

**Entropy and proton-proton collision
at UA1/UA5, TEVATRON
and CERN LHC (FCC?)**

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(HUN-REN WIGNER RCP)**

TSBIRO70, 12 June 2026

Content:

- 1. Collaborations between TSBiro and PLevai – publications with co-authorship**
- 2. Accelerators at high energies (CERN SPS/LEP/LHC, TEVATRON)**
- 3. Formation of QGP in high energy heavy ion collisions**
- 4. Proton-proton collisions at ultrarelativistic energies (TEVATRON & LHC)**
- 5. Proton structure – parton entanglement? Quantum World and QGP ?**
- 6. Conclusion**



Shared research activities of T.S. Biró and P. Lévai in 25 years (1990-2014):

DUKE-year in 1990: „Massive” gluons in the strongly interacting QGP

Strangeness production with "massive" gluons

TS Biro, P Levai, B Müller, Physical Review D 42 (9), 3078 (1990) [94]

Budapest-decade on hadronization (1995-2004)

A) Quark-coalescence model for hadronization – ALCOR:

ALCOR: a dynamical model for hadronization

TS Biró, P Lévai, J Zimányi, Physics Letters B347, 6-12 (1995) [220]

Strange hadrons from the ALCOR rehadronization model

TS Biro, P Levai, J Zimanyi, AIP Conference Proceedings 340, 405-418 (1995) [3]

Particle spectra from the ALCOR model

J Zimányi, TS Biró, T Csörgő, P Lévai, Acta Physica Hungarica A, Heavy Ion Physics 4, 15-32, (1996) [26]

The dependence of strange hadron multiplicities on the speed of hadronization

J Zimányi, TS Biró, P Lévai, Journal of Physics G23, 1941-1946 (1997) [19]

B) Quark-coalescence model and experimental data from SPS and RHIC:

Quark liberation and coalescence at CERN SPS („Last call for RHIC”)

J Zimányi, TS Biró, T Csörgő, P Lévai, Physics Letters B472, 243-246 (2000) [103]

Simple predictions from ALCOR_c for rehadronization of charmed quark matter

P Lévai, TS Biró, T Csörgő, J Zimányi, New Journal of Physics 2, 332 (2000) [8]

The Production of charm mesons from quark matter at CERN SPS and RHIC

P Levai, TS Biró, P Csizmadia, T Csörgő, J Zimanyi, Journal of Physics G27, 703-706, 2001 [47]

Quark coalescence in the mid-rapidity region at RHIC

TS Biro, P Levai, J Zimanyi, Journal of Physics G28, 1561-1566 (2002) [59]

C) Understanding of quark matter from the process of quark-coalescence:

Faces of quark matter

J Zimányi, P Lévai, TS Biró

Acta Physica Hungarica A, Heavy Ion Physics 17, 205-217 (2003) [15]

Properties of quark matter produced in heavy-ion collision

J Zimányi, P Levai, TS Biro, Journal of Physics G31, 711-718 (2005) [15]

D) Coalescence model and other models

Strange hyperon and antihyperon production from quark and string-rope matter (HIJING-BB)

P Csizmadia, P Lévai, SE Vance, TS Biró, M Gyulassy, J Zimányi, J. Phys G25, 321-330 (1999) [36]

Hadronization model with off-shell (distributed) quarks (1998-2007)

Hadronization of massive quark matter

TS Biró, P Lévai, J Zimányi, Journal of Physics G25, 311-320 (1999) [13]

Equation of state for distributed mass quark matter

TS Biro, P Levai, P Ván, J Zimanyi, Journal of Physics G32, S205-S212 (2006) [18]

Mass distribution from a quark matter equation of state

TS Biro, P Levai, P Van, J Zimanyi, Physical Review C75, 034910 (2007) [14]

Glueon radiation and its experimental confirmation

Non-Abelian bremsstrahlung and azimuthal asymmetries in high energy reactions

M Gyulassy, P Lévai, I Vitev, TS Biro, Physical Review D 90 (5), 054025 (2014) [59]

Total: 25 years, 25 publications on theory, 740 citations

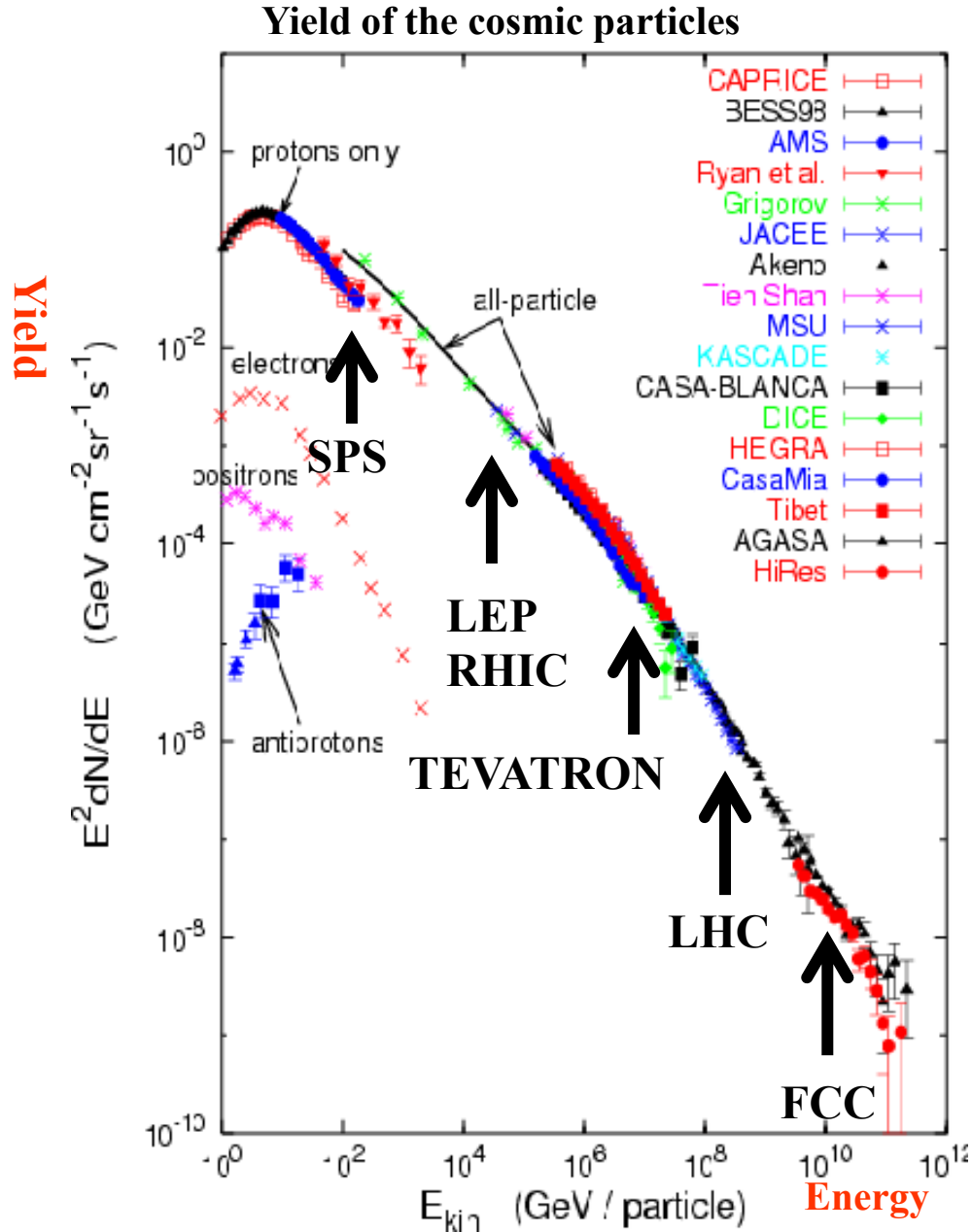
TSBiró → Nanoplasmonic fusion project

LevaiP → Administration

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- 2. Accelerators at high energies (CERN SPS/LEP/LHC, TEVATRON)**
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2. How large is the energy of TEVATRON, LHC, FCC ?



Cosmic rays - continuously:

max. $E_{kin} = 10^{12} \text{ GeV}$ – very rear

Fix target accelerators:

CERN SPS: $E_{kin} = 2 \cdot 10^2 \text{ GeV}$

Collider accelerators:

CERN LEP és BNL RHIC

$\sqrt{s} = 100 + 100 \text{ GeV}$

$\Rightarrow E_{kin} = 2 \cdot 10^4 \text{ GeV}$

TEVATRON

$\sqrt{s} = 900 + 900 \text{ GeV}$

$\Rightarrow E_{kin} = 2 \cdot 10^6 \text{ GeV}$

CERN LHC

$\sqrt{s} = 7000 + 7000 \text{ GeV}$

$\Rightarrow E_{kin} = 1,4 \cdot 10^8 \text{ GeV}$

CERN FCC

$\sqrt{s} = 50000 + 50000 \text{ GeV}$

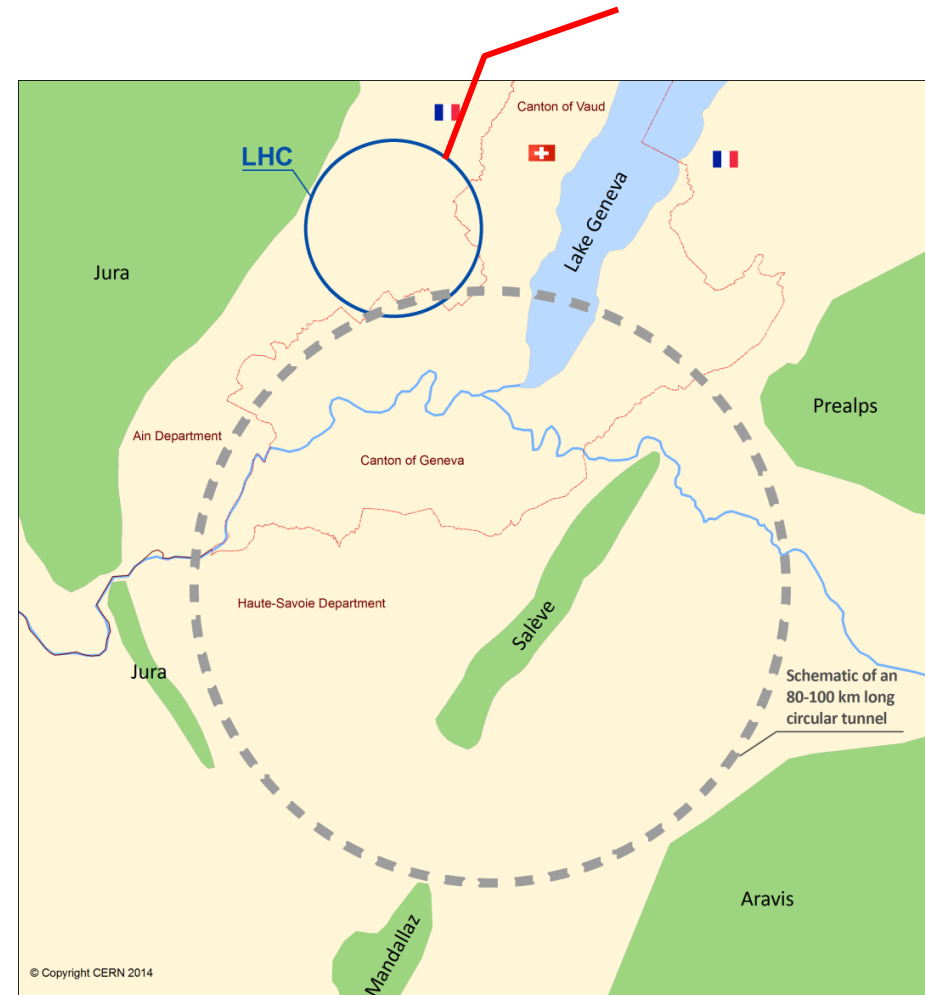
$\Rightarrow E_{kin} = 100 \cdot 10^8 \text{ GeV}$

2. Next Step: "High Energy LHC,, → FCC

First studies on a new 80 km tunnel in the Geneva area

- 42 TeV with 8.3 T using present LHC dipoles
- 80 TeV with 16 T based on Nb_3Sn dipoles
→ FCC-ee
- 100 TeV with 20 T based on HTS dipoles → FCC-hh

HE-LHC :33 TeV
with 20T magnets



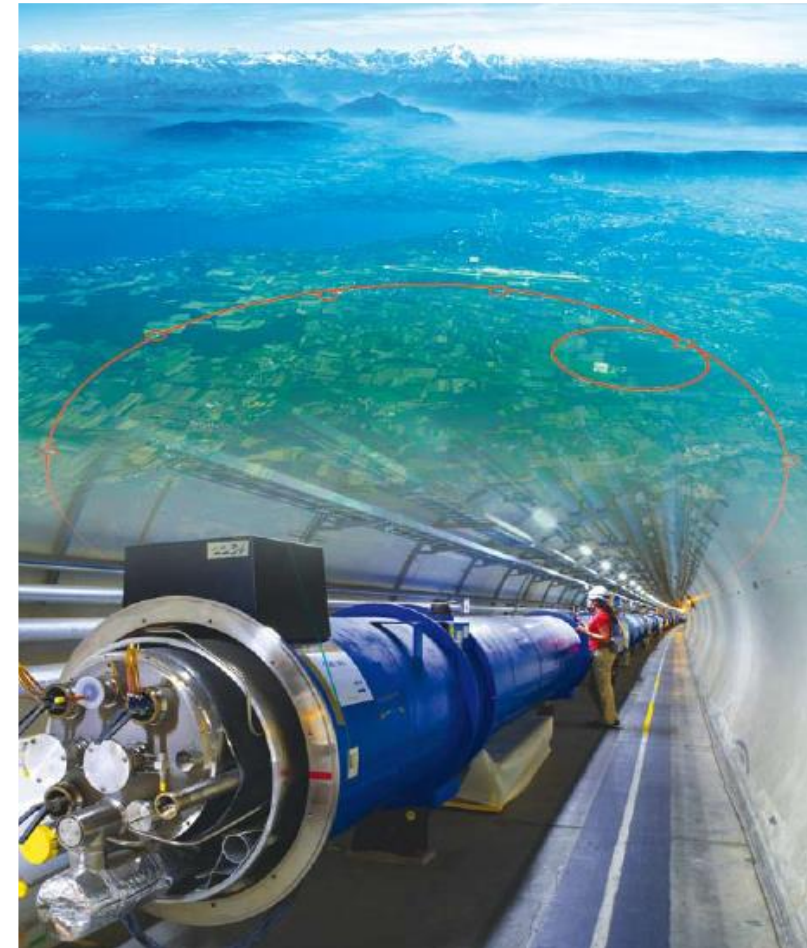
2. Machine: LHC (Large Hadron Collider)

14 TeV p-p collider in the LEP tunnel
6,5 ATeV A-A collider

1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval of the LHC by the CERN Council
1996-1999: Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000: Placement of the main production contracts
2004 : Start of the LHC installation
2005-2007: Magnets Installation in the tunnel
2006-2008: Hardware commissioning
2008-2009: Beam commissioning and repair
2009-2043: **Physics exploitation**

2026 May 22: Budapest, CERN Council ESPP ratification!

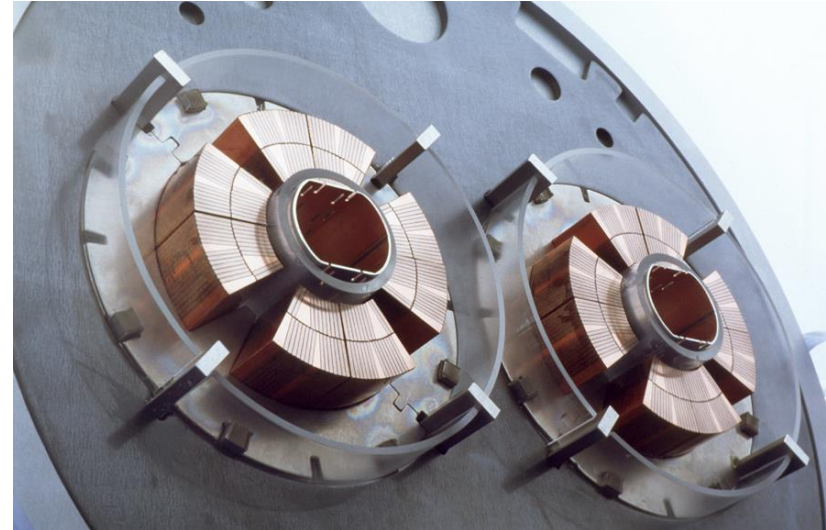
2020-2045: FCC planning and construction
2028-2062: FCC-ee operation
2028-2082: FCC-hh planning, construction → operation
2082-.....: Physics exploitation, „Portal” to the FUTURE



2. LHC is ready by the Summer of 2008



Dipol magnets - drawing



Quadrupol magnets - photo

CERN LHC planned luminosity:

Proton + proton collisions:

2808 bunch, with distance of 7 m (25 ns)

10^{11} proton (100 billion) in 1 bunch

Beam diameter 1 mm at flying, 16 μm at collisions (human hair: 50 μm)

Collision rate: 1+1 bunch 20 collisions

30 million overlap of the bunches during one second

→ 600 million p+p collision per second (10^{16} collision/year 15 P byte data)

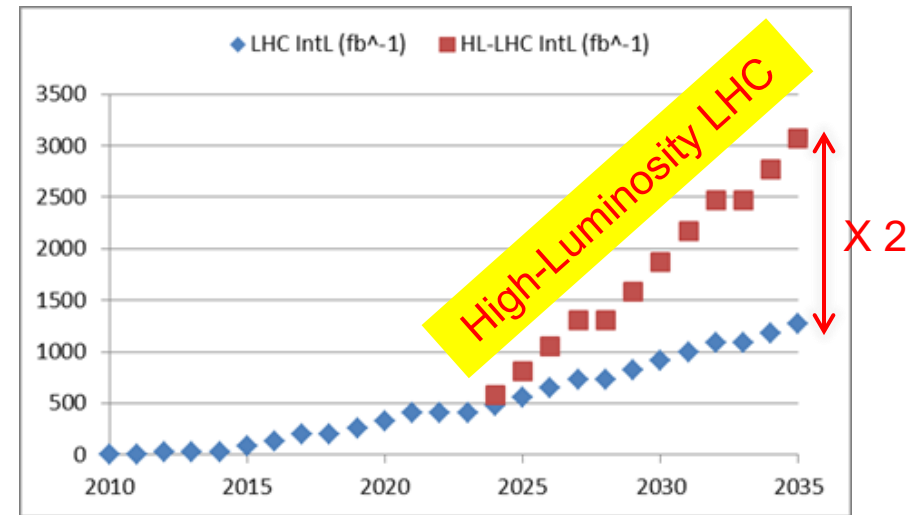
2. Luminosity → HL-LHC

$$LUMINOSITY = \frac{N_{event}/sec}{\sigma_r} = \frac{N_1 N_2 f_{rev} n_b F}{4\pi\sigma_x\sigma_y}$$

Intensity per bunch (points to N_1)
Number of bunches (points to n_b)
Geometrical Correction factors (points to F)
Beam dimensions (points to $\sigma_x\sigma_y$)

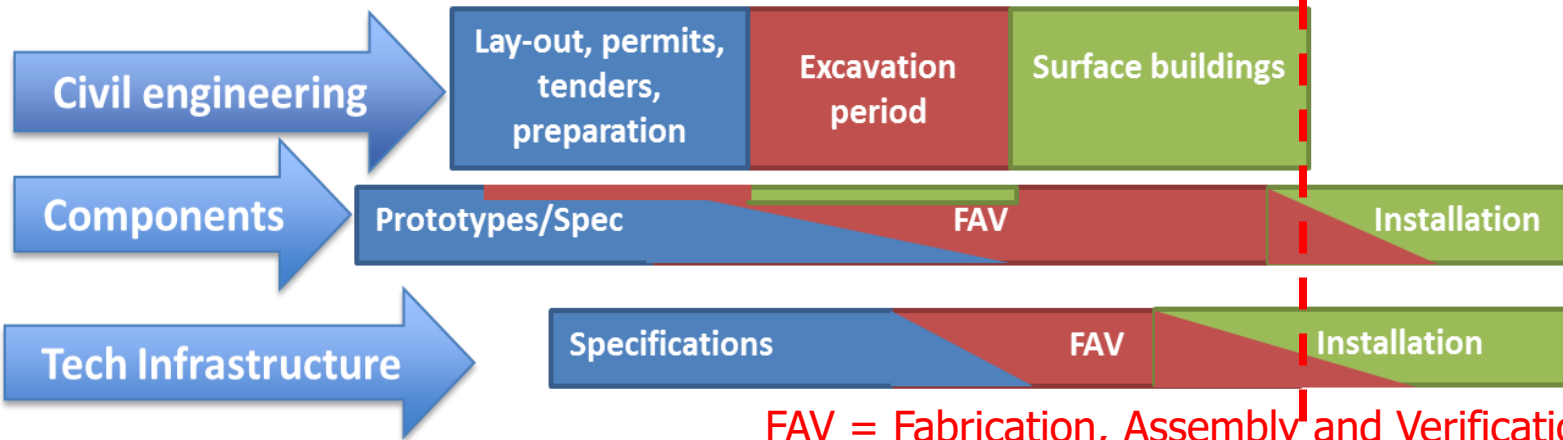
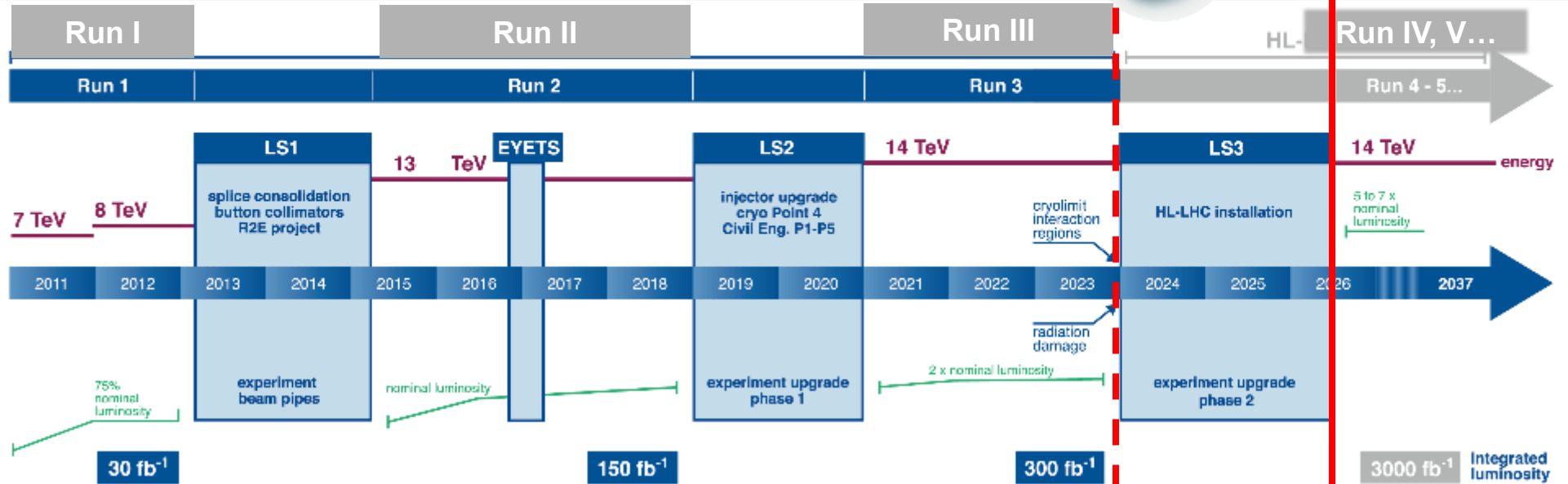
- More or less fixed:
 - Revolution period
 - Number of bunches

- Parameters to optimise:
 - Number of particles per bunch
 - Beam dimensions
 - Geometrical correction factors

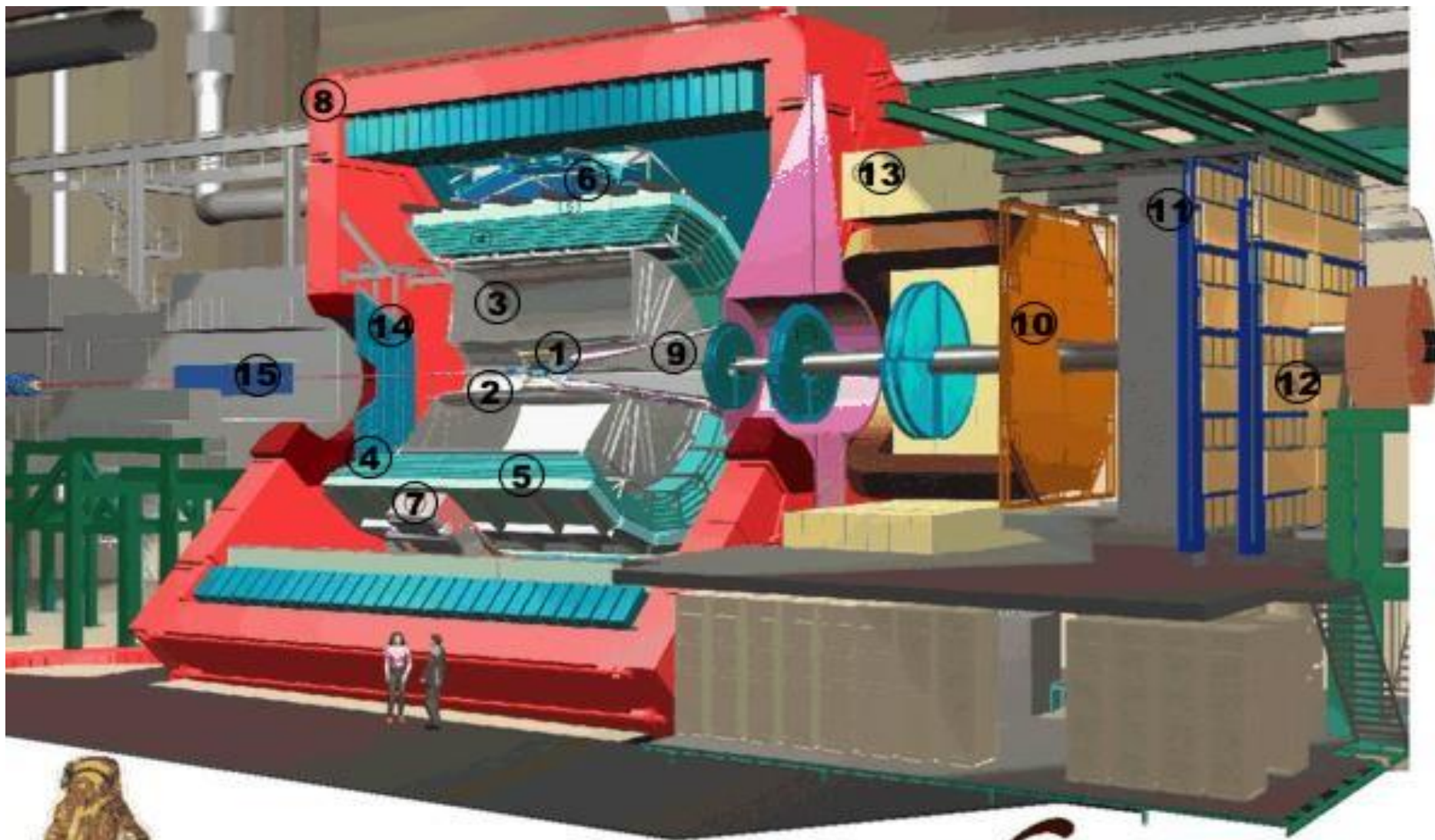


Plan → Today →

LHC / HL-LHC Plan



FAV = Fabrication, Assembly and Verification



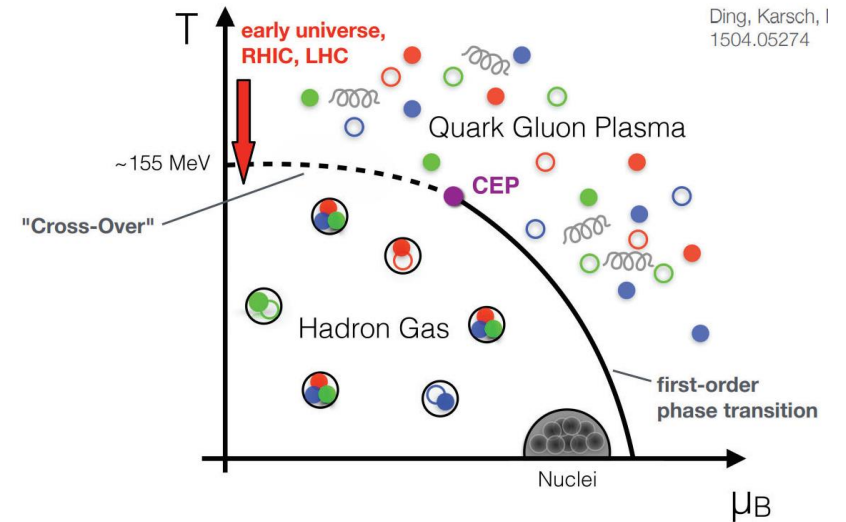
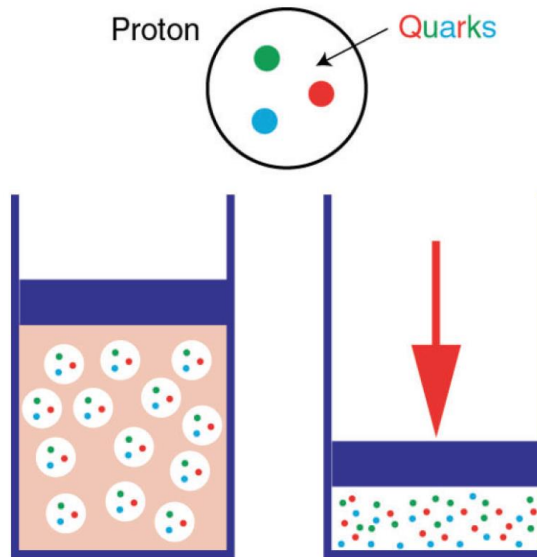
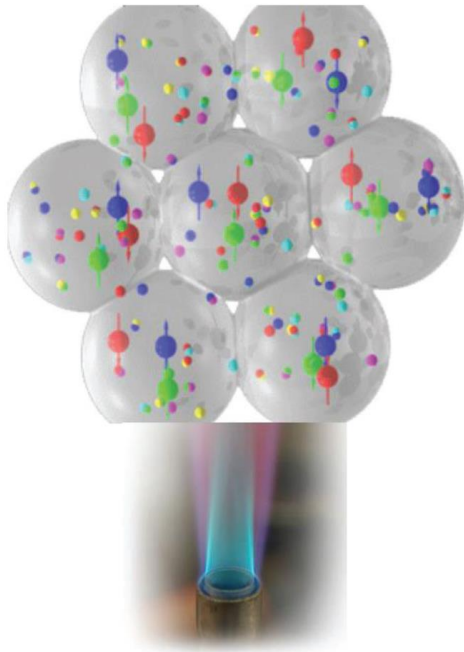
**Mission: Studying
the primordial matter
of the Universe → QGP
Tool: heavy ion collisions**

Alice

3. Formation of QGP in High Energy Heavy Ion Collisions:

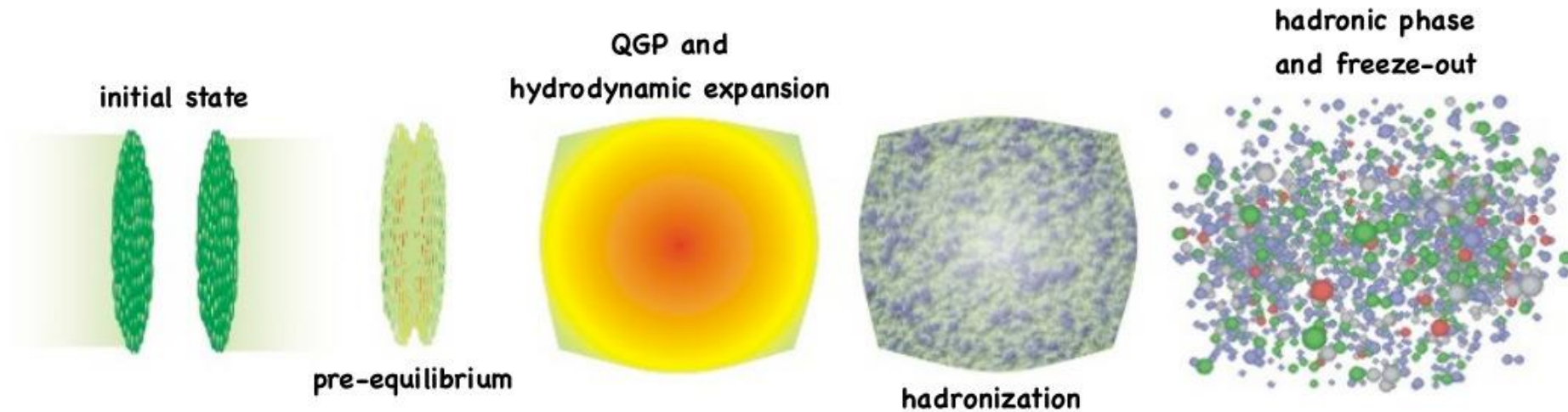
What happens to matter if you make it hotter or denser

- Solid \rightarrow liquid \rightarrow gas \rightarrow plasma \rightarrow hadron gas \rightarrow QGP



$$\sqrt{s}=5500 \text{ GeV/nucleon} \rightarrow \gamma \sim 3000$$

3. Standard Model of Heavy Ion Collisions: $\text{Pb}+\text{Pb} \rightarrow 15 \text{ fm}/3000 = 5 \text{ attometer}$



Phases:

- Initial condition: pre-equilibrium state
- Hydrodynamical evolution
perfect fluid, viscous fluid, EOS
- Hadronization mechanism
phase transition, coalescence/recombin.,
Cooper-Frye, incl. viscous corrections
- Hadronic afterburner
hadronic interactions, final state effects

Questions, problems:

- PDF, proton shape, color oscil.
- Gloun saturation, shadowing
- Space-time fluctuations
- EOS properties, finite size eff.
- Relativ. viscous hydrodynamics
- Confinement-deconfinement
- Order of phase transition
- Mesoscopic system, size effects
- Freeze-out characteristics
- Dense hadronic matter
- Resonance decays, ...

3. Standard Model of Heavy Ion Collisions:

**Question: What is the smallest size, where
this Standard Model (and hydro) remains valid?**

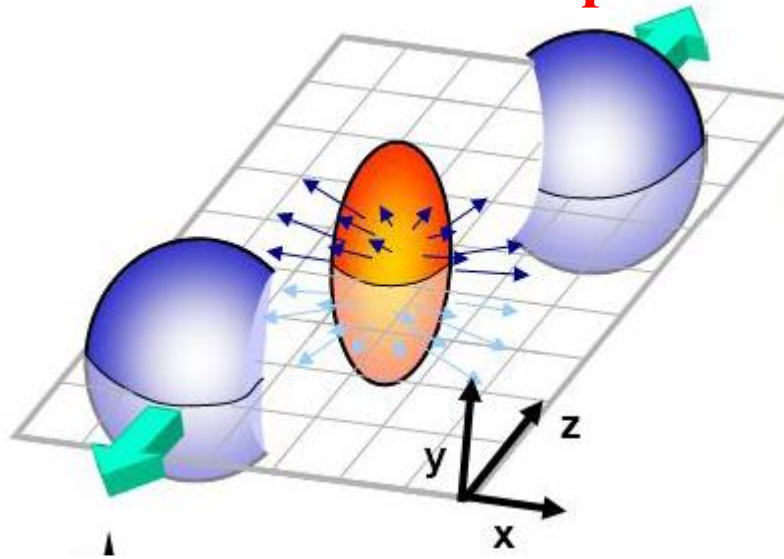
**What about if specific data display a good agreement between
periferic AA collisions
average pA collisions
high multiplicity pp collisions ??**

**Could we find consistent description and/or a new approach,
beyond the usual hydrodynamical description ?**

**What could we see in recent experimental data
in pton-proton collisions at LHC energies ?**

What did we see earlier? TEVATRON data?

2016/17 – Latest experimental results at RHIC and LHC: azimuthal particle distributions and anisotropic flow



Spatial anisotropy

→ eccentricities

2: ellipticity

3: triangularity

4: quadracity

5: pentacity

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2}}{\langle r^n \rangle}$$

→ Investigating peripheral AA collisions

→ Overlap region is asymmetric in space,
almond shape (or more complicated)

→ Spatial anisotropy generates
momentum anisotropy,
this is „pressure induced” → EOS

→ Fourier decomposition of
the azimuthal particle distributions
leads to the harmonic flow components

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left(1 + \sum_n 2 v_n \cos(n\phi) \right)$$

↓
?

v1: directed flow; v2: elliptic flow; v3: ...

2016/17: Data indicates strong similarities for anisotrop flow components in pPb collisions and peripheral PbPb collisions at the same multiplicity windows.

First conclusion: hydrodynamical behaviour in pPb and high multiplicity pp collisions at LHC energies

But:

Fuctuation contributions seems to be large

Hybrid model (IP Glasma + MUSIC)

does not work for pPb, but working for PbPb

Our suggestion:

Non-abelian beam jet bremsstrahlung

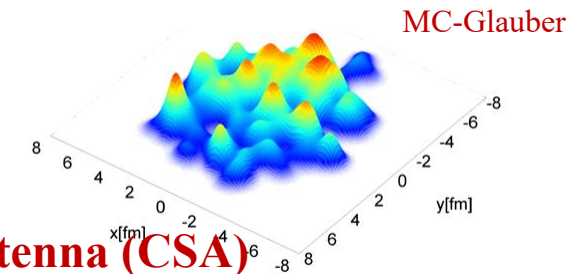
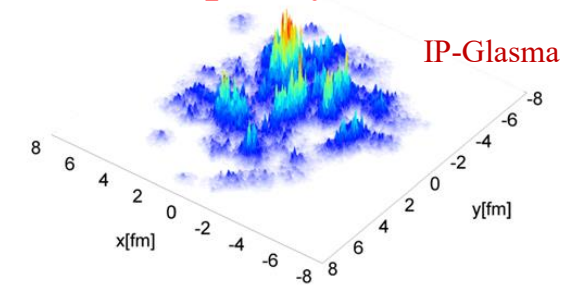
Projectile beam jet form Color Scintillation Antenna (CSA)

Bremsstrahlung from CSA clusters and arrays

Analitic calculations on the basis of GLV approximation

Including GLVB into HIJING for numerical calculations

Phys. Rev. D90 (2014) 054025. hep-ph/1805.7825



Non-Abelian Bremsstrahlung and Azimuthal Asymmetries in High Energy p+A

M. Gyulassy,^{1,2,*} P. Levai,¹ I. Vitev,³ and T. Biro¹

¹MTA WIGNER Research Centre for Physics, RMI, Budapest, Hungary

²Department of Physics, Columbia University, New York, NY 10027, USA

³Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

(Dated: May 13, 2014 v11)

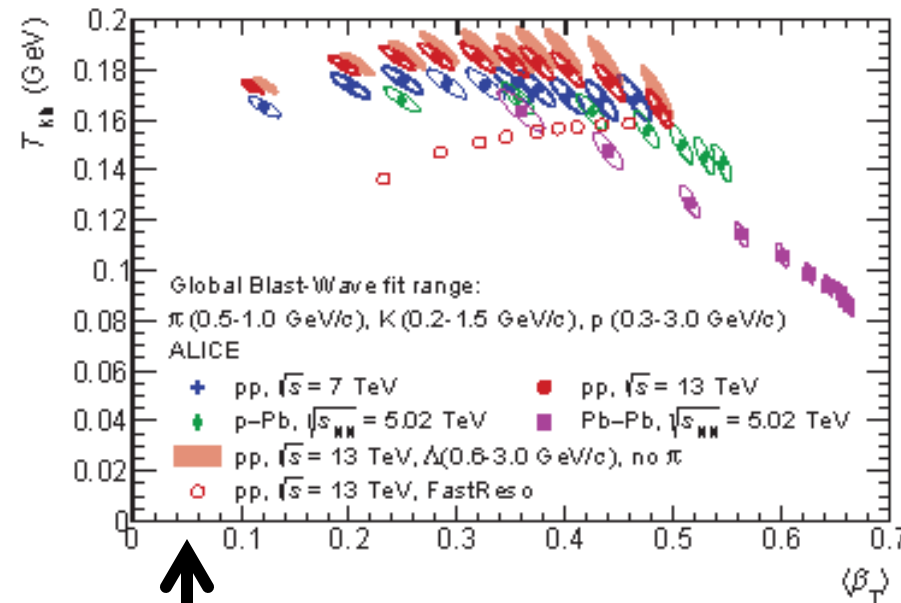
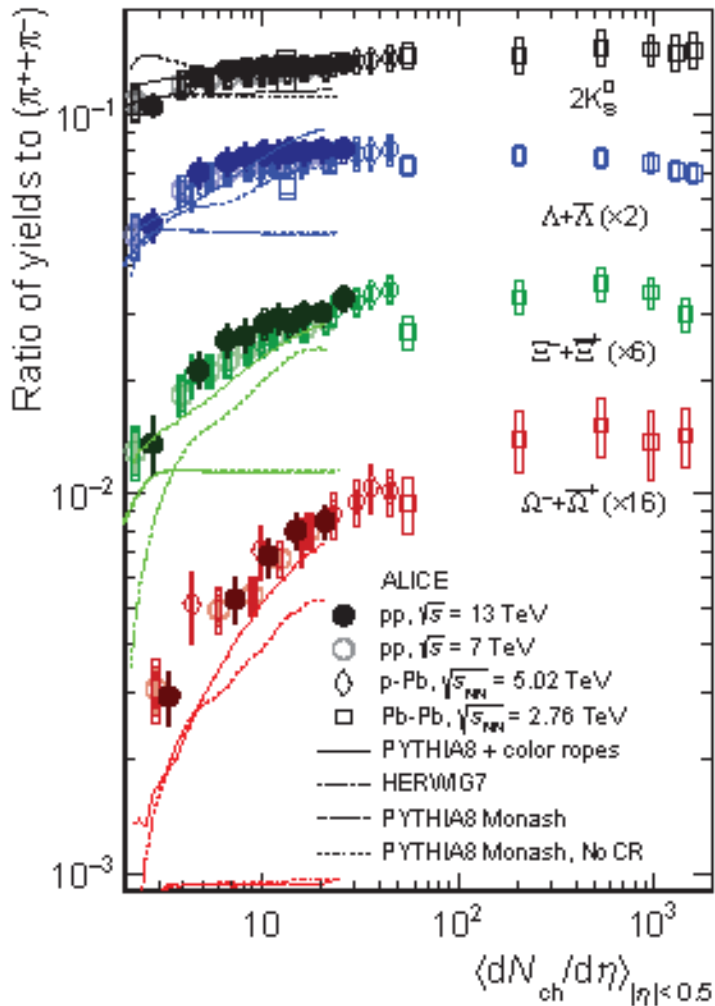
3. Similarities in pp, pA and AA collisions at LHC energies:

- strangeness production;
- hydrodynamical behaviour, „temperature”, „flow”;
- away-side jet broadening, „ridge”.

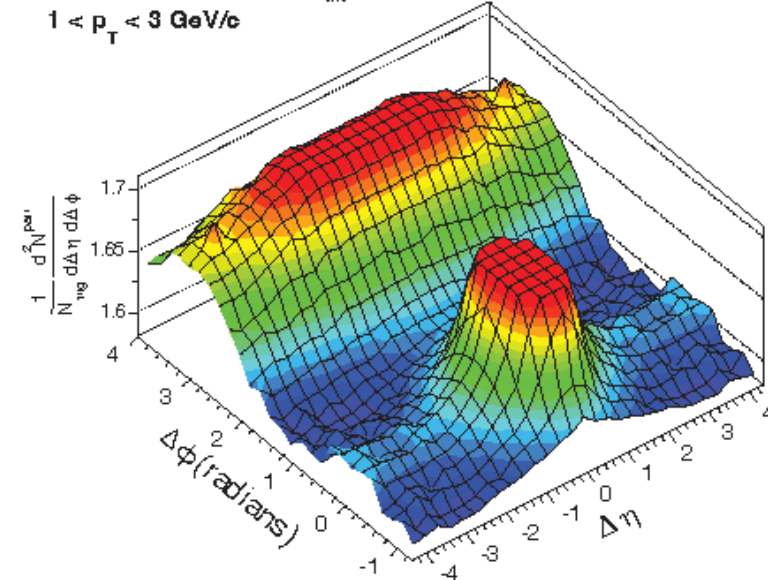
R. Sahoo:

arXiv: 2307.14665 [hep-ph]

27 July 2023



CMS pp $\sqrt{s} = 13$ TeV, $N_{\text{trk}}^{\text{offline}} \approx 105$
 $1 < p_T < 3$ GeV/c



S. Acharya et al: Eur. Phys. J. C80 (2020) 693.

J. Adam et al: Nature Physics 13 (2017) 535.

V. Khachatryan et al: Phys. Rev. Lett. 116 (2016) 172302.

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4. Proton-antiproton collisions at FERMILAB, $\sqrt{s} = 1.8$ TeV

VOLUME 67, NUMBER 12

PHYSICAL REVIEW LETTERS

16 SEPTEMBER 1991

Transverse Baryon Flow as Possible Evidence for a Quark-Gluon-Plasma Phase

Péter Lévai^(a) and Berndt Müller

Department of Physics, Duke University, Durham, North Carolina 27706

(Received 13 March 1991)

In order to investigate the coupling between the collective flow of nucleons and pions in hot pion-dominated hadronic matter, we calculate the pion-nucleon drag coefficient in linearized transport theory. We find that the characteristic time for flow equalization is longer than the time scale of the expansion of a hadronic fireball created in high-energy collisions. The analysis of transverse-momentum data from $p + \bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV reveals the same flow velocity for mesons and antinucleons. We argue that this may be evidence for the formation of a quark-gluon plasma in these collisions.

PACS numbers: 25.70.Np, 12.38.Mh, 13.85.Hd

Rather general arguments indicate that the state of high energy density temporarily formed in ultrarelativistic central collisions of nuclei, and possibly even of single hadrons, exhibits approximate local thermal equilibrium and thus can be characterized by a temperature. This scenario is generally supported by the observation that transverse-momentum spectra of emitted particles fall exponentially at high p_T . It has often been speculated that a collective outward flow may develop during the expansion and final breakup of the high-density state [1]. The presence of a collective flow would be manifest in a non-thermal shape of the transverse-momentum spectrum. Because the flow velocity is superimposed with the random thermal motion, this effect grows with the mass of the emitted particles, and should be most clearly visible in baryon spectra. So far, experimental evidence for the existence of transverse flow at center-of-mass energies far above 1 GeV/u has been inconclusive [2,3], in contrast to collisions below this energy [4].

Gerber, Leutwyler, and Goity [5] recently showed that the expansion of a dense pion gas, as is formed in the central rapidity region after a highly relativistic nuclear collision, must lead to a rapid transverse flow. Gavin [6] pointed out that the expansion is even so rapid that the

violation from local thermal equilibrium is not too severe. We will now calculate δ and θ from first principles.

We assume that the evolution of the phase-space distribution functions $f_i(x, p)$, $i = \pi, N$, of pions and nucleons in the dense hadronic phase is described by the relativistic Boltzmann equation:

$$p^\nu \partial_\nu f_i(x, p) = \sum_j \mathcal{C}_{ij}(x, p). \quad (3)$$

Here \mathcal{C}_{ij} are the collision terms, which can be calculated from the known cross section for collisions between particles of type i and type j . In order to make contact with collective variables, such as the local flow velocity u^μ , it is useful to consider the momentum-space-integrated form of Eq. (3), introducing the energy-momentum tensor $T_i^{\mu\nu}$. Dissipative terms can then be expressed as the failure of the energy-momentum tensor to be locally conserved for each fluid component separately:

$$\partial_\nu T_i^{\mu\nu} = \mathcal{S}_i^\mu \equiv \sum_j \int d\Gamma_p p^\mu \mathcal{C}_{ij}(x, p), \quad (4)$$

where $d\Gamma_p = d^3p / (2\pi)^3 p^0$ is the invariant volume element in momentum space and \mathcal{S}_i^μ is the covariant dissipation four-vector.

4. Proton-proton collisions at ultrarelativistic energies

--- parton structure of proton, neutrons, ...

Low energy: quarks and antiquarks form hadrons (protons, neutrons, ...)
hadron-spectroscopy, symmetries, group-theories, ...

proton: uud; neutron: ddu; Lambda: uds; ...

High energy: Feynman-x $x_i = p_i/P$; infinite-momentum frame ($P \rightarrow \infty$)

parton PDFs: $f_u(x)$, $f_d(x)$, $f_{u\text{sea}}(x)=f_{d\text{sea}}(x)$, $f_{\text{glue}}(x)$, $f_c(x)$, $f_b(x)$, ...

H. Plathow-Besch, CERN-PPE/92-123

PDFLIB : A Library of all available Parton Density Functions
of the Nucleon, the Pion and the Photon
and the corresponding α_s Calculations

The subroutine STRUCTM returns the following OUTPUT:

UPV	=	up valence quark
DNV	=	down valence quark
USEA	=	sea (\overline{up})
DSEA	=	sea (<i>down</i>)
STR	=	strange quark
CHM	=	charm quark
BOT	=	bottom quark
TOP	=	top quark
GL	=	gluon

4. Proton-proton collisions at ultrarelativistic energies

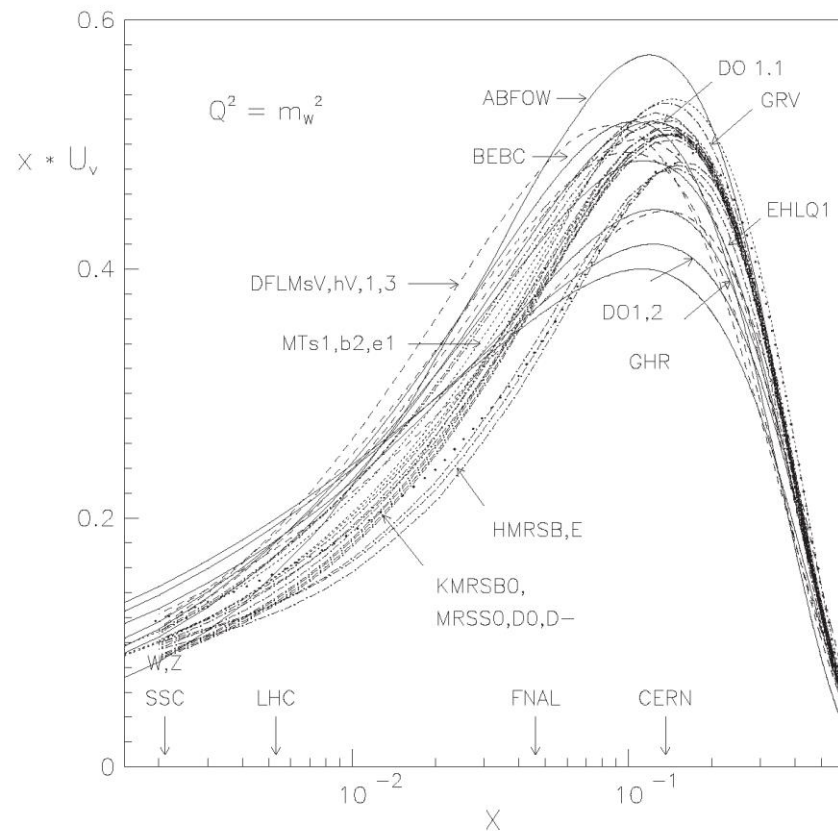
--- parton structure of proton, neutrons, ...

Feynman-x $x_i = p_i/P$; infinite-momentum frame ($P \rightarrow \infty$)

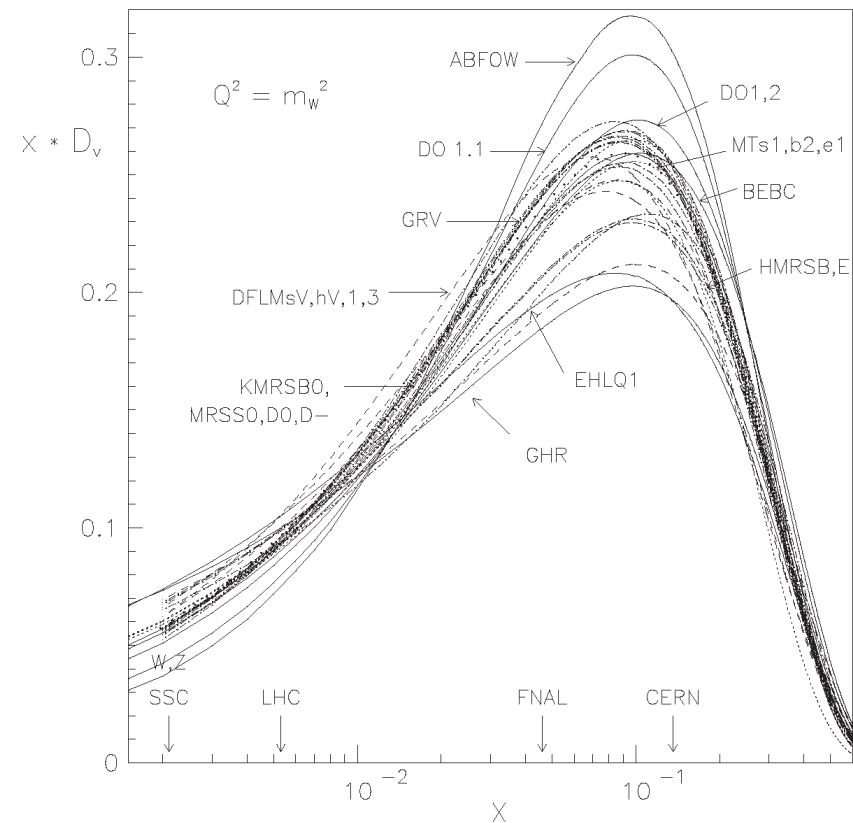
Valence-quarks: u and d \rightarrow connection to low energy region

Maximum of $f_u(x)$ and $f_d(x)$ in the region of $x=0,1 - 0,2$

Parton Density Functions of the Nucleon



Parton Density Functions of the Nucleon



4. Proton-proton collisions at ultrarelativistic energies

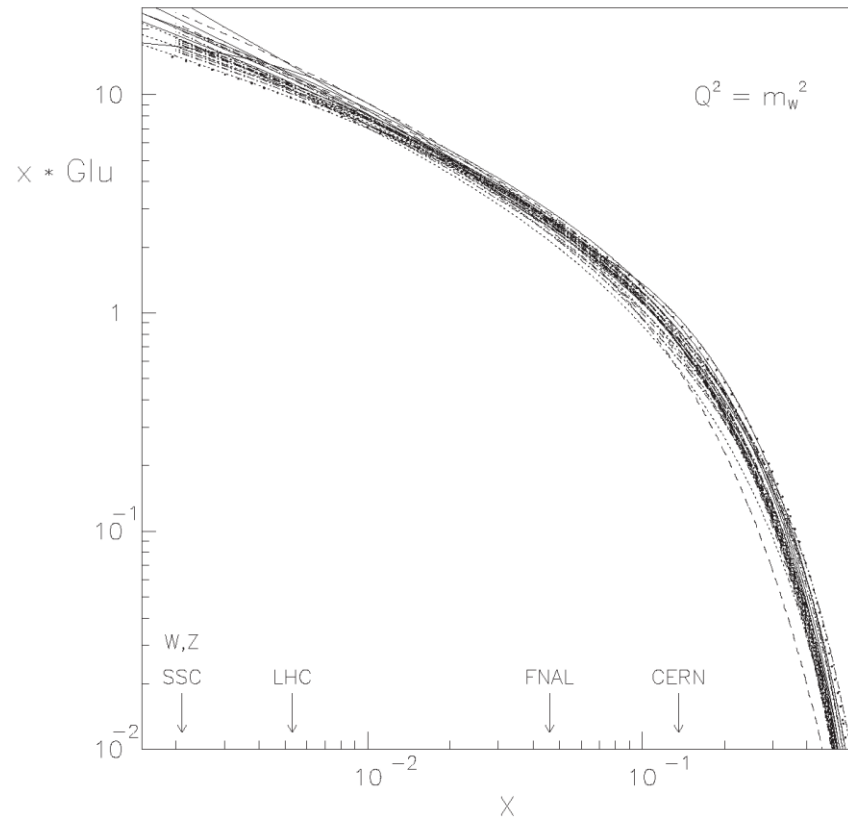
--- parton structure of proton, neutrons, ...

Feynman-x $x_i = p_i/P$; infinite-momentum frame ($P \rightarrow \infty$)

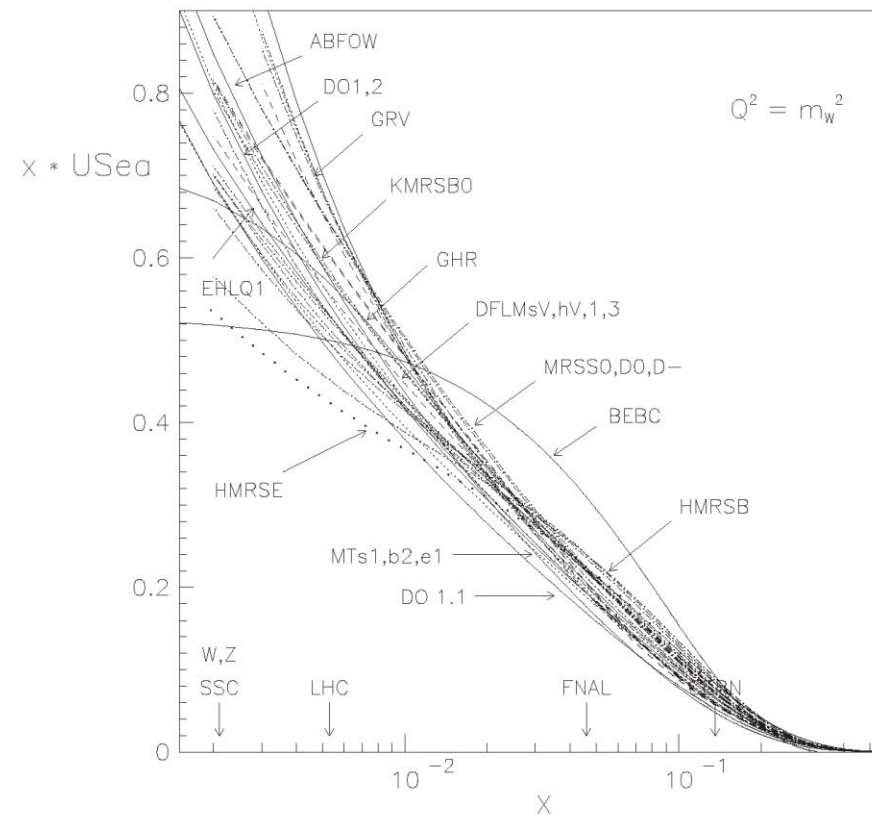
Gluons and „Sea” quark-antiquark pairs \rightarrow dominance in the high energy region

At small-x they are increasing by $1/x \rightarrow$ divergence (gluon-saturation !)

Parton Density Functions of the Nucleon



Parton Density Functions of the Nucleon



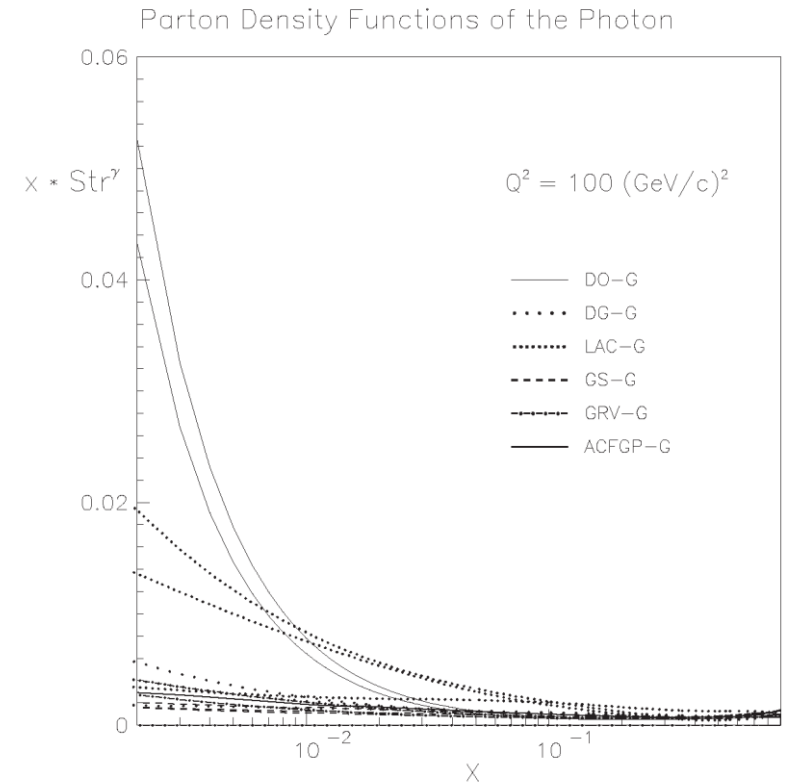
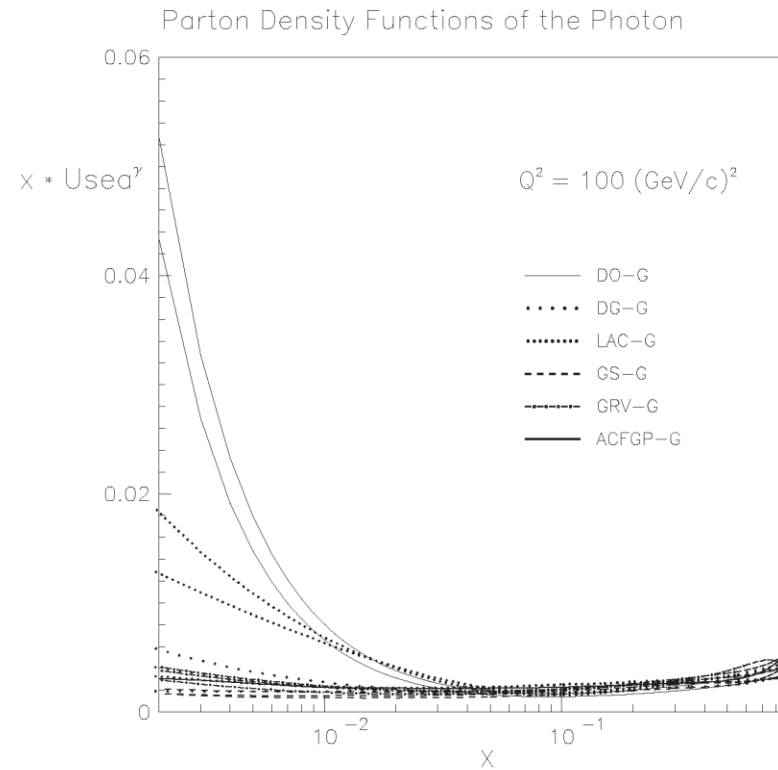
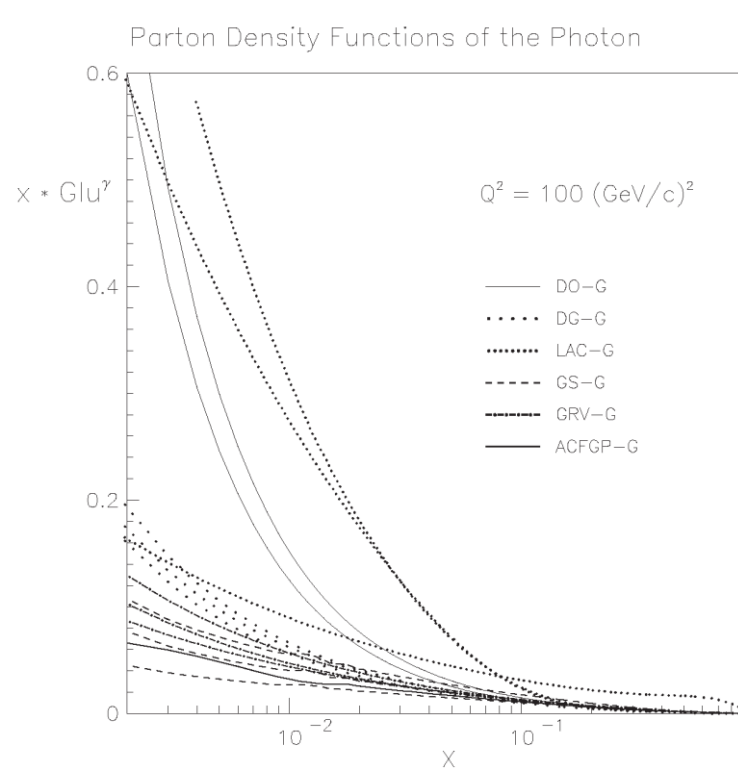
4. Proton-proton collisions at ultrarelativistic energies

--- parton structure of proton, neutrons, ..., PIONS, PHOTONS !!!

Feynman-x $x_i = p_i/P$; infinite-momentum frame ($P \rightarrow \infty$)

PHOTON has u, d, s, ... and their antiquark content !!!! (Weisacker-Williams !!)

At small-x they are increasing by $1/x \rightarrow$ divergence (saturation in photon ??!)



5. Proton structure and proton-proton collisions at ultrarelativistic energies

--- Partons in proton as a statistical ensemble

--- PDFs display a stationary state of a continuously interacting system

--- Statistical ensemble \rightarrow entropy \rightarrow final hadron production

\rightarrow Coherent state: $S=0$

\rightarrow Collision \rightarrow degrees of freedom become free:

minimal interaction \rightarrow kick-out of quantum phase

PP-collision as a PHASE FILTERING

P. Lévai, B. Müller, DUKE-preprint, 90-12 (1990)

PP or AA collisions – parton phase-space density (naive):

$$f_{i,A}(\vec{p}, \vec{r}) = \frac{(2\pi)^3}{d_i} \frac{dN_A}{d^3p d^3r} = \frac{(2\pi)^3}{d_i} \frac{1}{V_A^*} \frac{dN_A}{d^3p}$$

Momentum dependence is originated from the PDF (longitud.) + Gauss (transv.):

$$\frac{dN_A}{d^3p} = \frac{1}{P} \tilde{F}_{i,A}(x, p_T^2) \approx \frac{1}{P} A F_i(x) \frac{1}{2\pi p_0^2} H(p_T/p_0)$$

5. Proton structure and proton-proton collisions at ultrarelativistic energies

Interaction volume \rightarrow Lorentz-contraction is valid (L/γ):

$$V_A^* = \frac{4\pi R_A^2}{3} \frac{R_p}{\cosh y_{min}} .$$

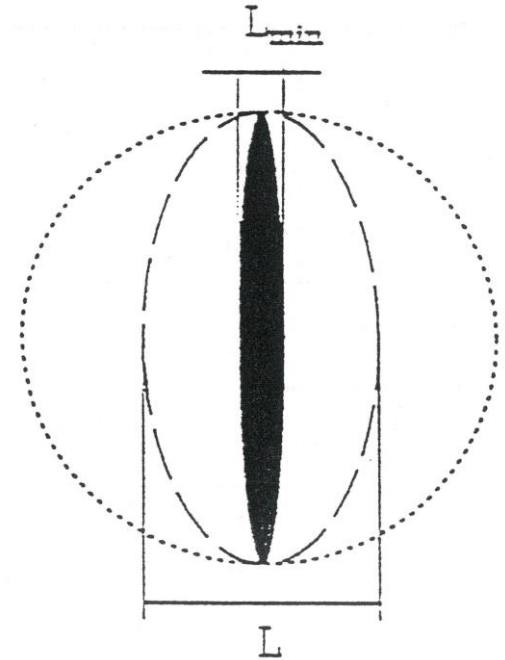
Phase-space element for integration:

$$\frac{d^3 p d^3 r}{(2\pi)^3} = \frac{1}{(2\pi)^2} p_T^2 dp_T dy \cosh y V_A^*$$

Phase-space density:

$$f_i = \frac{1}{d_i} \frac{(2\pi)^3}{V_A^* P} A F_i(x) \frac{1}{2\pi p_0^2} \exp(-p_T^2/2p_0^2)$$

Here we will choose $p_0=0.27$ GeV/c



5. Proton structure and proton-proton collisions at ultrarelativistic energies

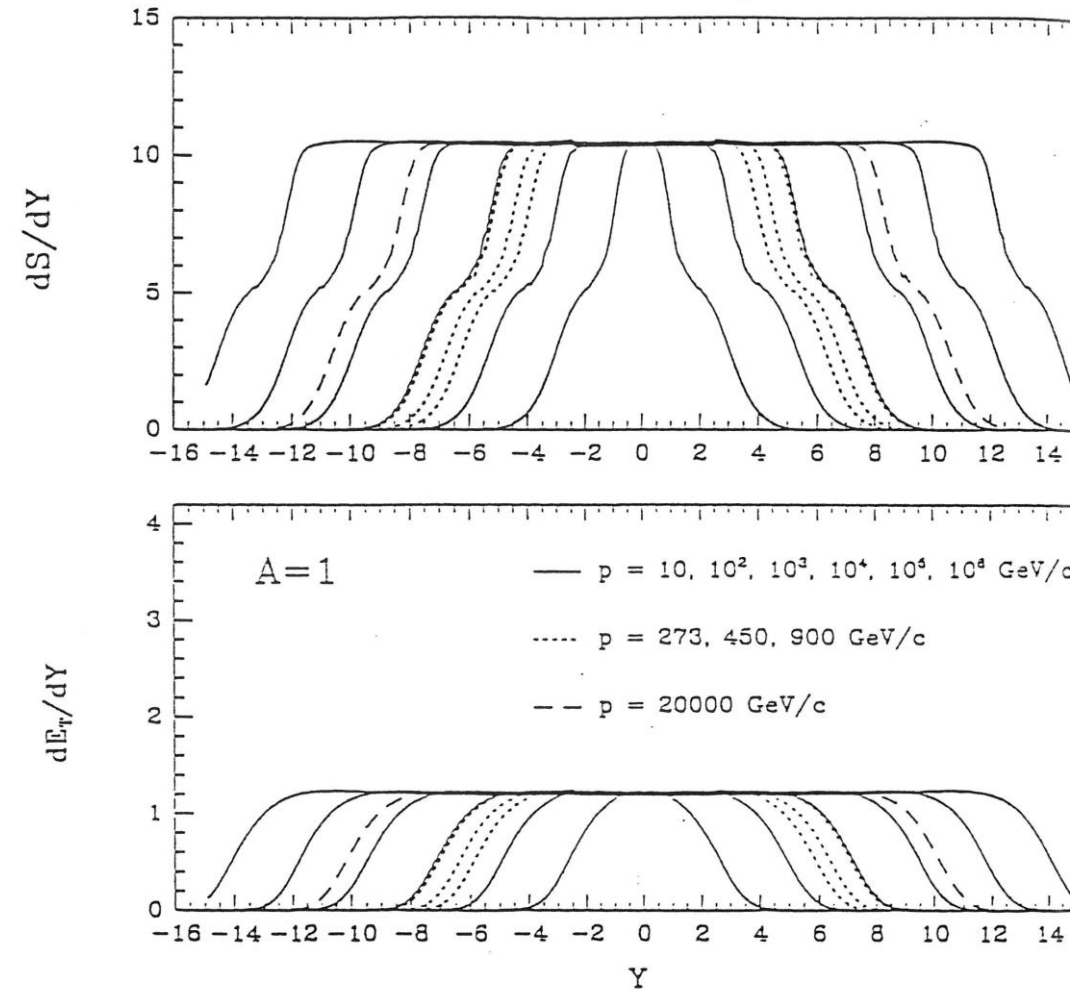
If we know the phase-space densities f_i ,
then we can determine/calculate
**Entropy distribution (dS/dy) and
Transverse energy distribution(dE_T/dy):**

$$\frac{dS}{dy} = \int_{p_T^{min}}^{\infty} \frac{dp_T}{(2\pi)^2} p_T^2 \cosh y V_A^* \sum_i d_i [f_i \ln f_i - (1 \pm f_i) \ln(1 \pm f_i)]$$

$$\frac{dE_T}{dy} = \int_{p_T^{min}}^{\infty} \frac{dp_T}{(2\pi)^2} p_T^2 \cosh y V_A^* \sum_i d_i f_i p_T$$

Hadronization:

Minimum the above values will be released.
Further parton collisions and
non-equilibrium processes,
and hadronic afterburner will increase
entropy and transverse energy.

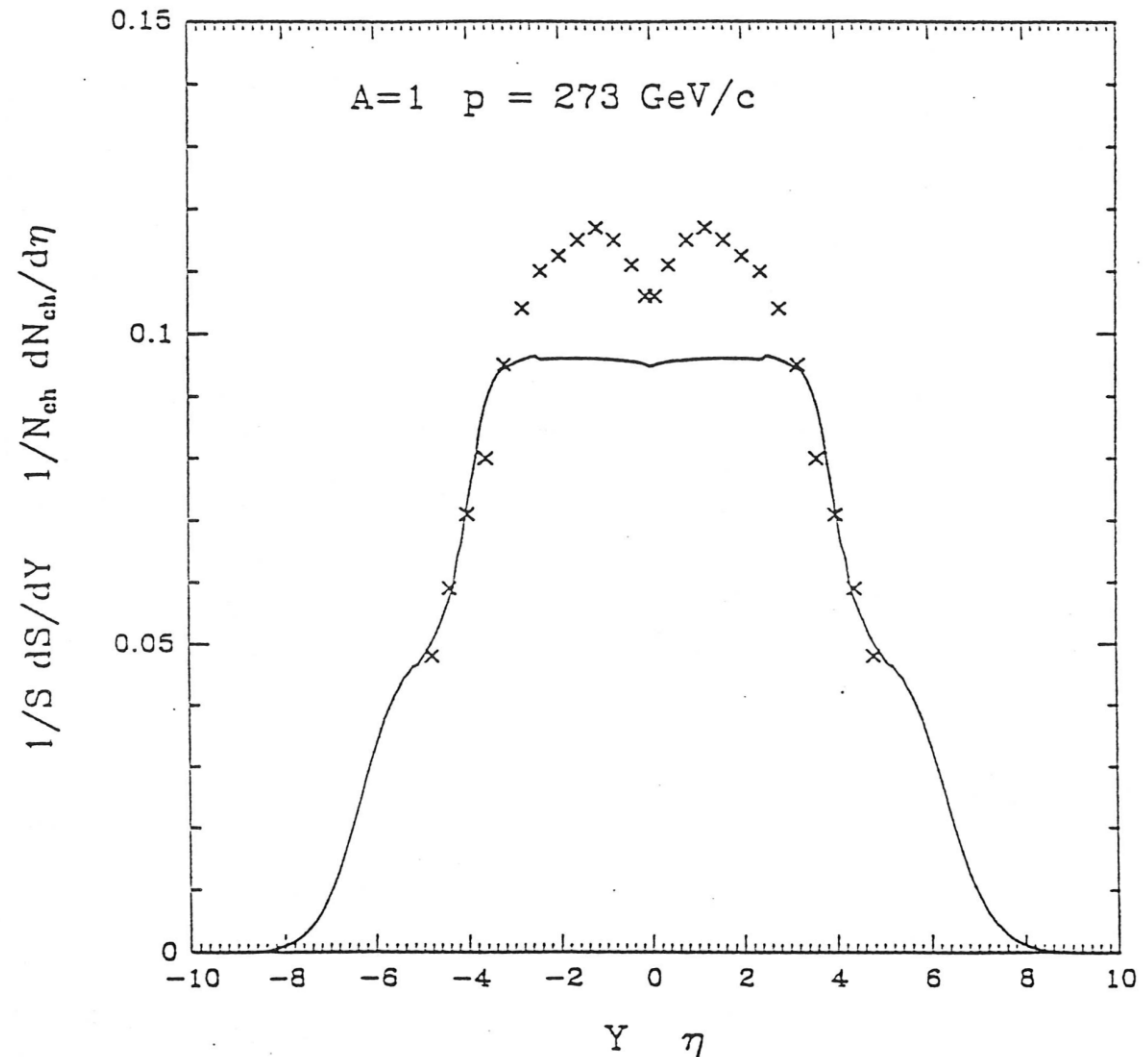


5. Proton structure and proton-proton collisions at ultrarelativistic energies

Testing the efficiency
of phase filtering by
existing proton data (1990):

proton-antiproton data
from CERN UA5 experiment
at $\sqrt{s} = 546 \text{ GeV}$

**Result: phase-filtering
covers 80 % of the produced
entropy connected to
charge particles (2/3 of total).**



Zhen Xie, ..., Dai-Mei Zhou, ... (Xian, Wuhan, Beijing), hep-ph/2603.12007

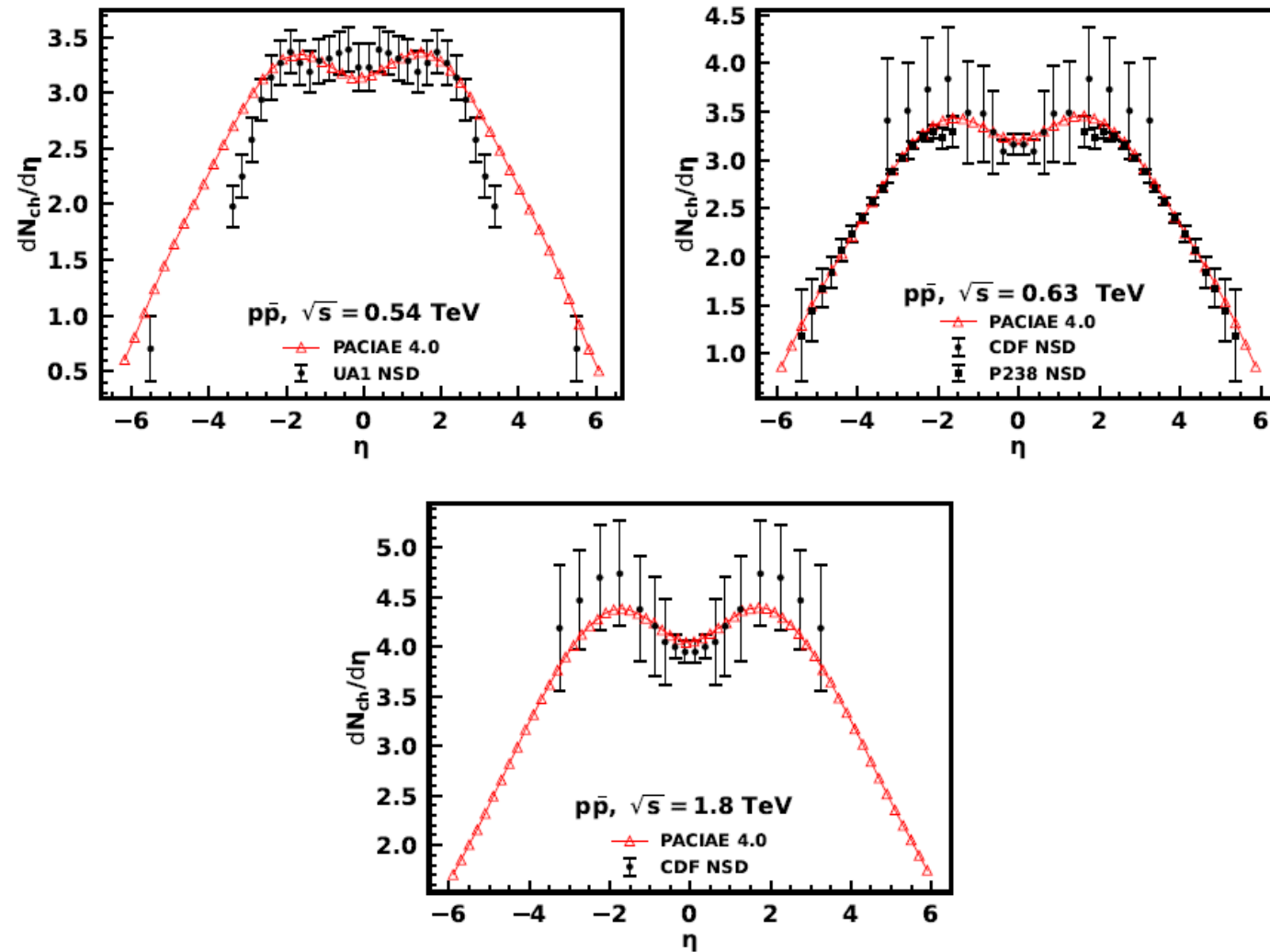


FIG. 2: The pseudorapidity density distributions of charged particles produced in NSD $p\bar{p}$ collisions at $\sqrt{s} = 0.54, 0.63, 1.8$ TeV from PACIAE 4.0 model simulations compared with experimental data from UA1, CDF and P238 collaborations [59–61].

Charged-particle multiplicities in proton-proton collisions

ALICE Collaboration

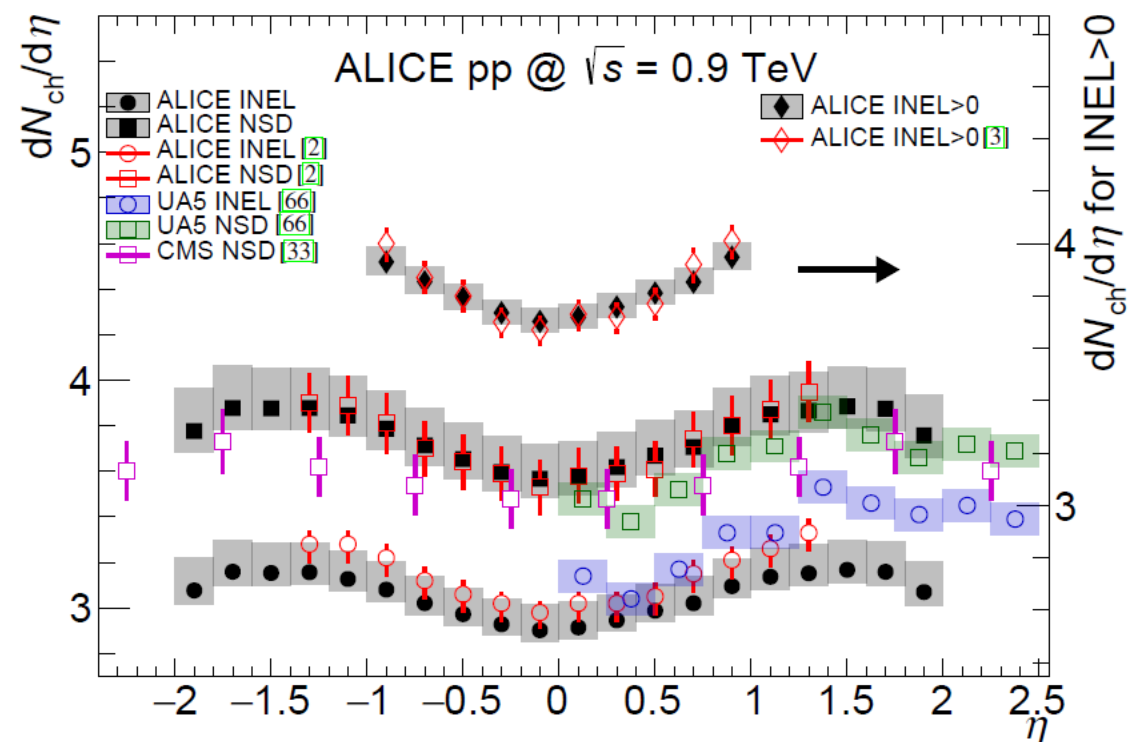


Fig. 8: $dN_{ch}/d\eta$ vs. η at $\sqrt{s} = 0.9$ TeV, for the three normalizations defined in the text, and a comparison with ALICE previous measurements [2, 3], UA5 [66] and CMS [33]. Note that to avoid overlap of data points on the figure, the INEL>0 data were displaced vertically, and for these data the scale is to be read off the right-hand side vertical axis. Systematic uncertainties on previous data are shown as error bars (except for UA5, with coloured bands), while they are shown as grey bands for the data from this publication.

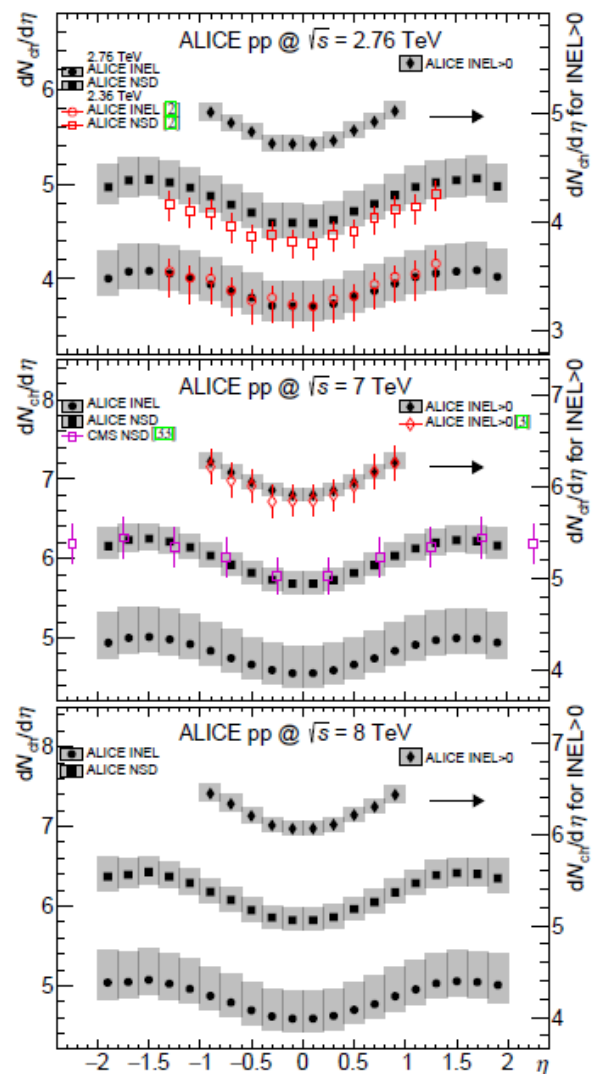


Fig. 9: $dN_{ch}/d\eta$ vs. η measurements: $\sqrt{s} = 2.76$ TeV compared with $\sqrt{s} = 2.36$ TeV taken from ALICE [2] (top); $\sqrt{s} = 7$ TeV and comparison with CMS [33] and ALICE [3] data (middle); $\sqrt{s} = 8$ TeV (bottom). Systematic uncertainties are shown as error bars for the previous data and as grey bands for the data from this publication. The scale is to be read off the right-hand side axis for INEL>0.

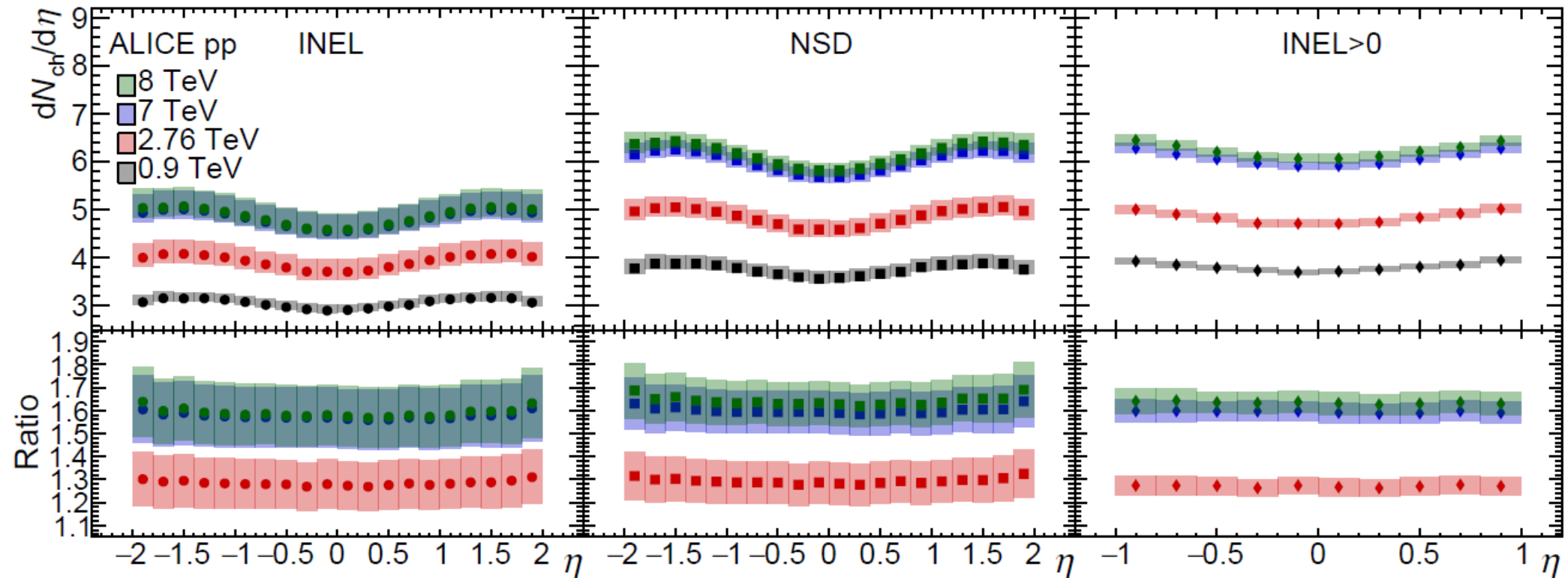


Fig. 10: Comparison of $dN_{ch}/d\eta$ vs. η measurements between the various centre-of-mass energies considered in this study: INEL (left), NSD (middle), and INEL>0 (right). The lower parts of the figures show the ratios of data at energies indicated to the data at 0.9 TeV, with corresponding colours. Systematic uncertainties are indicated as coloured bands.

5. Proton structure and parton entanglement

During 30 years our understanding became deeper:

Heavy ion collisions:

At RHIC and LHC energies we study the produced QGP matter

New features are recognized

Hard processes, jet-matter interaction, jettiness have been studied

Underlying events were explored in proton-proton collisions

Events without extensive jet-production were recognized

and experimentally analyzed

Parton entanglement was introduced and studied

Intensive activity is on this field: S. Skokov et al.

6. Conclusion

Inner structure of protons and other hadrons remain interesting and must be explored

Experiments at LHC and FCC energies are important

Experiment at RHIC, especially eA and e-proton collisions are also very interesting and important

What about electron-positron and photon-photon collisions?

Structure of protons \rightarrow structure of vacuum !!??