# Probing Proton+Proton Collisions at the LHC using Resonances and Charmonia

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**Indian Institute of Technology Indore, India &**
**CERN Scientific Associate, CERN, Switzerland**

# Plan:

- Introduction to the high-energy physics group at IIT Indore
- New excitements in pp physics
- Resonance and charmonia production
- Probing hadronic phase lifetime using resonance yields
- Event Topology  in pp collisions
- Summary


EXPLORE
GREENLAND
RUSSIA
CANADA
UNITED STATES
MEXICO
BRAZIL
PERU
CHINA
INDIA
ALGERIA
LIBYA
EGYPT
MONGOLIA
KAZAKHSTAN
TIBET
INDONESIA
AUSTRALIA
NEW ZEALAND
ALASKA
ICELAND
NORWAY
JAPAN


INDIA
States and Union Territories
INDIA FLAG
TAJIKISTAN
AFGHANISTAN
PAKISTAN
CHINA (TIBET)
NEPAL
BHUTAN
BANGLADESH
MYANMAR (BURMA)
SRI LANKA
LADAKH
Leh
Srinagar
JAMMU & KASHMIR
Jammu
HIMACHAL PRADESH
Shimla
PUNJAB
CHANDIGARH
Dehradun
UTTARAKHAND
HARYANA
DELHI
New Delhi
UTTAR PRADESH
Lucknow
Jaipur
RAJASTHAN
SIKKIM
Gangtok
ARUNACHAL PRADESH
Itanagar
Dispur
ASSAM
NAGALAND
Kohima
Shillong
MEGHALAYA
Imphal
MANIPUR
Agartala
TRIPURA
Aizawl
MIZORAM
BIHAR
Patna
JHARKHAND
Ranchi
WEST BENGAL
Kolkata
Gandhinagar
GUJARAT
Bhopal
MADHYA PRADESH
Raipur
CHHATTISGARH
ODISHA
Bhubaneswar
BAY OF BENGAL
Daman
DADRA & NAGAR HAVELI AND DAMAN & DIU
MAHARASHTRA
Mumbai
TELANGANA
Hyderabad
Amaravati
Yanam (Puducherry)
ARABIAN SEA
Panaji
GOA
ANDHRA PRADESH
KARNATAKA
Bengaluru
Chennai
Mahe (Puducherry)
PUDUCHERRY
LAKSHADWEEP (INDIA)
Kavaratti
KERALA
TAMIL NADU
Karaikal (Puducherry)
Thiruvananthapuram
Palk Strait
ANDAMAN & NICOBAR ISLANDS (INDIA)
Port Blair
International Boundary
State/UT Boundary
Country Capital
State/UT Capital
Map not to Scale
INDIAN OCEAN
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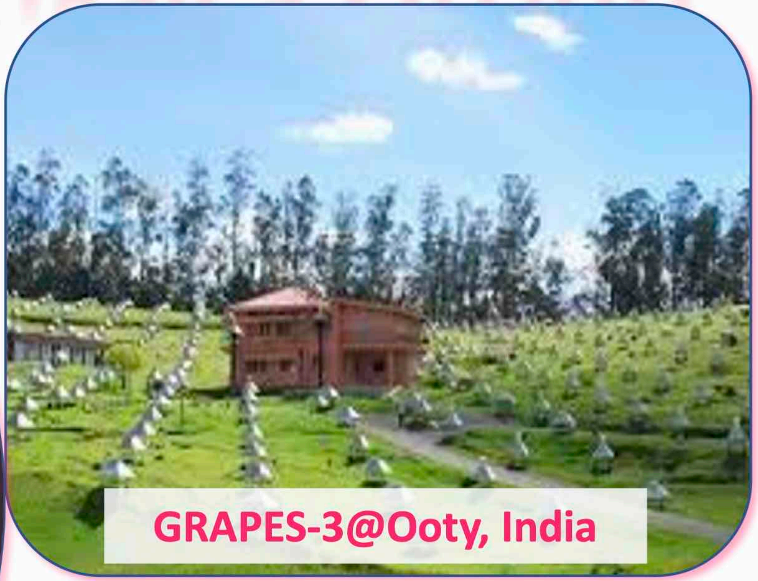
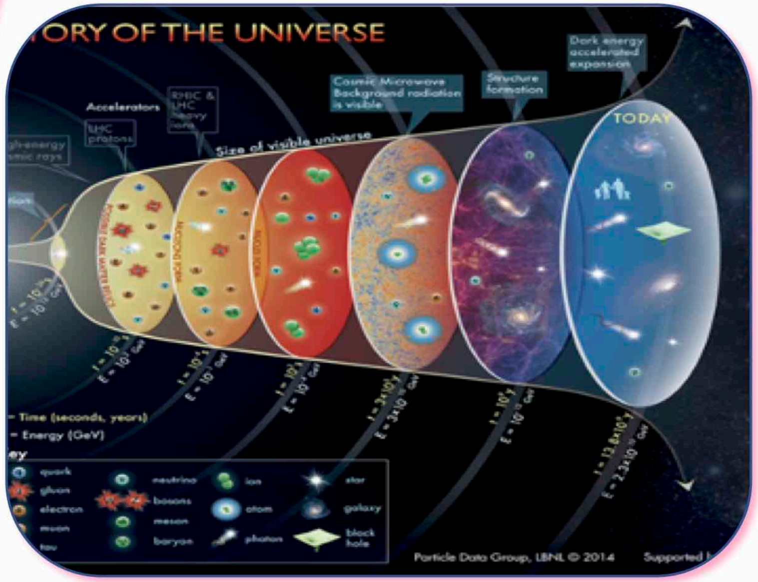
Indore

# Experimental High-Energy Physics Group










Contact: Prof. Raghunath Sahoo, FInstP
e-mail: raghunath@iiti.ac.in
Web: www.iiti.ac.in/~raghunath

# Ph.D. Students (Degree awarded)







## Dr. Aditya Nath Mishra

Thesis Title: Multihadron Production in High-Energy Collisions and Forward Rapidity Measurement of Inclusive Photons in Pb+Pb collisions at 2.76 TeV in ALICE Experiment at LHC. (01 July 2016) *(Presently Postdoc at: Wigner Research Centre, Budapest, Hungary)*

## Dr. Ajay Kumar

Thesis Title: Conceptual Design of Lambda Disks Detector for the PANDA Experiment. (Co-supervisor) [11 August 2016] *(Presently at: Benaras Hindu University (BHU), Varanasi, India (UGC D.S. Kothari Fellow))*

## Dr. Pooja Pareek

Thesis Title: Measurement of Neutral Pion and Eta Mesons in proton+proton collisions with ALICE at the Large Hadron Collider. (25 July 2018) *(Presently Postdoc at: VECC, Kolkata, [Selected for CCNU, China])*

Dr. Arvind Khuntia

Thesis Title: Study of $K^{0^*}$ and $\phi$ meson Production in proton+proton Collisions with ALICE at the LHC and Application of Non-extensive Statistics in High Energy Physics. ( 18 March 2019)

*(Presently Postdoc at Institute of Nuclear Physics, Polish Academy of Science (PAS), IFJ PAN, Krakow, Poland)*

Dr. Pragati Sahoo

Thesis Title: Measurement of $K(892)^{*\pm}$ in Proton+ Proton collisions with ALICE at the LHC and Study of Particle Production using Color String Percolation Model. (11 April 2019)

*(Presently Institute Postdoc at IIT Bombay)*

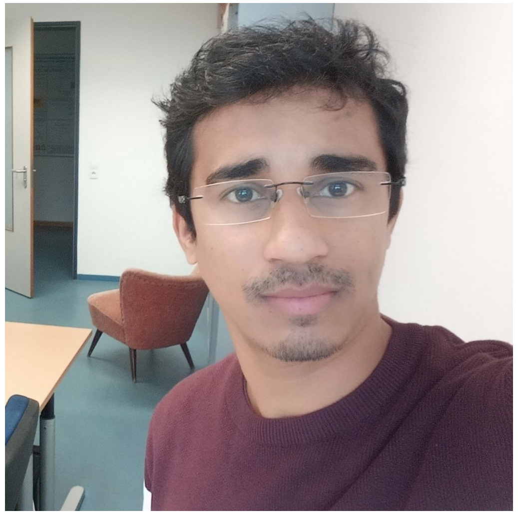
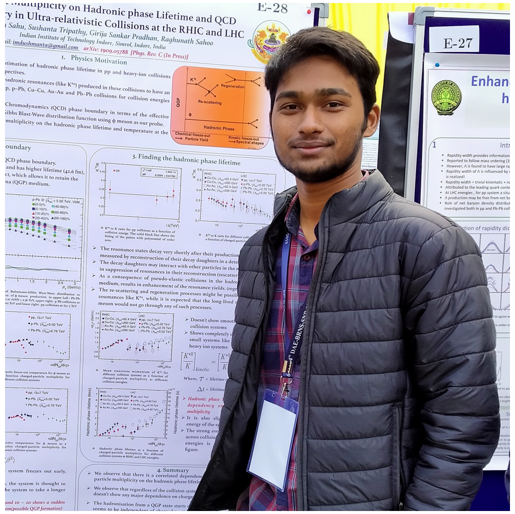
Dr. Dhananjaya Thakur

Thesis Title: Multiplicity dependence of Forward Rapidity $J/\psi$ production in proton+proton collisions with ALICE at the LHC and Study of Particle Production in High-Energy Collisions. (27 August 2019) *(Postdoc at Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou)*

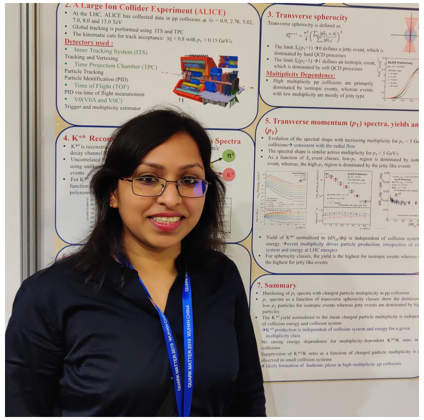
Dr. Sushanta Tripathy

Thesis Title: Event shape and Multiplicity dependence of $\phi$ meson production in Proton+Proton collisions with ALICE at the LHC and Characterization of Heavy-Ion Collisions using Relativistic Kinetic Theory. (18 October 2019) *(Presently Postdoc at: INFN Fellow, INFN Bologna, Italy)*

# Ph.D. Students (Ongoing)

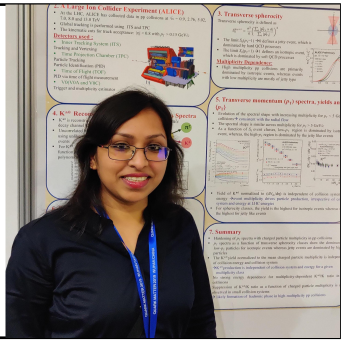






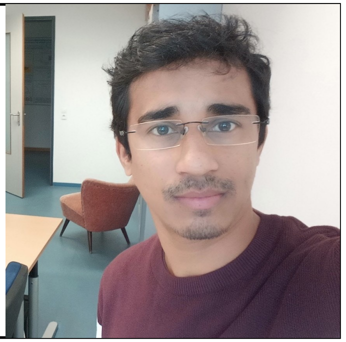

## Rutuparna Rath

Thesis Title: Event topology and multiplicity dependence of $K^{*}(892)^{0}$ productionin proton+proton collisions with ALICE at the LHC and probing TeV collisions through particle production and transport properties (July 2017 – Submitted: 15 Aug. 21)



## Suman Deb

Thesis Title: Measurement of event shape and multiplicity dependence of $K(892)^{*\pm}$ in Proton+Proton collisions with ALICE at the LHC (July 2017 - present)

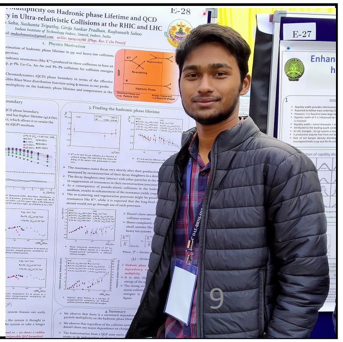


## Neelkamal Mallick

Thesis Title: Azimuthal anisotropy of forward rapidity J/ $\Psi$ in ALICE at the LHC (July 2019 - present)

## Dushmanta Sahu

Thesis Title: J/$\Psi$ polarization studies in high-multiplicity pp collisions in ALICE and possible Formation of QGP-Droplets in Proton+Proton Collisions at the LHC Energies (July 2019 - present)



Girija Sankar Pradhan

Thesis Title: Study of Hadronic Shower Models in Cosmic Ray events and Muon puzzle in GRAPES-3 Experiment at Ooty (July 2019 - present)

Ronald Scaria

Thesis Title: Study of Hadronic Composition of Cosmic Showers using GRAPES-3 Experiment (January 2020 - present)

Suraj Prasad:

(August 2020 - present)

Debadatta Behera: $J/\Psi$ production as a function of multiplicity and nuclear modification in O-O collisions with ALICE at the LHC

(August 2020 - present)

Kshitish Kumar Pradhan

(December 2020 - present)

# Postdoctoral Research Associate(s) :

Dr. Captain Rituraj Singh
Ph.D. BITS-Pilani, Postdoctoral Fellow-I (17 Nov. 2020 - present)

**11 postdoctoral fellows have worked in the group during 2013-2021.**

# Ph.D. Student Achievements :

- Mr. Suman Deb got 6-months McNet Fellowship to work in Germany and UK (2019)

- The paper by Dushmanta Sahu, Sushanta Tripathy, Girija Sankar Pradhan and Raghunath Sahoo (Phys. Rev. C 101, 014902 (2020)) got BEST POSTER award in DAE-BRNS Symposium on Nuclear Physics-2019, University of Lucknow

- The paper by Sushanta Tripathy, Rutunparna Rath, Sudipan De, M. Younus and Raghunath Sahoo (Phs. Rev. C 98, 064904 (2018)) got BEST POSTER award in DAE-BRNS Symposium on High Energy Physics-2018, IIT Madras

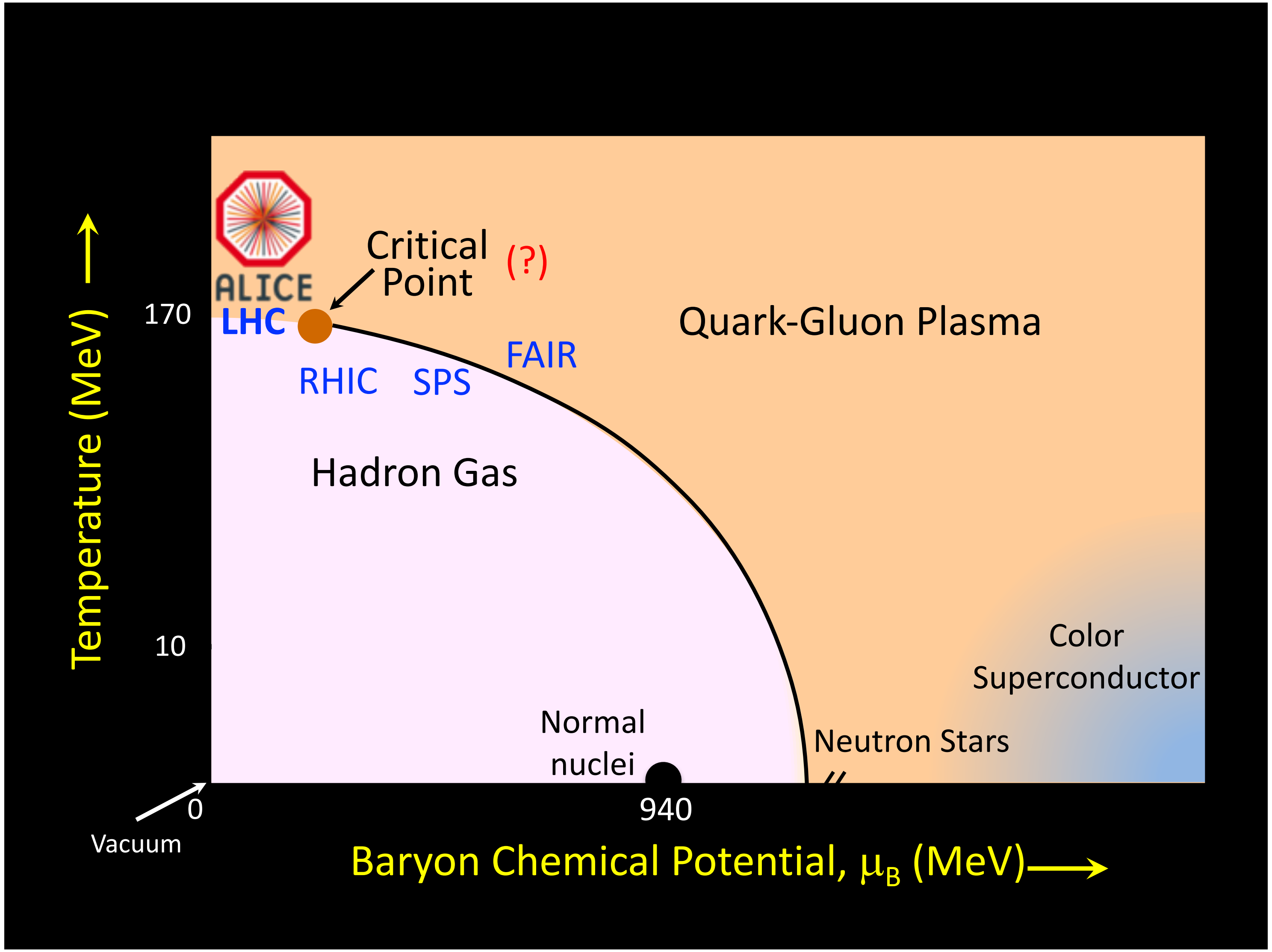
- Sushanta Tripathy got the BEST POSTER FLASH Talk presentation in Quark Matter-2018 (In 10/389 posters)

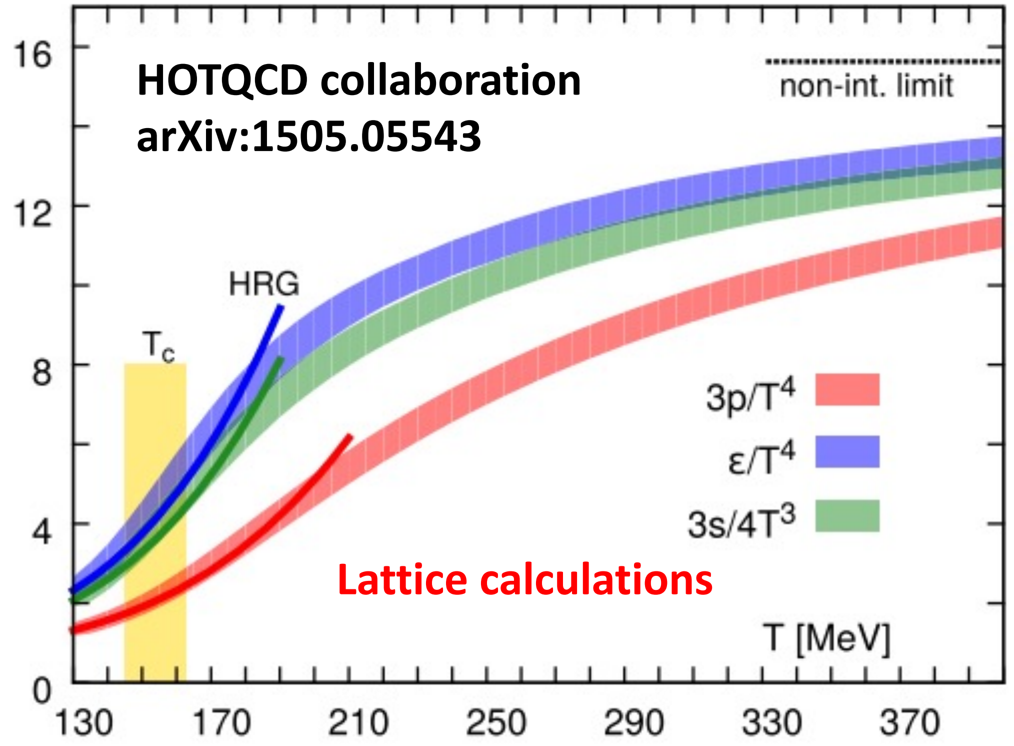
- Sushanta Tripathy has got INFN Fellowship-2021 (working in INFN, Bologna, Italy), PAG-MM, Convenor in ALICE

# Main Research Outcomes:

- 8 PhDs+ 11 Postdocs+ 42 MSc/BTech Research Awarded + 11 PhD (ongoing)
- 14 ALICE Analysis Notes
- 5- Experimental papers in ALICE
- 50+ papers in QGP Theory/Phenomenology

# The QCD Phase Diagram



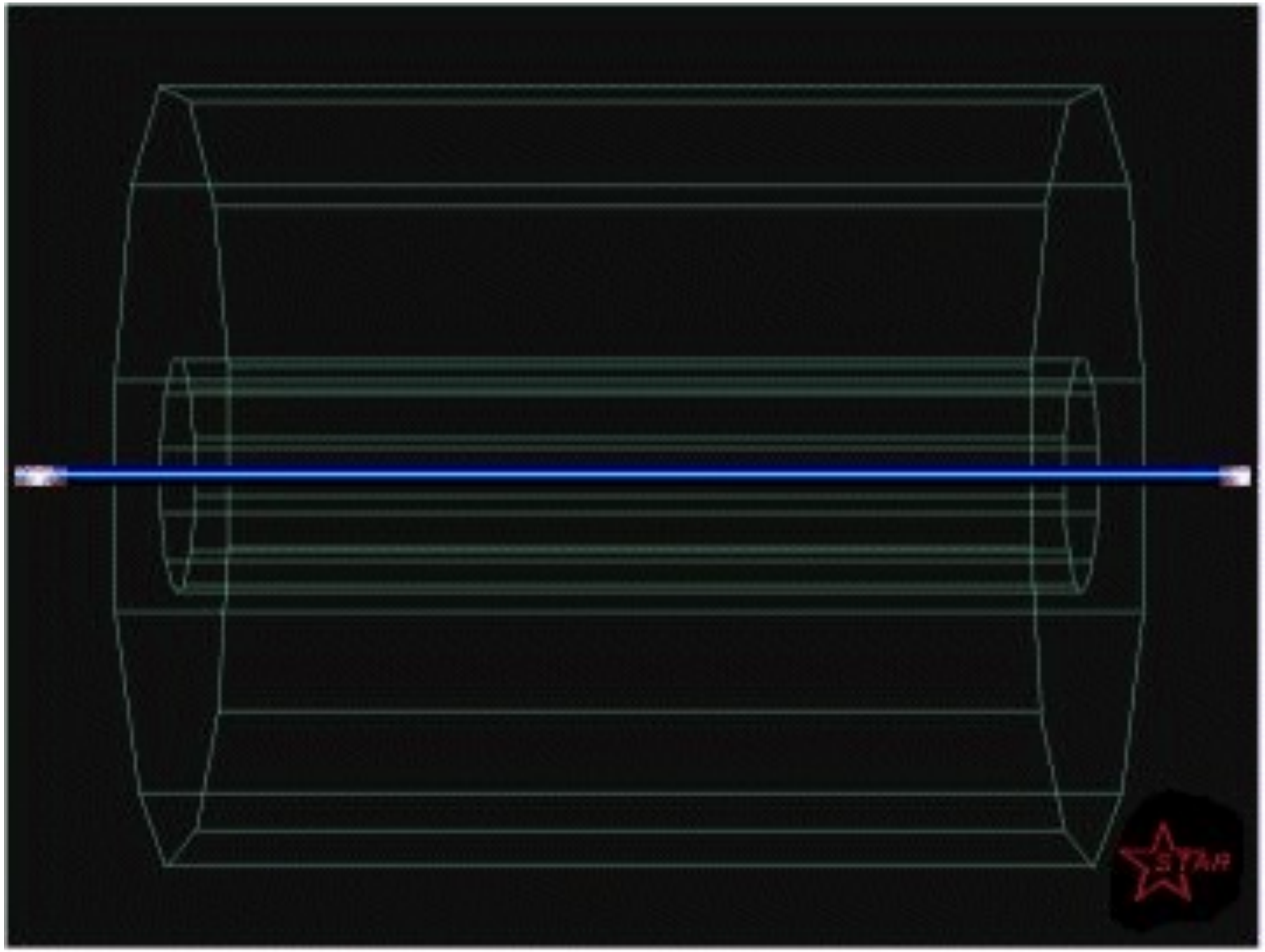

$T_C \approx 155$ MeV and $\varepsilon_C \approx 0.5$ GeV/fm$^3$

$$\varepsilon = g\frac{\pi^2}{30}T^4$$

- **For hadronic matter, g=3**
- **For QGP: degrees of freedom increases by a factor of about 10**

  (8 gluons, 2 quark flavours, 2 antiquarks, 2 spins, 3 colors)

# Creating the QGP state




Need to collide
**Heavy-Ions**

- Take a high-mass atom like Pb
- Take away the electron => ***Heavy-ion***)
- ***Accelerate the Ion*** to almost the speed of light
- ***Collide the Ions***
- Study the aftermath by specialized detectors which surround the collision point ***=> Experiment***

# Accelerator Facilities

USA

1984

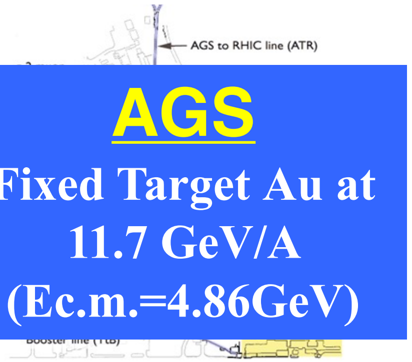
*Bevalac*

**Bevalac**
Fixed Target
Au at 1GeV/A

USA

1991

*AGS Layout*




**AGS**
Fixed Target Au at 11.7 GeV/A
(Ec.m.=4.86GeV)

CERN

1993 -


**SPS**
Fixed Target
Pb at 158GeV/A
(Ec.m.=17.3GeV)

*SPS Layout*

In 1988:
WA93, WA98

USA

2001 -


**RHIC**
Collider
Au+Au @ 200GeV/A

In 2001:
STAR

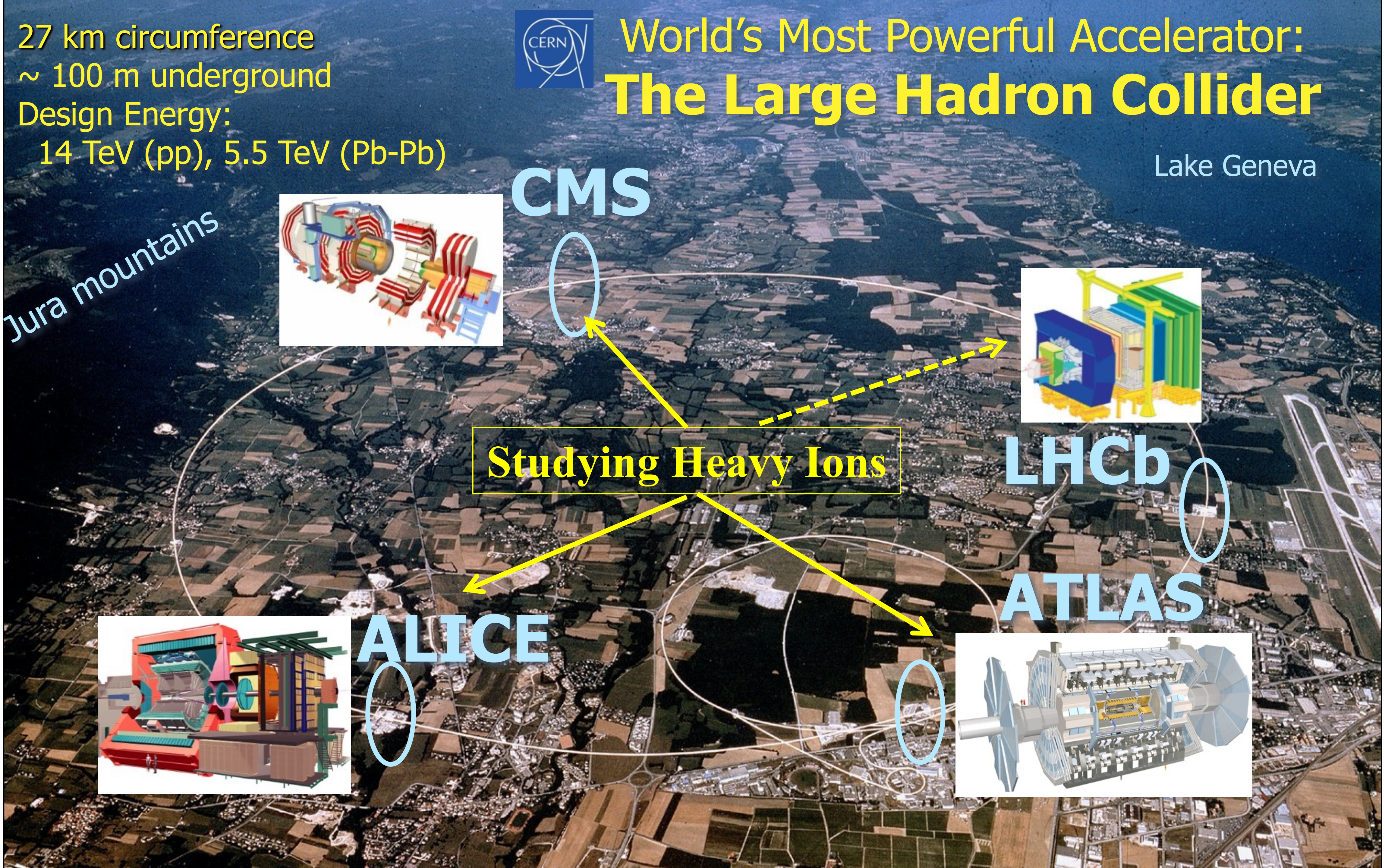
CERN

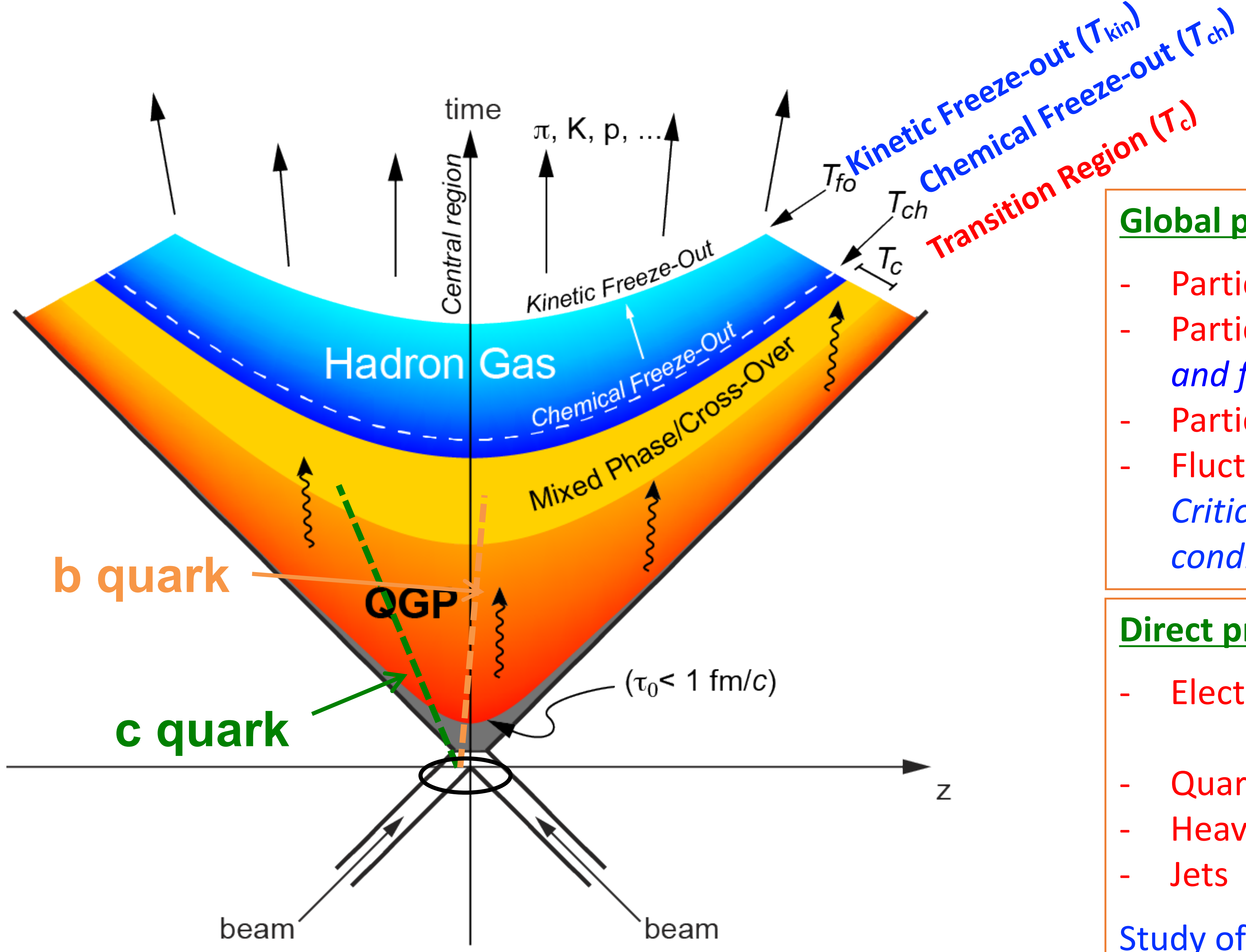
2009 -

**LHC**
Collider
Pb+Pb @5.5TeV/A

2009:
ALICE

# CERN


27 km circumference
~ 100 m underground
Design Energy:
14 TeV (pp), 5.5 TeV (Pb-Pb)
CERN
World's Most Powerful Accelerator:
The Large Hadron Collider
Lake Geneva
Jura mountains
CMS
LHCb
Studying Heavy Ions
ATLAS
ALICE




## Global properties & freezeout conditions

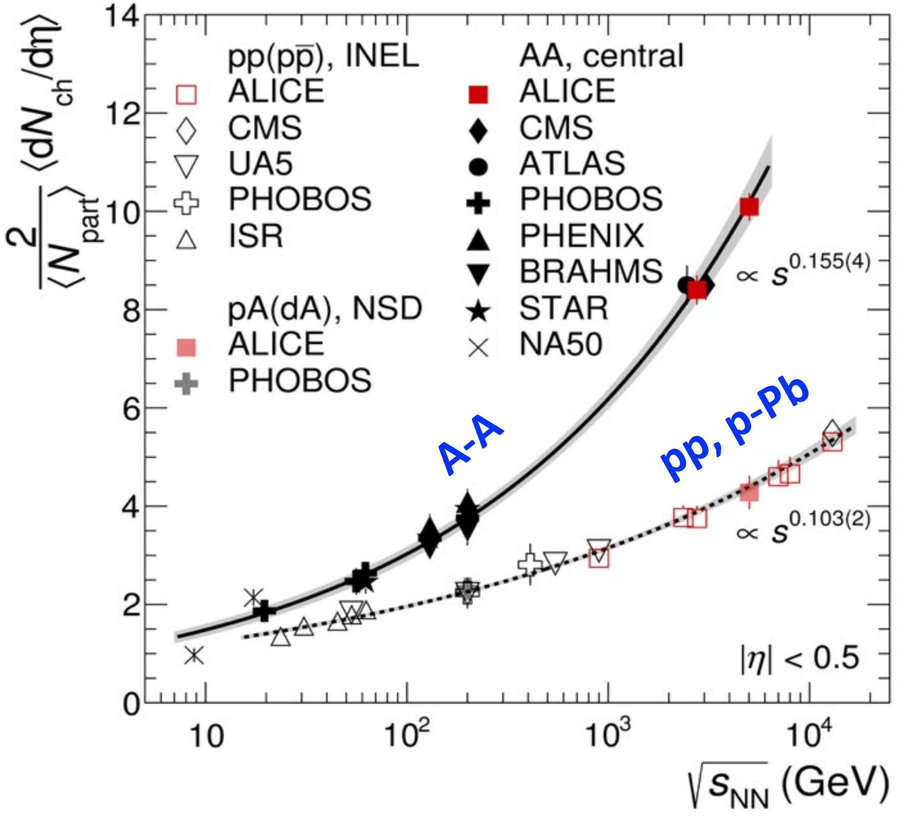
- Particle multiplicities: *energy densities*
- Particle spectra: *radial flow, expansion and freeze-out Temperatures*
- Particle flow: *Nature of matter*
- Fluctuations and correlations: *Access to Critical Phenomena, $T_c$ and freeze-out conditions, shape and size of the system*

## Direct probes of QGP

- Electromagnetic Probes: photons and dileptons
- Quarknonia, Strangeness enhancement
- Heavy Flavour
- Jets

Study of energy loss and nuclear modification factors

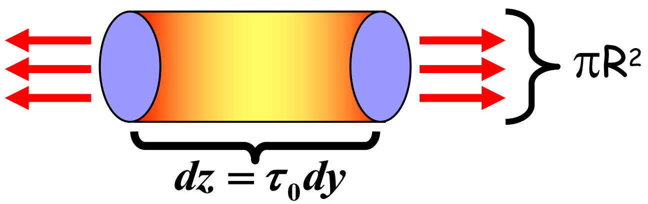
# Particle density & Energy density

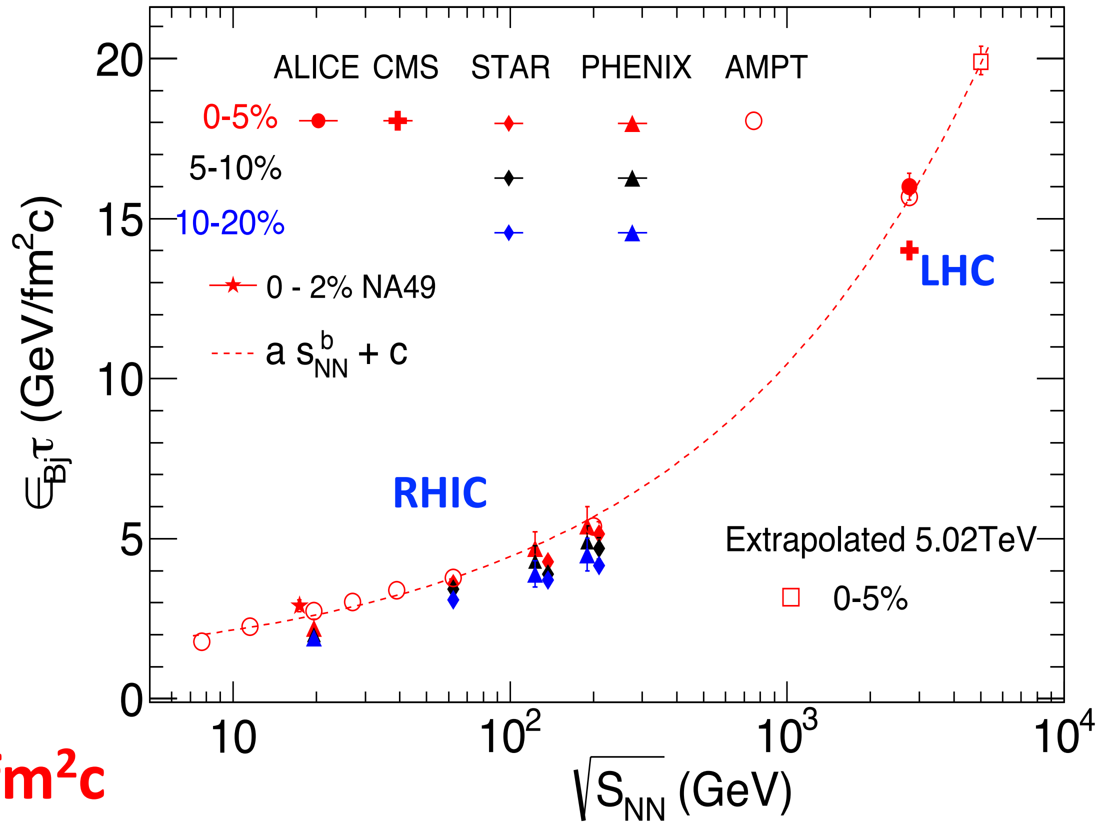



J. D. Bjorken

$$\varepsilon_{Bj}(\tau) = \frac{1}{\pi R^2 \tau}\frac{dE_T}{dy}$$

$$\approx \frac{1}{\pi R^2 \tau} < m_T > \frac{3}{2}\frac{dN_{ch}}{d\eta}$$




**$\varepsilon.\tau \sim 16\ \mathrm{GeV/fm^2c}$**

S. Basu et al. PRC 93 (2016) 064902
R. Sahoo et al. Adv. in HEP, Vol. 2015

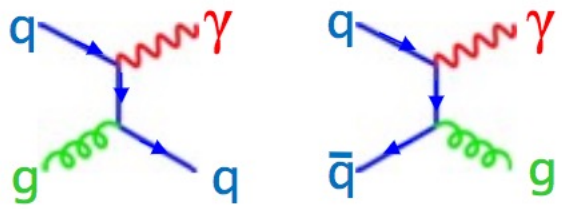
**Beam energy dependence:**

- **Pb-Pb curve rises faster ($s^{0.15}$) and stronger than in pp($s^{0.11}$).**

**LARGEST ENERGY DENSITIES EVER ACHIEVED ….**

# Photon Spectra and QGP temperature

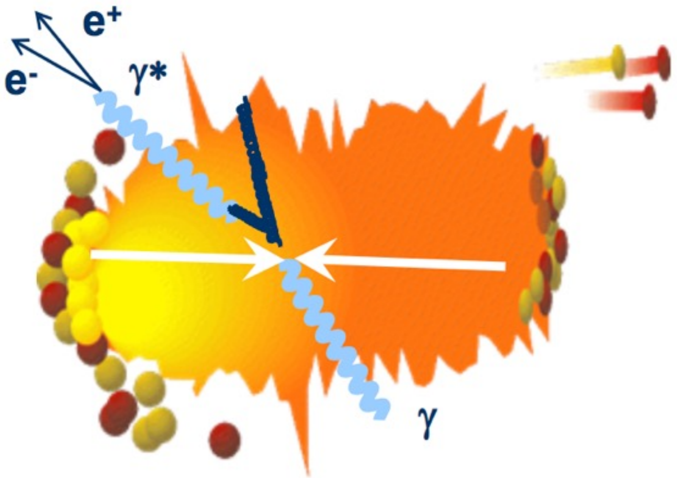
**Direct photons**



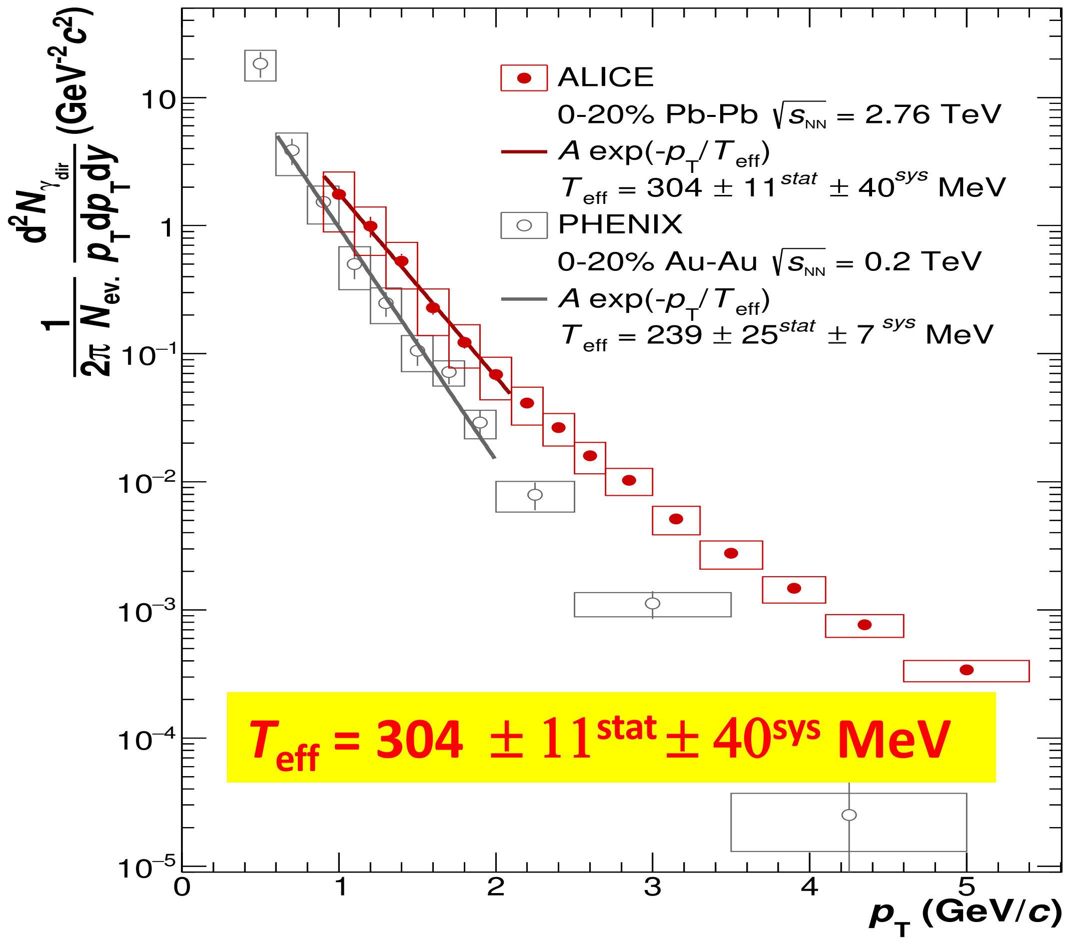

**Compton** **Annihilation**

***Direct photons*** *from initial* ***hard scattering*** *of quarks and gluons*

- Photons do not interact via the nuclear force → QGP is transparent to the medium
- Photons are emitted in all stages and are unaffected by the medium.




Phys. Lett. B 754 (2016) 235-248

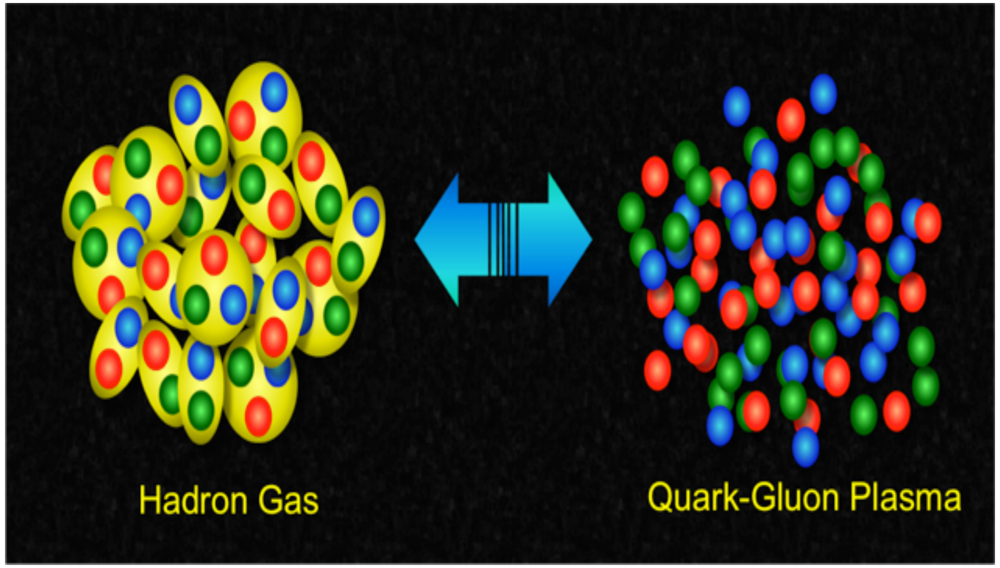


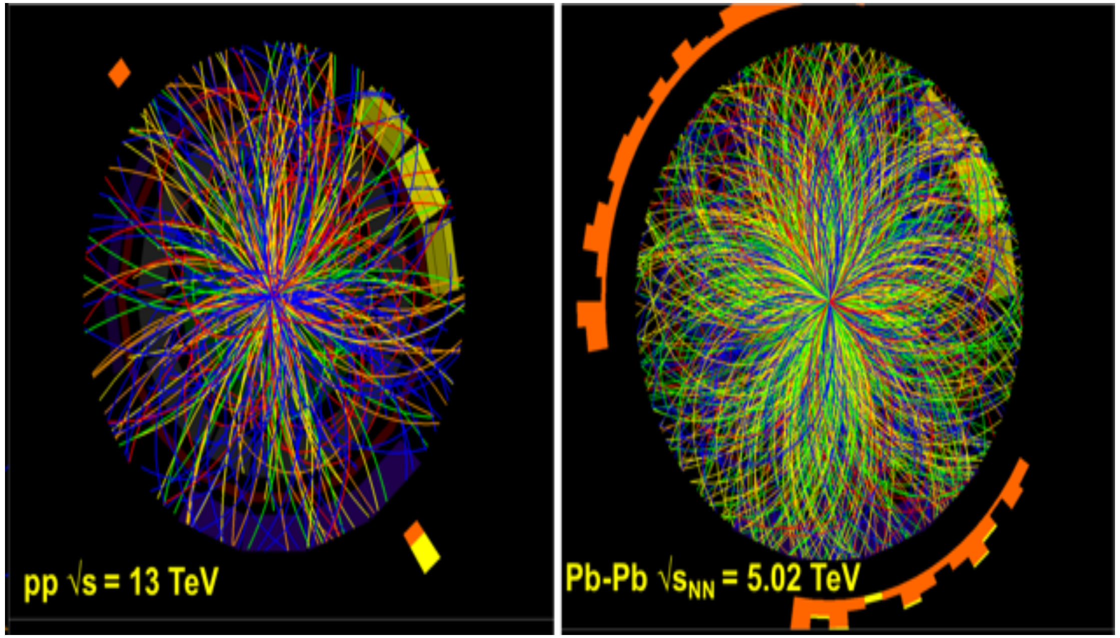

***Decay Photons*** from hadrons ($\pi^0$, $\eta$, etc):
Challenge is to separate the thermal part.

**(1eV=11605K)**

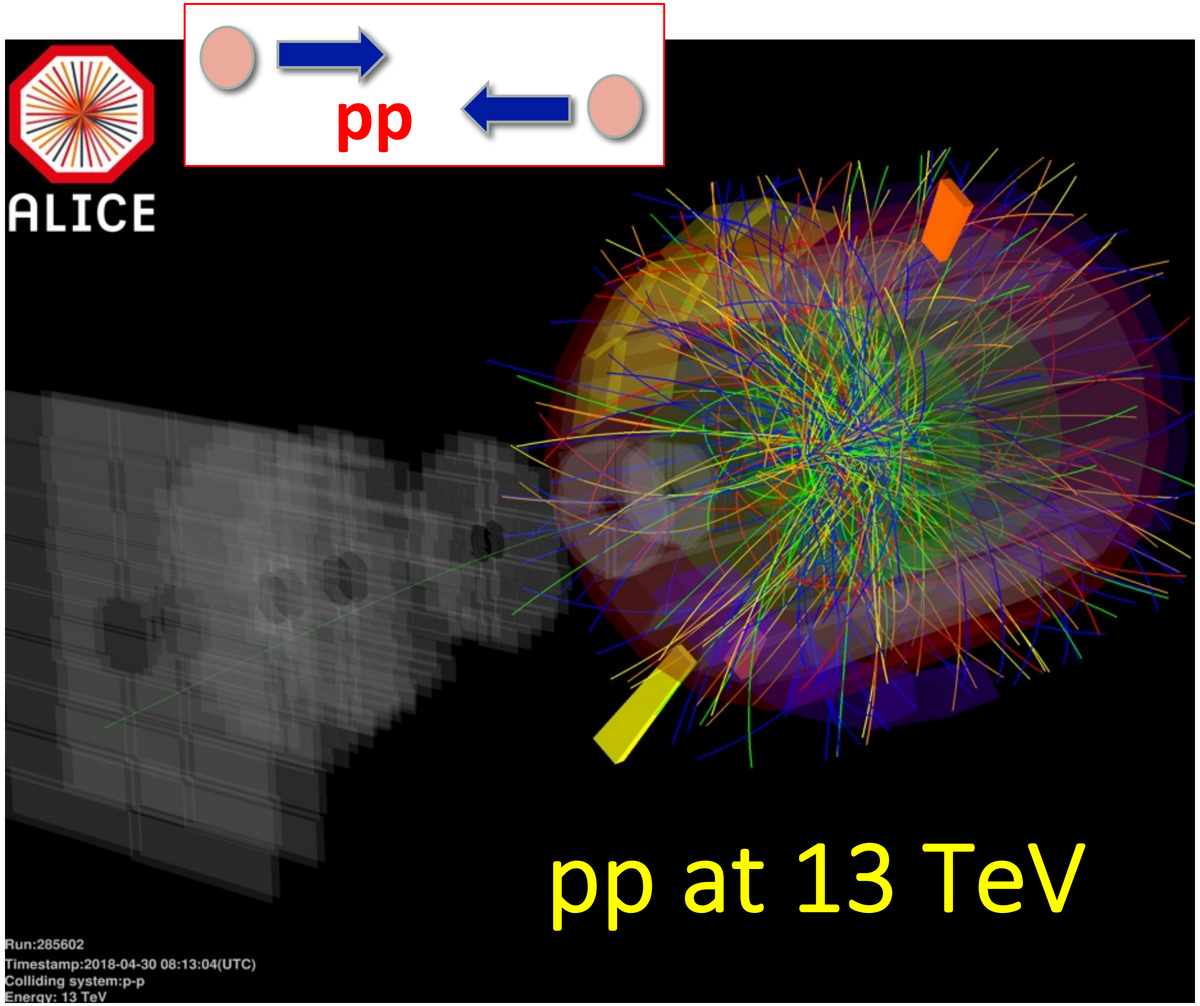
**LARGEST EVER TEMPERATURE REACHED IN THE LAB ….**

# Do we form droplets of QGP in pp collisions?

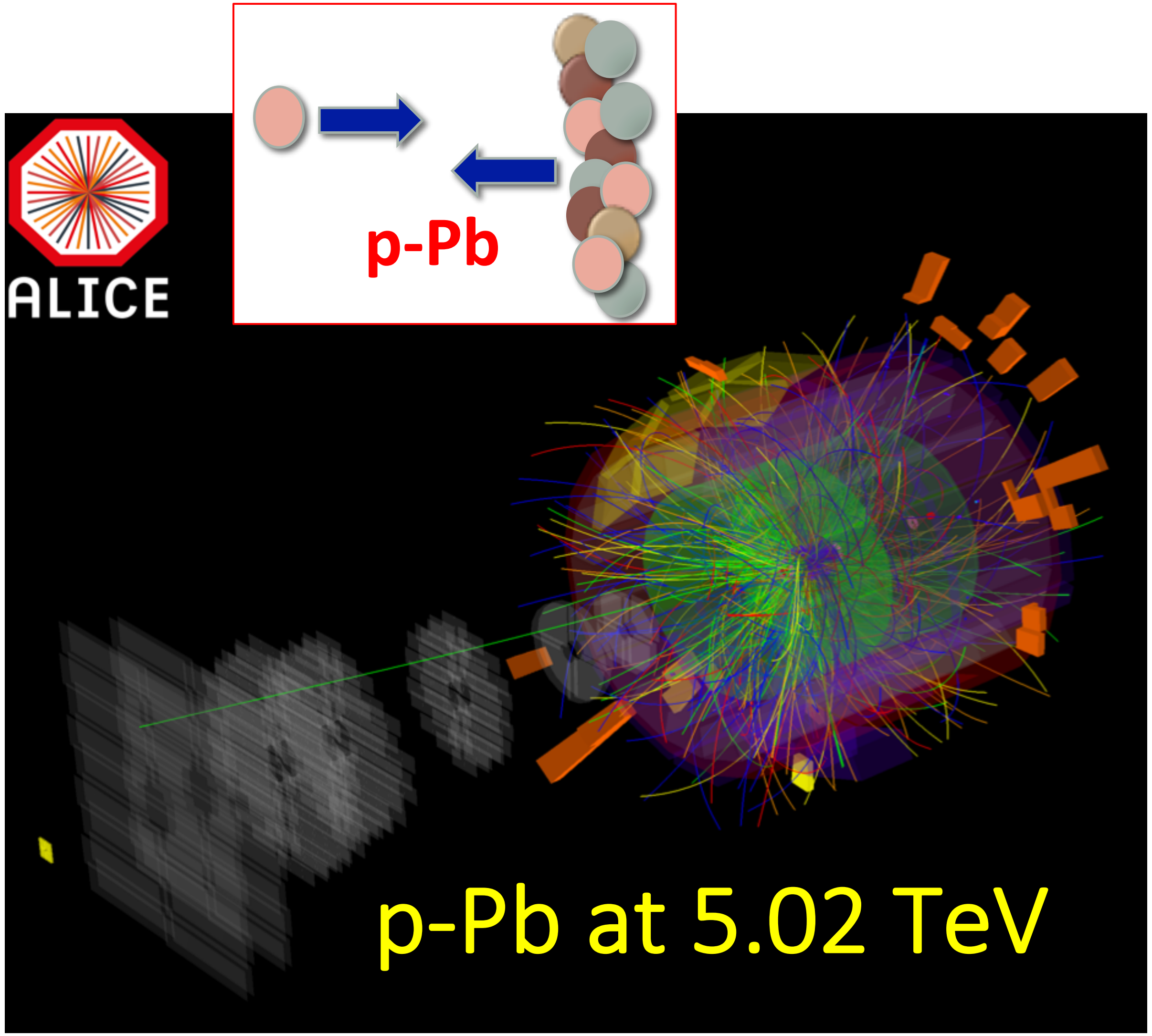


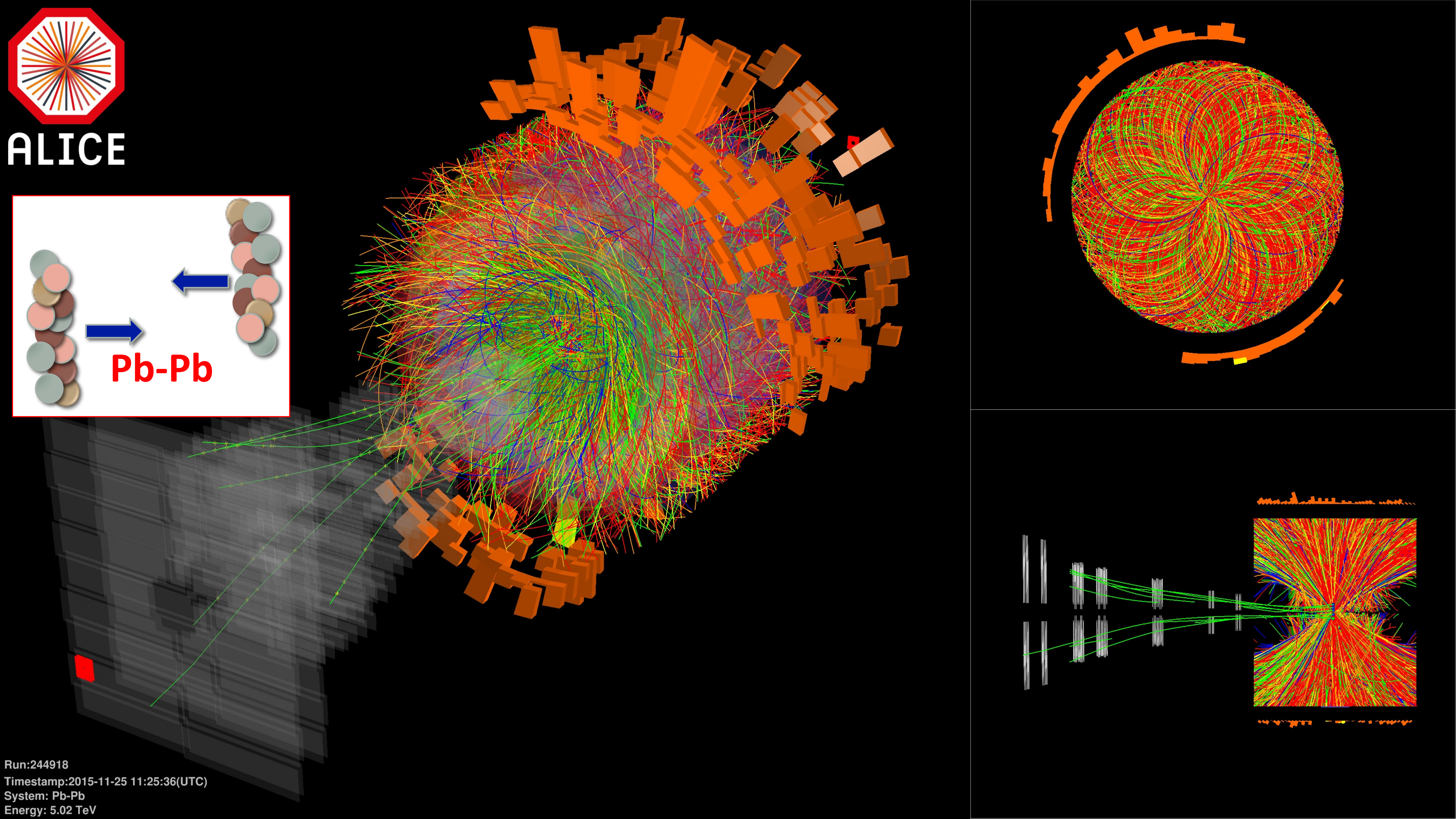



- Test of pQCD calculations from cross section measurements
- Provide reference for p-Pb and Pb-Pb collisions
- High multiplicity pp: what's the behaviour?




- Intermediary reference
- Address cold nuclear matter effects in initial and final states




ALICE
Pb-Pb
Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV

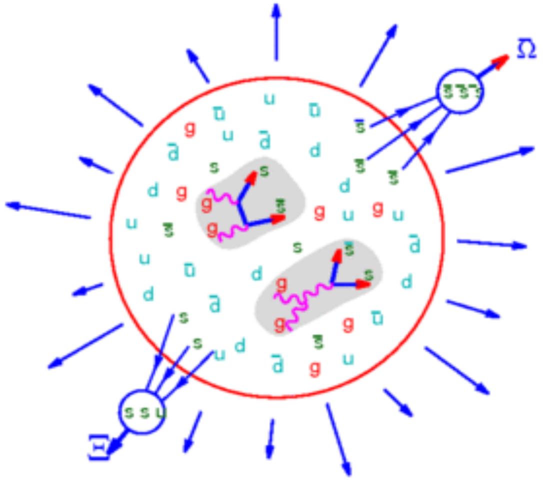
# Enhancement of Strangeness

✓ Enhanced production of strangeness (more pronounced for multistrange baryons) is a proposed signature of QGP.

- ❖ *s*-quarks are not part of the colliding nuclei (hadrons)
- ❖ *(u,d)*-quarks form ordinary matter
- ❖ *s(95 MeV):* are sufficiently light to be produced abundantly during the collision
- ❖ Strangeness is produced in hard partonic scattering processes by
- ❖ flavour creation: $gg \to s\bar{s}$

  $q\bar{q} \to s\bar{s}$
- ❖ flavour excitation: $gs \to gs$

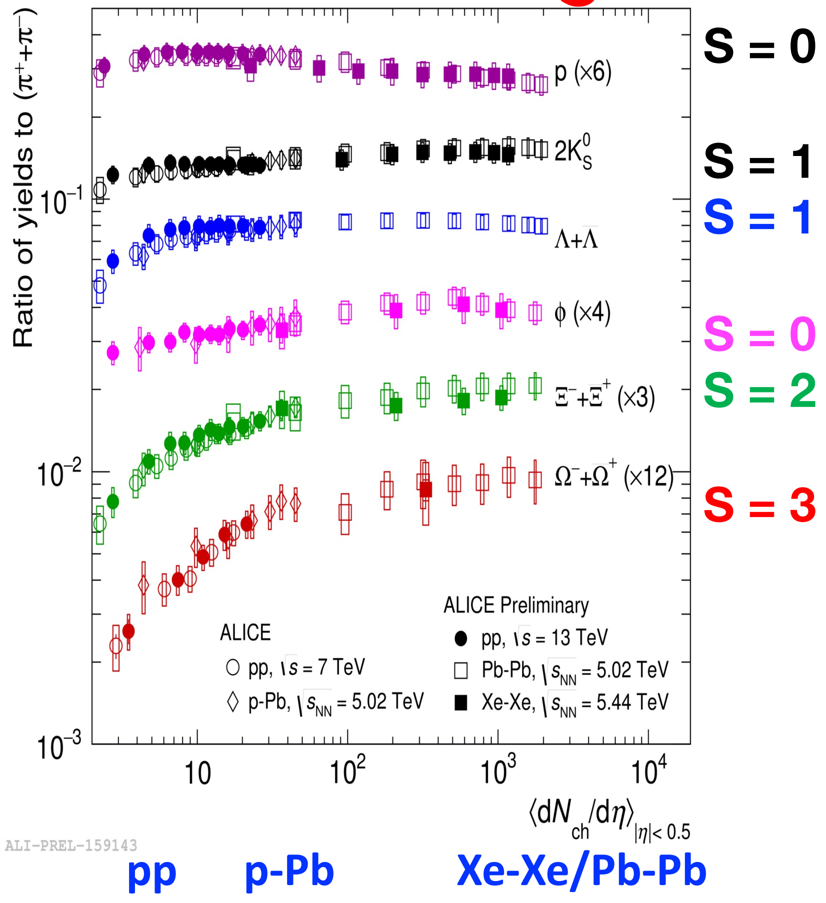
  $qs \to qs$
- ❖ gluon splitting: $g \to s\bar{s}$




J. Rafelski and B. Müller, PRL48, 1066 (1982)
P. Koch, B. Müller, J. Rafelski, Phys. Rep. 142, 167 (1986)

The enhanced production of strangeness relative to u and d quarks was proposed as one of the QGP signals.

# Strangeness enhancement: pp, pPb, XeXe to PbPb

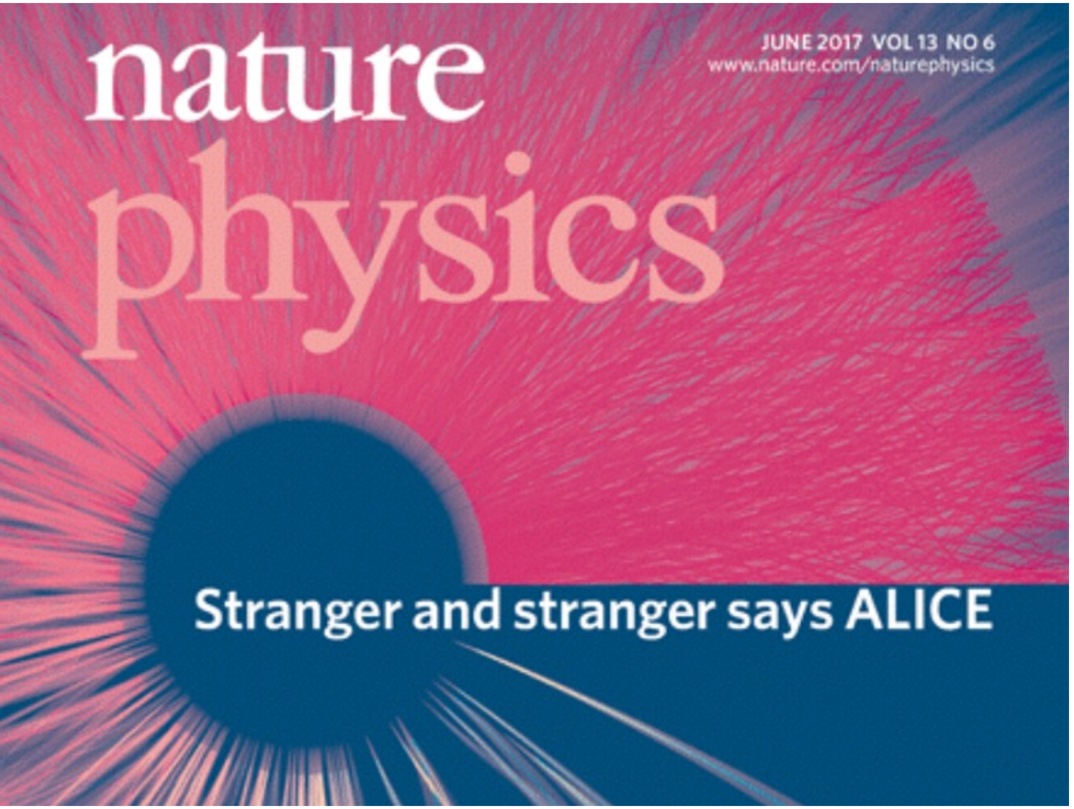


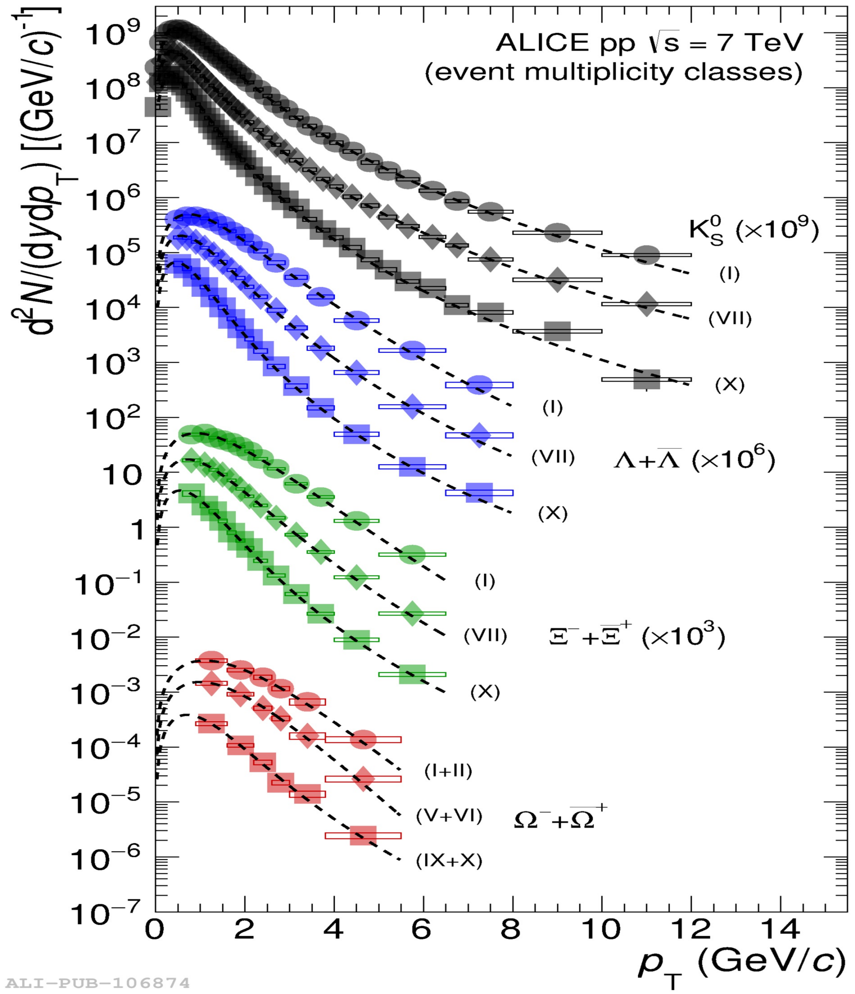

**Enhancement of strangeness in high-multiplicity pp collisions:**

**Does it signal the formation of QGP-droplets?**

- ✓ Smooth evolution as a function of event multiplicity (in pp, p-Pb and Pb-Pb collisions)
- ✓ Measurement at different energies as a function of multiplicity indicate that the hadron chemistry is driven by multiplicity regardless of the collision energy
- ✓ Ratios increase from low to high multiplicity in small systems and reach values similar to those observed in Pb-Pb collisions.
- ✓ Strangeness enhancement increases with strangeness content.

# Enhancement of Strangeness: Spectra




ALICE: Nature Phys. 13 (2017) 535

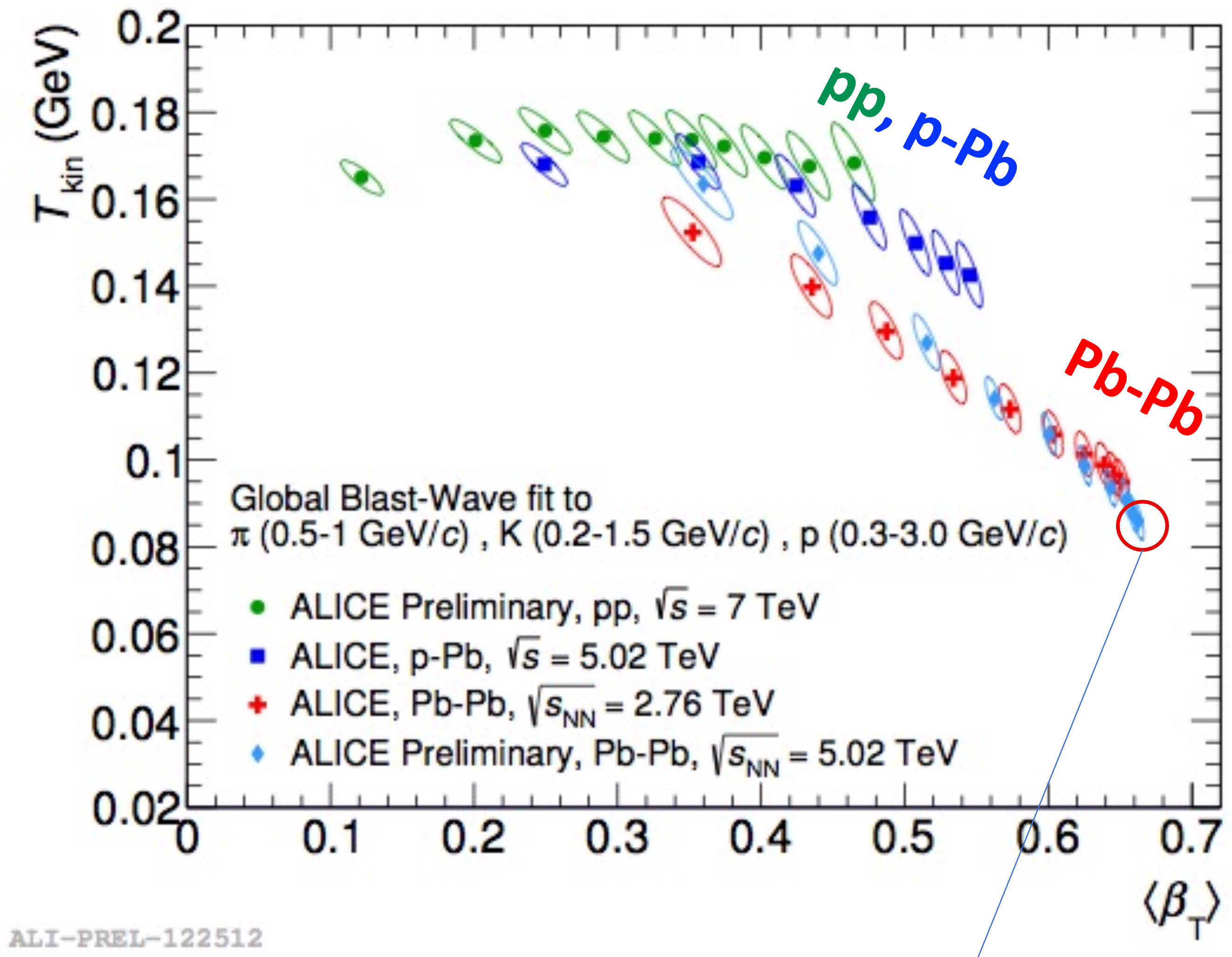
Simultaneous fit:

$T_{fo}$ = 163 ± 10 MeV,

$\langle\beta_T\rangle$ = 0.49 ± 0.02

- ✓ The FO temperature is in line with that the seen in heavy-ion collisions
- ✓ Close to the quark-hadron phase transition temperature, $T_c$

# Blast wave fits to particle spectra




**Largest $\beta_T$ ever**

**Boltzmann-Gibbs Blast-Wave model:**

Thermodynamic model with 3 fit parameters: $T_{kin}$ , $\langle \beta_T \rangle$ and n (velocity profile)

Describes the particle production from a thermalized source + a radial flow boost

**Simultaneous fits to *π,K,p* spectra gives:**

- increase of $<\beta_T>$ with centrality
- **Similar evolution of fit parameters in case of pp and p-Pb collisions**
- At similar multiplicities, $<\beta_T>$ is larger for smaller systems

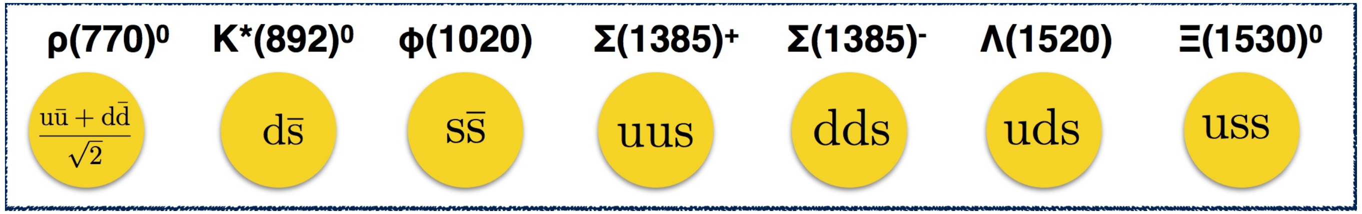
Extracting $T_{kin}$ (Kinetic freeze-out temperature) and $\langle \beta_T \rangle$ (Radial Flow velocity)

# Do we form QGP-droplets in high-multiplicity pp collisions at the LHC energies?

1. "Early universe signals in proton collisions at the Large Hadron Collider." Raghunath Sahoo and Tapan K. Nayak, Current Science (2021)

2. "Possible Formation of QGP-droplets in Proton-Proton Collisions at the CERN Large Hadron Collider." Raghunath Sahoo, arXiv:1908.10566, [Bulletin of Association of Asia Pacific Physical Societies (AAPPS), Vol-29, Page-16, August 2019 (Invited Article)]

# Resonance production – access to freeze-out times




Lifetime (fm/c)

$\rho$ < **K*** < $\Sigma^*$ < $\Lambda^*$ < $\Xi^*$ < $\phi$

1.3 < 4.2 < 5.5 < 12.6 < 21.7 < 46.2

- $K^{*0}$ decays within the medium (short lifetime) => decay products (π,K) re-scatter with other hadrons.
- In contrast, longer lifetime ϕ => both the re-scattering and regeneration effects are negligible.

| | Life time (fm/c) |
|---|---|
| K*⁰ | ~ 4.16 |
| ϕ | ~ 46.3 |

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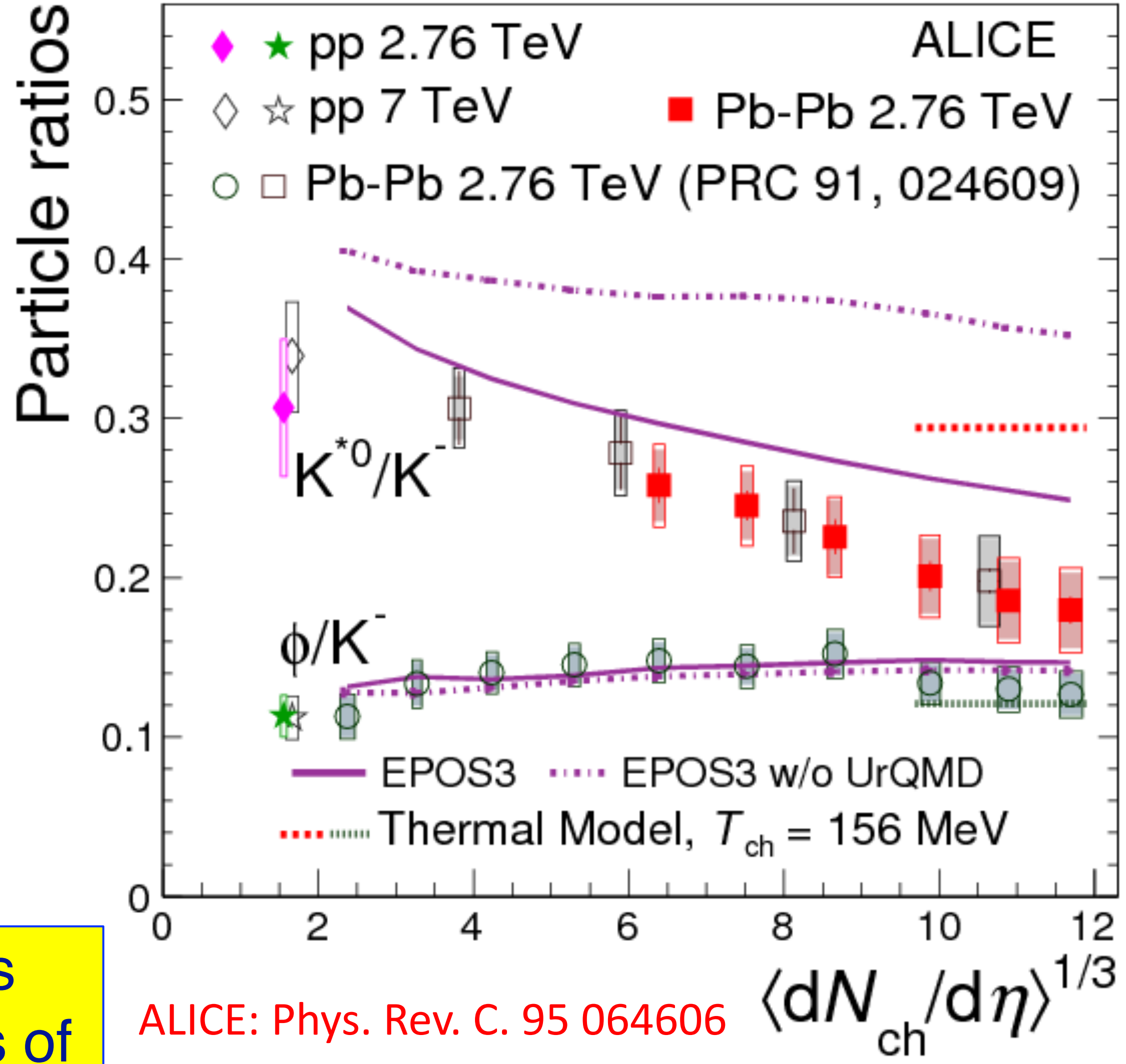
NEWS

ALICE zooms in on evolution of the quark–gluon plasma

10 July 2017




ALICE: Phys. Rev. C. 95 064606

Existence of re-scattering effects on resonances in the last stages of heavy-ion collisions.

# $K^*(892)^0$ and $\phi(1020)$ production at midrapidity in pp collisions at $\sqrt{s}$ = 8 TeV

Based on Phys. Rev. C 102, 024912 (2020) (ALICE Collab.)

PC: Raghunath Sahoo (Chair)
Sushanta Tripathy
Arvind Khuntia
Anders Knopse

# Physics message

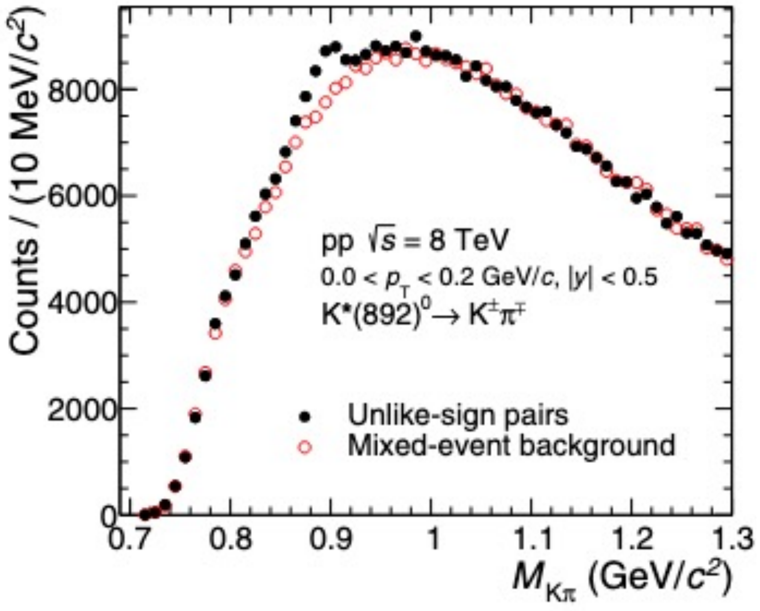
- First results for K*(892)$^0$ and ϕ(1020) in pp collisions at 8 TeV

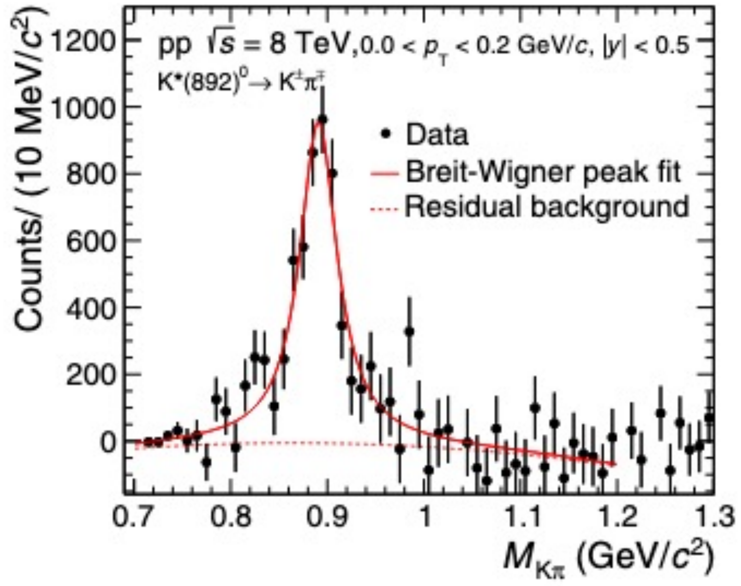
- Includes extension of K*(892)$^0$ to high-$p_T$ and improved re-analysis for ϕ(1020) in pp collisions at 7 TeV

- Serve as reference to study nuclear effects in p-Pb and Pb+Pb collisions

- Input to tune QCD-inspired MC event generators

# Analysis Details ($K^{*0}$)




- $K^*(892)^0 \rightarrow K+\pi$ (BR: 66.6%)
- Background Subtraction: Event Mixing
- Normalization Range: 1.1 – 1.5 GeV/$c^2$
- Fit Function: Breit-Wigner + Pol2
- Fitting Range : 0.7 – 1.2 GeV/$c^2$ and width is free. (Depending upon the shape of the signal)
- 28 $p_T$ bins from 0 GeV/c to 20 GeV/c

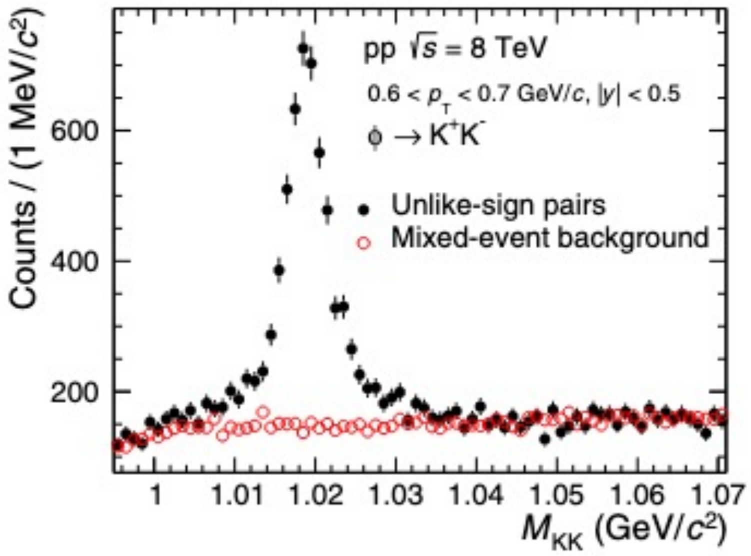
**Breit-Wigner:**

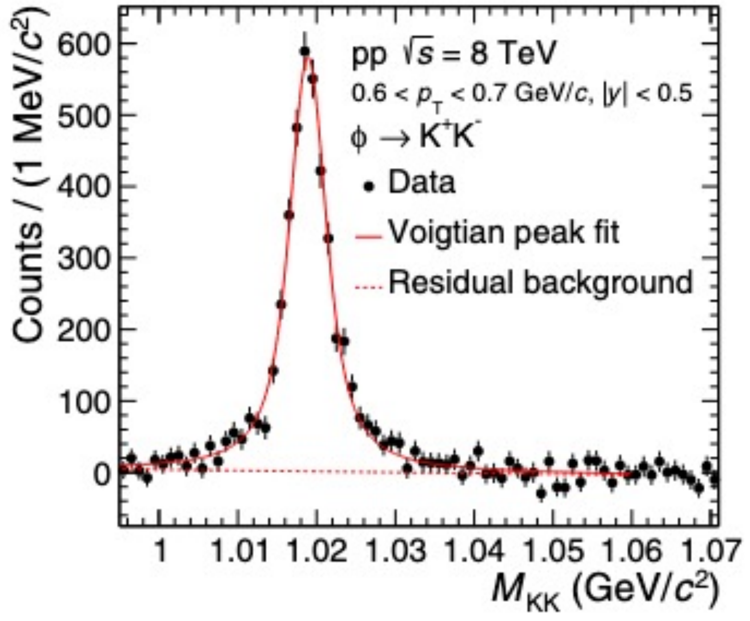
$$\frac{dN}{dm_{K\pi}} = \frac{A}{2\pi}\frac{\Gamma_0}{\left(m_{K\pi} - m_0\right)^2 + \frac{\Gamma^2}{4}}$$

**Pol2 :**

$$f(m) = a + bm + cm^2$$

# Analysis Details ($\phi$)



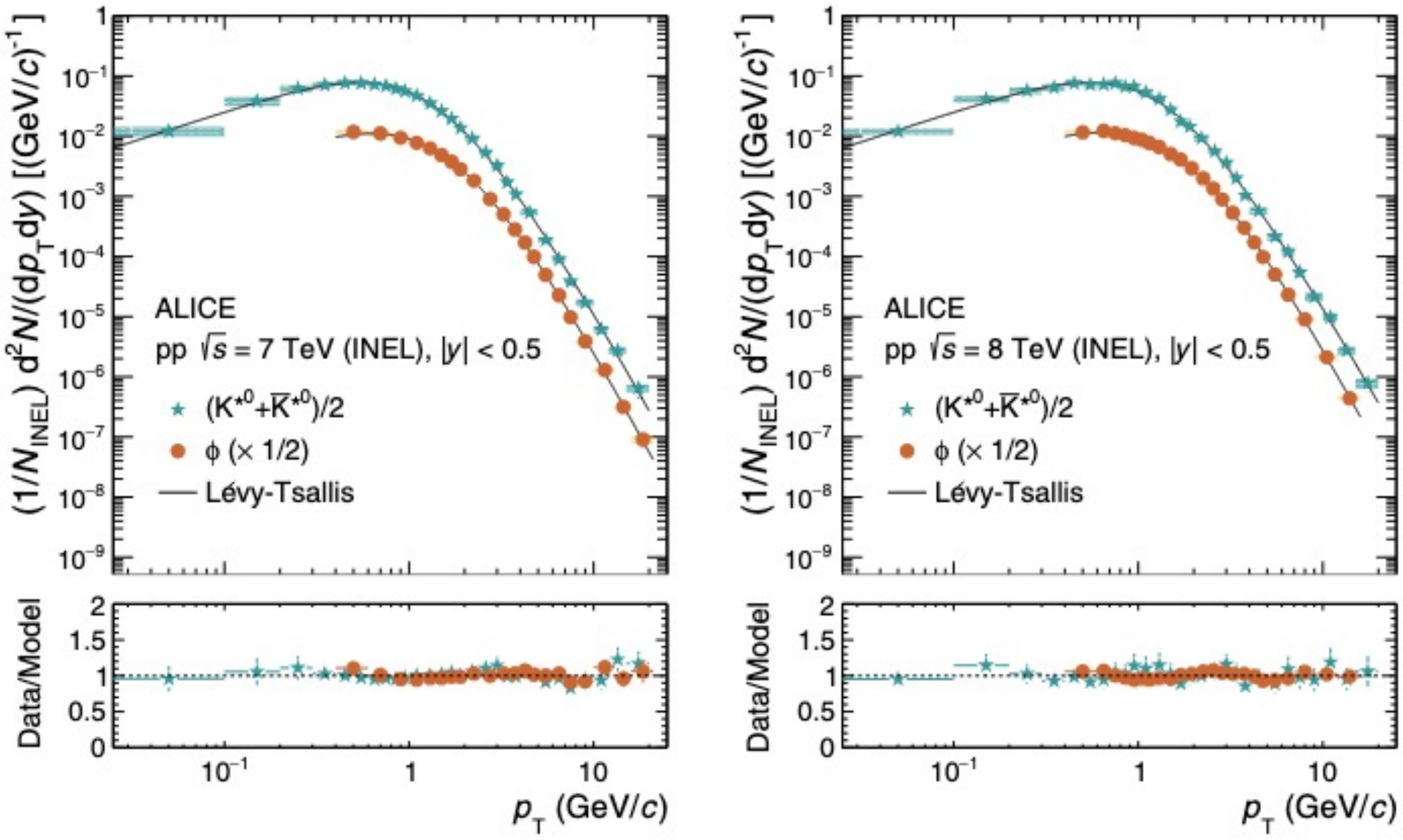




- $\phi(1020) \to K^+ + K^-$ (BR: 49.2%)
- Background Subtraction: Event-mixing
- Residual background : pol2
- Peak fit function: Voigtian function (BW+Gauss)

$$\frac{dN}{dm_{KK}} = \frac{A\Gamma}{(2\pi)^{3/2}\sigma}\int_{-\infty}^{\infty}\exp\left[-\frac{(m_{KK}-m')^2}{2\sigma^2}\right]\frac{1}{(m'-M)^2+\Gamma^2/4}dm'.$$

- Width is fixed to the PDG value.
- Mass and resolution are free.
- 23 $p_T$ bins from 0.4 GeV/c to 16 GeV/c.

# Corrected yield




$$\frac{d^2N}{dp_\mathrm{T}dy} = \frac{\mathrm{RawCounts}}{N_\mathrm{ev} \times \mathrm{BR} \times \Delta p_\mathrm{T} \times \Delta y} \frac{\epsilon_\mathrm{SL}}{\epsilon_\mathrm{rec}} \times f_\mathrm{norm} \times f_\mathrm{vertex}$$

BR: Branching Ratio

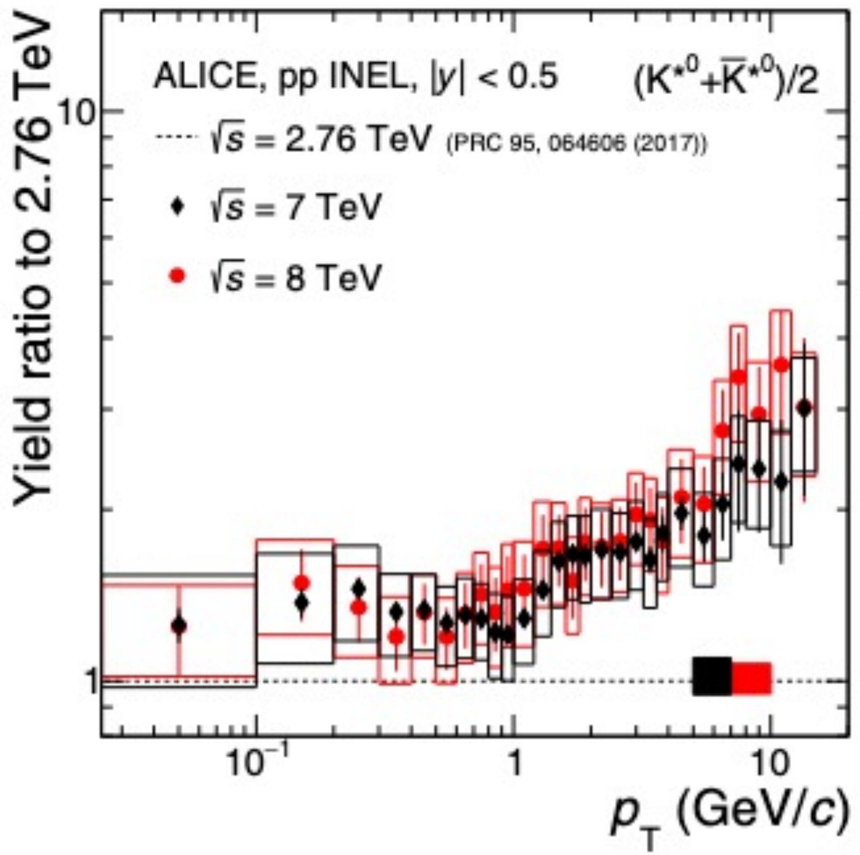
$f_{\mathrm{norm}}$: inelastic normalisation factor

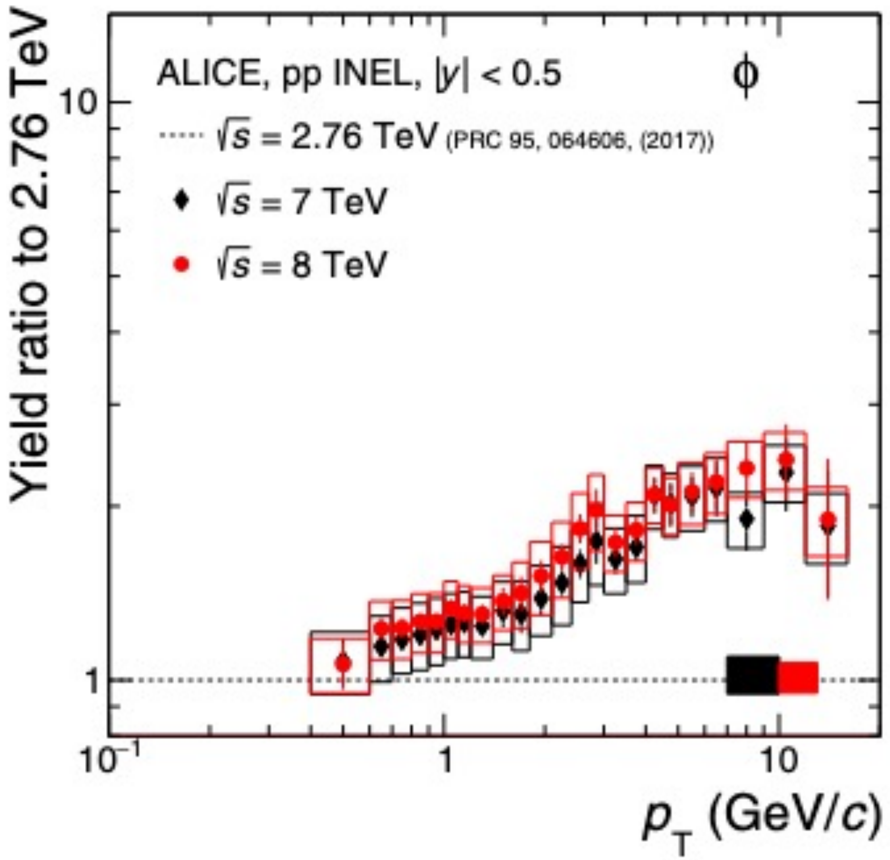
$f_{\mathrm{vertex}}$: vertex reconstruction efficiency

$\epsilon_{\mathrm{SL}}$: signal loss correction factor

- First results for $K^*(892)^0$ and ϕ(1020) in pp collisions at 8 TeV
- Includes extension of $K^*(892)^0$ to high-$p_\mathrm{T}$ and improved re-analysis for ϕ(1020) in 7 TeV

# Yield ratios to 2.76 TeV



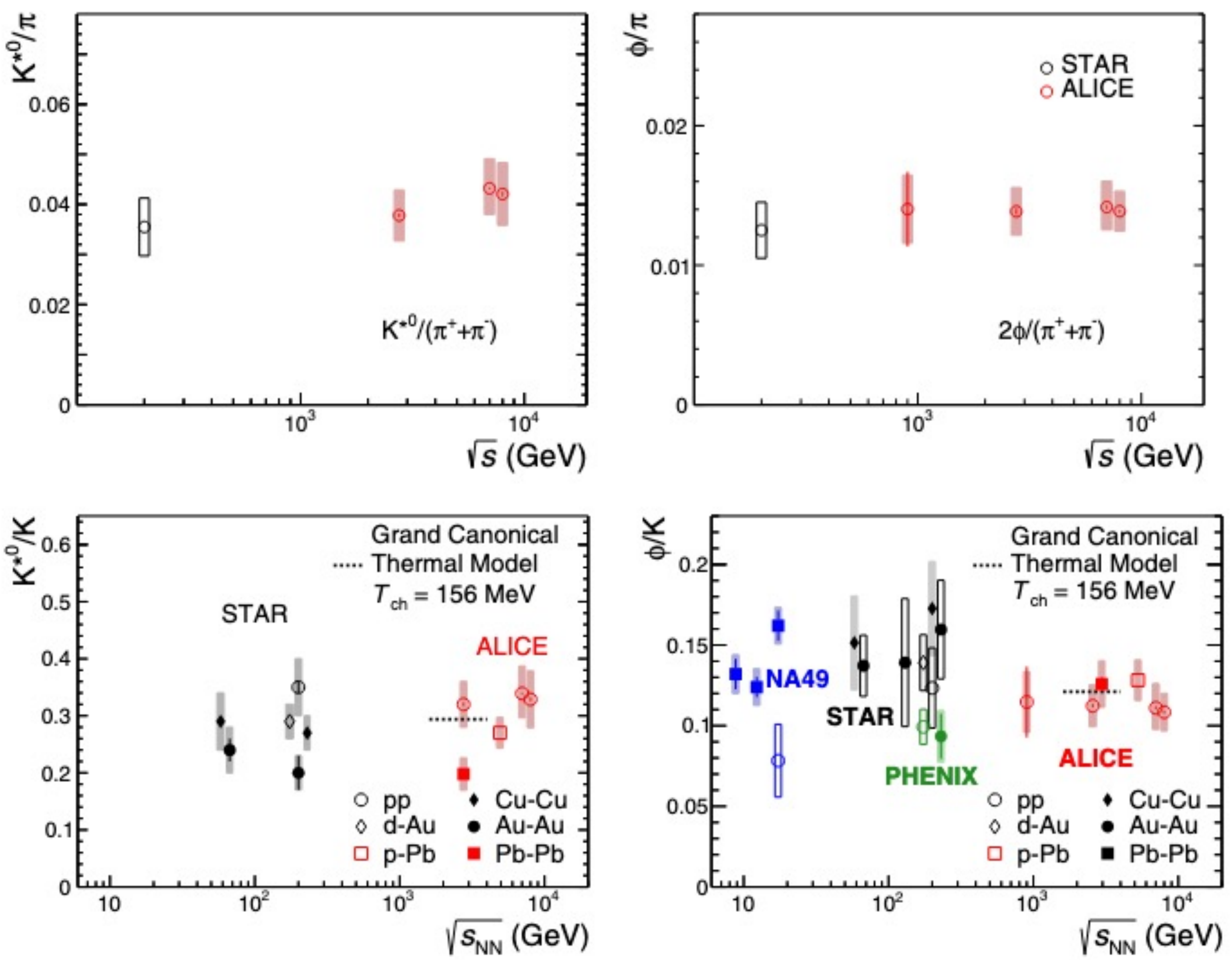

- The $p_T$-differential yield ratio to 2.76 TeV is consistent for 7 and 8 TeV within systematic uncertainties.
- For both $K^{*0}$ and ϕ, the differential yield ratios are independent of $p_T$ within systematic uncertainties up to about 1 GeV/*c* for different collision energies → particle production mechanism in soft scattering regions is independent of collision energy
- An increase in the slope of the differential yield ratios is observed for $p_T > 1$-2 GeV/*c*

# Energy dependence of yield ratios:

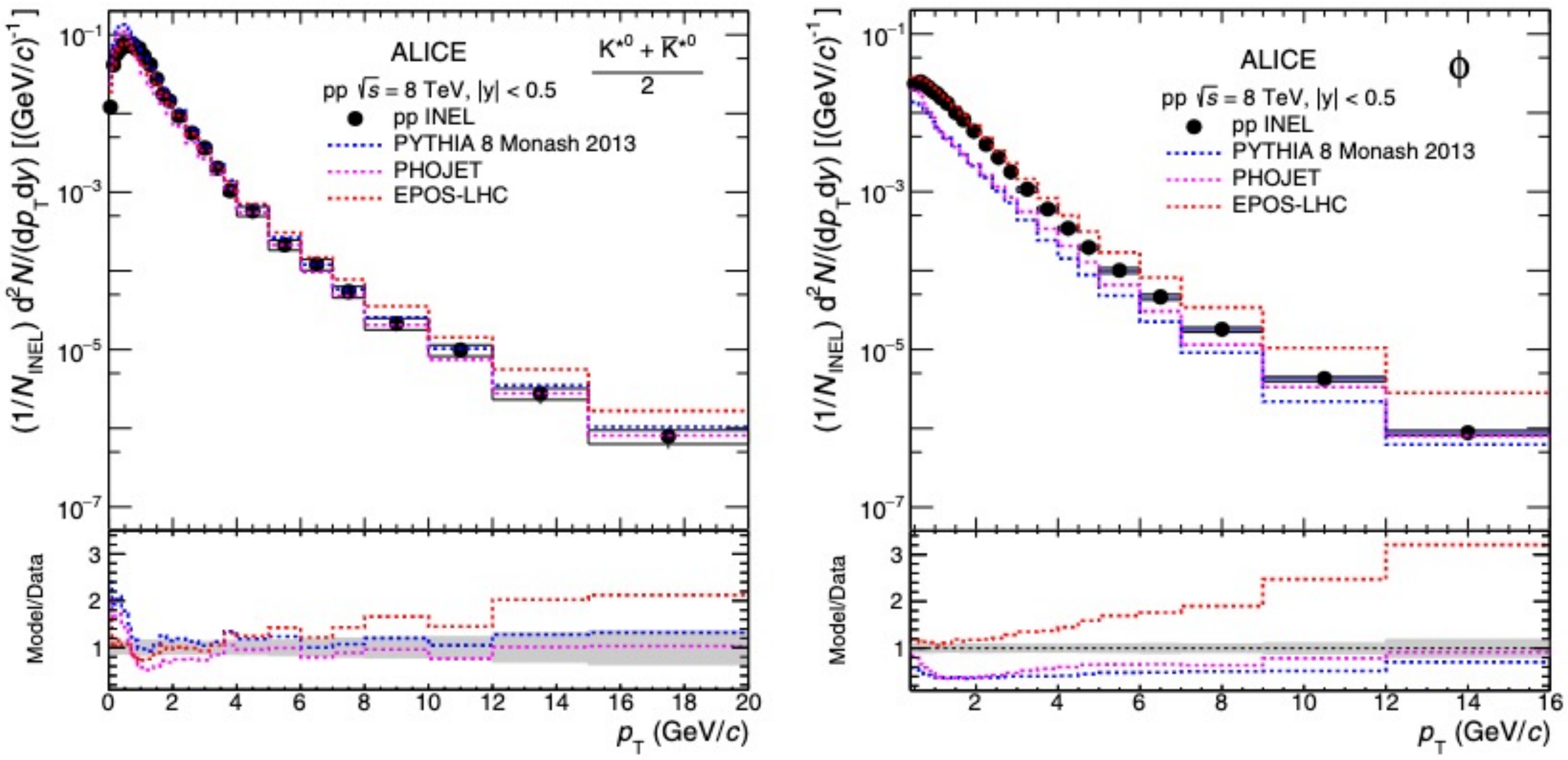
- $K^{*0}/\pi$ and $\phi/\pi$ ratios are independent of collision energy → the chemistry of the system is independent of the energy from RHIC to the LHC energies.

- Also indicates the strangeness production mechanisms do not depend on energy in inelastic pp collisions at LHC energies → no strangeness enhancement in minimum bias pp collisions

- $K^{*0}/K$ and $\phi/K$ ratios are independent of the collision energy → agrees with the prediction of a thermal model in the grand-canonical limit



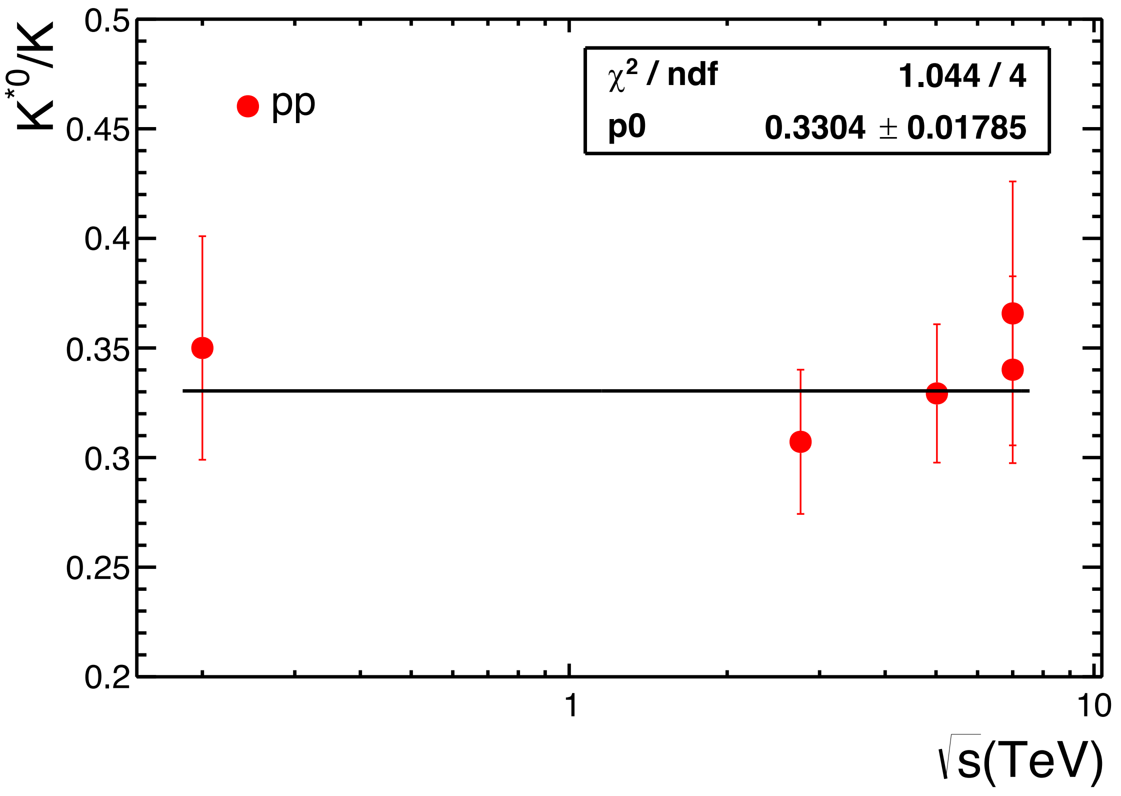
# MC Model comparison:

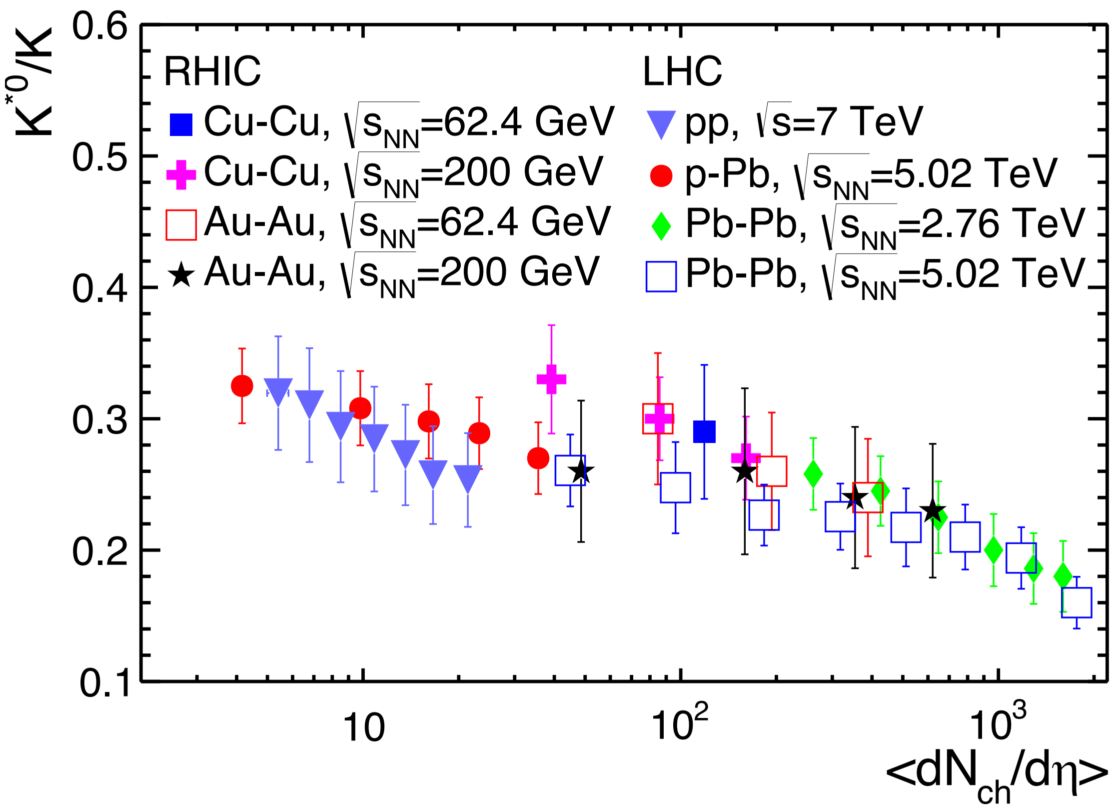



- None of the MC models seem to explain the $K^{*0}$ spectra over the full $p_T$ range whereas PHOJET and PYTHIA describe the data for the intermediate and high- $p_T$ regions.

- The MC models fail to explain the $p_T$ spectra of ϕ mesons completely

# Hadronic phase lifetime




*Figures are from D. Sahu, S. Tripathy, G. S. Pradhan and R. Sahoo, Phys. Rev. C 101, 014902 (2020)

$$\left[\frac{K^{*0}}{K}\right]_{kinetic} = \left[\frac{K^{*0}}{K}\right]_{chemical} \times e^{-\Delta t/\tau}$$

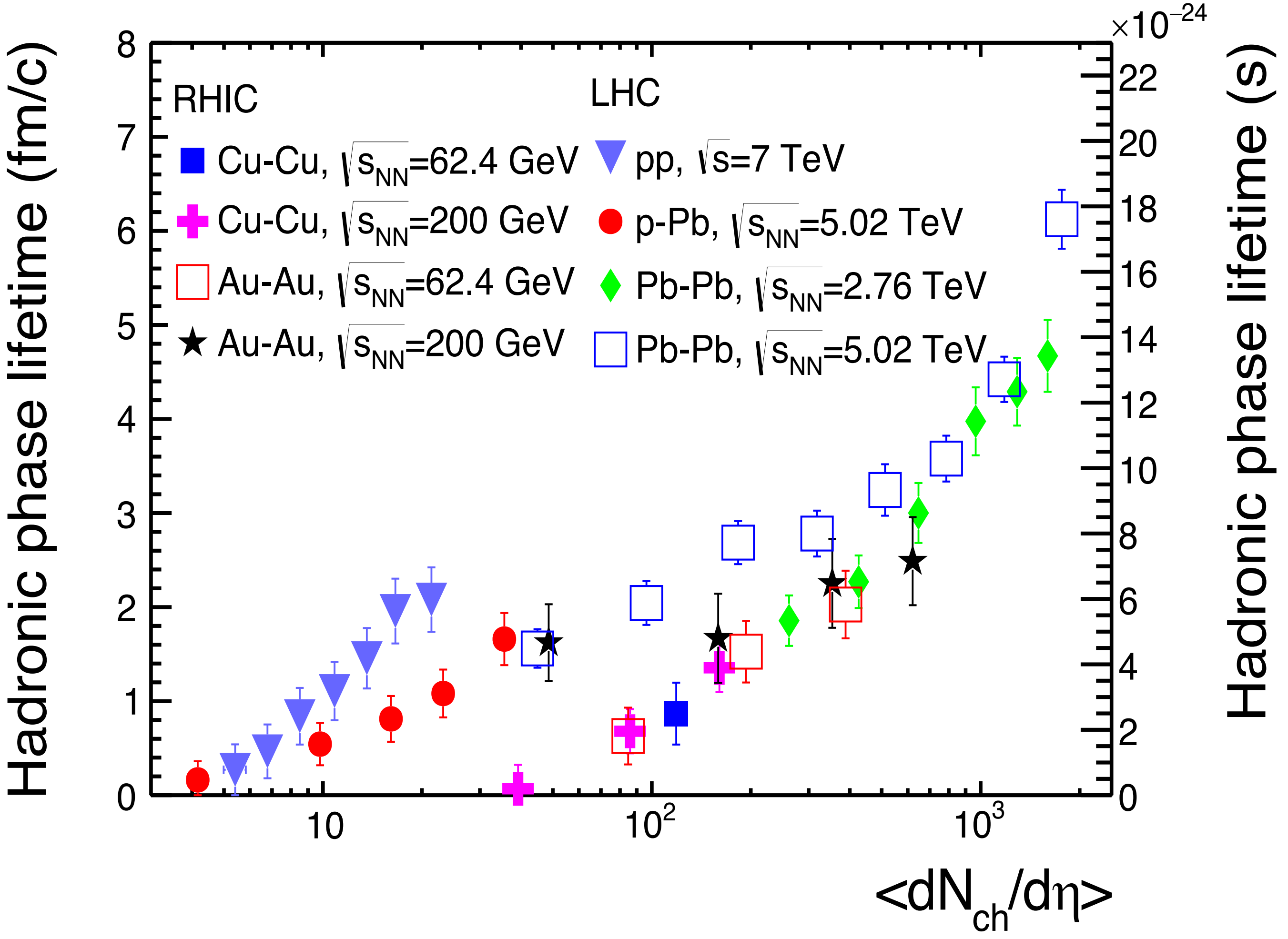
where, $\tau$ is the lifetime of the particle

$\Delta t$ is the lifetime of the hadronic phase

# Hadronic phase lifetime

$$\left[\frac{K^{*0}}{K}\right]_{kinetic} = \left[\frac{K^{*0}}{K}\right]_{chemical} \times e^{-\Delta t/\tau}$$

- This enables us to calculate the hadronic phase lifetime
- Shows a high dependency on charged particle multiplicity
- Slightly dependent on energy of the system
- High multiplicity pp collisions show finite hadronic phase lifetime




*Figures are from D. Sahu, S. Tripathy, G. S. Pradhan and R. Sahoo, Phys. Rev. C 101, 014902 (2020)

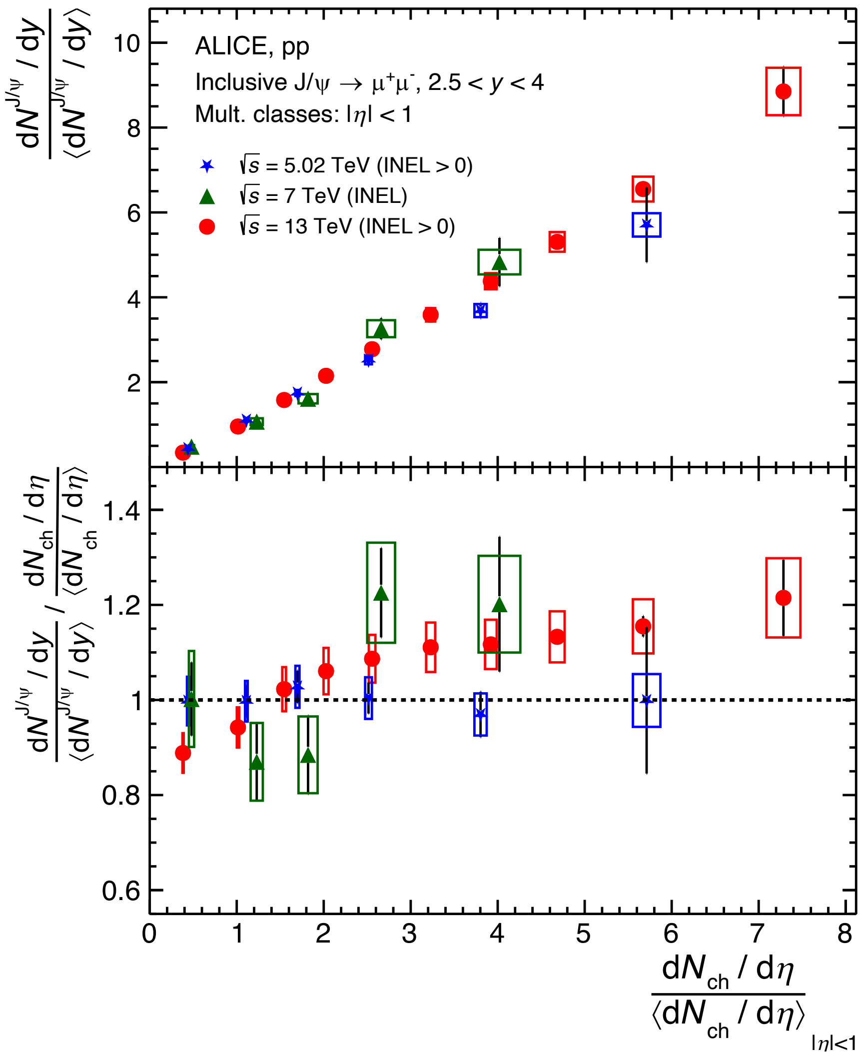
# Multiplicity dependence of J/$\psi$ production using ALICE at the LHC

Link to draft:
https://alicepublications.web.cern.ch/node/5122

PC: Raghunath Sahoo (Chair)
Dhananjaya Thakur,
Anisa Khatun,
Tinku Sarkar – Sinha,
Indranil Das

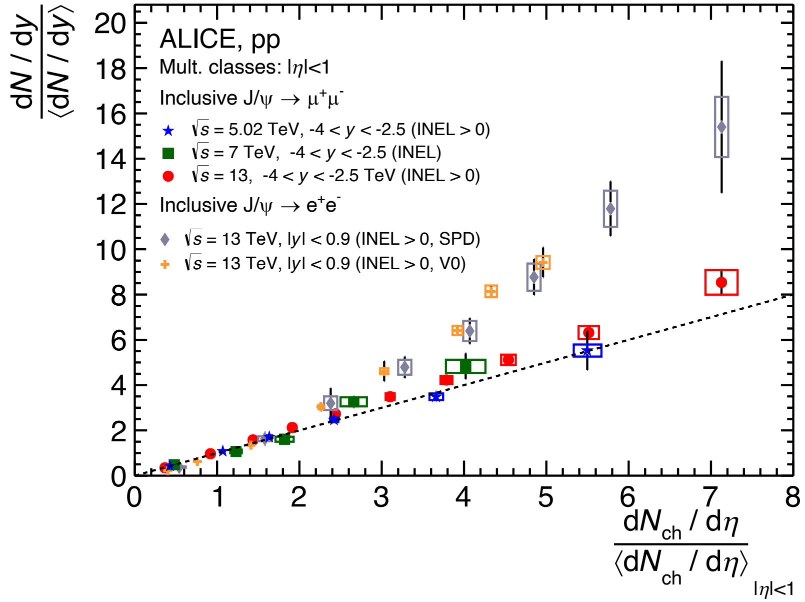
Paper status: Ready for CR2 (target journal JHEP)

# J/ψ production as a function of multiplicity

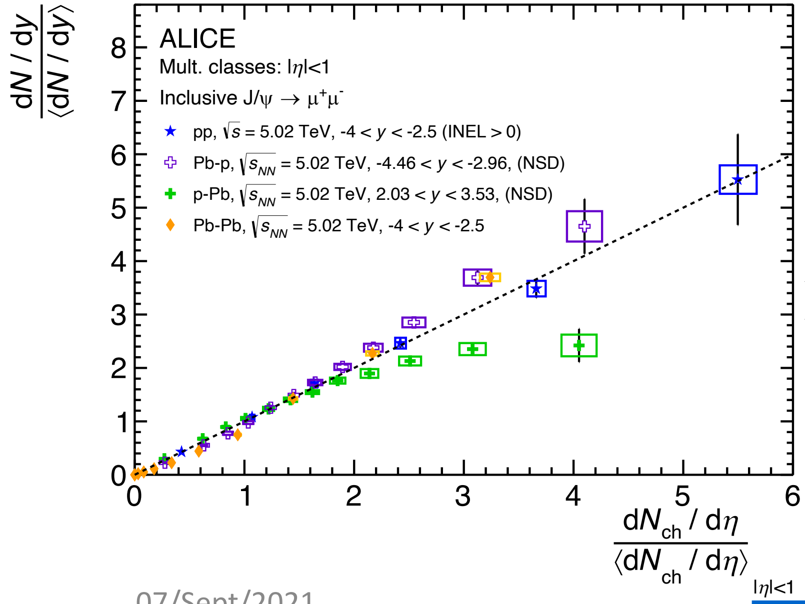



- ➢ $J/\psi$ yield increases with increasing charged-particle multiplicity, showing approximately a linear behavior.
- ➢ In the scenario of multiparton interaction: If MPI extend up to a regime of hard processes, the yield of $J/\psi$ should also scale with the number of partonic interactions, leading to a linear correlation of $J/\psi$ yield with event multiplicity.
- ➢ The points are above the line along unity around $N_{ch}/<N_{ch}>$ 1.6 for pp at $\sqrt{s} = 13\ TeV$.
- ➢ additional mechanisms such as collectivity, color reconnection, percolation, saturation physics etc. come to the play and are becoming prominent at higher center-of-mass energy.

# System and rapidity dependence



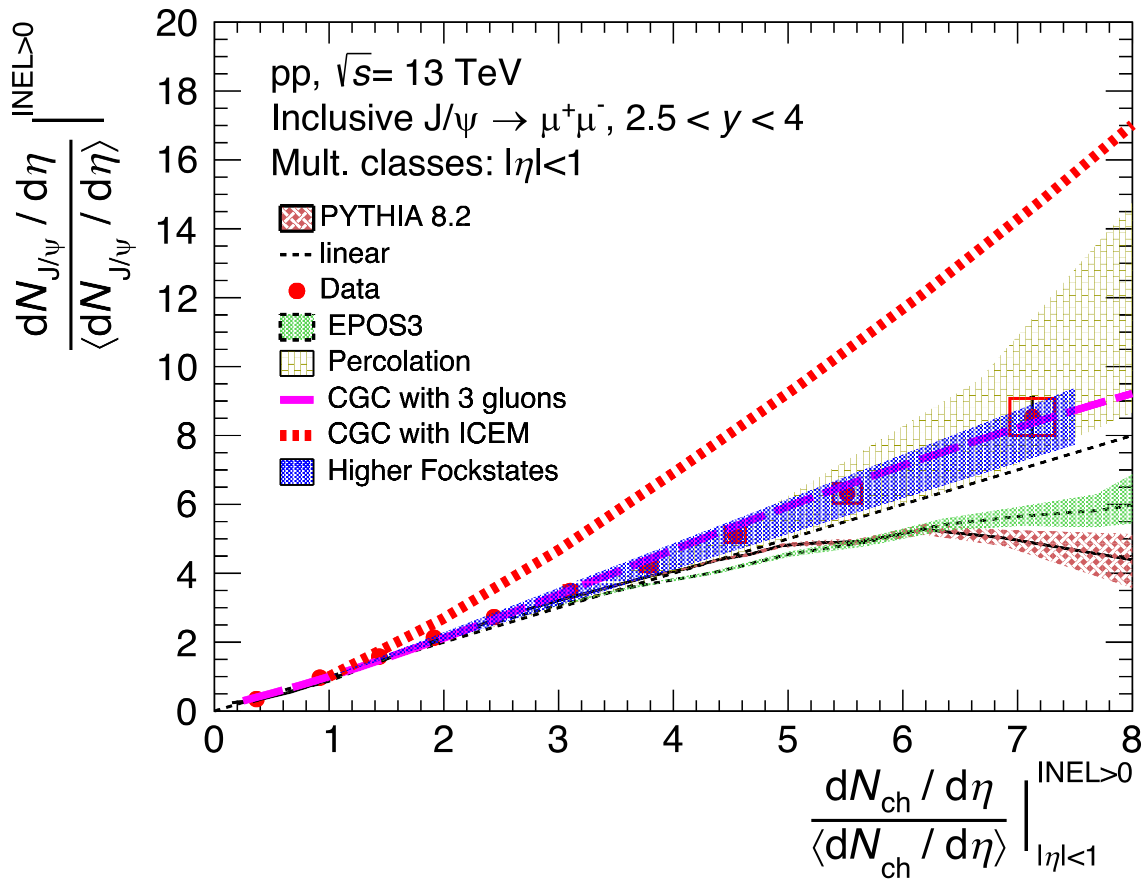

- At forward rapidity, approximately linear increase whereas the trend is faster than linear at the mid-rapidity, irrespective of the multiplicity estimator: different production dynamics




- Similar trend across collision system at the same rapidity.

- Event activities associated with the production of J/$\psi$ are independent of collision energy and colliding systems, but are largely dependent on rapidity

# Model comparison



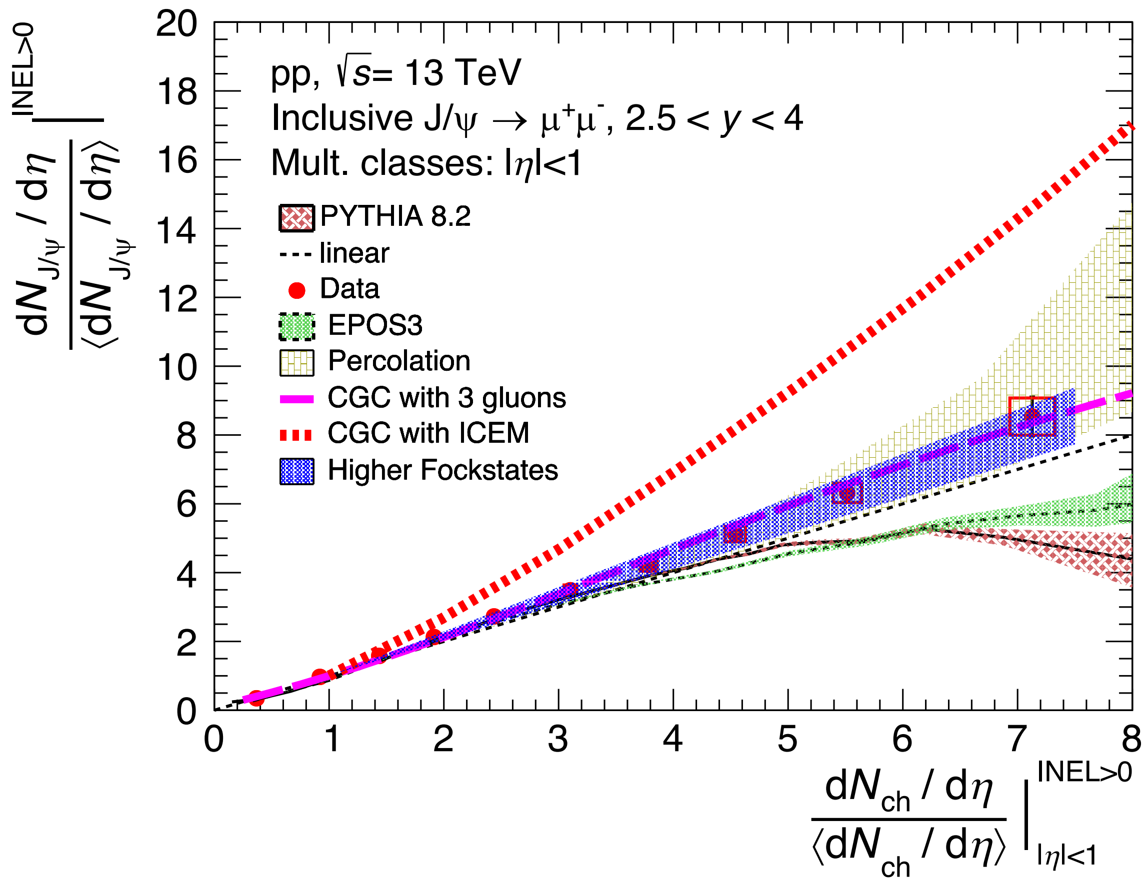

- Higher Fockstates :arXiv:1910.09682
- CGC+ICEM : Phys. Rev. D98, (2018)
- QCD with 3 gluons: arXiv:1910.13579
- Percolation: Phys.Rev. C86 (2012)
- EOPS3: Phys. Rev. C89, (2014)
- PYTHIA8: Comput. Phys. Commun. 191 (2015)

- PYTHIA8 includes MPI along with color reconnection, where the charm and bottom quarks can be involved in MPI 2→2 hard subprocesses is able to predict the linear increase

- EPOS3 includes parton-based Gribov-Regge formalism as initial conditions followed by the hydrodynamical expansion of the system

- Model with higher fock states: The production of $q\bar{q}$ by gluons is more involved, both the incoming gluon and produced $q\bar{q}$ interact with the target and screen each other. Correspondingly, charm quarks and charmonia are shadowed considerably compared to the light quarks

# Model comparison

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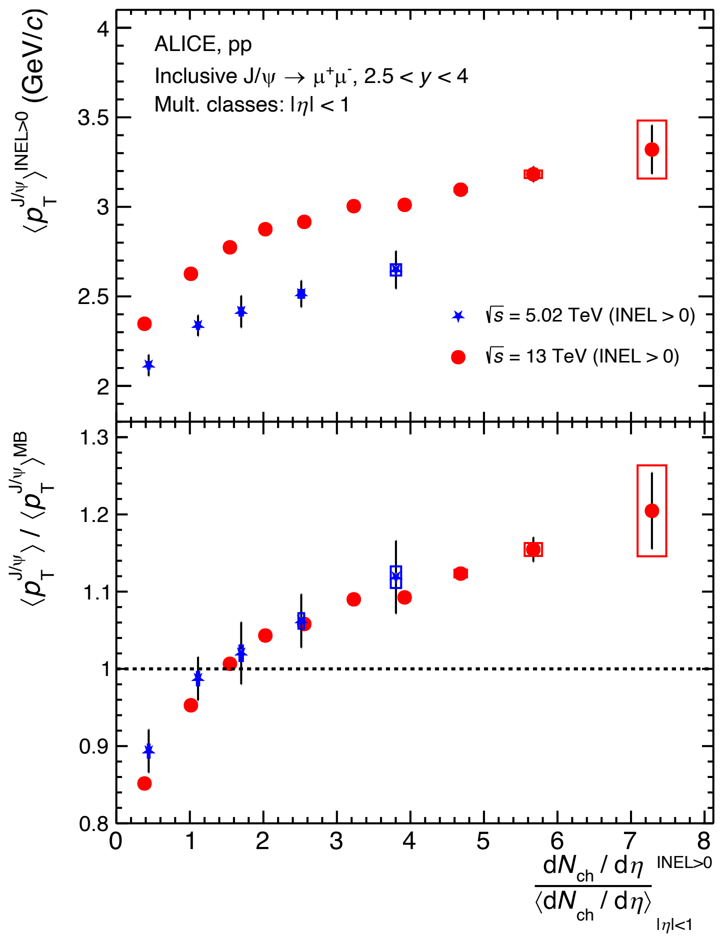
- PYTHIA8: Comput. Phys. Commun. 191 (2015)

➢ CGC+ICEM: Color Glass Condensate (CGC) approach, employing NRQCD framework. The dynamics of such configurations are controlled by semi-hard saturation scale Qs (x) in each of the colliding hadrons. The interplay between soft and hard mechanisms may change with change of energy, centrality (multiplicity) due to change of x.

➢ CGC with the 3-gluon fusion model assumes that the dominant contribution comes from gluon-gluon fusion, and the heavy quarks formed in the process might emit soft gluons in order to hadronize into D-mesons or form quarkonia states.

➢ Percolation model considers high-energy hadronic collisions as driven by the exchange of colour sources – strings, between the projectile and the target. The charged particle multiplicities can suffer a reduction due to the interaction among the sources.

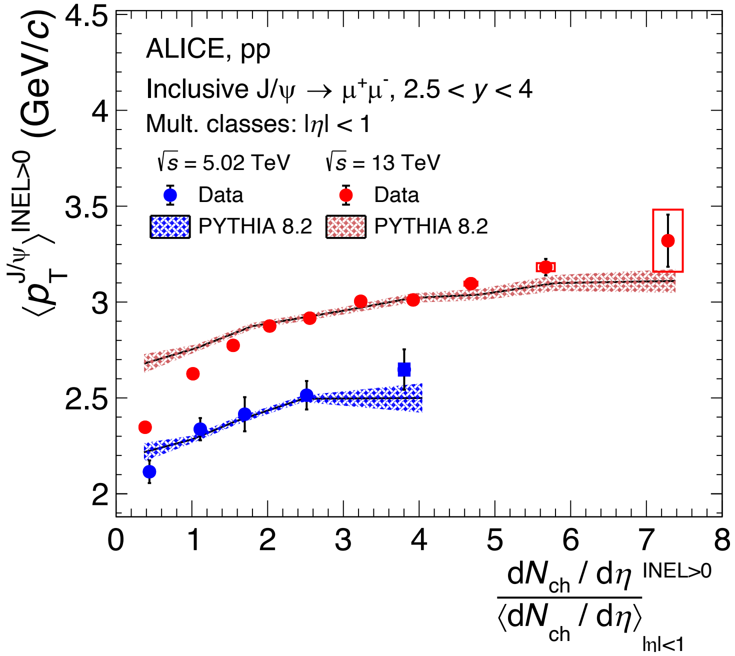
# $<p_T>$ of J/ψ vs. multiplicity




- An increase in $<p_T>$ of with multiplicity is observed with a moderate increase at high multiplicity

- In the MPI perspective: The high multiplicity events are produced by MPIs and the incoherent superposition of such interactions would lead to the saturation of the $<p_T>$ towards the higher multiplicity

- The relative $<p_T>$ of J/ψ is independent of center-of-mass energy.



# Neutral K* Vs. spherocity in pp-collisions at $\sqrt{s}$ = 5.02 and 13 TeV

Raghunath Sahoo
Rutuparna Rath

Status: Analysis ongoing

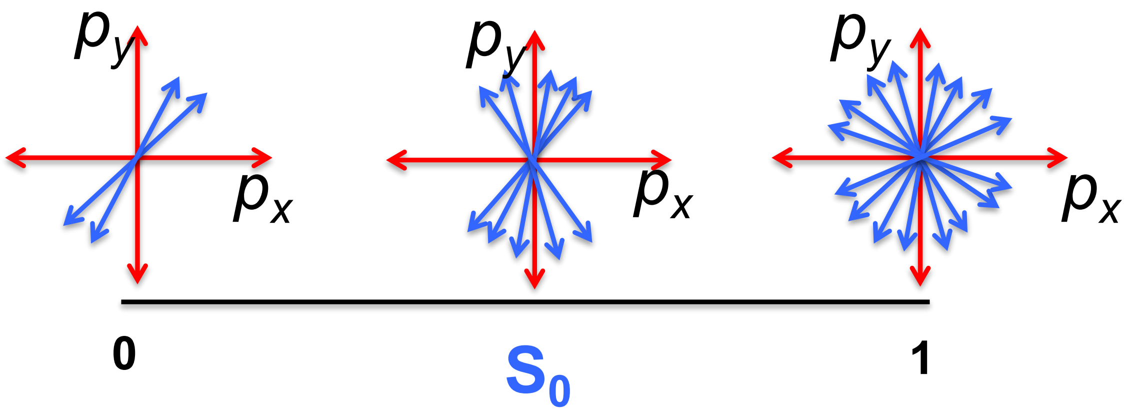
**Analysis Note:** https://alice-notes.web.cern.ch/node/947

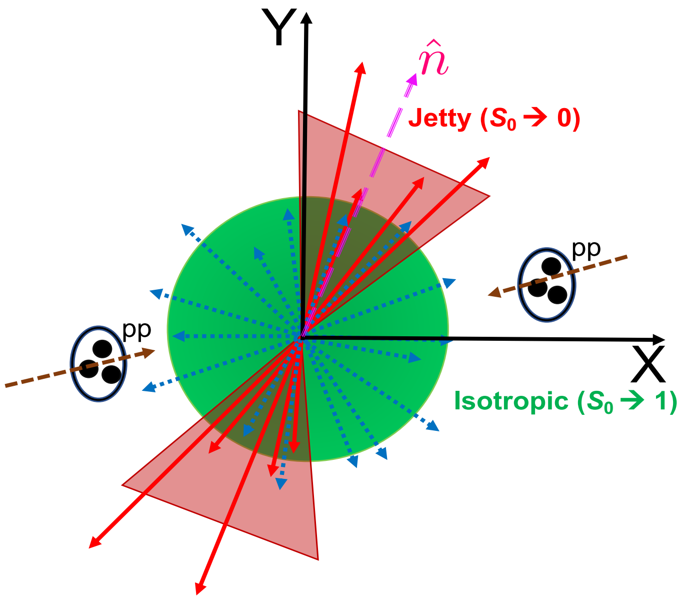
# Introduction

Event shapes are characterised using **transverse spherocity**

$$S_0^{p_{\rm T}=1} = \frac{\pi^2}{4}\left(\frac{\sum_i |\vec{p_{\rm T}}_i \times \hat{n}|}{\sum_i |\vec{p_{\rm T}}_i|}\right)^2$$

where $\hat{n}$ is a two-dimensional unit vector in the transverse plane, chosen in a way so that $\boldsymbol{S_0}$ is minimized.

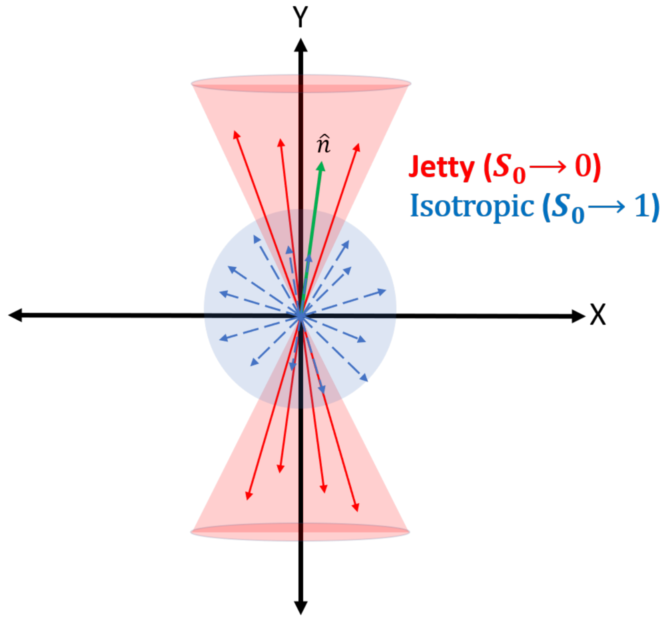


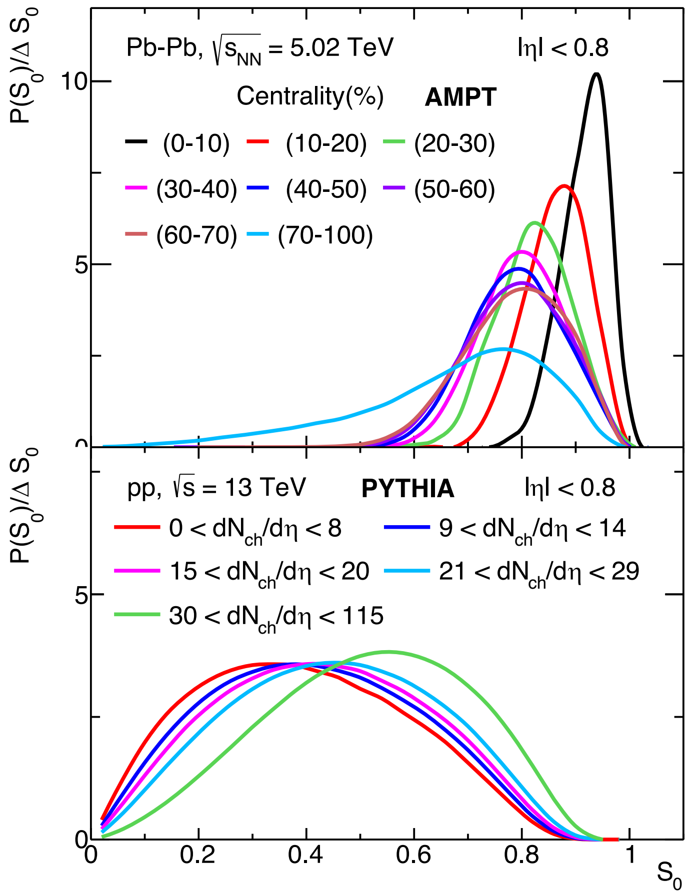

$S_0$ → 0 (jetty limit)
(Dominated by hard QCD processes)
$S_0$ → 1 (isotropic limit)
(Dominated by soft QCD processes)

# Event Topology in pp collisions@ LHC

**Transverse Spherocity:**




$$S_0 = \frac{\pi^2}{4}\left(\frac{\Sigma_i \; |\vec{p}_{T_i} \times \hat{n}|}{\Sigma_i \; p_{T_i}}\right)^2$$



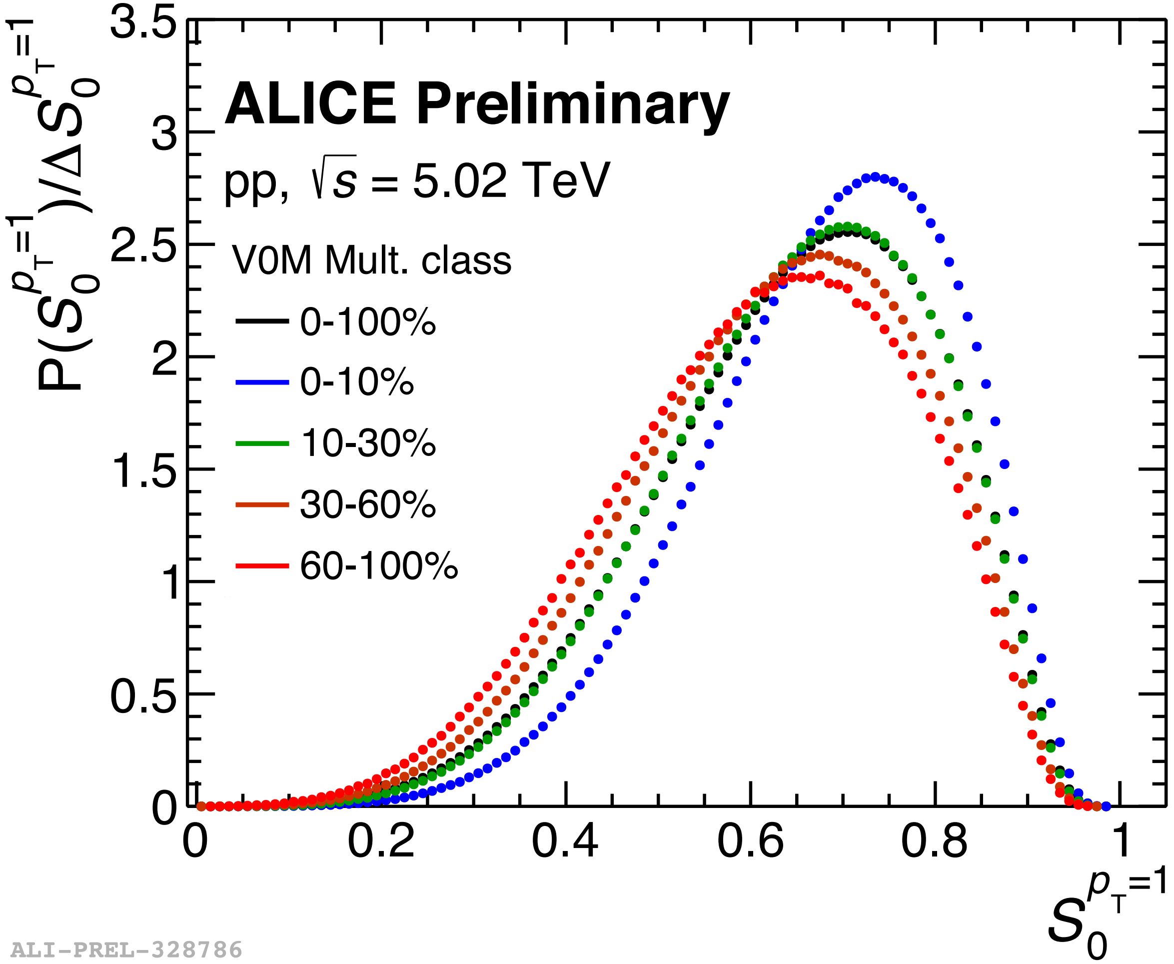

N. Mallick, R. Sahoo, S. Tripathy and A. Ortiz, J. Phys. G 48 (2021) 4, 045104, arXiv:2001.06849,
N. Malliick, S. Tripathy, A.N. Mishra and R. Sahoo, Phys. Rev. D 103 (2021) 094031

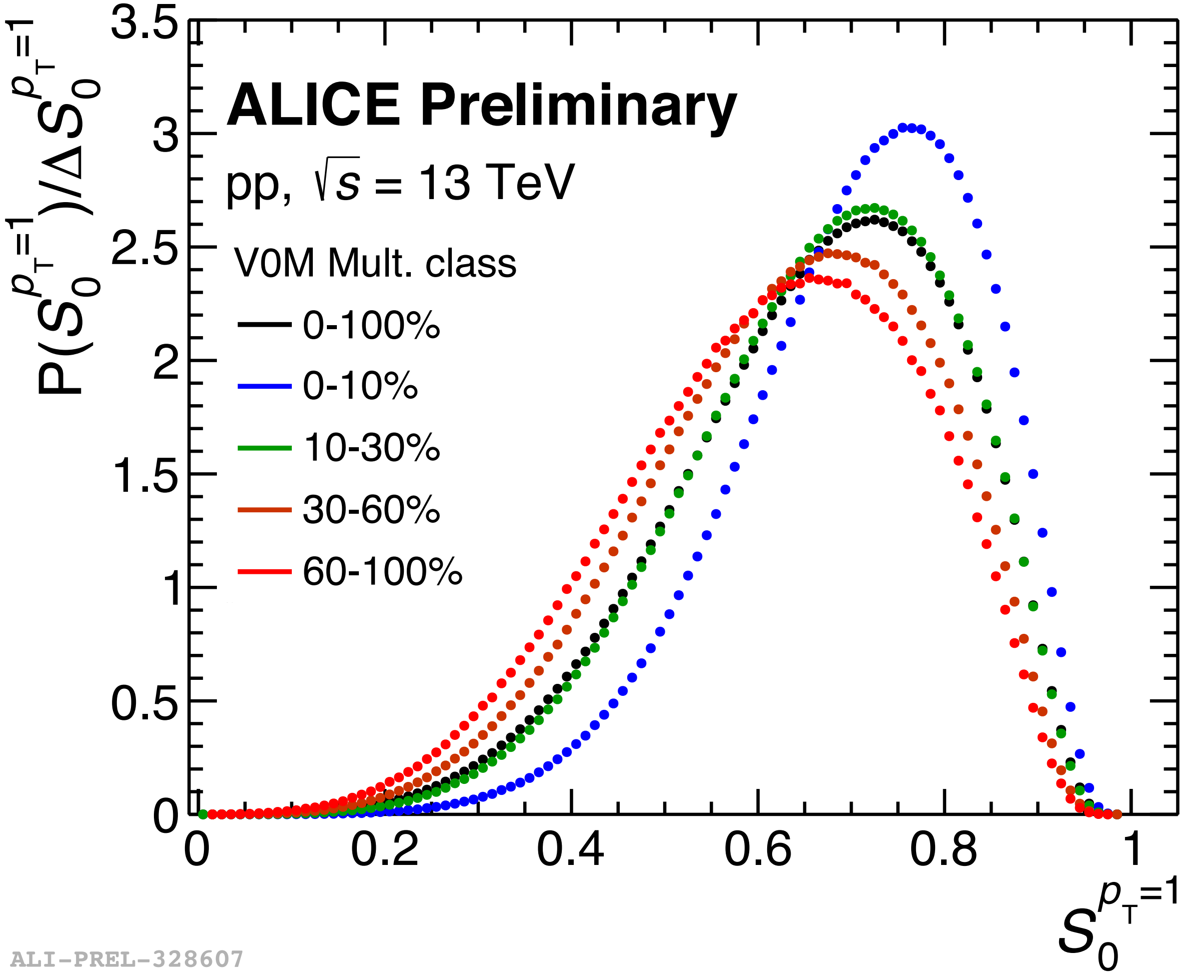
A. Khuntia, S. Tripathy, A. Bisht, and R. Sahoo, J. Phys. G: Nucl. and Part. Phys. 48, 035102 (2021)

R. Rath, A. Khuntia, R. Sahoo, and J. Cleymans, J. Phys. G: Nucl. and Part. Phys. 47, 055111 (2020)

A. Khatun, D. Thakur, S. Deb, and R. Sahoo, J. Phys. G: Nucl. and Part. Phys. 47, 055110 (2020)

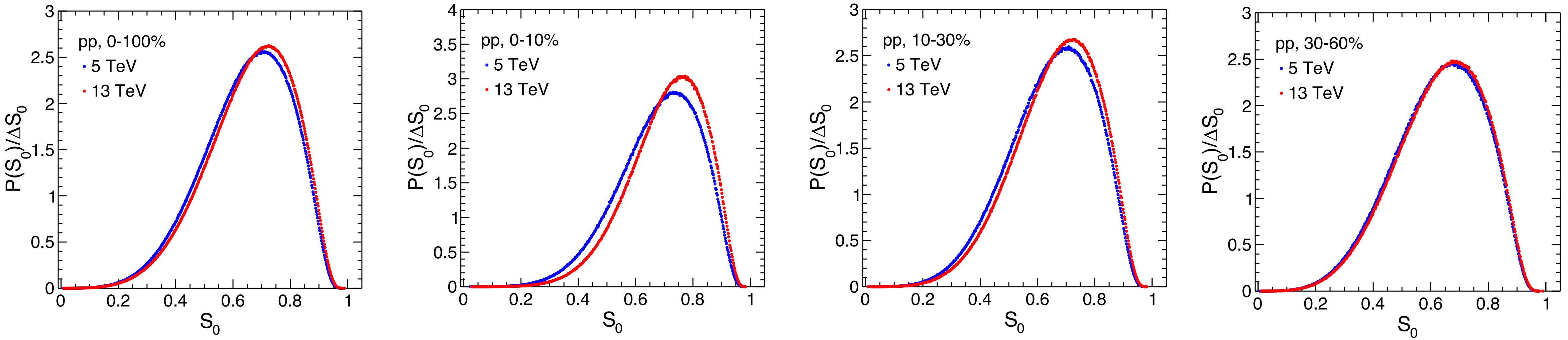
# Spherocity distribution



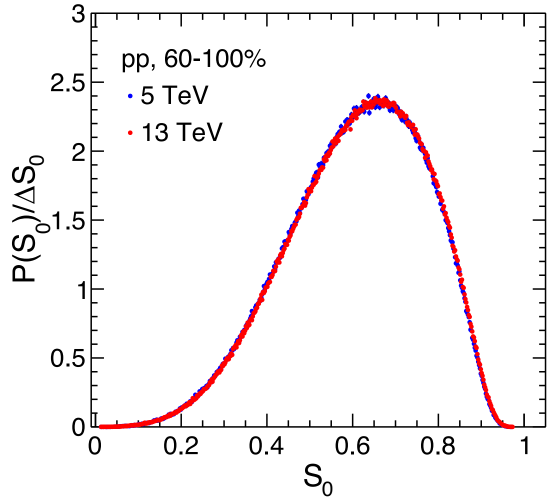




- **Dominance of isotropic events in high multiplicity pp collisions.**
- **Dominance of jetty events in low multiplicity pp collisions.**

# Spherocity Distribution (Energy dependence)

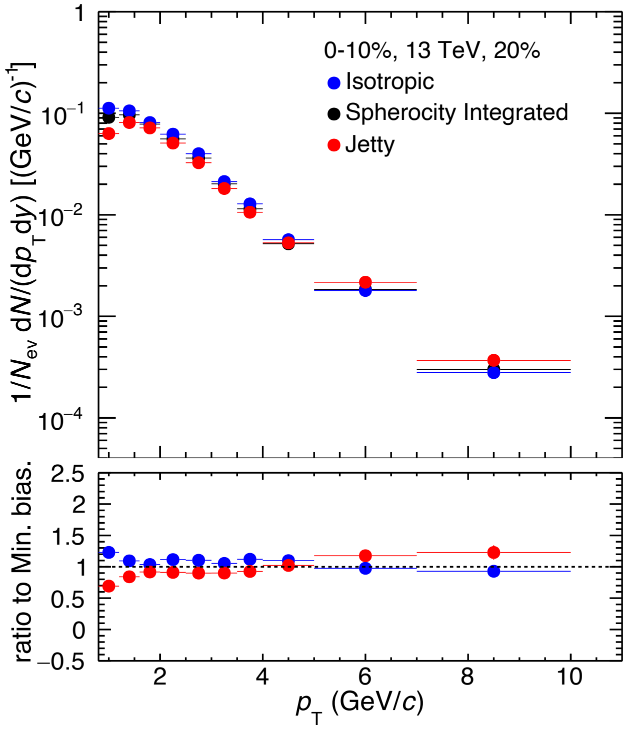



- ➢ Energy dependence of spherocity distribution is observed which is more prominent for higher multiplicity classes
- ➢ The system becomes more isotropic for higher collision energy

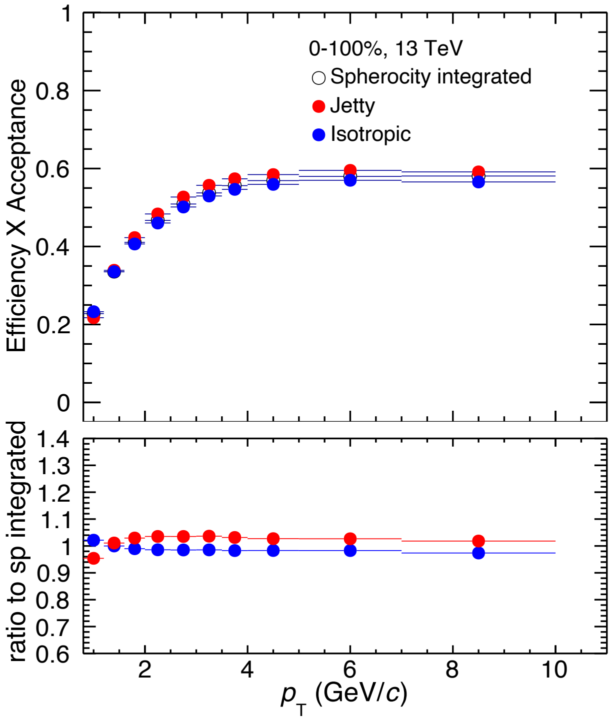


# Results: $p_T$ spectra (V0M I-III)

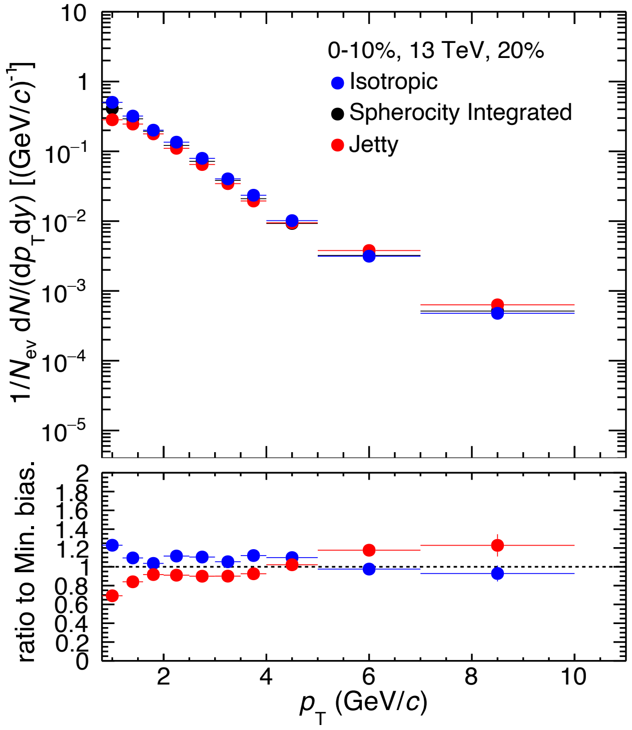
**Raw $p_T$ spectra**




**Efficiency X Acceptance**




**Corrected $p_T$ spectra**

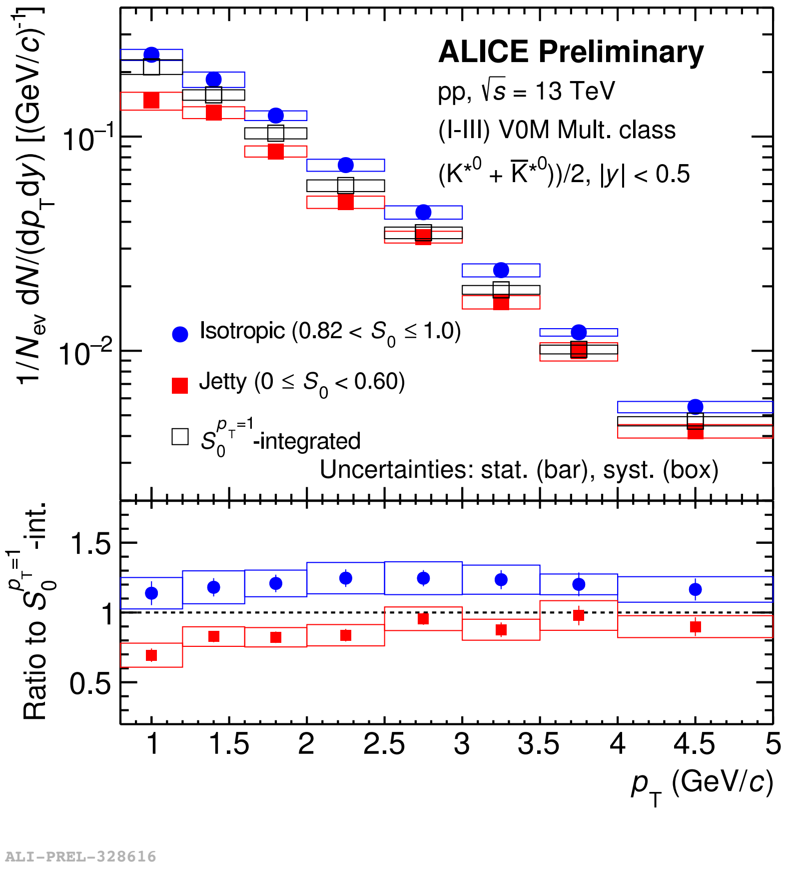



$$Efficiency\ X\ Acceptance = \frac{Reconstructed\ K^{*0}}{Generated\ K^{*0}}$$

- Isotropic and jetty events are chosen for top and bottom 20% of the spherocity distribution respectively
- Corrected $p_T$ spectra is obtained after correcting the raw $p_T$ spectra with efficiency X acceptance

**Similarly, results are also obtained for other multiplicity and finer spherocity bins**

# Transverse momentum spectra, yield and $\langle p_T \rangle$




| Spherocity class | dN/dy | $\langle p_T \rangle$ (GeV/c) |
|---|---|---|
| Isotropic | 0.8824 ±0.0263 ± 0.0604 | 1.3354 ± 0.0214 ± 0.0289 |
| $S_0$-integrated | 0.7647 ± 0.0087 ± 0.0522 | 1.2996 ± 0.0084 ± 0.0287 |
| Jetty | 0.5781 ± 0.0149 ± 0.0450 | 1.3938 ± 0.0196 ± 0.0376 |

- The integrated yield is the highest for isotropic events
- The mean transverse momentum is the highest for jetty events but consistent within systematic uncertainties

**Results with finer spherocity bins (10%, 1%) are ongoing.**

# Summary

- pp minimum bias: No signal of strangeness enhancement
- High-multiplicity pp becomes interesting with heavy-ion-like signatures
- pp@LHC is no longer going to be a baseline study for QCD medium formation in AA collisions
- Resonance production: access to FO dynamics and particle production
- Charmonia: rapidity depdnece production dynamics
- MPI+CR explains the charmonia production: Effect of Underlying events
- Requirement of differential studies: Multiplicity and event topology

IIT Indore- WRCP MoU will be a greate initiative of collaborative research in high-energy nuclear physics and beyond