



ALICE results  
on system-size dependence of  
charged-particle multiplicity density  
in p-Pb, Pb-Pb and Xe-Xe collisions



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# CHARGED-PARTICLE MULTIPLICITY DENSITY

- Study interplay between soft and hard QCD

## AA collisions

- Direct relation to the initial  $\epsilon$  of QGP<sup>1</sup>  
$$\epsilon = \frac{dE_T/dy}{\tau_0 \pi R^2} \approx \frac{3}{2} \langle m_T \rangle \frac{dN_{ch}/d\eta}{\tau_0 \pi R^2} > 1 \text{ GeV/fm}^3$$

## pp collisions

- Reference data for nuclear effect
- Study MPI in high  $N_{ch}$  collisions

## p–Pb collisions

- Discriminate between FSR in AA and ISR of nuclei themselves

- QGP-like effects even in pp and p–Pb collisions at LHC energies

proton (A=1) — p–Pb ————— Xe (A=129) ————— Pb (A=208)

- System size and  $\langle dN_{ch}/d\eta \rangle \rightarrow$  starting of the story

<sup>1</sup>See the discussion: system-size dependence of  $\langle dN_{ch}/d\eta \rangle$  at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  at QM 2017 by Christian Holm Christensen

# A LARGE ION COLLIDER EXPERIMENT

## V0 (Scintillator hodoscopes)

- triggers forward activity
- $-3.7 < \eta < -1.7, 2.8 < \eta < 5.1$

## SPD (Silicon Pixel Detector)

- Two-layer silicon detector
- counting tracklets at mid rapidity
- $-2 < \eta < 2$

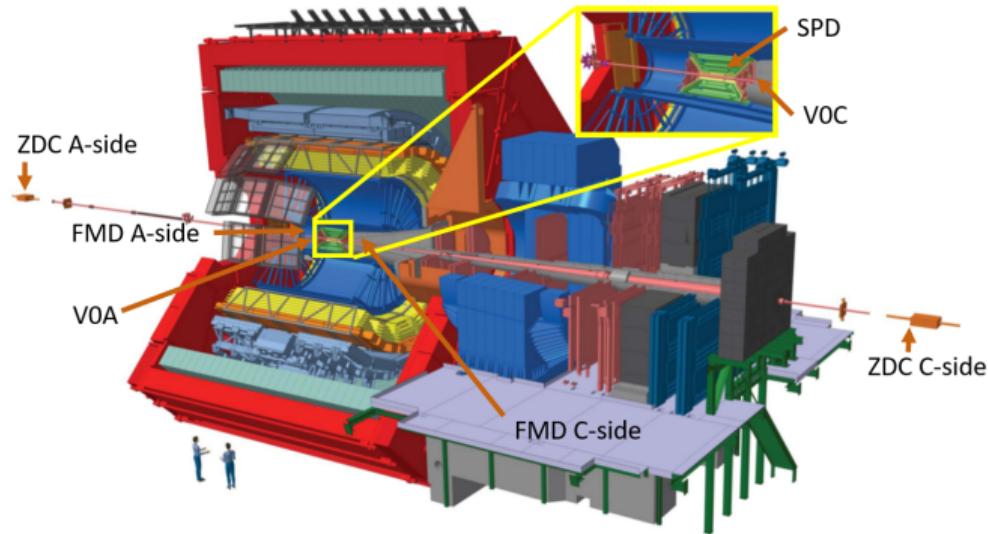
## FMD (Forward Mult. Detector)

- three sets of Si strip sensors
- counting  $N_{\text{ch}}$  at forward rapidity
- $-3.7 < \eta < -1.7, 1.7 < \eta < 5.1$

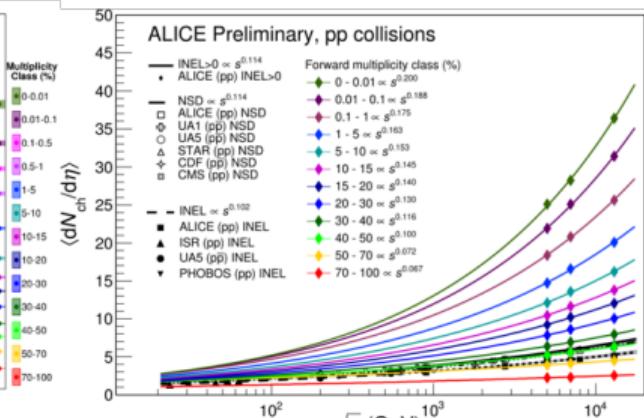
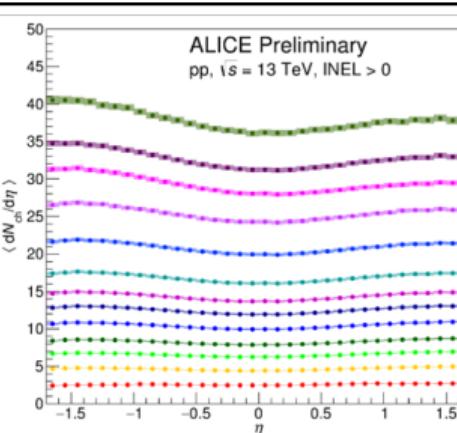
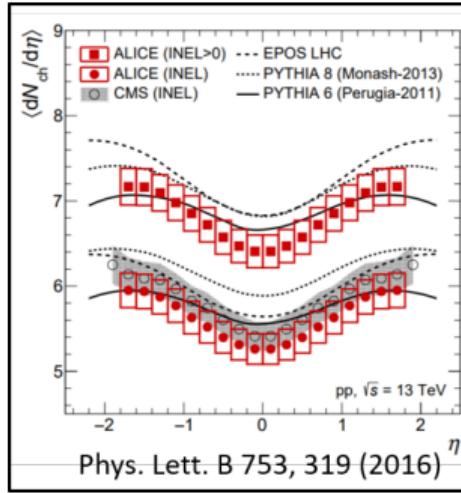
## ZDC (Zero Degree Calorimeter)

- measuring  $E$  of spectator nucleons
- $\eta \sim \pm 10$

► 18 detectors, sensitivity at low  $p_T$ , excellent PID



# $\langle dN_{ch}/d\eta \rangle$ IN pp COLLISIONS

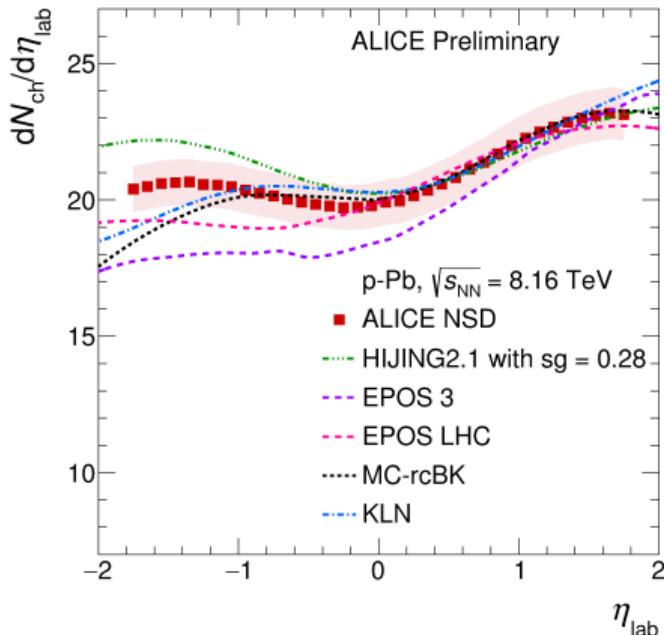


- Inclusive study : INEL  $\propto s^{0.102}$ , NSD  $\propto s^{0.114}$  and INEL<sub>>0</sub><sup>1</sup>  $\propto s^{0.114}$
- Multiplicity dependence study<sup>2</sup>
  - $\langle dN_{ch}/d\eta \rangle$  for different multiplicity classes
  - The evolution of  $\langle dN_{ch}/d\eta \rangle$  with  $\sqrt{s}$  : steeper for higher multiplicity class (MPI)

<sup>1</sup>INEL requiring at least one charged particle in  $|\eta| = 1$

<sup>2</sup>"Multiplicity dependence study of the  $\eta$ -density distribution of charged particles in pp collisions with ALICE" by Prabhakar Palni

# $\langle dN_{\text{ch}}/d\eta \rangle$ IN p – Pb COLLISIONS



ALI-PREL-129135

All models lie within 15% of data

HIJING (Phys. Rev. C86 (2012) 051901)

- strong  $b$  dependence of parton shadowing
- combines pQCD and soft QCD
- reproduces magnitude and shape for Pb-going side

EPOS LHC (Phys. Rev. C92 (2015) 034906)

- collective effects like flow included
- reproduces Pb-going side

EPOS 3 (Phys. Rev. C89 (2014) 064903)

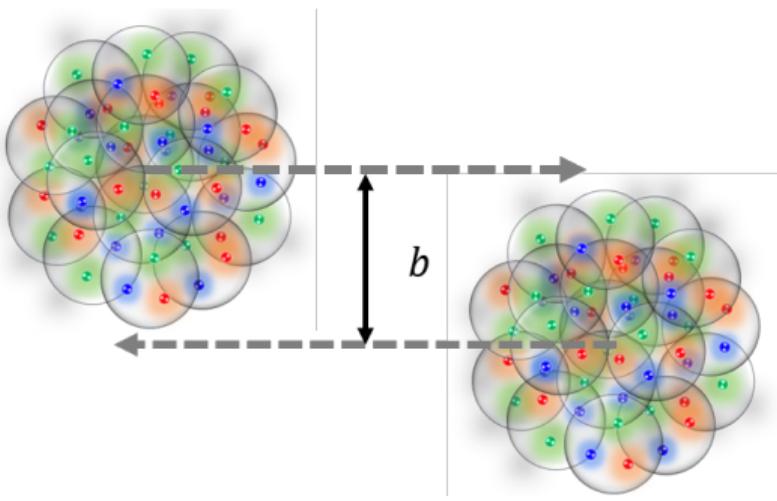
- includes a full viscous hydrodynamical simulation
- only the most forward part in the Pb-going side

rc-BK (Nucl. Phys. A897 (2013) 1-27)

KLN (Phys. Rev. C85 (2012) 044920)

- saturation based models
- perform better in  $\eta_{\text{lab}} > -1.3$

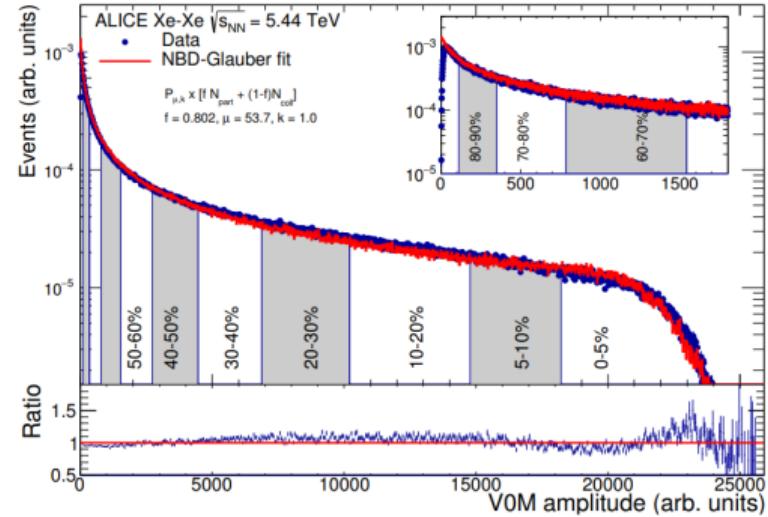
# CENTRALITY ESTIMATION



Impact parameter ( $b$ )

- The degree of geometrical overlap
- Centrality : fraction of geometrical cross-section
- $N_{\text{part}}, N_{\text{coll}}$

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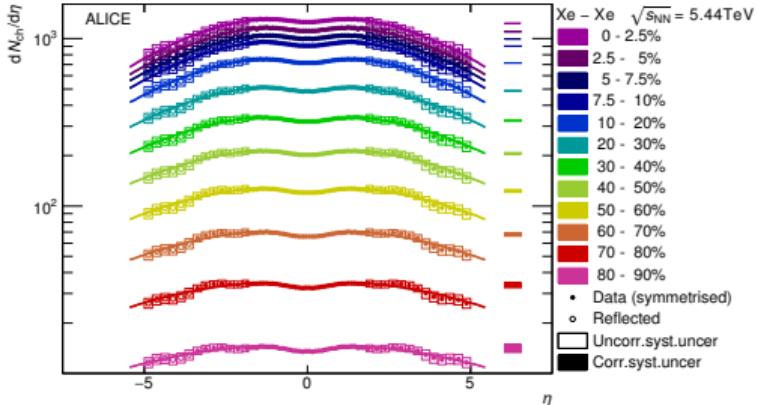


Centrality estimation for Xe-Xe

- Deformation of the nuclear density considered
- Multiplicity with the V0 detector
- NBD Glauber fit coupled to a two component model

# $\langle dN_{\text{ch}}/d\eta \rangle$ AND $N_{\text{ch}}^{\text{tot}}$ IN Pb – Pb AND Xe – Xe COLLISIONS

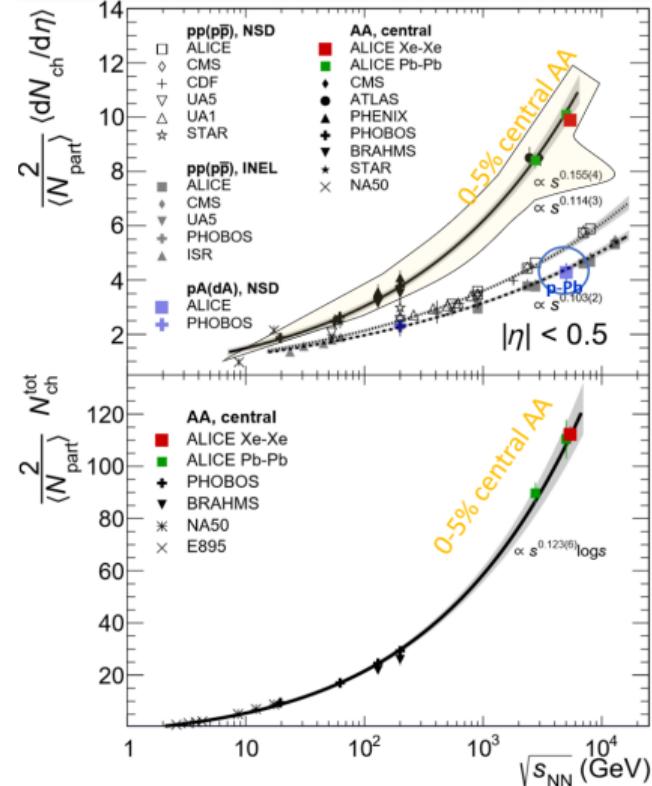
arXiv:1805.04432



$$\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}}/d\eta \rangle \text{ and } \frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}}$$

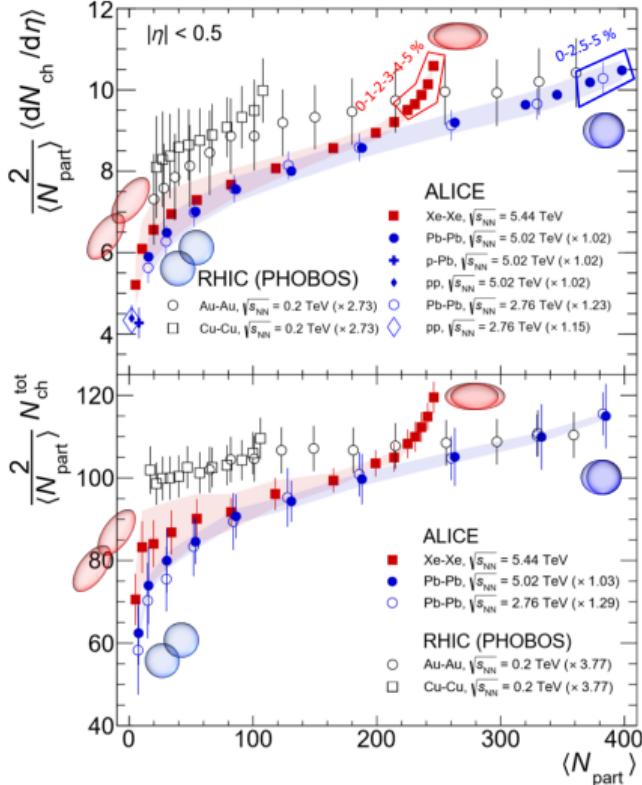
- for the most 5% central collisions
- Xe–Xe result is in agreement with the trend
- A stronger rise w.r.t  $\sqrt{s_{\text{NN}}}$  than for pp
- At  $|\eta| < 0.5$  p–Pb fits with INEL pp points

arXiv:1805.04432



# $\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}} / d\eta \rangle$ AND $\frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}}$ AS A FUNCTION OF $\langle N_{\text{part}} \rangle$

arXiv:1805.04432

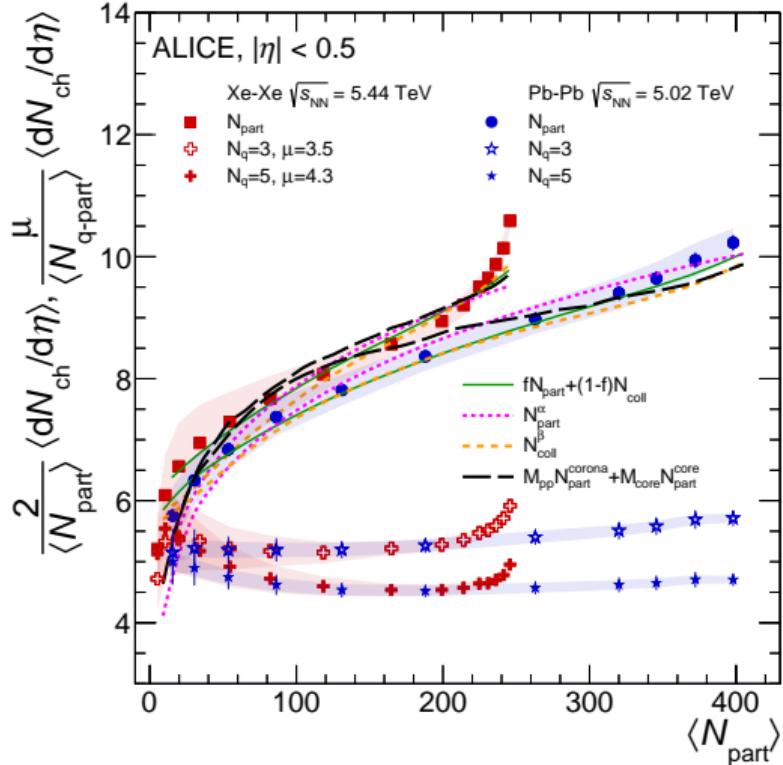


Data are scaled to  $\sqrt{s}$ ,  $\sqrt{s_{\text{NN}}} = 5.44 \text{ TeV}$  (prev.) to match with Xe–Xe results.

- ALICE data decreasing by 2 from the most central to the peripheral
- smoothly connect to pp and p–Pb
- Xe–Xe shapes exceed Pb–Pb at similar  $\langle N_{\text{part}} \rangle$  for the top 10 % central collisions
- RHIC data show hint of same behaviour

# SCALING OF $\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}} / d\eta \rangle$

arXiv:1805.04432



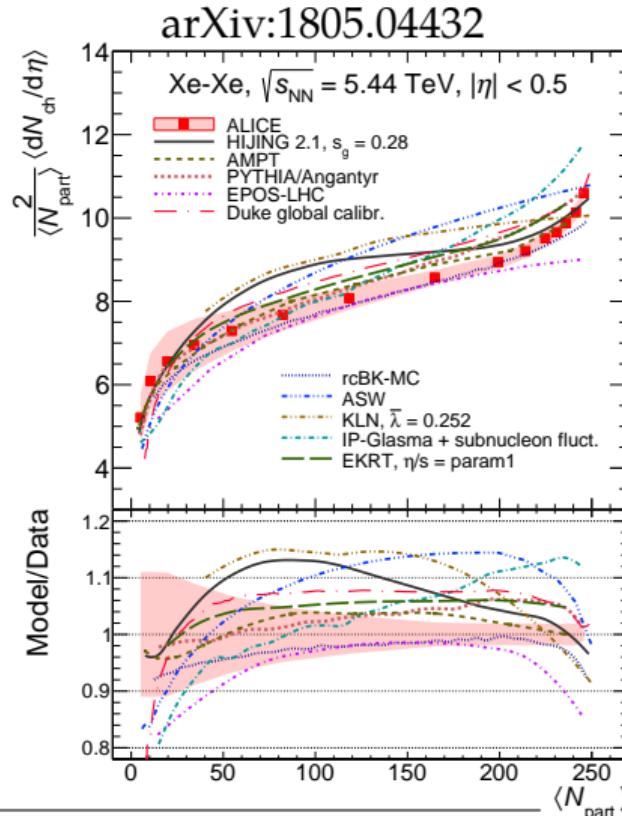
Different scalings for particle production

1. Power law function
2. Two component model
3. Core and corona model  
(Phys. Rev. Lett. 98 (2007) 152301))
4. Quark-Glauber parametrisation

(Phys. Rev. C67 (2003) 064905 , Phys. Rev. C94 no. 2, (2016) 024914)

- ▶ using wounded constituent quarks
- ▶  $N_q = 3$  and  $5$
- ▶ A scaling violation for the 0–5% centrality range in Xe–Xe collisions (0-1-2-3-4-5% binning)

# $\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}} / d\eta \rangle$ AND MODELS IN Xe – Xe COLLISIONS



AMPT (Phys. Rev. C72 (2005) 064901)

- initial state by HIJING
- and then hydrodynamical evolution

PYTHIA/Angantyr (JHEP 10 (2016) 139)

- performing each nucleon-pair (parton level)
- Lund strings hadronised as an ensemble

Duke global (Phys. Rev. C92 no. 1, (2015) 011901)

- viscous hydrodynamics coupled to a hadronic cascade model

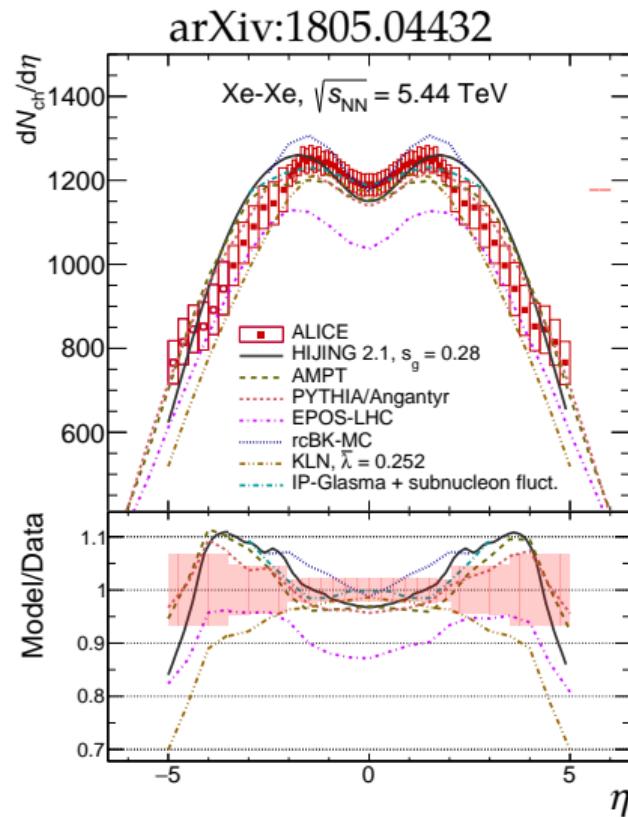
rc-BK, KLN, ASW<sup>1</sup>, IP-Glasma<sup>2</sup> and EKRT<sup>3</sup>

- saturation-inspired models to limit  $N_{\text{parton}}$

All models describe data within  $\pm 20\%$

<sup>1</sup>1. Phys. Rev. Lett. 94 (2005) 022002, 2. Phys. Rev. Lett. 108 (2012) 252301, 3. Phys. Rev. C97 no. 3, (2018) 034911

# $dN_{\text{ch}}/d\eta$ vs $\eta$ AND MODELS FOR 0–5% CENTRAL Xe–Xe COLLISIONS



## HIJING

Good match in mid, overestimate at forward  $\eta$   
(due to large value of  $s_g$ )

## AMPT and PYTHIA/Angantyr

fairly good, slight overestimate at forward  $\eta$

## EPOS LHC

underestimate data overall

rcBK-MC: overall overestimation

KLN: matches in mid  $\eta$ , not true for forward  $\eta$

IP-Glasma: wider than data

# SUMMARY

Charged-particle multiplicity density studies on various collision systems and energies in centre of mass

## pp and p–Pb collisions

- ▶ Compared to various theoretical models: for p–Pb better agreement with saturation based models
- ▶  $|\eta| < 0.5 \langle dN_{\text{ch}}/d\eta \rangle$  ( $|\eta| < 0.5$ ) in p–Pb fits with INEL pp points

## Pb–Pb and Xe–Xe collisions

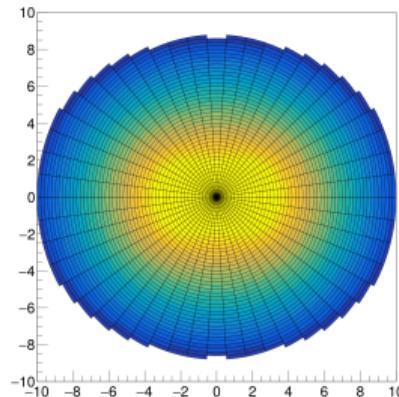
- ▶ The high statistics distributions are useful to constrain the available models
- ▶  $\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}}/d\eta \rangle$  and  $\frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}}$  for the top 5% central Xe–Xe collisions in agreement with the previous AA power-law trend
- ▶ steep rise of  $\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}}/d\eta \rangle$  and  $\frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}}$ , and  $N_{\text{part}}$ -scaling violation for the 0–5% central Xe–Xe

# Backup

► Xe ion (deformed)

$$\rho(r, \vartheta) = \rho_0 \frac{1}{1 + \exp\left(\frac{r-R(\vartheta)}{a}\right)}$$

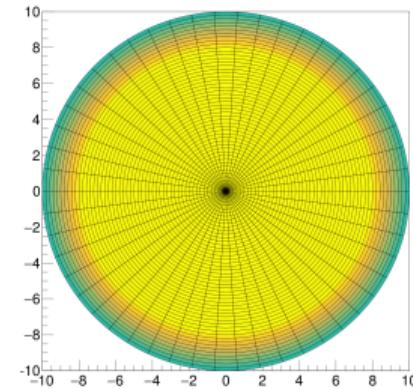
- $\rho_0$  : the nucleon density
- The nuclear skin thickness  $a = 0.59 \pm 0.07 \text{ fm}^1$
- Nuclear radius  $R(\vartheta) = R_0[1 + \beta_2 Y_{20}(\vartheta)]$



► Pb ion (spherical)

$$\rho(r, \vartheta) = \rho_0 \frac{1}{1 + \exp\left(\frac{r-R}{a}\right)}$$

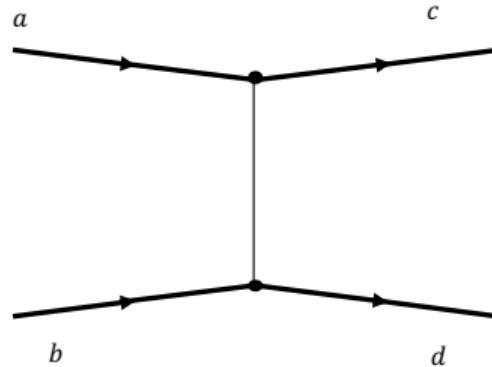
- $\rho_0$  : the nucleon density
- The nuclear skin thickness  $a = 0.546 \pm 0.01 \text{ fm}$
- Nuclear radius  $R = 6.62 \pm 0.06 \text{ fm}$



<sup>1</sup>Phys. Rev. Lett. 118 no. 26, (2017) 262501

# DIFFRACTION

When the squared momentum transfer is much less than  $\sqrt{s}$



$$t = (p_a - p_c)^2 \ll \sqrt{s}$$

- ▶ Help us understand QCD in the non-perturbative regime  
( $t \sim 0$  or  $q^2 < \Lambda_{\text{QCD}}^2$ )
- ▶ By Regge theory <sup>1 2 3</sup>, diffraction proceeds via the exchange of Pomerons  
( $gg_{\text{leading order}} + ggg_{\text{next leading order}} + \dots$ )

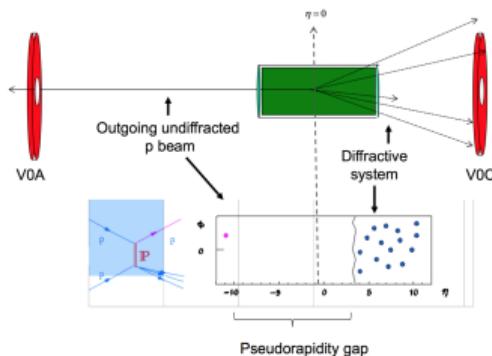
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<sup>1</sup>P.D.B.Collins,An Introduction to Regge Theory and High Energy Physics, Cambridge, 1977

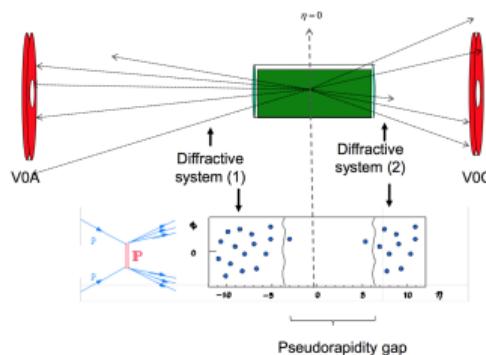
<sup>2</sup>A.B.Kaidalov,Phys.Rep.50,157,1979

<sup>3</sup>V. Barone, E. Predazzi, High-Energy Particle Diffraction ,Springer, Berlin, 200

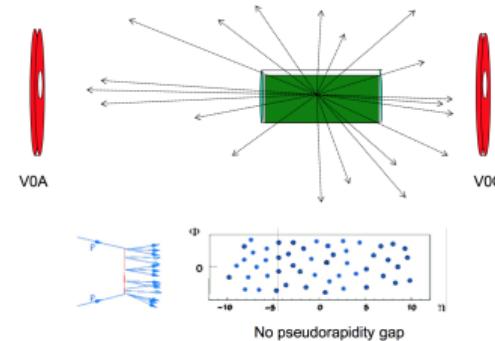
# SD, DD AND ND



SD

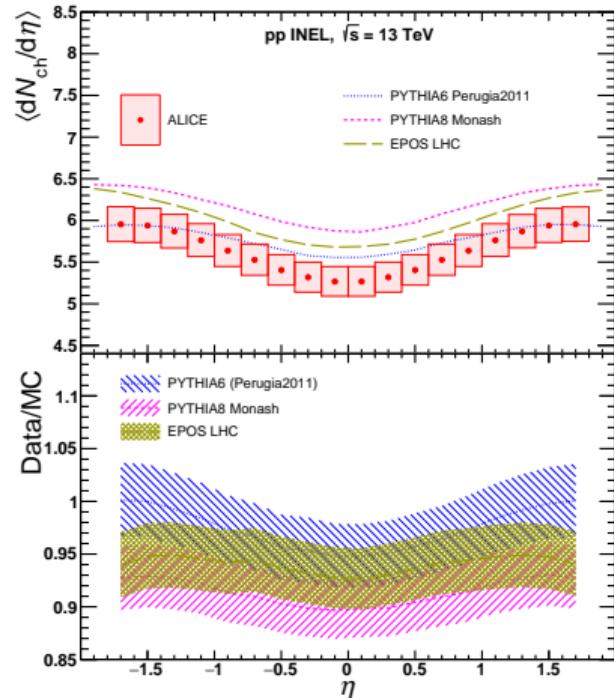
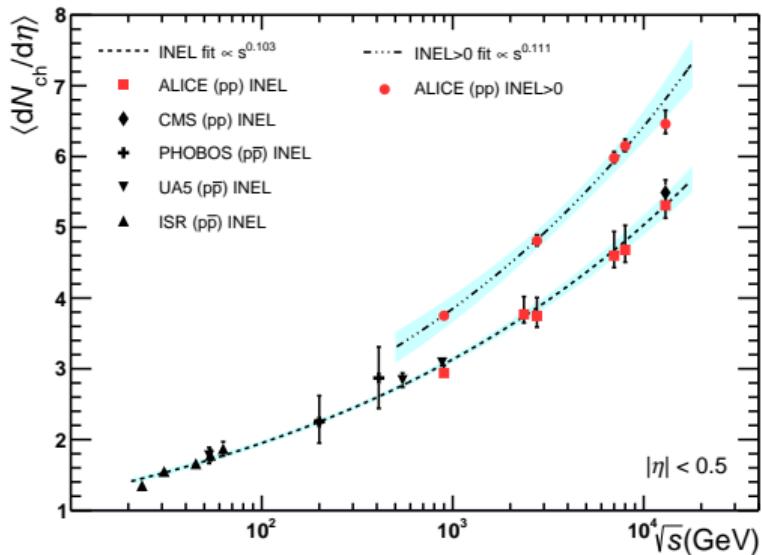


DD



ND

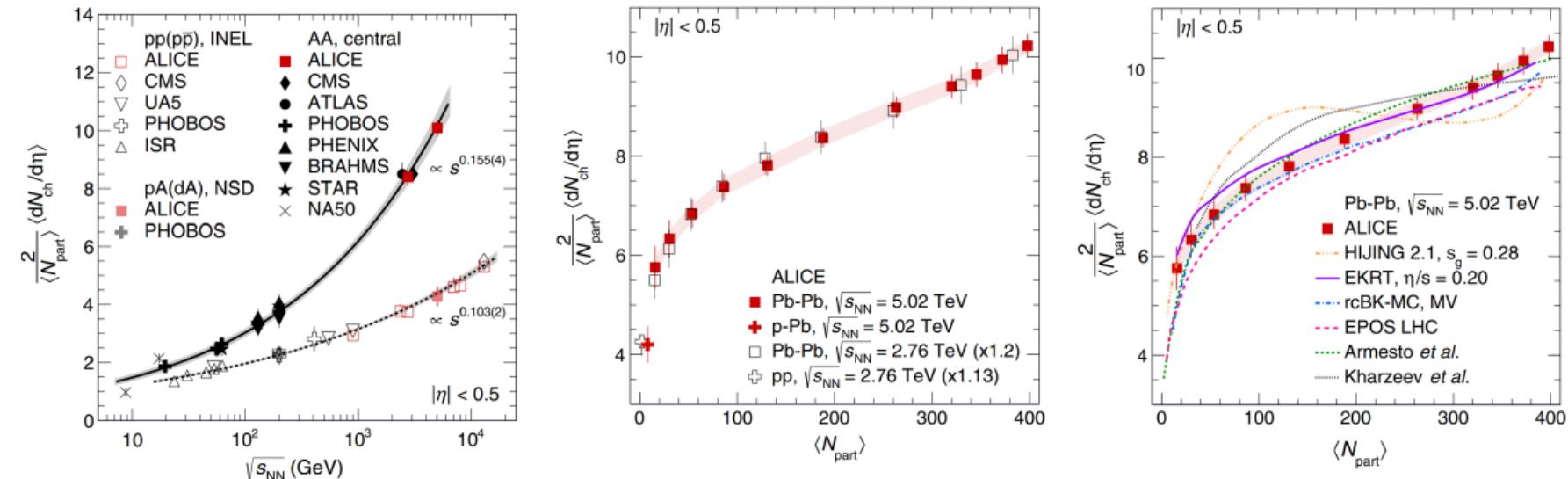
# $N_{\text{ch}}$ IN pp COLLISIONS



$$\text{INEL} \propto s^{0.103}$$

$$\text{INEL}_{>0} \propto s^{0.111}$$

# $N_{\text{ch}}$ IN Xe – Xe COLLISIONS



- ▶ HIJING using gluon shadowing parameter  $s_g = 0.28$
- ▶ EPOS based on Gribov-Regge theory incorporated with collected effect
- ▶ Saturation-inspired models : rcBK-MC, Armesto, Kharzeev and EKRT

# $N_{\text{ch}}$ IN pp COLLISIONS

- Published multiplicity papers

Type	$\sqrt{s}$ (TeV)	paper
pp	0.9, 2.76, 7 and 8 13	Eur. Phys. J. C 77 (2017) 33 Phys. Lett. B 753 (2016) 319-329

- Reference data to study nuclear effect
  - in nucleus–nucleus
  - in proton–nucleus collisions
- Big contribution from non-perturbative QCD processes
  - INEL<sup>1</sup> : ND + SD + DD + CD ...
  - NSD : ND + DD (to ignore large uncertainty from SD)
  - INEL<sub>>0</sub> : INEL + at least one activity in  $|\eta| = 1$   
(effective filter for SD and DD events)

<sup>1</sup>INEL = ND( $\sim 70\%$ ) + SD ( $\sim 20\%$ ) + DD ( $\sim 10\%$ ) + CD ( $< 1\%$ ) arXiv:1208.4968

# $N_{\text{ch}}$ IN p – Pb COLLISIONS

- ▶ Published (ongoing) multiplicity papers

Type	$\sqrt{s_{\text{NN}}}$ (TeV)	paper
p-Pb	5.02	PRL 110 (2013) 032301
	8.16	preliminary

- ▶ Valuable tool to discriminate between
  - ▶ final state effects in nucleus–nucleus
  - ▶ initial state effect of nuclei themselves
- ▶  $N_{\text{ch}}$ 
  - ▶ Discriminate the initial and final state effects
  - ▶ A tool to study the various models of gluon saturation<sup>1</sup>
  - ▶ Providing constraints to the initial state and small Bjorken- $x$  modeling

<sup>1</sup>Different descriptions of the upper limit in growth of the parton density

# $\langle dN_{\text{ch}} d\eta \rangle$ IN Pb – Pb AND Xe – Xe COLLISIONS

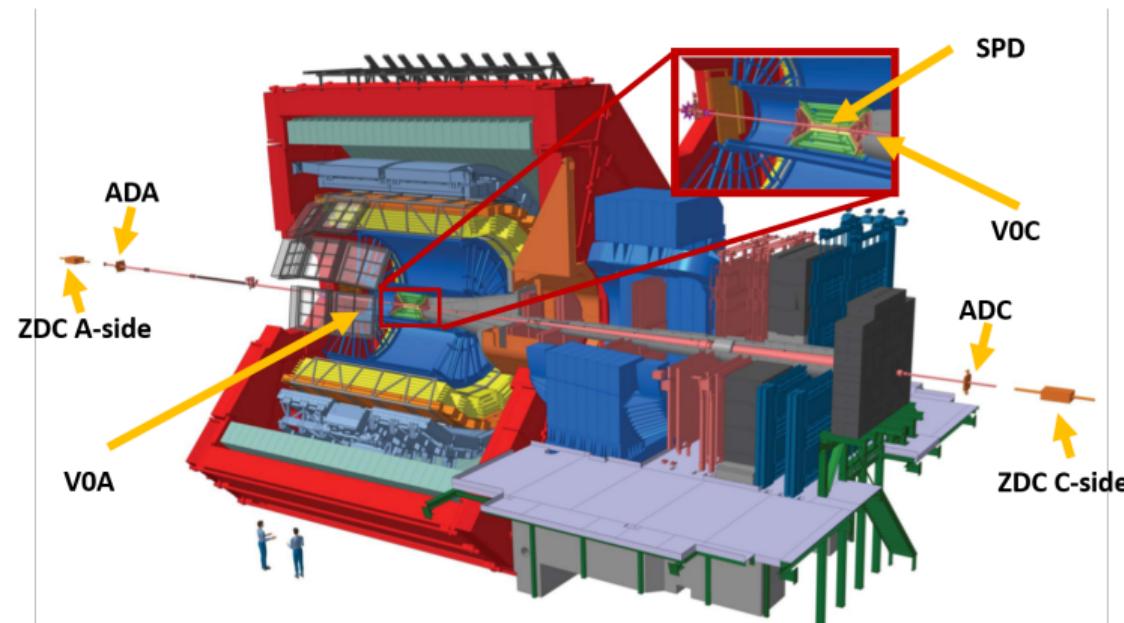
- Published (and ongoing) multiplicity papers

Type	$\sqrt{s_{\text{NN}}}$ (TeV)	paper
Pb-Pb	2.76	Phys. Rev. Lett. 106, (2011) 032301
	5.02	Phys. Rev. Lett. 116 (2016) 222302
Xe-Xe	5.44	

- $N_{\text{ch}}$  : A key observable in the QGP (initial energy density)
- Impact parameter ( $b$ ): The degree of geometrical overlap
- Centrality : Experimental proxy of  $b$
- $N_{\text{part}}$  : the number of nucleons participating in the collision
- $N_{\text{coll}}$  : the number of binary nucleon-nucleon collisions among the participant nucleons

# A LARGE ION COLLIDER EXPERIMENT

- 17 different detectors, Low  $p_T$  sensitivity, excellent PID



## Trigger detectors

	$\eta_{\min}/\eta_{\max}$	
A side		C side
SPD	-2/2	
V0	2.8/5.1	-3.7/-1.7
AD	4.8/6.3	-7/-4.9
ZDC	$\sim \pm 10$	

SPD (Silicon Pixel Detector)

- Innermost two-layer silicon detector
- $r = 3.9, 7.6$  cm
- Triggers central activity

V0 (Scintillator hodoscopes)

- Triggers forward activity
- $z = -0.9, 3.3$  m

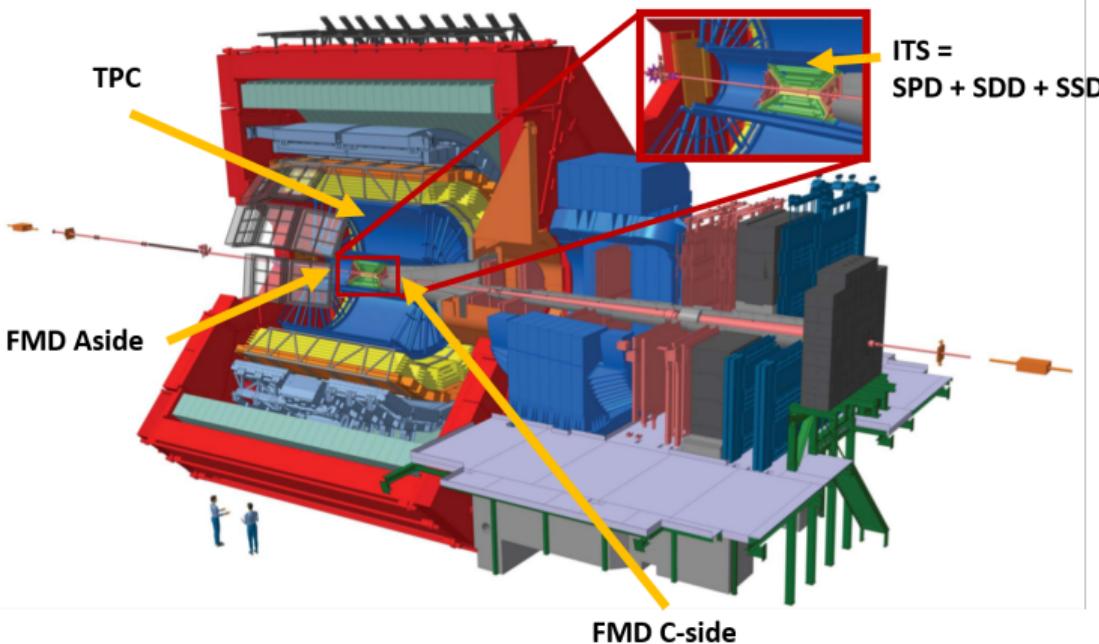
AD (Alice Diffraction)

- Scintillation counters
- $z = -19.5, 17$  m

ZDC :

# A LARGE ION COLLIDER EXPERIMENT

- ▶ 17 different detectors, Low  $p_T$  sensitivity, excellent PID



## Data taking detectors

	$\eta_{\min} / \eta_{\max}$	
	A side	C side
ITS	-1.4/1.4	
TPC	-0.9/0.9	
FMD	1.7/5.1	-3.4/-1.7

### ITS (Inner Tracking System)

- ▶ 6 layers of Si detectors
- ▶ Containing SPD

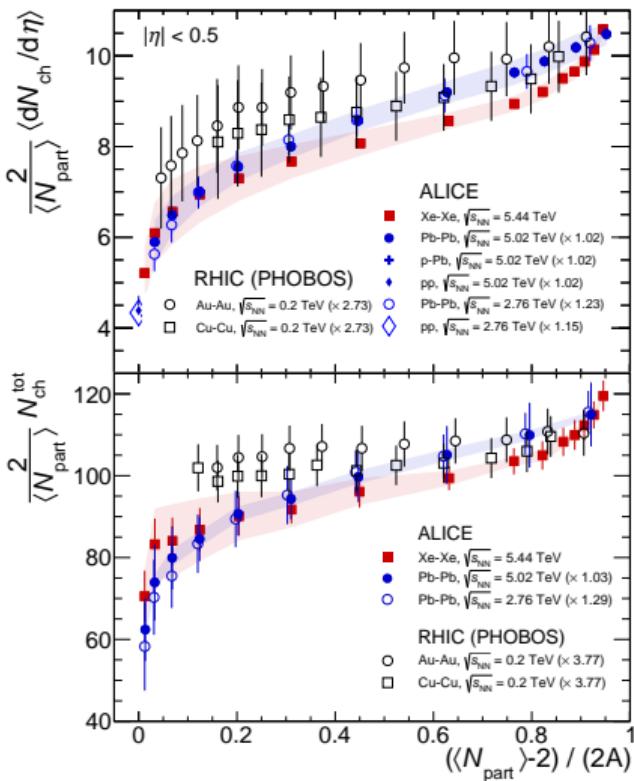
### TPC (Time Projection Chamber)

- ▶ Large cylindrical detector
- ▶  $-250 < z < 250$  cm
- ▶  $86 < r < 250$  cm
- ▶ 558 k readout channels

### FMD (Forward Multiplicity Detector)

- ▶ Two sets of Si strip sensors
- ▶ close to V0 detectors

# $\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}} / d\eta \rangle$ AND $\frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}}$ AS A FUNCTION OF CENTRALITY



Data are scaled to  $\sqrt{s}$ ,  $\sqrt{s_{\text{NN}}} = 5.44 \text{ TeV}$  (prev.) to match with Xe–Xe results.

- ▶ ALICE data decreasing by 2 from the most central to the peripheral
- ▶ smoothly connect to pp and p–Pb