

Soft QCD measurements with ALICE



ALICE

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For the ALICE Collaboration



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SOFT QCD IN PP COLLISIONS

At LHC energy → more contributions from hard-processes

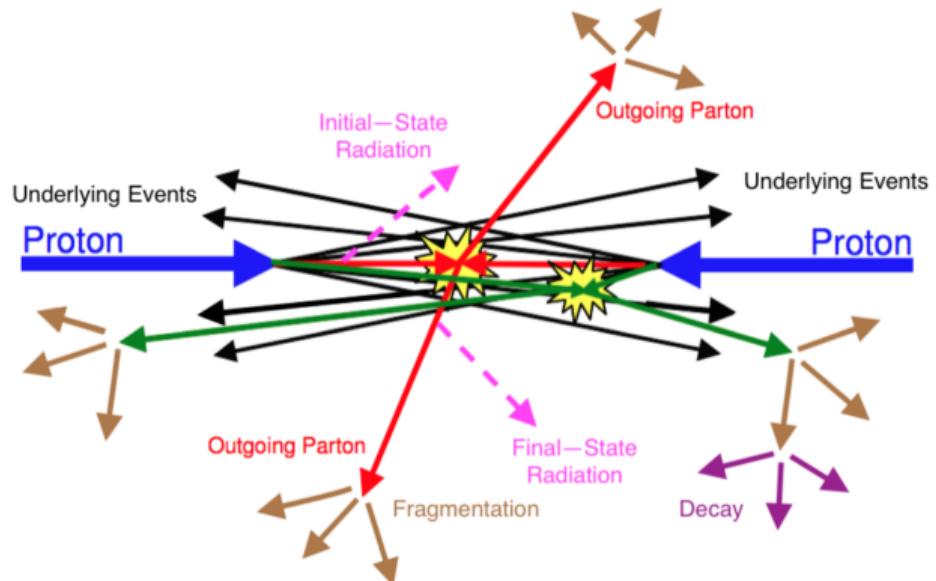
- ▶ Multi Parton Interactions (MPI) : more than one hard scattering

Still particle production dominated by Soft-QCD processes

- ▶ ISR + FSR (gluon-strahlung)
- ▶ colour-connected beam remnant
- ▶ infrared MPI (not primary)

- ▶ $p_T \sim$ few GeV
- ▶ non perturbative
- ▶ phenomenology
- ▶ modelling

EPJC 62 (2009) 237-242



SOFT QCD IN AA COLLISIONS

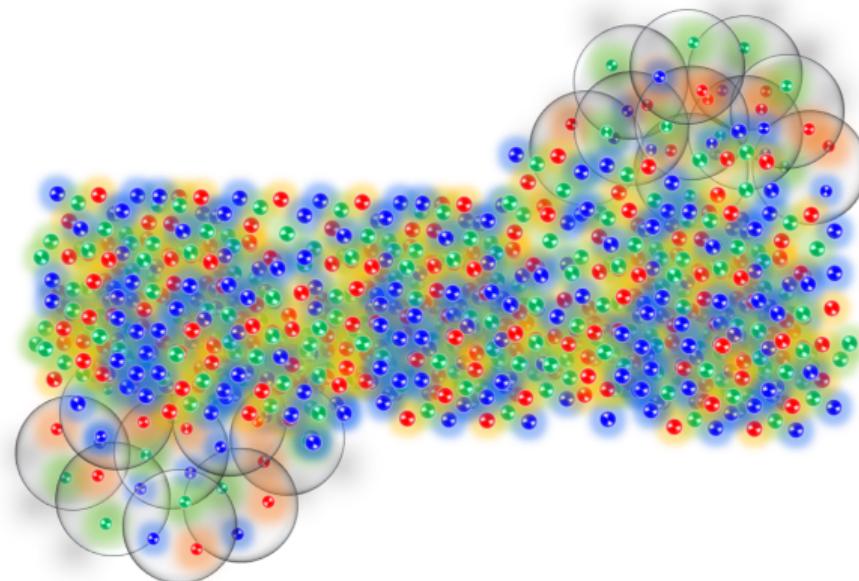
New QCD phase (QGP) is created for central AA collisions

- Most of particles are soft (thermalised from the hot and dense-state medium)

Statistical approach for Soft-QCD processes

- many observables are soft

- Light flavours
- flow
- multiplicity



A LARGE ION COLLIDER EXPERIMENT

V0 (Scintillator hodoscopes)

- triggers forward activity
- multiplicity & centrality estimation

FMD (Forward Multiplicity Detector)

- Three sets of Si strip sensors
- close to V0 detectors

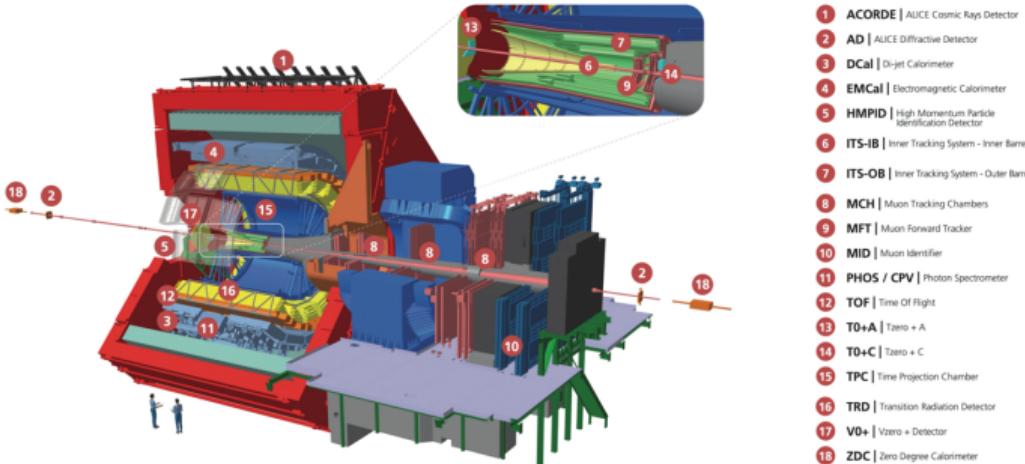
SPD (Silicon Pixel Detector)

- Two-layer silicon detector
- counting tracklets at mid rapidity

TPC (Time Projection Chamber)

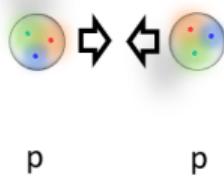
- Large cylindrical detector
- designed upto $dN_{ch}/d\eta \sim 8000$

- ▶ 18 detectors, sensitivity at low p_T , excellent PID
- ▶ Optimized for soft QCD physics



	η_{min} / η_{max}	
	A side	C side
V0	2.8/5.1	-3.7/-1.7
FMD	1.7/5.1	-3.4/-1.7
SPD		-2/2
TPC		-0.9/0.9

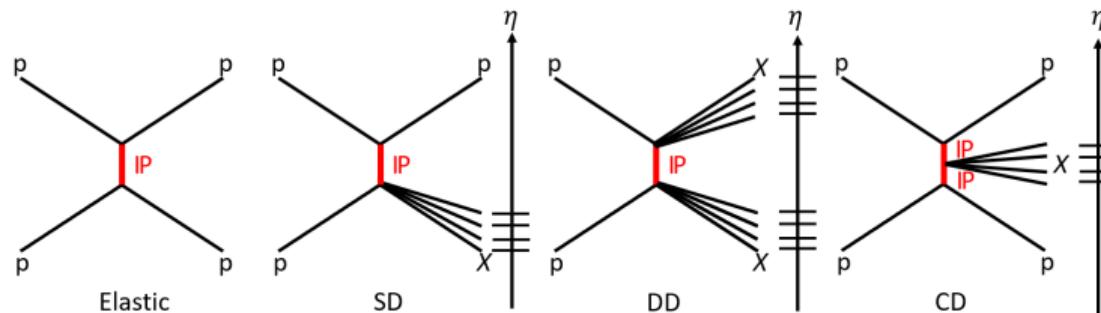
Inclusive and diffractive cross-sections



INCLUSIVE AND DIFFRACTIVE CROSS-SECTIONS

Inelastic cross-section in pp collision

$$\sigma_{\text{INEL}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}$$



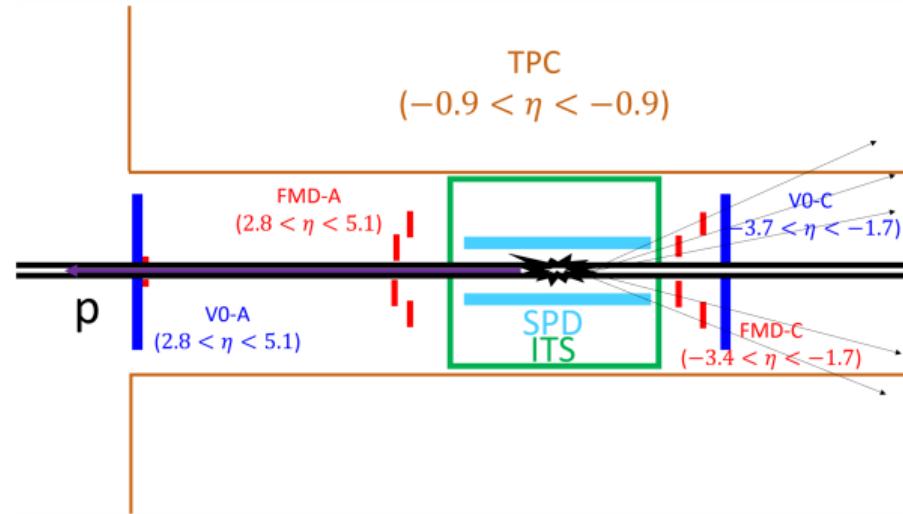
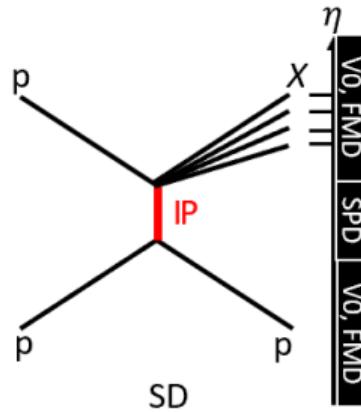
- ▶ SD, DD and CD in pp : pure soft processes
- ▶ ND : Underlying event + hard scattering
- ▶ Diffractive process about 25% of inelastic collisions^{1,2} by CDF($\sqrt{s} = 1.8$ TeV)

¹F.Abeetal.(CDFCollaboration),Phys.Rev.D50,5535(1994), 1994

²F.Abeetal.(CDFCollaboration),Phys.Rev.Lett.74,855(1995), 1995

INCLUSIVE AND DIFFRACTIVE CROSS-SECTIONS

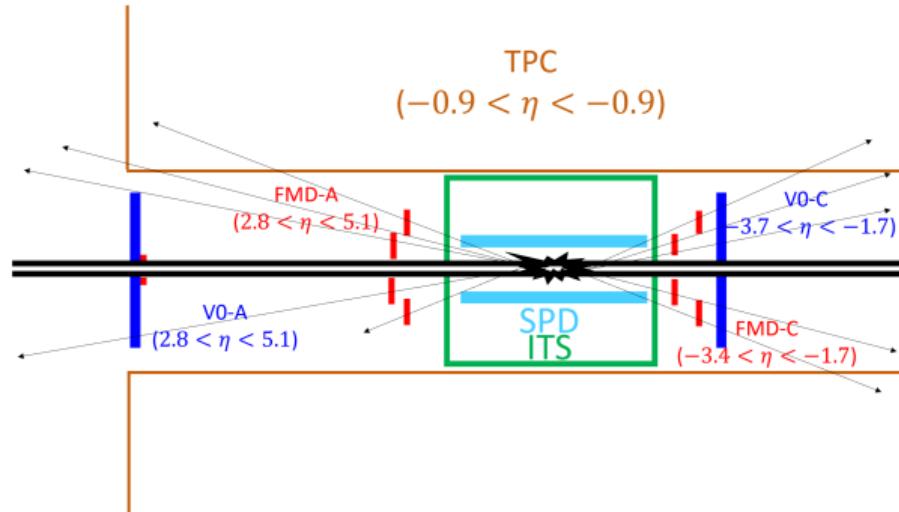
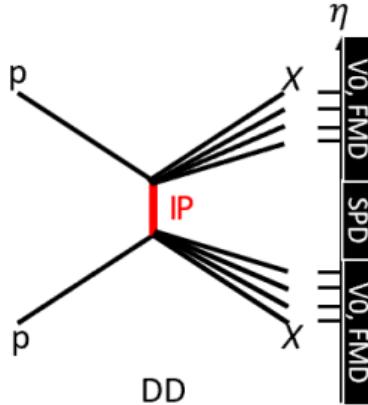
$$\sigma_{\text{INEL}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}$$



- SD : Activity in one-side V0-FMD and no activity in TPC and other side V0-FMD
- M_x : Diffracted mass (ΣM of scattered particles)
- $\Delta\eta \sim \Delta y \sim \ln(s/M_X^2)$, $\Delta\eta \sim 13(7)$ for $M_X = 10$ (200) GeV/c^2 at $\sqrt{s} = 7 \text{ TeV}$

INCLUSIVE AND DIFFRACTIVE CROSS-SECTIONS

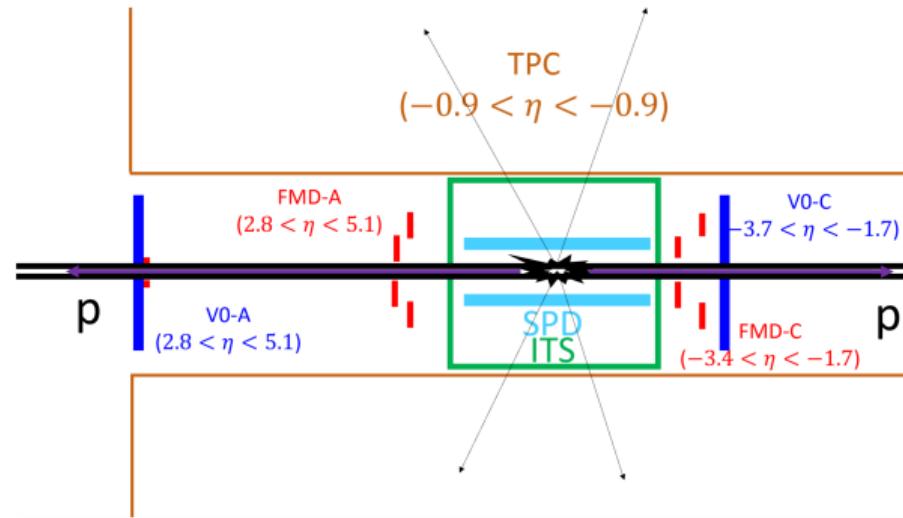
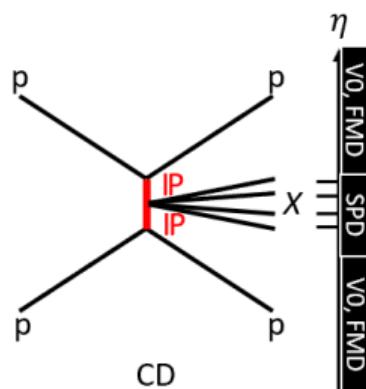
$$\sigma_{\text{INEL}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}$$



- DD : Activities in both side V0-FMD and no activity in TPC
- M_x : Diffracted mass (ΣM of scattered particles)
- $\Delta\eta \sim \Delta y \sim \ln(ss_0/M_{X_1}^2 M_{X_2}^2)$, $\Delta\eta \sim 8.5$ for $M_{X_1} = M_{x_2} = 10 \text{ GeV}/c^2$ at $\sqrt{s} = 7 \text{ TeV}$

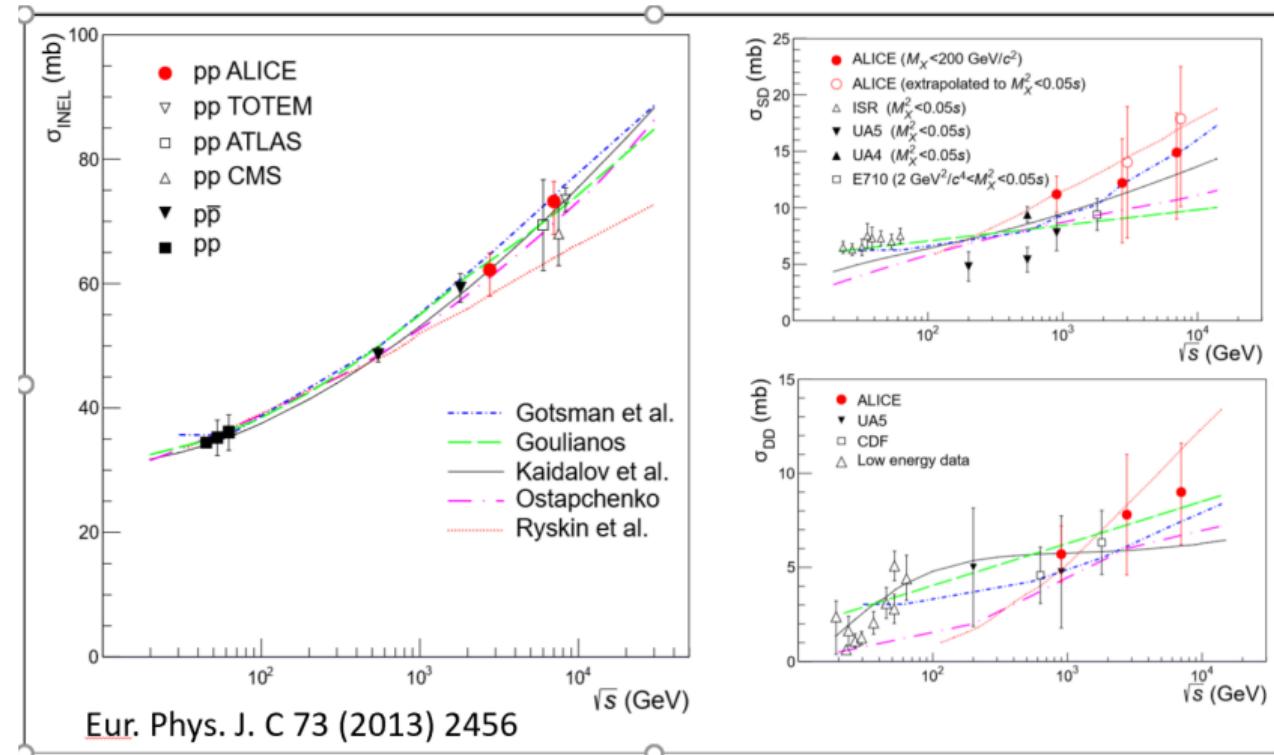
INCLUSIVE AND DIFFRACTIVE CROSS-SECTIONS

$$\sigma_{\text{INEL}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}$$



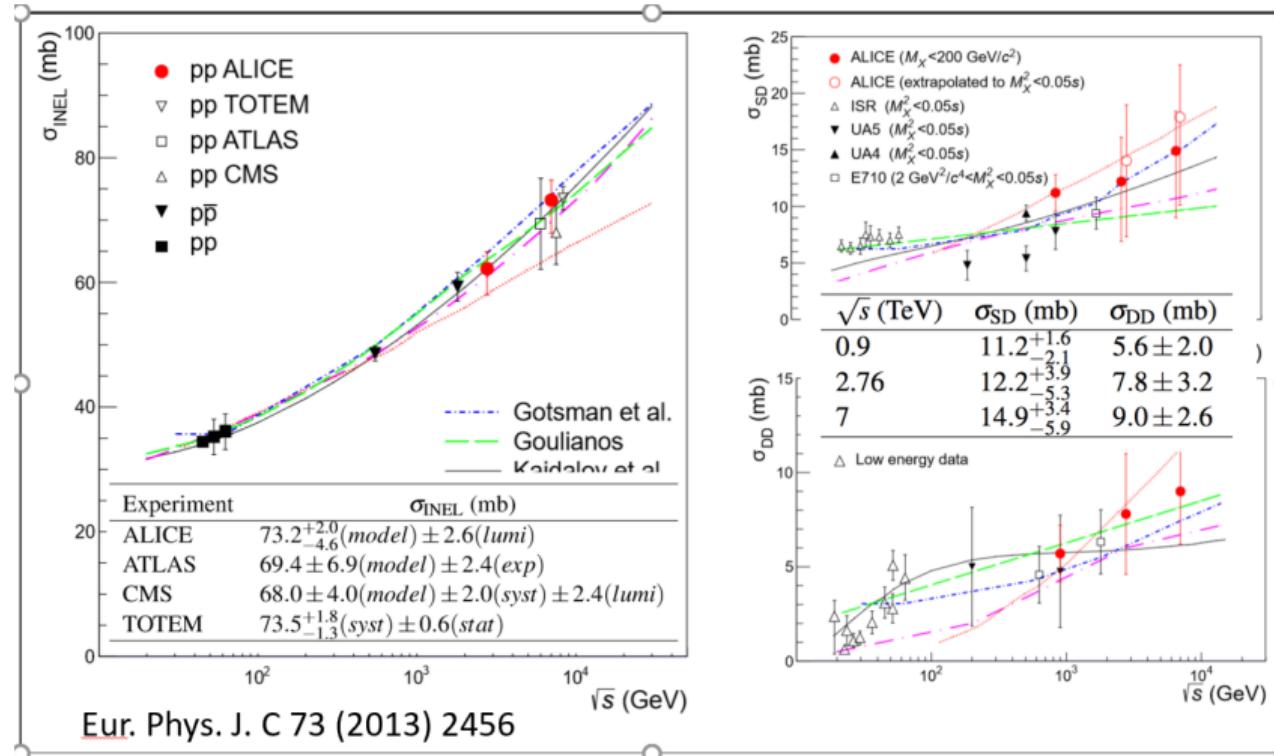
- CD : Activity in TPC and no activities in both side V0-FMD (double-gap event)
- M_x : Diffracted mass (ΣM of scattered particles)

CROSS-SECTION IN PP COLLISIONS (INEL, SD AND DD)



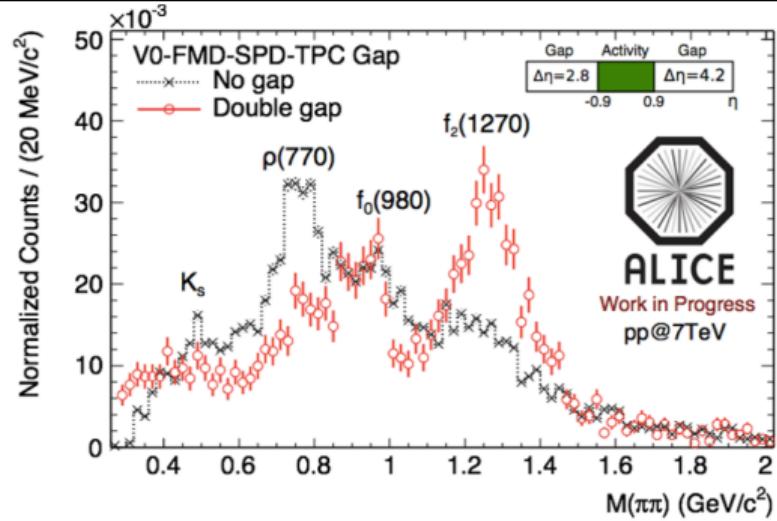
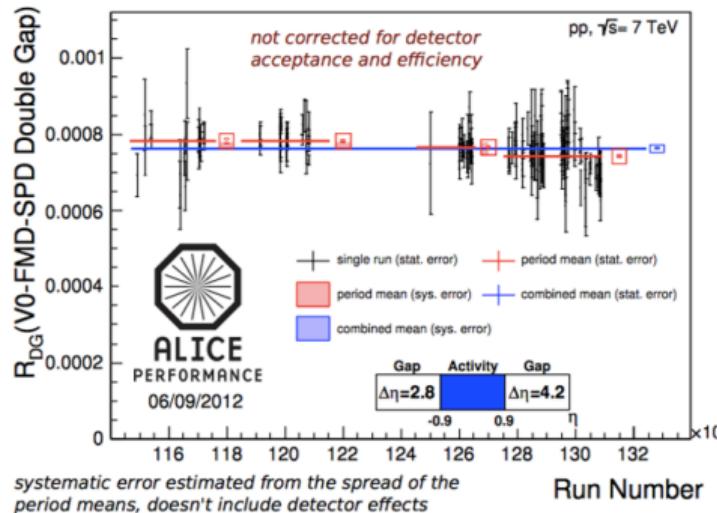
- Cross-section measurement depends on the modelling for the SD component

CROSS-SECTION IN PP COLLISIONS (INEL, SD AND DD)



► Cross-section measurement depends on the modelling for the SD component

CROSS-SECTION IN PP COLLISIONS (CD)

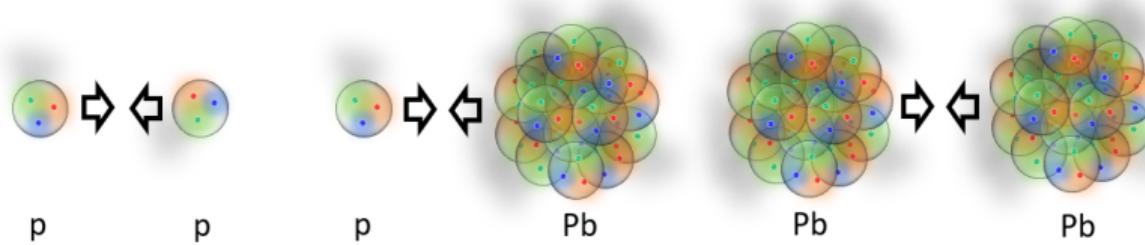


$$R_{DG}(2.8, \pm 0.9, 4.2) = \frac{N_{DG}}{N_{MB}} \text{ limits on } \frac{N_{CD}}{N_{INEL}}$$

$$R_{DG}(2.8, \pm 0.9, 4.2) = \frac{N_{DG}}{N_{MB}} = (7.63 \pm 0.02_{\text{stat}} \pm 0.87_{\text{sys}}) \times 10^{-4} \rightarrow \sigma_{CD}/\sigma_{INEL} < 1\%$$

- Quantum numbers restricted **except the vacuum ($I^G = 0^+$)**
- Clear confinement behaviour : reduced $\rho^0(770)$, enhanced $f_0(980)$ and $f_2(1270)$

Charged-particle multiplicity and multiplicity density



CHARGED-PARTICLE MULTIPLICITY AND DENSITY

- Study interplay between soft and hard QCD

AA collisions

- Direct relation to the size and energy density of the QGP

pp collisions

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

p-Pb collisions

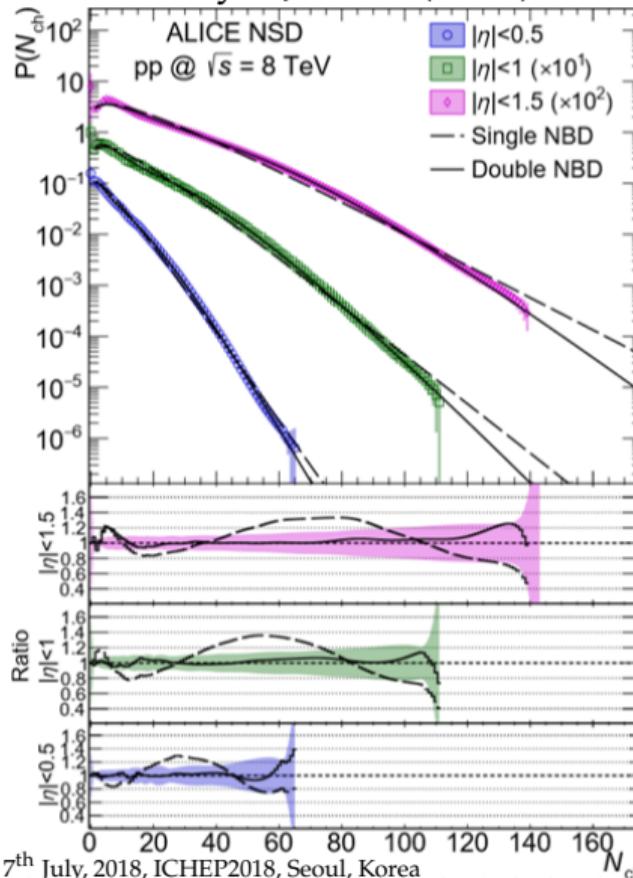
- Discriminate between FSR in AA and ISR of nuclei themselves

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

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

CHARGED PARTICLE MULTIPLICITY IN PP COLLISIONS

Eur. Phys. J. C 77 (2017) 33



Single NBD fit

- Traditional parametrisation of particle multiplicity

$$P_{\text{NBD}}(n, \langle n \rangle, k) = \frac{\Gamma(n+k)}{\Gamma(k)\Gamma(n+1)} \left[\frac{\langle n \rangle}{\langle n \rangle + k} \right]^n \times \left[\frac{k}{\langle n \rangle + k} \right]^k$$

- Single NBD fit overestimates the data at LHC

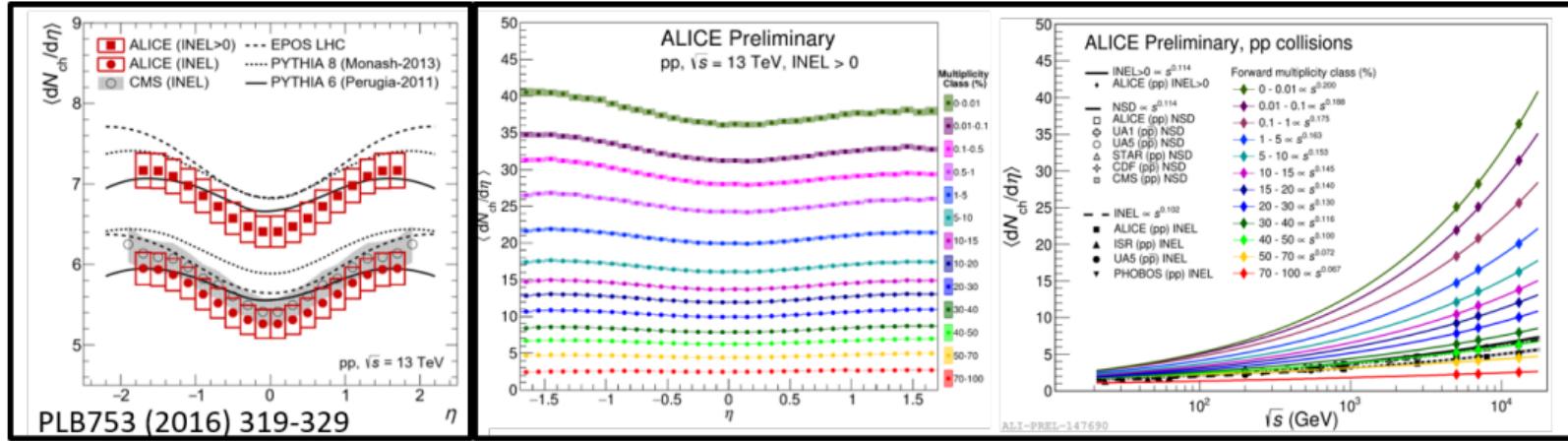
Double NBD fit

- Weighted sum of two NBD functions

$$P(n) = \lambda [\alpha P_{\text{NBD}}(n, \langle n_1 \rangle, k_1) + (1 - \alpha) P_{\text{NBD}}(n, \langle n_2 \rangle, k_2)]$$

- α : soft and MPI (not primary)
- $1 - \alpha$: hard scattering
- Describes the data better → some hints of MPI

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

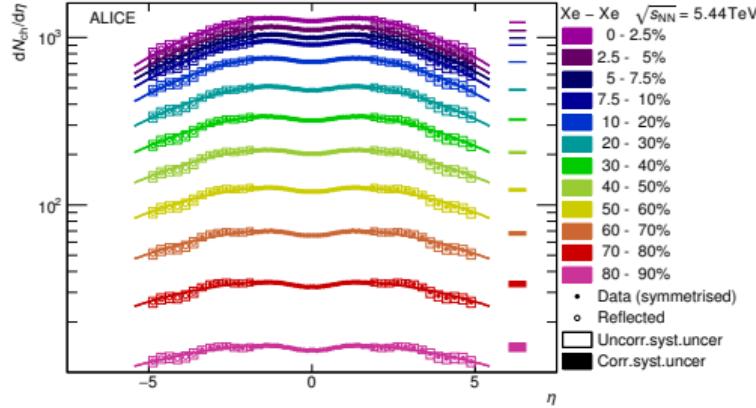


- ▶ Inclusive study : $INEL \propto s^{0.102}$, $NSD \propto s^{0.114}$ and $INEL_{>0}^1 \propto s^{0.114}$
- ▶ Multiplicity dependence study
 - ▶ $\langle dN_{ch}/d\eta \rangle$ for different multiplicity classes
 - ▶ The evolution of $\langle dN_{ch}/d\eta \rangle$ with \sqrt{s} : steeper for higher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

¹INEL >0 : INEL requiring at least one charged particle in $|\eta| = 1$ introduced for tuning models

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

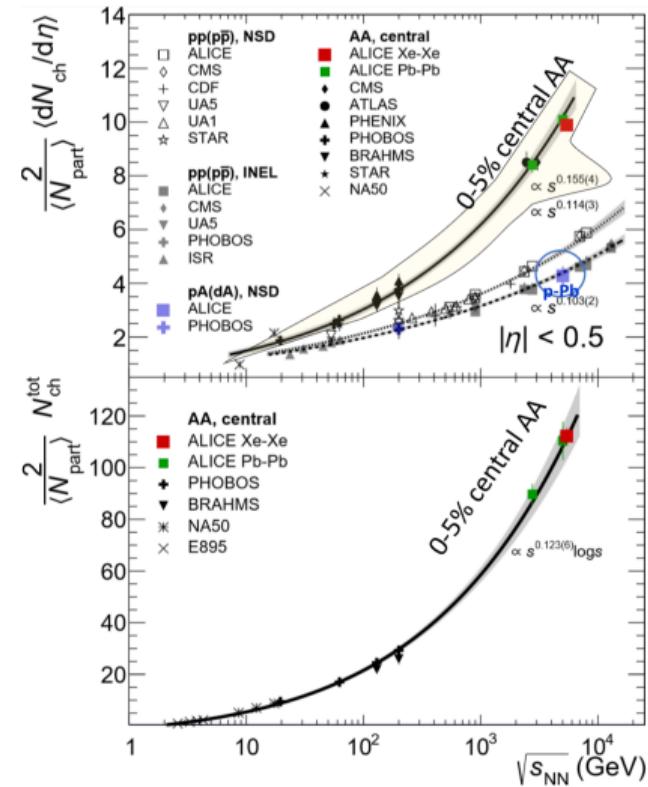
arXiv:1805.04432



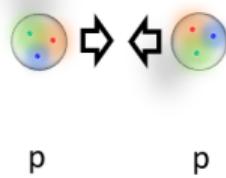
$$\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}}/d\eta \rangle \text{ and } \frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}}$$

- 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



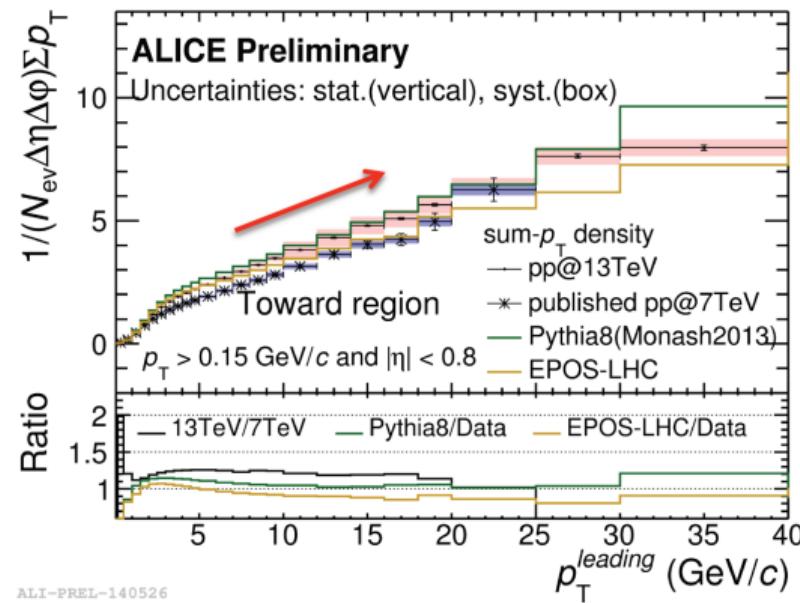
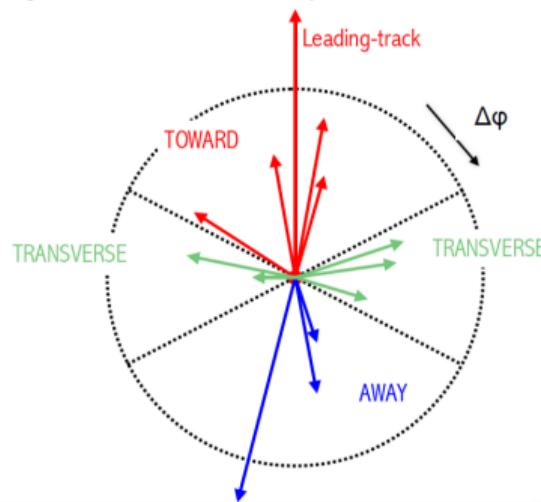
Underlying Events



UNDERLYING EVENT IN PP COLLISIONS

Average charged-particle density vs. $p_{T,LT}$
Toward and Away regions

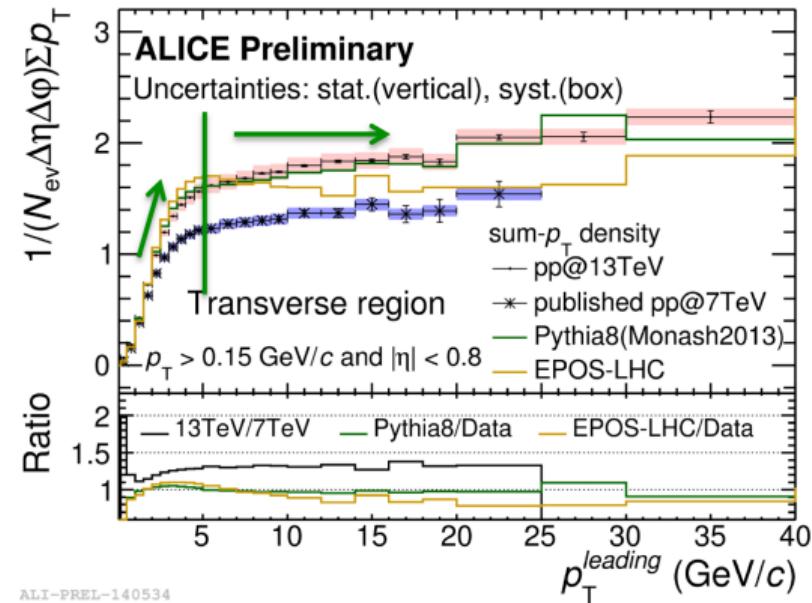
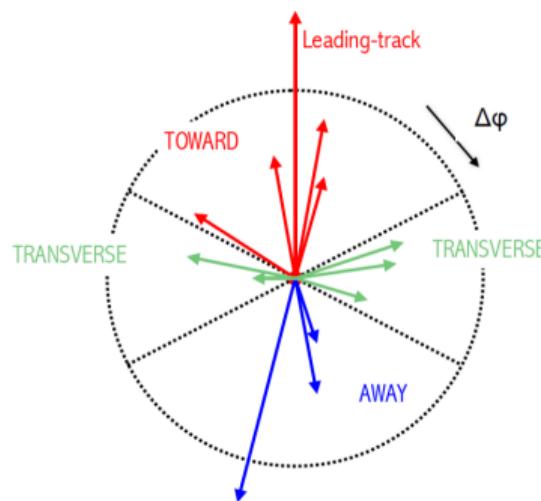
- ▶ Collect fragmentation from hard scattering
→ increasing monotonically



UNDERLYING EVENT IN PP COLLISIONS

Average charged-particle density vs. $p_{T,LT}$
Transverse regions

- ▶ Underlying Event
- ▶ First increase : Multi Parton Interactions
- ▶ flattens : Soft processes



SUMMARY

Soft QCD measurements at LHC have greatly improved
Last 8 years

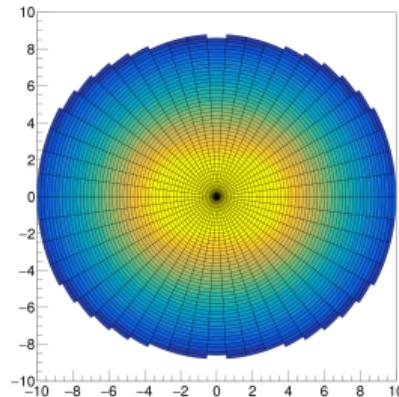
- ▶ pp collisions at $\sqrt{s} = 0.9, 2.76, 7, 8$ and 13 TeV
- ▶ p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02, 8.16$ TeV
- ▶ Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76, 5.02$ and 5.5 (planned) TeV
- ▶ Xe-Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV
- ▶ \sqrt{s} behaviour of $dN_{\text{ch}}/d\eta$ established
- ▶ Evidence for MPI from various measurements
- ▶ Medium-sized Xe-ion acts like a heavy ion
- ▶ Models have been tuned but still need more constraints

Backup

► Xe ion (deformed)

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

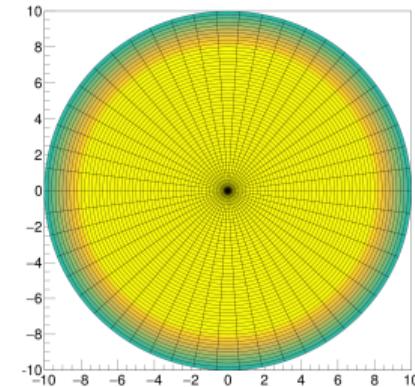
- ρ_0 : the nucleon density
- The nuclear skin thickness $a = 0.59 \pm 0.07 \text{ fm}$ ¹
- Nuclear radius $R(\vartheta) = R_0[1 + \beta_2 Y_{20}(\vartheta)]$



► Pb ion (spherical)

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

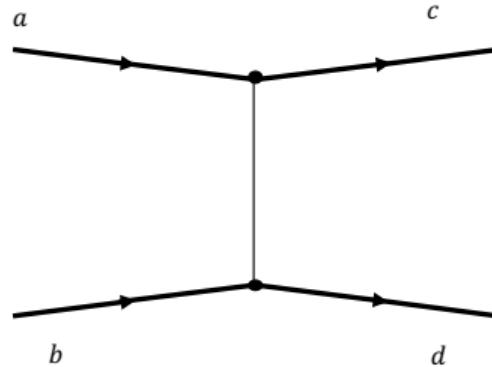
- ρ_0 : the nucleon density
- The nuclear skin thickness $a = 0.546 \pm 0.01 \text{ fm}$
- Nuclear radius $R = 6.62 \pm 0.06 \text{ fm}$



¹Phys. Rev. Lett. 118 no. 26, (2017) 262501

DIFFRACTION

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



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

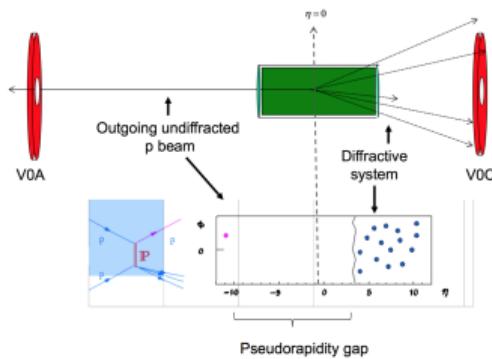
- ▶ Help us understand QCD in the non-perturbative regime
($t \sim 0$ or $q^2 < \Lambda_{\text{QCD}}^2$)
- ▶ By Regge theory ^{1 2 3}, diffraction proceeds via the exchange of Pomerons
($gg_{\text{leading order}} + ggg_{\text{next leading order}} + \dots$)

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

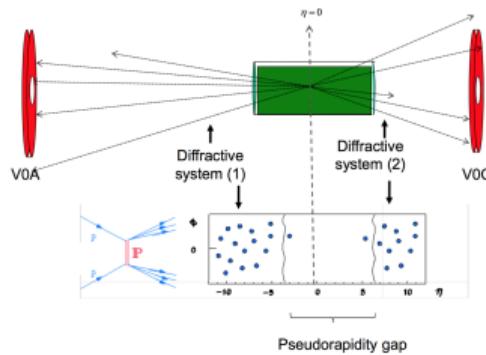
²A.B.Kaidalov, Phys. Rep. 50, 157, 1979

³V. Barone, E. Predazzi, High-Energy Particle Diffraction, Springer, Berlin, 200

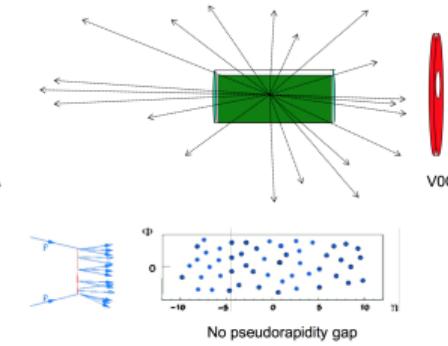
SD, DD AND ND



SD

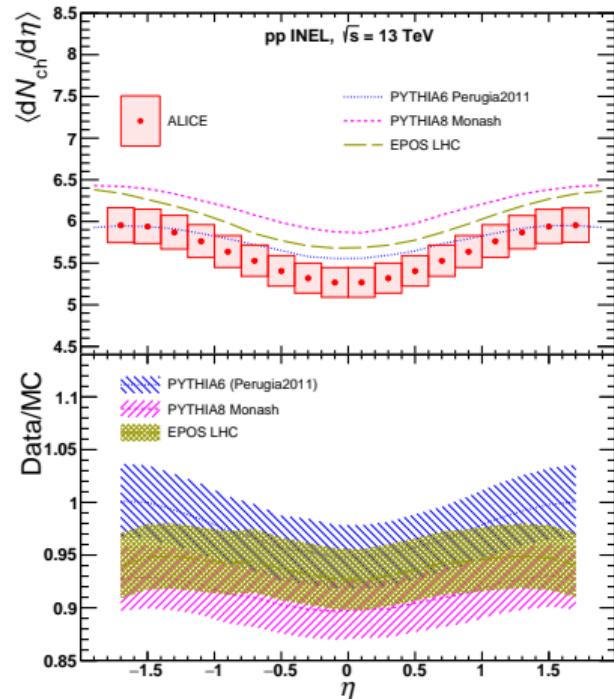
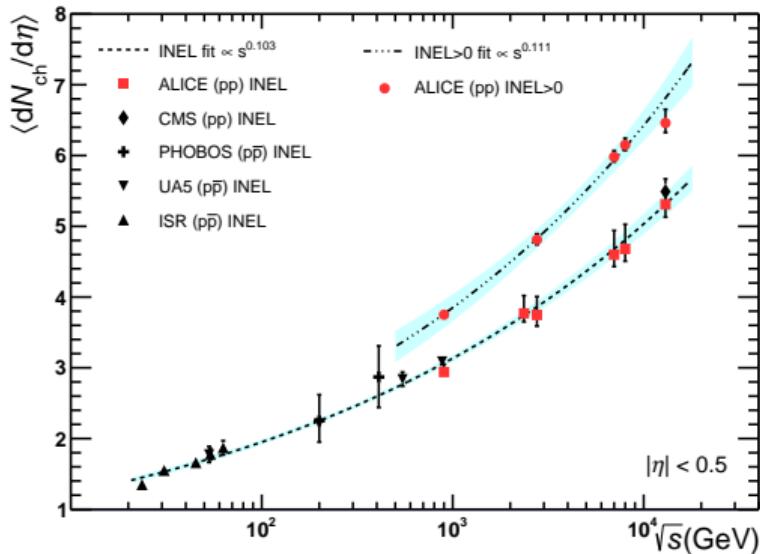


DD



ND

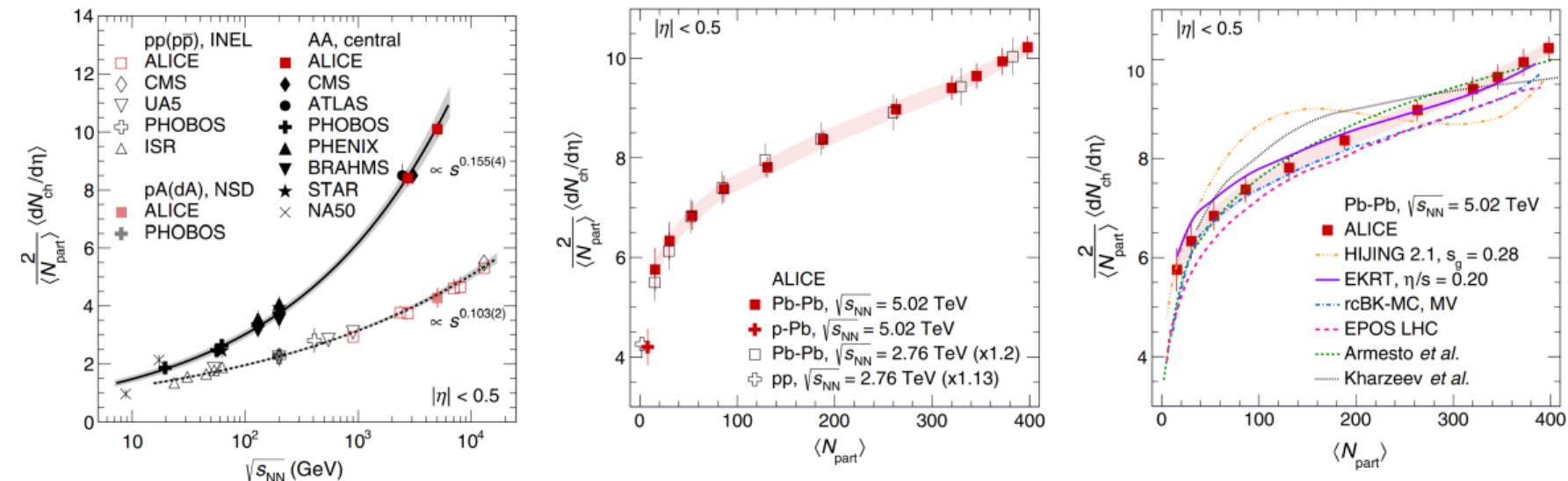
N_{ch} IN pp COLLISIONS



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

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

N_{ch} IN Pb – Pb 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_{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
 - ▶ INEL¹ : ND + SD + DD + CD ...
 - ▶ NSD : ND + DD (to ignore large uncertainty from SD)
 - ▶ INEL_{>0} : INEL + at least one activity in $|\eta| = 1$
(effective filter for SD and DD events)

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

N_{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_{ch}
 - Discriminate the initial and final state effects
 - A tool to study the various models of gluon saturation¹
 - Providing constraints to the initial state and small Bjorken- x modeling

¹Different 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

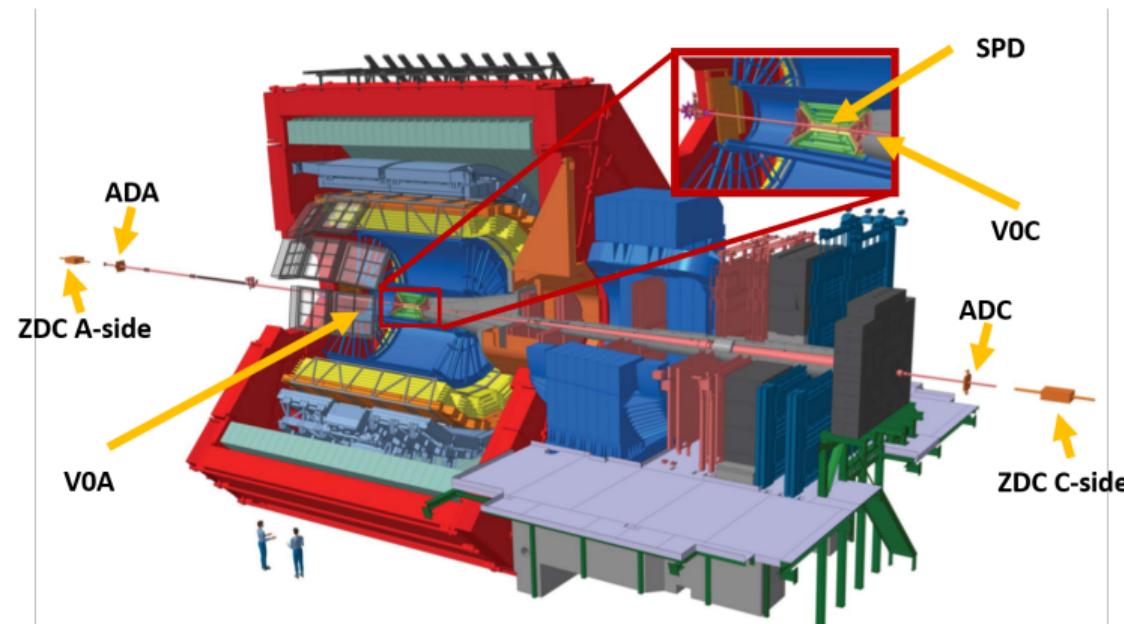
- Published (and ongoing) multiplicity papers

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_{ch} : A key observable in the QGP (initial energy density)
- Impact parameter (b): The degree of geometrical overlap
- Centrality : Experimental proxy of b
- N_{part} : the number of nucleons participating in the collision
- N_{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

	η_{\min}/η_{\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

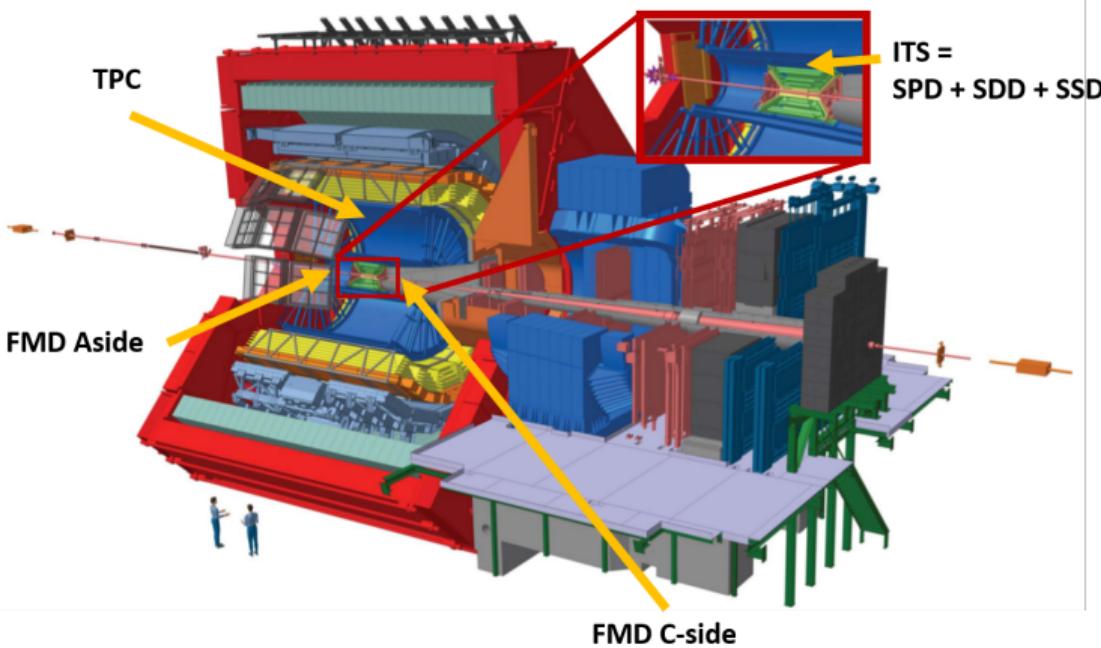
AD (Alice Diffraction)

- 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

	η_{\min}/η_{\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

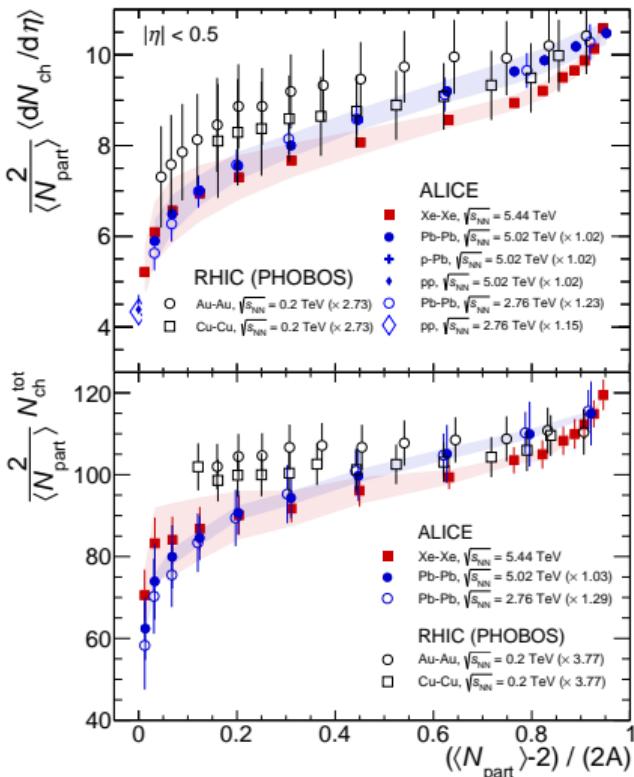
TPC (Time Projection Chamber)

- ▶ 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

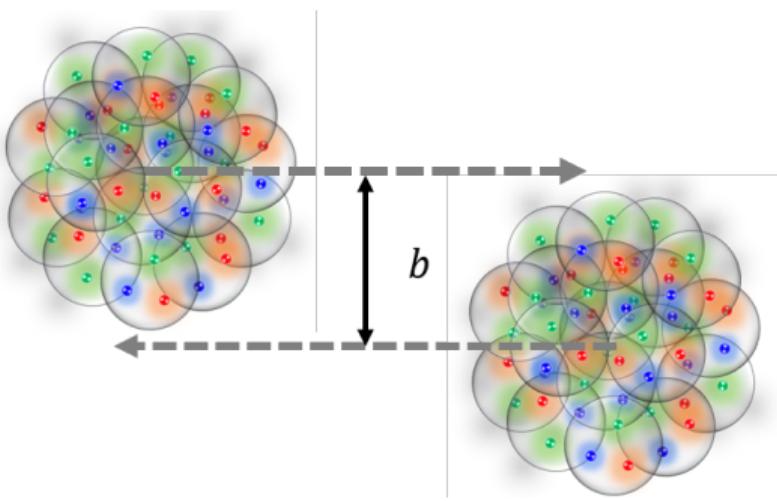
$\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}} / d\eta \rangle$ AND $\frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}}$ AS A FUNCTION OF CENTRALITY



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

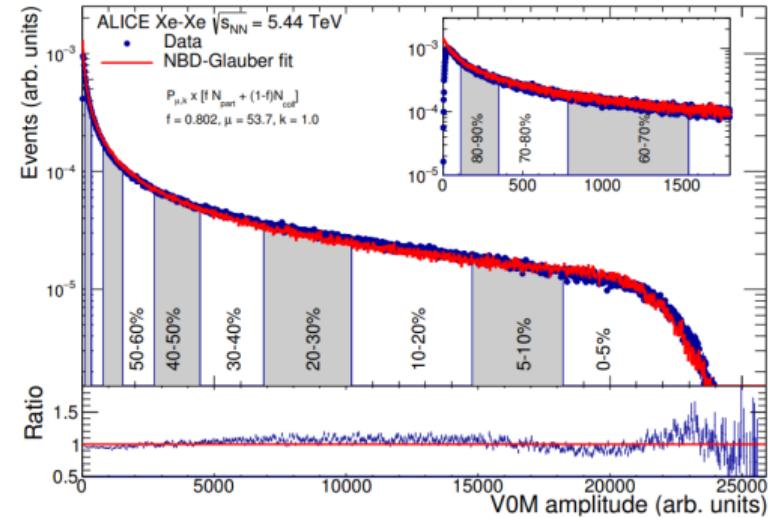
CENTRALITY ESTIMATION



Impact parameter (b)

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

ALICE-PUBLIC-2018-003

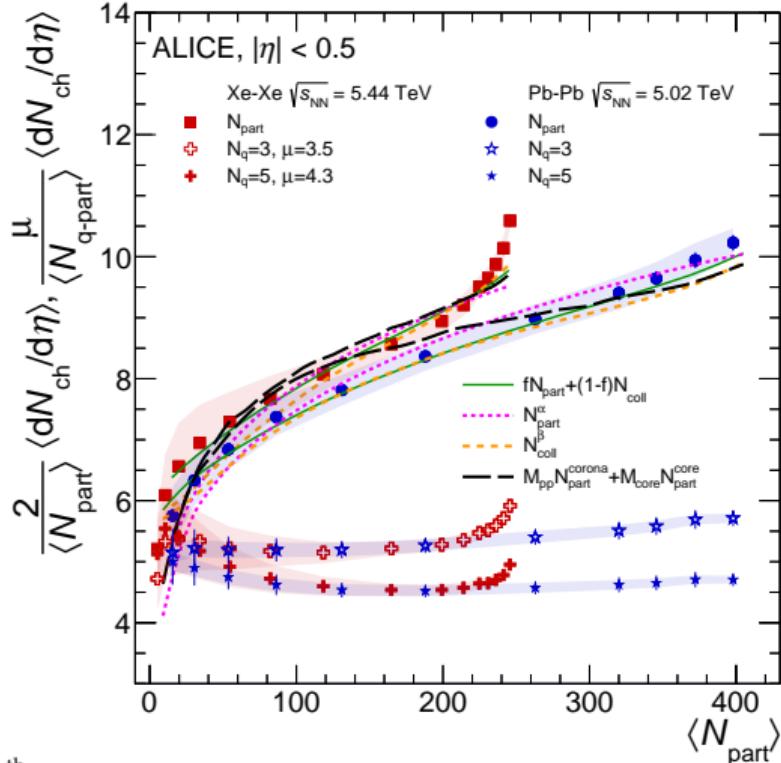


Centrality estimation for Xe-Xe

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

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

arXiv:1805.04432



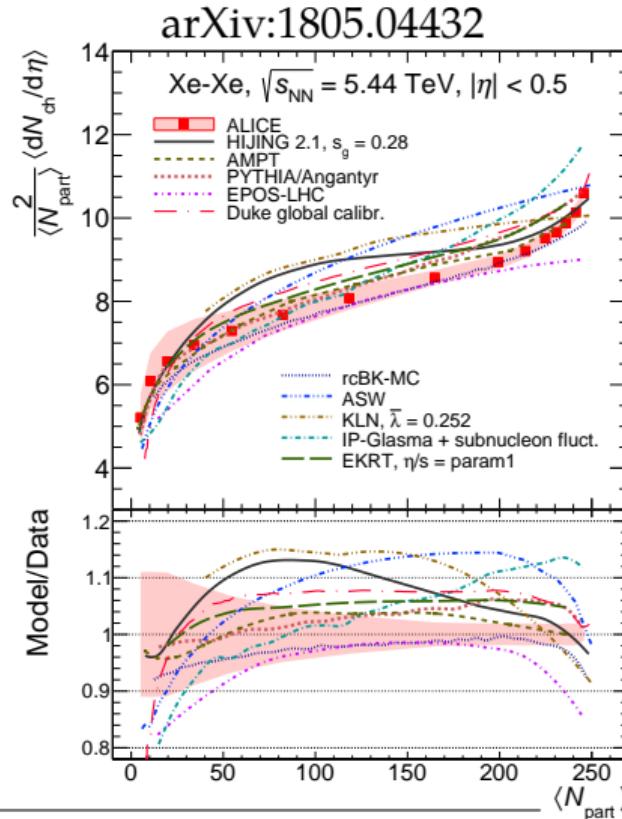
Different scalings for particle production

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, ASW¹, IP-Glasma² and EKRT³

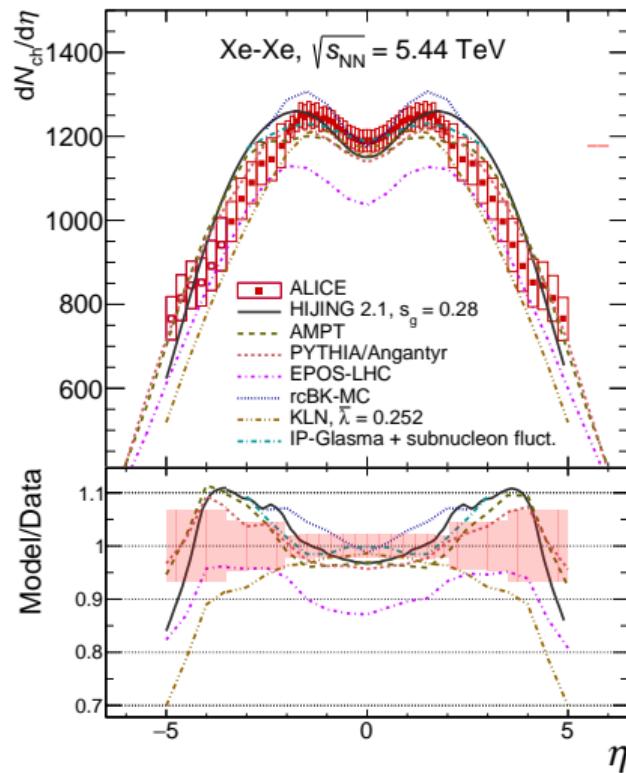
- saturation-inspired models to limit N_{parton}

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

7th July, 2018; ICHEP2018, Seoul, Korea
⁰1. Phys. Rev. Lett. 94 (2005) 022002, 2. Phys. Rev. Lett. 108 (2012) 252301, 3. Phys. Rev. C97 no. 3, (2018) 034911
 Beomkyu Kim

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

arXiv:1805.04432



HIJING

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

AMPT and PYTHIA/Angantyr

fairly good, slight overestimate at forward η

EPOS LHC

underestimate data overall

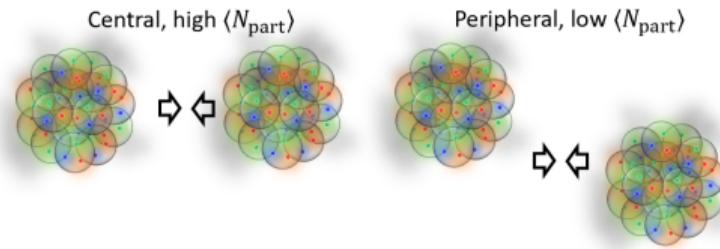
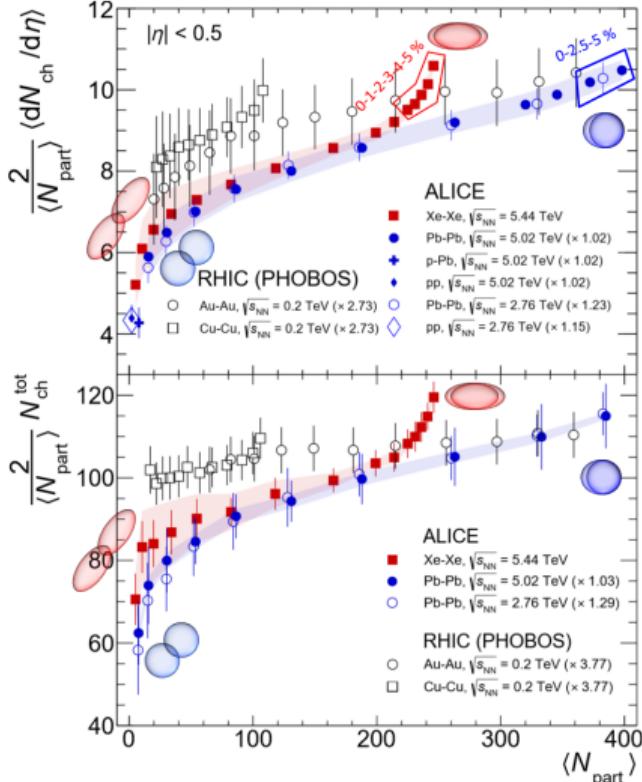
rcBK-MC: overall overestimation

KLN: matches in mid η , not true for forward η

IP-Glasma: wider than data

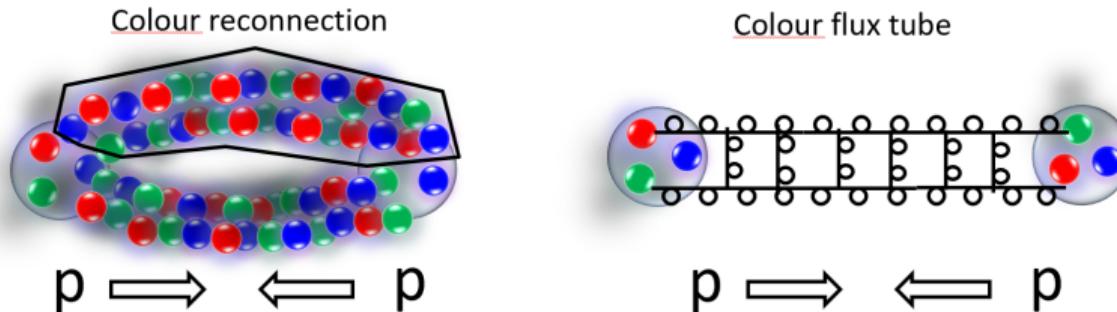
$\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}} / d\eta \rangle$ AND $\frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}}$ AS A FUNCTION OF $\langle N_{\text{part}} \rangle$

arXiv:1805.04432



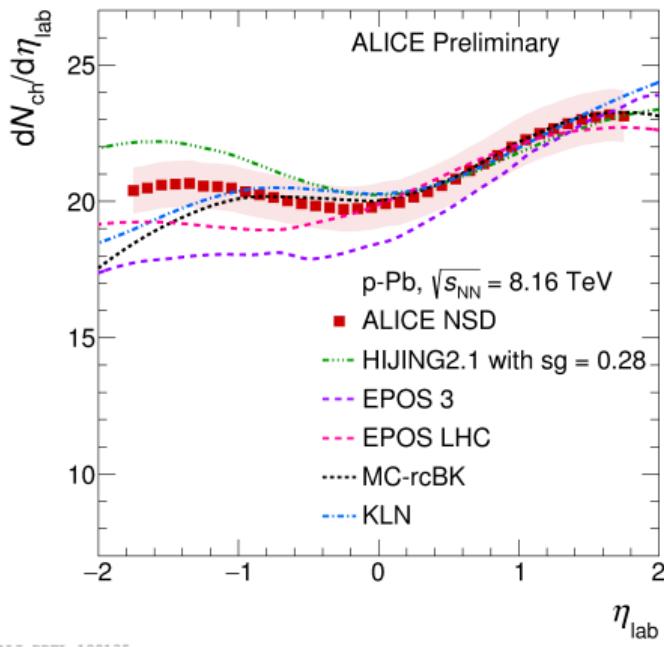
- ALICE data decreasing by a factor of 2 from the most central to the peripheral
- smoothly connect to pp and p-Pb
- Xe–Xe shapes exceed Pb–Pb at similar $\langle N_{\text{part}} \rangle$ for the top 10 % central collisions
- RHIC data show hint of same behaviour

MPI SCENARIOS



- ▶ Colour reconnection
 - ▶ colour strings from two hard scatterings are connected
 - ▶ two hard scatterings start to be dependent in high mul pp collisions
 - ▶ the rise of $\langle p_T \rangle$ with multiplicity like flow boost
- ▶ Core & corona (EPOS-LHC)
 - ▶ multiparton scattering froms a coulur-flux tune
 - ▶ Tube's high density region → thermalised as a flow-like(core)
 - ▶ Tube's edge region → hadronised as conventional

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



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

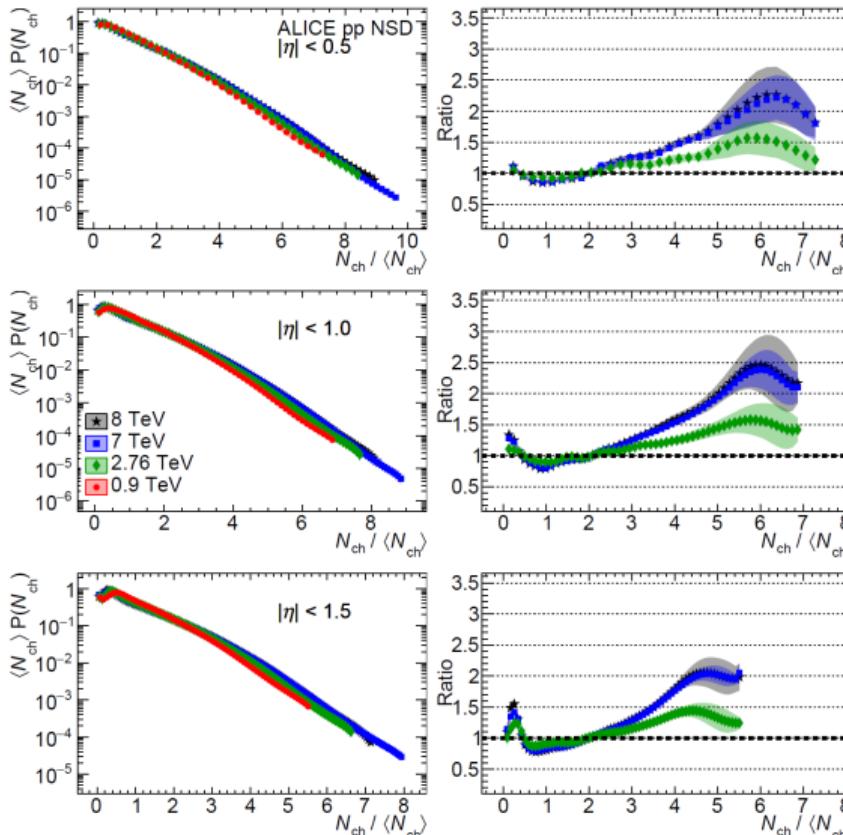
rc-BK (Nucl. Phys. A897 (2013) 1-27)

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

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

CHARGED PARTICLE MULTIPLICITY IN PP COLLISIONS

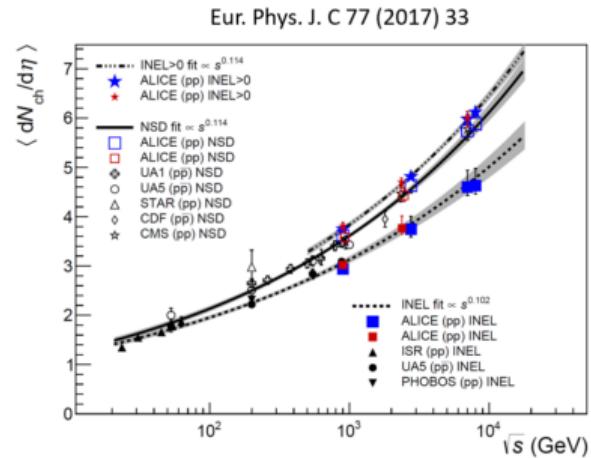
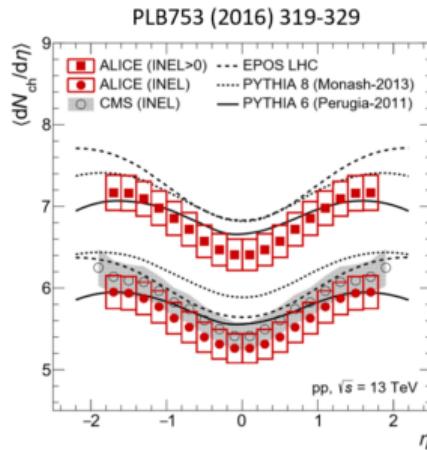
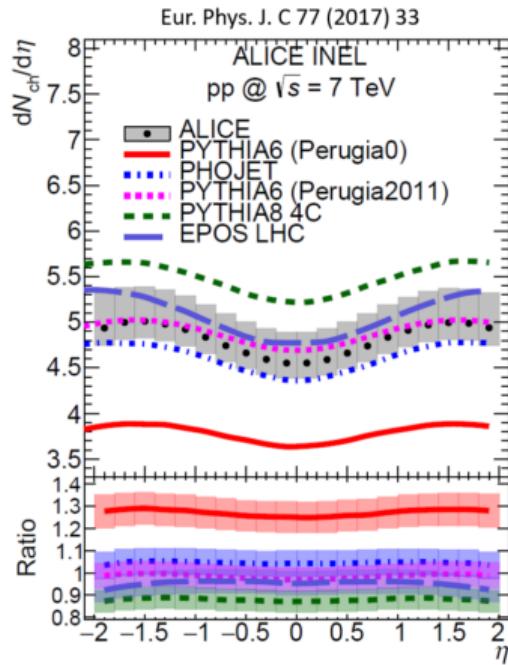
Eur. Phys. J. C 77 (2017) 33



KNO scaling

- ▶ scaling by $\langle N_{\text{ch}} \rangle$
- ▶ remove \sqrt{s} dependence of particle production
- ▶ higher $\sqrt{s} \rightarrow$ more scaling violation at high N_{ch}
- ▶ contributions from MPI

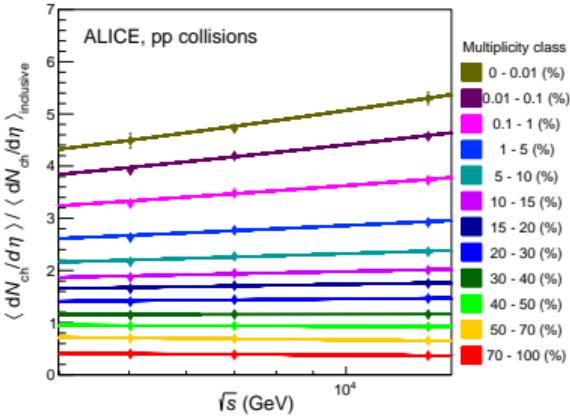
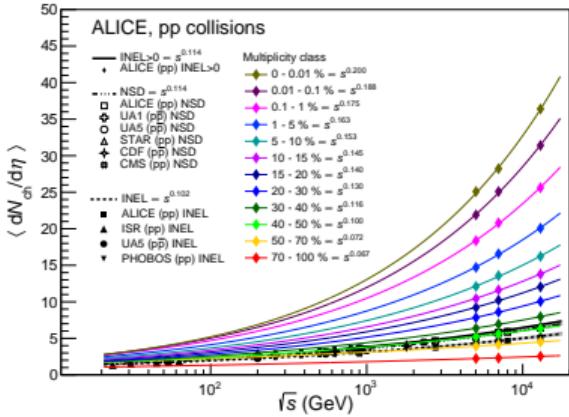
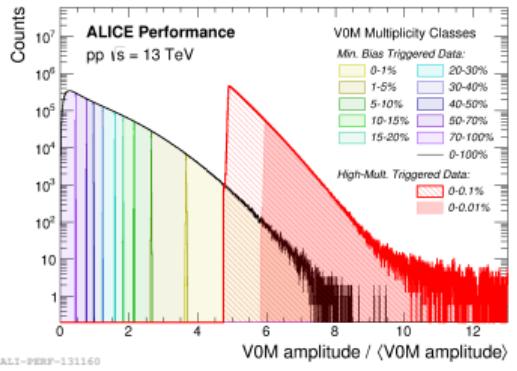
$\langle dN_{\text{ch}}/d\eta \rangle$ IN pp COLLISIONS



► Inclusive study : INEL $\propto s^{0.102}$, NSD $\propto s^{0.114}$ and INEL_{>0}¹ $\propto s^{0.114}$

¹INEL_{>0} : INEL requiring at least one charged particle in $|\eta| = 1$ introduced for tuning models

$\langle dN_{\text{ch}}/d\eta \rangle$ IN pp COLLISIONS (MULTIPLICITY SLICING)



- The evolution of $\langle dN_{\text{ch}}/d\eta \rangle$ with \sqrt{s} for different classes is parameterised by a power law function: $a s^b$
- The evolution of $\langle dN_{\text{ch}}/d\eta \rangle / \langle dN_{\text{ch}}/d\eta \rangle_{\text{inclusive}}$ vs \sqrt{s}
→ KNO scaling violation (MPI in high $\langle N_{\text{ch}} \rangle$)