Soft QCD measurements with ALICE

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4th July, 2018, HIM, Korea Univ.

At LHC energy → more contributions from hard-processes

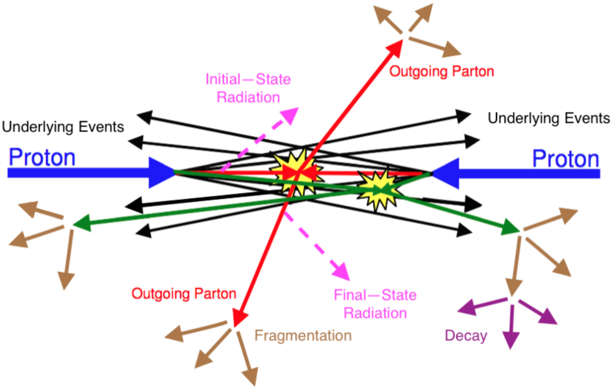
- Multi parton interaction (MPI) : more than one hard scattering

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

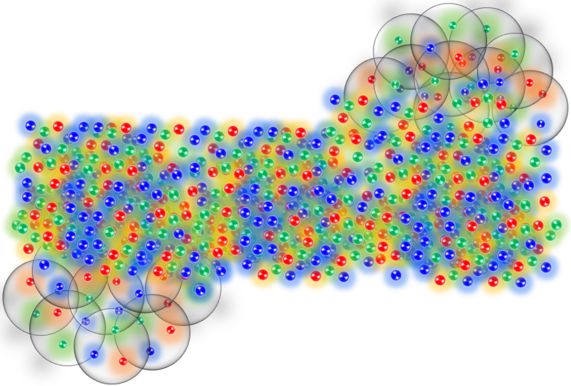


New QCD phase (QGP) is created for central AA collisions

- 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
- -3.7< η <-1.7, 2.8< η <5.1

SPD (Silicon Pixel Detector)

- Two-layer silicon detector
- counting tracklets at mid rapidity
- -2< η <2

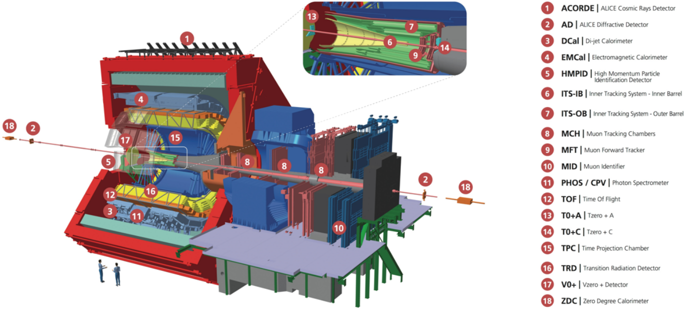
TPC (Time Projection Chamber)

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

FMD (Forward Multiplicity Detector)

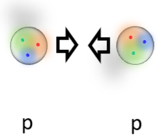
- Two sets of Si strip sensors
- close to V0 detectors

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



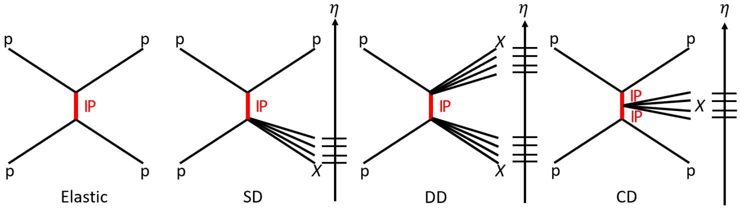
	η_{min}/η_{max} A side	η_{min}/η_{max} C side
SPD	-2/2	
V0	2.8/5.1	-3.7/-1.7
TPC	-0.9/0.9	
FMD	1.7/5.1	-3.4/-1.7

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)

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

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

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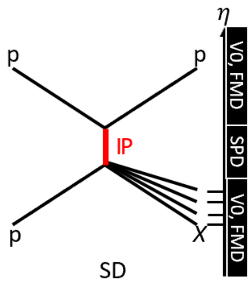
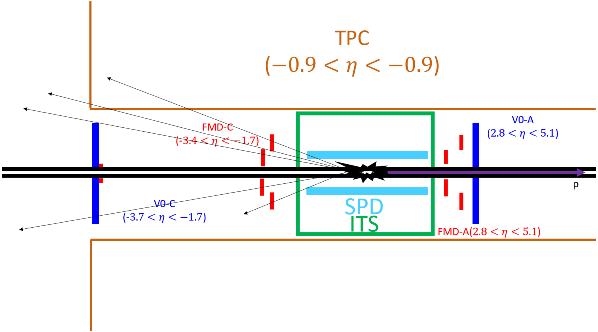
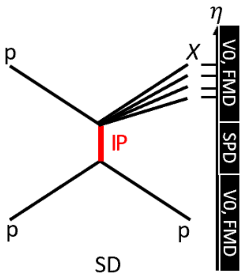
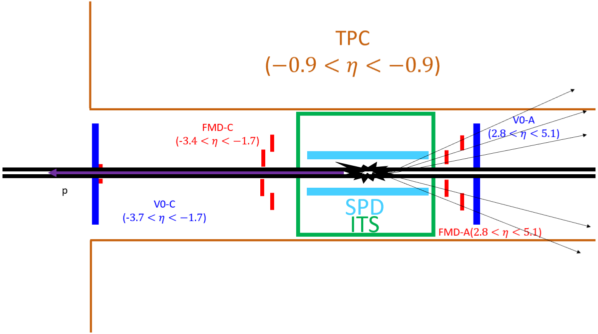




- SD : Activity in one-side V0-FMD and no activity in SPD and other side V0-FMD
- M_x : Diffracted mass (ΣM of scattered particles)
- $\Delta\eta \sim \Delta y \sim \ln(s/M_X^2)$, $\Delta\eta \sim 13(7)$ for $M^X = 10$ (200) GeV$/c^2$ at $\sqrt{s} = 7$ TeV

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





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Inclusive and diffractive cross-sections

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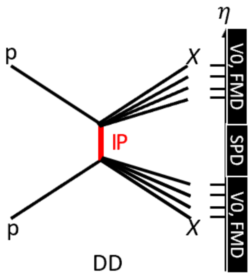
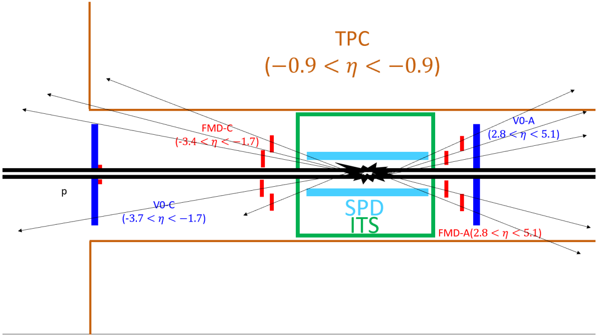
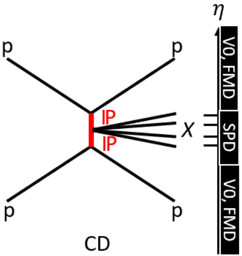
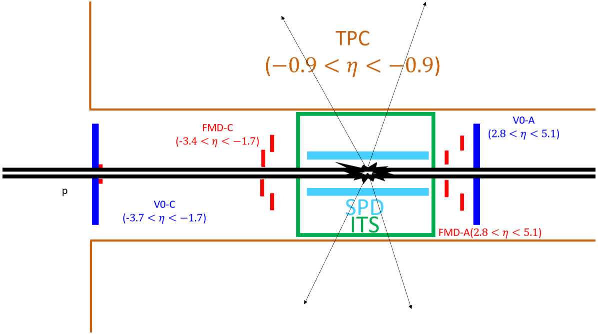




- DD : Activities in both side V0-FMD and no activity in SPD
- M_x : Diffracted mass (ΣM of scattered particles)
- $\Delta\eta \sim \Delta y \sim \ln(ss_0/M^2_{X_1}M^2_{X_2})$, $\Delta\eta \sim 8.5$ for $M_{X_1} = M_{x_2} = 10\ \text{GeV}/c^2$ at $\sqrt{s} = 7$ TeV

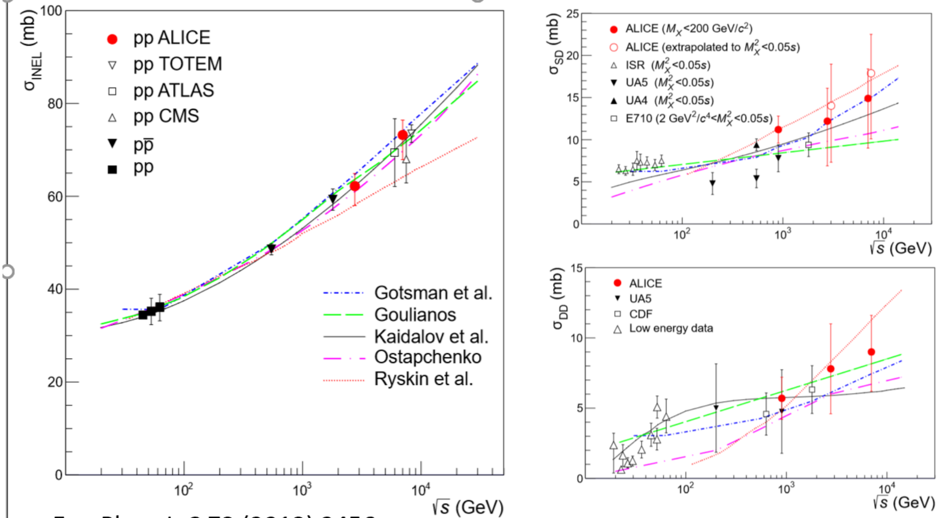
$$\sigma_{\text{INEL}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}$$





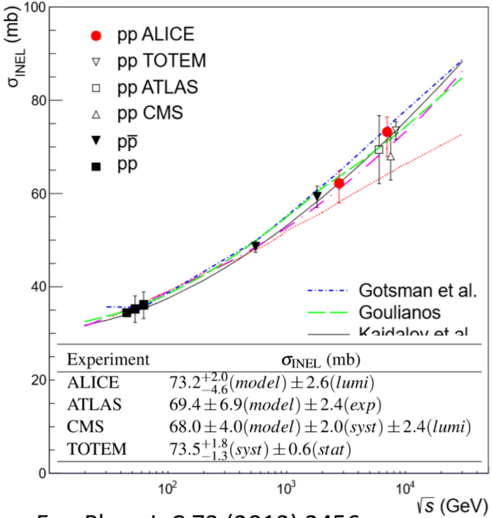
- CD : Activity in TPC and no activities in both side V0-FMD (double-gap event)
- M_x : Diffracted mass (ΣM of scattered particles)

Cross-section in pp collisions (INEL, SD and DD)



Eur. Phys. J. C 73 (2013) 2456

Cross-section in pp collisions (INEL, SD and DD)



Experiment	σ_{INEL} (mb)
ALICE	$73.2^{+2.0}_{-4.6}(model) \pm 2.6(lumi)$
ATLAS	$69.4 \pm 6.9(model) \pm 2.4(exp)$
CMS	$68.0 \pm 4.0(model) \pm 2.0(syst) \pm 2.4(lumi)$
TOTEM	$73.5^{+1.8}_{-1.3}(syst) \pm 0.6(stat)$

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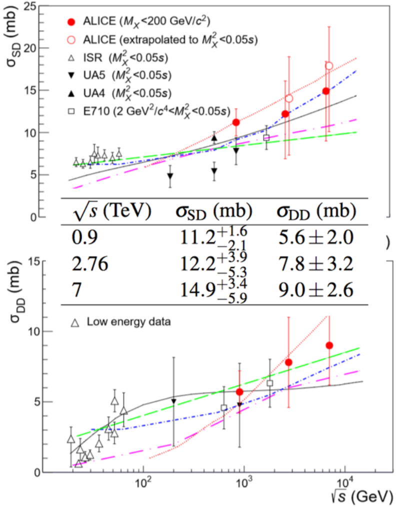
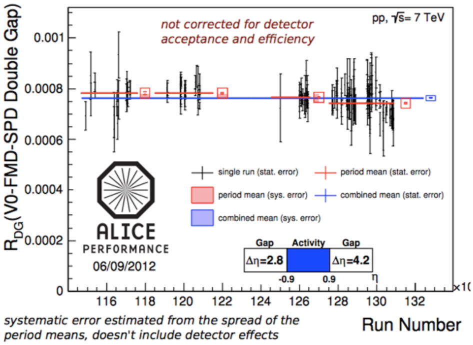
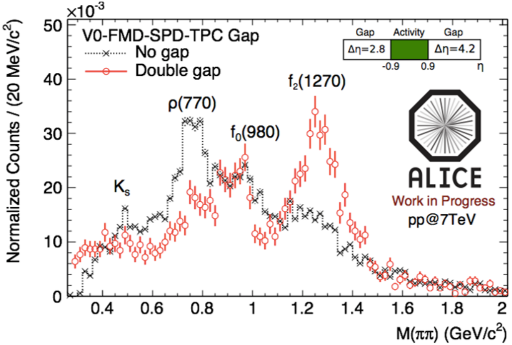


$\sqrt{s}$ (TeV)	σ_{SD} (mb)	σ_{DD} (mb)
0.9	$11.2^{+1.6}_{-2.1}$	5.6 ± 2.0
2.76	$12.2^{+3.9}_{-5.3}$	7.8 ± 3.2
7	$14.9^{+3.4}_{-5.9}$	9.0 ± 2.6

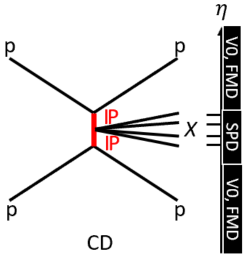
Cross-section in pp collisions (CD)



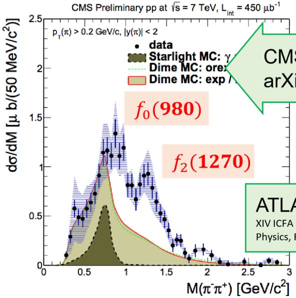


$$R_{DG}(2.8, \pm 0.9, 4.2) = \frac{N_{DG}}{N_{MB}} = (7.63 \pm 0.02_{stat} \pm 0.87_{sys}) \times 10^{-4} \rightarrow \sigma_{CD}/\sigma_{INEL} < 1\%$$

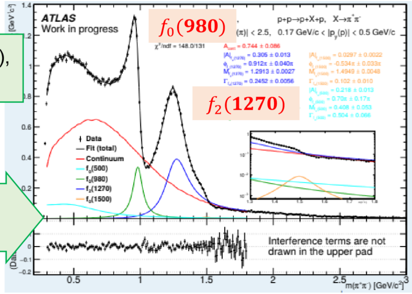
- Quantum numbers restricted in CD system (double $\mathbb{P}$ exchange)
- Clear confinement behaviour
  - reduced $\rho^0(770)$
  - enhanced $f_0(980)$ and $f_2(1270)$



- Ideal tool to search for glueball and hybrid (glue-rich environment)
- Spectroscopy for light scalar mesons
- Restrict quantum numbers of the produced systems i.e $I^G J^{PC} = 0^+ \text{even}^{++}$ for two-pion decay

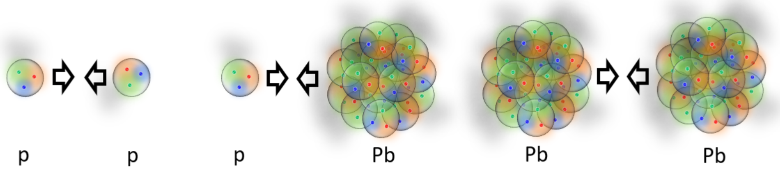


CMS $d\sigma_{\pi^+\pi^-}/dM$ result (7 TeV), arXiv:1610.08775v2



ATLAS result (13 TeV),
XIV ICFA School on Instrumentation in Elementary Particle Physics, R. Sikora

Charged-particle multiplicity and multiplicity density



- Study interplay between soft and hard QCD

AA collisions

- Direct relation to the QGP medium

pp collisions

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

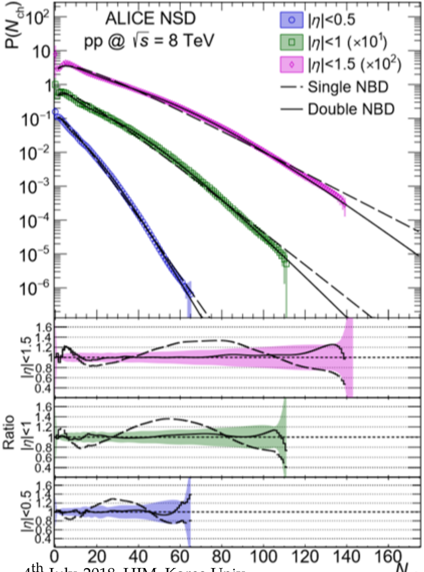
p-Pb collisions

- 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)

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



Single NBD fit

- Traditional parametrisation of particle multiplicity

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

- Single NBD fit overestimates the data at LHC

Double NBD fit

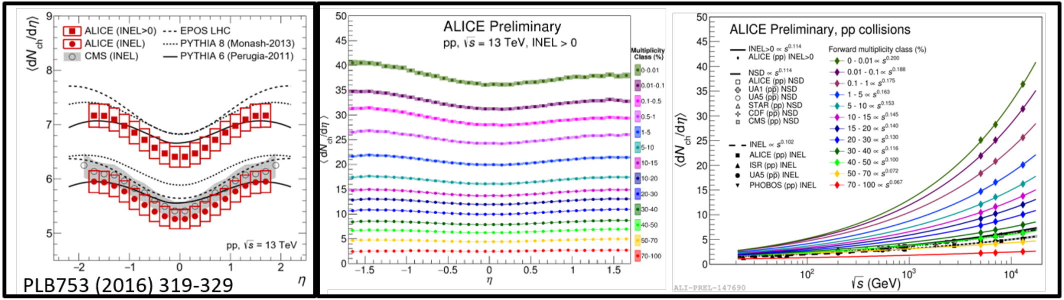
- Weighted sum of two NBD functions

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

  - α : soft and MPI (not primary)
  - $1-\alpha$: hard scattering

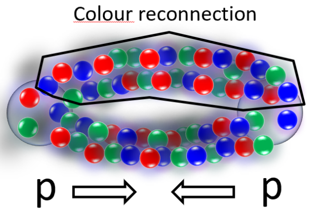
- Desribes the data better → some hints of MPI

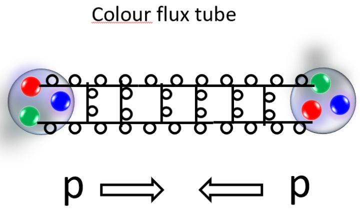
$\langle dN_{ch}/d\eta \rangle$ IN pp COLLISIONS



- Inclusive study : INEL $\propto s^{0.102}$, NSD $\propto s^{0.114}$ and $\text{INEL}_{>0}$[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)

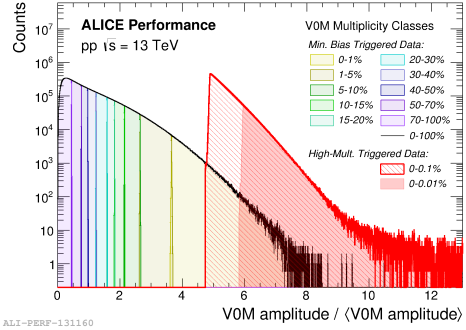
[1] INEL requiring at least one charged particle in $|\eta| = 1$

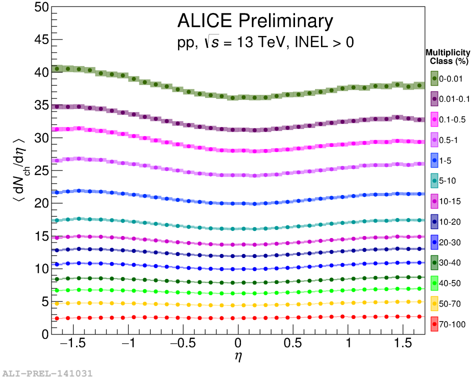




- Colour reconnection
  - clour strings from two hard scatterings are connected
  - two hard scatterings start to dependent in high mul pp collisions
  - the rise of $\langle p_{\mathrm{T}} \rangle$ with multiplicity like flow boost
- Core & corona (EPOS-LHC)
  - multiparton scattering froms a coulur-flux tube (Pomeron ladder)
  - Tube's high density region $\rightarrow$ thermalised as a flow-like(core)
  - Tube's edge region $\rightarrow$ hadronised as conventional

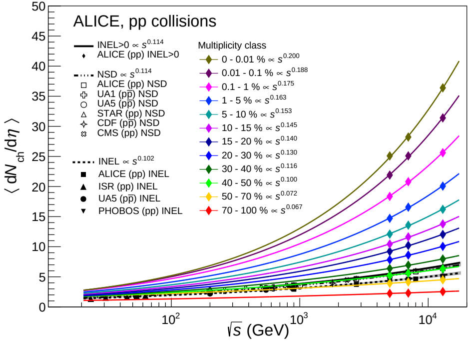
Multiplicity dependent $dN_{ch}/d\eta$

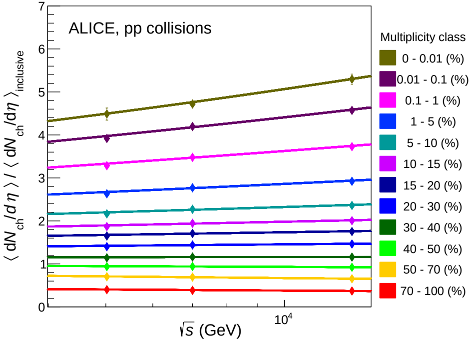




- Measurements provide input for the tuning of perturbative and soft QCD models
- Reference data for all multiplicity dependent study

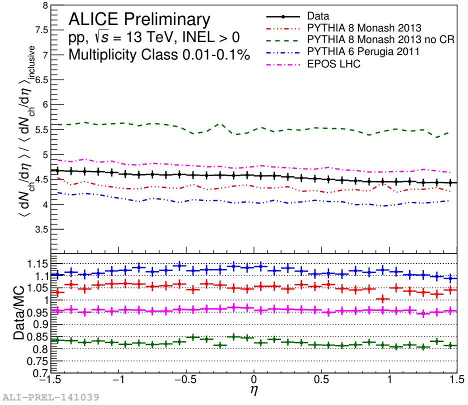
Multiplicity dependent $\langle dN_{ch}/d\eta \rangle$

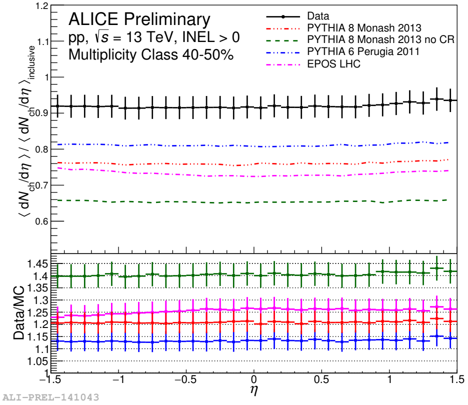




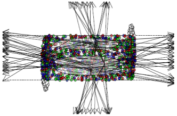
- The evolution of $\langle dN_{ch}/d\eta \rangle$ with $\sqrt{s}$ for different classes is parameterised by a power law function: $a\,s^b$
- The evolution of $\langle dN_{ch}/d\eta \rangle / \langle dN_{ch}/d\eta \rangle_{\text{inclusive}}$ vs $\sqrt{s}$

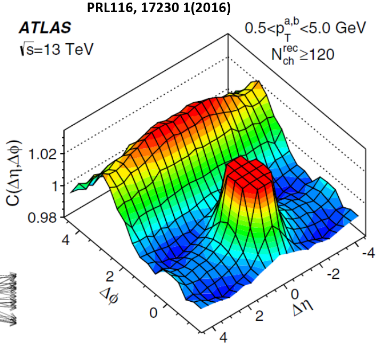
Multiplicity dependent $\langle dN_{ch}/d\eta \rangle$

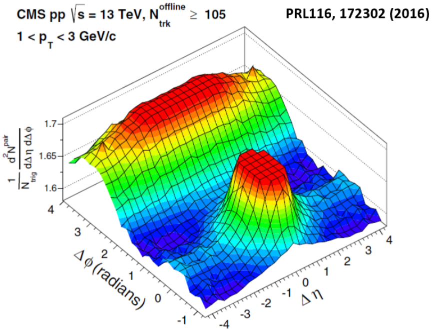




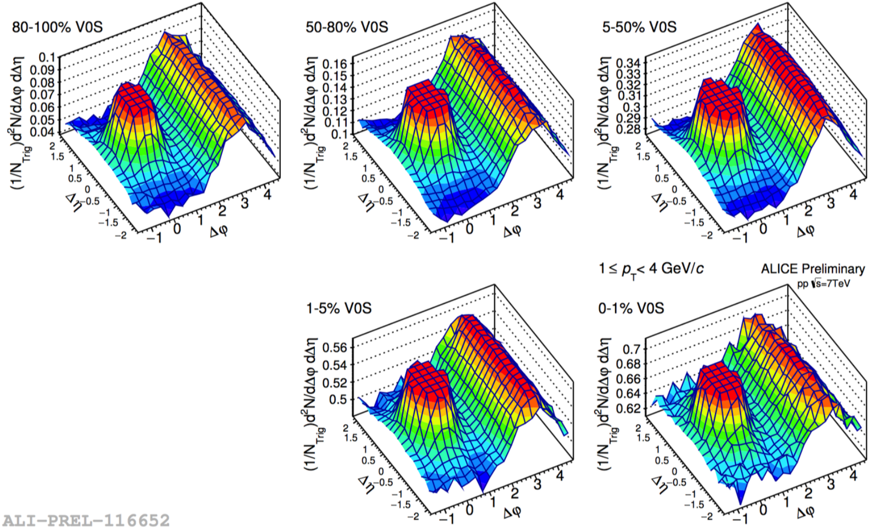
- The models generally agree within $\sim 20\%$ with data, except PYTHIA8 no Color-Reconnection
- Hydrodynamically inspired EPOS LHC also agrees well with data



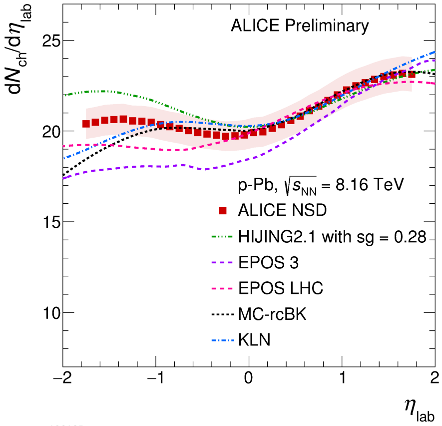




- "Ridge"-like structure is clearly seen at $\Delta\phi \sim 0$
- Reproduced with MC that a collectivity is implemented
  - PYTHIA8 : color reconnection for MPI
  - EPOS-LHC : core (flow-like) and corona(normal hadronisation)


80-100% V0S
50-80% V0S
5-50% V0S
1-5% V0S
0-1% V0S
$1 \le p_T < 4$ GeV/c
ALICE Preliminary
pp √s=7TeV
(1/N_Trig)d²N/dΔφ dΔη
Δη
Δφ
ALI-PREL-116652

$\langle dN_{ch}/d\eta \rangle$ 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)

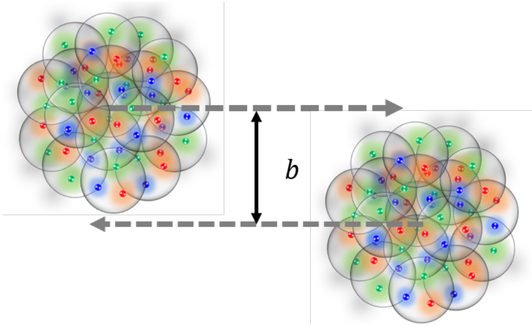
– collective effects like flow included
– reproduces Pb-going side

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 $\eta_{lab} > -1.3$



Impact parameter (b)

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

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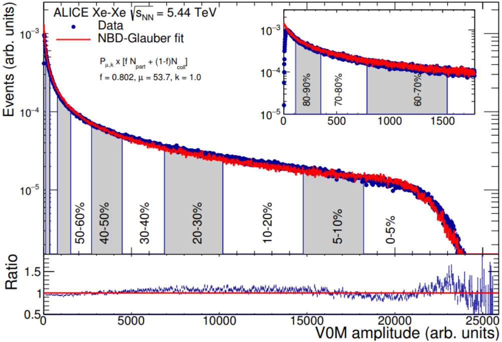


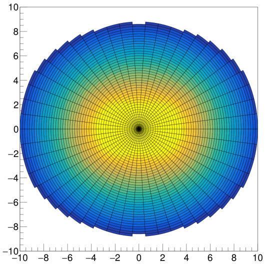
Centrality estimation for Xe–Xe

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

- Xe ion (deformed)

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

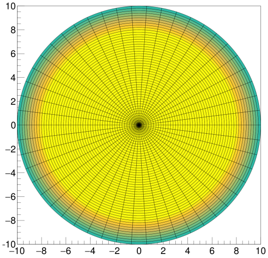
  - ρ_0 : the nucleon density
  - The nuclear skin thickness $a = 0.59 \pm 0.07$ fm [1]
  - Nuclear radius $R(\vartheta) = R_0[1+\beta_2 Y_{20}(\vartheta)]$



- Pb ion (spherical)

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

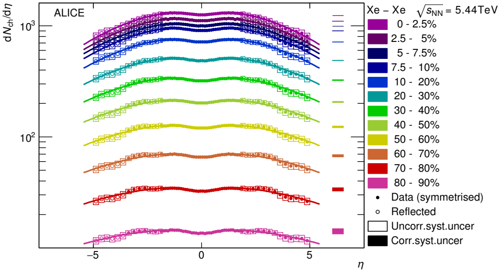
  - ρ_0 : the nucleon density
  - The nuclear skin thickness $a = 0.546 \pm 0.01$ fm
  - Nuclear radius $R = 6.62 \pm 0.06$ fm



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

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

arXiv:1805.04432



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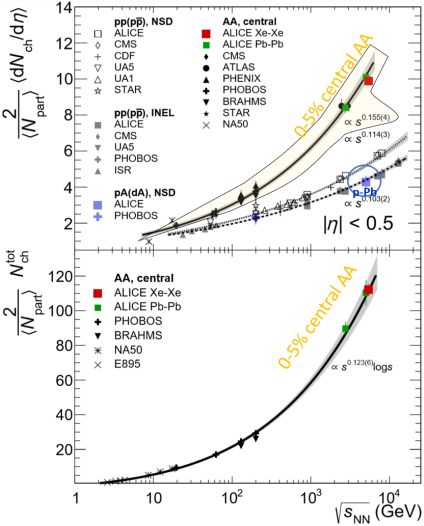
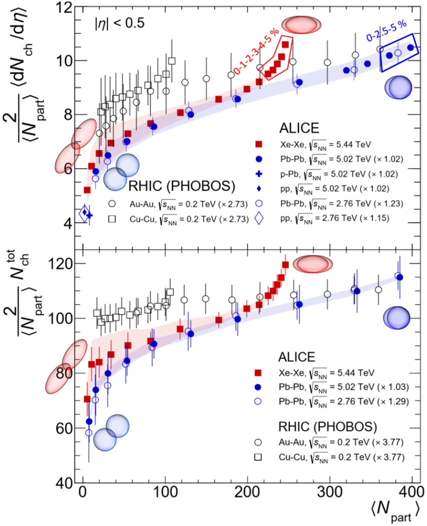


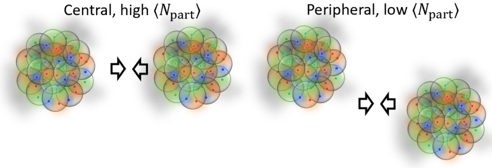
$\frac{2}{\langle N_{part} \rangle} \langle dN_{ch}/d\eta \rangle$ and $\frac{2}{\langle N_{part} \rangle} N_{ch}^{tot}$

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

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

arXiv:1805.04432





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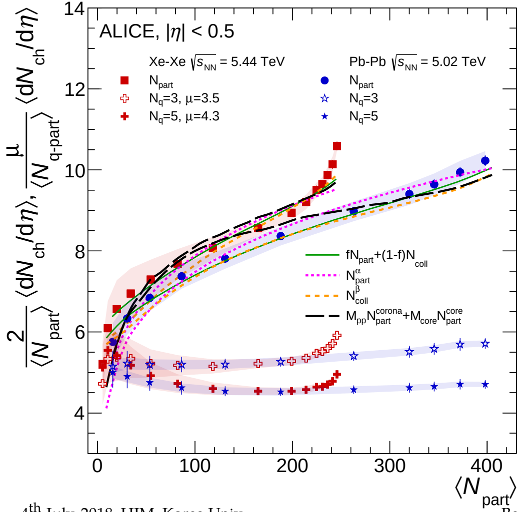

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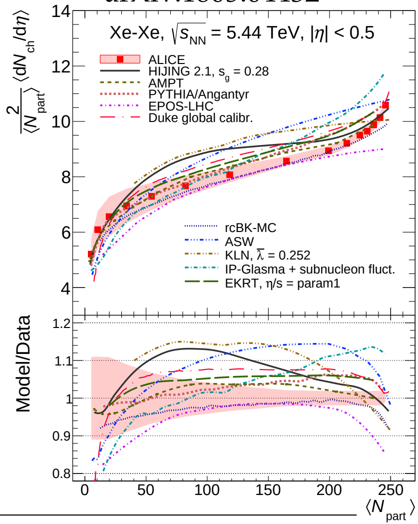

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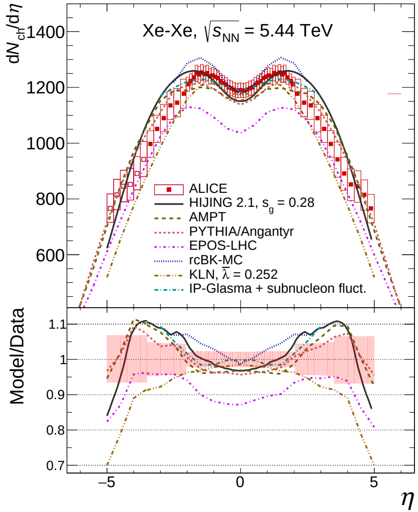

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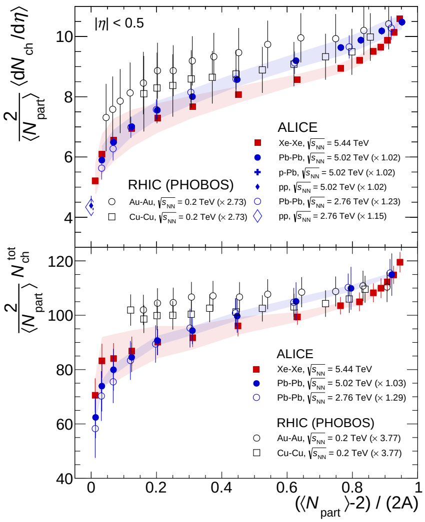

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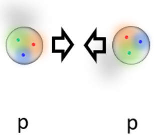
Underlying events

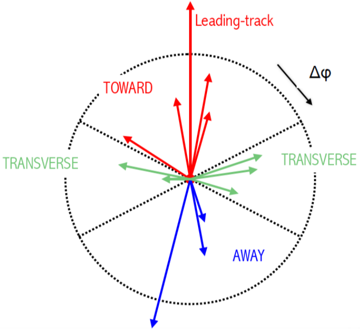


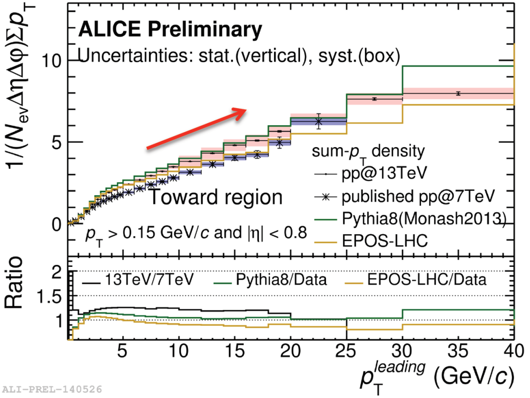
Average charged-particle density vs. $p_{T,LT}$

Toward and Away regions

- Collect fragmentation from hard scattering

$\rightarrow$ increasing monotonically

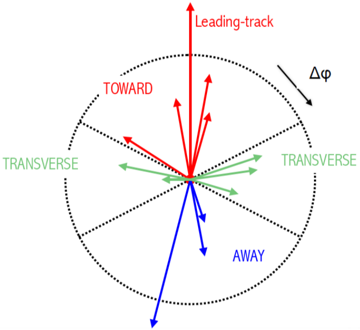


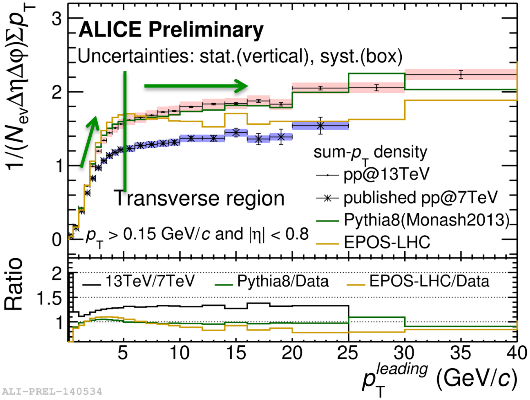


Average charged-particle density vs. $p_{T,LT}$

Transverse regions

- Underlying Event
- First increase : MPI
- flattens : Soft processes





Soft QCD measurements at LHC have deeply improved
Last 8 years

- pp collisions at $\sqrt{s} = 0.9, 2.76, 7, 8$ and 13 TeV
- p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76, 5.02$ and 5.5 (planned) TeV
- Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV

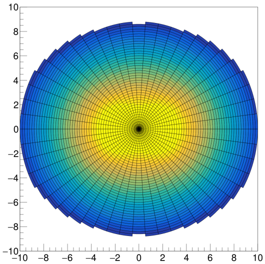
- ALICE has better performance on soft QCD measurements
- Soft QCD : Diffraction, underlying
- Semi soft QCD : Multiplicity, MPI
- Models have been tuned .. still further constraints

Backup

- Xe ion (deformed)

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

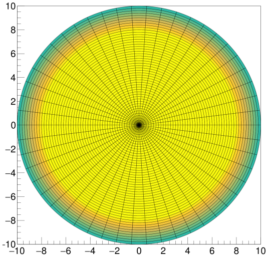
  - ρ_0 : the nucleon density
  - The nuclear skin thickness $a = 0.59 \pm 0.07$ fm [1]
  - Nuclear radius $R(\vartheta) = R_0[1+\beta_2 Y_{20}(\vartheta)]$



- Pb ion (spherical)

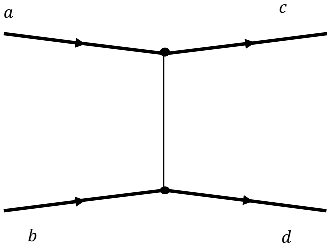
$$\rho(r,\vartheta) = \rho_0 \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

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



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

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



$$t = (p_{\mathrm{a}} - p_{\mathrm{c}})^2 \ll \sqrt{s}$$

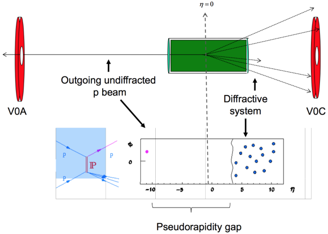
- Help us understand QCD in the non-perturbative regime ($t \sim 0$ or $q^2 < \Lambda^2_{\mathrm{QCD}}$)
- By Regge theory [1] [2] [3], diffraction proceeds via the exchange of Pomerons ($gg_{\text{leading order}} + ggg_{\text{next leading order}} + \cdots$)

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

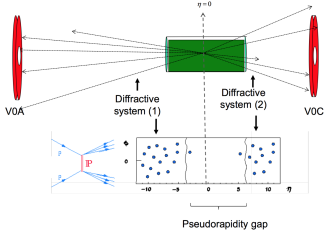
[2] A.B.Kaidalov,Phys.Rep.50,157,1979

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

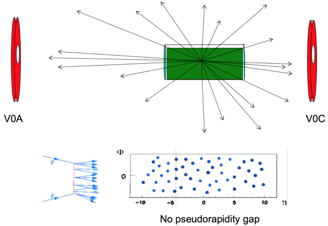
SD, DD and ND



SD

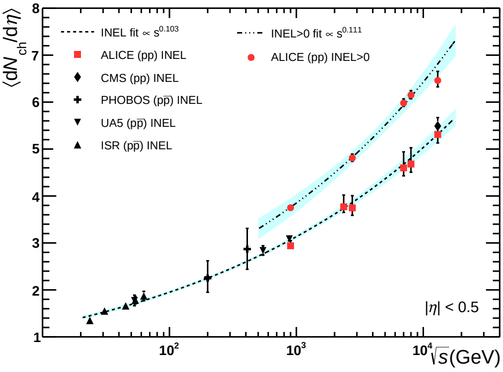


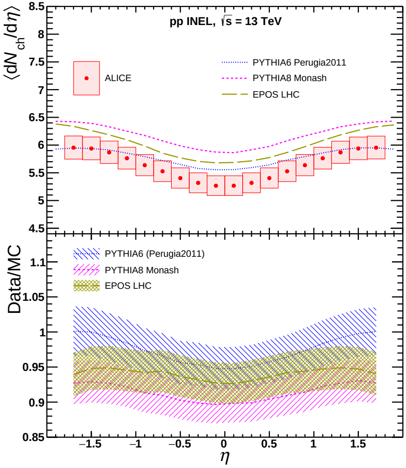
DD



ND

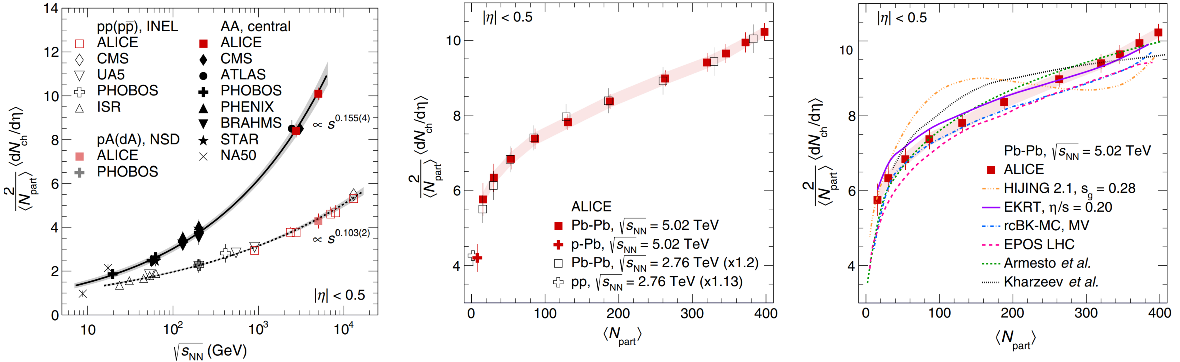
N_{ch} IN PP COLLISIONS





$$\mathrm{INEL} \propto s^{0.103}$$
$$\mathrm{INEL}_{>0} \propto s^{0.111}$$

N_{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

- Published multiplicity papers

Type	$\sqrt{s}$ (TeV)	paper
pp	0.9, 2.76, 7 and 8	Eur. Phys. J. C 77 (2017) 33
	13	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[1] : ND + SD + DD + CD ...
  - NSD : ND + DD (to ignore large uncertainty from SD)
  - $\text{INEL}_{>0}$: INEL + at least one activity in $|\eta| = 1$ (effective filter for SD and DD events)

[1] INEL = 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	$\sqrt{s_{NN}}$ (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 saturation[1]
  - Providing constraints to the initial state and small Bjorken-x modeling

[1] Different descriptions of the upper limit in growth of the parton density

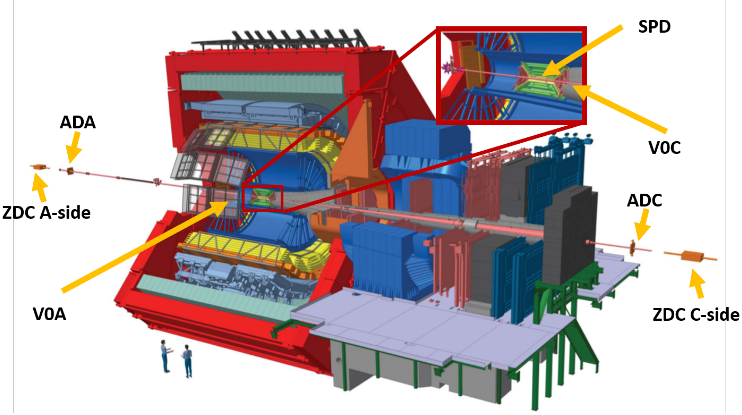
$\langle dN_{ch} d\eta \rangle$ in Pb − Pb and Xe − Xe collisions

- Published (and ongoing) multiplicity papers

Type	$\sqrt{s_{NN}}$ (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

- 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

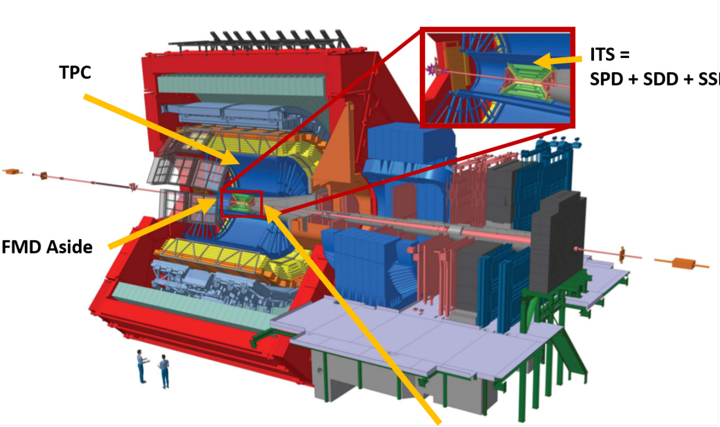
AD (Alice Diffraction)

- 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)

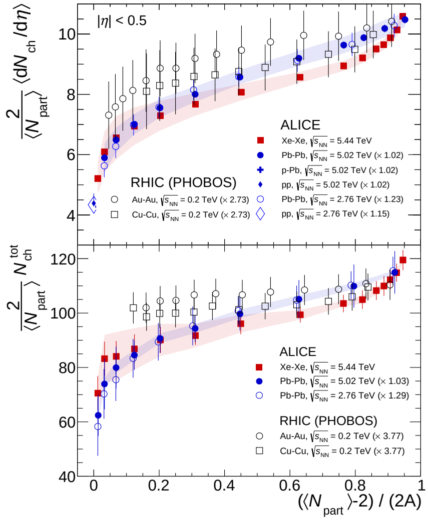
- 6 layers of Si detectors
- Containing SPD

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



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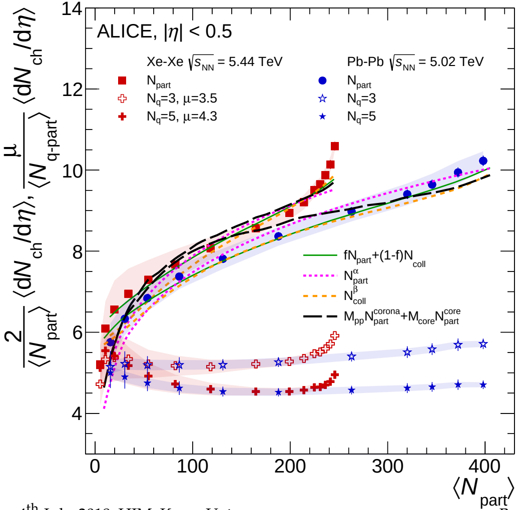

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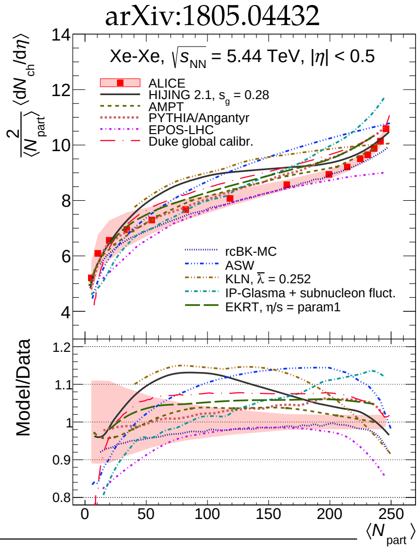

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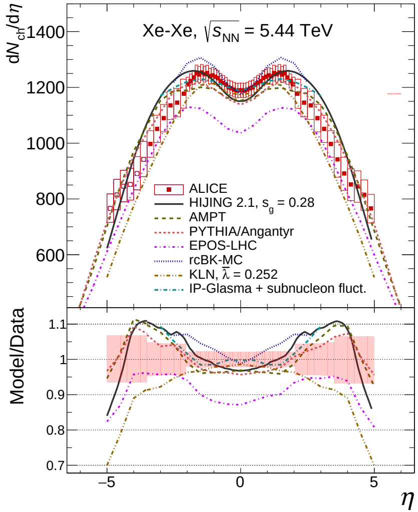

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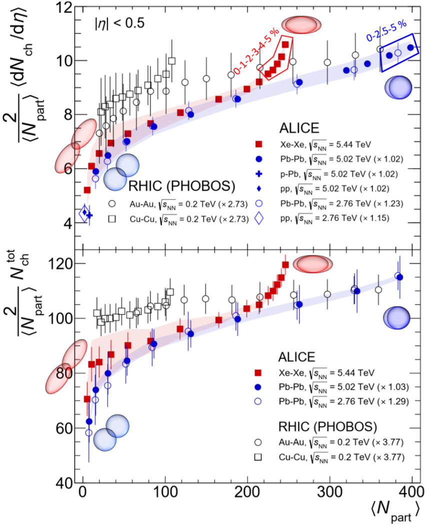

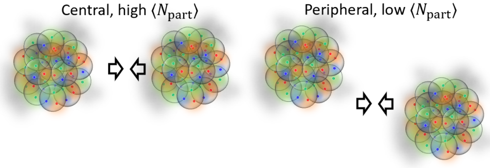

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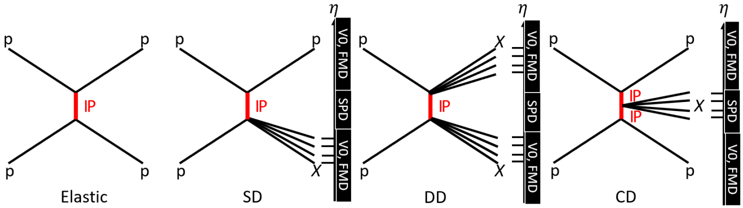
Inelastic cross-section in pp collision

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



- SD : Activity in one-side V0-FMD and no activity in SPD and other side V0-FMD
- DD : Activities in both side V0-FMD and no activity in SPD
- CD : Activity in TPC and no activities in both side V0-FMD (double-gap event)

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

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