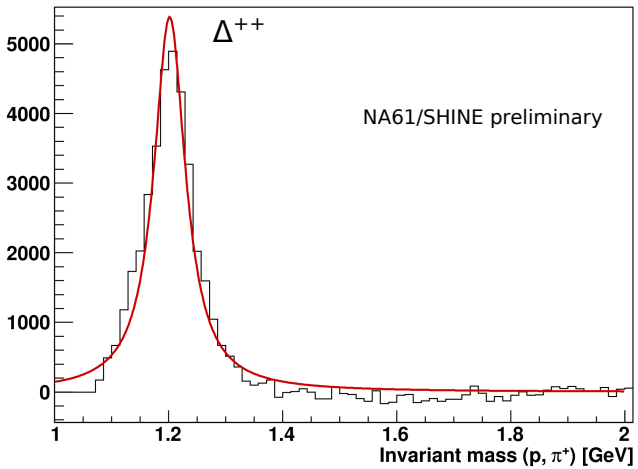


Preliminary Results

Λ, K^0_S and Δ^{++} Yields in p+C Collisions at 31 GeV







Summary

NA61/SHINE shows how much there is still left to study far from the high-energy frontier of the LHC.
We look forward to sharing *many* more results with you in the future!

THANK YOU