First p+p Results from Alice

Graduate Days
Of the Graduate School of Fundamental Physics, Heidelberg
4-8 October, 2010

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Plan for these Lectures

- LHC p+p physics: the usual suspects
  - Standard model, physics beyond the standard model
  - Higgs search, supersymmetric particles, mini black holes, extra dimensions, …
  - Will be largely pursued by ATLAS and CMS
- However, ALICE has some unique p+p physics capabilities
  - Comparison data for heavy-ion program
  - Comprehensive study of minimum bias events:
    ➜ soft & semi-hard QCD
- These lectures aim at providing background and details on the (early) p+p measurements in ALICE

Slides will be available at http://www.physi.uni-heidelberg.de/~reygers/#Teaching
Underlined text in the pdf file is a hyperlink to the referenced material.

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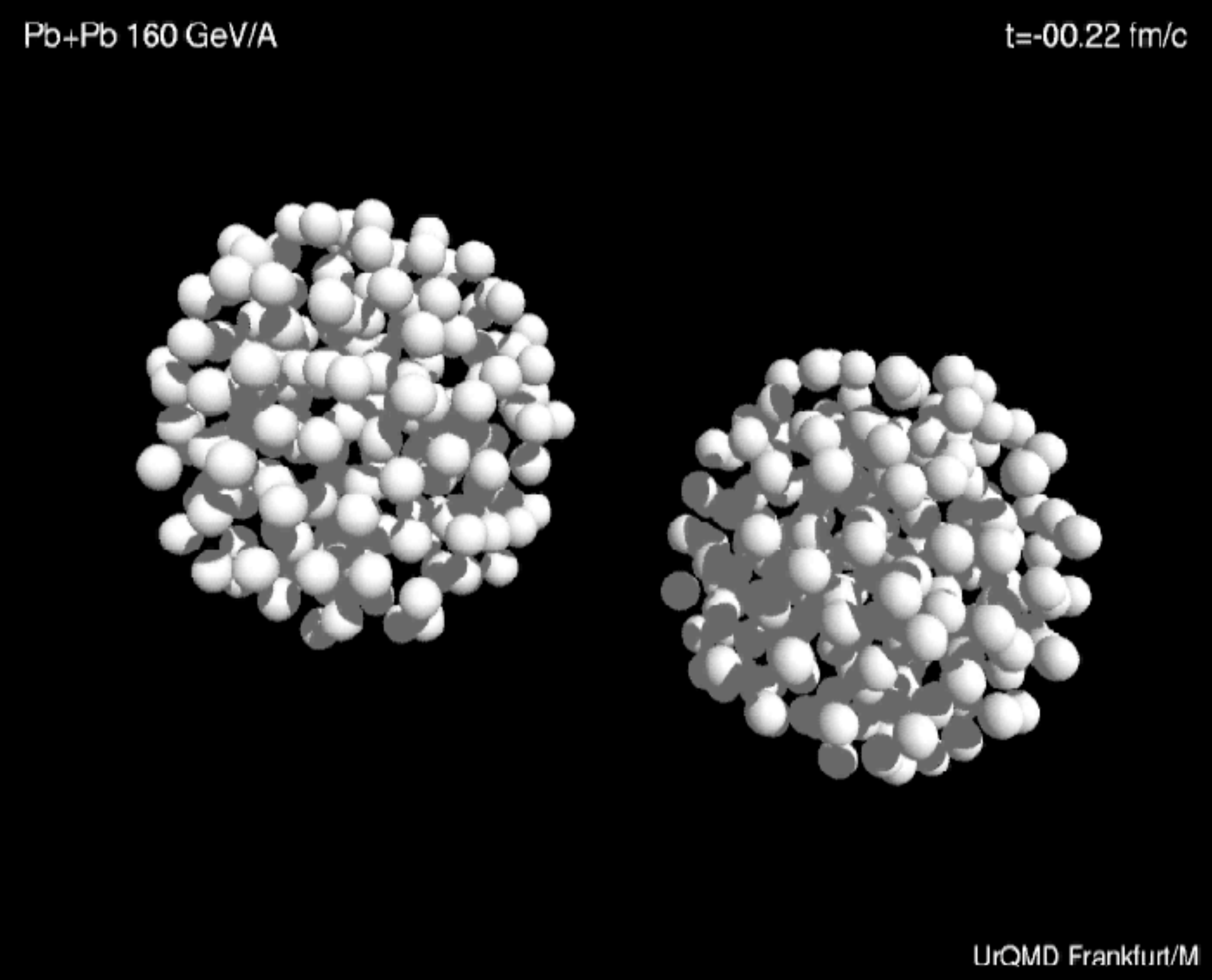
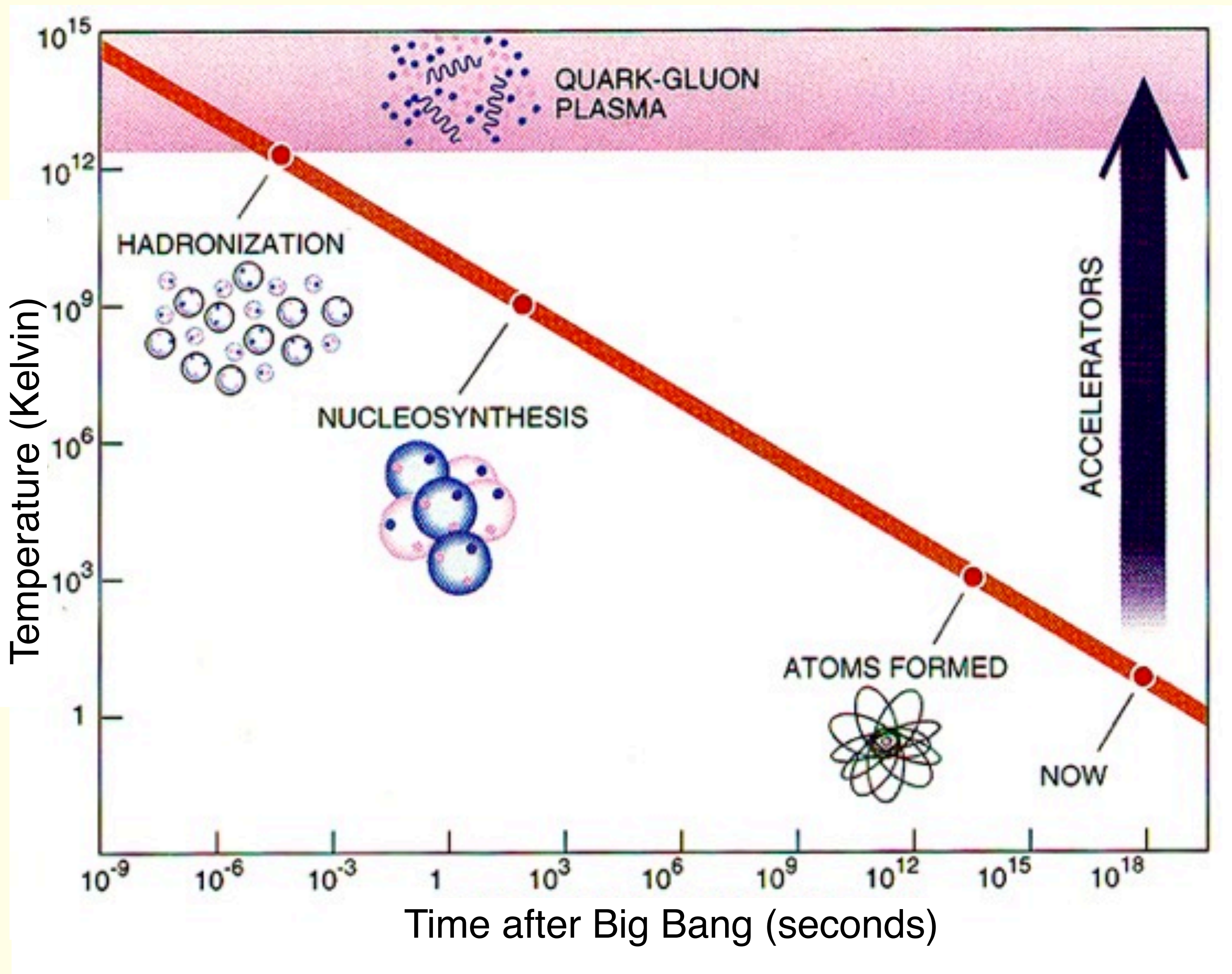
1. Introduction
2. The Alice experiment
3. Average particle multiplicity: $dN_{ch}/d\eta$
4. Charged-particle Multiplicity Distributions
5. Transverse momentum spectra
6. QGP in p+p?
7. pbar/p ratio: baryon transport
8. Strange particle production
9. Outlook: The upcoming heavy-ion run

1. Introduction

Alice's Core Business: Identification and Characterization of the QGP produced in Ultra-Relativistic Nucleus-Nucleus Collisions



Nucleus-Nucleus Collisions: „Mini Big Bang in the Laboratory“



- Transition from the Quark-Gluon Plasma to a gas of hadrons at ~ 10^{12} °C
- 100 000 hotter than the core of the sun
- Early universe: QGP $\rightarrow$ hadron gas a few microseconds after the Big Bang

QCD and Heavy-Ion Physics

Nobel prize in physics (2004)

David J. Gross **H. David Politzer** **Frank Wilczek**

- Confinement:
  Isolated quarks and gluons cannot be observed, only color-neutral hadrons

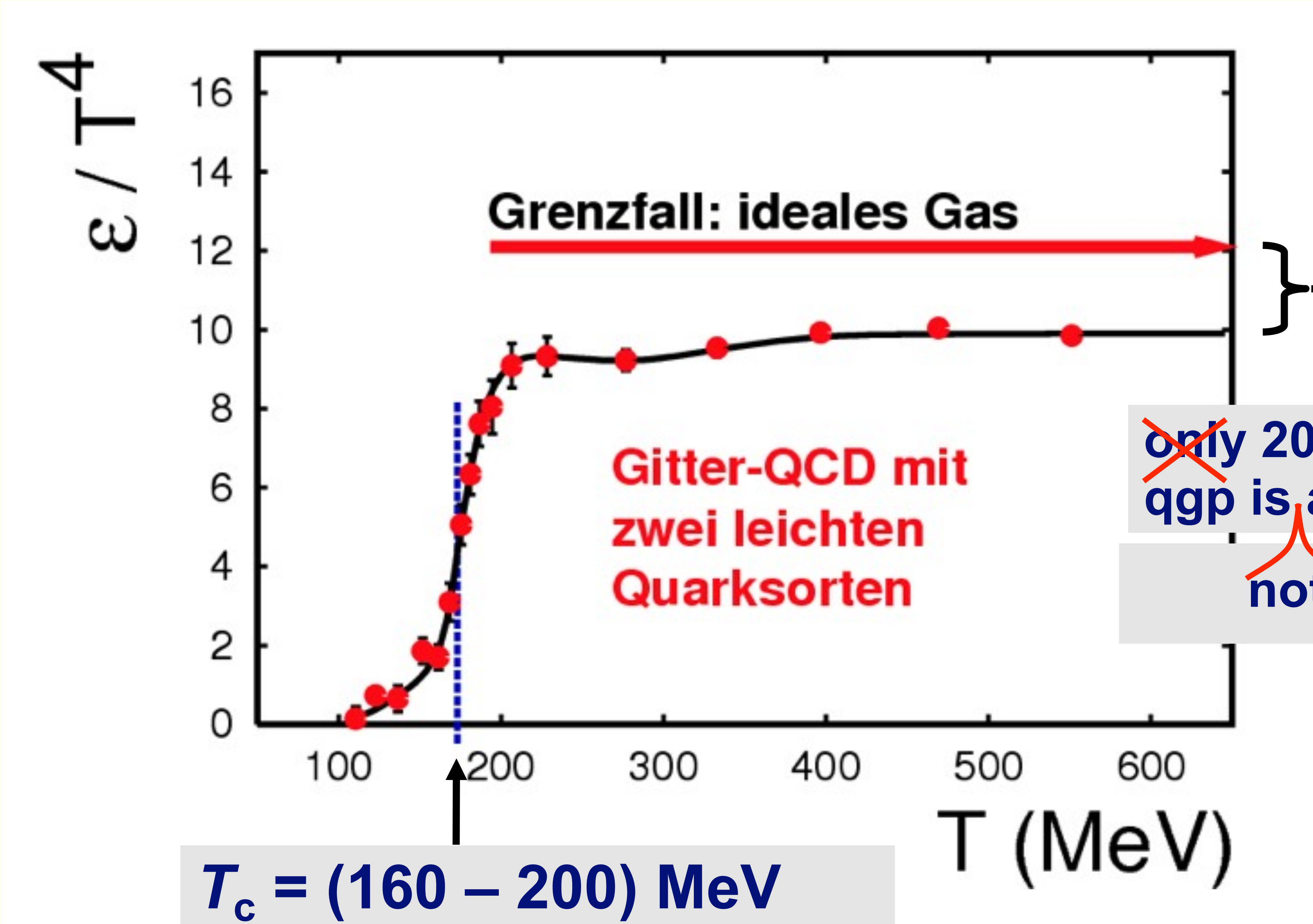
- Asymptotic freedom:
  Coupling α_s between color charges gets weaker for high momentum transfers, i.e., for small distances (Perturbative methods applicable for $r < 1/10$ fm)

- Limit of low particle densities and weak coupling experimentally well tested ($\rightarrow$ QCD perturbation theory)

- Nucleus-Nucleus collisions: High temperature and density limit of QCD („QCD thermodynamics")

Predictions from First Principles: Lattice QCD

F. Karsch, E. Laermann, hep-lat/0305025



2 quark flavors:

$$\varepsilon_{SB} = g \cdot \frac{\pi^2}{30} \cdot T^4$$

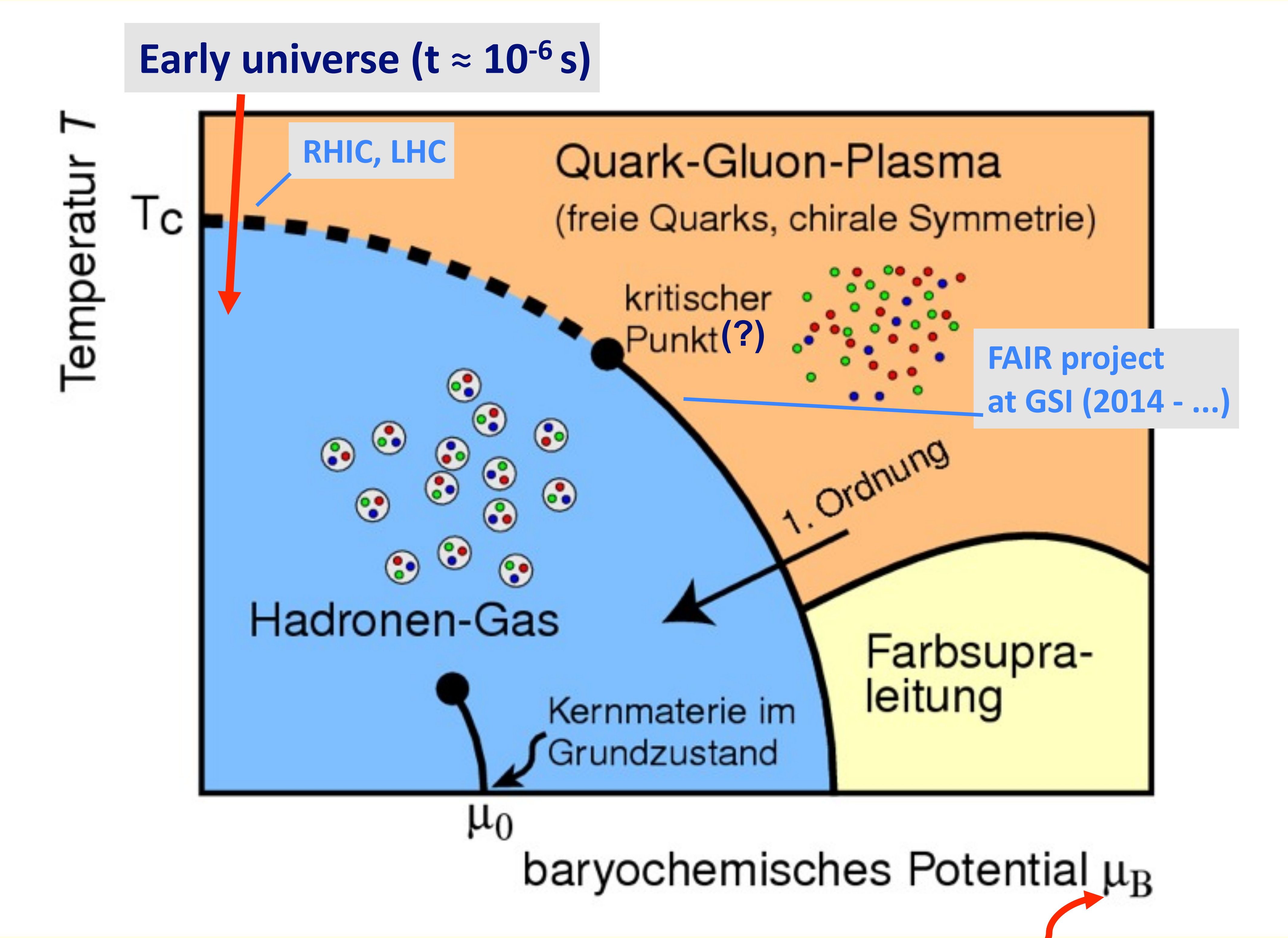
with $g = 37$

~~only~~ 20% deviation:
qgp is not an ideal gas

T_c = **(160 – 200) MeV**

$\varepsilon_c \approx$ **0.7 – 1.0 GeV/fm^3**

Expected QCD Phase Diagram

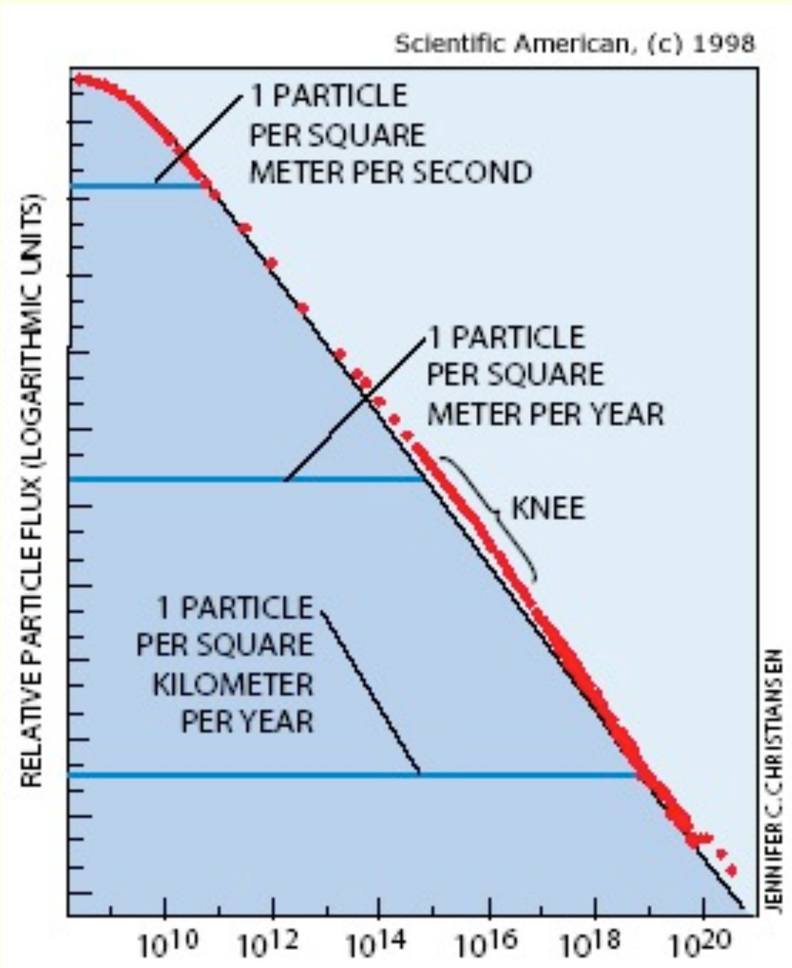


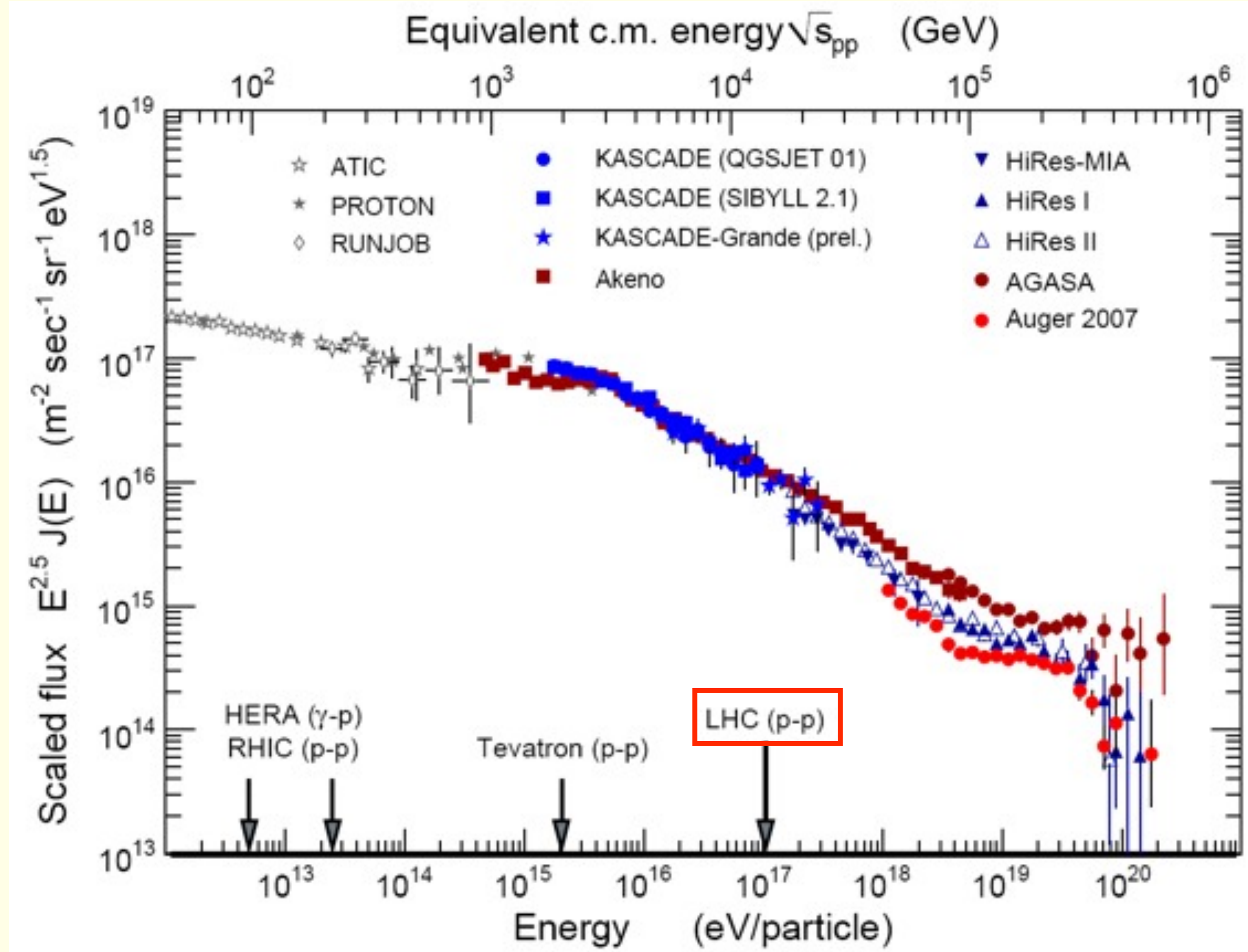
Measure of the net baryon density ρ

Incomplete List of QGP Signatures

- Collective behavior of the produced particle: flow
- Strangeness enhancement relative to p+p
- Yields of different particle species describable with a temperature *T* close to the expected transition temperature (statistical particle production)
- Energy loss of high-energy quarks and gluons: jet quenching
- J/ψ suppression at „lower" $\sqrt{s}$ (including RHIC) turning into a J/ψ enhancement at LHC energies
- Thermal photons reflecting the temperature of the thermalized medium
- ...

Let's turn to p+p Collisions at the LHC:
LHC Energy Compared to Cosmic Rays



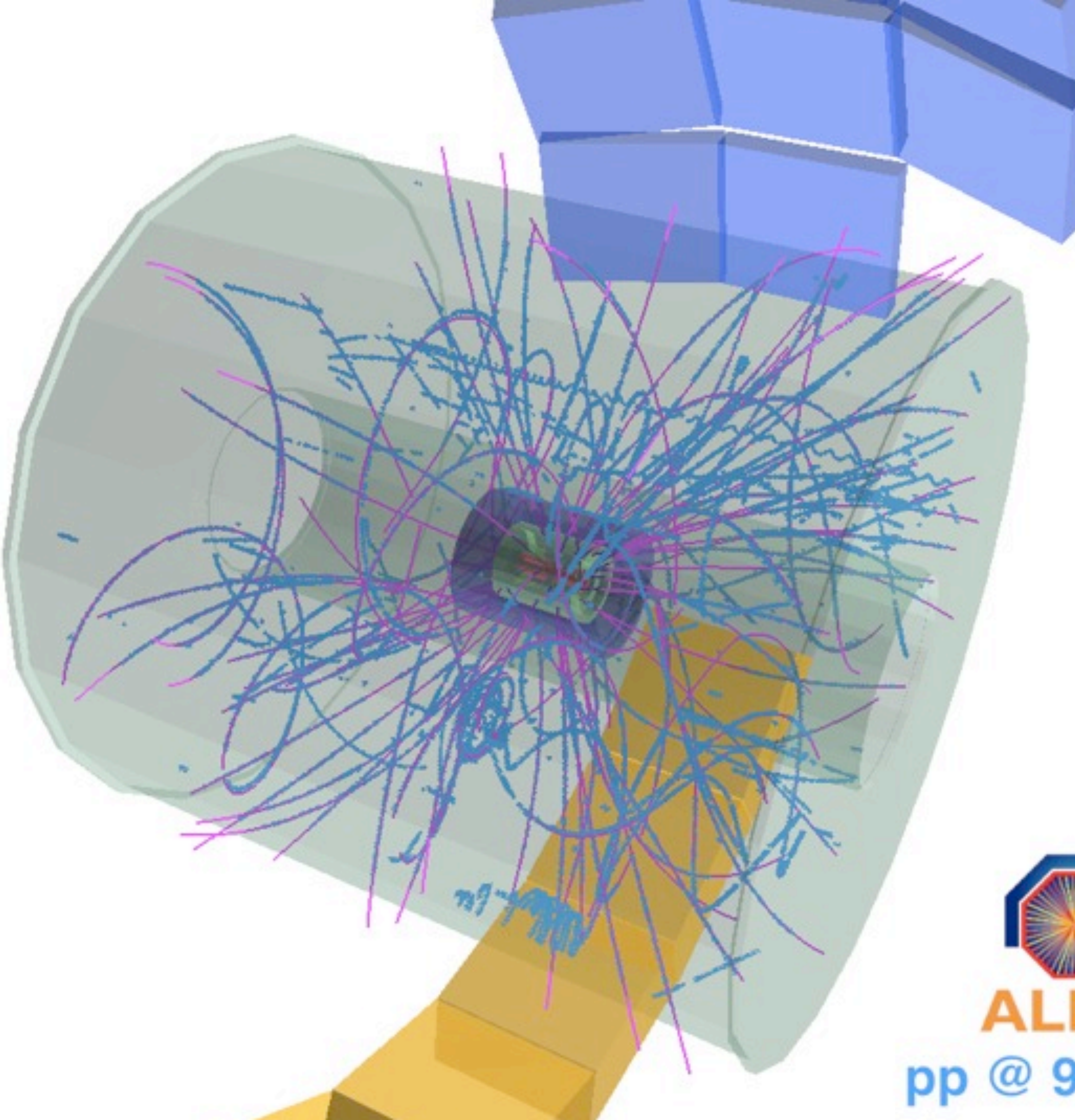


"Fixed Target" Beam energy that corresponds to LHC energy:

$$\sqrt{s} = 14\ \text{TeV} = \sqrt{m_1^2 + m_2^2 + 2E_1^{lab} m_2}$$

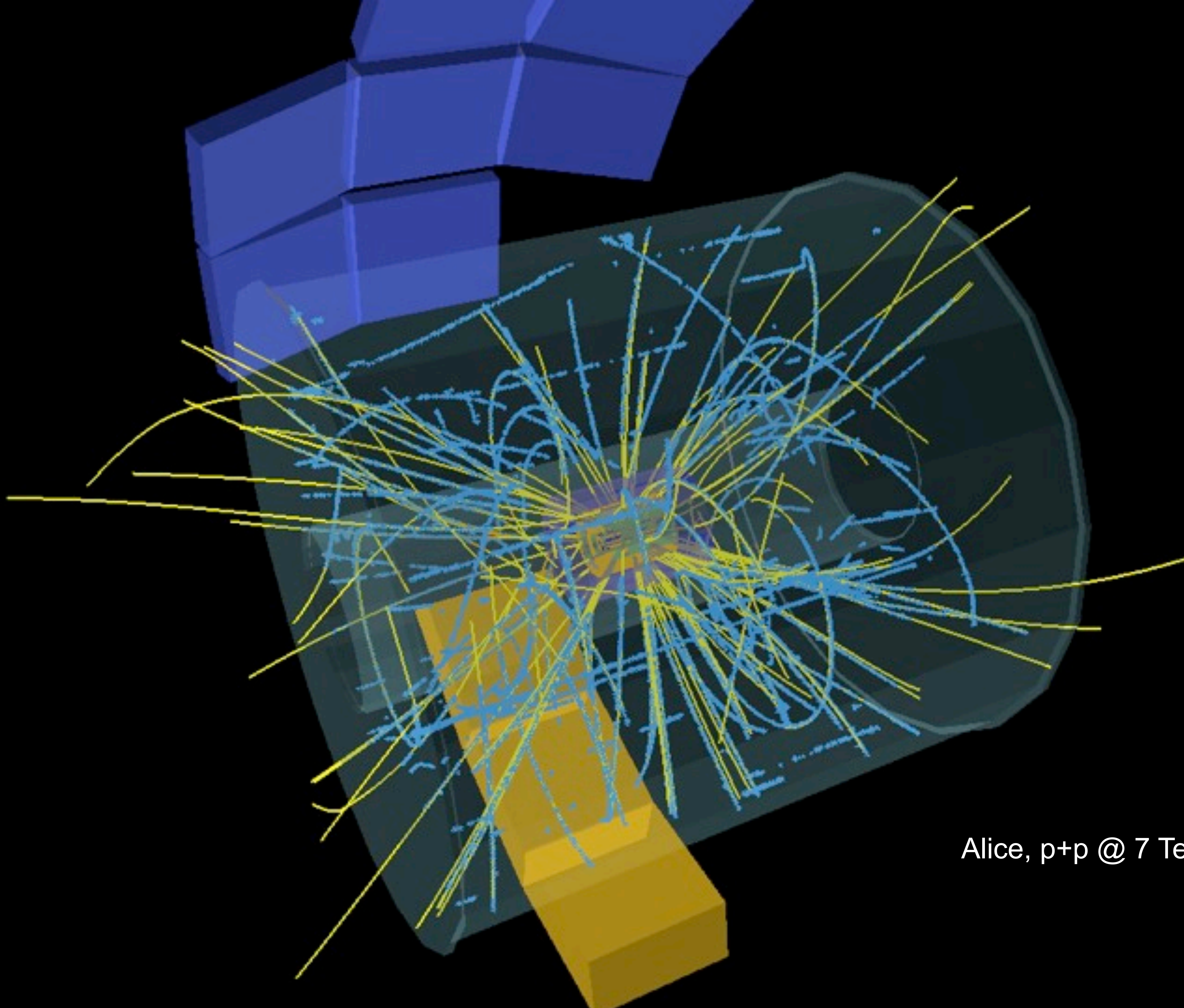
$$\overset{E_1^{lab} \gg m_1, m_2}{\approx} \sqrt{2E_1^{lab} m_2} \rightarrow E_1^{lab} \approx 10^{17}\ \text{eV}$$

For billions of years Nature has been producing collisions in the LHC energy regime



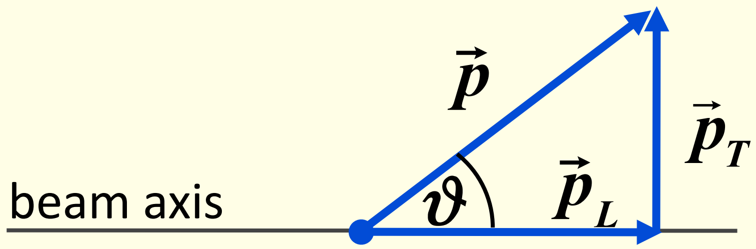
ALICE

pp @ 900 GeV



Alice, p+p @ 7 TeV

Reminder:
Rapidity, Pseudorapidity, Transverse Momentum



$$p = \sqrt{p_L^2 + p_T^2}, \quad m_T := \sqrt{m^2 + p_T^2}, \quad p_T = p \cdot \sin\vartheta$$

$$y := \frac{1}{2}\ln\frac{E + p_L}{E - p_L} = \frac{1}{2}\ln\frac{1+\beta_L}{1-\beta_L}$$

rapidity

$$y \approx \beta_L \text{ for } \beta_L \ll 1$$

$$e^y = \sqrt{\frac{E+p_L}{E-p_L}}, \quad e^{-y} = \sqrt{\frac{E-p_L}{E+p_L}}$$

$$E = m_T \cdot \cosh y, \quad p_L = m_T \cdot \sinh y$$

$$\beta_L = \frac{p_L}{E} = \tanh y$$

***y* is additive under Lorentz transformation:**

$$y = y' + y_{S'}$$

rapidity in system S

rapidity in S'

rapidity of S' measured in S

Pseudorapidity η:

$$y = \frac{1}{2}\ln\frac{E + p\cos\vartheta}{E - p\cos\vartheta} \overset{p \gg m}{\approx} \frac{1}{2}\ln\frac{1+\cos\vartheta}{1-\cos\vartheta} = \frac{1}{2}\ln\frac{2\cos^2\frac{\vartheta}{2}}{2\sin^2\frac{\vartheta}{2}} = -\ln\left[\tan\frac{\vartheta}{2}\right] =: \eta$$

In particular: $y = \eta \text{ for } m = 0$

Summary: Kinematic Variables

Transverse momentum

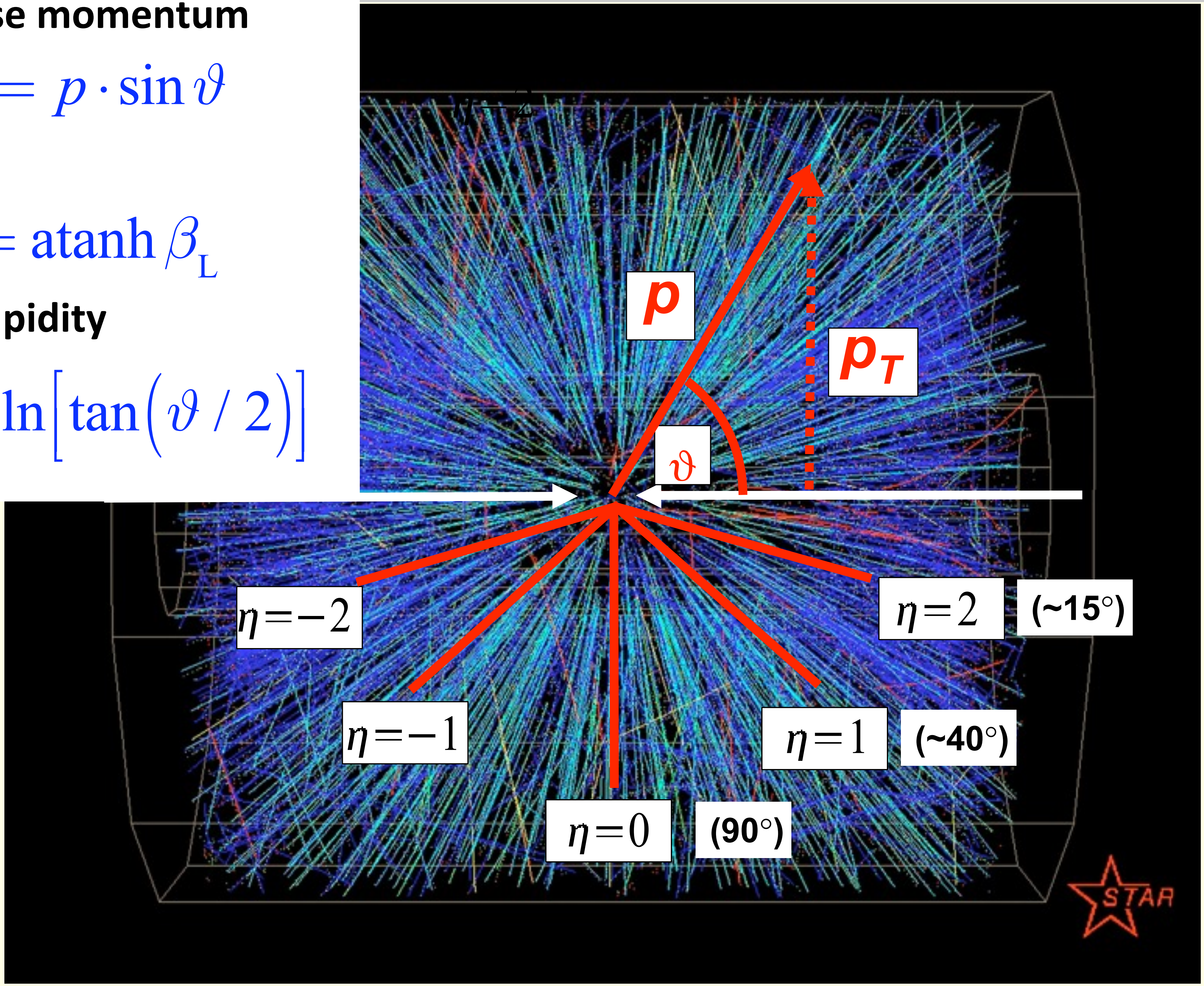
$$p_T = p \cdot \sin \vartheta$$

Rapidity

$$y = \text{atanh}\, \beta_L$$

Pseudorapidity

$$\eta = -\ln\left[\tan\left(\vartheta / 2\right)\right]$$



p+p Physics with ALICE

ALICE is the only dedicated heavy-ion experiment at the LHC.
ALICE has several features that also make it an important contributor to p+p physics at the LHC

- Particle identification and tracking over a broad momentum range
  - 100 MeV/c < p_T < 100 (or more) GeV/c
  - Very low-p_T cut-off: Unique for studying low p_T phenomena due to small magnetic field (B = 0.5 T) and low material budget (~ 10% X_0 on average between the vertex and the active volume of the TPC)
    (cf. ATLAS: B = 2 T at the center, CMS: B = 3.8 T)
  - Important for minimum bias physics and understanding of the underlying event in specialized searches, e.g. Higgs search.
    Access to very low Bjorken-x (down to $x \sim 10^{-5} - 10^{-6}$)
    (cf. HERA: $x \sim 10^{-4}$ for Q^2 in the perturbative regime of several GeV^2)
- Excellent determination of secondary vertices
  (e.g., reconstruction of particles containing c- and b quarks)

Alice Physics Papers (as of October 2010)

- First proton-proton collisions at the LHC as observed with the ALICE detector: Measurement of the charged particle pseudorapidity density at $\sqrt{s}$ = 900-GeV, Eur.Phys.J.C65:111-125,2010

  } $dN_{ch}/d\eta$

- Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s}$ = 0.9 and 2.36 TeV with ALICE at LHC, Eur.Phys.J.C68:89-108,2010.
- Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s}$ = 7 TeV with ALICE at LHC, Eur.Phys.J.C68:345-354,2010.

  } $dN_{ch}/d\eta$ and multiplicity distributions

- Midrapidity antiproton-to-proton ratio in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV measured by the ALICE experiment, Phys.Rev.Lett.105:072002,2010

  } $\bar{p}/p$ ratio

- Transverse momentum spectra of charged particles in proton-proton collisions at $\sqrt{s}$ = 900 GeV with ALICE at the LHC, Phys. Lett. B 693 (2010) 53-68

  } high p_T charged hadrons

- Two-pion Bose-Einstein correlations in pp collisions at $\sqrt{s}$ = 900 GeV, arXiv:1007.0516

  } HBT

Access to Published Alice Data: HepData

http://hepdata.cedar.ac.uk/reaction

The Durham HepData Project

Durham University

REACTION DATABASE • DATA REVIEWS • PARTON DISTRIBUTION FUNCTION SERVER • OTHER HEP RESOURCES

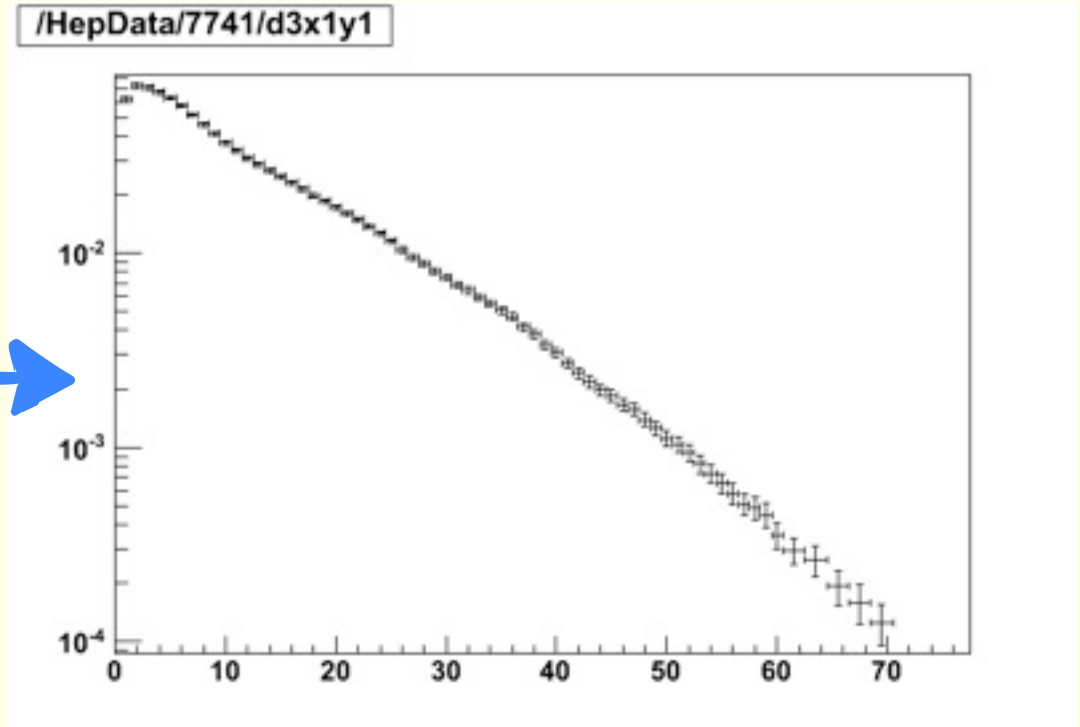
Reaction Database Search Result

Search: **exp alice**
Result: **6** documents found (displaying **1** to **6**)

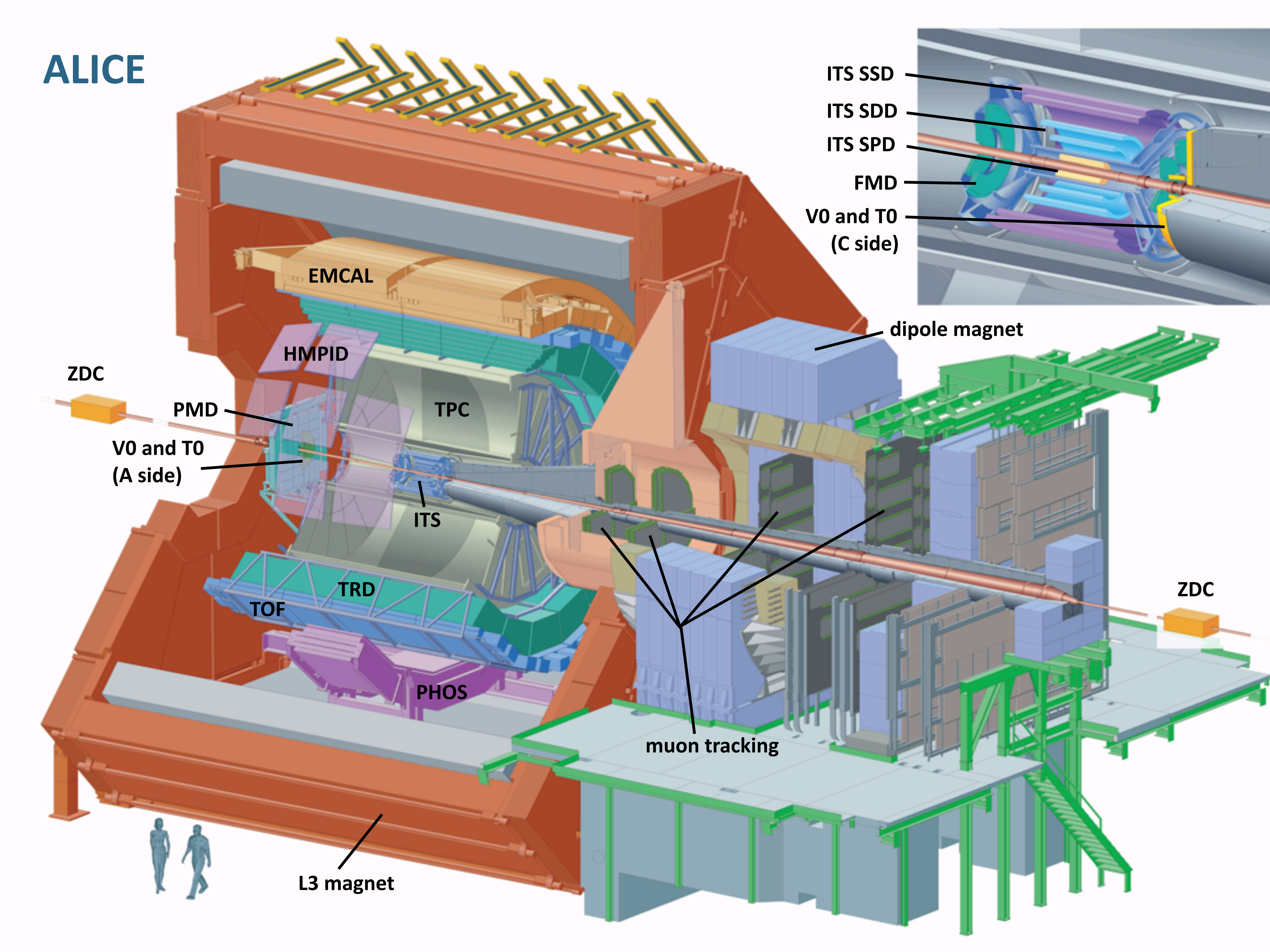
Enter query: exp alice [Search again]

...need help with searching?

- Data available as plain text files and root macros
- Example: Alice multiplicity distribution in p+p at 7 TeV plotted root macro created automatically by HepData

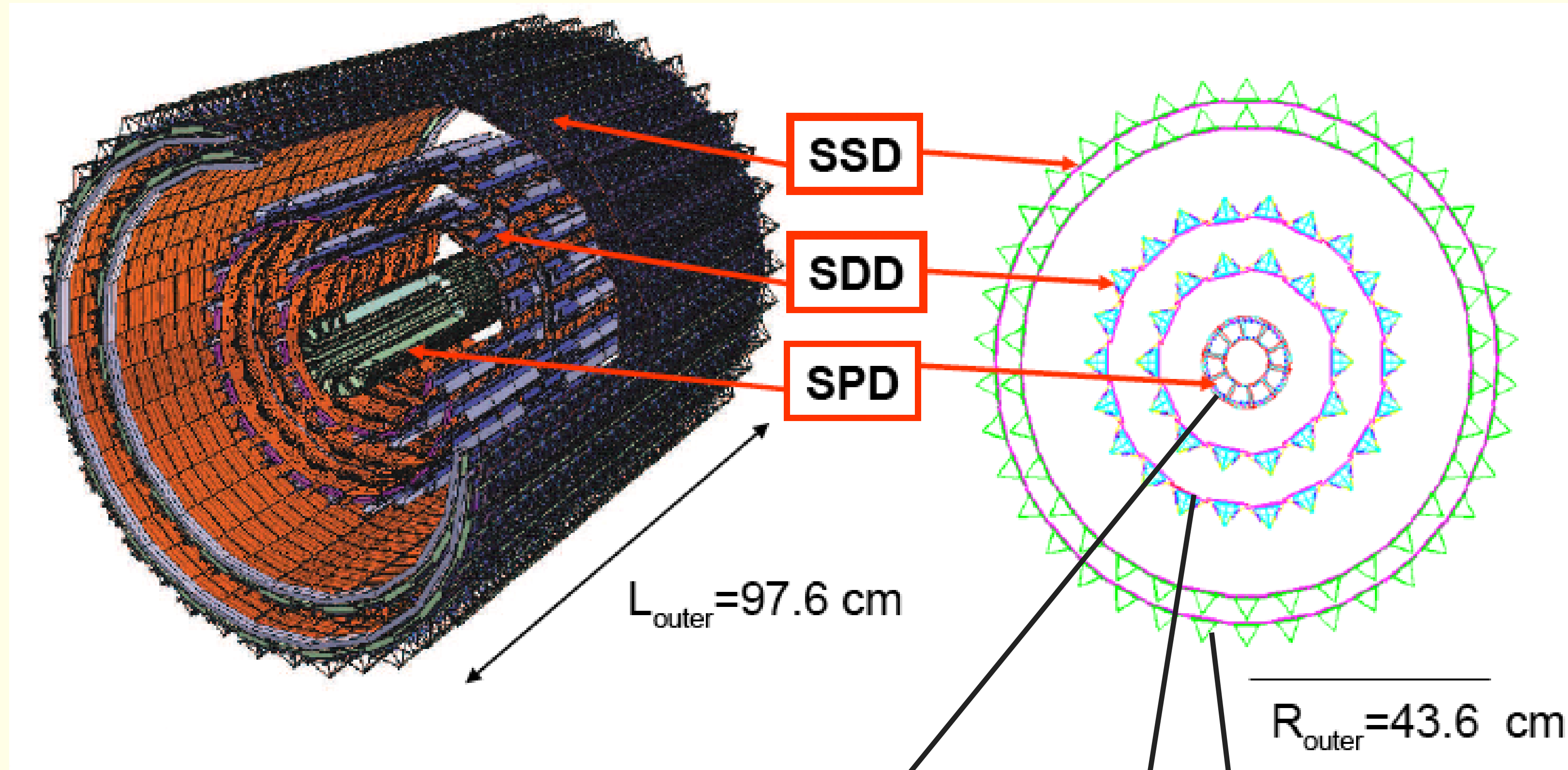


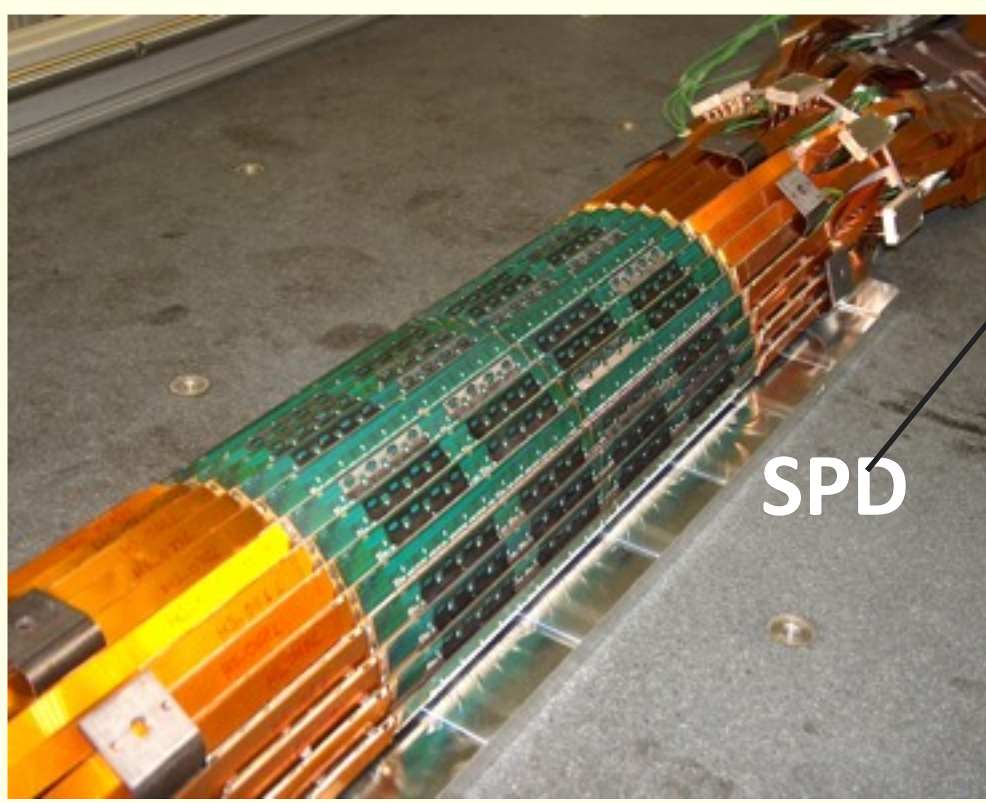
2. The Alice Experiment

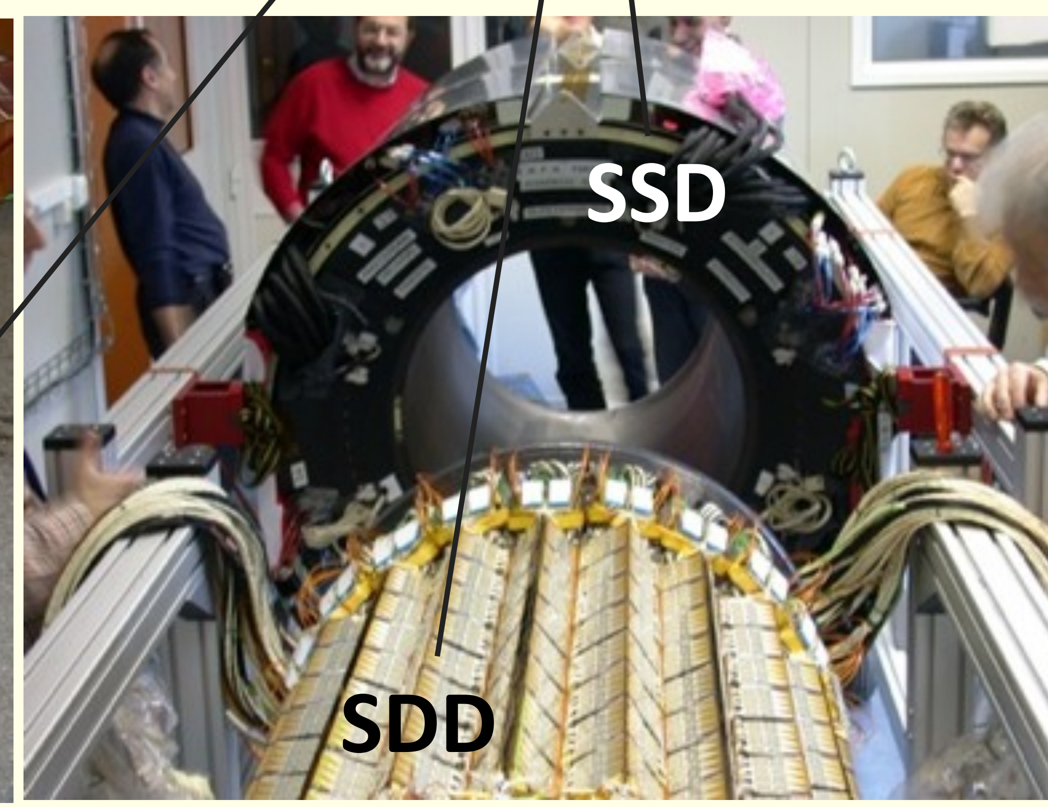

ALICE
ITS SSD
ITS SDD
ITS SPD
FMD
V0 and T0
(C side)
EMCAL
dipole magnet
HMPID
ZDC
PMD
TPC
V0 and T0
(A side)
ITS
TRD
TOF
ZDC
PHOS
muon tracking
L3 magnet

Inner Tracking System (ITS)

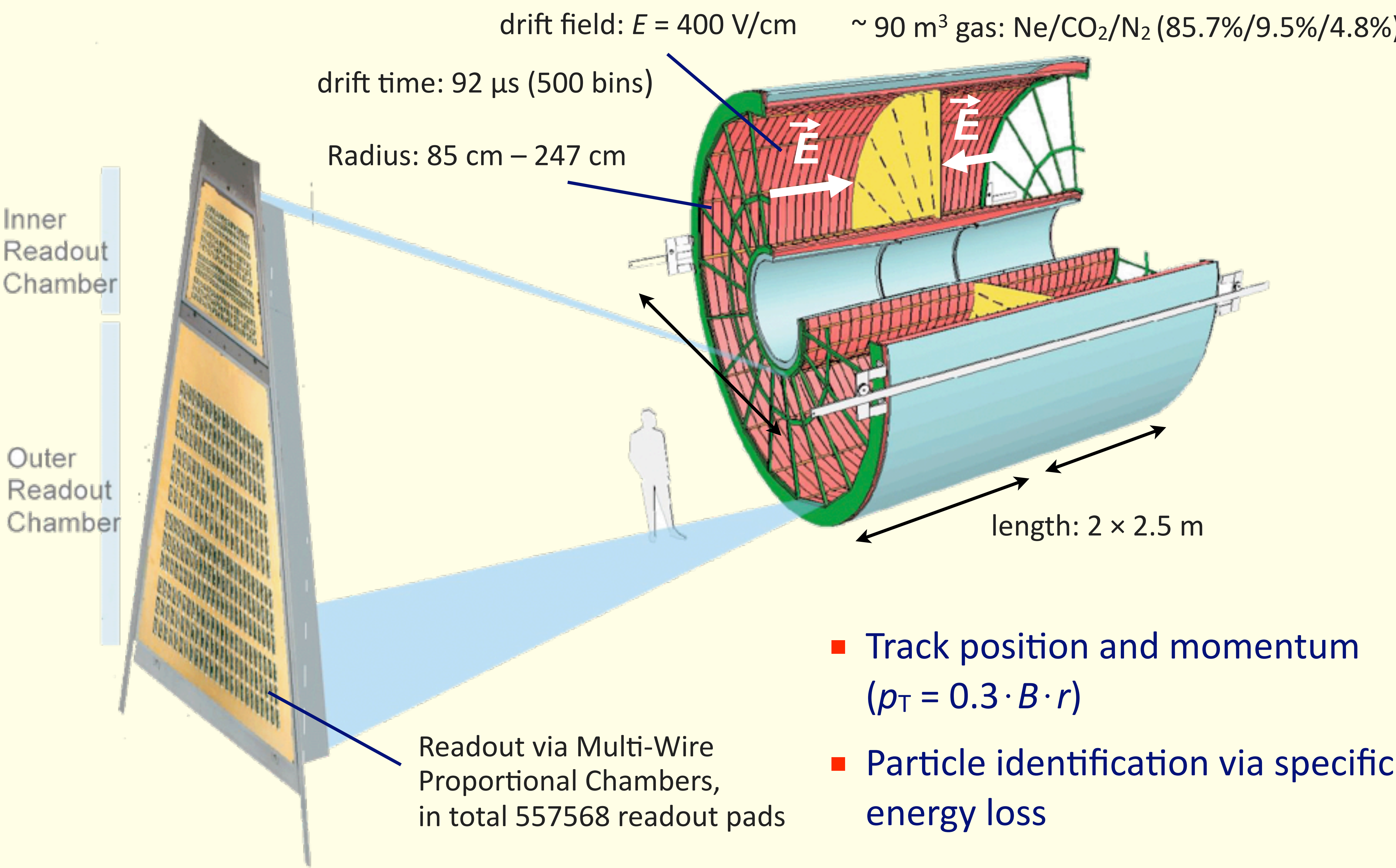
- 6 layers silicon
  - 2 pixel detectors (SPD), 9.8 M channels
  - 2 drift detectors (SDD), 133k channels
  - 2 strip detector (SSD), 2.6M channels
- Coverage: |η| < 0.9
- Reconstruction of primary vertex (σ < 100 μm)
- Secondary vertices, e.g., for heavy-quark measurements



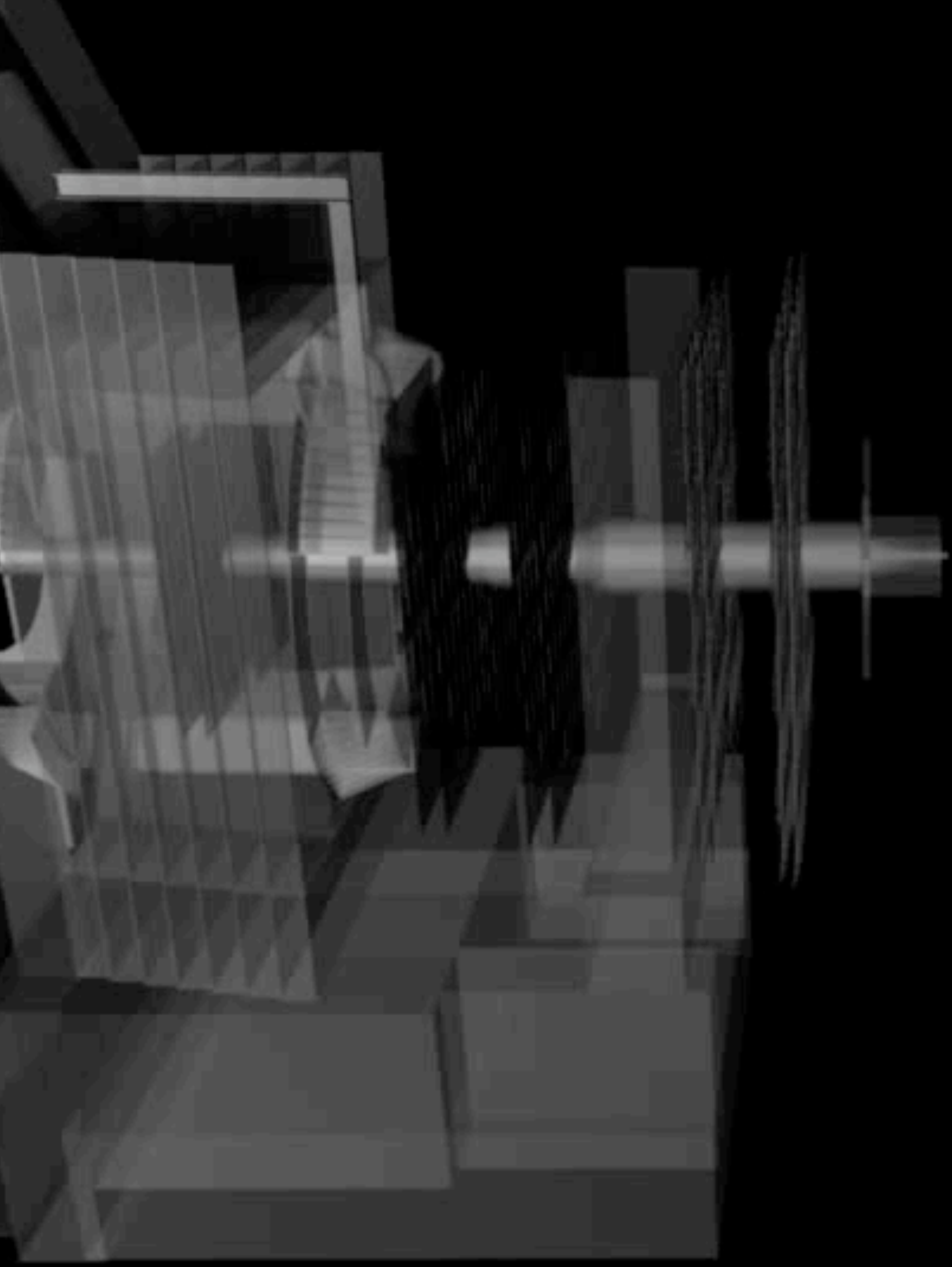




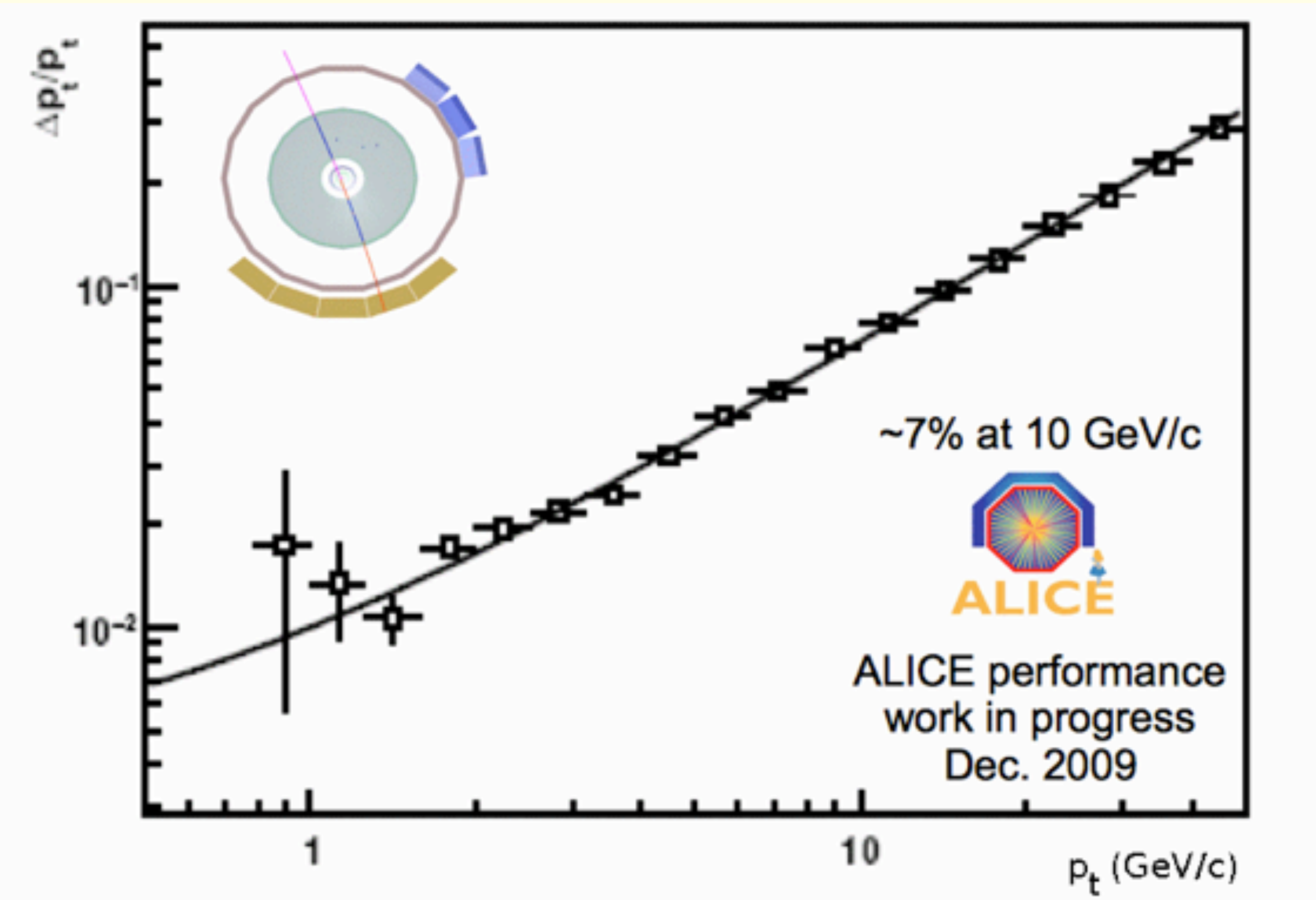
The ALICE-TPC:
The World's Largest Time Projection Chamber (TPC)

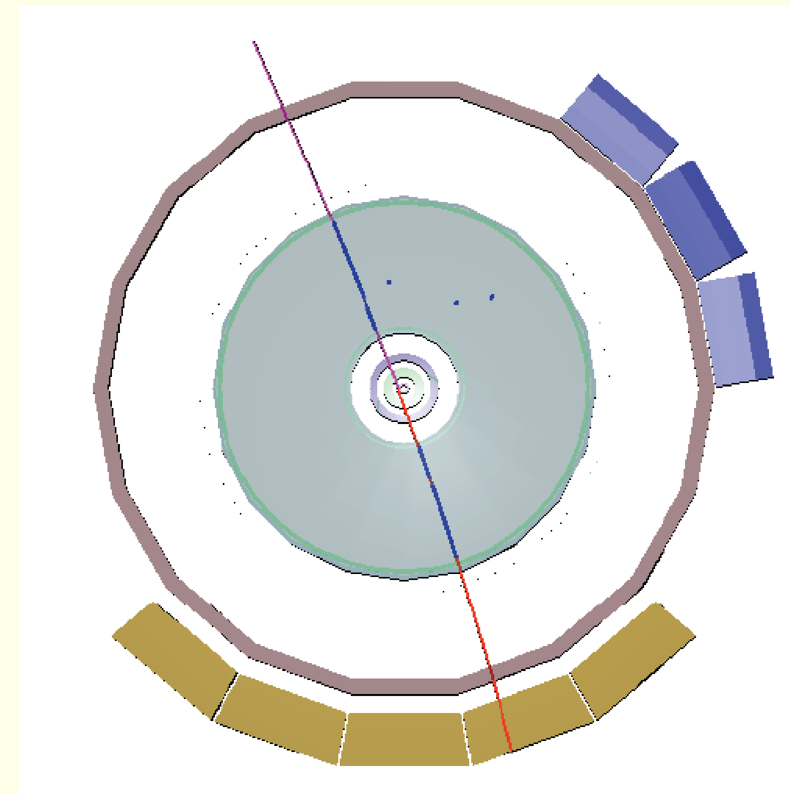


- Track position and momentum ($p_T = 0.3 \cdot B \cdot r$)
- Particle identification via specific energy loss



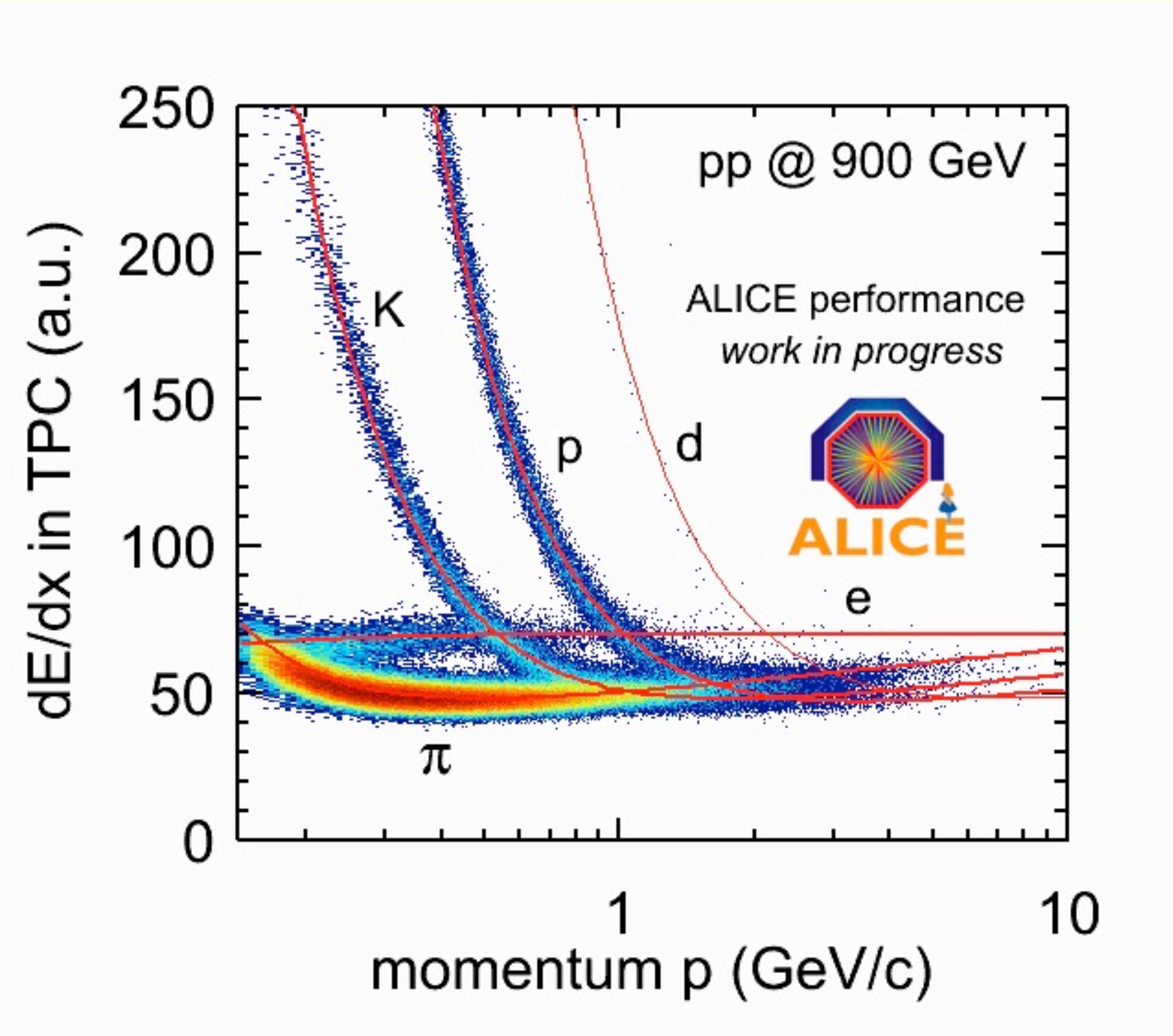
TPC Momentum Resolution





- Cosmic muon tracks treated independently in two halves of TPC
- Comparison of p_T at vertex gives resolution
- Design goal: 4.5% at 10 GeV/*c*
- Achieved: 6.5% at 10 GeV/*c*

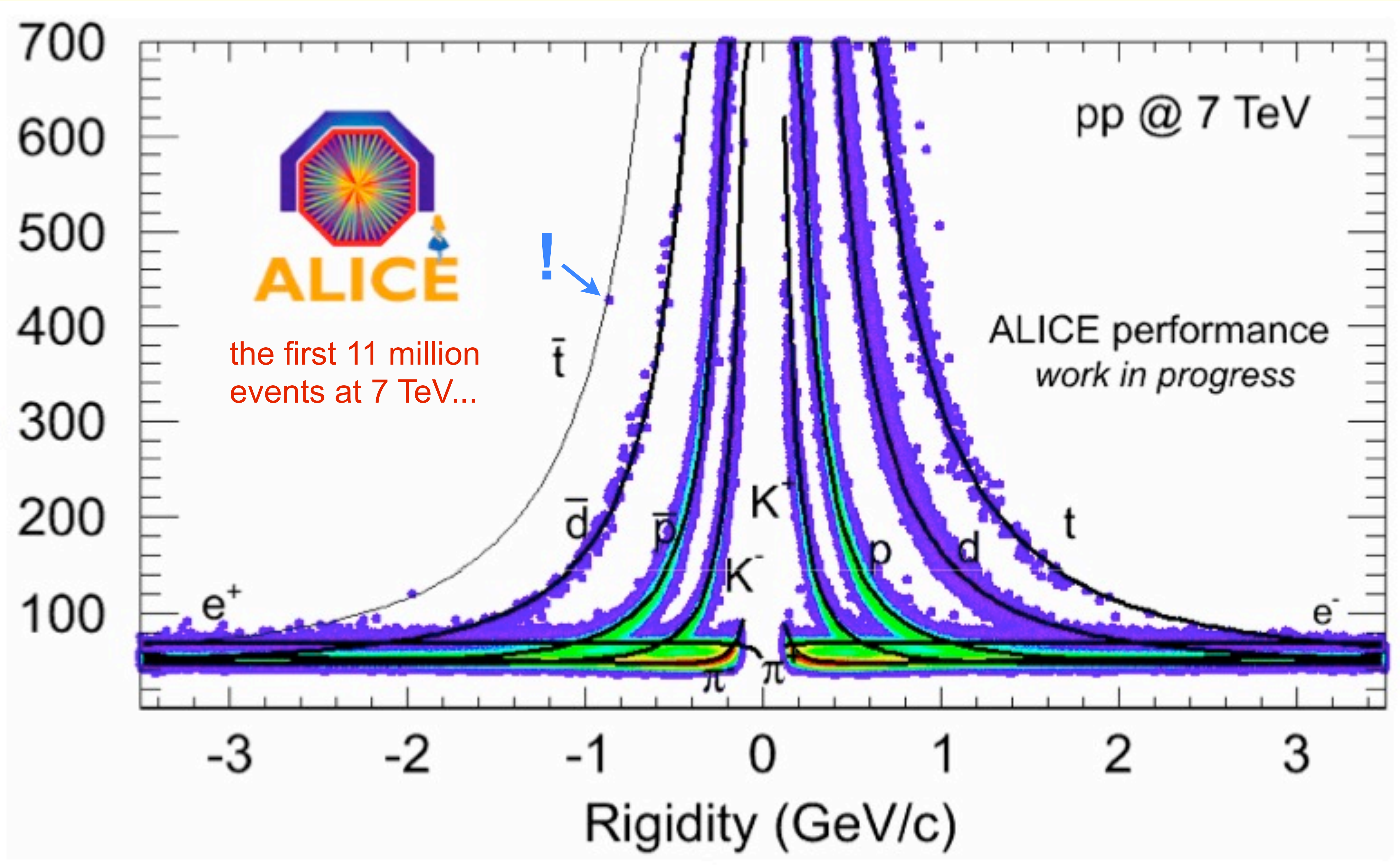
TPC dE/dx spectra: p+p at 900 GeV



- dE/dx resolution: $\sigma_{dE/dx} \approx 5\%$
- Characteristic bands of various particles clearly visible
- ALEPH parameterization of the Bethe-Bloch curve

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}}\left(P_2 - \beta^{P_4} - \ln(P_3 + \frac{1}{(\beta\gamma)^{P_5}})\right)$$

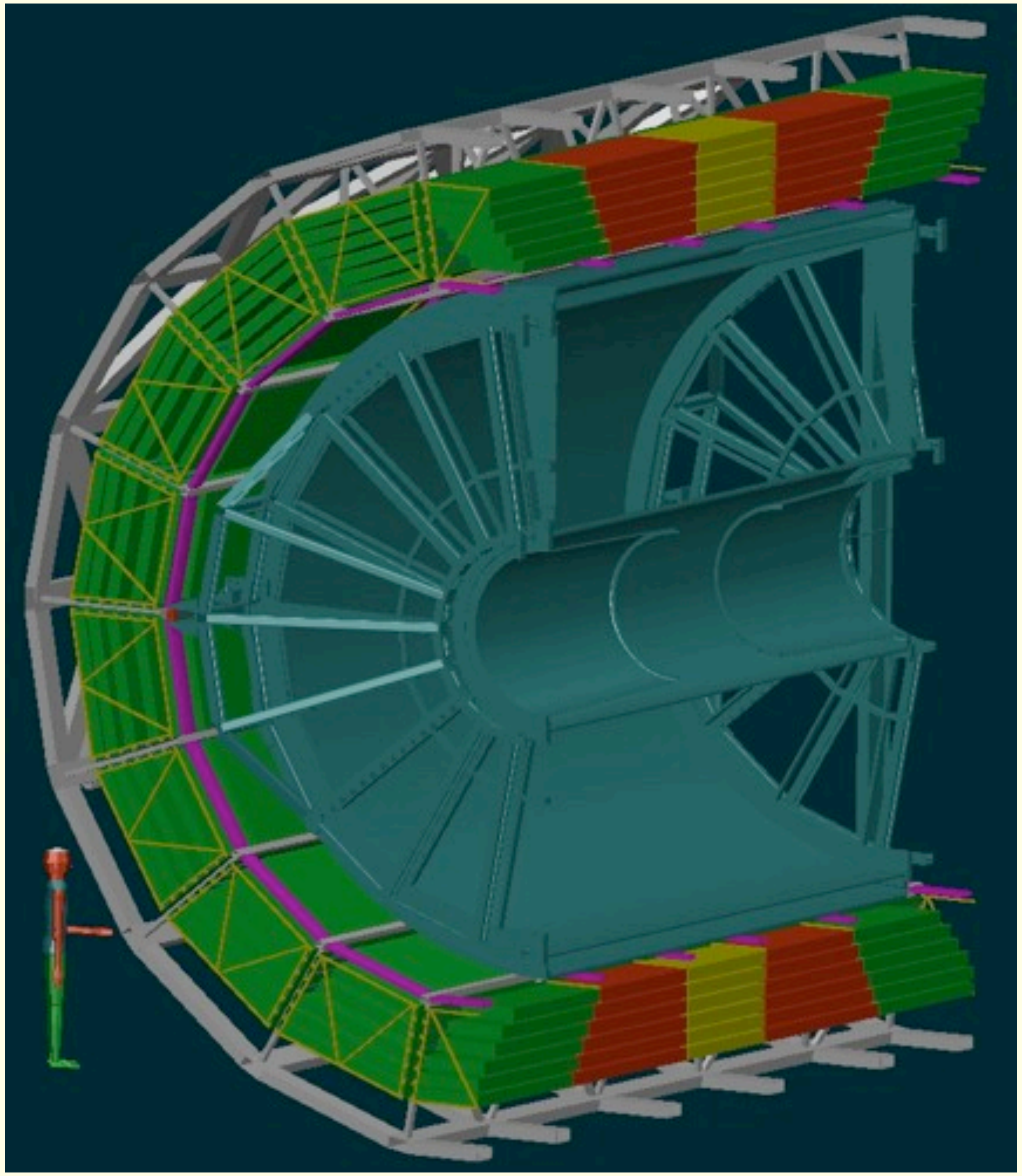
TPC d*E*/d*x* spectra: p+p at 7 TeV



The Transition Radiation Detector (TRD)

task: electron id by TR
J/ψ, ϒ → $e^+ e^-$
D, B → e + anything (semi-leptonic)
trigger on high p_T electrons

- 540 chambers /18 supermodules
- total area: 694 m^2
- gas volume: 25.8 m^3 (Xe-CO_2)
- resolution (rϕ): 400 µm
- trigger: 275 000 CPUs, 6.5µs /event



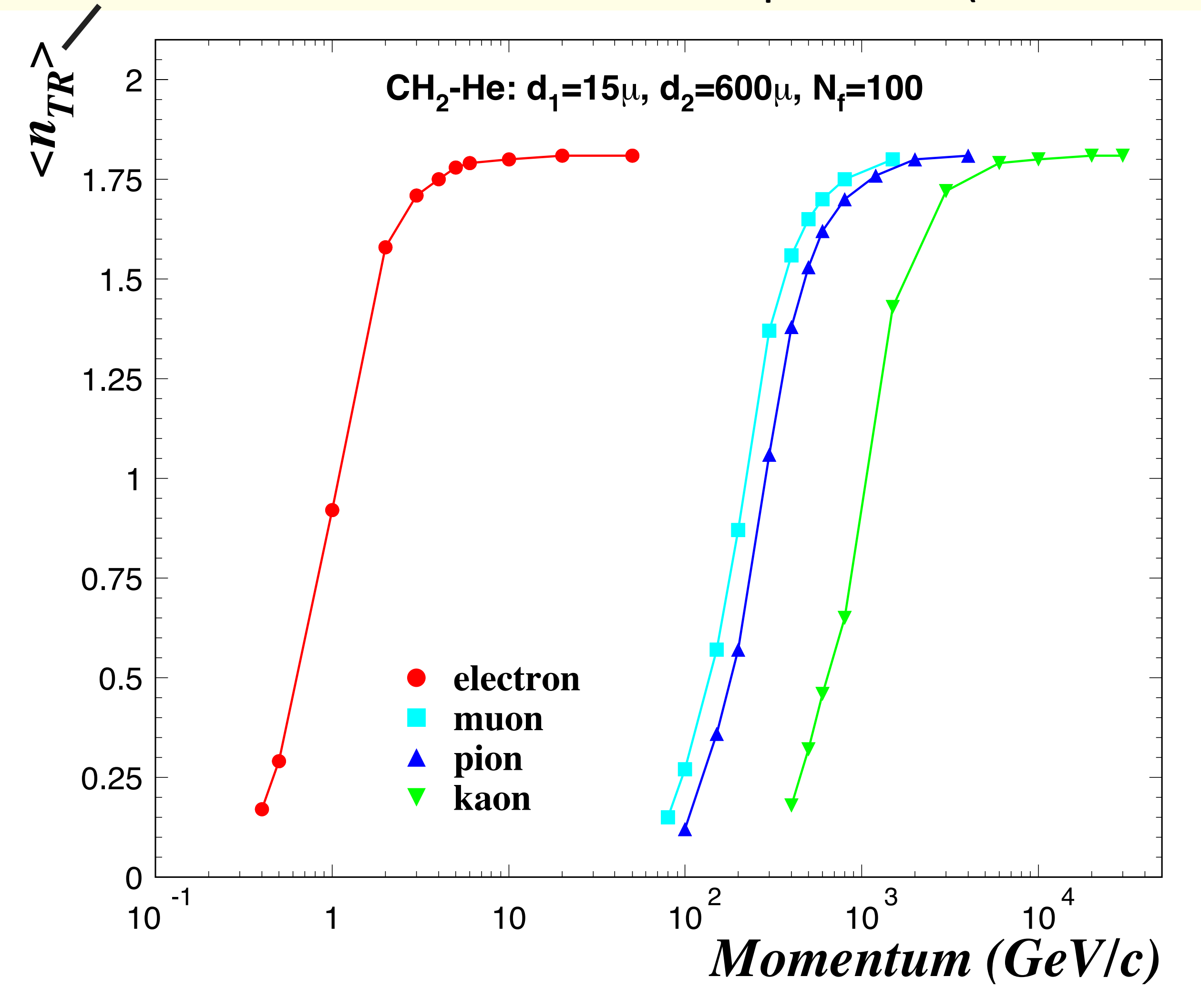
status:

- chamber production finished
- 7 supermodules operational in 2009/2010

90% funded by Germany: GSI, Univ. DA, HD, FRA, MS, FH Cologne, Worms

Transition Radiation (TR)

number of transition radiation photons (simulation)



- Charged particles emit photons („transition radiation") when they cross boundaries of media with a different dielectric constant ε
- Small probability

  ⇒ many boundaries ($n_{TR} \sim \alpha_{em} \times N_{transitions}$)

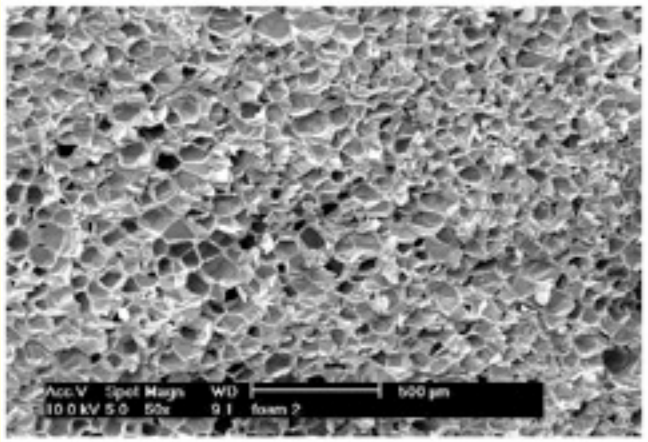
- $E_{photon} \sim \gamma$, $\theta_{photon} \sim 1/\gamma$ (i.e. approx. collinear)
- Threshold: Lorentz factor $\gamma = E/m > 1000$

  ⇒ essentially only electrons emit TR

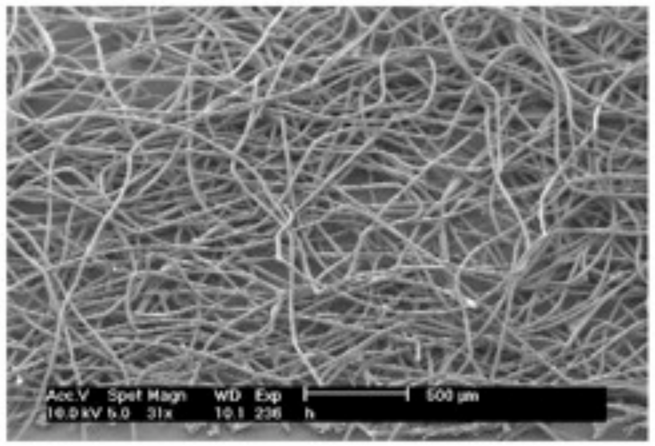
  ⇒ identify electrons !

Typical TR radiators:

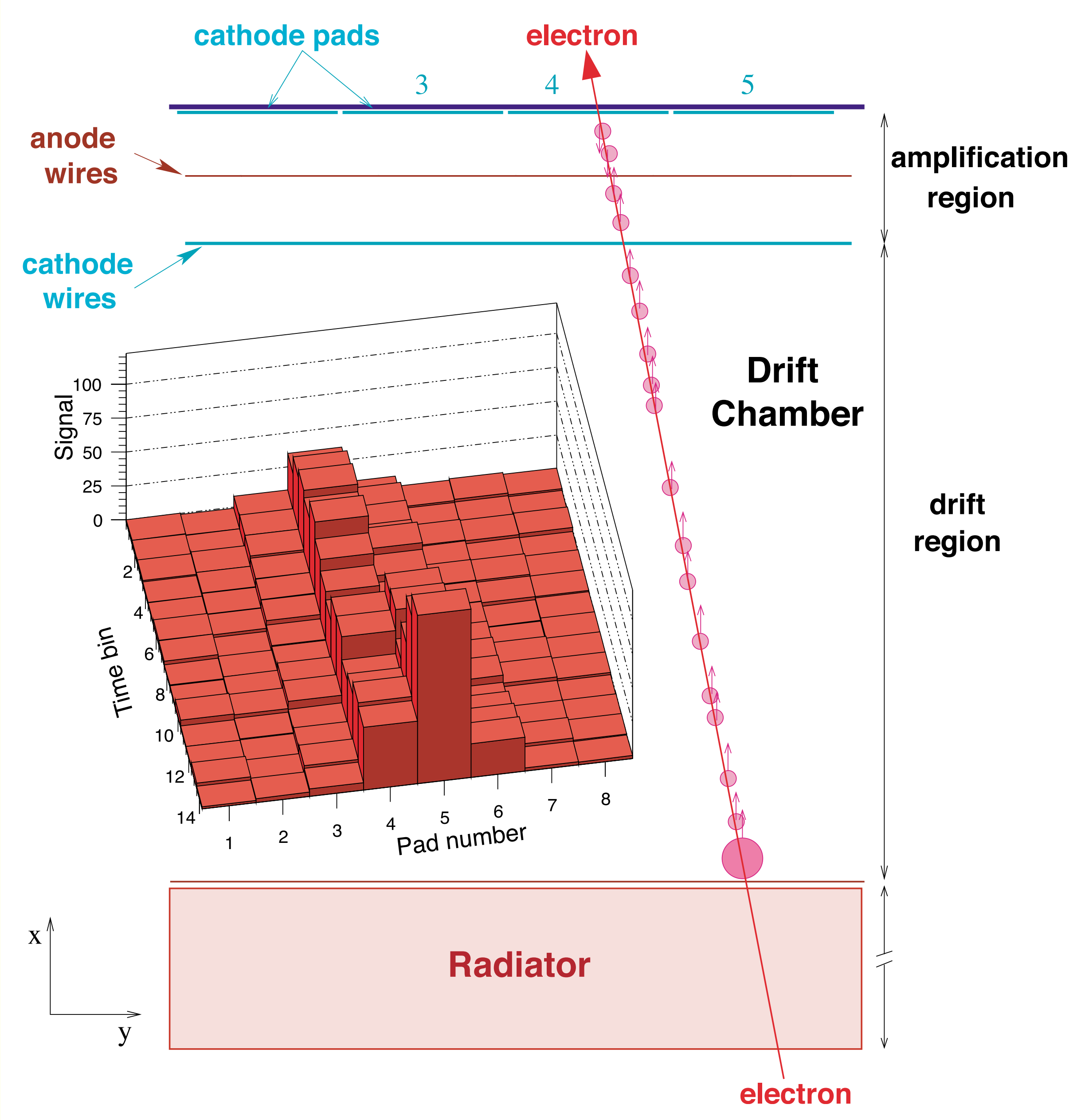
Foams

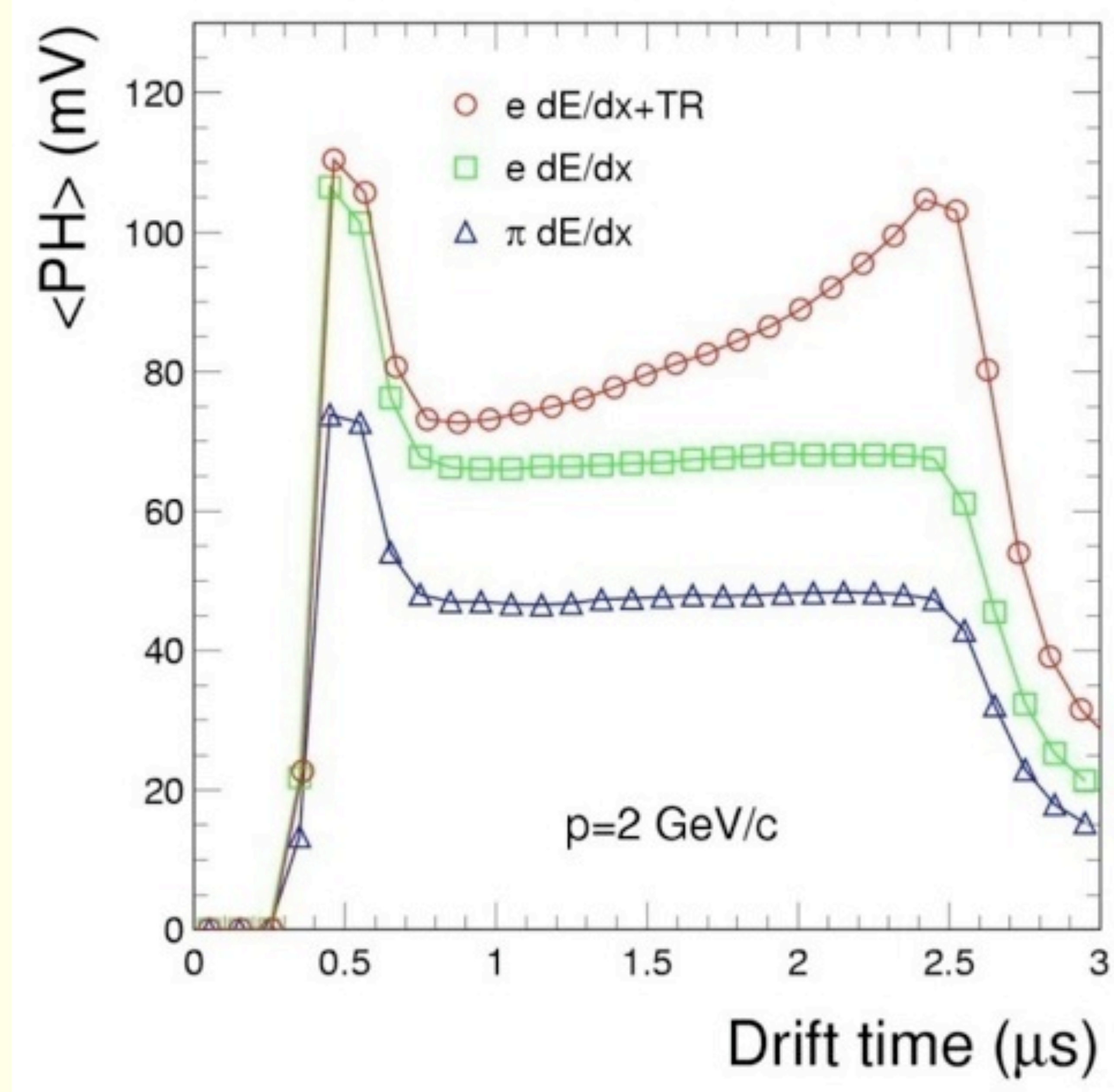


Fibers



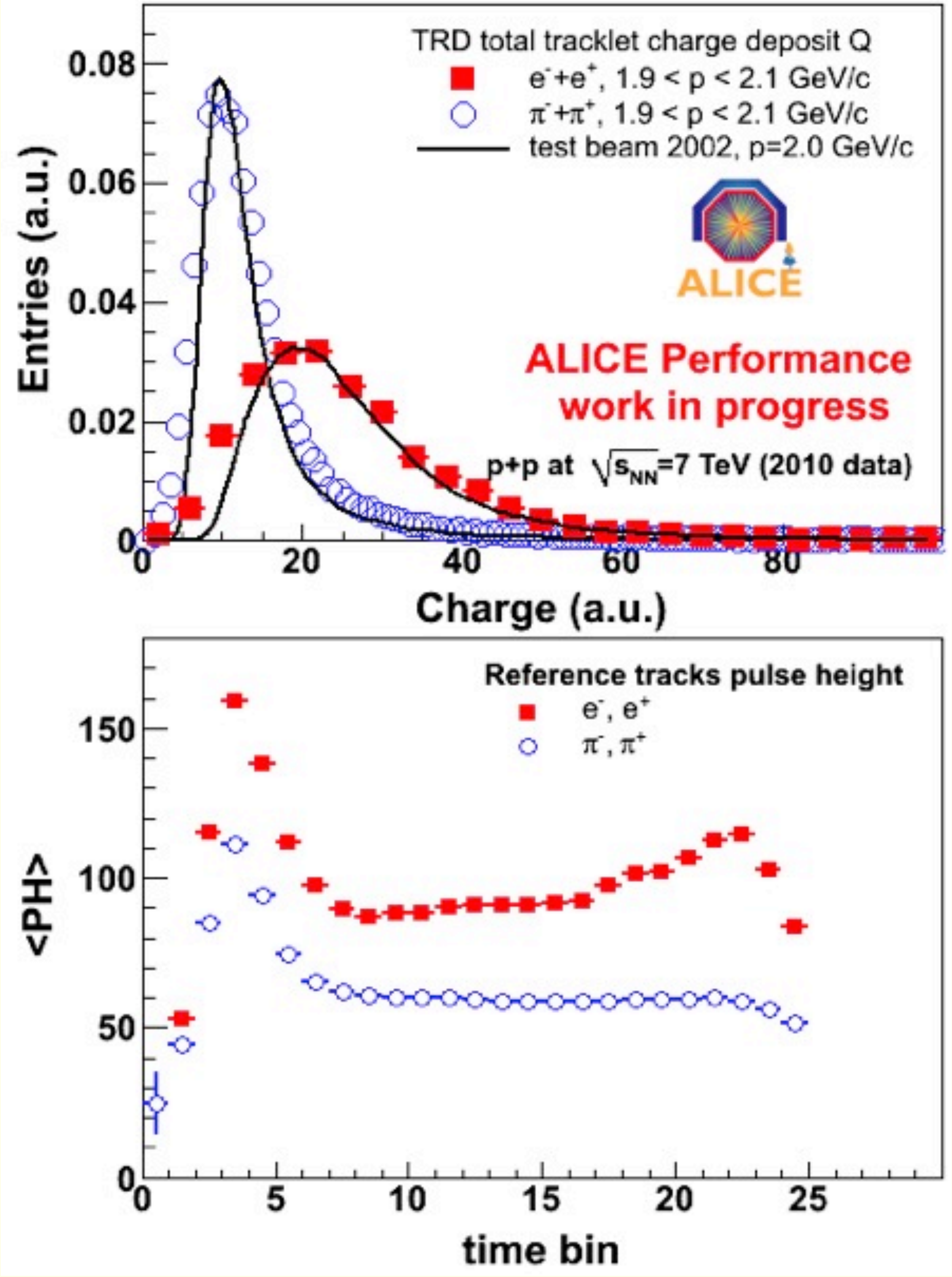
TRD – Signal Generation



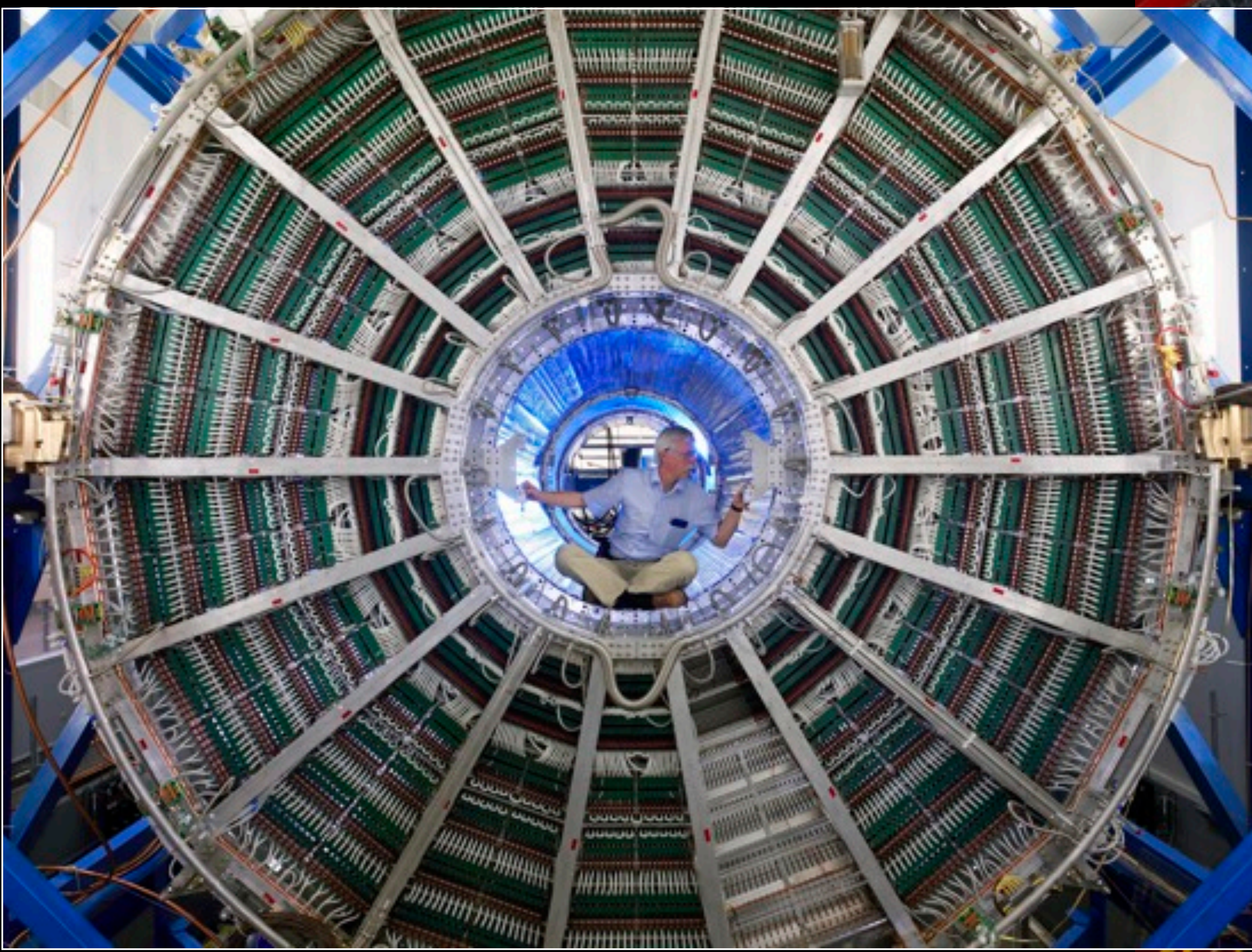


- Charged particles induce a signal in the detector
- Only electrons produce transition radiation
- Electron ID, misidentified pions 1 % or less

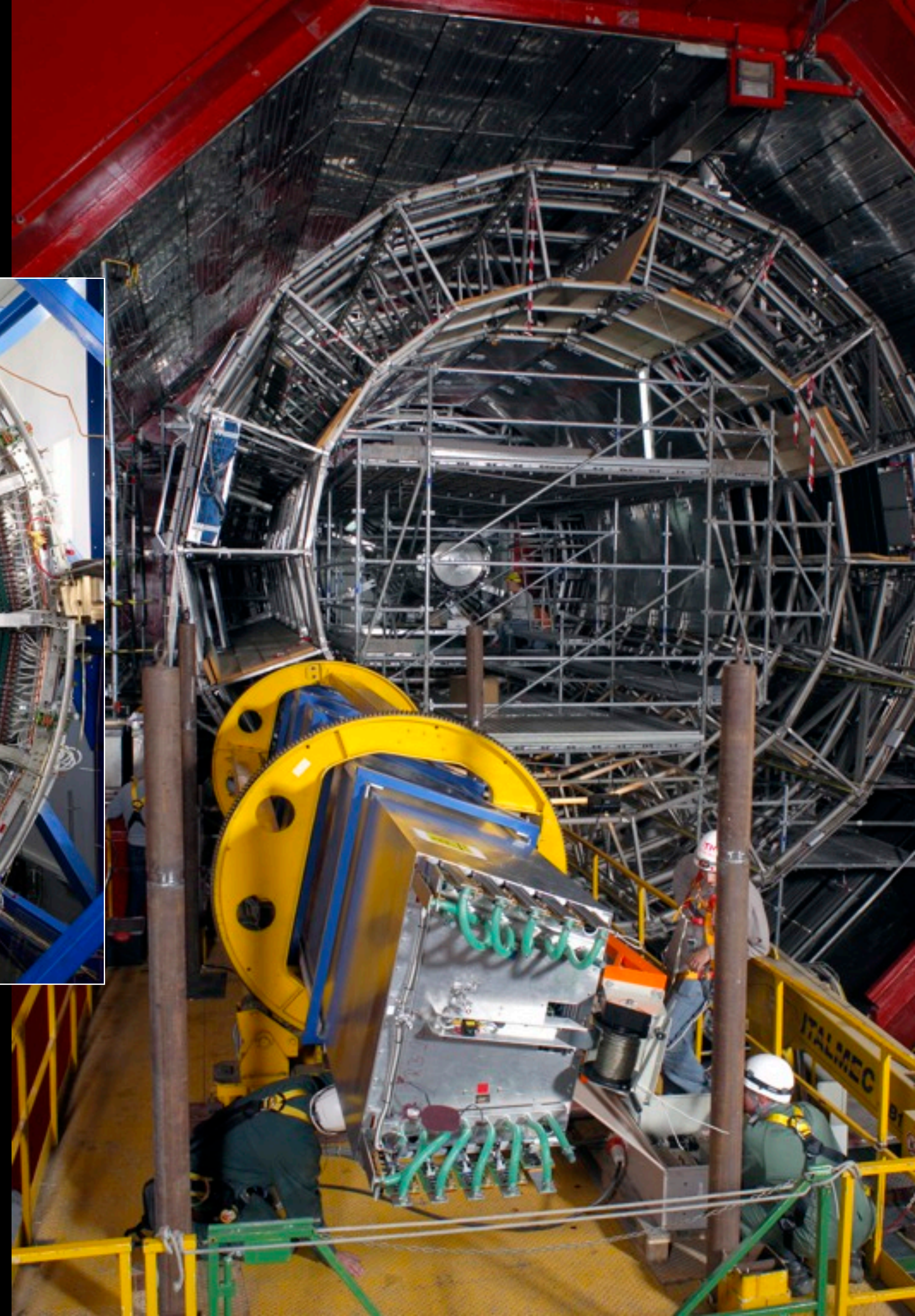
TRD Performance in 7 TeV p+p Collisions



TPC and TRD

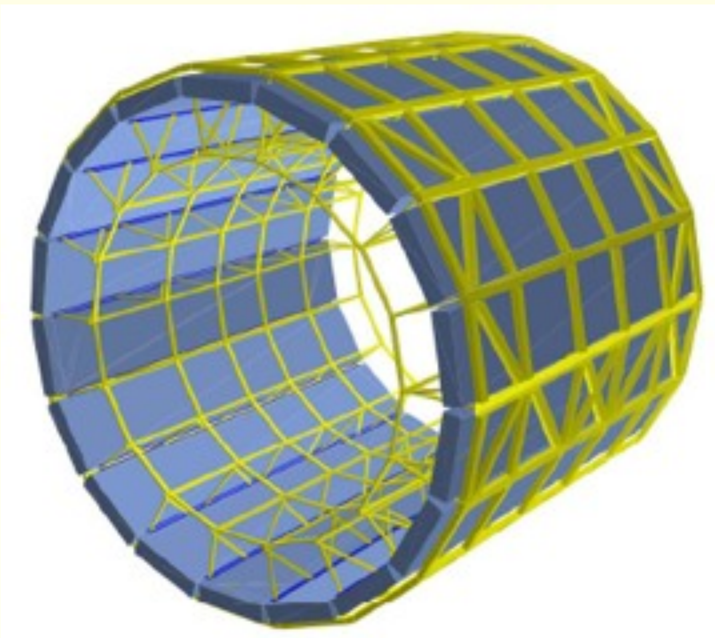


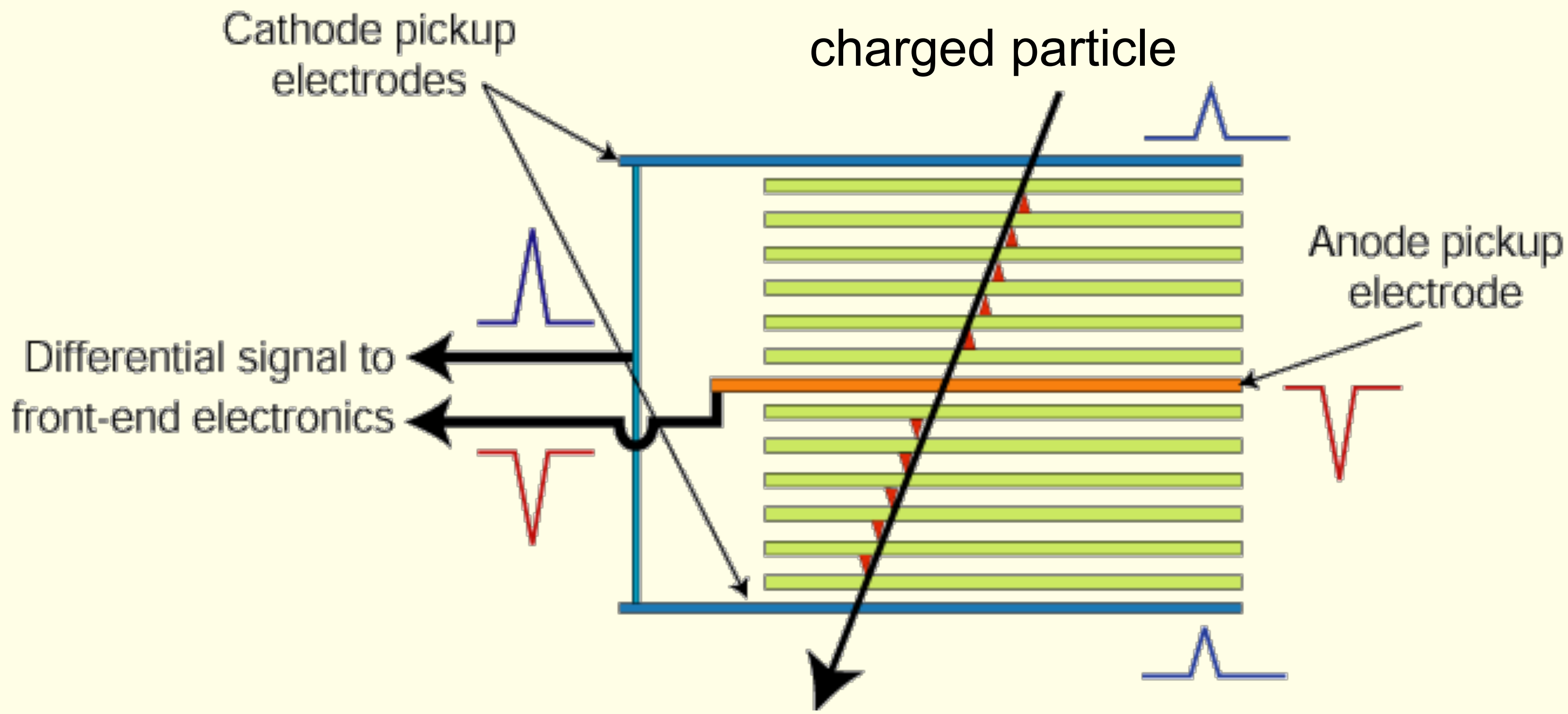
Time Projection Chamber (TPC)



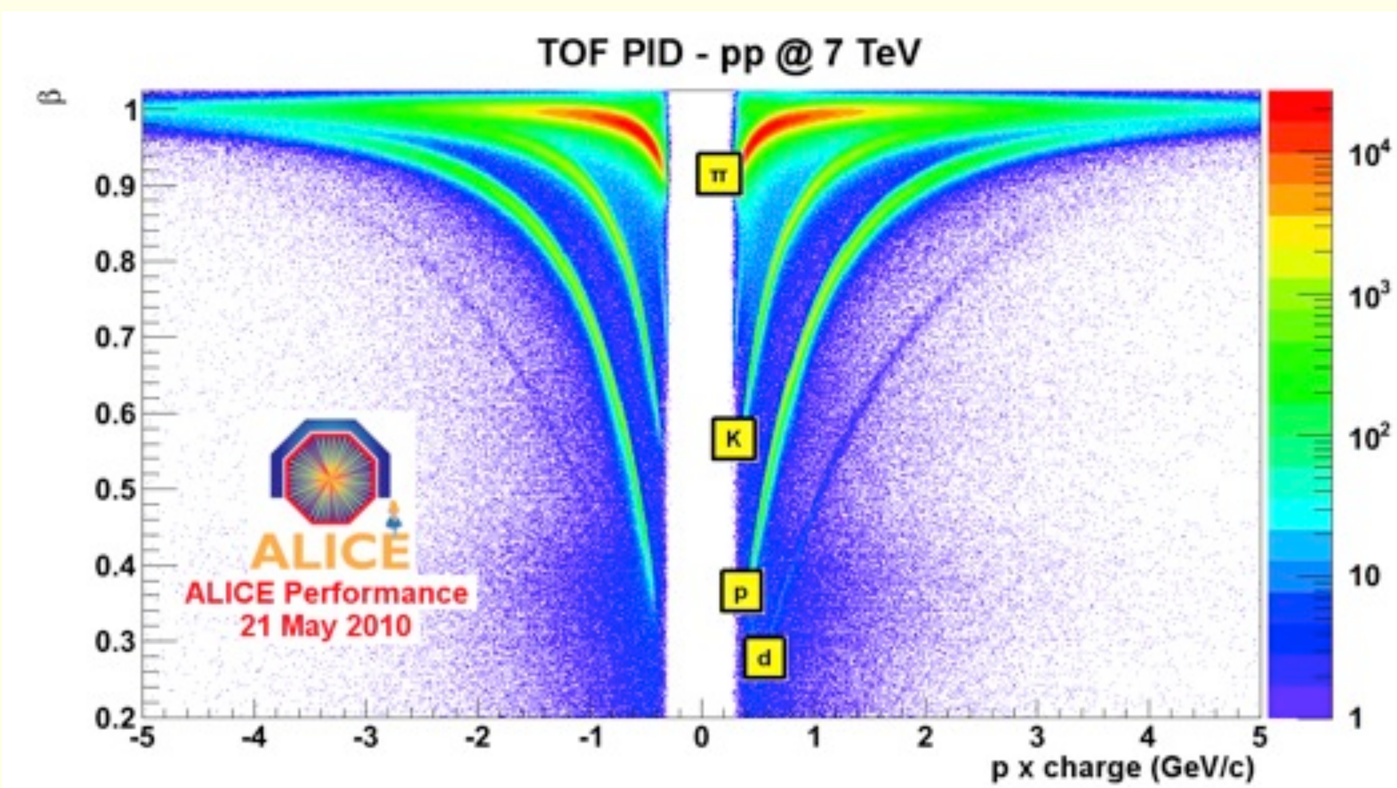
Installation of the
first TRD supermodule
(October 2006)

TOF (Time of Flight)



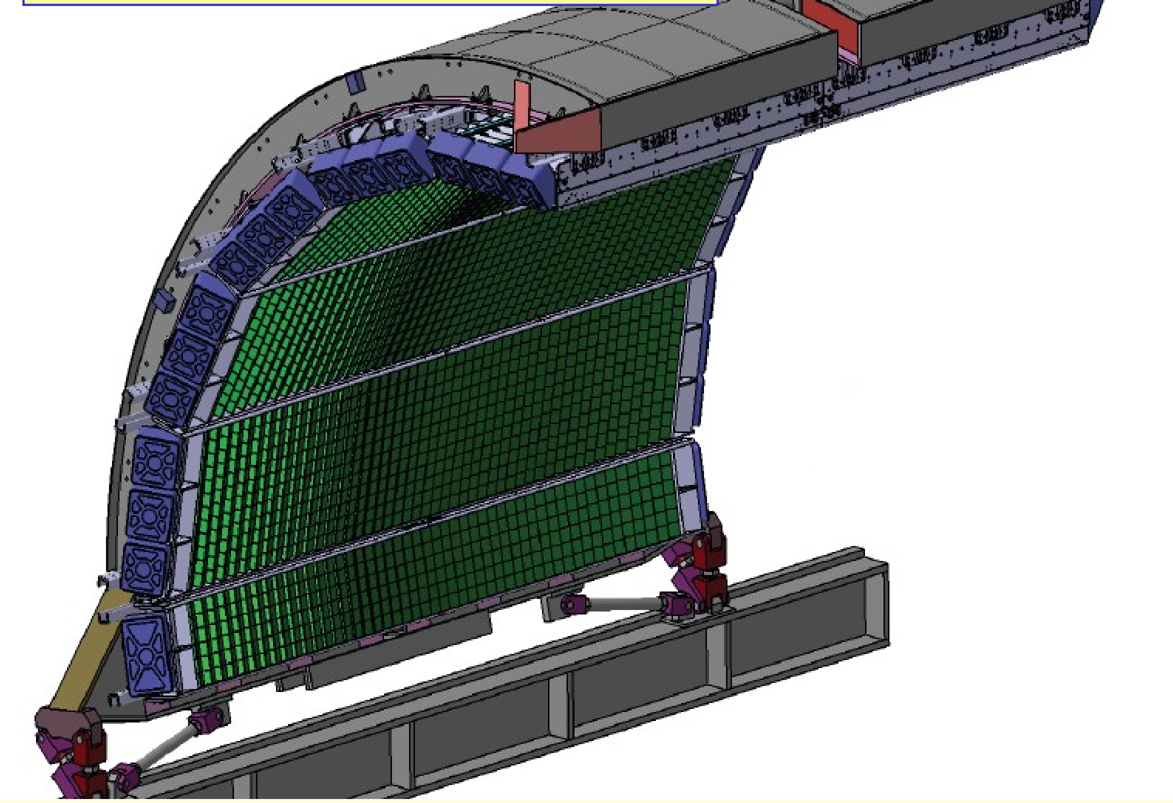


- Multi-gap Resistive Plate Chambers (MRPC)
- 18 sectors covering the whole azimuthal angle, |η|<0.9
- ~153k readout channels
- Granularity: 2.5x3.5 cm^2 at ~3.7 m from the primary vertex
- Resolution reached so far: ~100 ps

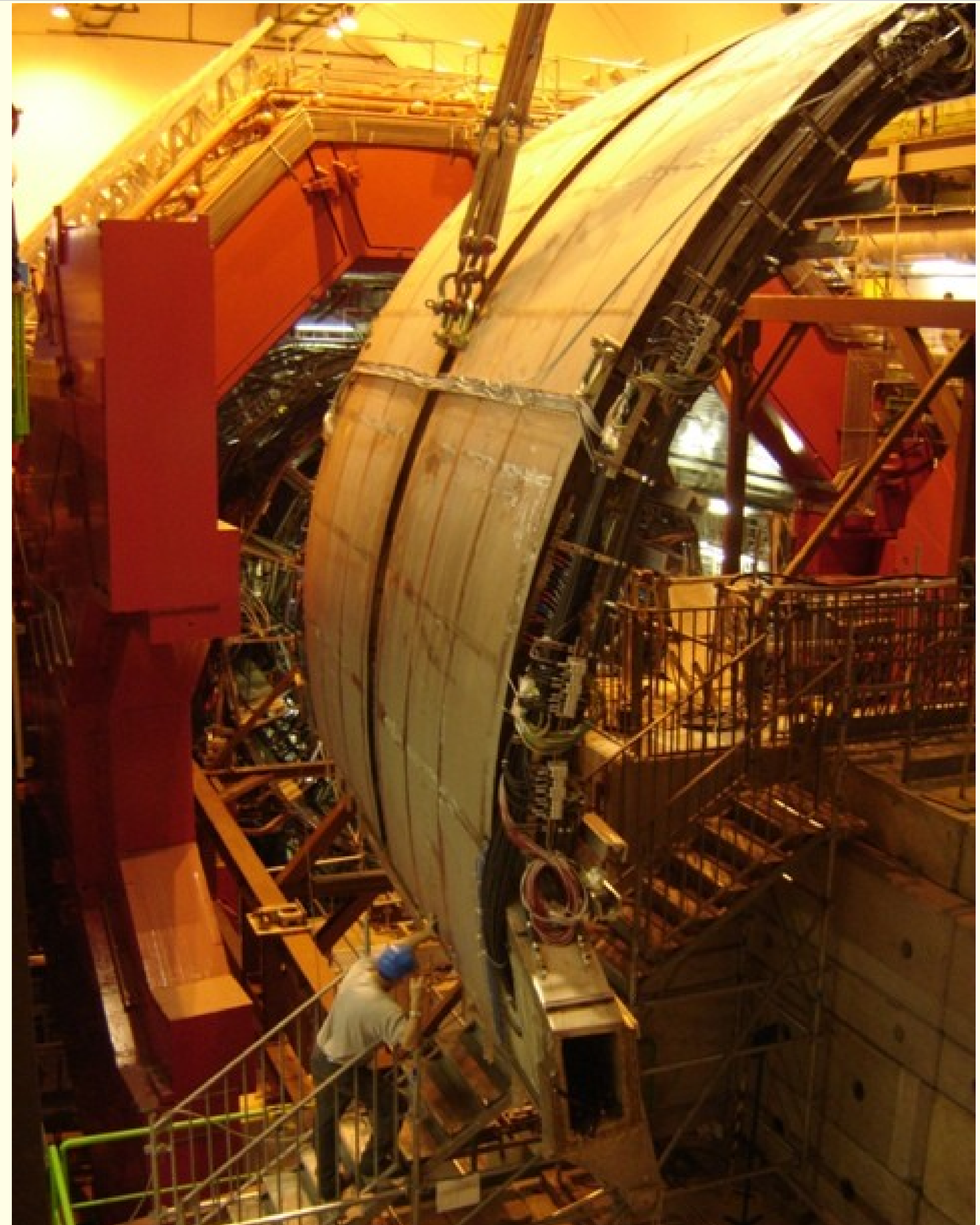


Electromagnetic Jet Calorimeter

44 m^2 Pb-Scint sampling calo,
20 X_0, 13 k FEE APD R/O
$|\eta|<0.7$ $\Delta\phi = 110^{o}$ $r = 4.4$ m

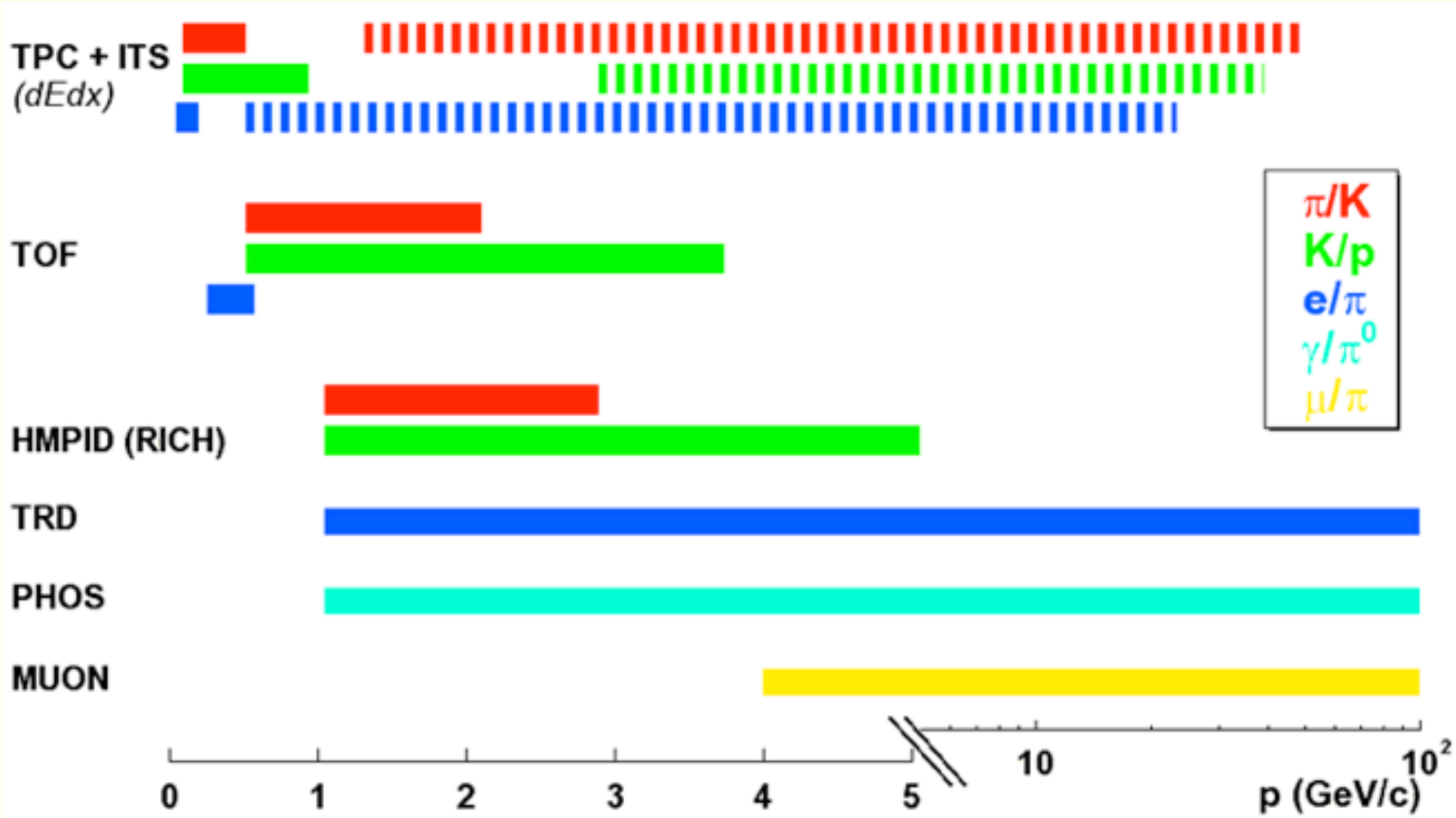


- construction start April 2008
- approved & funded Dec 2008
- US, Italy, France, Finland
- approx. 20% installed
- complete in 2010



Nov 2007: EMCAL support

Particle Identification in ALICE



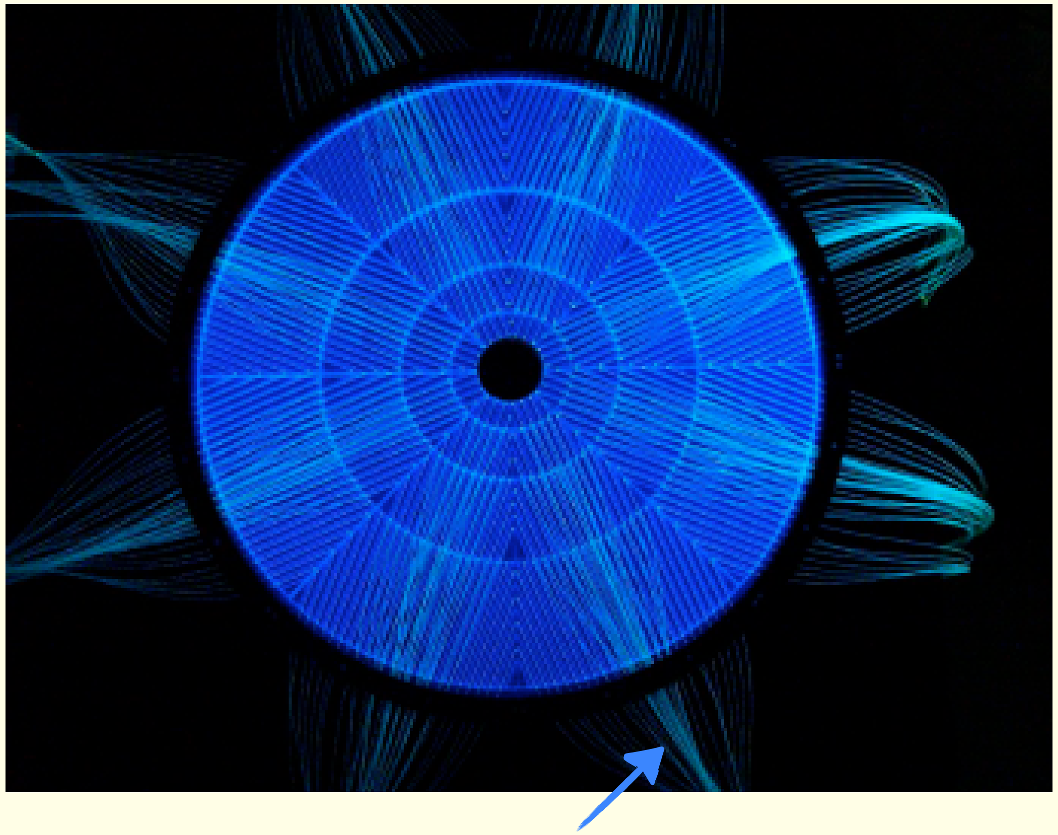
Alice has excellent momentum reconstruction and particle ID capabilities at low transverse momenta

- 'Stable' hadrons (π, K, p): 100 MeV < p < 5 GeV (few 10 GeV)
  - dE/dx in silicon (ITS) and gas (TPC) + time-of-flight (TOF) + Cherenkov (RICH)
- Decay topologies: Kinks (K^+, K^-) [e.g., K $\rightarrow \mu + \nu$] and invariant mass analysis of decay products (K_S^0, Λ, ϕ, D)
  - Secondary vertex reconstruction
- Leptons (e, μ), photons, η, π^0
  - Electrons TRD: p > 1 GeV, muons: p > 5 GeV, π^0 in PHOS/EMCal and via conversions

Forward Detectors

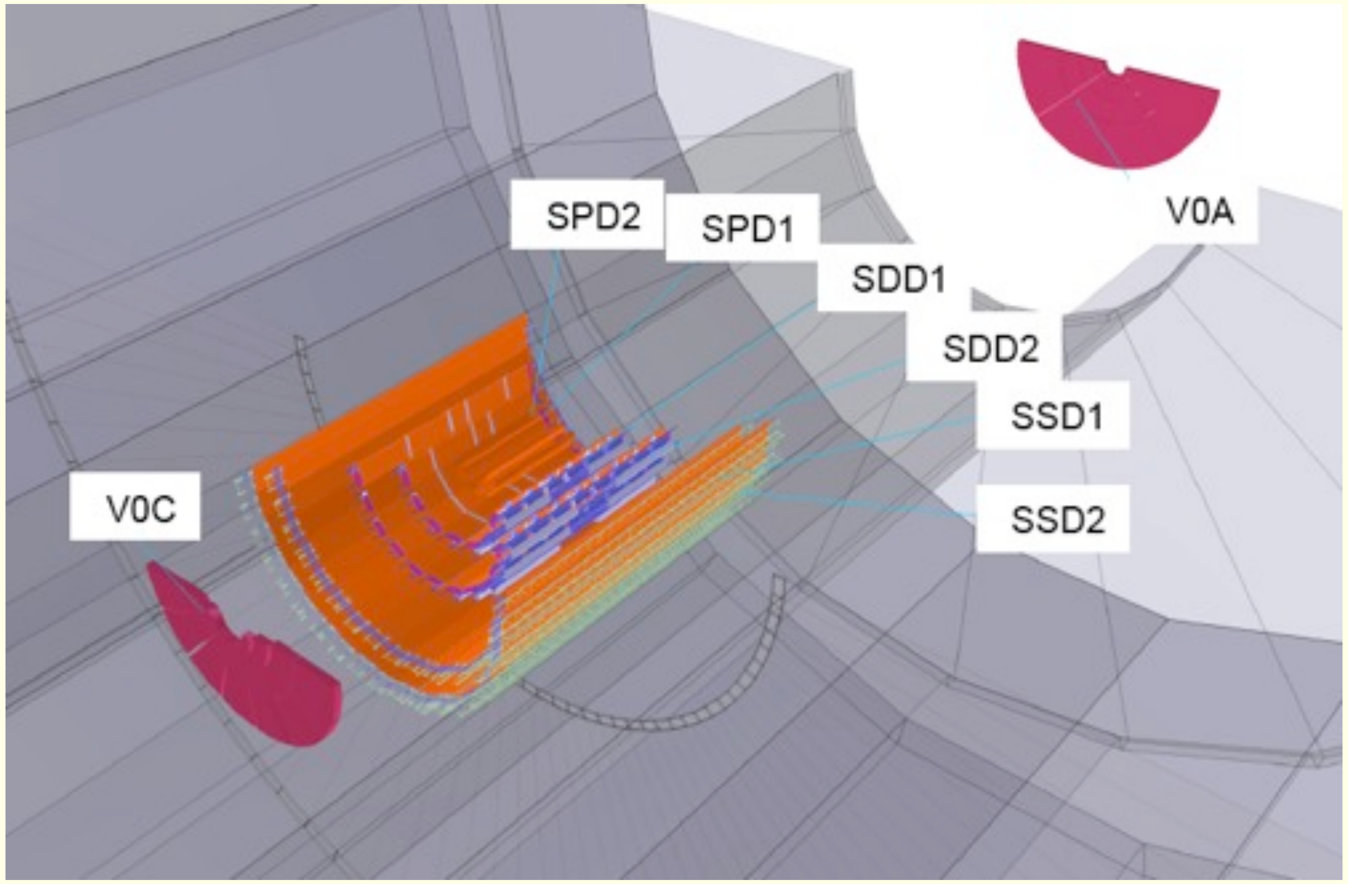
- FMD (Forward Multiplicity Detector)
  - 3 planes Si-pad, $-3.4 < \eta < -1.7$,
    $1.7 < \eta < 5.0$
- T0
  - 2-arrays 12 quartz Cherenkov counters
  - 30ps res.
  - Start for TOF detector
- V0
  - 2 scintillator arrays, 32 tiles
  - V0A: $1.7 < \eta < 5.0$, V0C: $-3.7 < \eta < -1.7$
  - Minimum bias trigger in p+p and A+A
- ZDC (Zero Degree Calorimeter)
  - 2-neutron, 2-proton calorimeters, 116m from IP
- PMD (Photon Multiplicity Detector)
  - $2.3 < \eta < 3.5$

V0A detector:



wave length shifting fibers

ALICE p+p Minimum Bias Trigger



Trigger efficiencies from MC:

0.9 TeV (in %)		ND	SD	DD
Pythia	MB_{OR}	100	77	92
	MB_{AND}	98	29	49
Phojet	MB_{OR}	100	86	98
	MB_{AND}	98	34	66

- pp @ 0.9 and 7 TeV
  - SPD ($|\eta|<2$) or V0-A or V0-C (at least one particle in 8 units of η)
  - In coincidence with passing bunches (BPTX beam pickups)
  - Also control triggers to measure beam-induced and accidental background
- pp @ 2.36 TeV
  - SPD only + BPTX
- Collected minimum bias pp samples:
  - 2009: 0.9 and 2.36 TeV, ~0.5 M events (10.3 μb^{-1})
  - 2010: 0.9 and 7 TeV, ~700 M events (9.4 nb^{-1}) of which ~10 M events @ 0.9 TeV

3. Average particle multiplicity: $dN_{ch}/d\eta$

Diffractive Events (I)

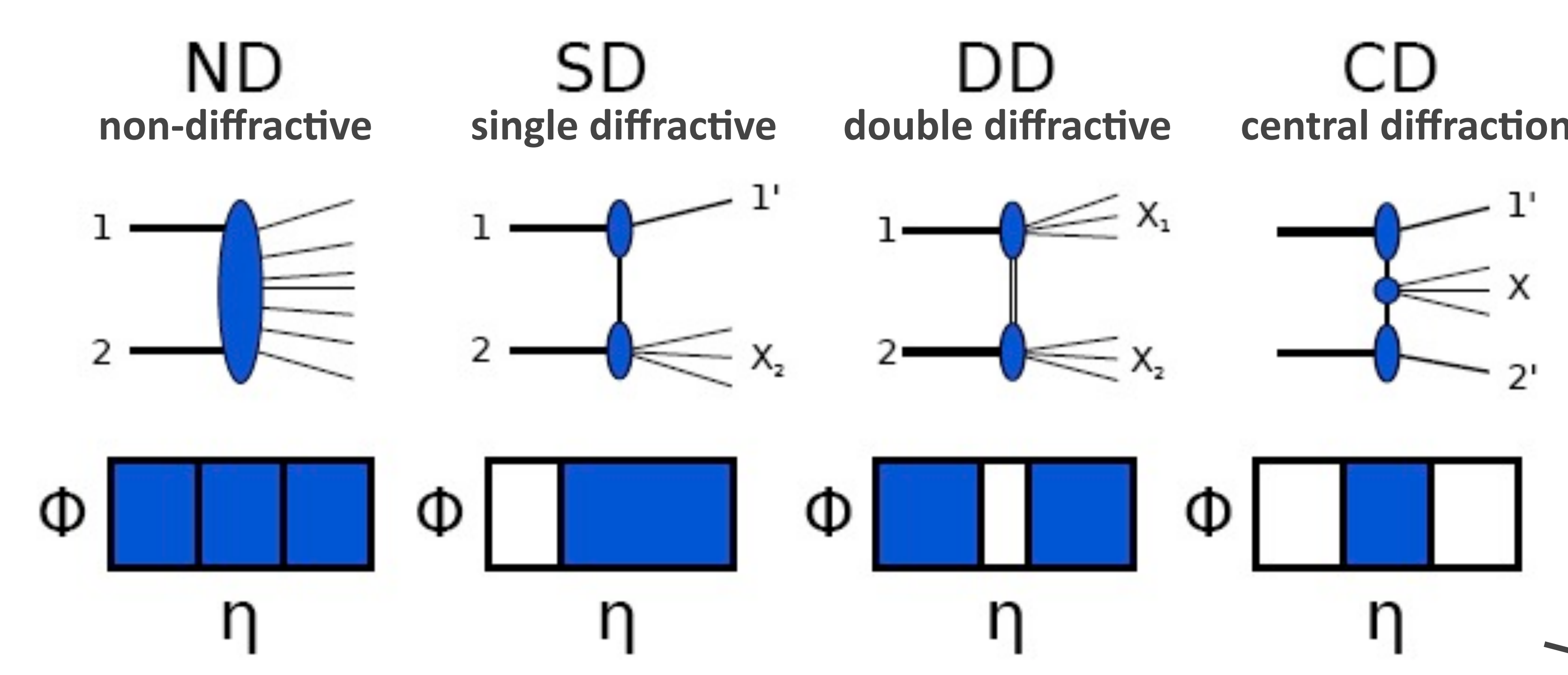
- (Single) diffraction in p+p:
  "Projectile" proton is excited to a hadronic state X with mass *M*

$$p_{\text{proj}} + p_{\text{targ}} \rightarrow X + p_{\text{targ}}$$

- The excited state *X* fragments giving rise to the production of (a small number) of particles in the forward direction

- Theoretical view:
  - Exchange of multi-gluon states („Pomeron exchange")
  - No exchange of quantum numbers (like color or charge)

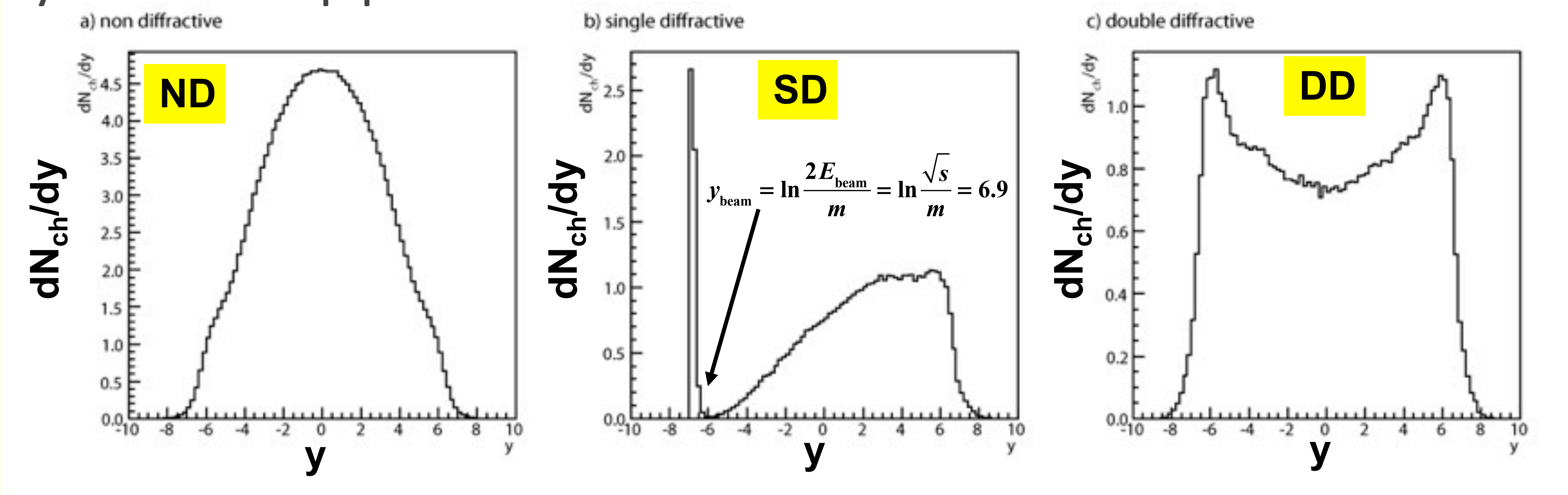
Diffractive Events (II)



- Rapidity gaps are characteristic of diffractive events

plot: F. Reidt, Bachelor thesis

Pythia simulation: p+p at $\sqrt{s}$ = 900 GeV:



Diffractive Events (III)

small, < 1 mb

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inel} \qquad \sigma_{inel} = \sigma_{ND} + \sigma_{SD} + \sigma_{DD} + \sigma_{CD}$$

Example: Result from UA5

$p + \bar{p}$	$\sqrt{s}$ = 200 GeV	$\sqrt{s}$ = 900 GeV
Total inelastic	(41.8 ± 0.6) mb	(50.3 ± 0.4 ± 1.0) mb
Single-diffractive	(4.8 ± 0.5 ± 0.8) mb	(7.8 ± 0.5 ± 1.8) mb
Double-diffractive	(3.5 ± 2.2) mb	(4.0 ± 2.5) mb
Non-diffractive	≈ 33.5 mb	≈ 38.5 mb

UA5, Z. Phys. C33, 175 (1986)

About 20-25% of the inelastic cross section is due to diffractive processes for $\sqrt{s}$ = 200 - 900 GeV

Expectation for p+p at 14 TeV:

σ_{tot} = 102 mb, σ_{ND} = 76 mb, σ_{SD} = 12 mb (nucl-ex/0701067)

Soft QCD Models: Pythia vs. Phojet

- Pythia
  - Extends a perturbative high-p_T picture down to the low p_T region
  - Hard processes:
    almost all $2 \rightarrow 1$ and $2 \rightarrow 2$, a few $2 \rightarrow 3$ processes from the Standard Model
  - Includes initial and final state radiation (jet shower evolution)
  - Multiple hard parton interactions within the same p+p collisions
  - Hadronization via Lund string fragmentation
- Phojet
  - Two-component model using Reggeon theory for soft and leading order perturbative QCD for hard interactions
  - Each Phojet collision includes multiple hard and multiple soft pomeron exchanges
  - In these processes color neutral strings are formed. These strings are hadronized in Phojet using the Lund model as implemented in Pythia.

Average Charged Particle Multiplicity: $dN_{ch}/d\eta$

- Total number of produced charged particles in a p+p collision
  - related to soft processes and hence difficult to calculate from first QCD principles
  - Thus, a large variety of models describing soft particles production exists
  - $dN/d\eta$ measurements at the LHC help to kill inadequate models
- History
  - Feynman concluded in the 1970‘s that for asymptotically large energies the mean total number of procuced particles increases as

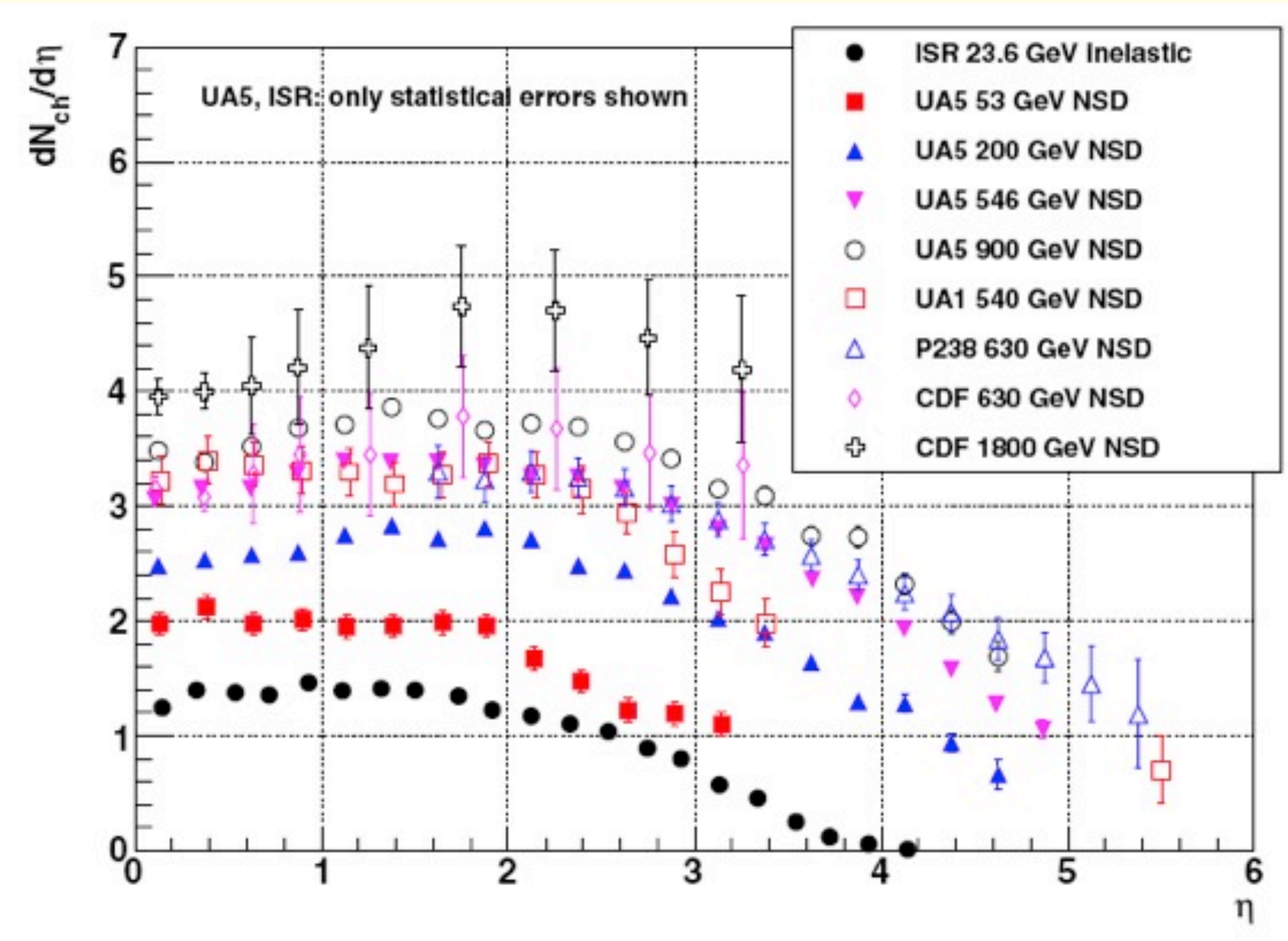
$$\langle N_{ch} \rangle \propto \ln\sqrt{s} \quad \text{(follows from "Feynman scaling",}$$

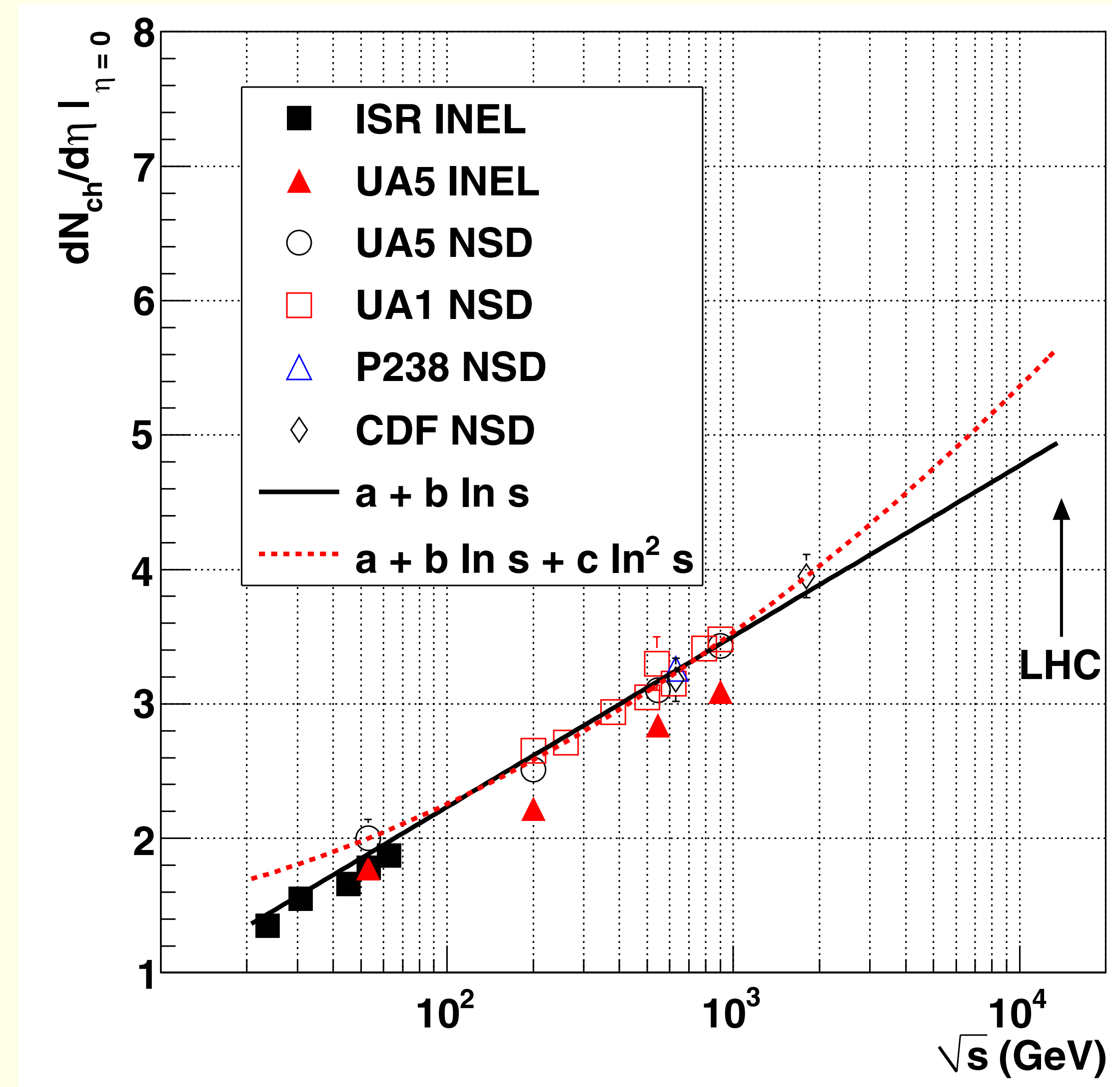
$$\text{i.e., from } E\frac{d^3\sigma}{d^3p} = F(x_F)\cdot F(p_T) \stackrel{!}{=} B\cdot F(p_T),\;\; x_F = \frac{p_L^*}{\sqrt{s}/2})$$

  - Maximum beam rapidity also scales as ln √s, thus Feynman scaling implies

$$dN/dy = \text{constant}$$

√s Dependence of dN_{ch}/dη

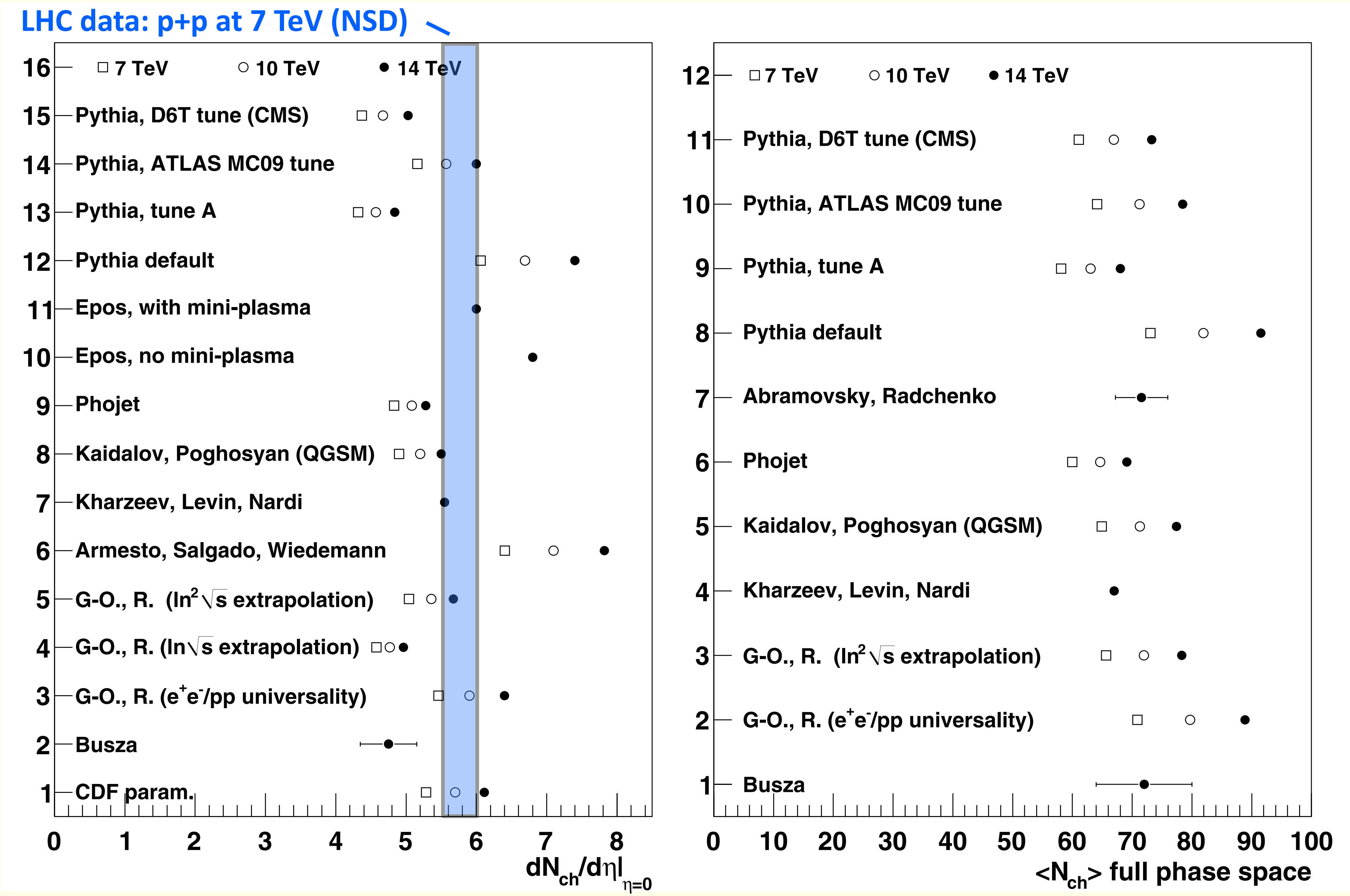




- Experimentally, it was found the dN_{ch}/dη increases with √s:
  ⇒ Feynman scaling is violated (at currently available energies)

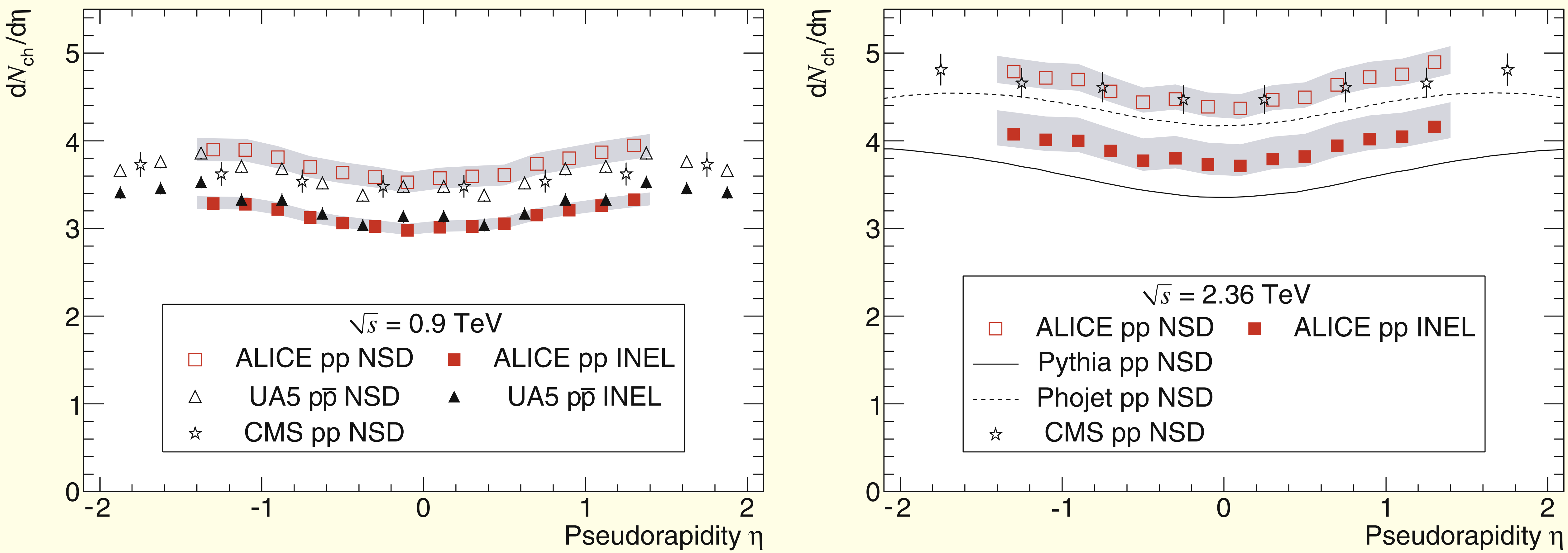
Range of Predictions Prior to First LHC p+p data

Jan Fiete Grosse-Oetringhaus, K.R., J. Phys. G. 37, 083001



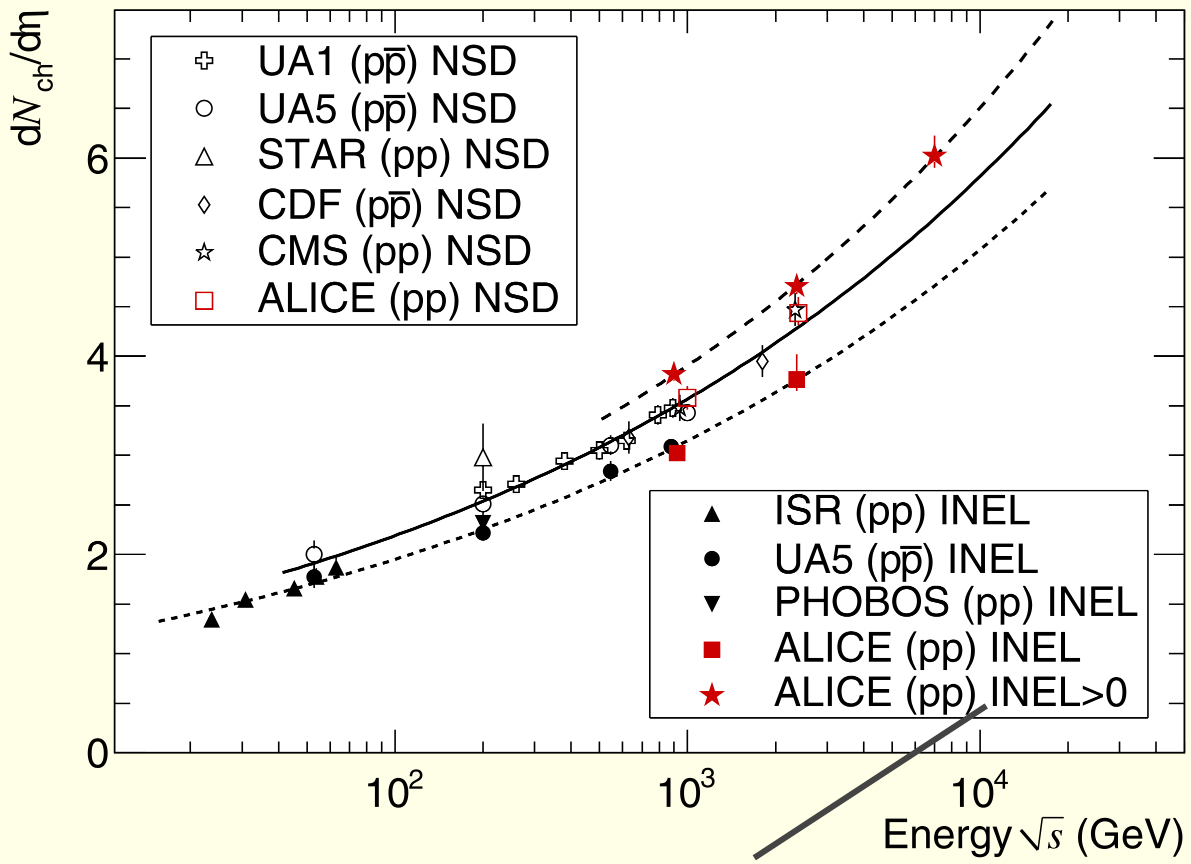
- Pythia tunes optimized with Tevatron data signifcantly below 7 TeV LHC data

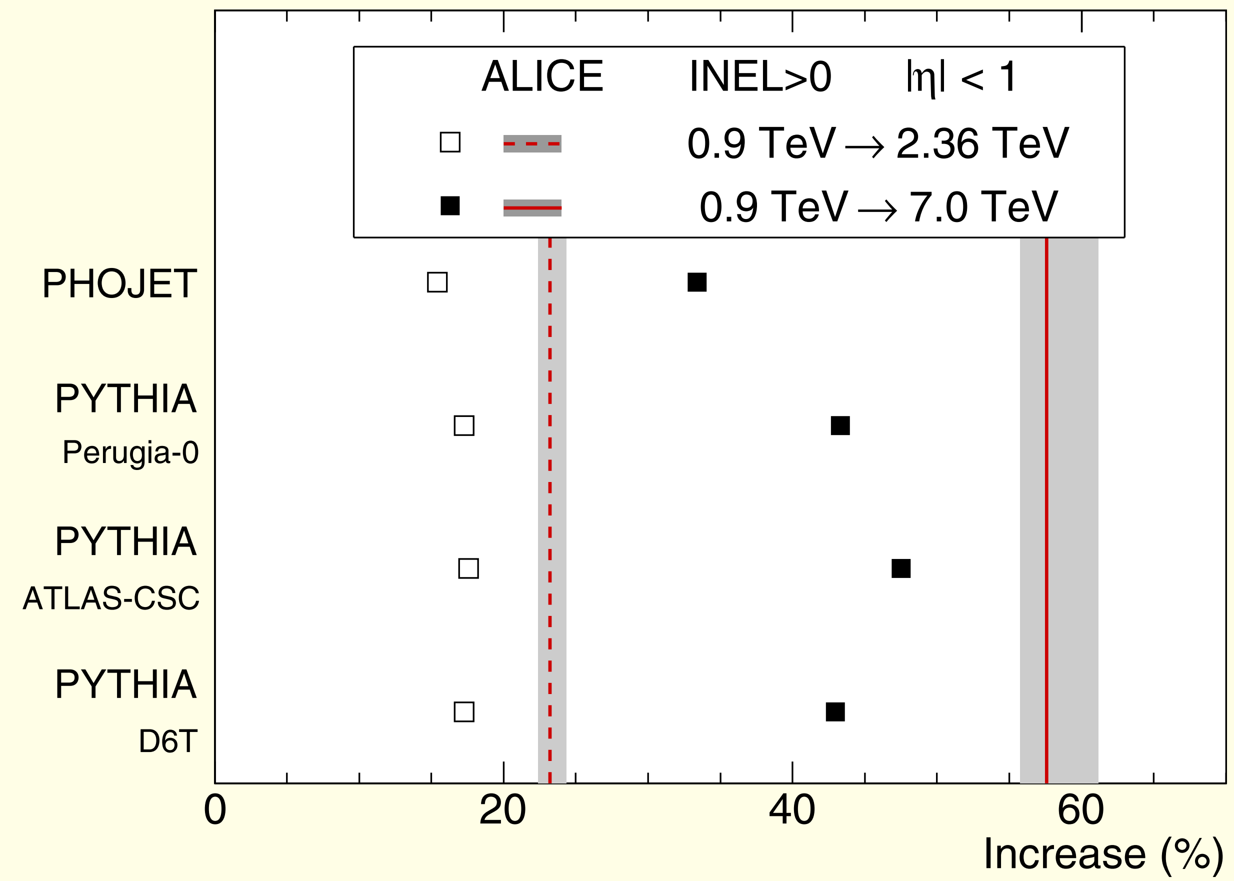
ALICE dN_{ch}/dη Results (I)



- Triggers for INEL and NSD results
  - INEL: SPD (|η|<2) OR V0-A OR V0-C
  - NSD: V0-A AND V0-C
- Good agreement between different experiments
- Pythia D6T tune (CMS) significantly below data

ALICE dN_{ch}/dη Results (II)

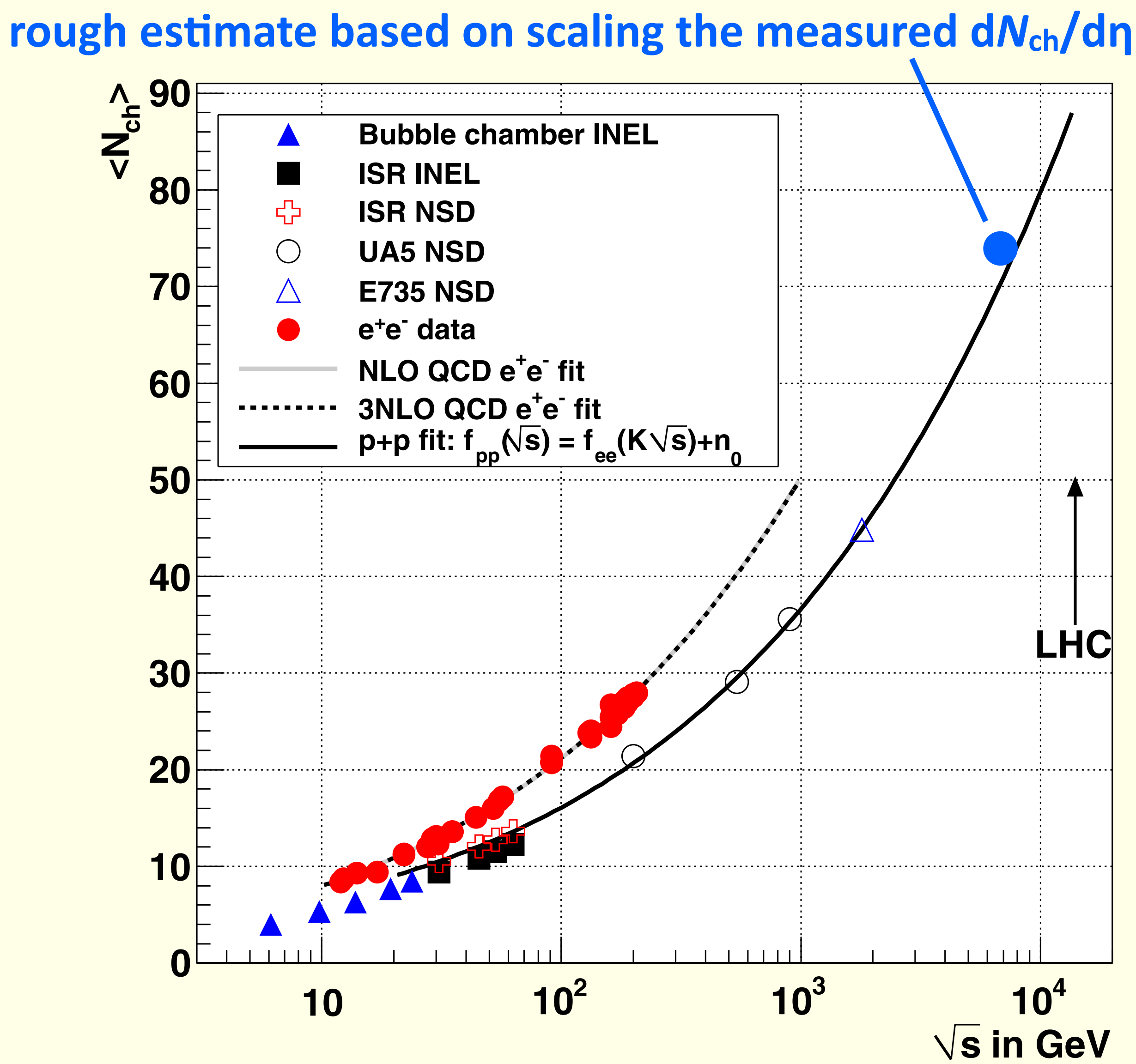


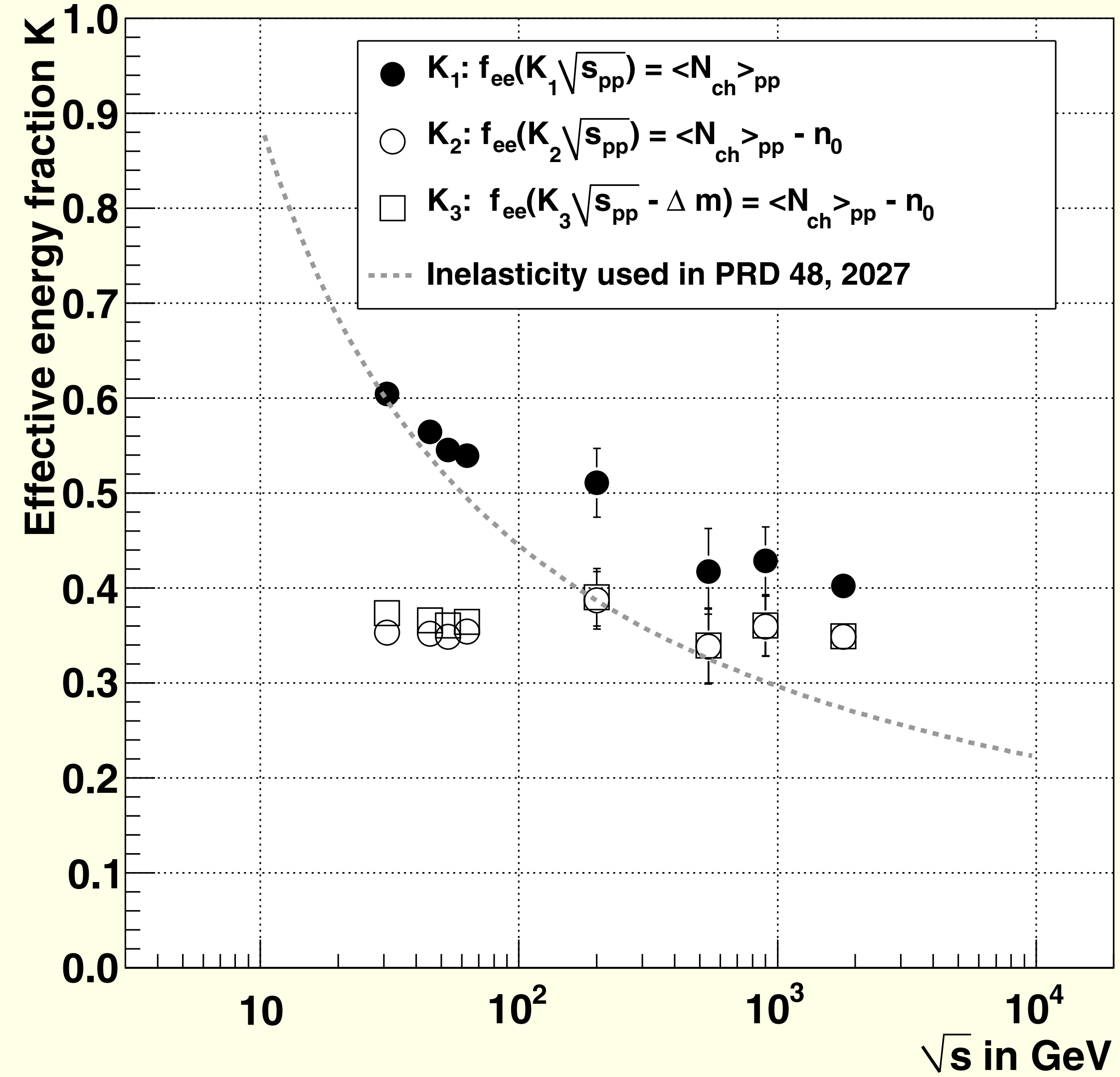


INEL > 0: at least one charged particle in |η| < 1

- Increase in dN_{ch}/dη from 0.9 TeV to 7 TeV: 60%
- Larger than predicted by Phojet and and most Pythia tunes

An Intriguing Similarity: Multiplicities in p+p and e^++e^-





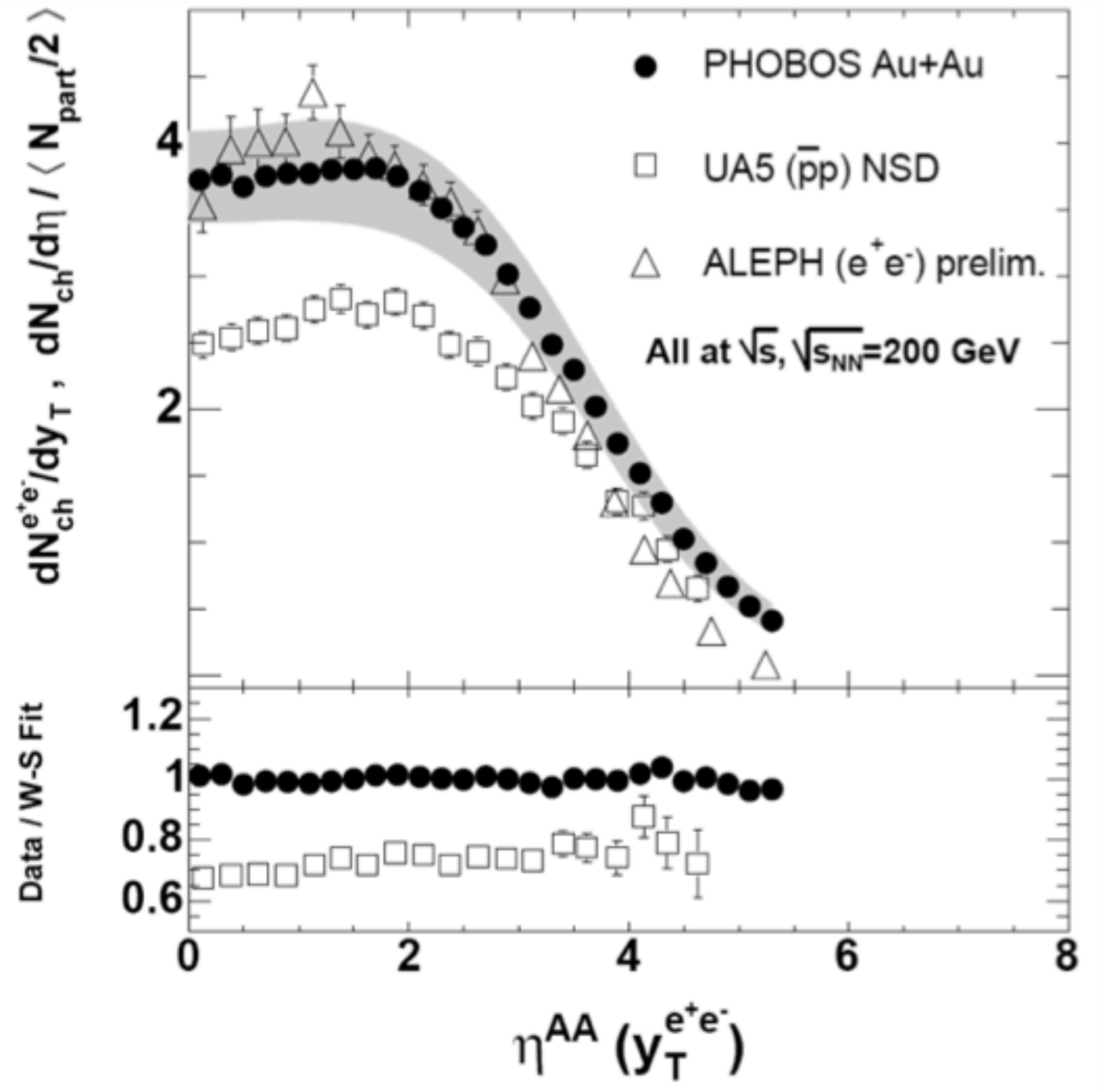
- Ansatz: In p+p only a certain fraction *K* of √s is available for particle production:

$$N_{ch}^{p+p}(\sqrt{s}) = N_{ch}^{e^+ + e^-}(K \cdot \sqrt{s}) + n_0$$

- Seems to work surprisingly well
- Inelasticity *K* at √*s* > 100 GeV somewhere between 0.3 - 0.5

Similarity of dN_{ch}/dy in e^+e^-, p+p, and A+A

PHOBOS, Nucl. Phys. A757, 28 (2005)



Rapidity w.r.t. thrust axis $\vec{n}_{\text{thrust}}$:

$$y_T = \frac{1}{2}\ln\left(\frac{E + \vec{p}\cdot\vec{n}_{\text{thrust}}}{E - \vec{p}\cdot\vec{n}_{\text{thrust}}}\right)$$

Remarkable similarity between particle production in e^++e^-, p+p, and A+A

Effectice energy fraction $K \approx 100\%$ in Au+Au

Hint at universal production mechanism?

4. Charged-Particle Multiplicity Distributions

Multiplicity Distributions: Basics

- Multiplicity distribution (MD): Probability distribution for the production of *n* (charged) particles

$$P_n = \frac{\sigma_n}{\sum_n \sigma_n}$$

- Contains information on particle production mechanism and particle correlations

- Analysis of MD's via moments

mean: $\langle n \rangle$

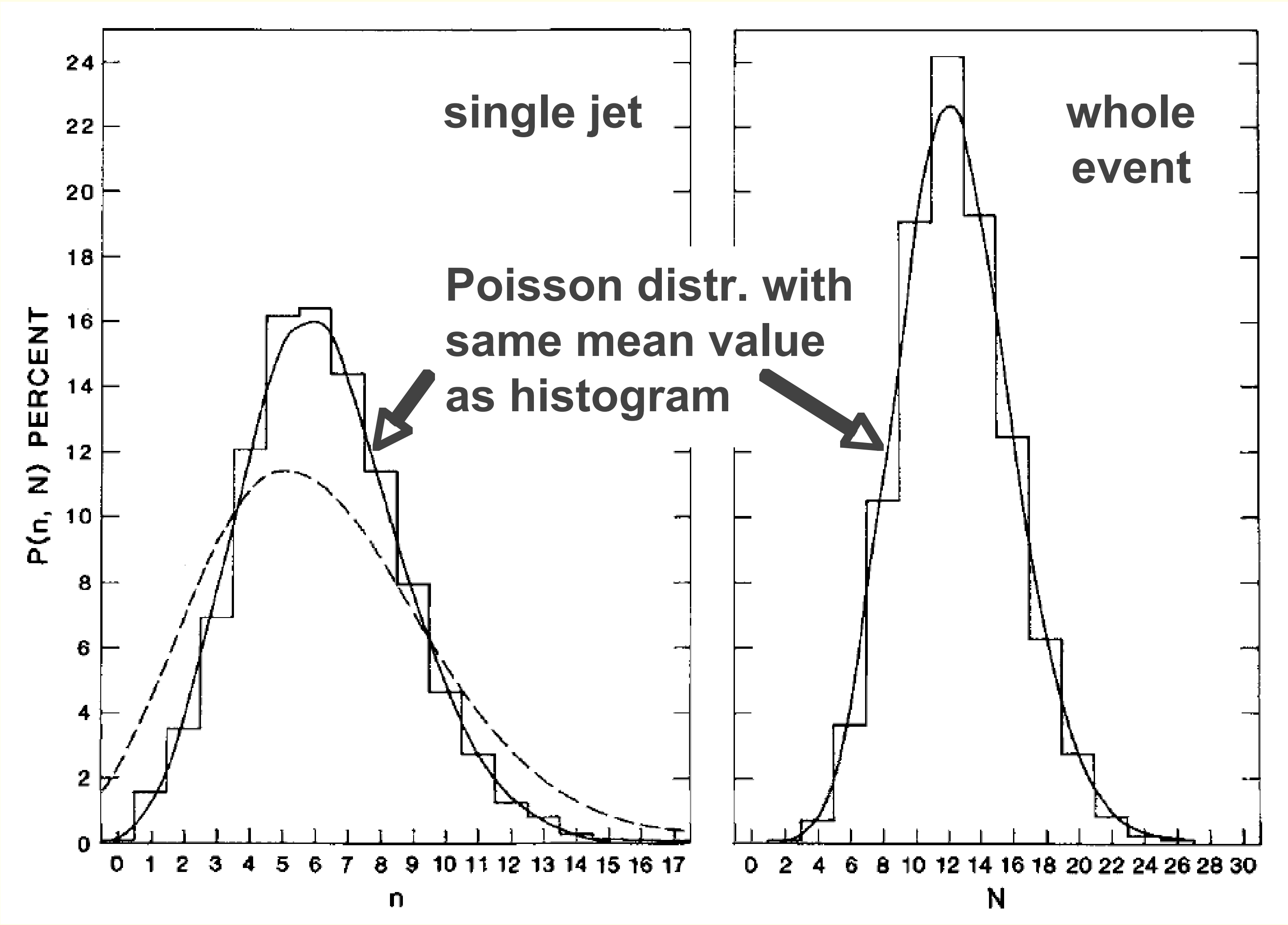
dispersion: $D = \sqrt{\langle n^2 \rangle - \langle n \rangle^2}$

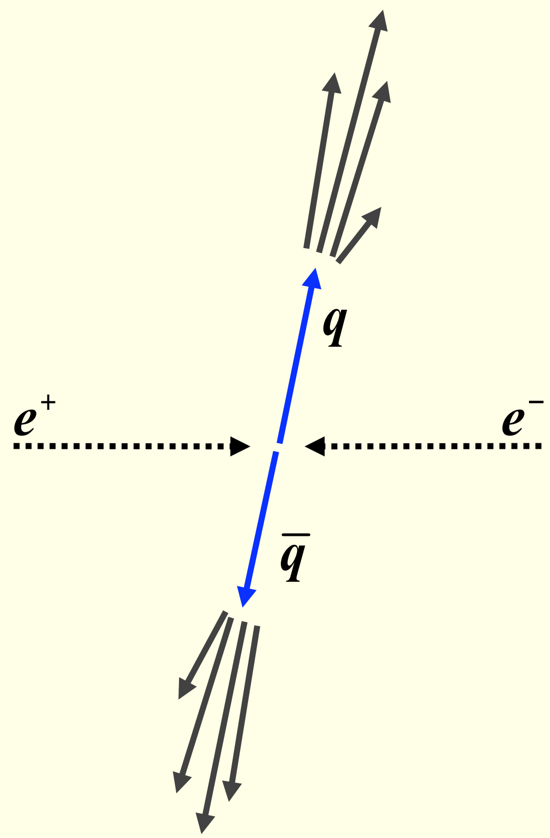
- In the absence of correlations (independent particle production)

P_n = **Poisson distr.**

$$P_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}, \quad D = \sqrt{\langle n \rangle}$$

Multiplicity Distributions (MDs) in e^+e^- at $\sqrt{s}$ = 29 GeV





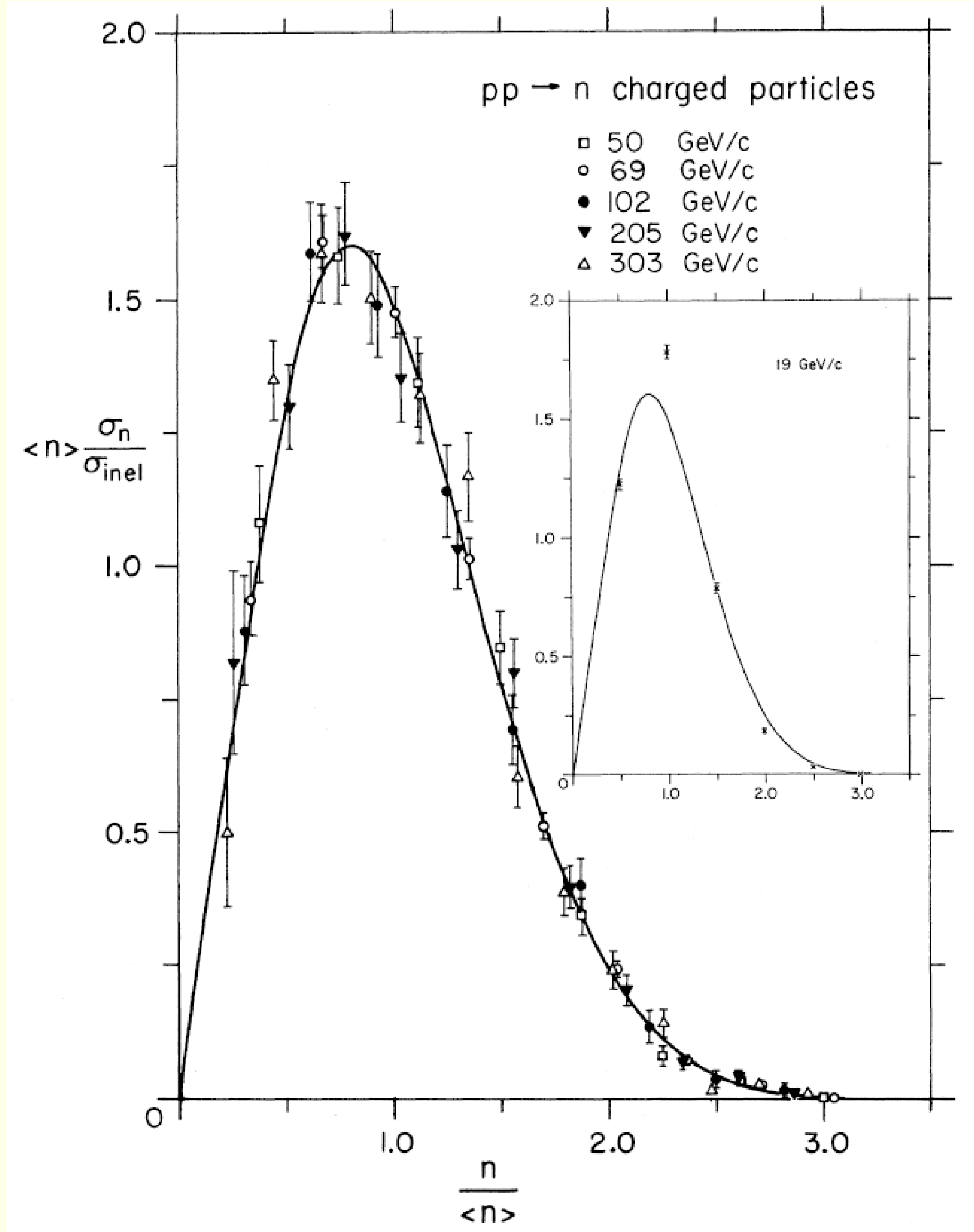
- Multiplicity distributions in e^+e^- at $\sqrt{s}$ = 29 GeV follow a Poisson distribution
- However, it turned out that this is true only for this particular energy
- MDs in p+p are generally broader than in e^+e^-: Impact parameter fluctuations?

Brief History of Multiplicity Measurements (I): KNO Scaling

- Interest in multiplicity distributions was stimulated by a paper of Koba, Nielsen and Olesen in 1972
- Based on Feynman scaling they derived theoretically that multiplicity distributions at asymptotically high energies should follow a universal function

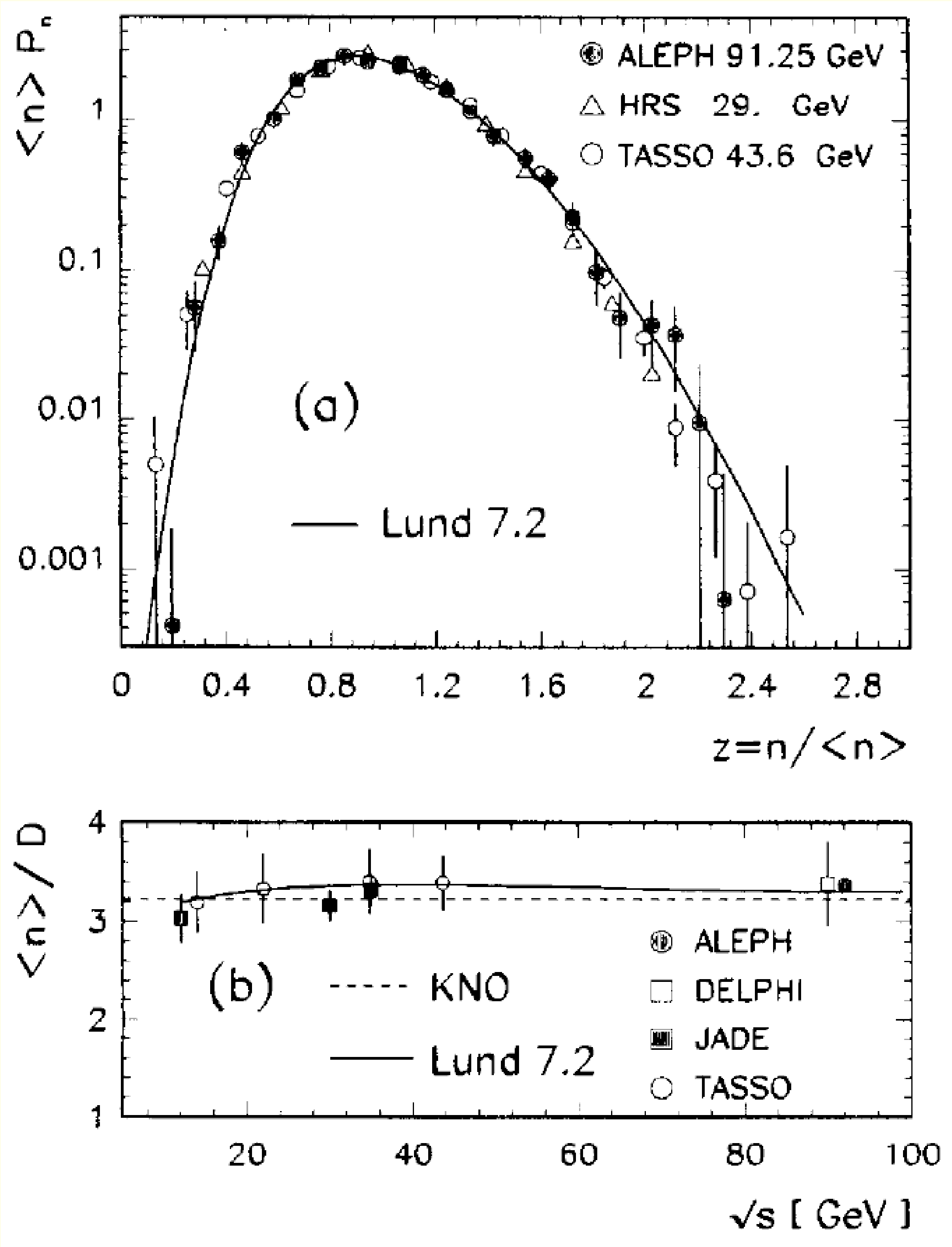
$$\Psi(z) := \langle n \rangle \cdot P_n \quad \text{with} \quad z = \frac{n}{\langle n \rangle} \qquad \text{(KNO scaling)}$$

- Approximately satisfied in p+p collisions with $\sqrt{s}$ < 63 GeV



Koba, Nielsen, Olesen, Nucl. Phys. B 40, 317 (1972)
P. Slattery, Phys. Rev. Lett. 29, 1624 (1972)

Brief History of Multiplicity Measurements (II): KNO Scaling in e^+e^-



- KNO scaling also observed in e^+e^- for $29 < \sqrt{s} < 91$ GeV
- KNO scaling implies

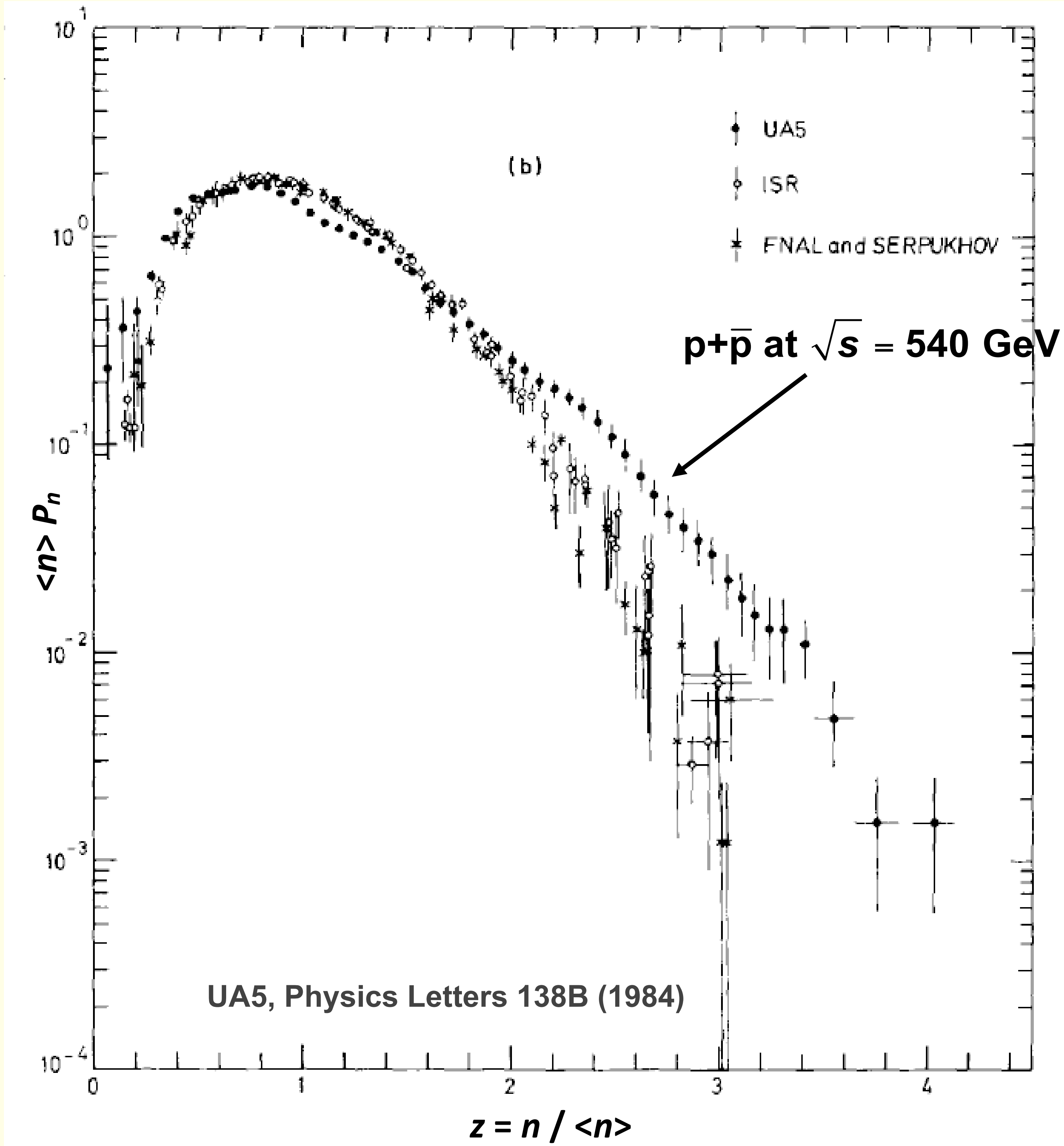
$$\langle n \rangle / D = \text{const.}$$ (confirmed by data)

- Connection to QCD
  - KNO scaling in jet fragmentation can be derived from QCD
  - Next-to-leading order pQCD

$$R_2 := \frac{\langle n(n-1) \rangle}{\langle n \rangle^2} = \frac{11}{8}\left(1 - 0.55\sqrt{\alpha_s}\right)$$

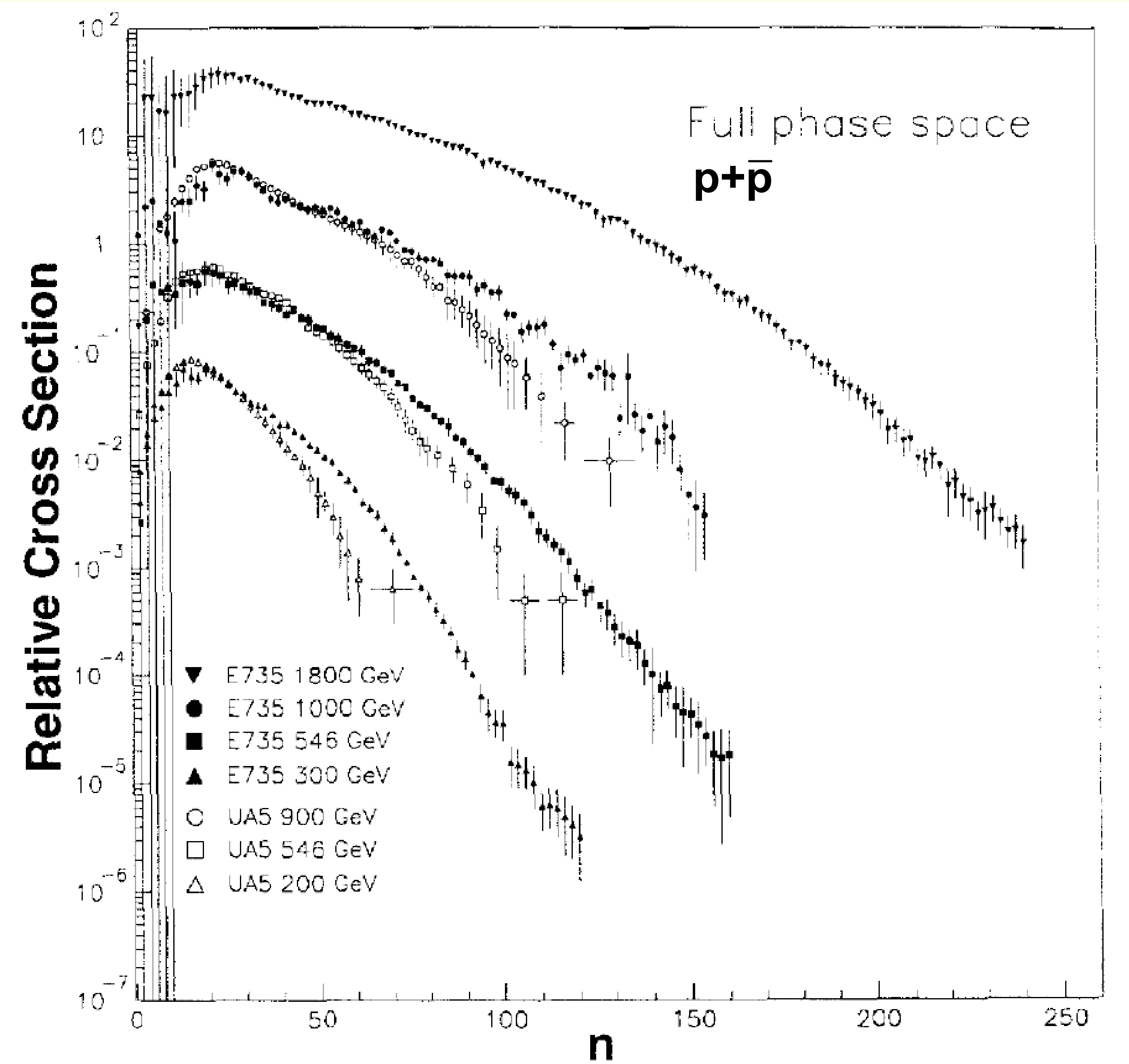
Aleph, Physics Reports 294, 1, (1998)
Malaza, Webber, Nucl. Phys. B 267, 702 (1986)

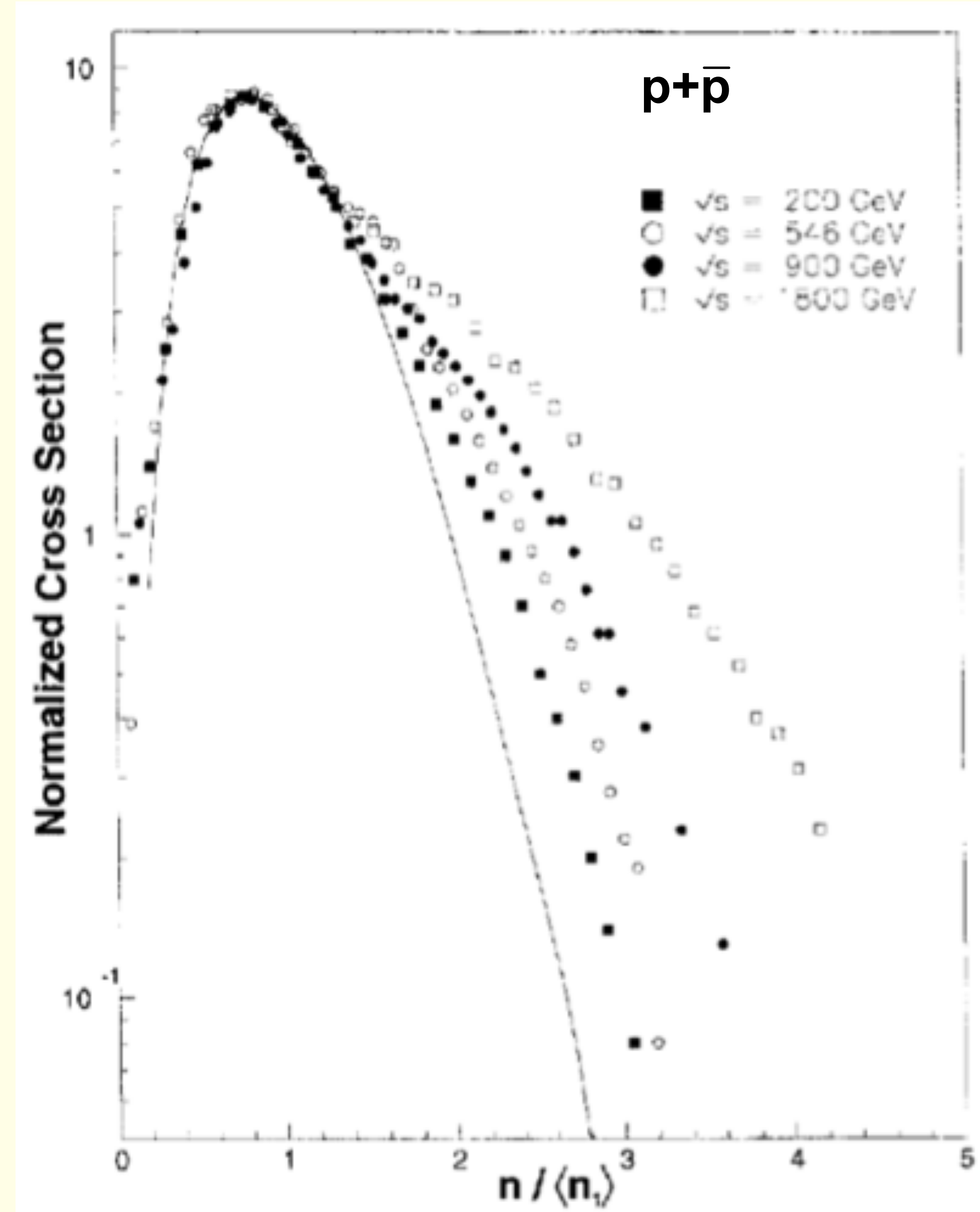
Brief History of Multiplicity Measurements (III): Violation of KNO Scaling Discovered by UA5



Deviation from KNO form observed at √*s* = 540 GeV

Brief History of Multiplicity Measurements (IV): Confirmed by E735 at the Tevatron





E735, Phys. Lett. B435, 453 (1998)

Deviation from KNO form visible for √*s* > ~200 GeV

A New Empirical Description: The Negative Binomial Distribution

UA5, Phys. Rep. 154, 247 (1987)

UA5 discovered that the negative binomial distribution (NBD) provides an excellent representation of multiplicity distributions in p+p (p+pbar)

$$P_n^{NB}(\mu, k) = \binom{n+k-1}{n} \left(\frac{\mu}{\mu + k} \right)^n \left(\frac{k}{\mu + k} \right)^k$$

First two moments:

$$\langle n \rangle = \mu, \qquad D = \sqrt{\langle n^2 \rangle - \langle n \rangle^2} = \sqrt{\mu \left(1 + \frac{\mu}{k} \right)}$$

NBD is broader than the Poisson distribution. In the limit $k \to \infty$ it turns into a Poisson distribution.

$1/k \to 0:$	Poisson distribution
$k = 1:$	Bose-Einstein distribution
integer $k, k < 0:$	Binomial distribution $(N = -k, p = -\langle n \rangle / k)$

Hence the name NBD

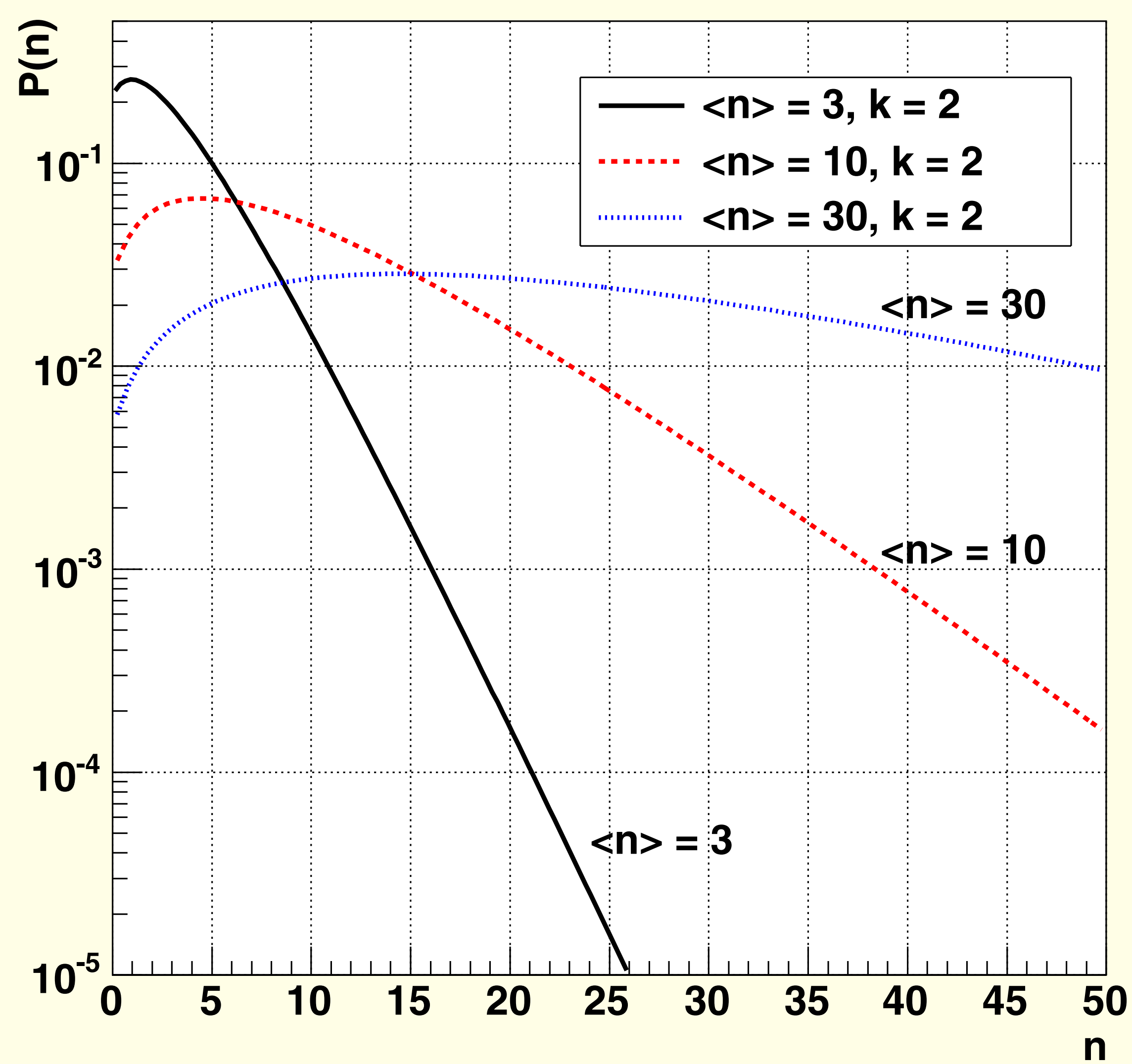
Mathematical Digression: NBD (I)

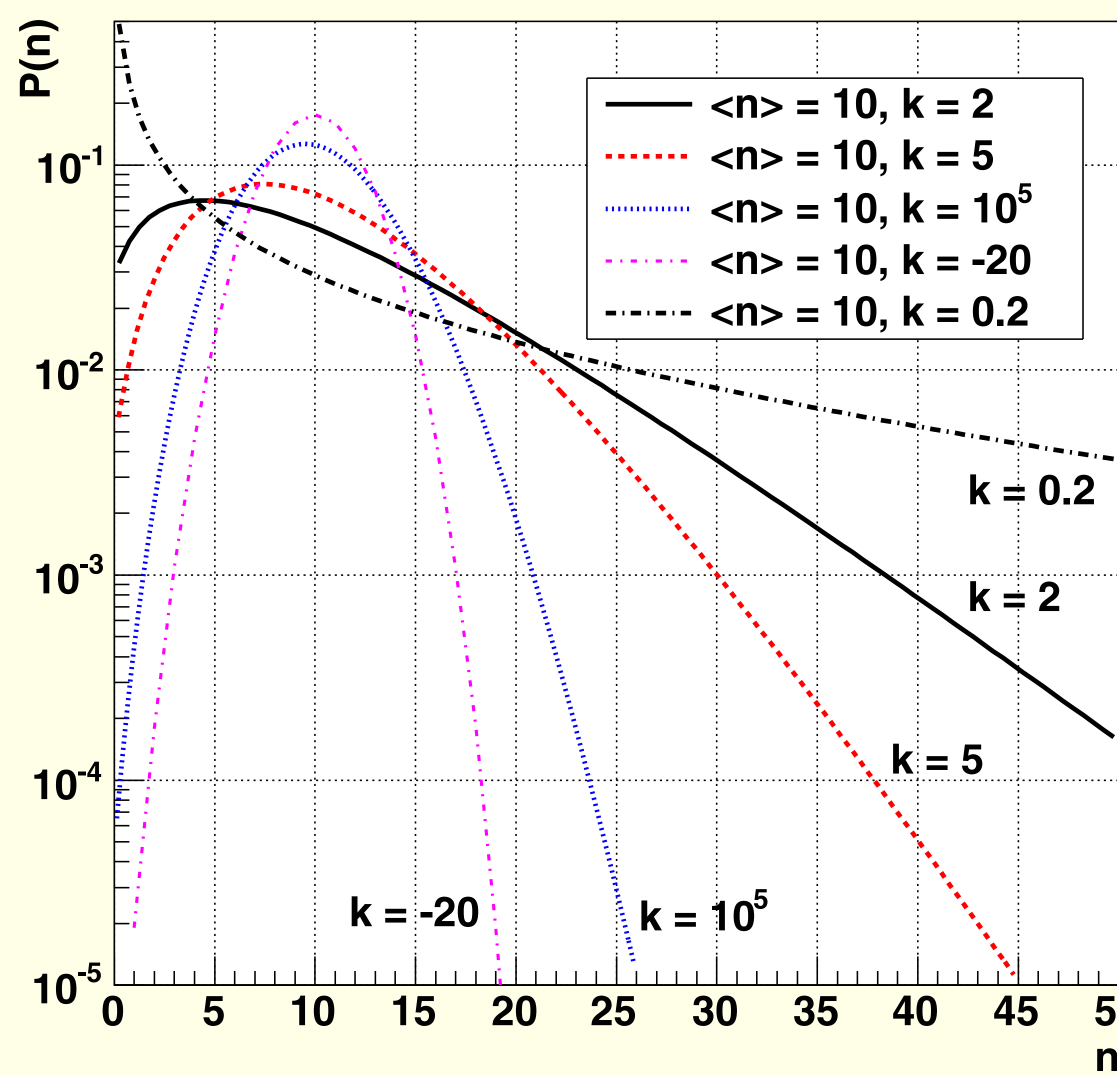
Note that for any real number $x > 0$ we have $x! := \Gamma(x+1)$, thus:

$$\binom{n+k-1}{n} = \frac{(n+k-1)!}{n!(k-1)!} = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)}$$

$$= \frac{(n+k-1)\cdot(n+k-2)\cdot\ldots\cdot k}{\Gamma(n+1)}.$$

Examples of the NBD‘s for different parameters:





Mathematical Digression: NBD (II)

- Urn model with success probability *p* (balls placed back to the urn): Probability for *n* failures prior to the *k*-th success

$$P_{p,k}^{\mathrm{NBD}}(n) = \binom{n+k-1}{n} (1-p)^n \; p^k$$

- Thus, in contrast to the binomial distribution the number of draws is not fixed

- The mean <*n*> of the distribution is related to *p* by: $p^{-1} = 1 + \langle n \rangle / k$

- This leads to the form of the NBD that is used to describe multiplicity distributions and was presented before

- NBD has many practical applications
  - accident statistics
  - many biological applications, e.g., number ticks per sheep (R.A. Fisher)
  - number of kids with *n* = 0, 1, 2, ... cavities in their teeth

The NBD Describes Multiplicity Distributions in Many Systems

NBD describes multiplicity distributions in

- e^+e^-
- Hadron-hadron
- Lepton-hadron
- Hadron-nucleus

- Underlying explanation remains a mystery so far
- Possible explanations
  - Cascading or clan models
  - Stimulated Emission
  - No physical explanation?

Clan (or Cluster) Model

A. Giovannini, L. Van Hove, CERN-Th.4894/87

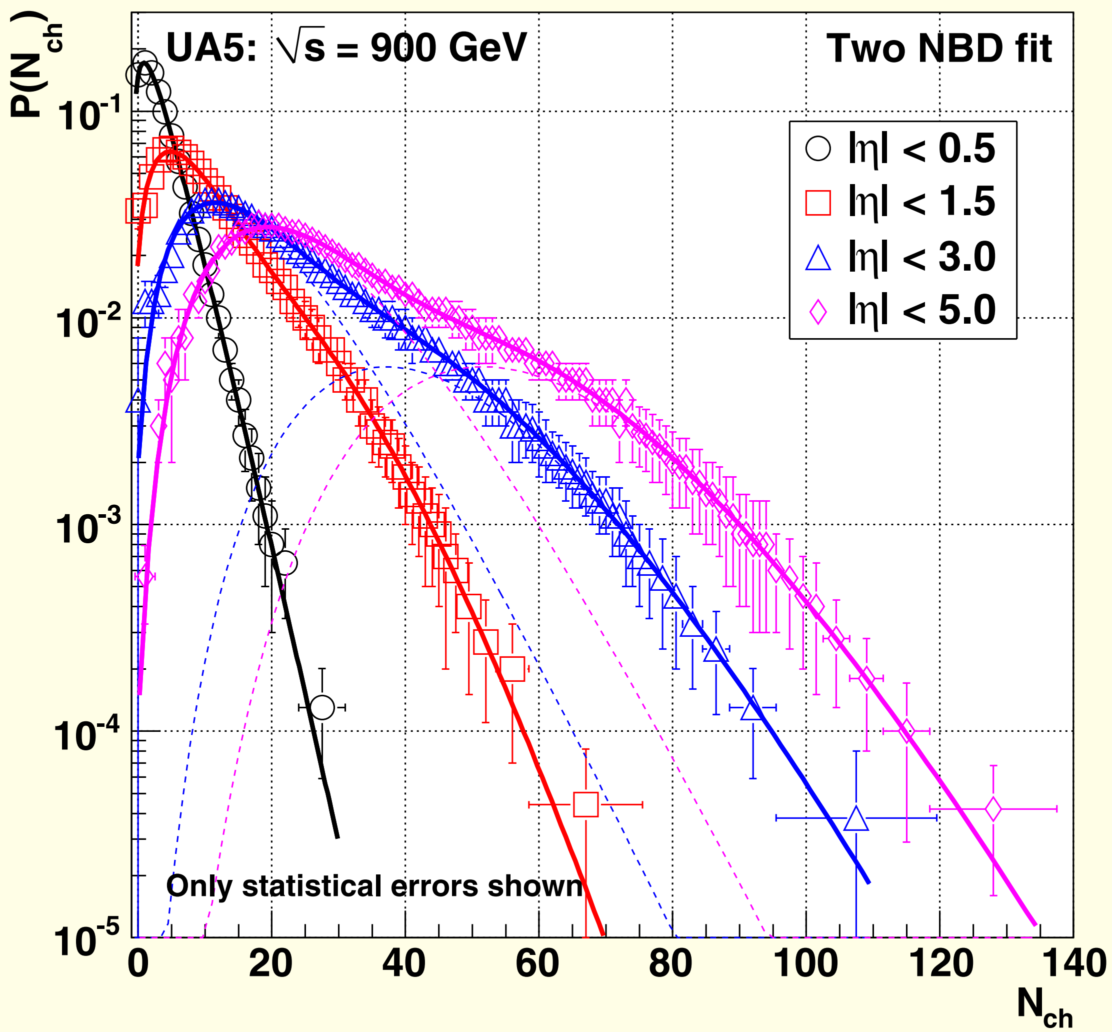
- N ancestor particles are produced independently (Poisson distribution)
- An ancestor particles decays into n_C charged particles (the “clan”)
- The production of an additional particle in a clan is proportional to the number of already existing particles
- $\langle N \rangle$, $\langle n_C \rangle$ from NBD parameters μ, k:

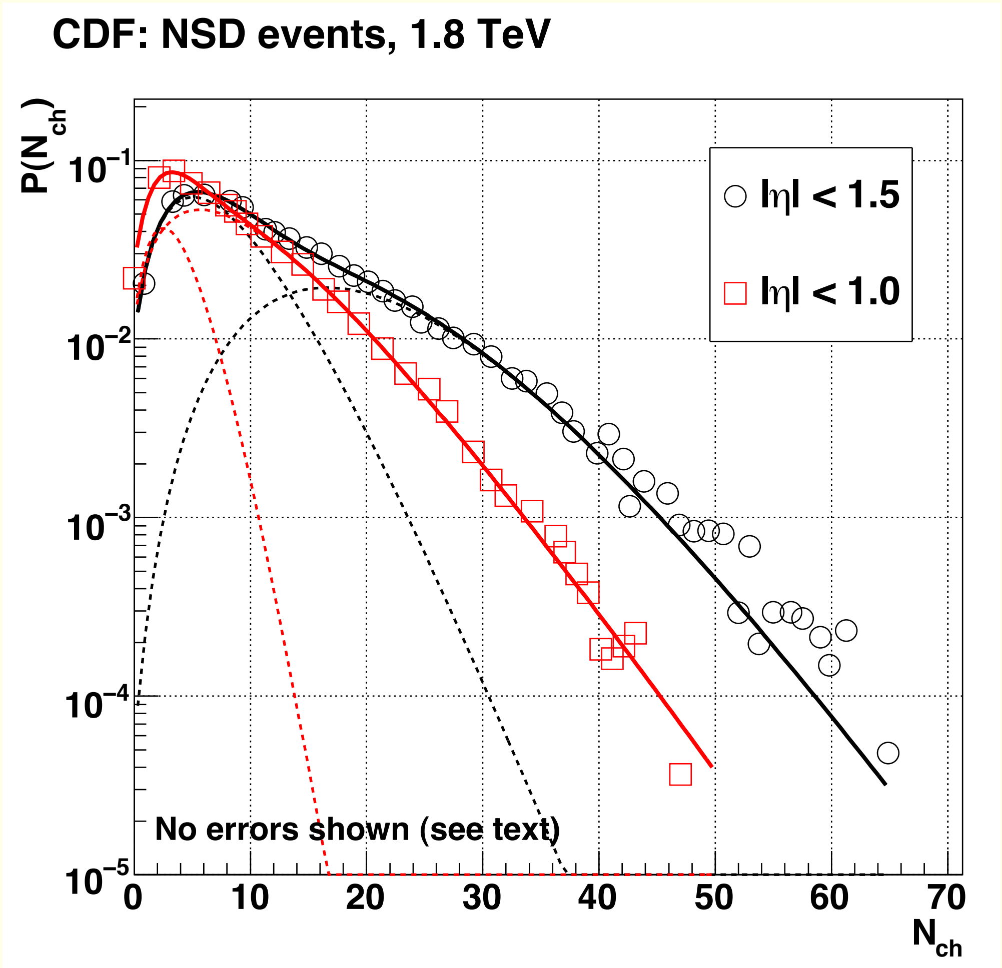
$$\langle N \rangle = \frac{\langle n \rangle}{\langle n_c \rangle} = k \ln \left(1 + \frac{\langle n \rangle}{k} \right)$$

- k is a measure of the aggregation of particles in clans.
  In particular, for the case of particle multiplicity $n = 2$:

$$k^{-1} = \frac{P_1(2)}{P_2(2)} \quad \text{where} \quad \begin{cases} P_1(2): \text{ Probability for 1 clan} \\ P_2(2): \text{ Probability for 2 clans} \end{cases}$$

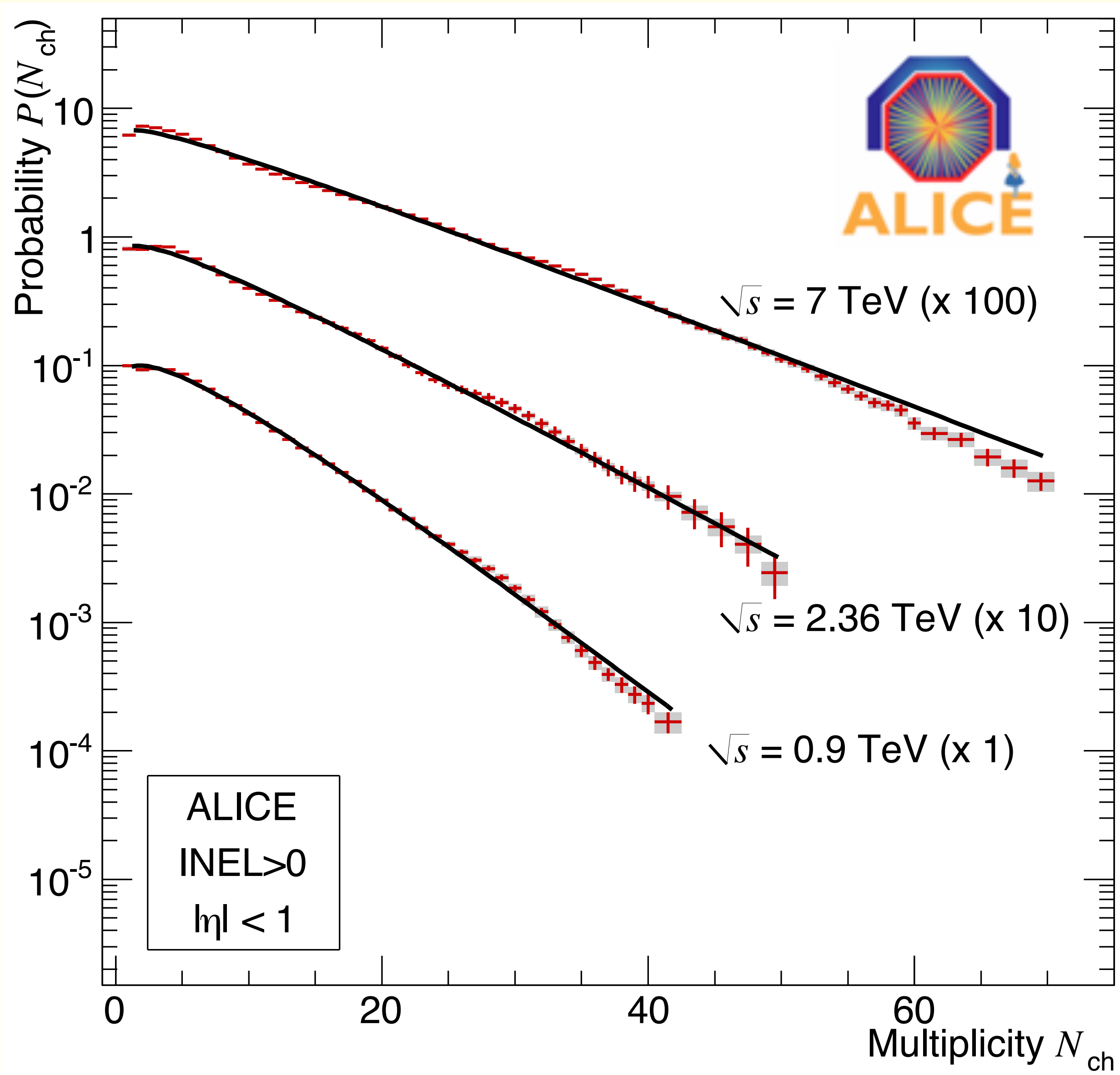
Deviations from NBD Discovered by UA5

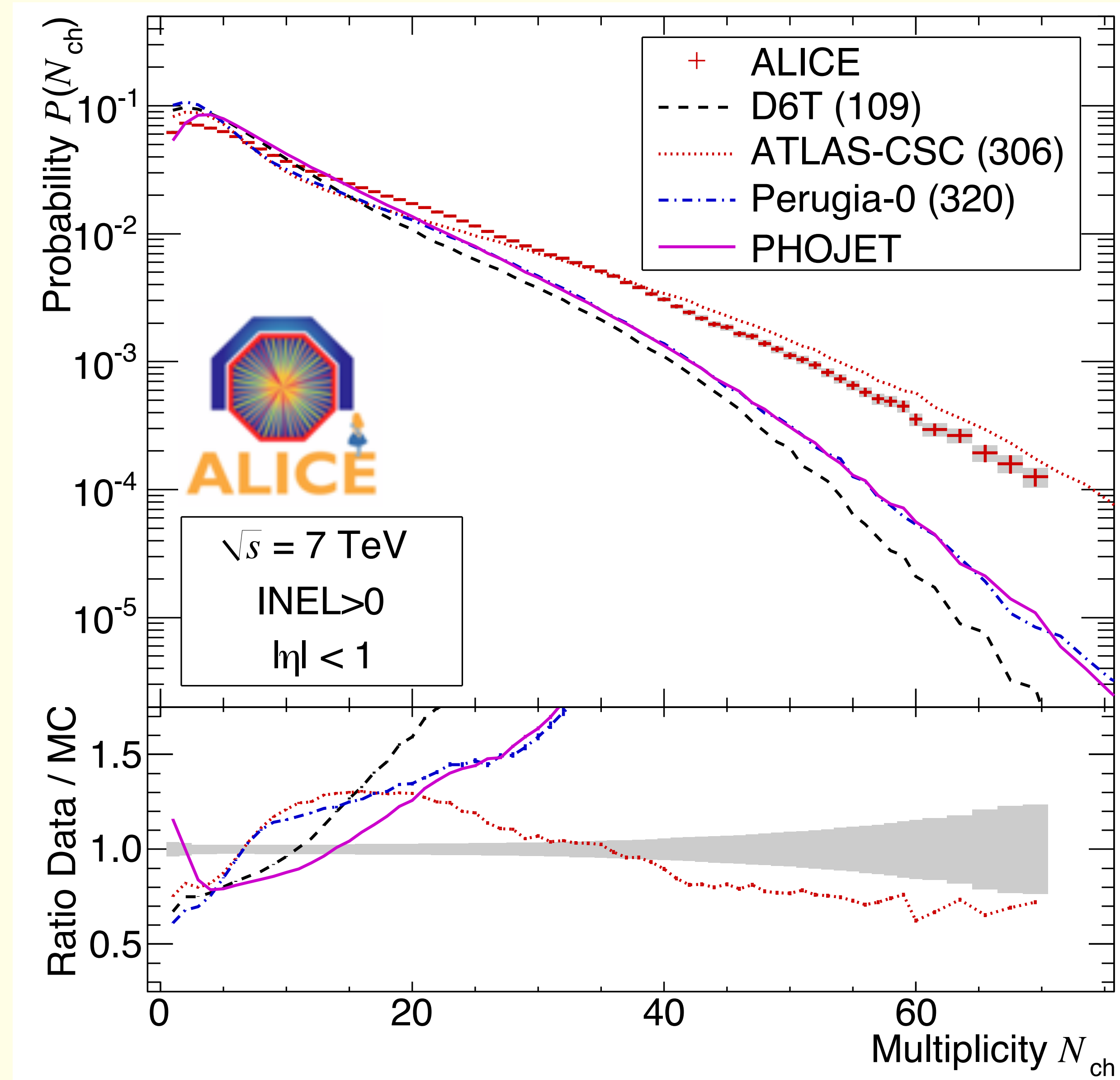




- UA5 found that multiplicity distributions in the full η-interval up to √s = 540 GeV can be well described by a NBD
- Deviations from the NBD were discovered by UA5 at √*s* = 900 GeV and later confirmed at the Tevatron at √*s* = 1800 GeV (shoulder structure at $n \approx 2 \langle n \rangle$)
- This lead to two-NBD models (interpreted as soft and hard component)
- In limited η-intervals (|η| < 0.5) NBD describes the distributions up to 1.8 TeV

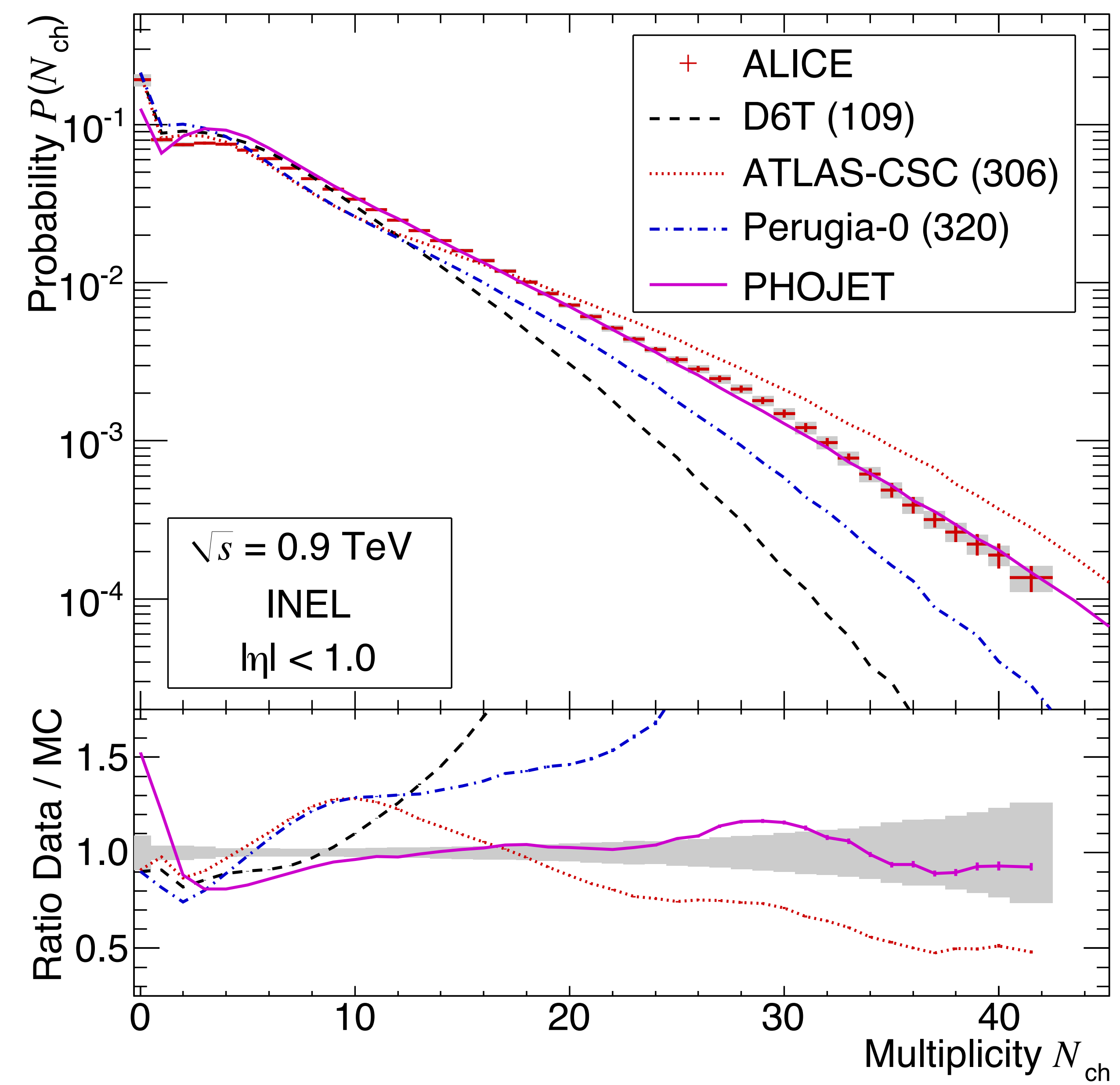
Multiplicity Distributions from Alice (√s = 0.9, 2.36, 7 TeV)

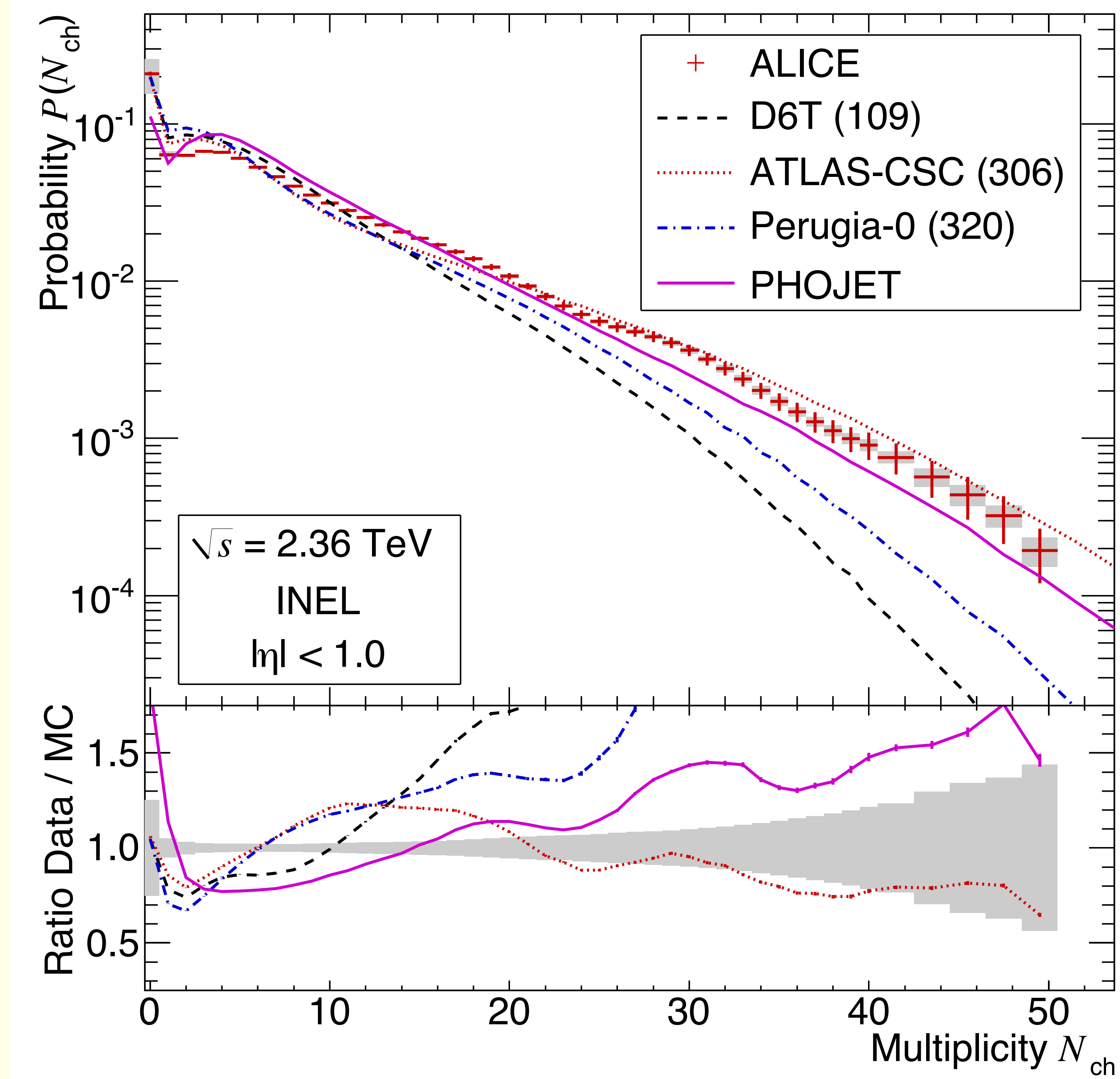




- MD up to 7 TeV for |η| < 1 fairly well described by a single NBD
- Neither Phojet nor various Pythia tunes provide a good description of the data

Multiplicity Distributions from Alice: Comparison to Data at √s = 0.9 and 2.36 TeV



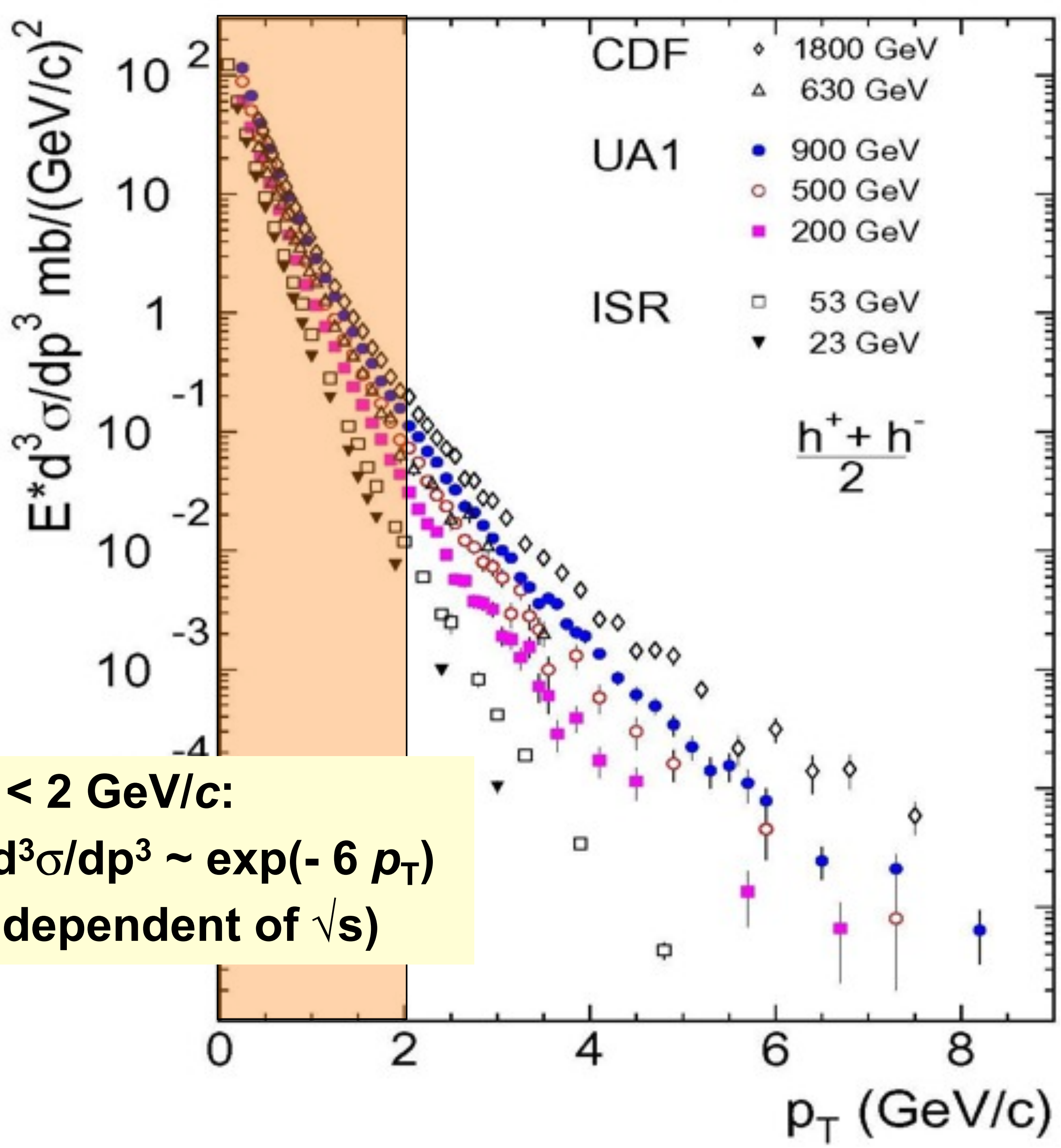


- Same trend as observed at 7 TeV

5. Transverse momentum spectra

Particle Production: Hard vs. Soft Processes (I)

p_T spectra of charged particles for various √s



p_T < 2 GeV/*c*:
$E \cdot d^3\sigma/dp^3 \sim \exp(-6\, p_T)$
(independent of √s)

High p_T part of the spectrum flattens with increasing √s

Low p_T (< 2 GeV/c):

$$\frac{1}{p_\mathrm{T}}\frac{\mathrm{d}N_x}{\mathrm{d}p_\mathrm{T}} = A(\sqrt{s}) \cdot e^{-6\,p_\mathrm{T}}$$

High p_T:

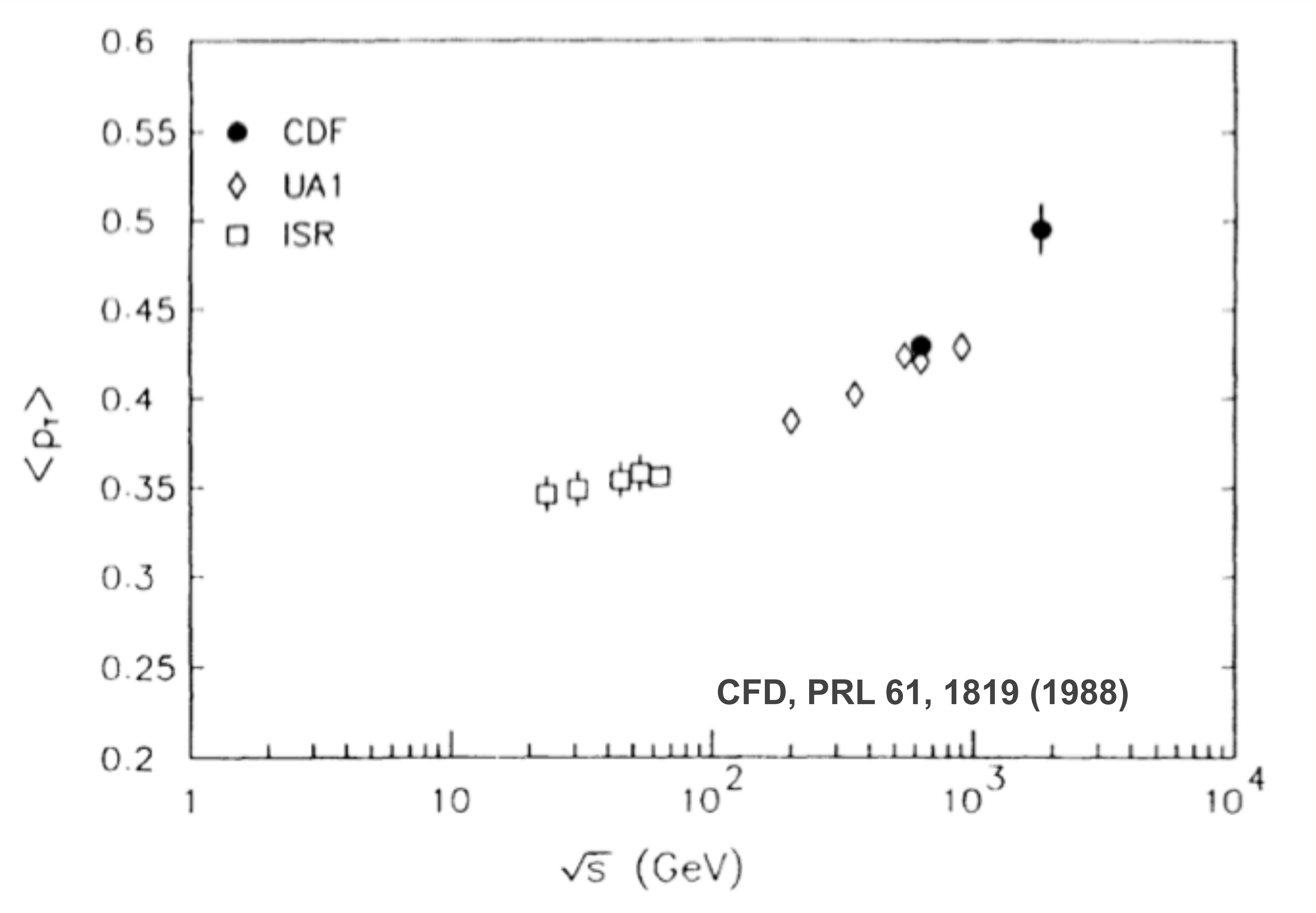
$$\frac{1}{p_\mathrm{T}}\frac{\mathrm{d}N_x}{\mathrm{d}p_\mathrm{T}} = A(\sqrt{s}) \cdot \frac{1}{p_\mathrm{T}^n}$$

Average transverse momentum:

$$\langle p_\mathrm{T} \rangle = \frac{\int_0^\infty p_\mathrm{T} \frac{\mathrm{d}N_x}{\mathrm{d}p_\mathrm{T}} \mathrm{d}p_\mathrm{T}}{\int_0^\infty \frac{\mathrm{d}N_x}{\mathrm{d}p_\mathrm{T}} \mathrm{d}p_\mathrm{T}} \approx 300 - 400 \text{ MeV}/c$$

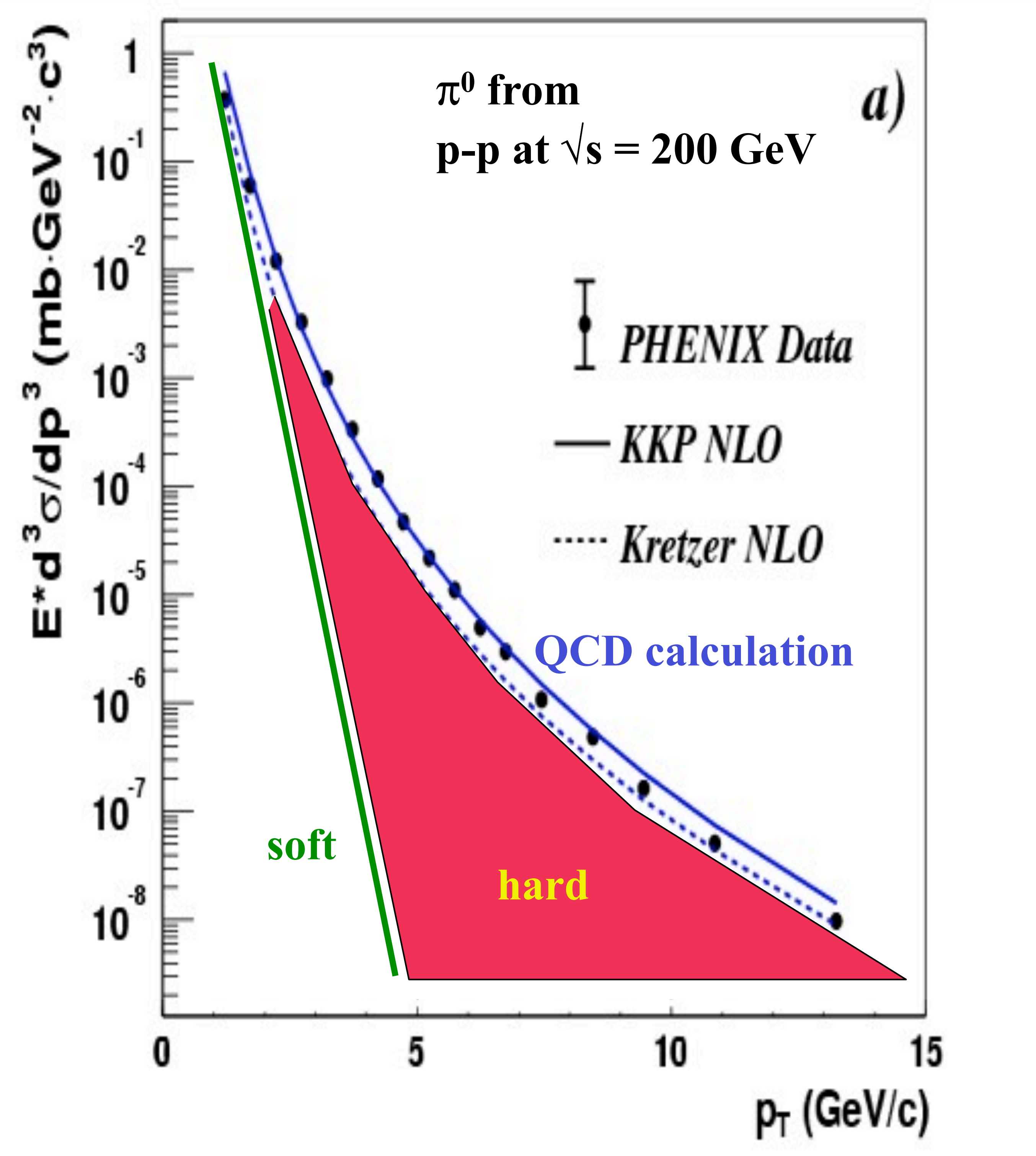
Fairly independent of √s (up to √s = 100 GeV)

Particle Production: Hard vs. Soft Processes (II)
$\langle p_T \rangle$ vs. $\sqrt{s}$ in p+p(bar)



Increase of $\langle p_T \rangle$ (most likely) reflects increase in hard scattering

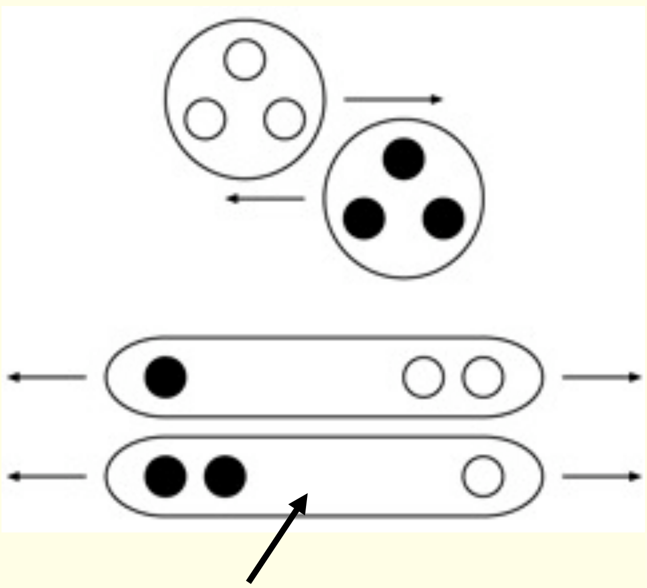
Particle Production: Hard vs. Soft Processes (III)



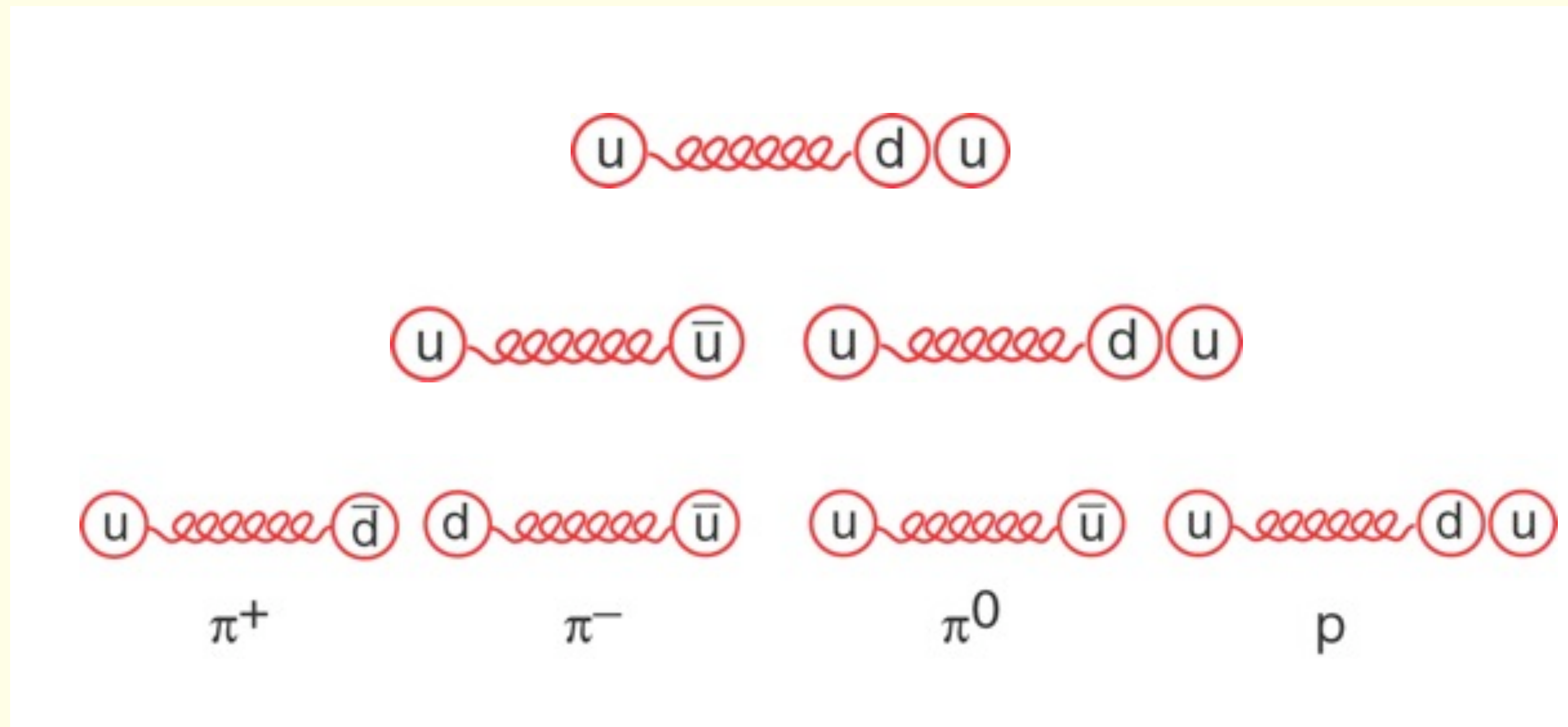
Hard vs. soft particle production

Particle Production: Hard vs. Soft Processes (IV): String Models

A model for soft particle production: the string model



"fragmentation of the beam jet"



Strings:

- Due to self-interaction of the gluons the field between two color charges forms a color flux tube (string)
- Transverse size: ~ 1 fm
- Energy density of a string: ~ 1GeV/fm

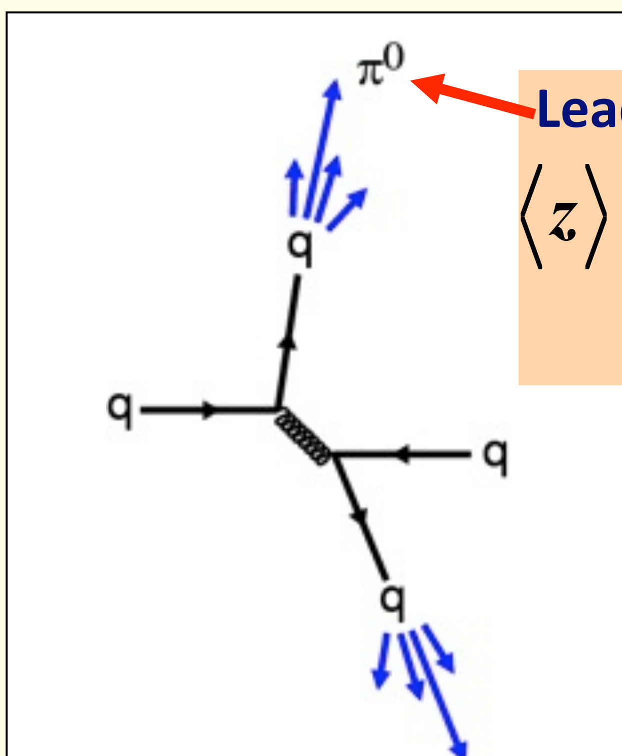
String fragmentation models explain:

- $\sqrt{s}$ independence of the p_T of produced particles (p_T ~ 350 MeV/c) („string breaking is a local process")
- Shape of the rapidity distribution of produced particles, in particular the plateau at mid-rapidity

Particle Production: Hard vs. Soft Processes (V): Hard Scattering

Hard scattering: Particle production at high p_T

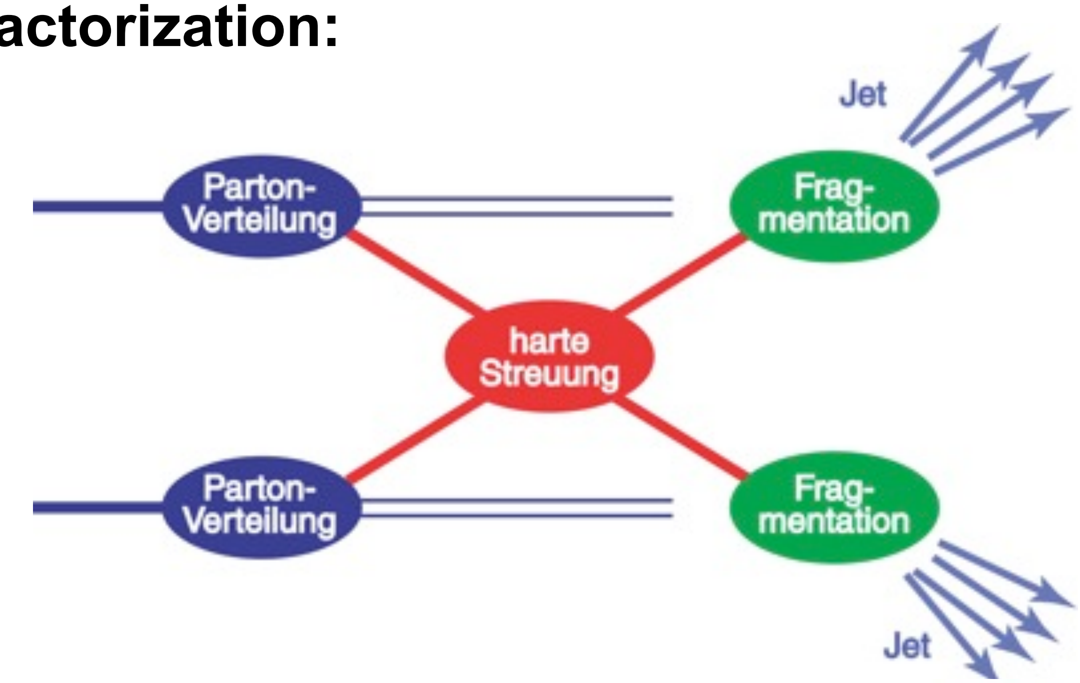
- Scattering of pointlike partons described by QCD perturbation theory (pQCD)
- Soft processes described by universal, phenomenological functions
  - Parton distribution function from deep inelastic scattering
  - Fragmentation functions from e^+e^- collisions



Leading hadron:

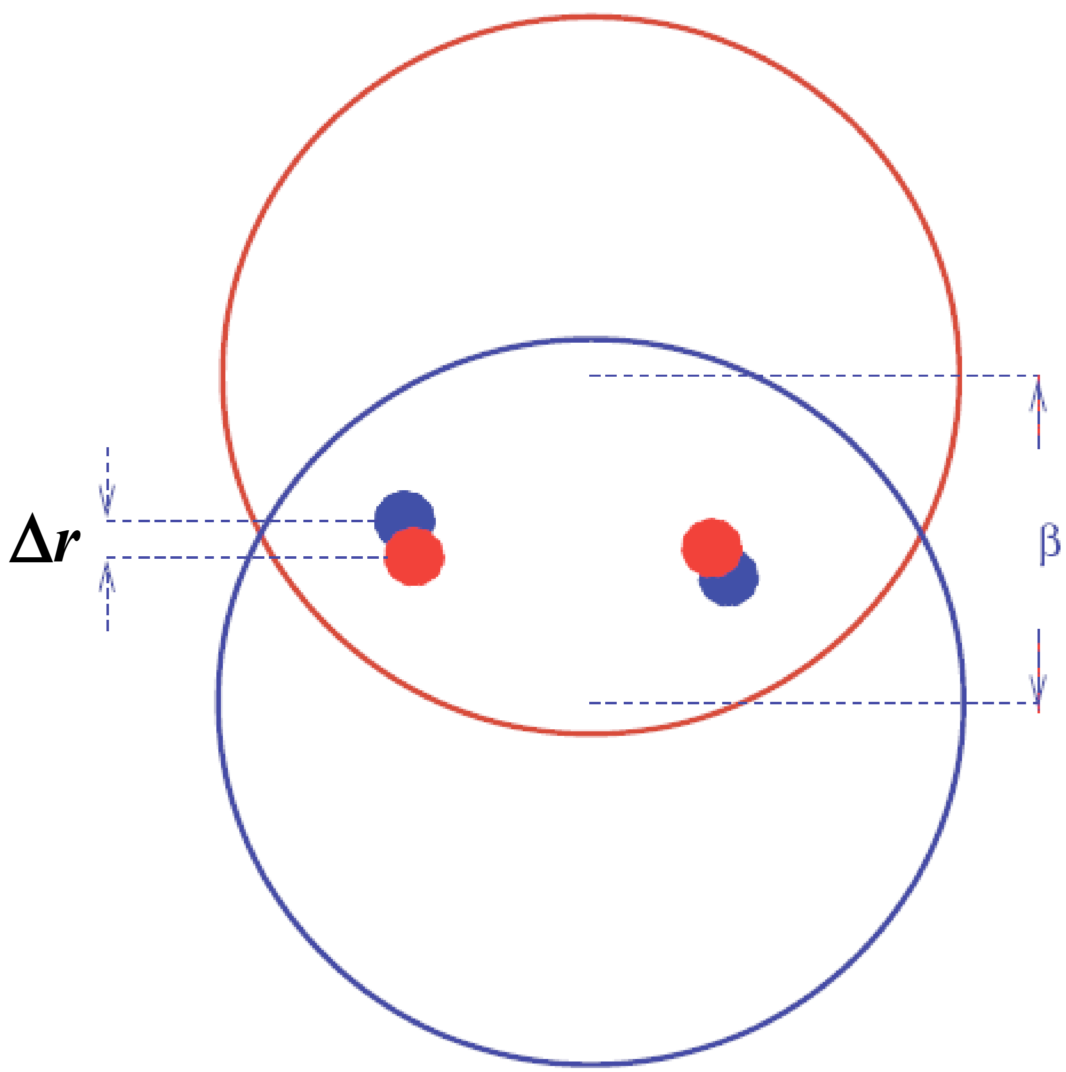
$$\langle z \rangle = \langle p_{\text{hadron}} / p_{\text{parton}} \rangle \approx 0.25$$

factorization:



$$d\sigma = \sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{c}_{ab} \otimes D_c^{Hadron}$$

Multiple Parton Interactions (I):
What are Multiple Partonic Interactions?



$$\Delta p_T^{\min} \cdot \Delta r \approx \hbar$$

$$\Delta r \approx \frac{\hbar c}{\Delta p_T^{\min} \cdot c} = \frac{0{,}2\ \text{GeV fm}}{\Delta p_T^{\min}\ (\text{GeV})}$$

Multiple parton interaction:

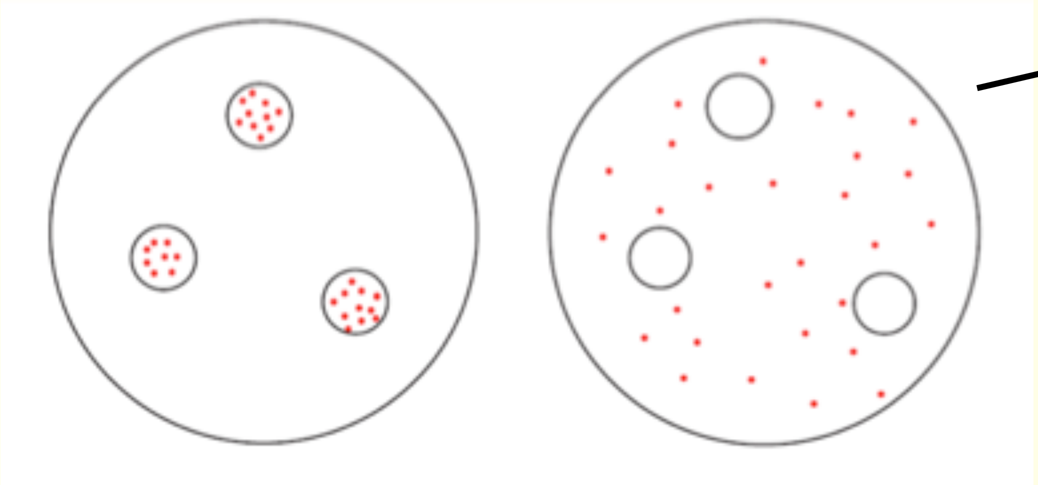
- Two or more pairs of partons interacting in the same inelastic p+p collision
- Momentum transfer larger than some lower cut-off p_T^{min} which establishes the hard scale
- p_T^{min} should correspond to a transverse size much smaller than the overlap area
- Thus, the two interaction region are well separated in space and should add incoherently to the cross section

Multiple Parton Interactions (II):
Motivation for Studying Multiple Parton Interactions

- Important for understanding of minimum bias p+p collisions at the Tevatronand the LHC
  - Tevatron: ~ 2 – 6 hard interactions per collision
  - LHC: ~ 4 – 10 hard interactions per collision

- Understanding of the “underlying event” important in specialized analyses, e.g., Higgs searches
  - Pedestal effect:
    Events with high-p_T jets have more underlying activity than minimum-bias events

- Study distribution of the partons in the plane transverse to the beam axis



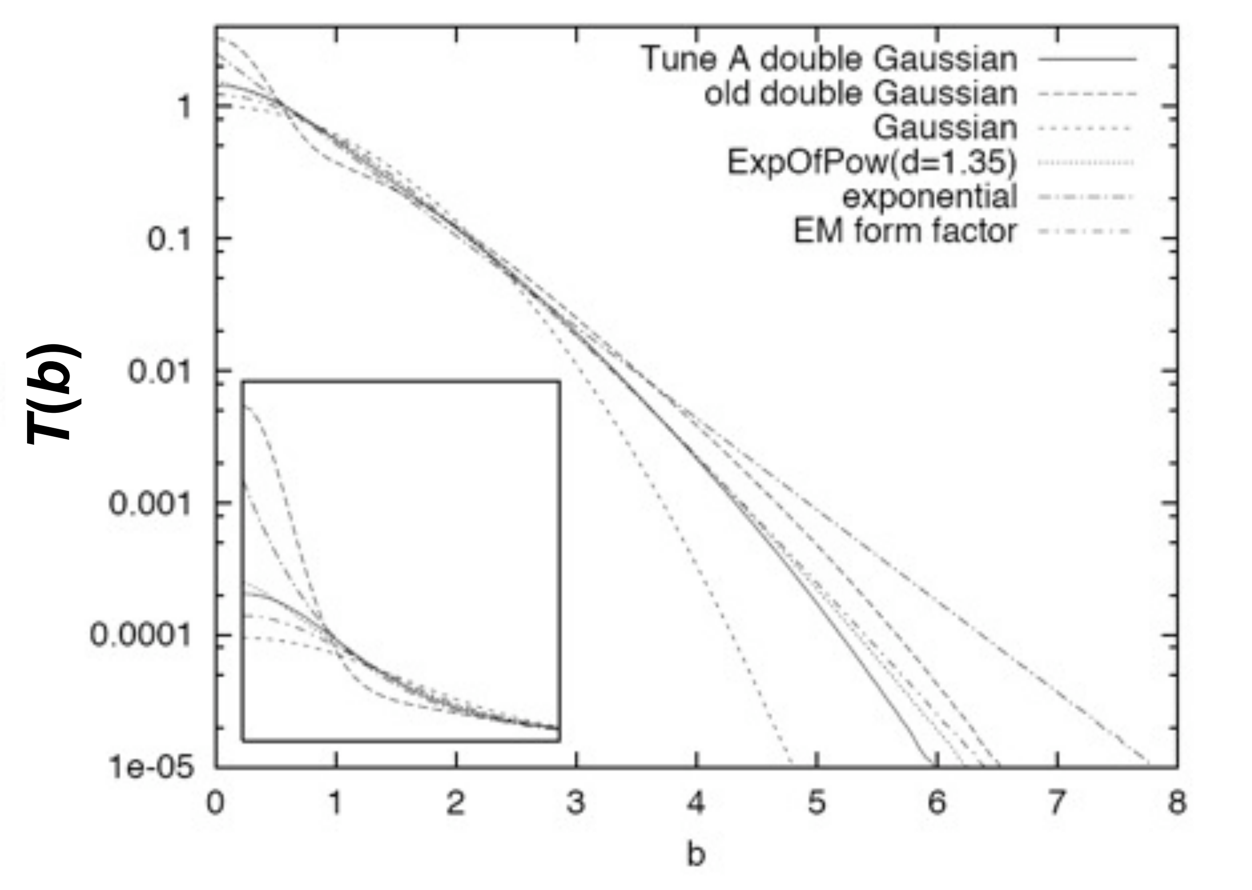
Where are the gluons and the sea quarks?
Inside the constituent quarks? Or outside?

FELIX coll., J. Phys. G: Nucl. Part. Phys. 28 (2002) R117–R215

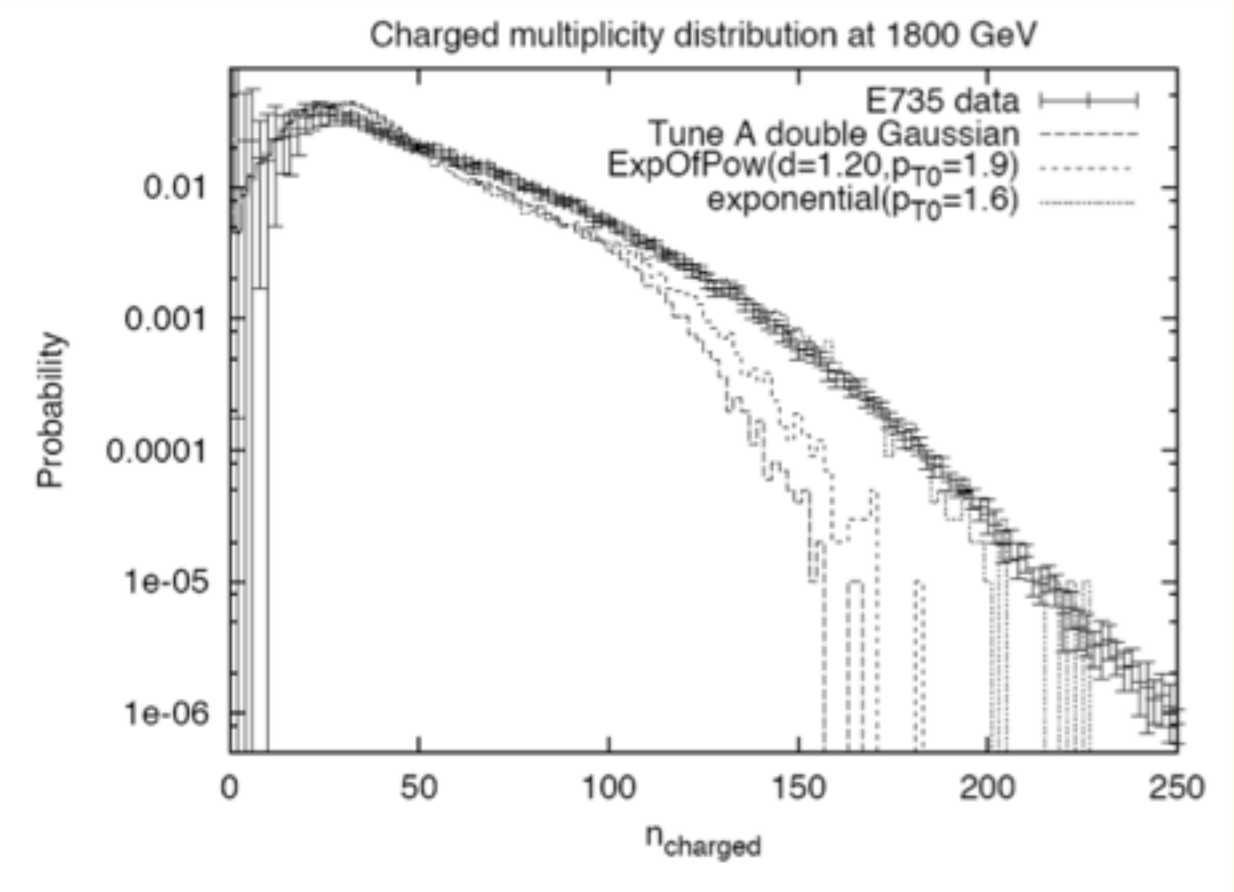
Multiple Parton Interactions (III):
An Example from Pythia: Effect of the Proton Density Profile

Multiple Parton Interaction can be switched on in Pythia:

Overlap function for different parton profiles of the proton:



Corresponding multiplicity distributions in p+pbar at 1800 GeV:



T. Sjöstrand, P. Skands, JHEP03 (2004) 053 (arXiv:hep-ph/0402082)

Measured multiplicity distributions constrain the parton profile of the proton

$\langle p_T \rangle$ vs. N_{ch}:
Correlations observed in p+pbar at $\sqrt{s}$ = 630 GeV

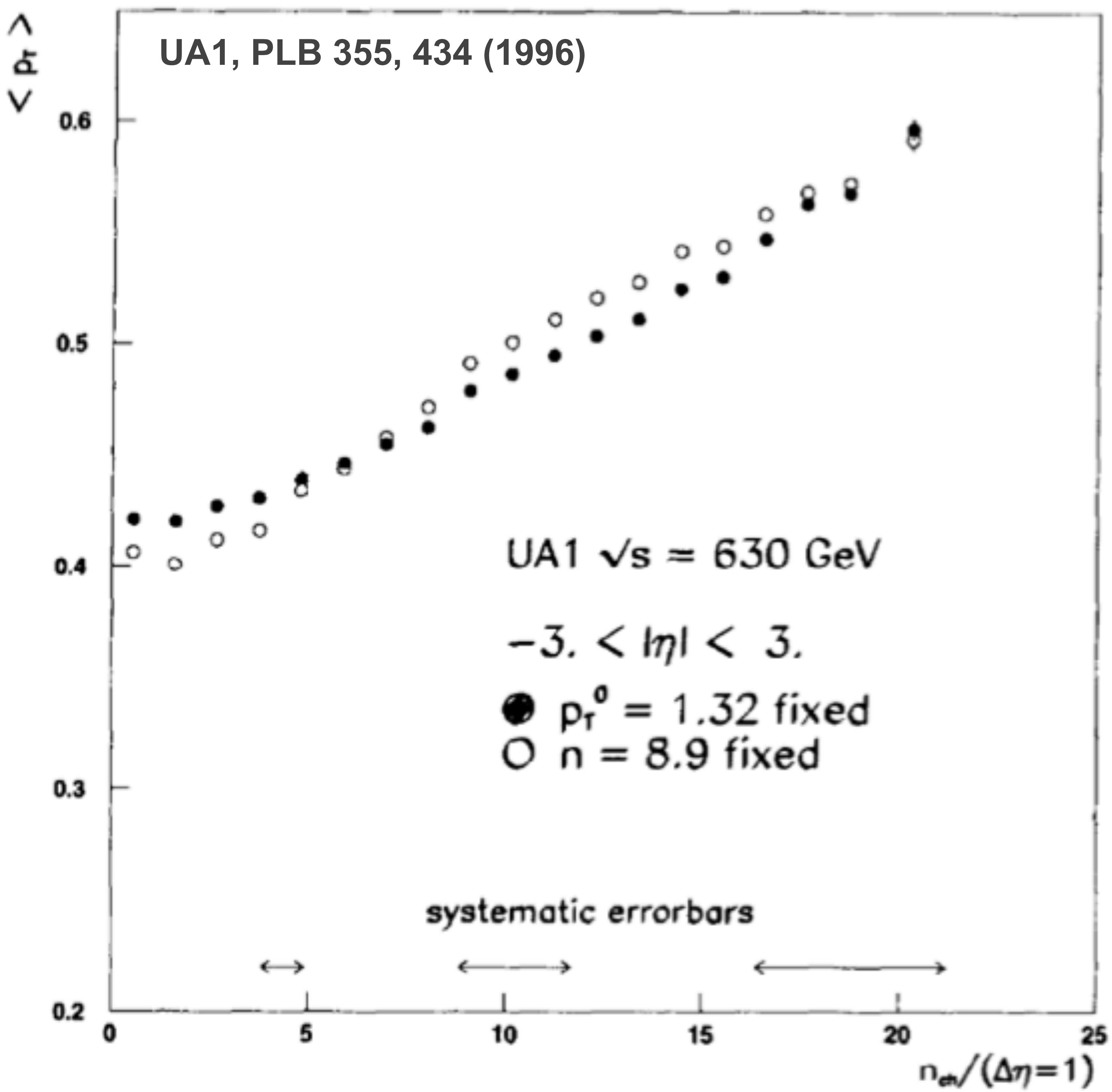
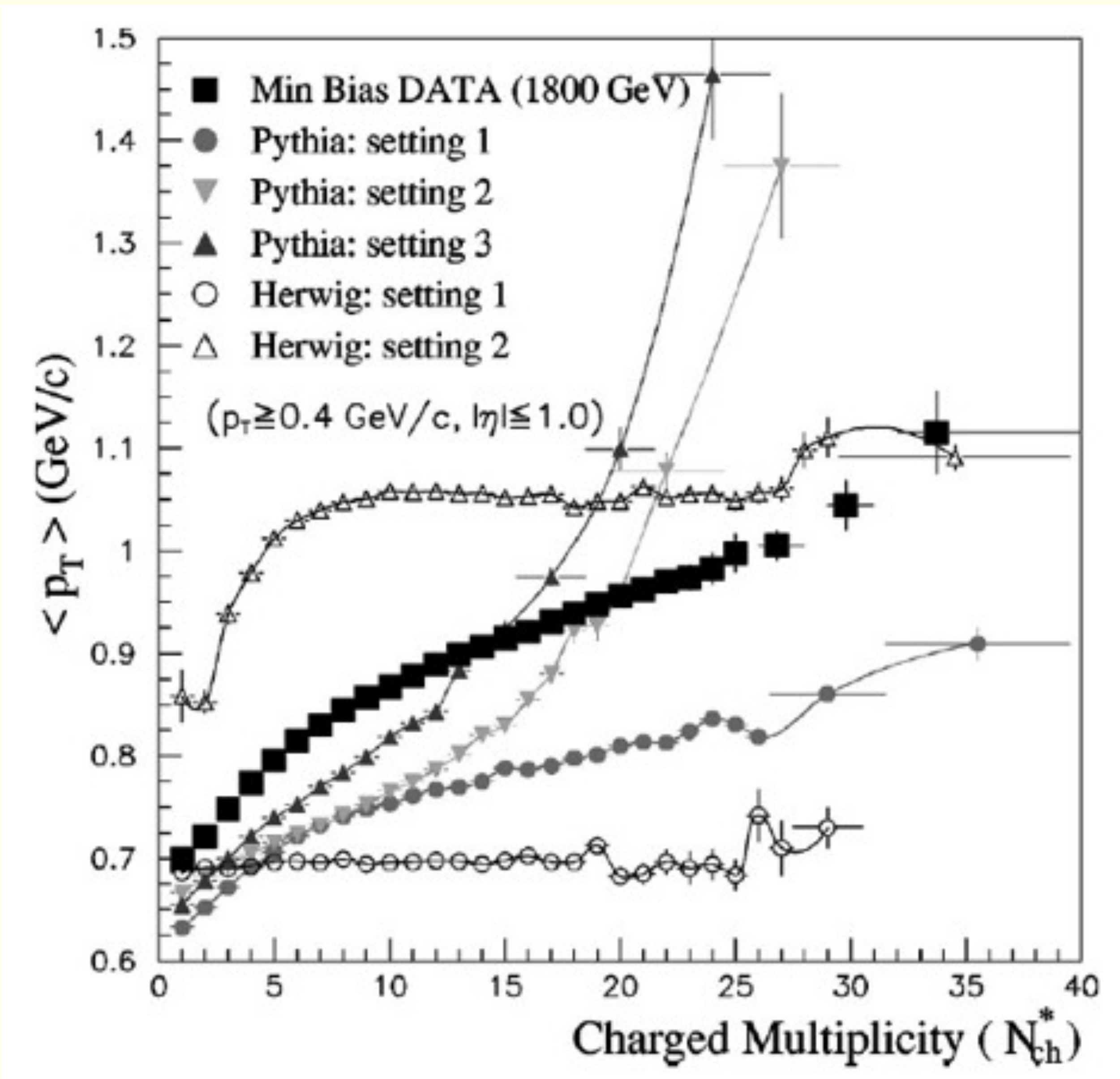


Fig. 5. Dependence of mean p_T on charged track multiplicity.

Increase of $<p_T>$ with charged particle multiplicity observed at the CERN SPS

The increase of $<p_T>$ with n_{ch} is most likely related to multiple parton interactions

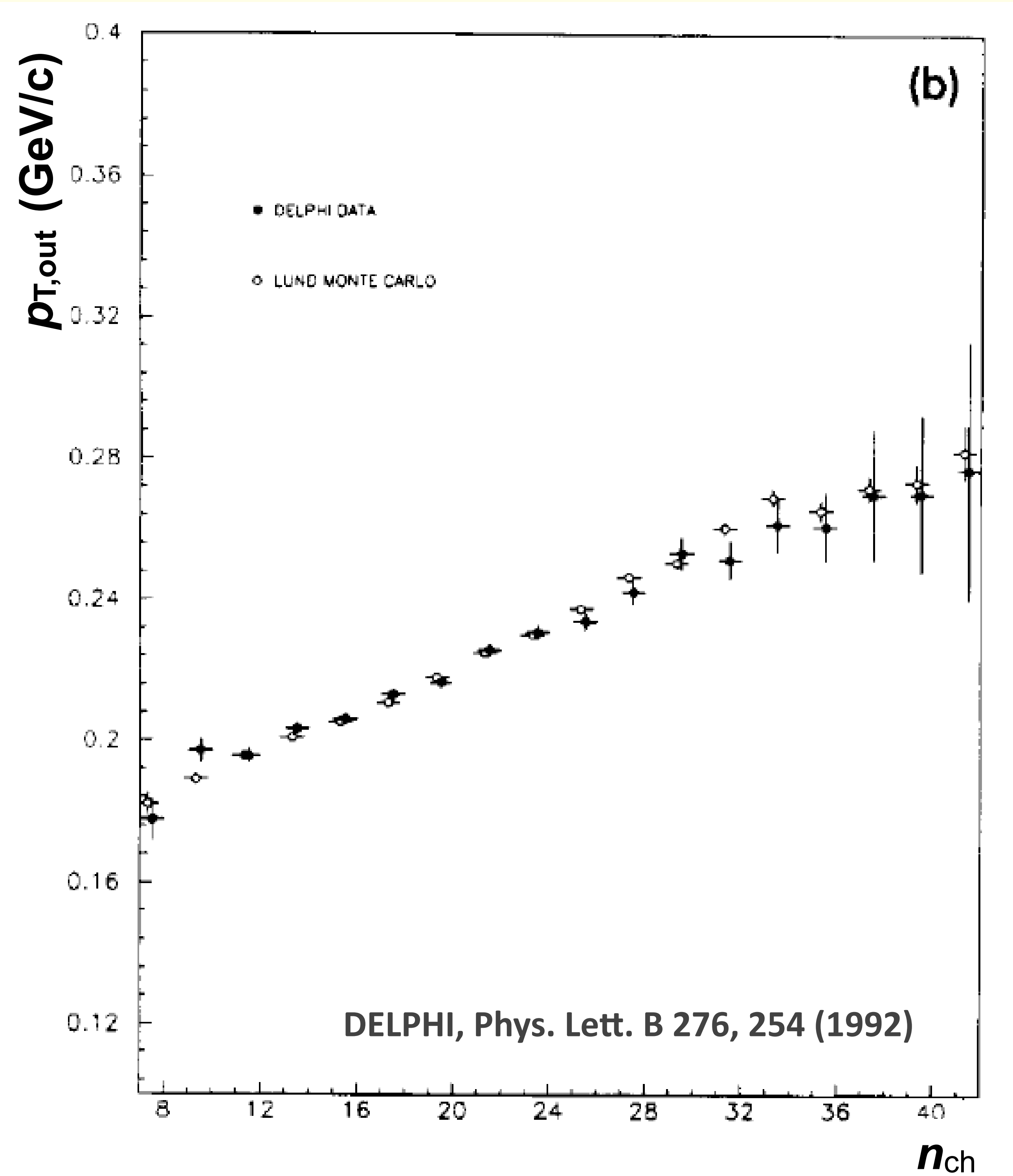
$\langle p_T \rangle$ vs. N_{ch}: Correlations also Observed at the Tevatron



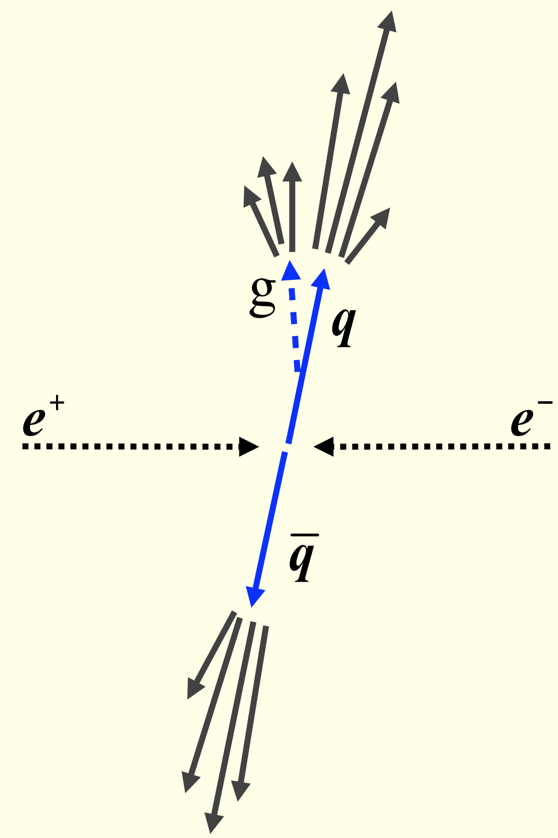
CDF, PRD 65, 072005 (2002)

- Rise of $\langle p_T \rangle$ with N_{ch} also observed at Tevatron energies
- QCD event generators like Pythia and Herwig couldn't describe this effect for quite some time
- Qualitatively the rise of $<p_T>$ with N_{ch} can be understood with multiple hard parton interactions within a p+p collision
  - Large multiplicity implies many interac-tions and therefore more perturbatively generated p_T to be shared between the hadrons
  - For it to work, however, each new interaction should add proportionately less to the total n_{ch} than to the total p_T

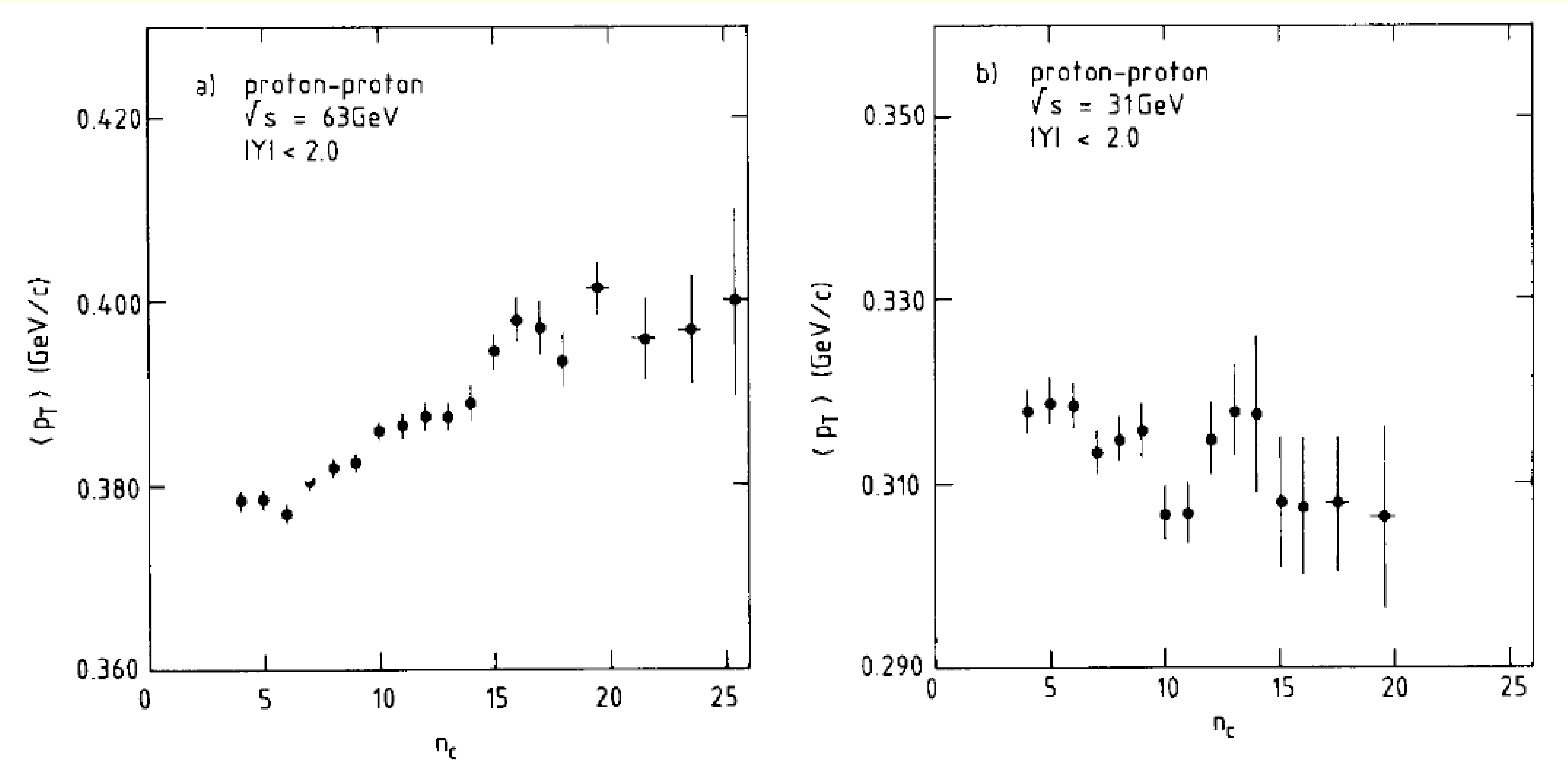
$\langle p_T \rangle$ vs. N_{ch}: Similar Correlations even in e^+e^-



- Increase of $\langle p_T \rangle$ with respect to the jet axis also observed in e^+e^- collisions at $\sqrt{s}$ = 91 GeV
- Can be explained by minijet branching



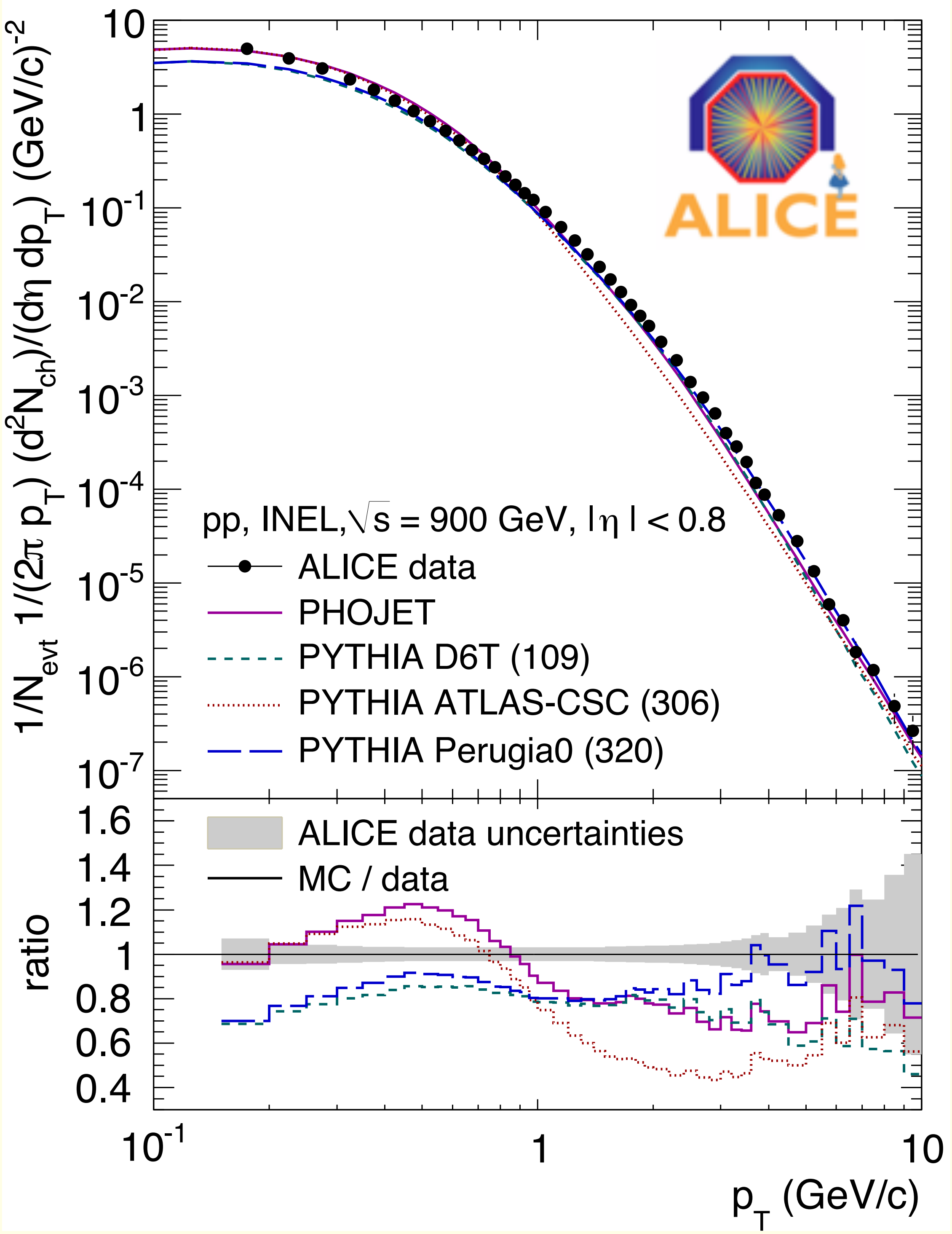
$\langle p_T \rangle$ vs. N_{ch}: Correlations absent at $\sqrt{s}$ = 31 GeV



Breakstone at al., PLB 132, 463 (1983)

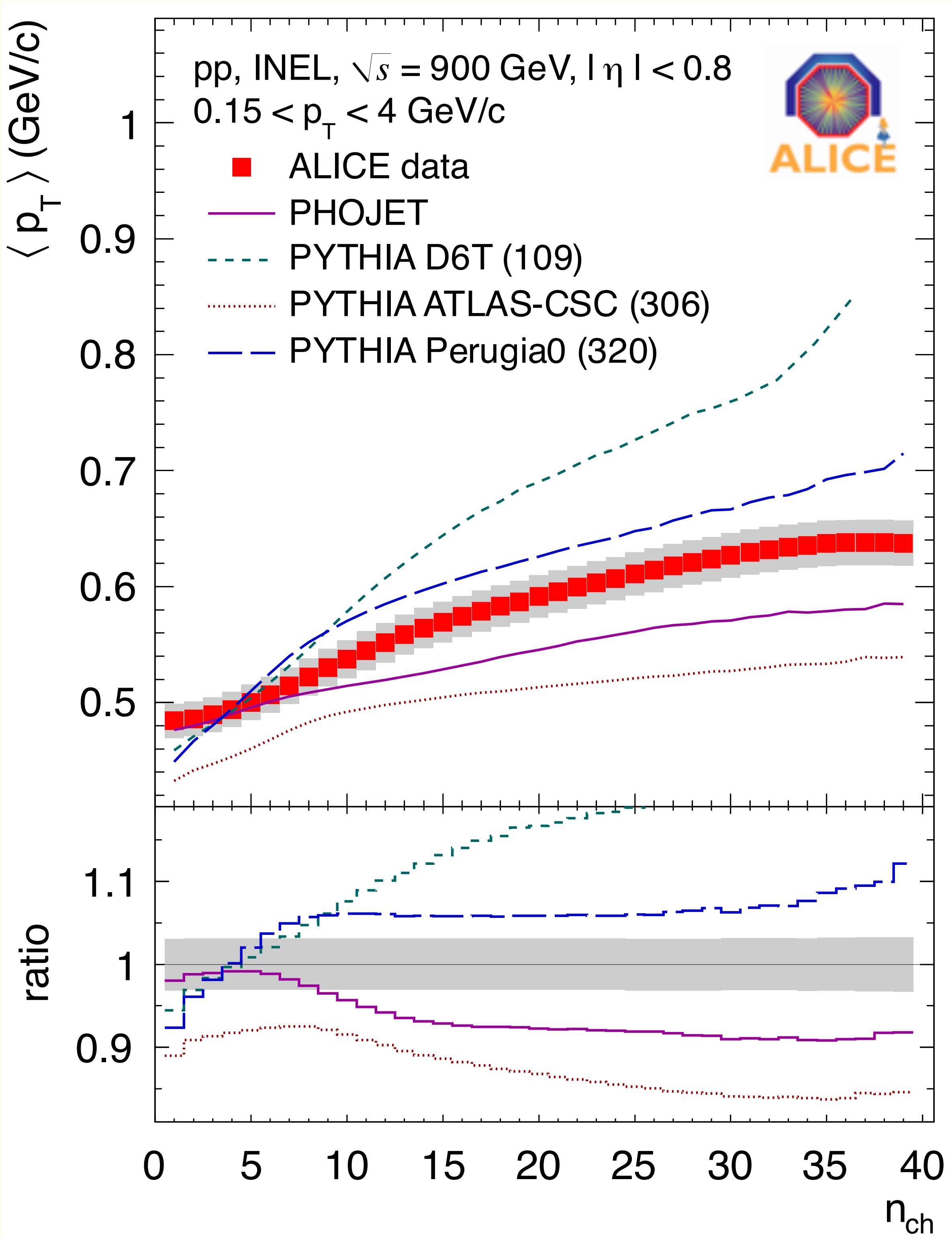
ISR data: Increase of $\langle p_T \rangle$ of with N_{ch} largely absent for $\sqrt{s}$ < 63 GeV

Charged Hadron p_T Spectrum at $\sqrt{s}$ = 0.9 GeV



- Tracks reconstructed from TPC and ITS information
- None of the MC models gives a good description of the spectrum
- Spectral shape predicted by PHOJET and ATLAS-CSC differs significantly from data
- Note that these MC's (PHOJET and ATLAS-CSC) agree best with the charged particle multiplicity distributions at $\sqrt{s}$ = 0.9, 2.36, and 7 TeV

$\langle p_T \rangle$ vs. N_{ch}



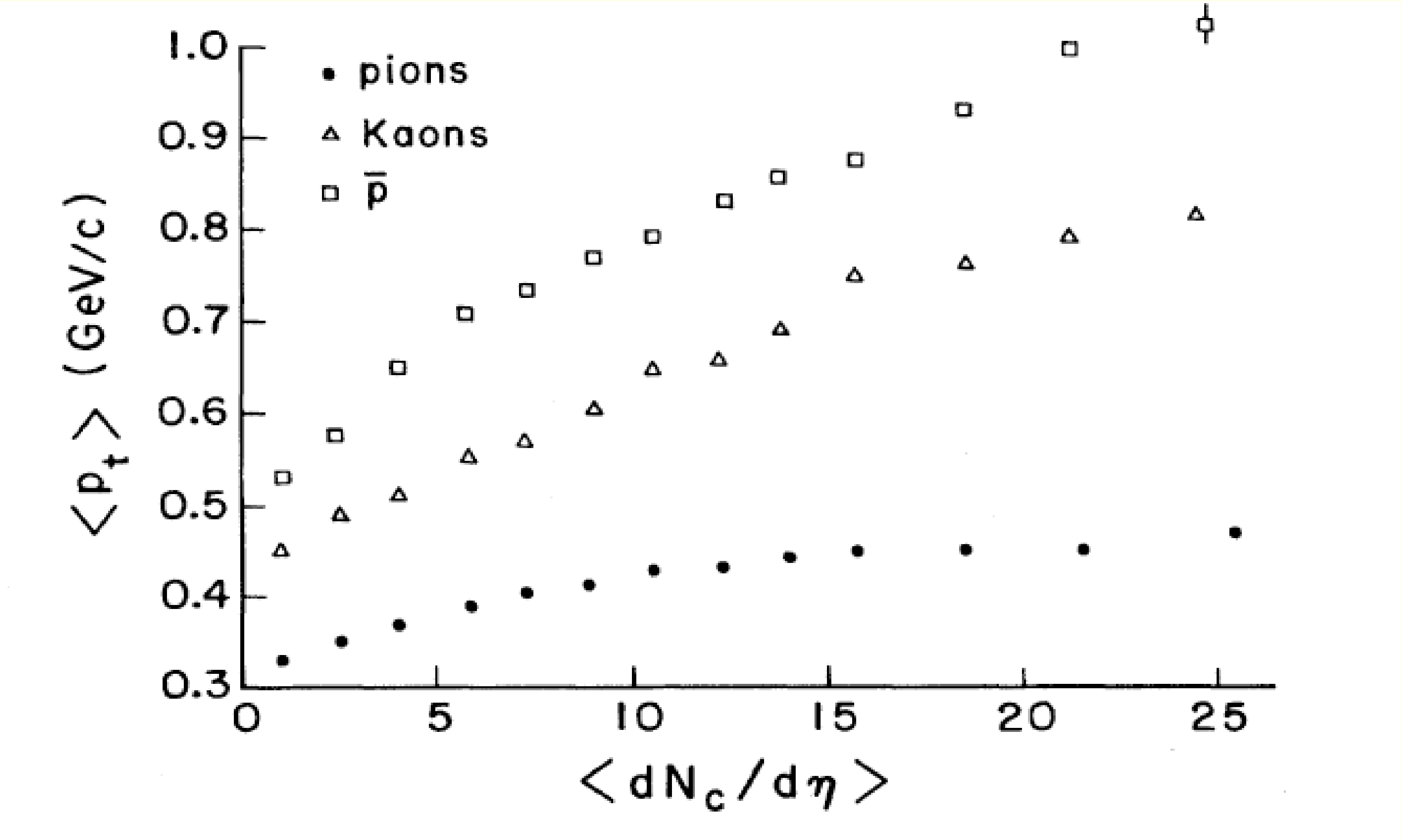
- Neither Phojet nor various Pythia tunes describe the data well

- Summary on data vs. models
  - None of the even generators simultaneously describes all observables presented so far
  - Better tuned versions will surely be available soon
  - The question is whether it will be sufficient to modify some parameters or whether qualitatively new physics is still missing in the models

$\langle p_T \rangle$ vs. N_{ch}: What Else Could be Studied?

$p + \bar{p}$ at $\sqrt{s} = 1800$ GeV

E735, PRD 48, 985 (1993)



- Increase is stronger for heavier particles
- In A+A collisions this is usually attributed to collective radial flow of the quark-gluon plasma

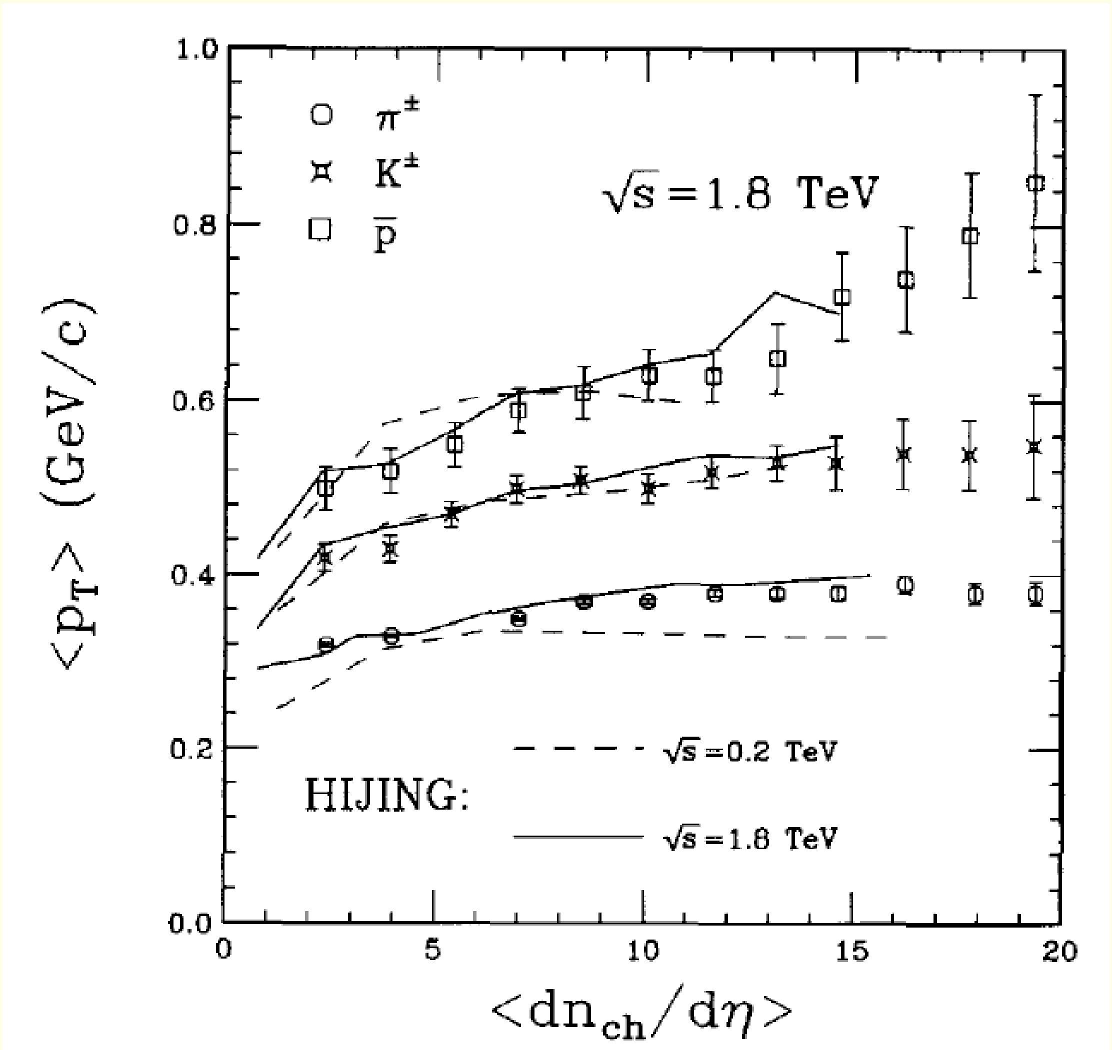
Possible Interpretations

- QGP formation in p+p?
  - Increase of $\langle p_T \rangle$ of with N_{ch} largely indicative of collective flow
  - "A collective flow which is established in a QGP phase would naturally account for this phenomenon"
    Levai, Müller, PRL 67, 1590 (1991)
- More mundane explanation:
  - "Multiple minijet production"
  - p+p collisions with high multiplicity:
    - Several partons with p_T > 2 GeV ("minijets") are produced
    - $\langle p_T \rangle$ increases with #minijets
    - Gyulassy, Wang, PLB 282, 466 (1992)
  - This also explains the violation of the KNO scaling

Increase of $\langle p_T \rangle$ and Violation of KNO Scaling due to Minijet Production

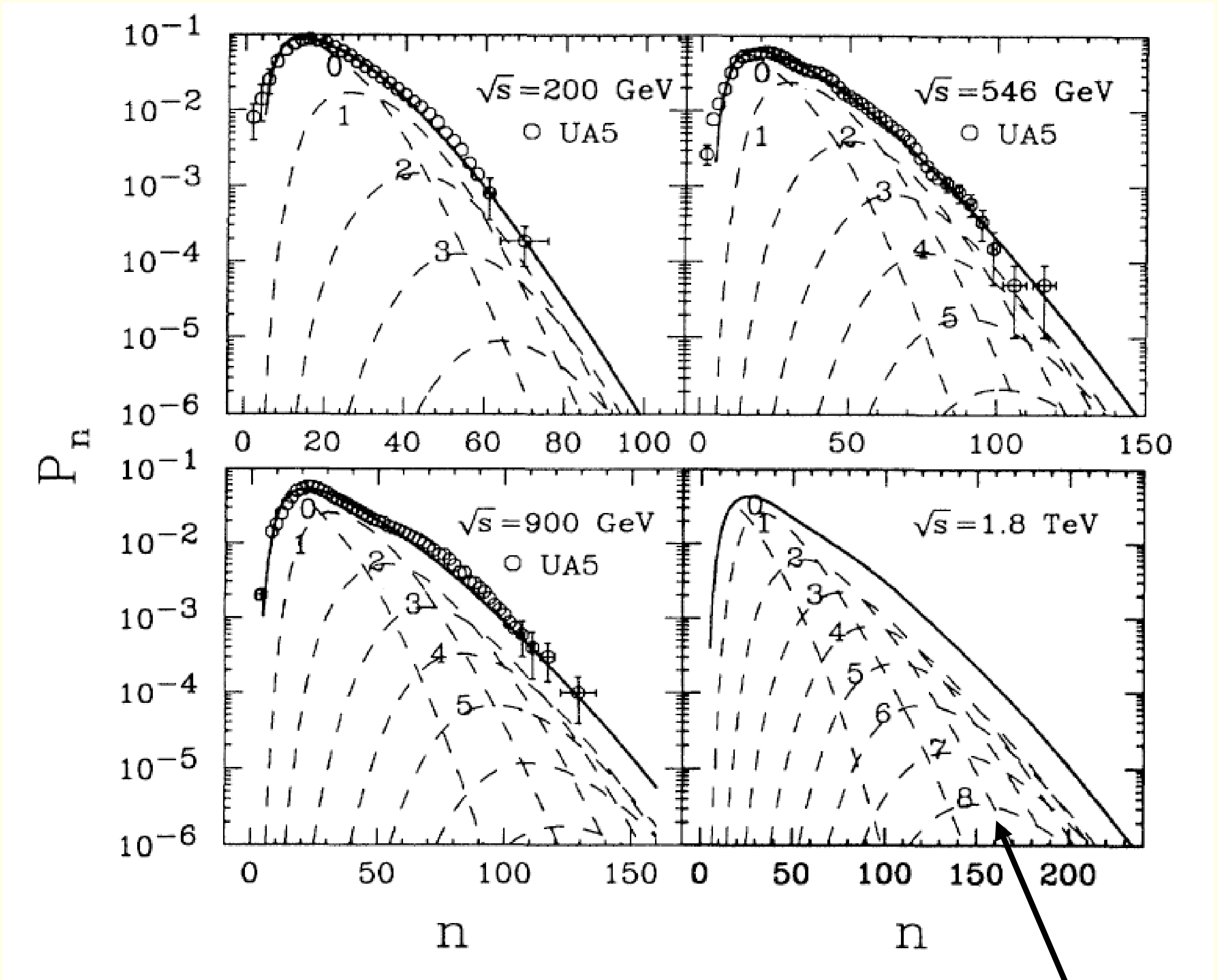
Multiple minijet production explains:

Increase of $\langle p_T \rangle$ of with N_{ch}



Gyulassy, Wang, PLB 282, 466 (1992)

Violation of KNO scaling



Wang, PRD 43, 104 (1991)

Number of minijets

6. QGP in p+p?

QGP in p+p? Arguments Put Forward by E735

E735, PLB 528, 43 (2002)

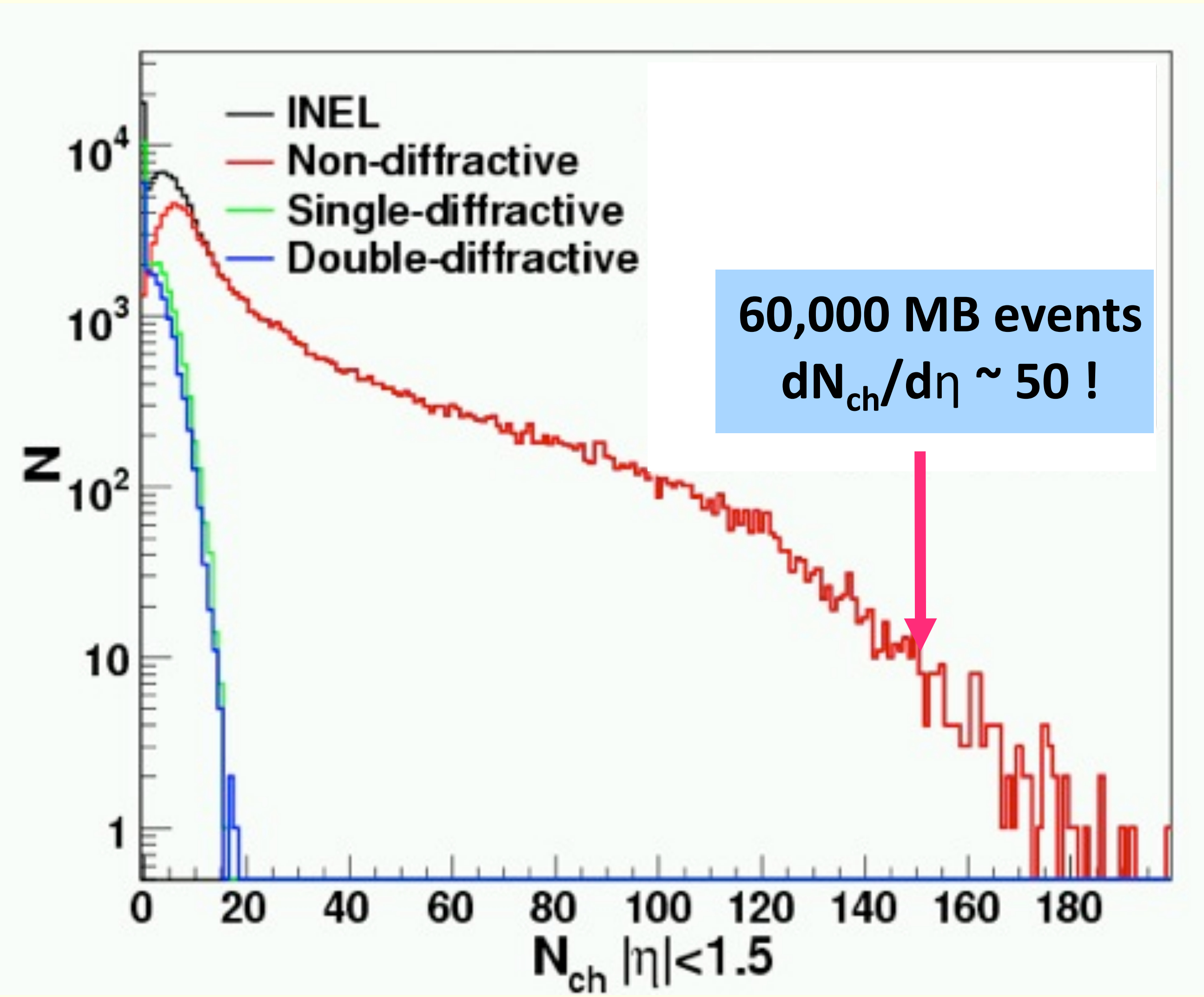
- "Cluster" size from forward-backward correlations:
  Increase of cluster size suggests QGP threshold near $dN_{ch}/d\eta = 7$
- Freeze-out density of pions:
  $n_\pi = 1.57 \pm 0.25 / \text{fm}^3$
  independent of multiplicity for $dN_{ch}/d\eta > 7$
- Freeze-out volume $dN_{ch}/d\eta$:
  $V = 4.4 - 13 \text{ fm}^3$ for
  $dN_{ch}/d\eta = 6.75 - 20.2$
- Freeze-out energy density:
  $\varepsilon_f = 1.1 \text{ GeV/ fm}^3$
  close to critical density predicted by lattice QCD
- Initial energy density:
  well above critical energy density
- Number of degrees of freedom:
  $g = 24.8 \pm 6.2$
  nearly 8 times higher than g = 3 for a pion gas

Expectation for p+p at 14 TeV

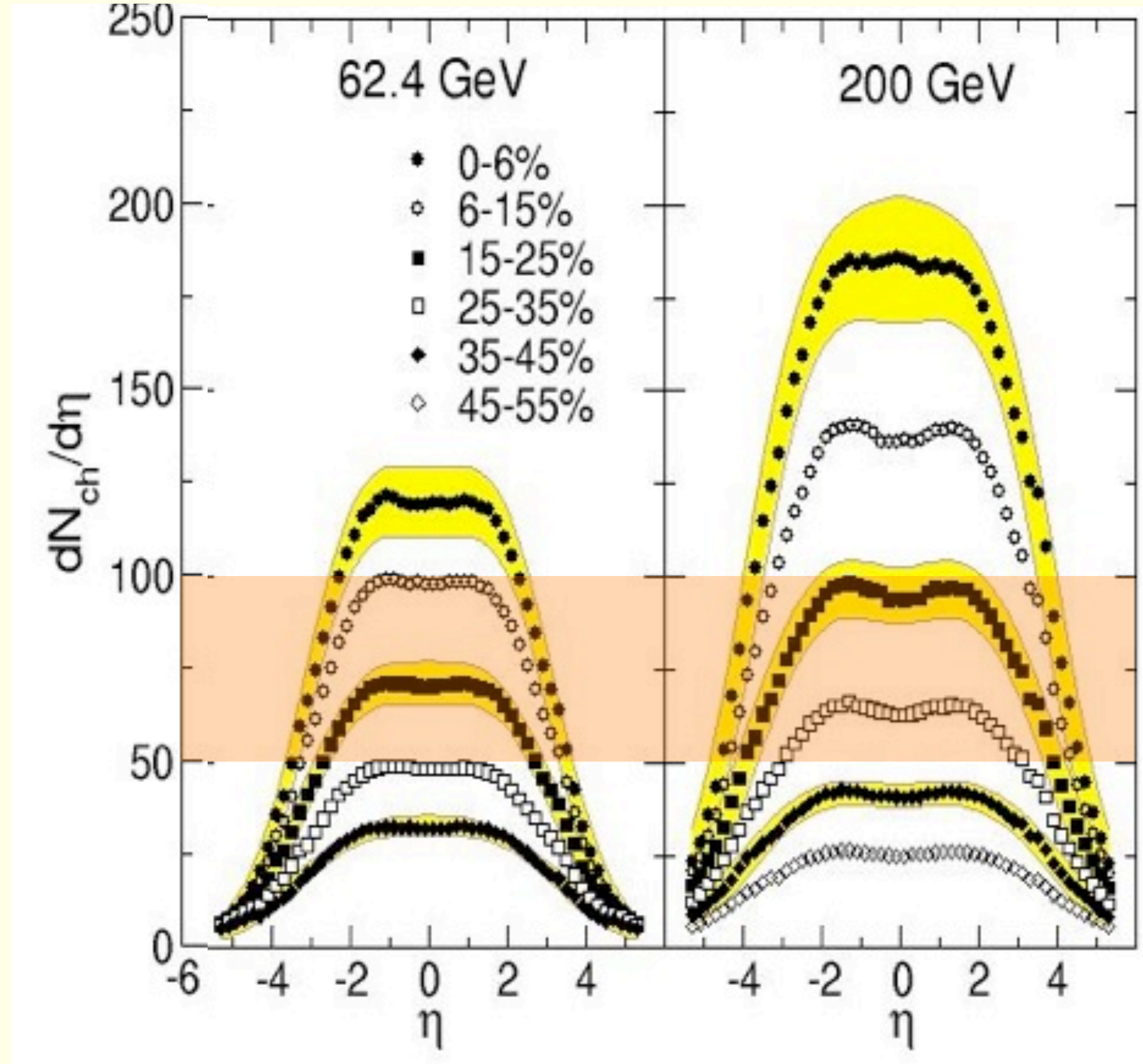
- $dN_{ch}/d\eta$ in some events up to 50 - 100
- ε_i up to 10 GeV/fm^3

Light Ion Physics with p+p at the LHC?

J. Schukraft, QuarkMatter 2008



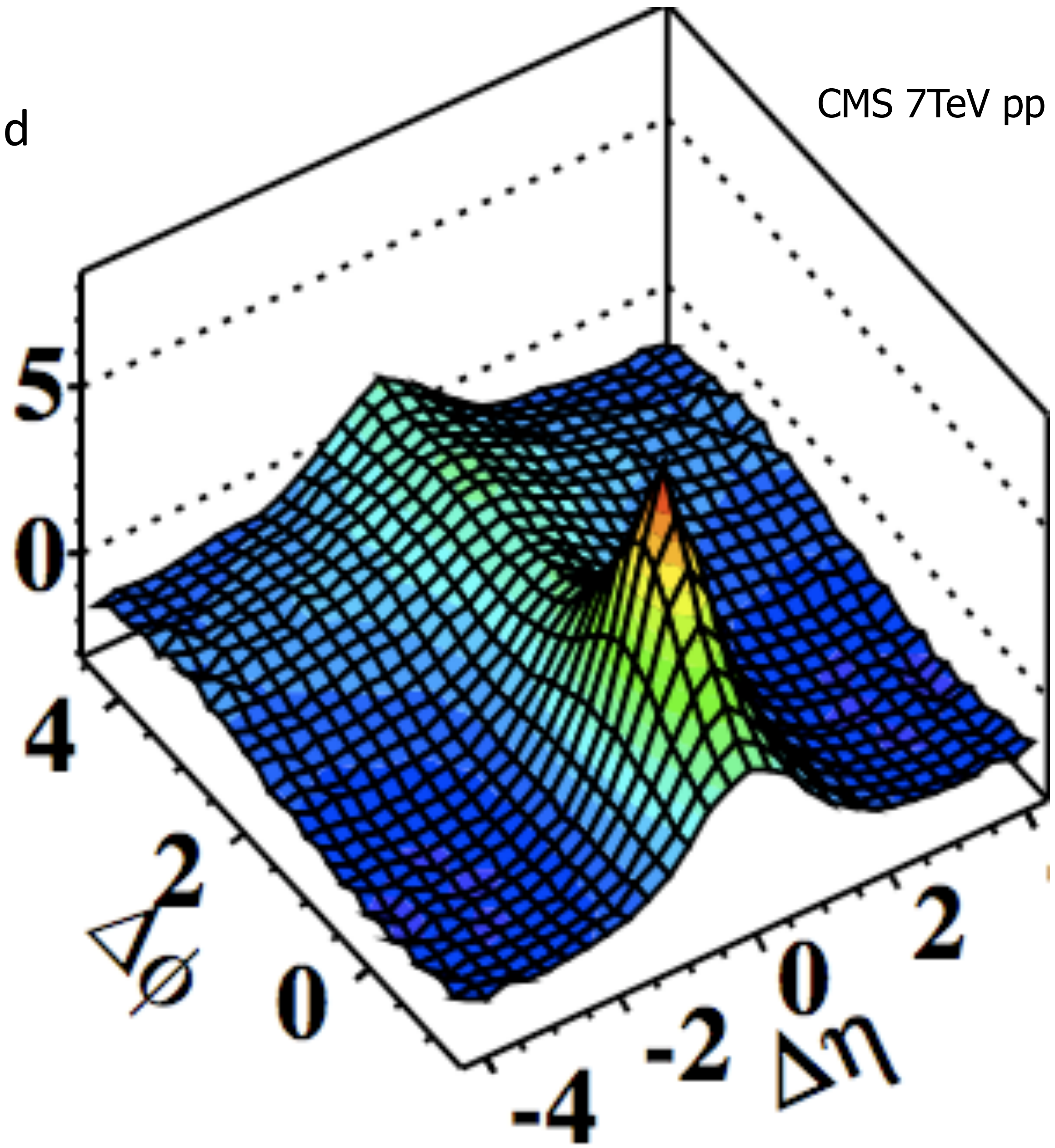
Phobos Cu-Cu



$dN_{ch}/d\eta$ in high multiplicity p+p events at the LHC similar to semi-central Cu+Cu collisions at RHIC

Two-Particle Angular Correlations Function

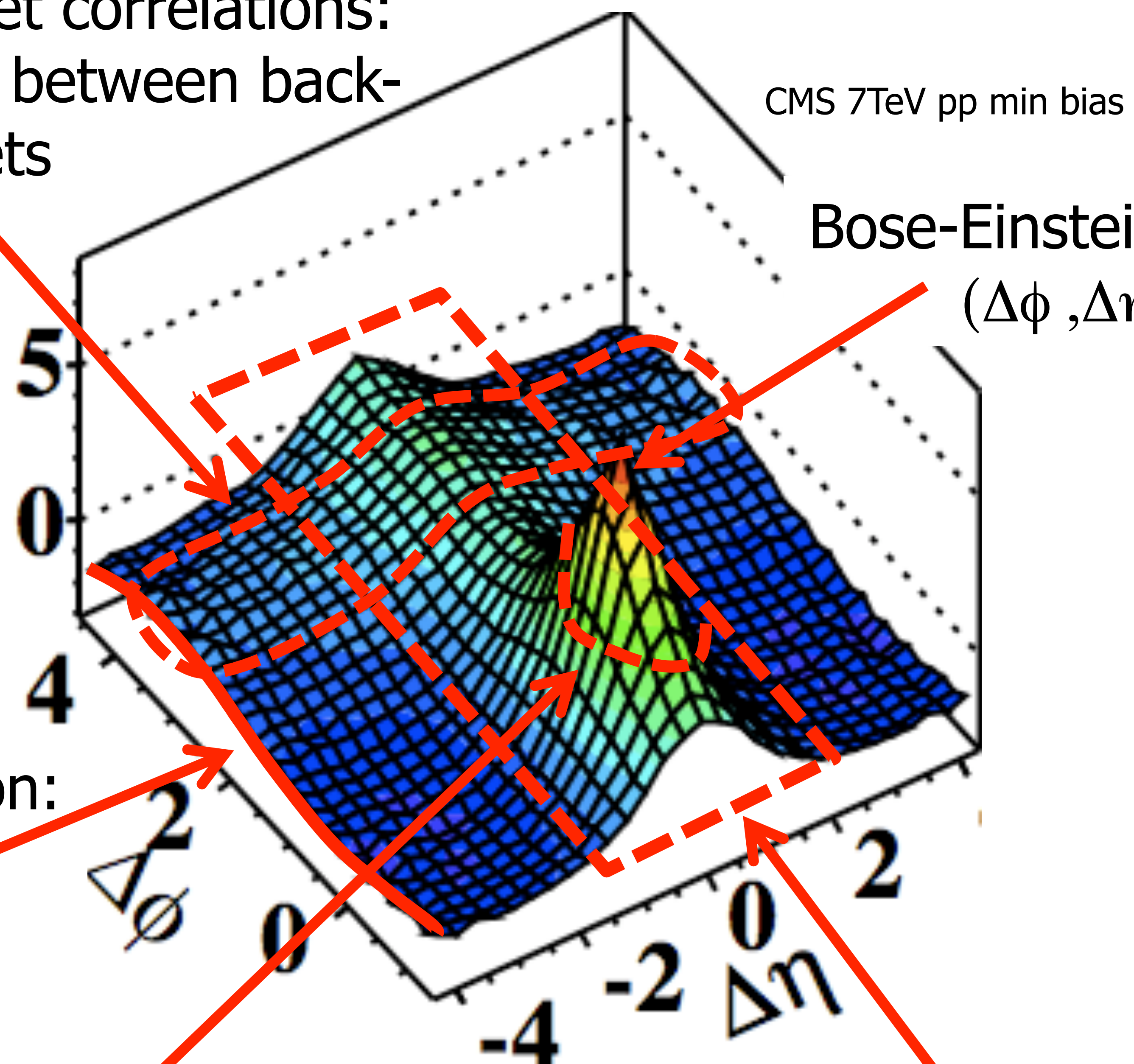
What is shown is the ratio signal/background



Two-Particle Angular Correlations Function

“Away-side” ($\Delta\phi \sim \pi$) jet correlations:
Correlation of particles between back-to-back jets

Bose-Einstein correlations:
($\Delta\phi$,$\Delta\eta$) ~ (0,0)



Momentum conservation:
~ -cos($\Delta\phi$)

“Near-side” ($\Delta\phi \sim 0$) jet peak:
Correlation of particles within a single jet

Short-range correlations ($\Delta\eta < 2$):
Resonances, string fragmentation, “clusters”

The CMS Result that Got Some Media Attention

Talk G.Roland

Intermediate p_T: 1-3 GeV/c

MinBias   high multiplicity (N>110)

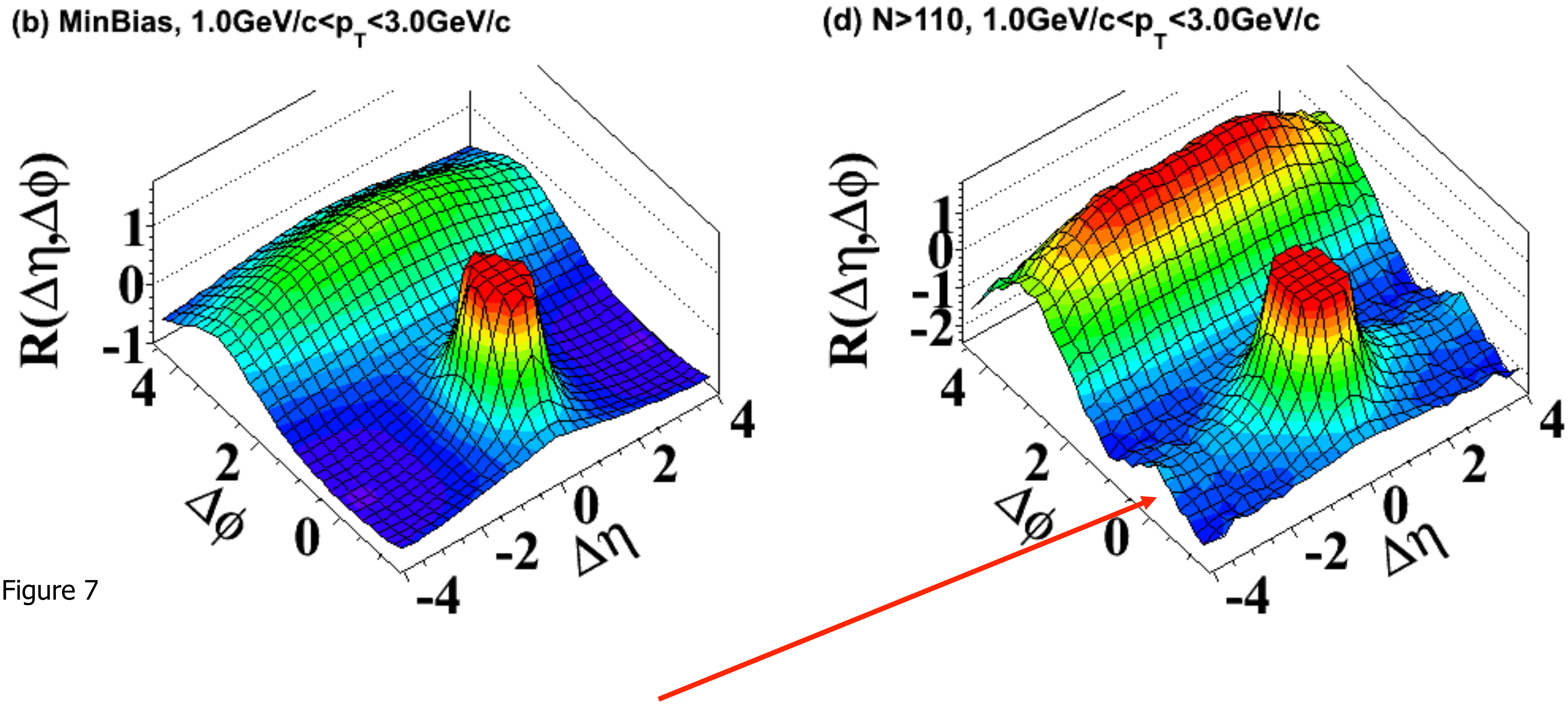


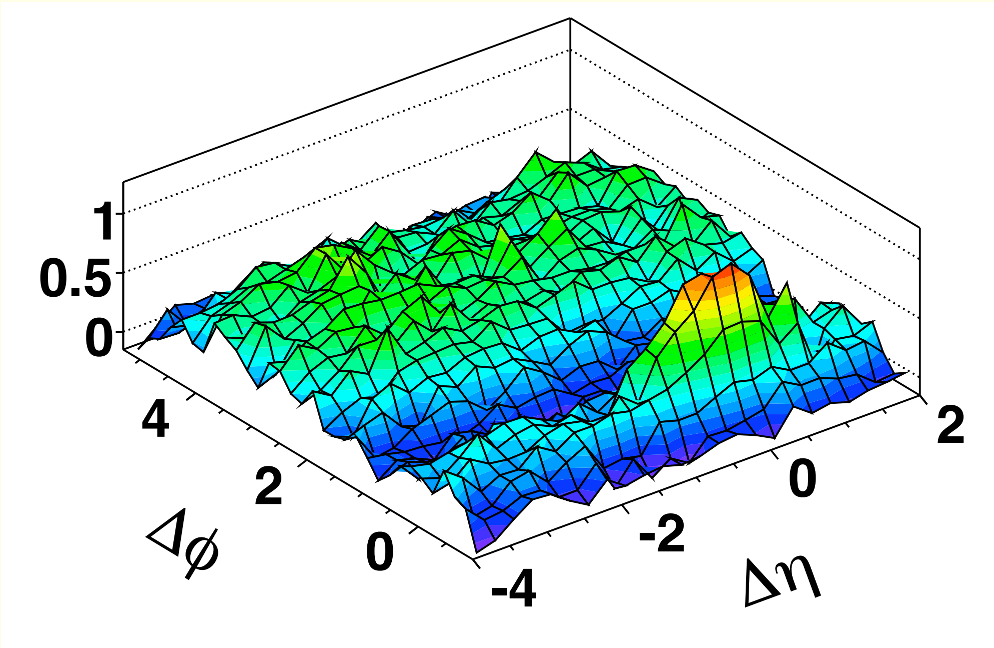
Figure 7

Pronounced structure at large $\delta\eta$ around $\delta\phi \sim 0$!

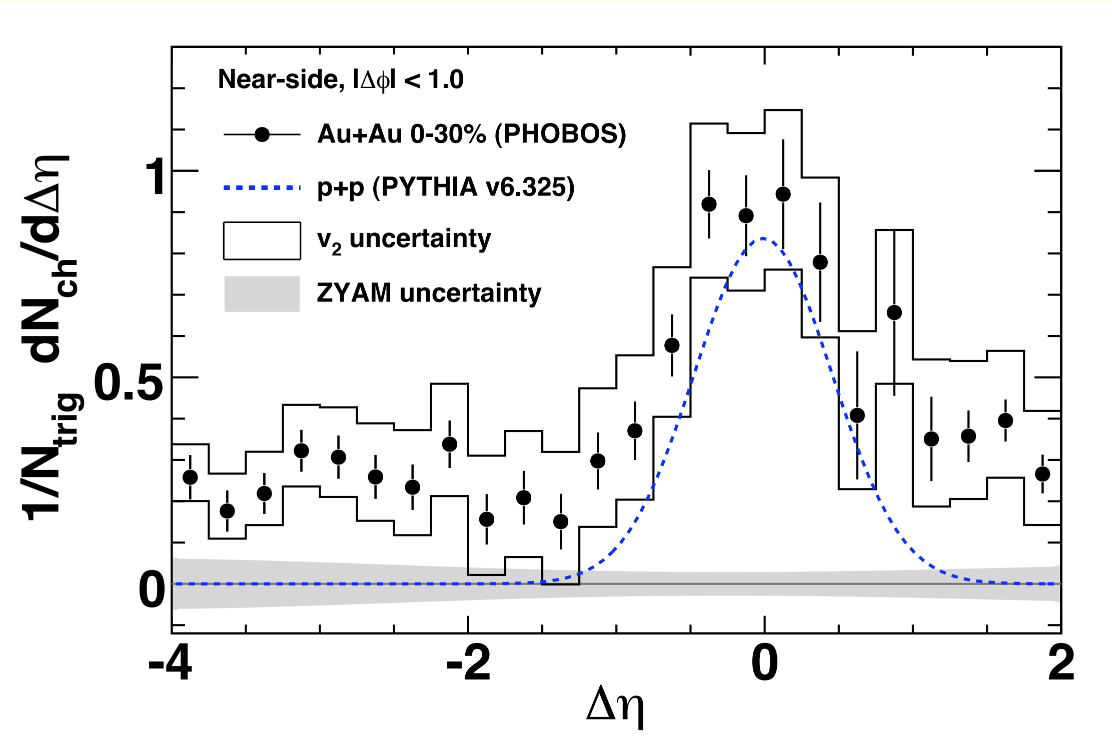
Already discovered at ISR by BFS collaboration, M. Albrow et al, Nuclear Physics B145 (1978) 305-348 (?), see http://arxiv.org/abs/1010.0964

Why is this Potentially Interesting?

Phobos, PhysRevLett.104.062301



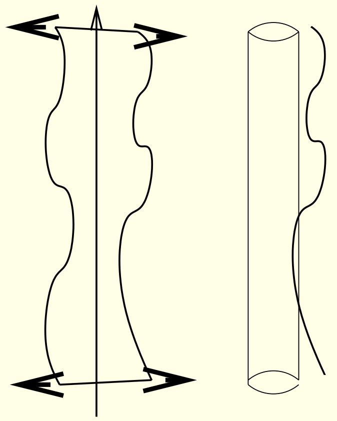
(b) Au+Au 0-30% (PHOBOS)



(c) Near-side $\Delta\eta$ projection ($|\Delta\phi| < 1$)

- As similar long-range correlation in $\Delta\eta$ at $\Delta\phi \approx 0$ was observed in Au+Au collisions at RHIC (and termed „the ridge“)
- Might be related to the presence of a quark-gluon plasma
- However, this phenomenon is theoretically not understood

Possible explanation of the CMS signal by E. Shuryak



Particles from string fragmentation blown away by a tube of exploding quark-gluon plasma

7. pbar/p ratio: baryon transport

Baryon Number Stopping

Garvey, Kopeliovich, Povh, hep-ph/0006325

Basic question: Which partons in the proton carry the baryon number (BN)?

Naïve expectation: Baryon number is associated with valence quarks

Remember: $$\sum_{i=u,d,s} \int_0^1 \mathrm{d}x \left[q_i(x) - \bar{q}_i(x) \right] = \sum_i \int_0^1 \mathrm{d}x \, q_i^{\text{valence}}(x) = 3$$

Dependence of BN on Bjorken-x would then be: $q(x) - \bar{q}(x)$

However, consider the reaction:

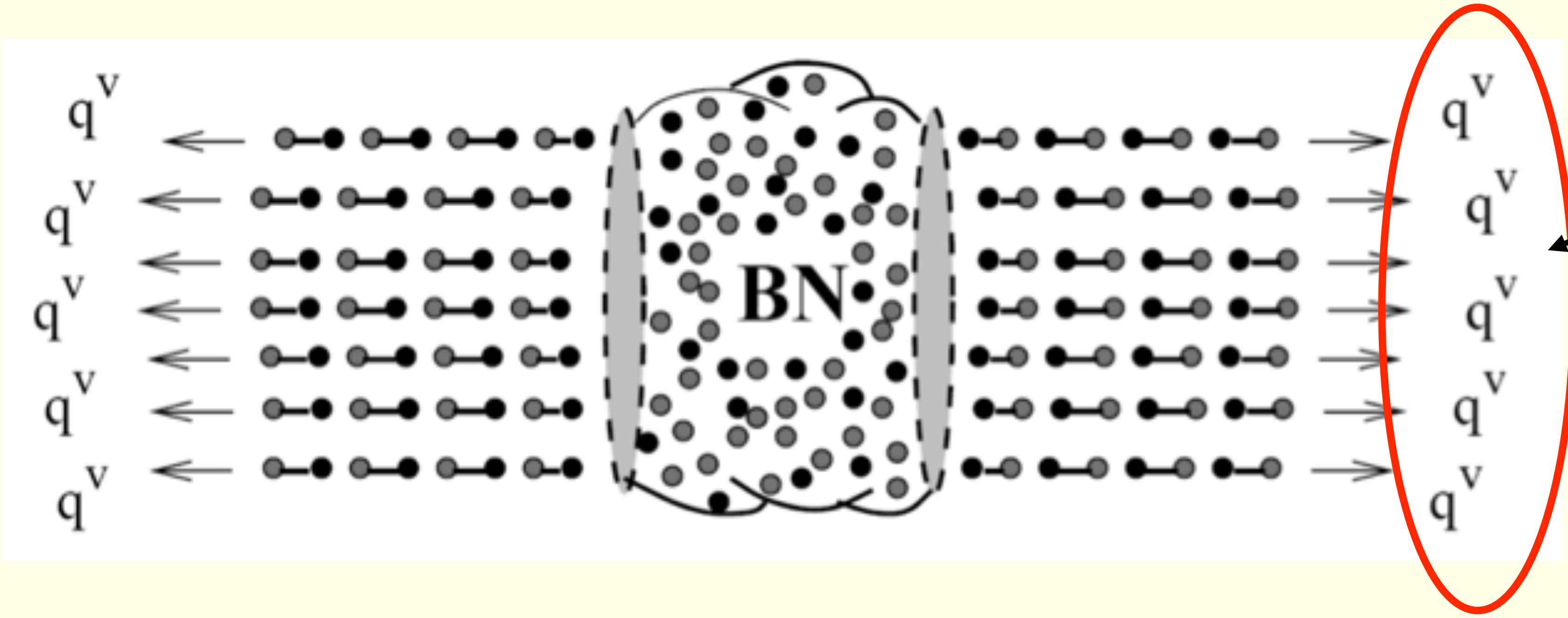
$$\Omega^- = (s, s, s)$$

$$\pi^- + p \rightarrow \Omega^- + K^+ + 2K^0$$

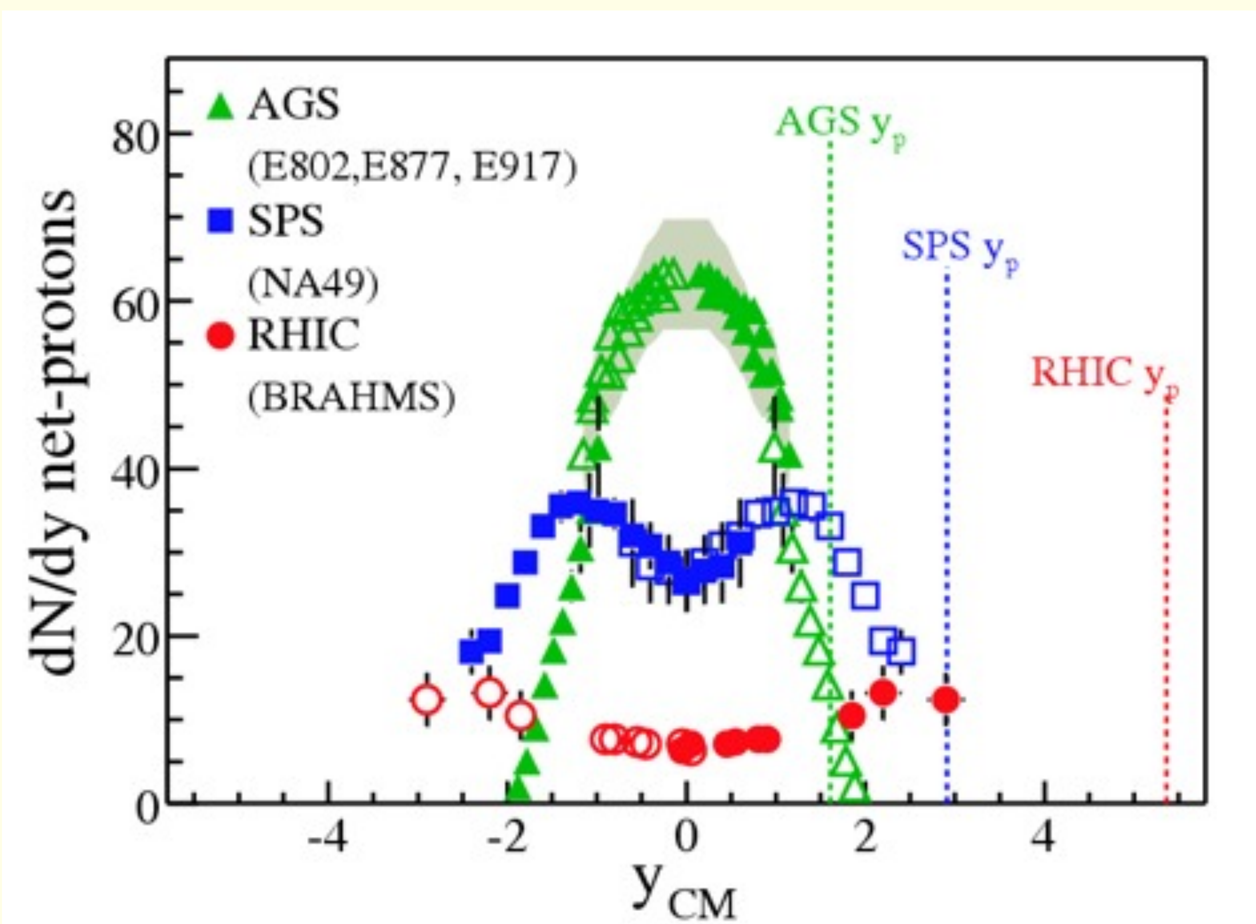
→ Baryon number conserved, but none of the initial valence quarks of the proton appear as valence quarks in the Ω.

Indication that BN is not carried by valence quarks, but probably by gluons

Valence Quark and Baryon Number Stopping in A+A



- Valence quarks of the incoming nucleus are hardly stopped (ΔE ~ 10 GeV)
- However, BN is transferred to mid-rapidity
- BN stopping ≠ energy stopping



Baryon number stopping in a heavy-ion collision suggests that BN is to large extent not carried by valence quarks

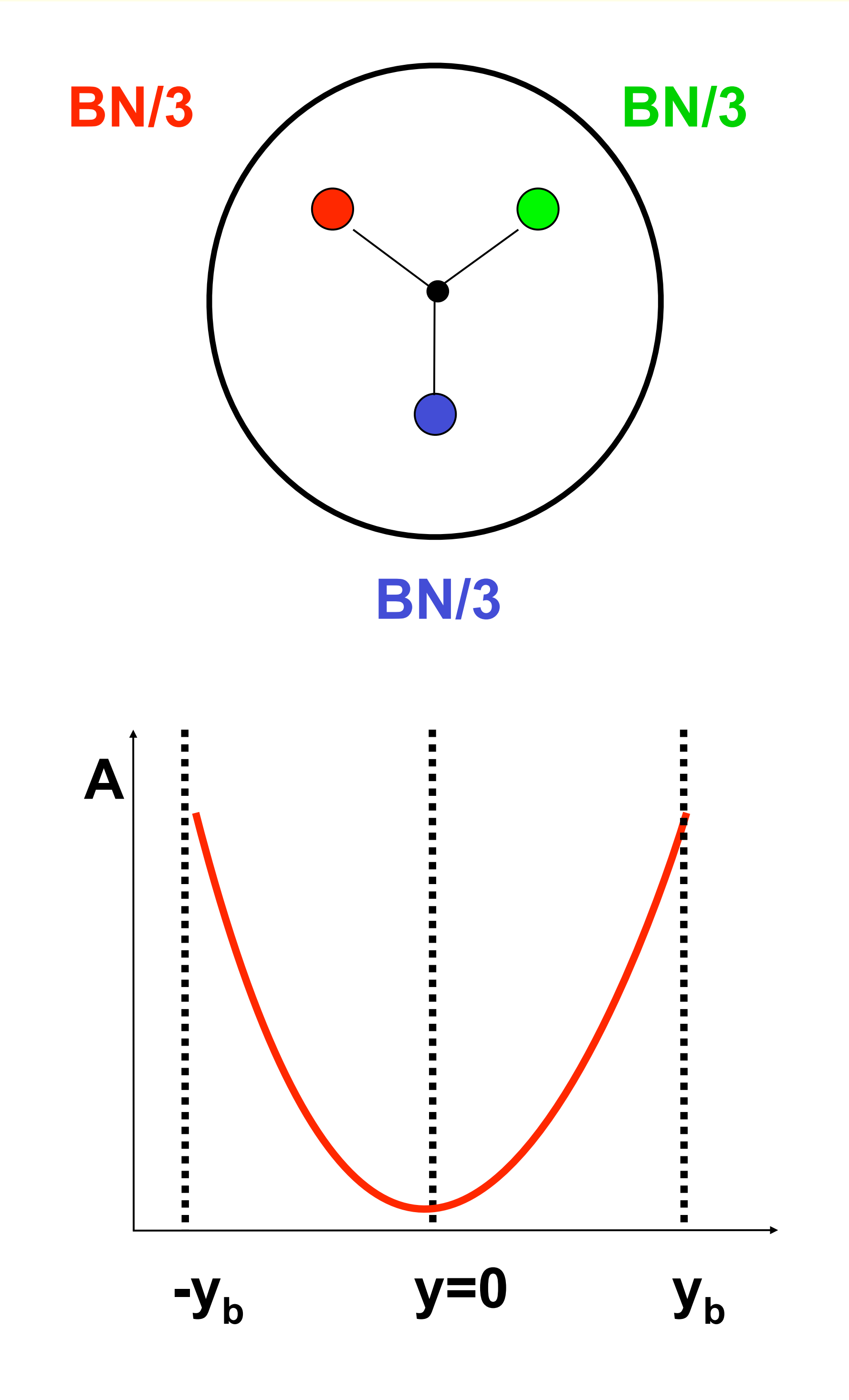
Baryon Number Asymmetry

Observable:
Asymmetry of produced baryons and anti-baryons

$$A := 2\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}$$

Asymmetry A measures ratio of stopped baryons to baryons created from the vacuum

Scenario 1: BN Associated with Valence Quarks

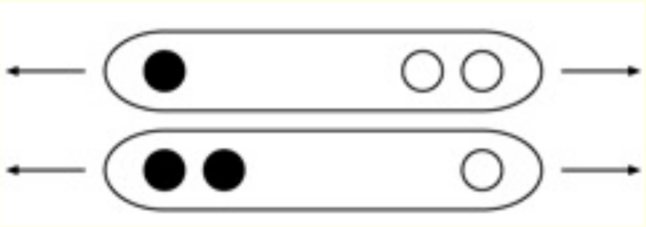


- Rapidity distribution of stopped baryon reflects fluctuations of the primary momentum of the valence quarks

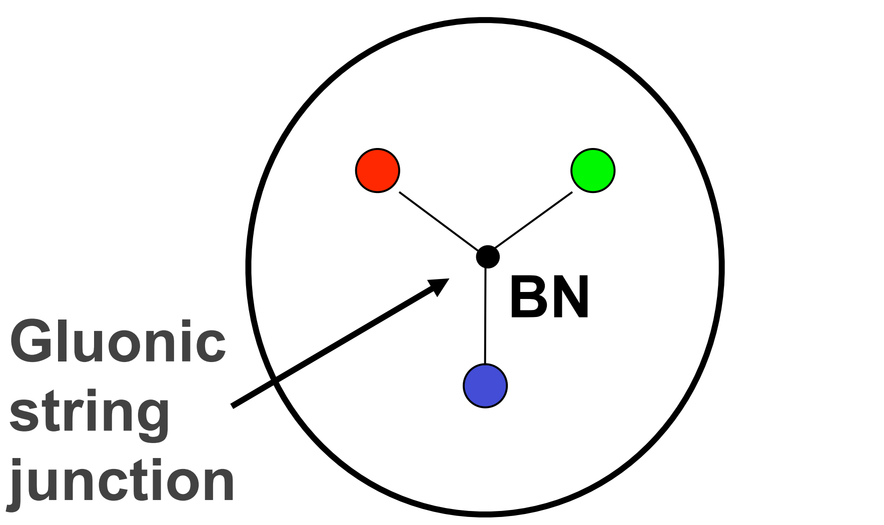
$$A \sim \exp\left(\frac{y - y_{\mathrm{beam}}}{2}\right) + \exp\left(\frac{-(y + y_{\mathrm{beam}})}{2}\right)$$

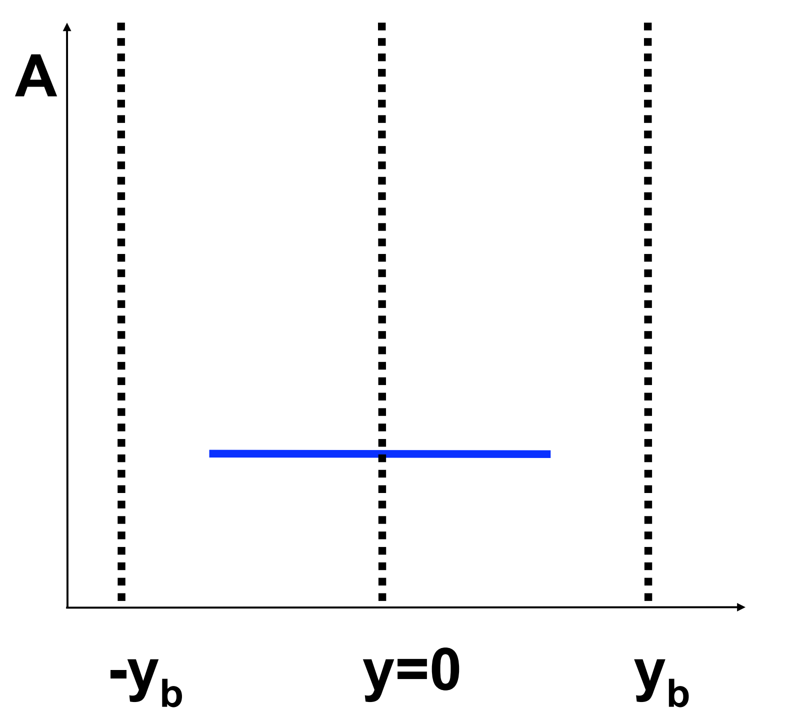
- Thus, the asymmetry should vanish at mid-rapidity, esp. for large rapidity gaps Δy between the incoming protons in p+p (or nucleons in A+A) collisions.
- Remember: y_{beam} = 8.92 for √s = 7 TeV

A standard picture would be the following: p+p collisions leads to two strings in a diquark-quark configuration. The diquark hadronizes into a new particle which carries the baryon number of the incoming proton



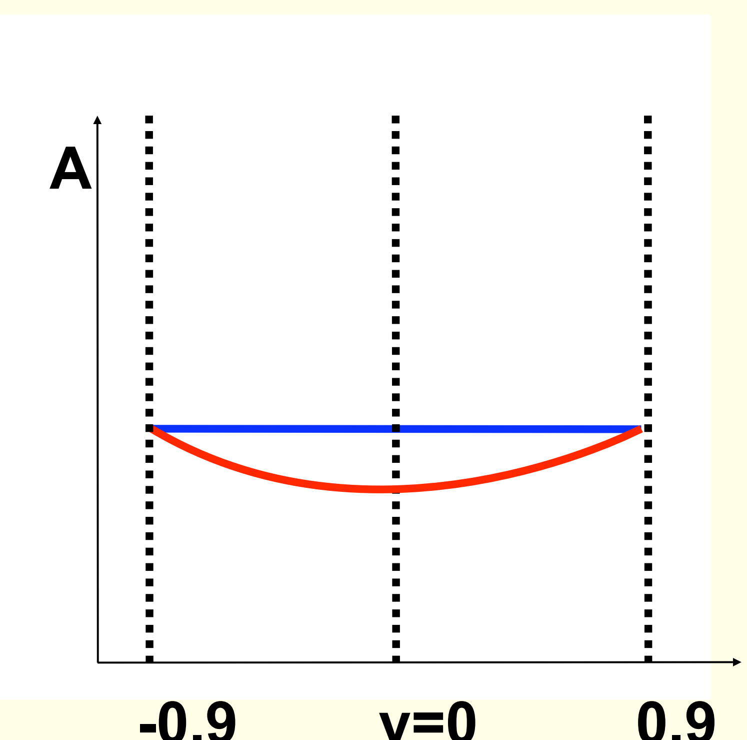
Scenario 2: BN Associated with Gluonic String Junction





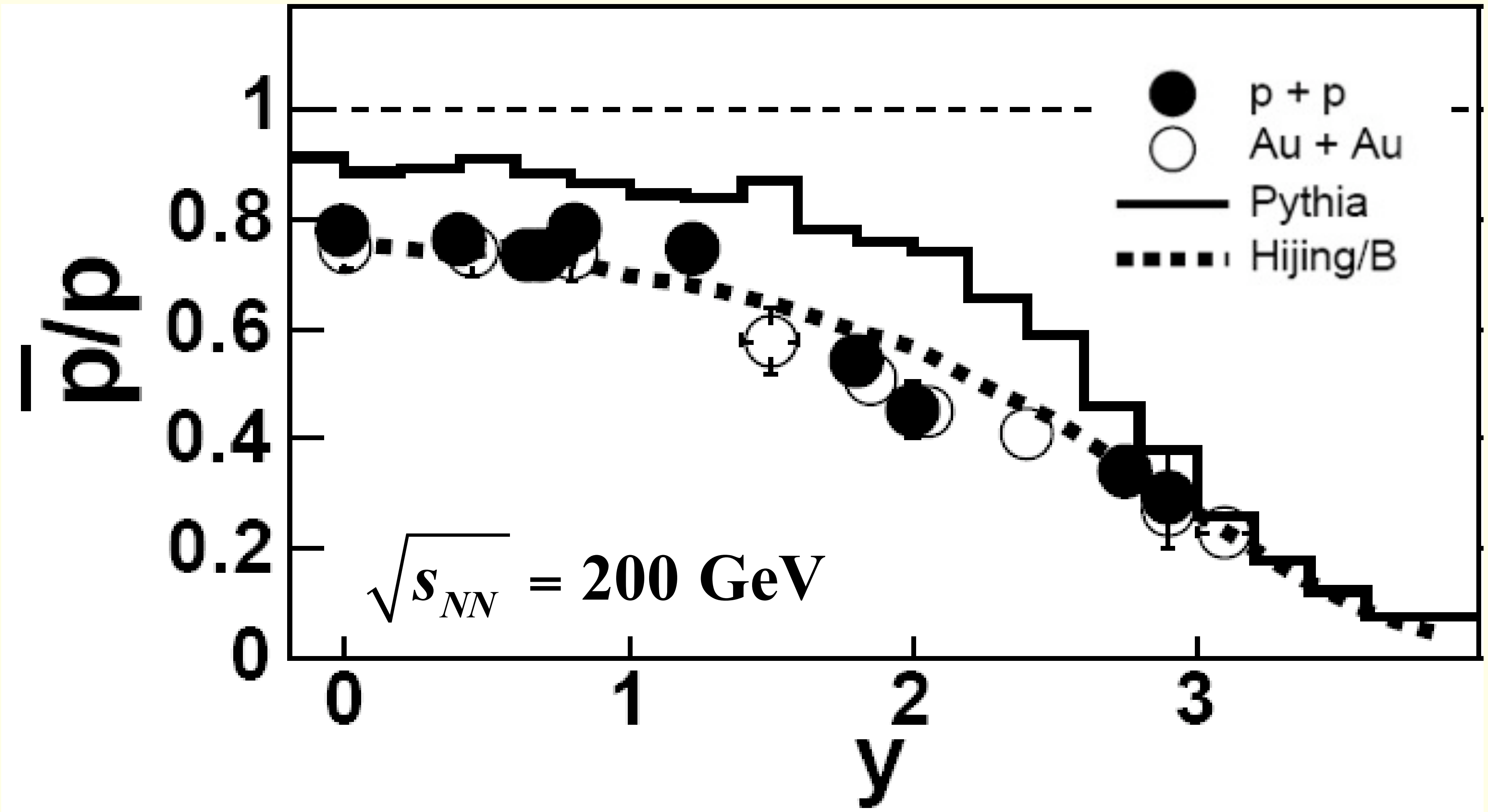
- Proton = 3 valence quarks + 3 strings connected by a gluonic string junction
- New approach:
  baryon number stopping = stopping of the string junction
- If the baryon number BN is associated with the gluons, the probability to stop it is independent of the rapidity gap Δ*y*
- The asymmetry is constant vs. rapidity, esp. it is non-zero at mid-rapidity!
- However, the predicted asymmetry is only on the order of a few %. Thus, it will be challenging to discriminate between the models.

Comparison of the two scenarios:



Baryon Number Stopping: Earlier Results

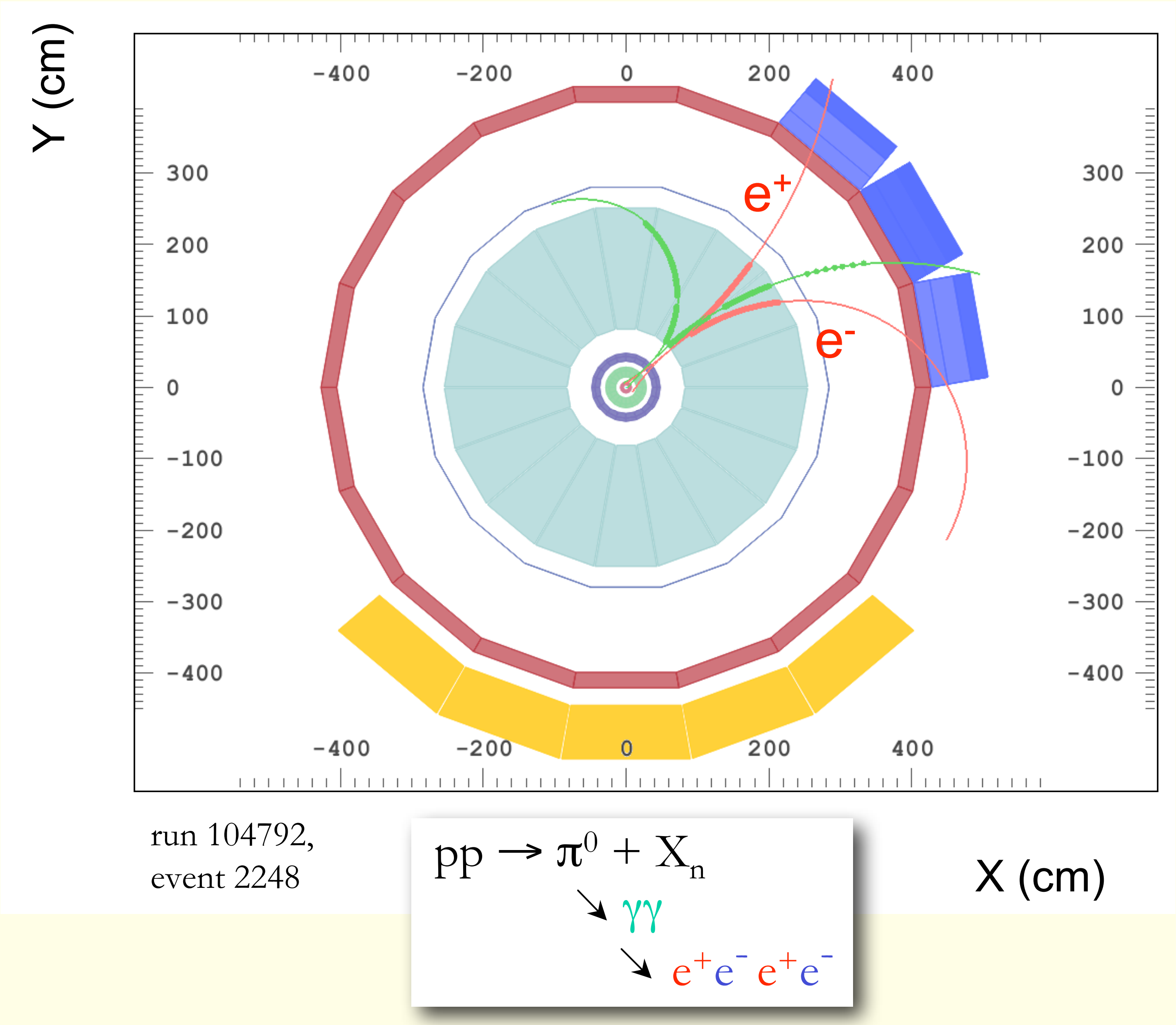
BRAHMS: Phys. Lett. B607 (2005) 42



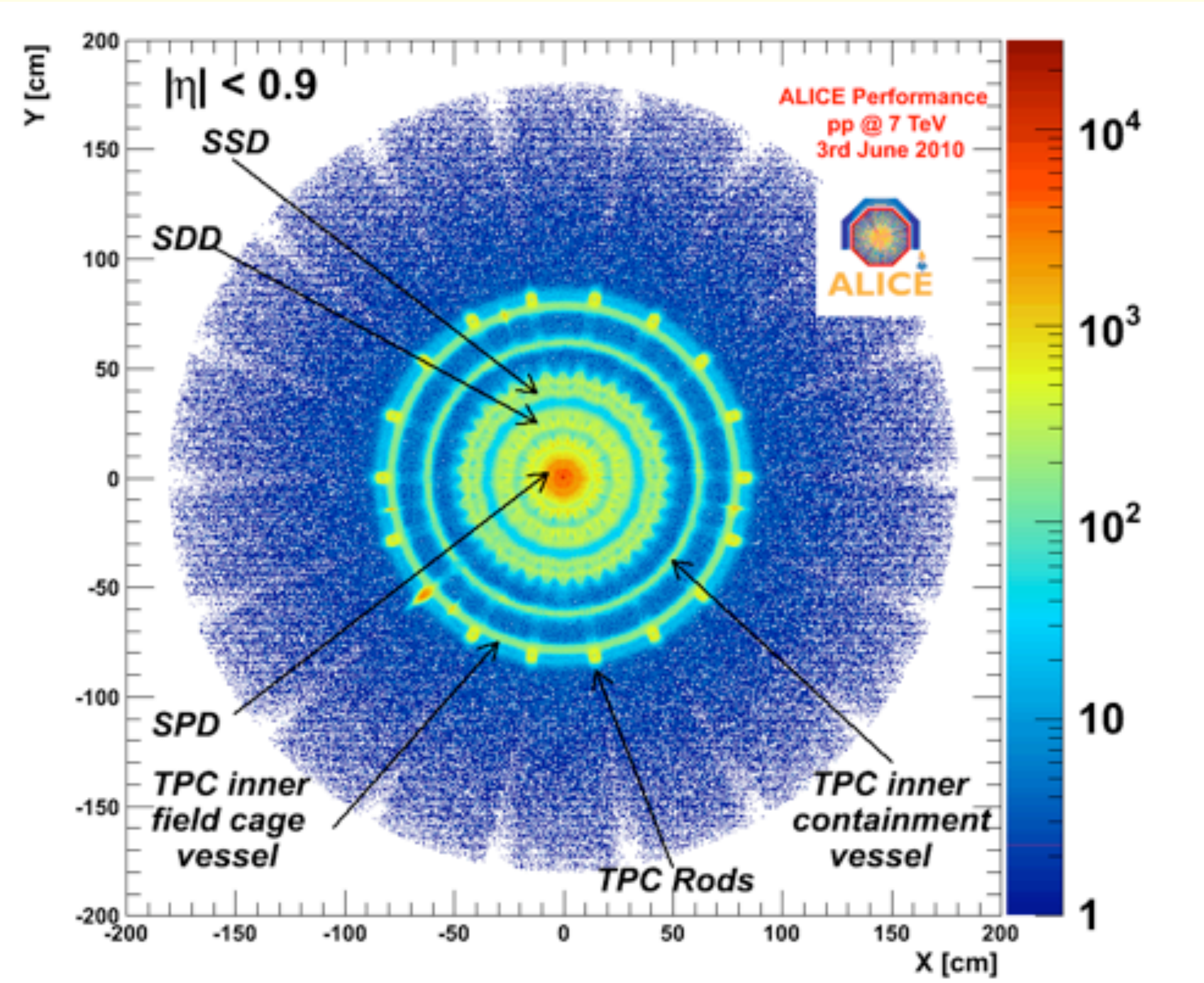
- HIJING/B: Implementation of string junction stopping
- HIJING/B describes data better than Pythia
- Evidence for BN stopping via string junctions

Antiproton/Proton Measurement: Very Good Knowledge of the Material Budget Necessary

A real event (900 GeV) with two photon conversions:

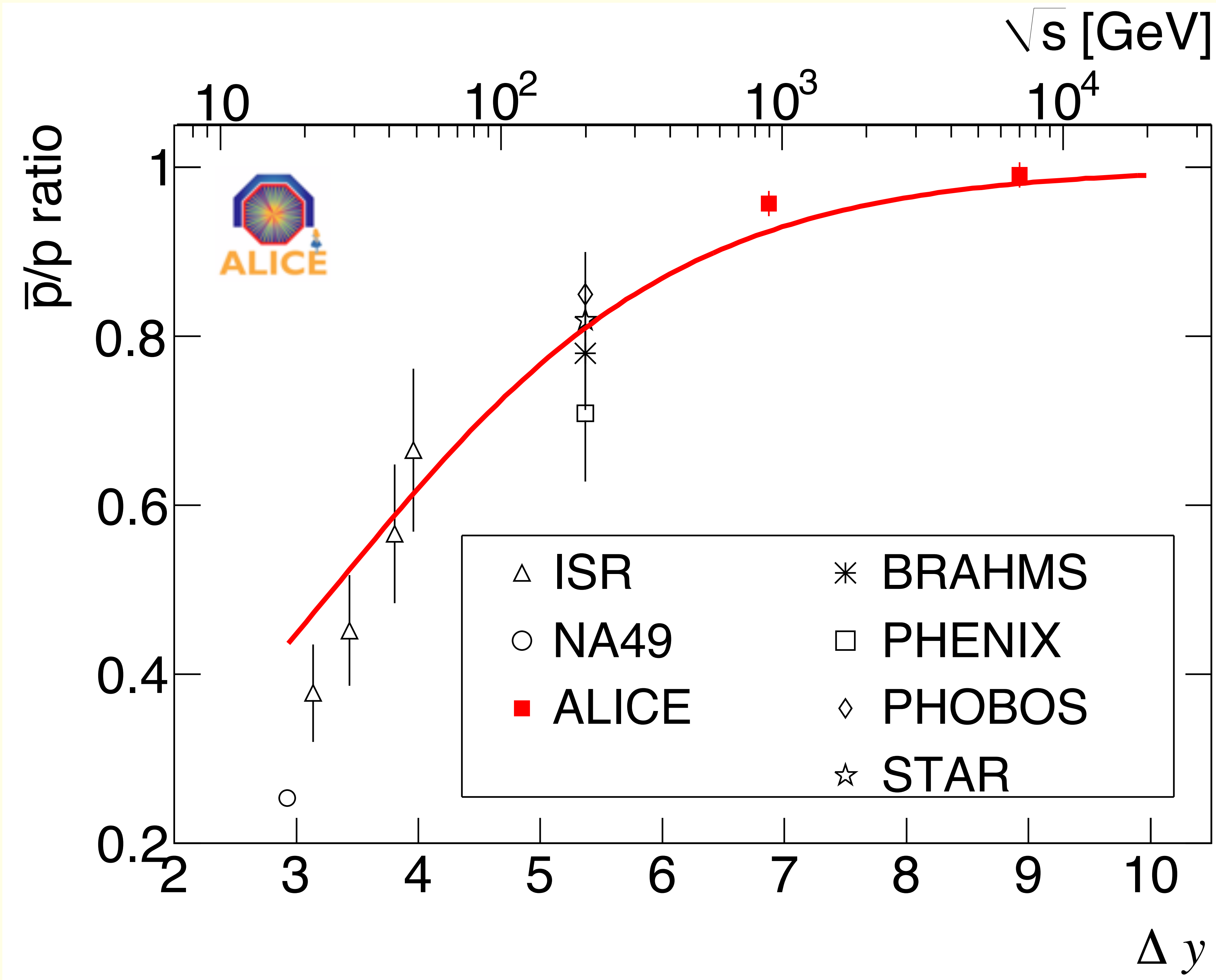


Map of the photon conversion points (real data):



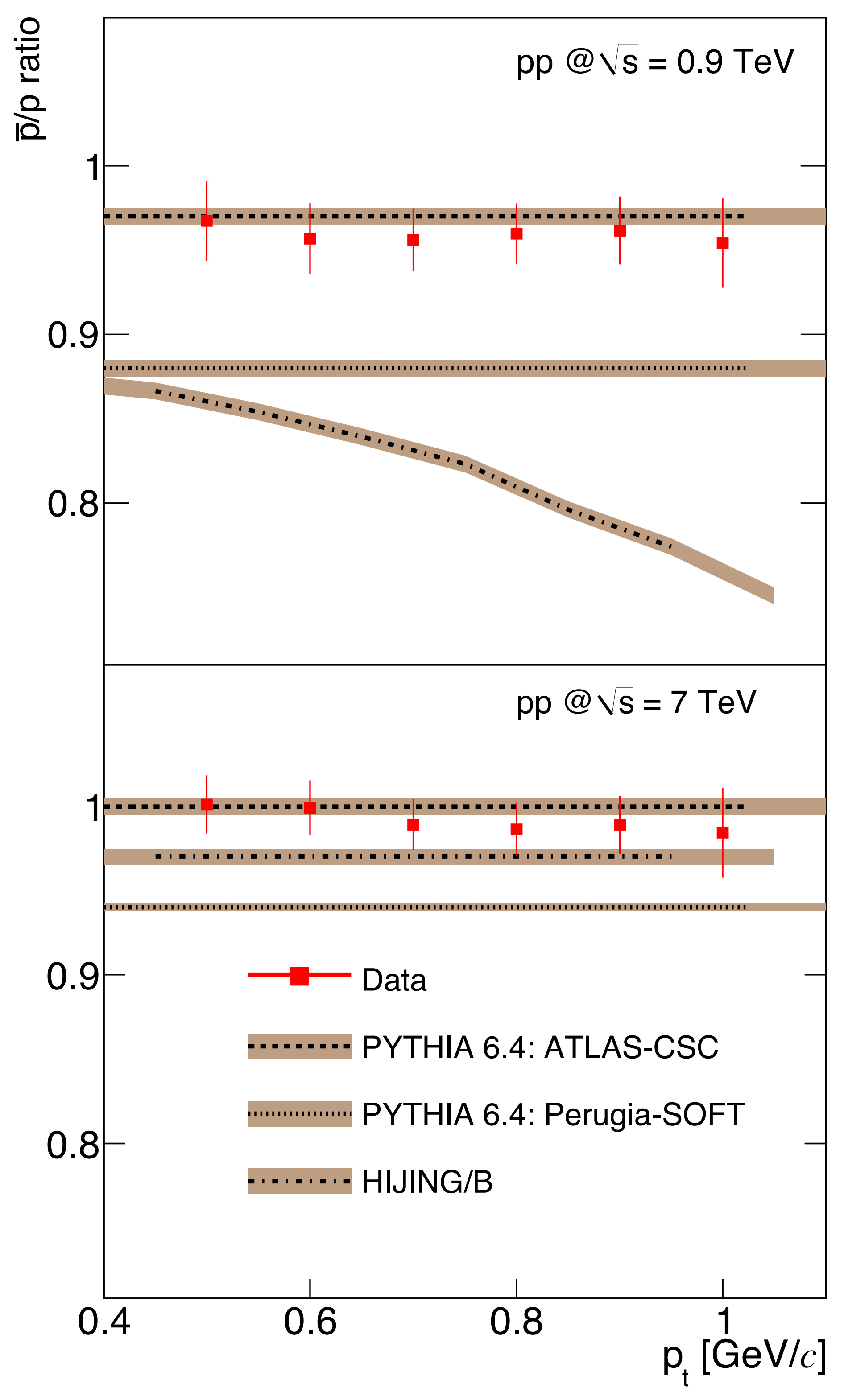
- e^+e^- from photon conversions allow to take an „X-ray“ picture of the detector
- Alice: Very good agreement (on the 7% level) between data and detector simulation (Geant)

Antiproton/Proton Ratio From Alice (I)



Antiproton/Proton ratio around mid-rapidity very close to unity at $\sqrt{s}$ = 7 TeV

Antiproton/Proton Ratio From Alice (II)



- R = antiprotons / protons
  - 0.9 TeV: $R_{|y|<0.5}$ = 0.957 ± 0.006(stat.) ± 0.014(syst.)
  - 7 TeV: $R_{|y|<0.5}$ = 0.991 ± 0.005(stat.) ± 0.014(syst.)
- The difference in the pbar/p ratio, 0.034 ± 0.008(stat.), is significant because the systematic errors at both energies are fully correlated
- Within statistical errors, the measured ratio R shows no dependence on transverse momentum (or rapidity)
- At 7 TeV R is consistent with unity
- The results are consistent with the conventional model of baryon-number transport and set stringent limits on any additional contributions to baryon-number transfer over very large rapidity intervals in pp collisions

8. Strange Particle Production

Mini-Introduction: Strangeness (I)

Particles with strange quarks:

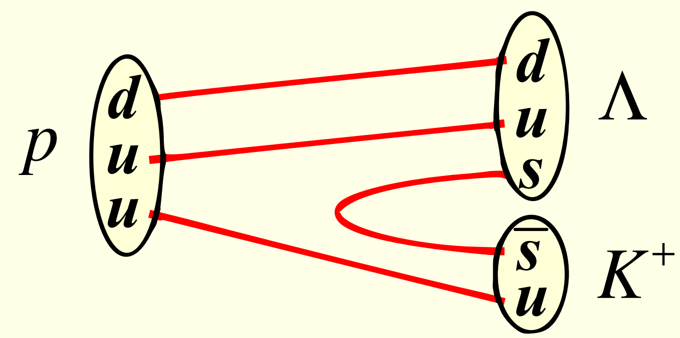
Hidden strangeness

$$K^+ = u\bar{s}, \quad K^0 = d\bar{s}, \quad \bar{K}^0 = \bar{d}s, \quad K^- = \bar{u}s, \quad \phi = s\bar{s}$$

$$\Lambda = uds, \quad \Sigma = qqs, \; \Xi = qss, \; \Omega^- = sss$$

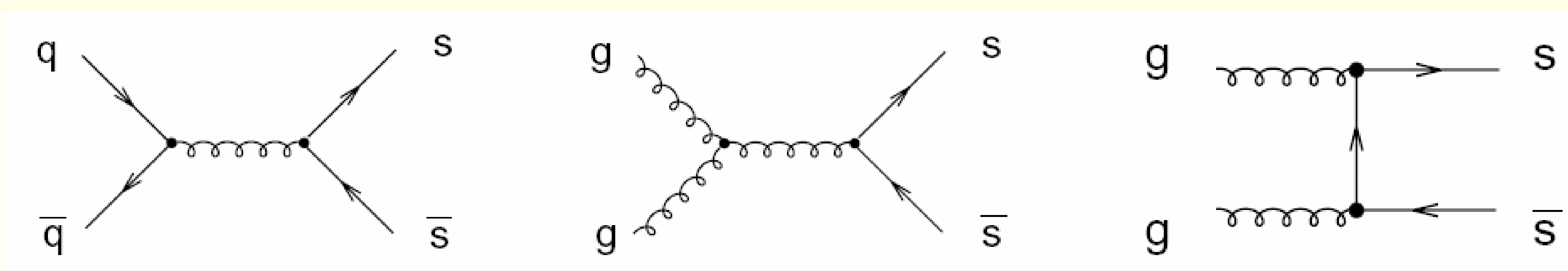
Example for the production of strangeness in low-energy hadronic collisions:

$$p + p \rightarrow p + K^+ + \Lambda$$



„associate production of strangeness“

Production for strange quark pairs in the QGP:



Mini-Introduction: Strangeness (II)

Example: p+p at $\sqrt{s}$ = 13.8 GeV (fixed-target experiment with p_{beam} = 100 GeV/c)

	p	n	π^+	π^0	π^-	Λ	K^+	K^-	K^0	$\bar{K}^0$	$\bar{p}$
$\langle N \rangle$	1,4	0,5	2,3	2,0	1,76	0,11	0,17	0,10	0,14	0,10	0,01

Counting quark numbers yields:

	u	$\bar{u}$	d	$\bar{d}$	s	$\bar{s}$
insg.	6,88	2,88	5,41	3,41	0,31	0,31
vorher	4	-	2	-	-	-

Fraction of strange quarks:

$$(N_s + N_{\bar{s}}) / (N_{u,d} + N_{\bar{u},\bar{d}}) = 0{,}033$$

Expectation for the strangeness content of a QGP with $T \approx m_s$:

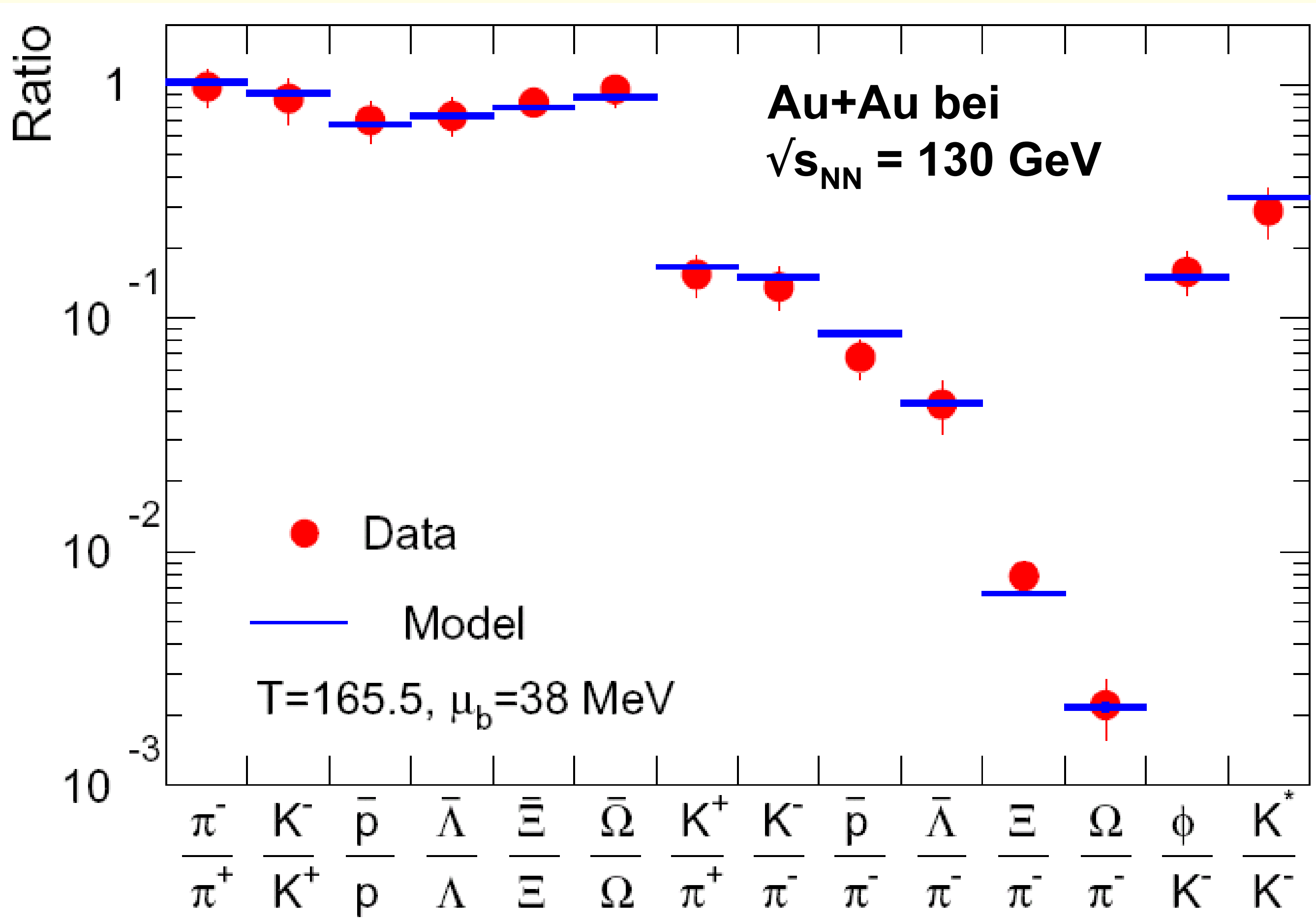
$$n_{\text{Quark}} = N_c N_s \frac{4\pi}{(2\pi)^3} \int_0^\infty \left(\frac{p^2}{1 + e^{\left(\sqrt{p^2 + m_{\text{Quark}}^2} - \mu_{\text{Quark}}\right)/T}} \right) \mathrm{d}p$$

- n_{Quark}: u, d oder s
- N_c: 3 (Farbe)
- N_s: 2 (Spin)
- m_{Quark}: Stromquarkmasse: $m_{u,d} \approx 5 - 10$ MeV, $m_s \approx 100$ MeV

$$(N_s + N_{\bar{s}}) / (N_{u,d} + N_{\bar{u},\bar{d}}) \approx 0{,}5$$

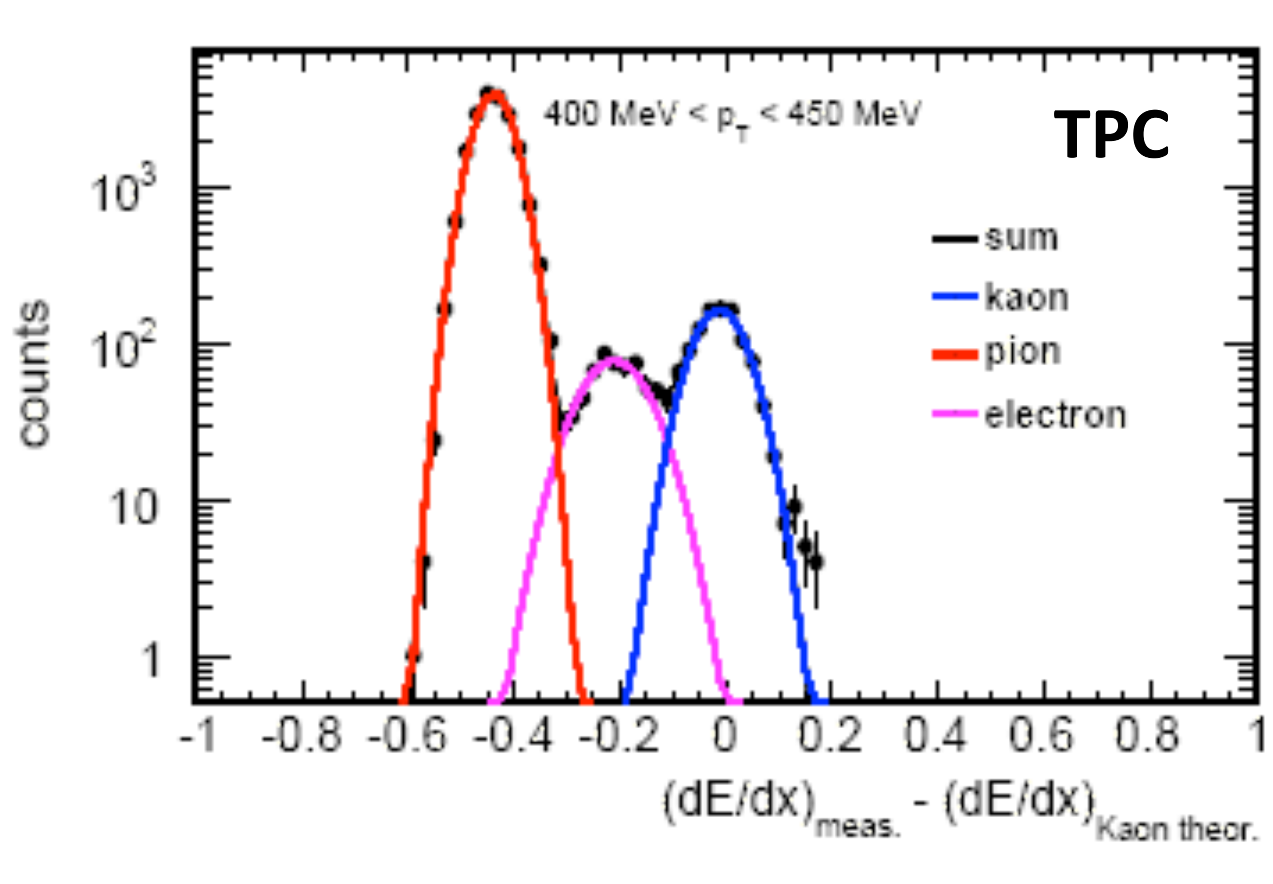
A significant enhancement of strangeness is considered to be a signature for the QGP!

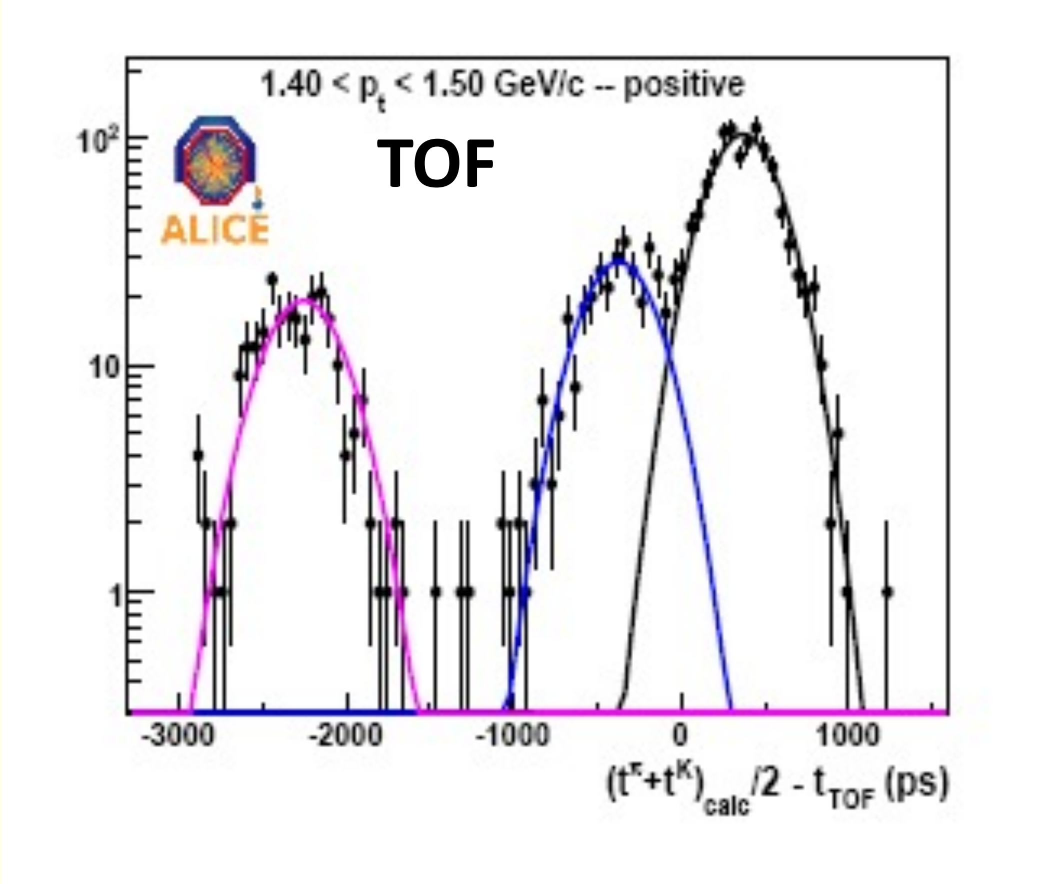
Statistical Particle Production in Heavy-Ion Collisions



- Hadron yields in Au+Au at RHIC well described by statistical models
  - Assume hadronic resonance gas
  - Yields of all particle species quantitatively described by only 3 parameters (T, μ_B, V)
- Data can be used to determine the chemical freeze-out temperature
- As a function of $\sqrt{s}$, T reaches a limiting value of $T \approx 160$ MeV
- Indirect evidence for the QGP ⟶ hadron gas phase transition

Particle Identification With TPC and TOF

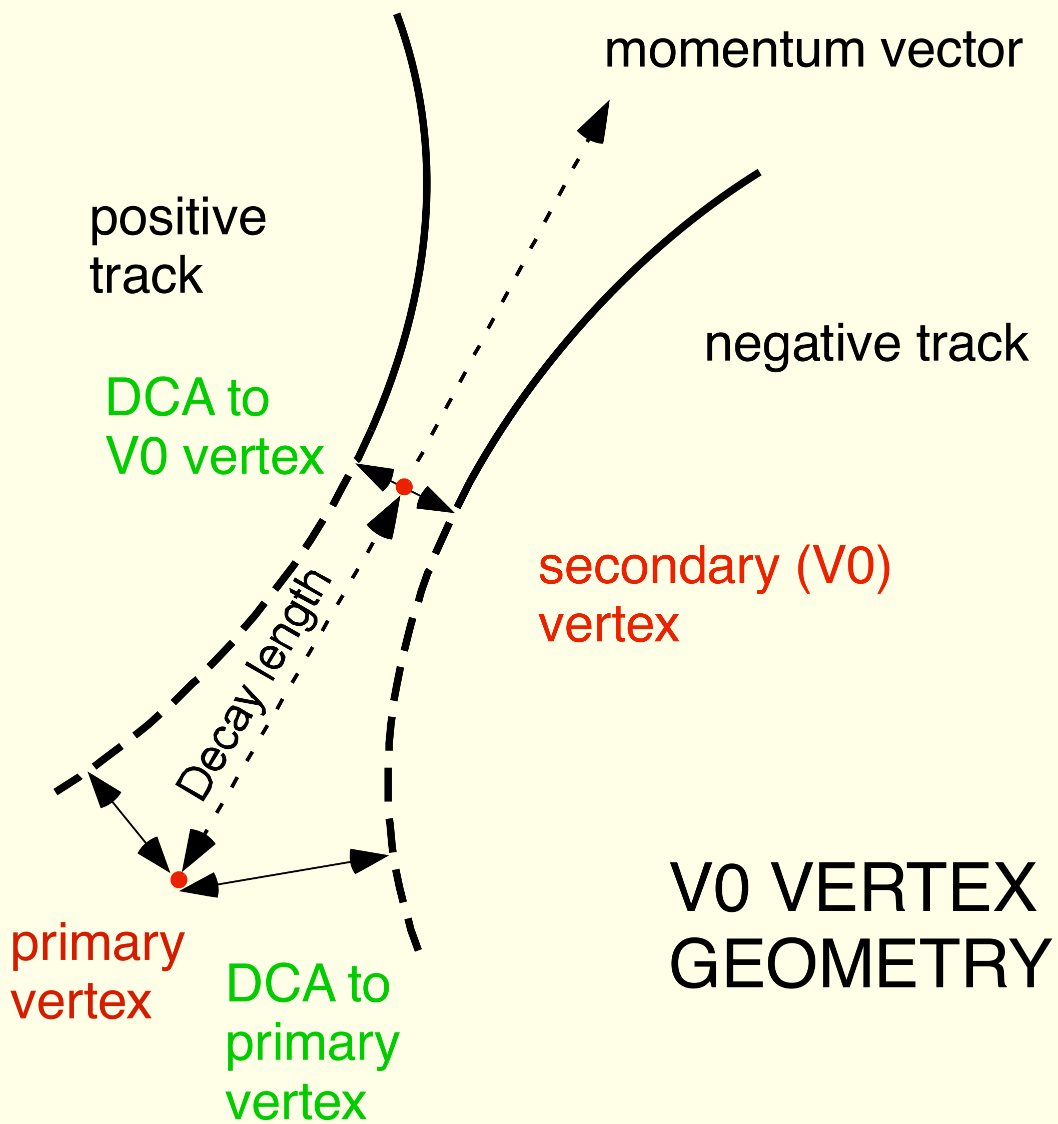




Gaussian unfolding for the determination of the raw yields

Reconstruction of K_s^0‘s and Λ‘s

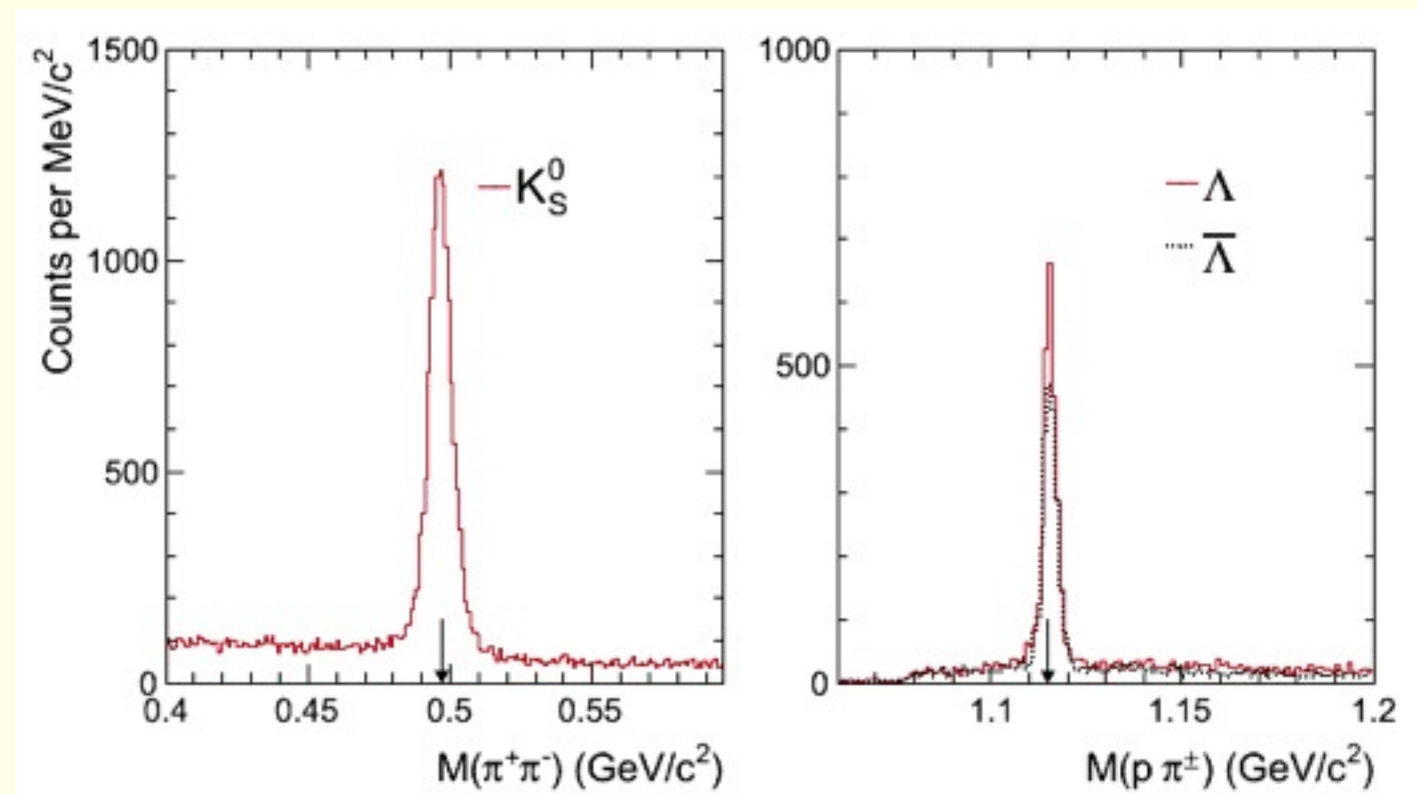
dca = distance of closest approach



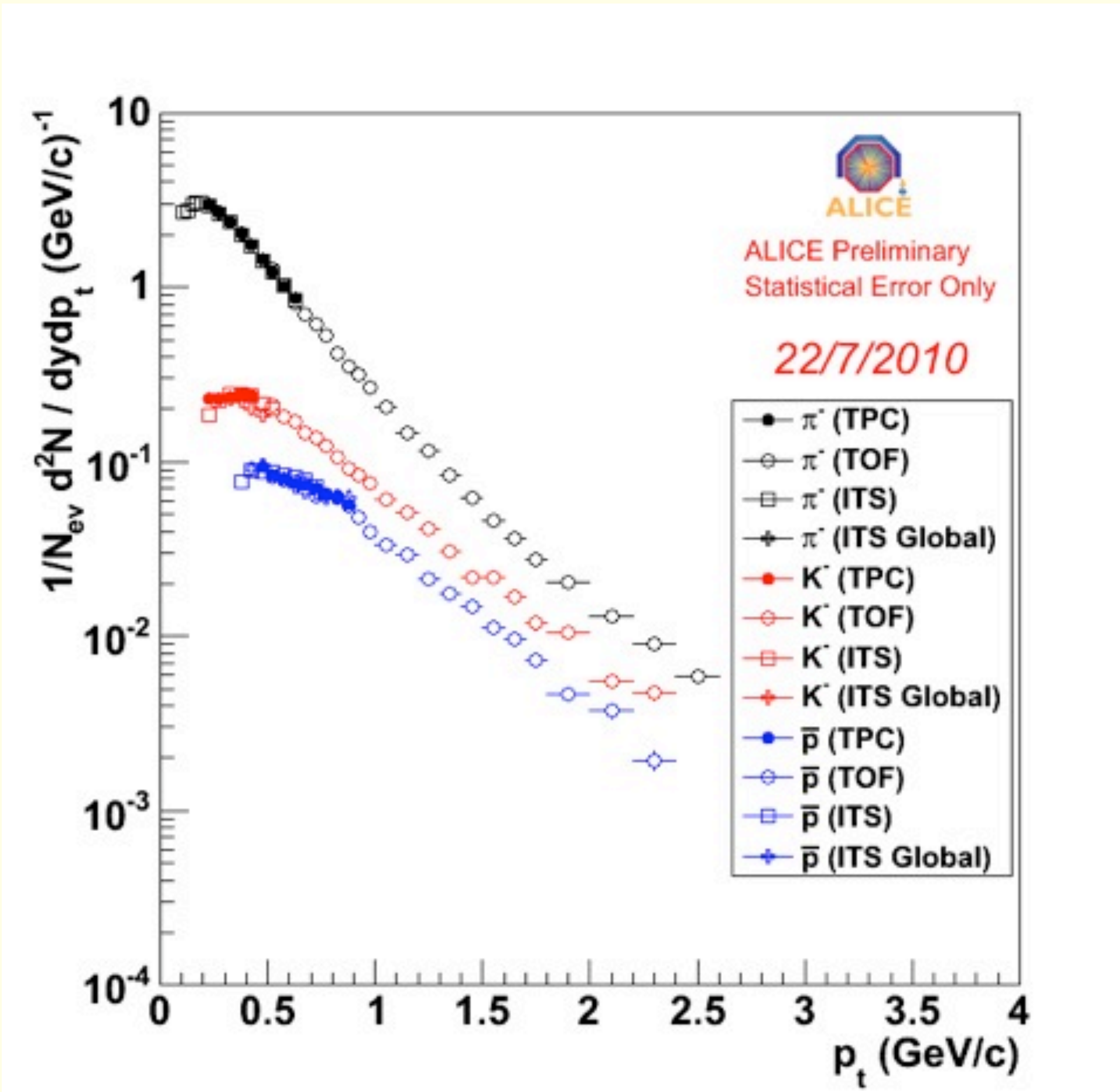
Particle	Decay	Branching ratio	cτ (cm)
Λ	p π^-	63.9%	7.89
Λ	p π^+	63.9%	7.89
K^0_s	$\pi^+\pi^-$	69.2%	2.68

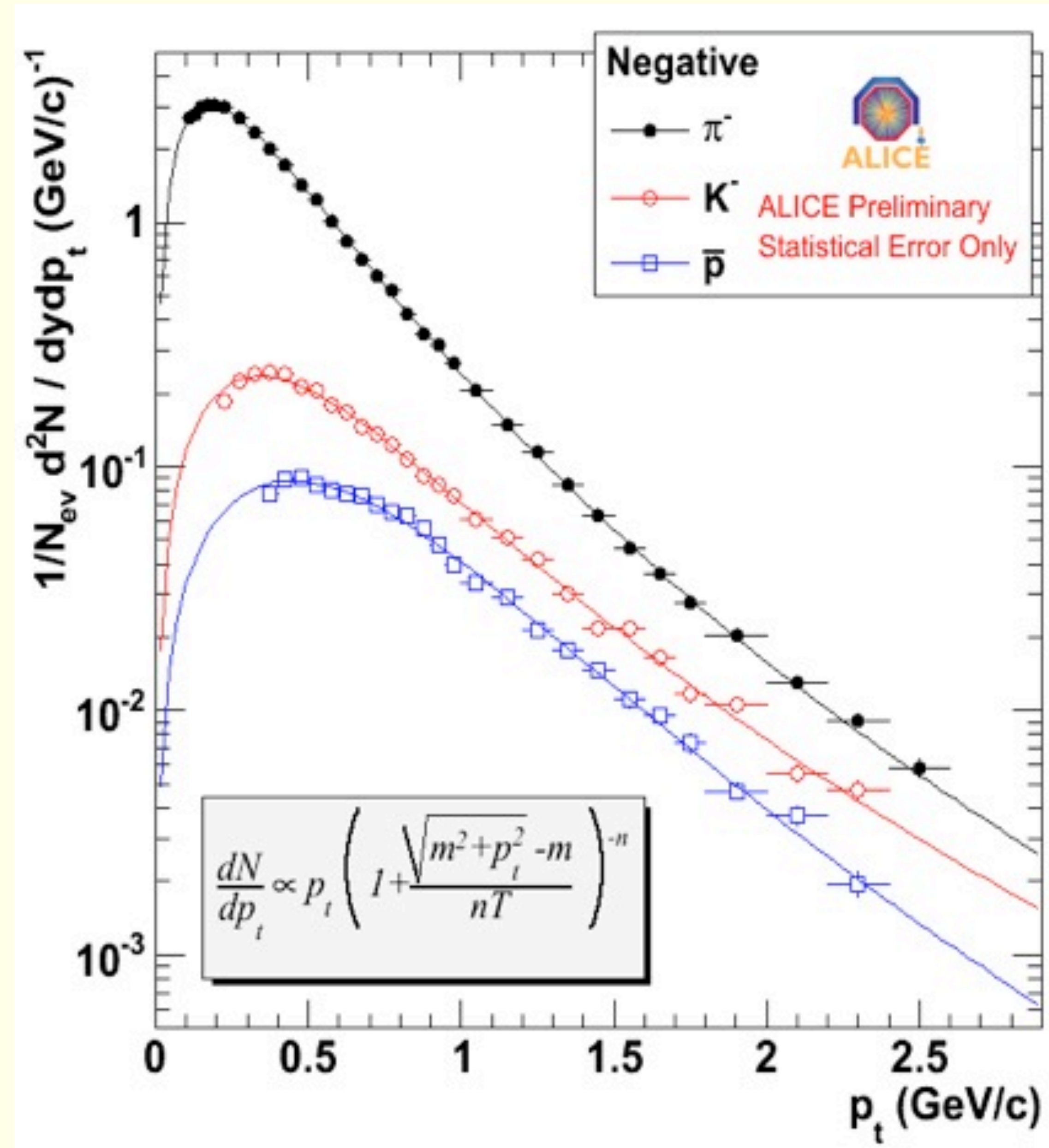
- Select secondary tracks from DCA to primary vertex
- Select secondary vertex by DCA of secondary tracks to possible vertex

Invariant mass distributions:



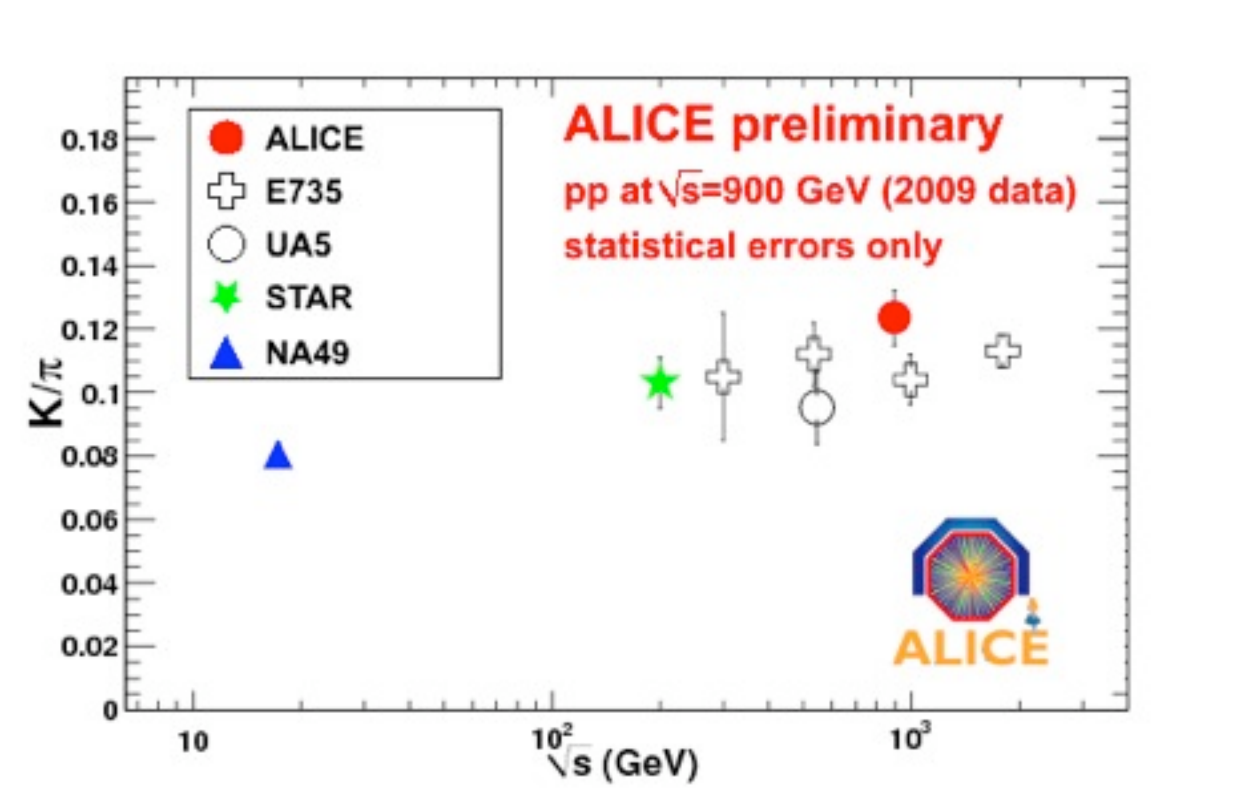
Identified Particle Spectra from Alice



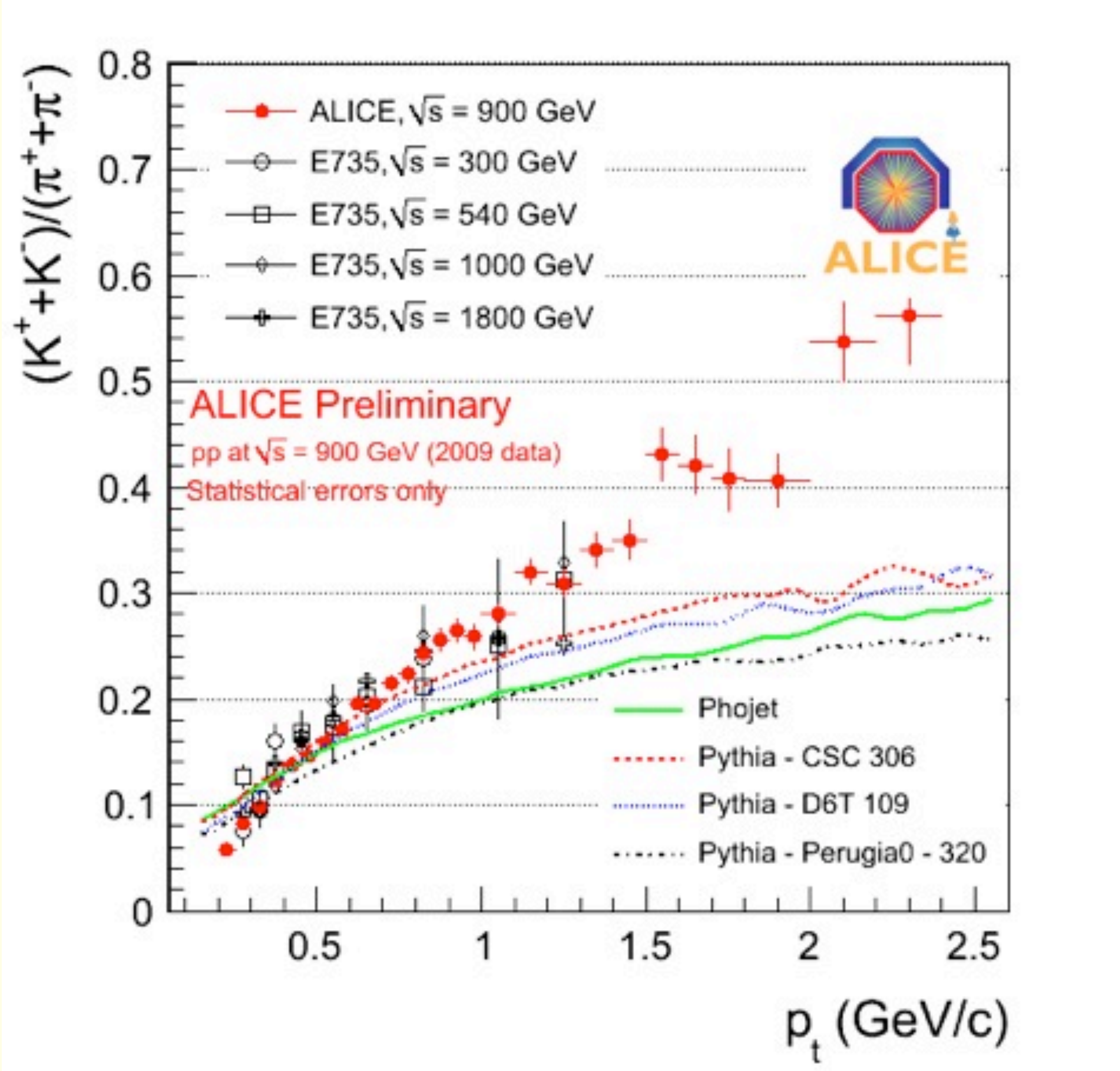


- Very good agreement between different particle identification methods

K/π Ratio Measured by Alice

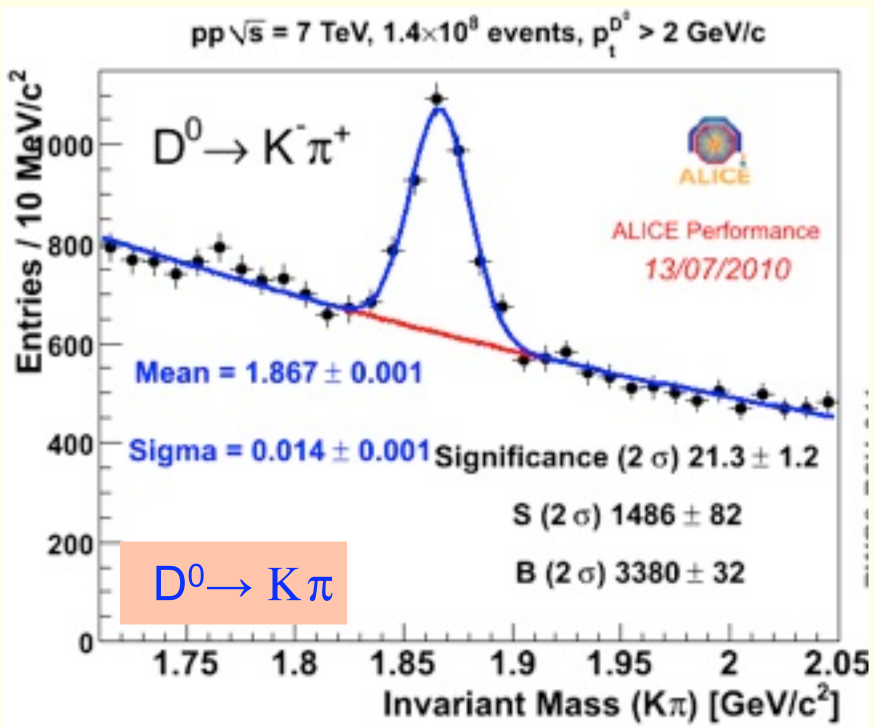


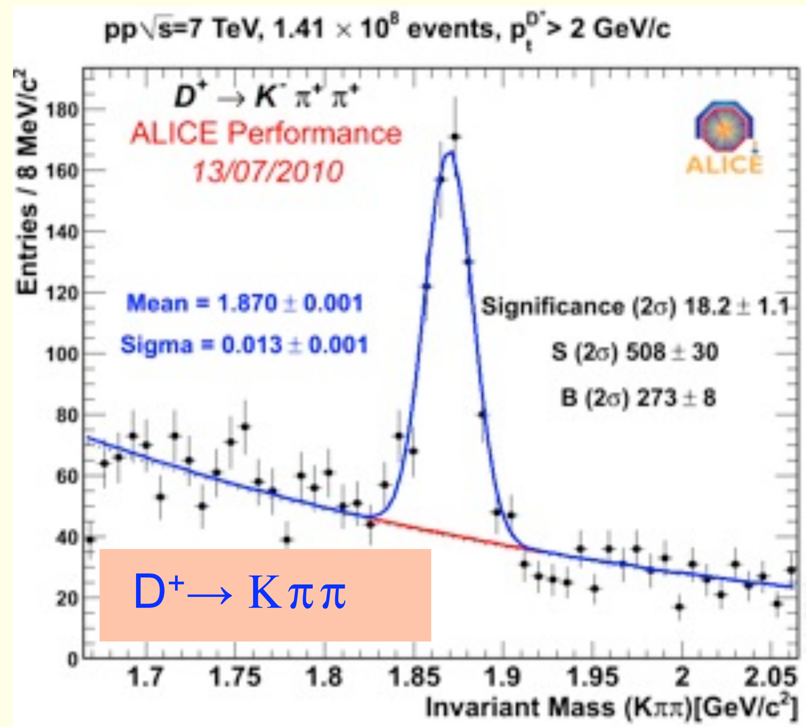
ALICE point was obtained using the yields extracted from the Lévy-fits shown on the previous slide (fit range: 0.2 < pt < 2.4 GeV/*c* for K and π)

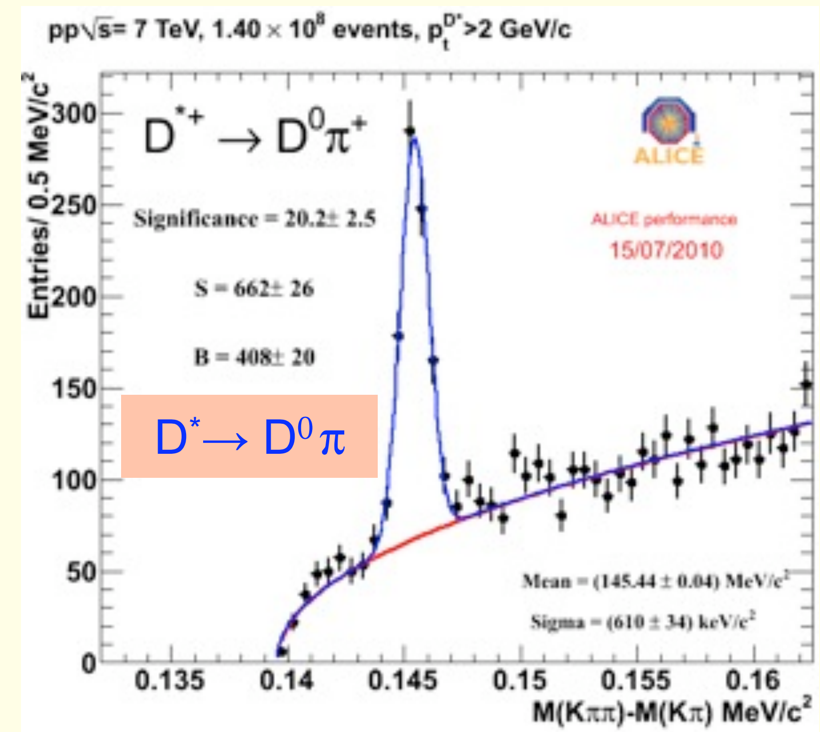


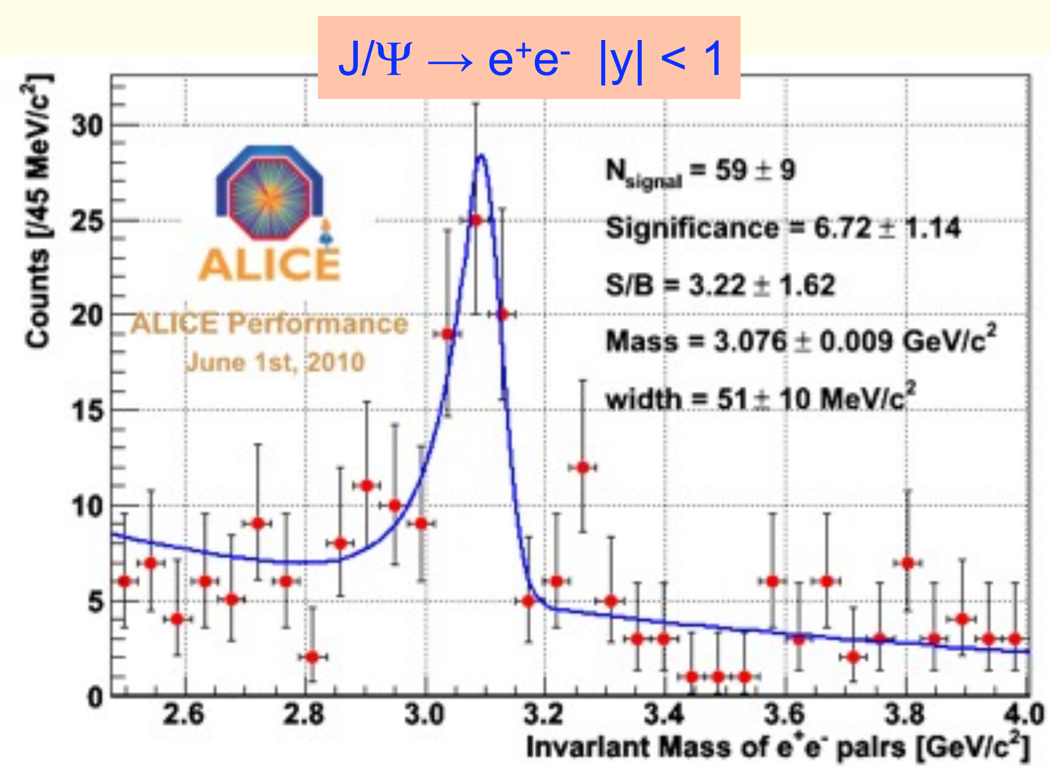
- K/π ratio seems to be rising slowly with √*s*
- Significant discrepancy between Phojet and Pythia predictions and measured K/π

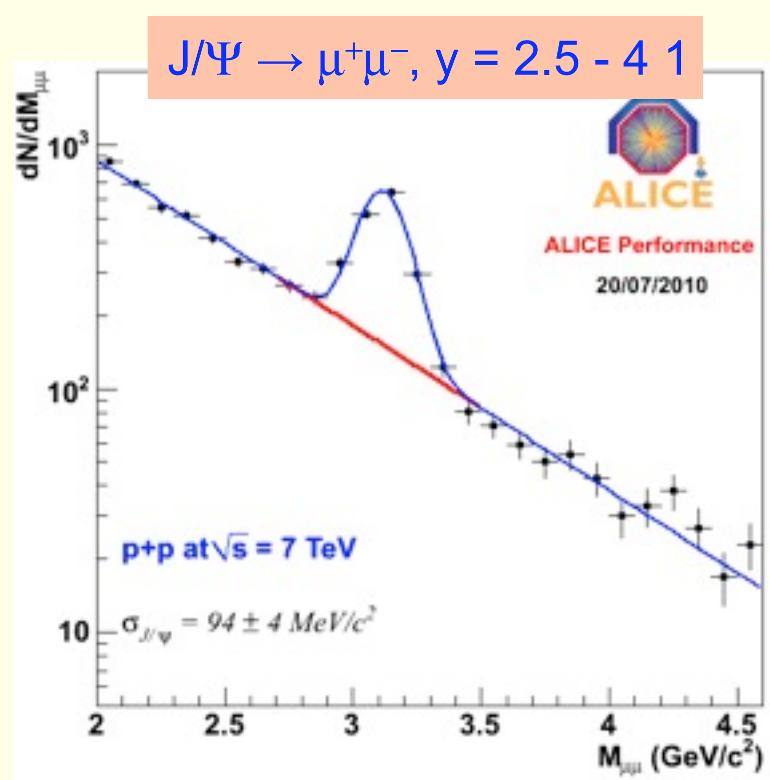
A Quick Look at Charm Production at 7 TeV

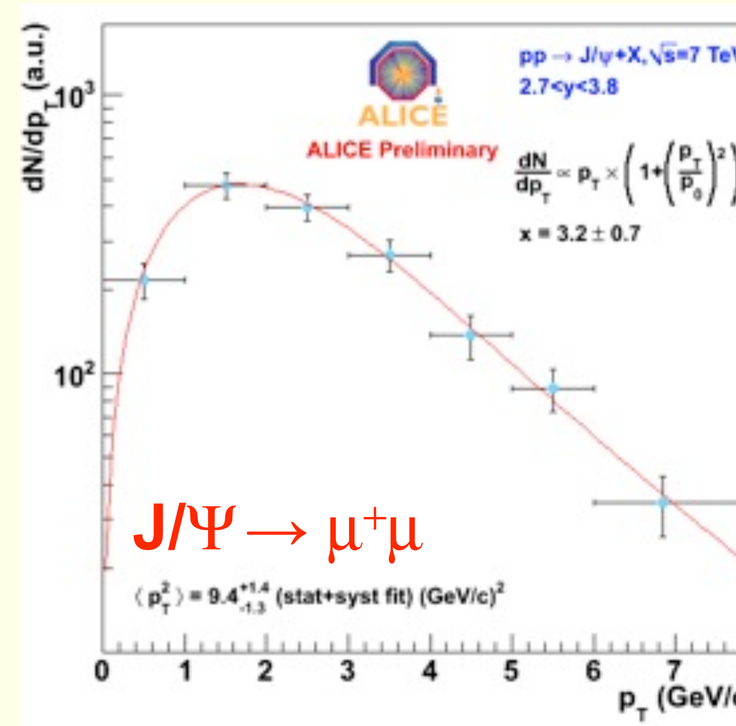






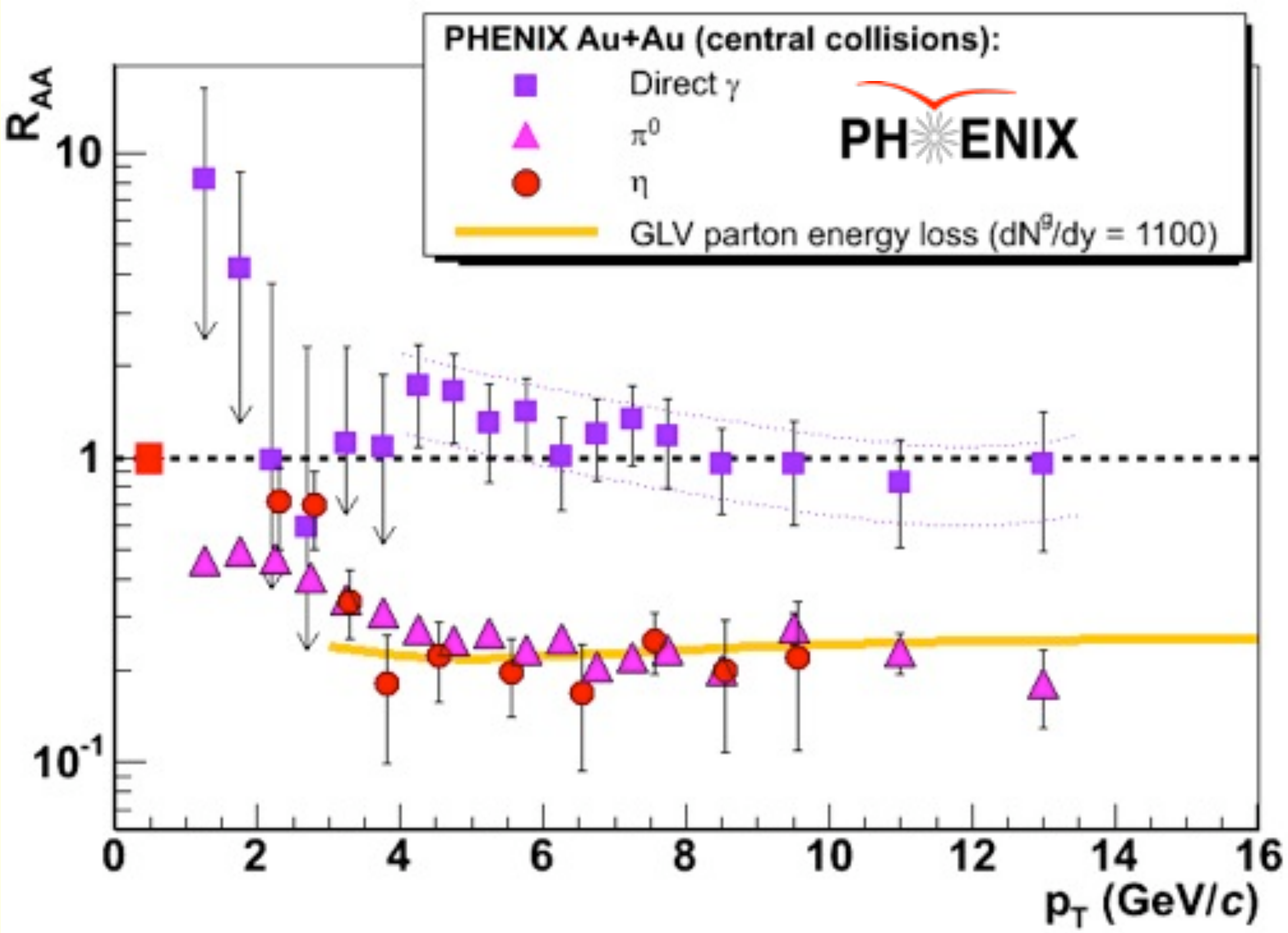


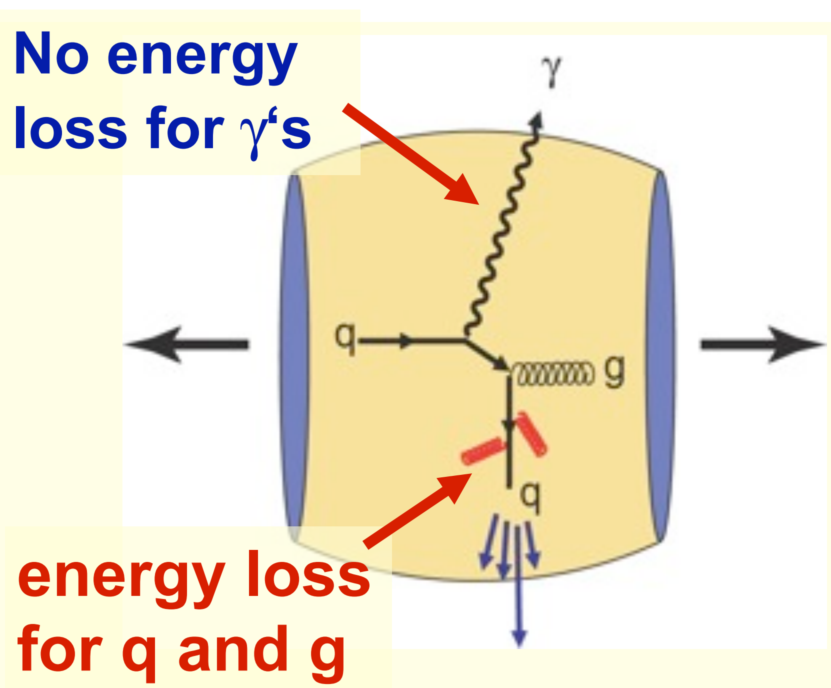




9. Outlook: The upcoming heavy-ion run

Discoveries Made at RHIC (I): Jet Quenching





$$R_{AB} = \frac{\mathrm{d}N / \mathrm{d}p_T\big|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}} \rangle \times \mathrm{d}\sigma_{\mathrm{inv}} / \mathrm{d}p_{\mathrm{T}}\big|_{\mathrm{p+p}}},$$

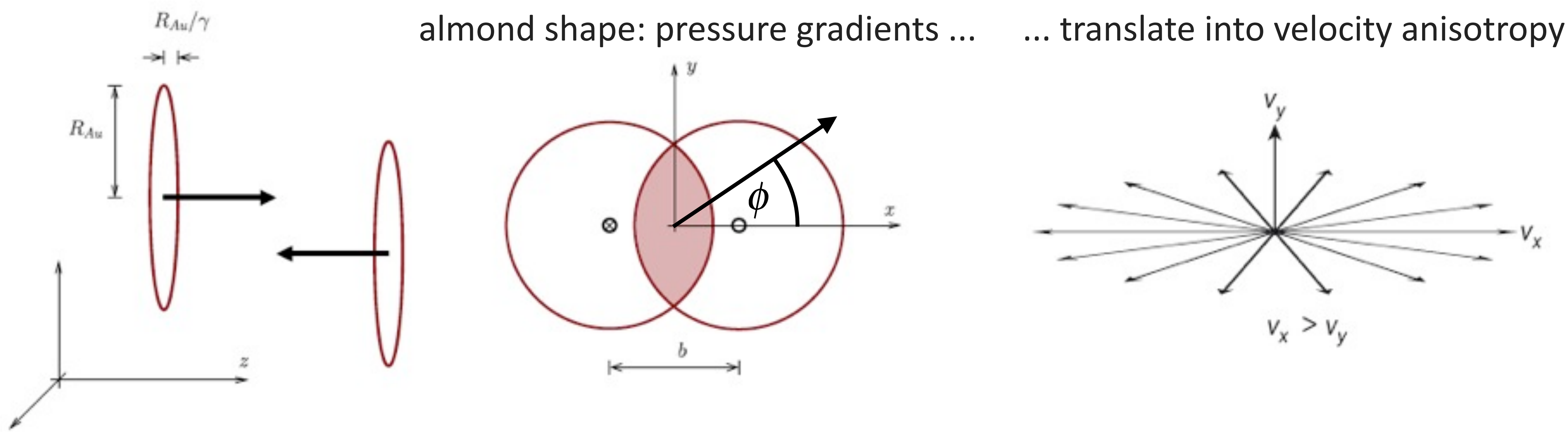
$$\text{where } \langle T_{\mathrm{AB}} \rangle = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

- Hadrons are suppressed, direct photons are not
- No suppression in d+Au (not shown here)
- Evidence for parton energy loss

PHENIX: Phys.Rev.Lett.88:022301, 2002
PHENIX: Phys.Rev.Lett.91:072301, 2003
PHENIX: Phys.Rev.Lett.94:232301, 2005

STAR: Phys.Rev.Lett.89:202301,2002
STAR: Phys.Rev.Lett.90:082302,2003
STAR: Phys.Rev.Lett.91:172302,2003

Discoveries Made at RHIC (II): Evidence for Collective Behavior: Elliptic Flow



- Impact parameter vector and beam axis define the *reaction plane*
- Orientation of the reaction plane can be measured event-by-event
- Particle yields as a function of the angle ϕ w.r.t. the reaction plane:

$$E \frac{dN}{d^3p}\bigg|_{p_z=0} = N_0(p_T) \cdot \left[1 + 2v_2(p_T)\cos(2\phi) + 2v_4\cos(4\phi) + \ldots\right]$$

- For a typical mid-central collision at RHIC (b ≈ 6 fm): $v_2 \approx 6\%$
- Interpretation: Hydrodynamic evolution converts initial pressure gradients to velocity gradients in the final state

The Upcoming Heavy-ion Run

- 1 month/year heavy-ion program, initially ^{208}Pb + ^{208}Pb
  - later: p+Pb, light A+A, ...
- Initial $\sqrt{s}$ = 2.76 TeV (factor 13.8 increase compared to RHIC)
  - Later up to factor 28 beyond RHIC
- Higher $\sqrt{s}$ provides
  - higher initial QGP temperature, longer QGP lifetime and thus clearer signals from the QGP phase of the reaction
  - an abundant production of hard probes (jets, heavy quarks, ...) for QGP diagnostics
- First Pb+Pb run will start on November 6
- Initial luminosity: 10^{25} cm^{-2} s^{-1} (factor 100 below nominal)
- expected data sample?
  - e.g.: 20 days at 50 Hz min bias at 20% overall duty factor: $1.5 \cdot 10^7$ min bias events
- First physics
  - Charged particle multiplicity
  - Flow (v_2)
  - Charged hadron p_T spectra: R_{AA} jet quenching