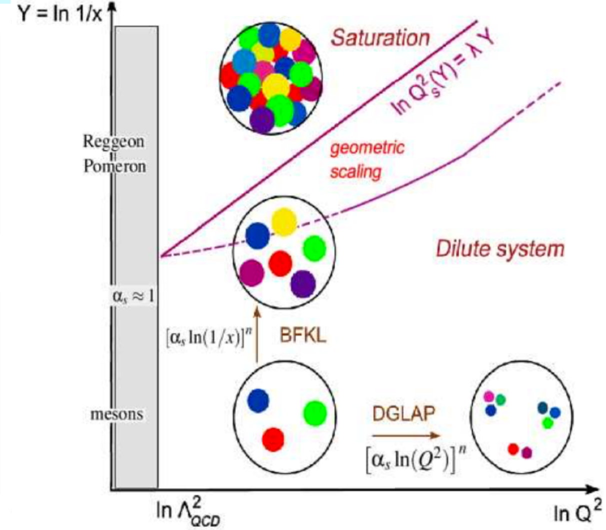
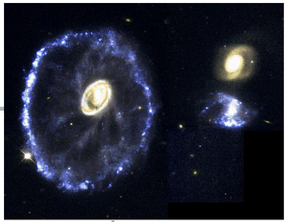
What's really new at LHC energies ?

HADRON PHYSICS DEPARTMENT

Mihai Petrovici, Summer Student Program, Bucharest, July 31, 2019

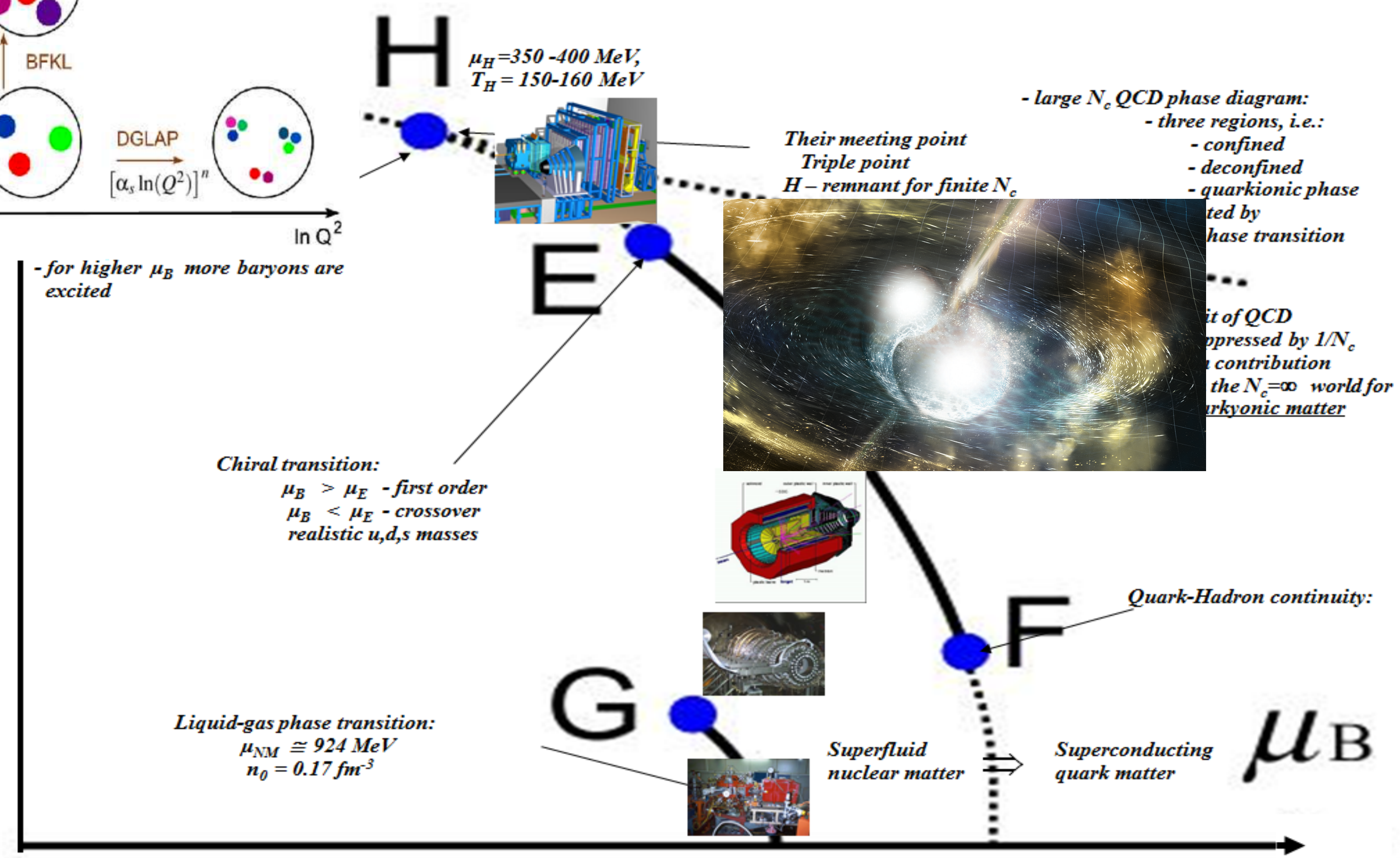


What is really new at LHC ?



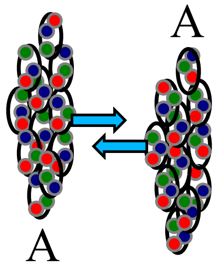
Expectations based on QCD

QCD Critical Points

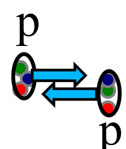


K. Fukushima and T. Hatsuda, Rept.Prog.Phys.74(2011)014001

p+p high charged particle multiplicities @ LHC

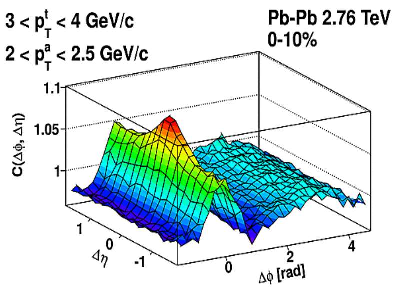


Long range near side correlations

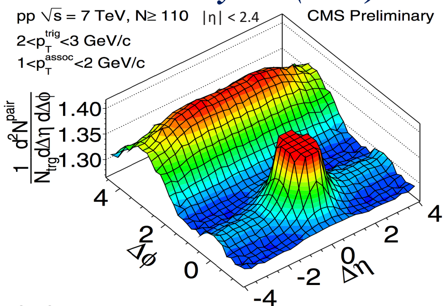


C.Aamodt et al., ALICE Collaboration, Eur.Phys.J. C68(2010)345

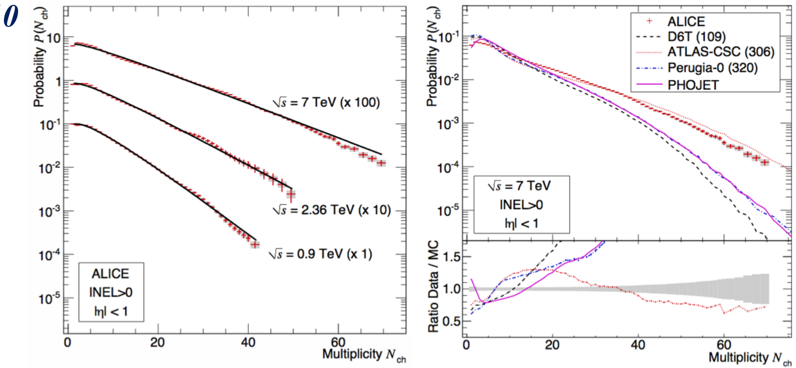
T.Guido and R.Gunther, CERN Seminar, 21.09.2010
J. Phys. G Nucl. Part. Phys. 38(2011)124051



ALICE Phys.Lett. B708(2014)249

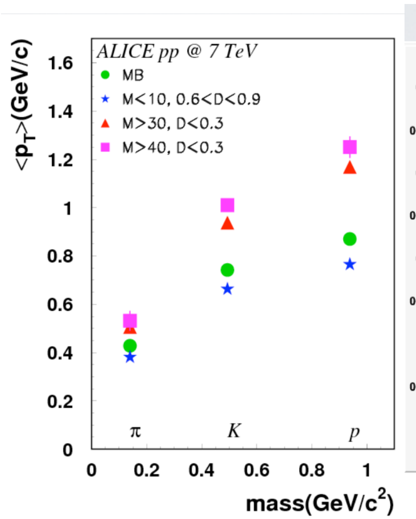


CMS

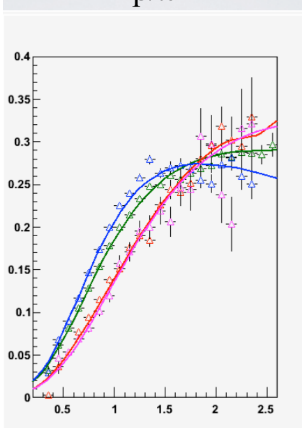


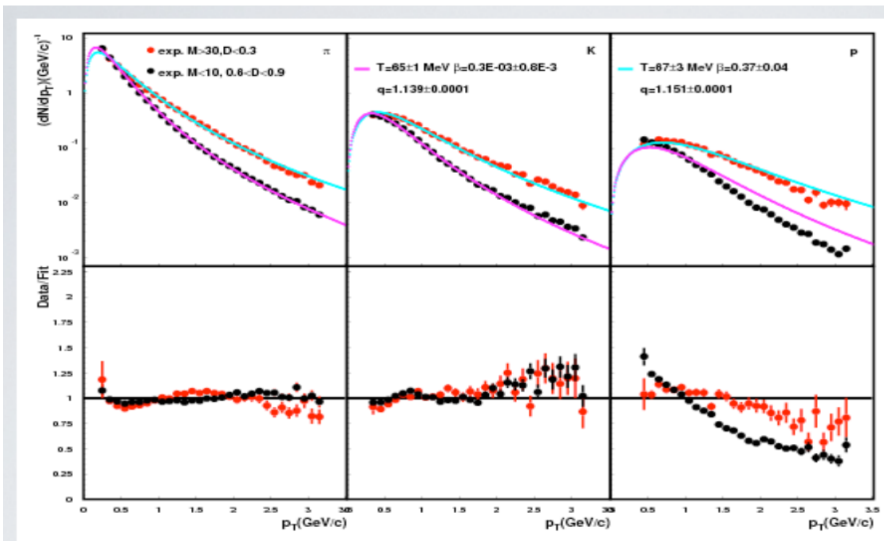
C.Andrei et al., ALICE Week, PWG2-Soft Physics, 9.11.2010
C.Andrei et al., Paper draft, 14.03.2011

$$f(p_t) = m_t \int_{-Y}^{Y} cosh(y)dy \int_{-\pi}^{\pi} d\phi \int_{0}^{R} rdr(1+\frac{q-1}{T}(m_t cosh(y)cosh(\rho) - p_t sinh(\rho)cos(\phi)))^{-1/(q-1)}$$



p/π





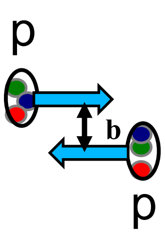
M<10;0.6<D<0.9
T= 65±1
<β>=0.3e-3±0.0008
q=1.139±0.0001

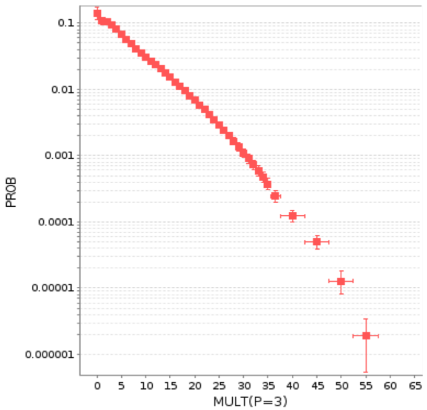
M>30;D<0.3
T= 67±3
<β>=0.37±0.04
q=1.151±0.0001

$$D = \frac{|\sum_i p_t^i|}{\sum_i |p_t^i|}|_{\eta>0},$$

p+p high charged particle multiplicities @ LHC

pp collision geometry

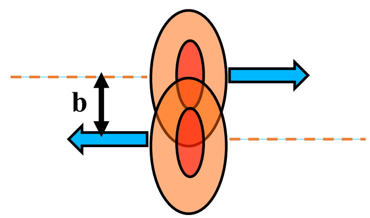




CMS JHEP 1101(2011)079

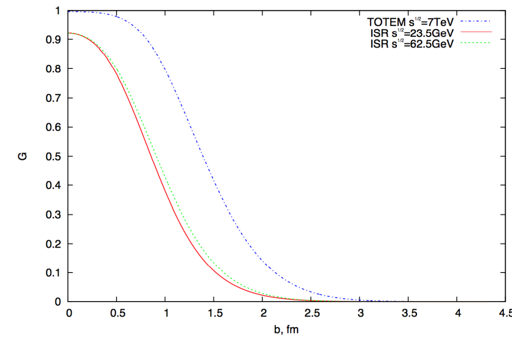
PYTHIA

$$\rho(r) \propto \frac{1-\beta}{a_1^3} \exp\left(-\frac{r^2}{a_1^2}\right) + \frac{\beta}{a_2^3} \exp\left(-\frac{r^2}{a_2^2}\right)$$



or

I.M. Dremin, et al., arXiv:1306.5384 [hep-ph]



Using TOTEM data on the differential cross section of elastic pp-scattering at 7 TeV G. Antchev et al. EPL 101 (2013) 21004

$$O(b) \propto \frac{(1-\beta)^2}{2a_1^2} exp\{-\frac{b^2}{2a_1^2}\} + \frac{2\beta(1-\beta)}{a_1^2+a_2^2} exp\{-\frac{b^2}{a_1^2+a_2^2}\} + \frac{\beta^2}{2a_2^2} exp\{-\frac{b^2}{2a_2^2}\}$$

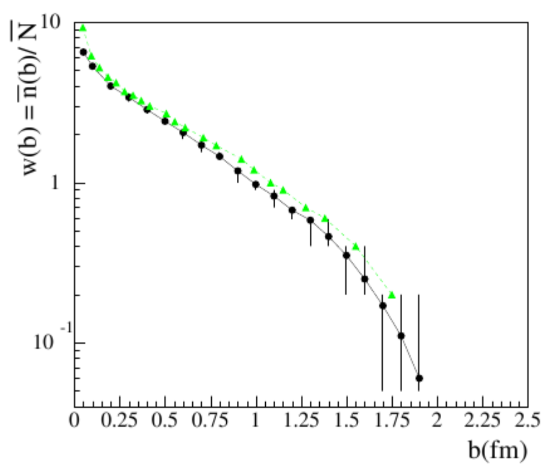
$$\sigma_{in}(b,s) = 1 - e^{-kO(b)}$$

$$\sigma_{in} = 2\pi \int_0^\infty b\sigma_{in} db$$

Geometrical model of particle production A.Bialas and E.Bialas, Acta.Phys.Polonica B5(1974)373 and references therein

$$\int_0^{w(b)} \psi(w)dw = \frac{1}{\sigma} \int_b^\infty d^2b\sigma(b)$$

$$\mathrm{w(b)}=\bar{n}(b)/\bar{N} \quad \bar{N}\mathrm{P(n)}=\psi(z,\bar{N}) \quad \mathrm{z=n}/N$$



p+p high charged particle multiplicities @ LHC
Bjorken energy density

$$\epsilon_{Bj} = \frac{dE_t}{dy}\frac{1}{S_t \tau}$$

$$\frac{d\bar{E}_t}{dy} \approx 3\left(< m_t > \frac{dN}{dy}\right)_{\pi^+} + 4\left(< m_t > \frac{dN}{dy}\right)_{K^+,p}$$

$\varepsilon_{Bj} \cdot \tau$

- Pb+Pb 0-5% centrality

B.Abelev et al., ALICE Coll., Phys.Rev. C88(2013)044910

17.44 ± 0.965 GeV/fm^2

<b> =2.46 fm

r_{Pb}=6.62 +/- 0.06 fm

At the highest multiplicity

- *$\varepsilon_{Bj} \cdot \tau$ has similar value for:*
  - *the highest multiplicity in pp*
  - *&*
  - *the most central Pb-Pb*
- *Is the subsequent evolution of the systems similar?*

- p+p 7 TeV
  - N_{ch}=130; $|\eta| < 2.4$
  - relative yields $|y|<0.1$ *V.Khachatryan et al., CMS Coll., Eur.Phys.J C72(2012)2164*
  - Nch $|\eta| < 2.4$ - $|\eta| < 0.8$ PYTHIA
    => 5th mult. bin. of above presentation
  - b=0.15 fm
  - r_p = 1.081 fm (σ_{in} = 73.5 mb)
  - $<p_T>$ - EPOS *K.Werner et al., arXiv:[nucl-th]13121233*

9.9 +/- 1.4 GeV/fm^2

Bjorken energy density

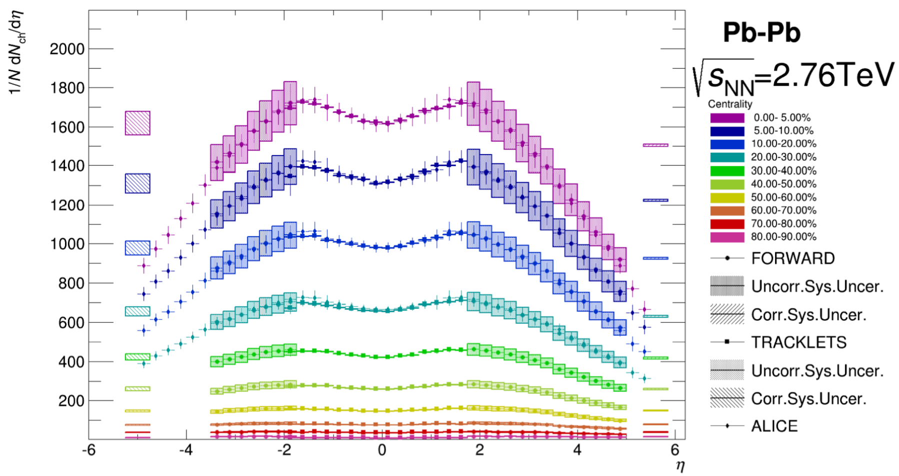
Basic assumption:
“central-plateau” structure for particle production as a function of rapidity

$$\varepsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{S_T\tau}$$

$$\frac{dE_T}{dy} \approx \frac{3}{2}(< m_T > \frac{dN}{dy})_{\pi^{\pm}} + 2(< m_T > \frac{dN}{dy})_{K^{\pm},p,\overline{p}} \qquad < m_T >= \sqrt{< p_T >^2 + m_0^2}$$

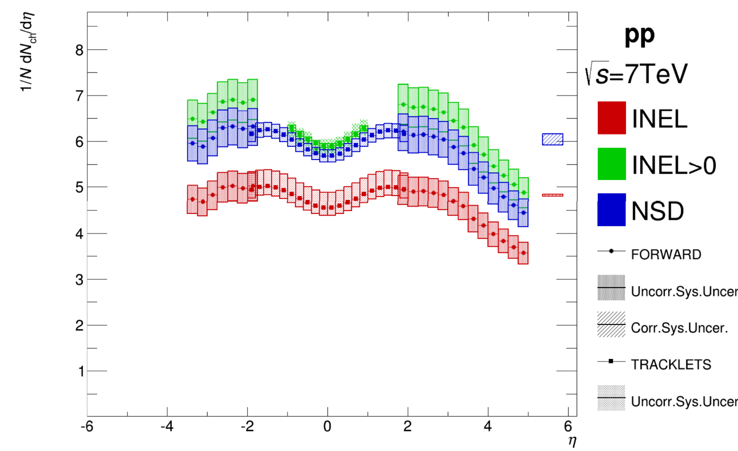
Pb+Pb

- highly non-homogeneous initial state
- Bjorken energy estimate is based on S_T supposing a uniform distribution



p+p

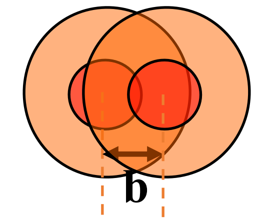
S_T estimated based on geometrical model approach



Bjorken energy density - p+p at 7 TeV

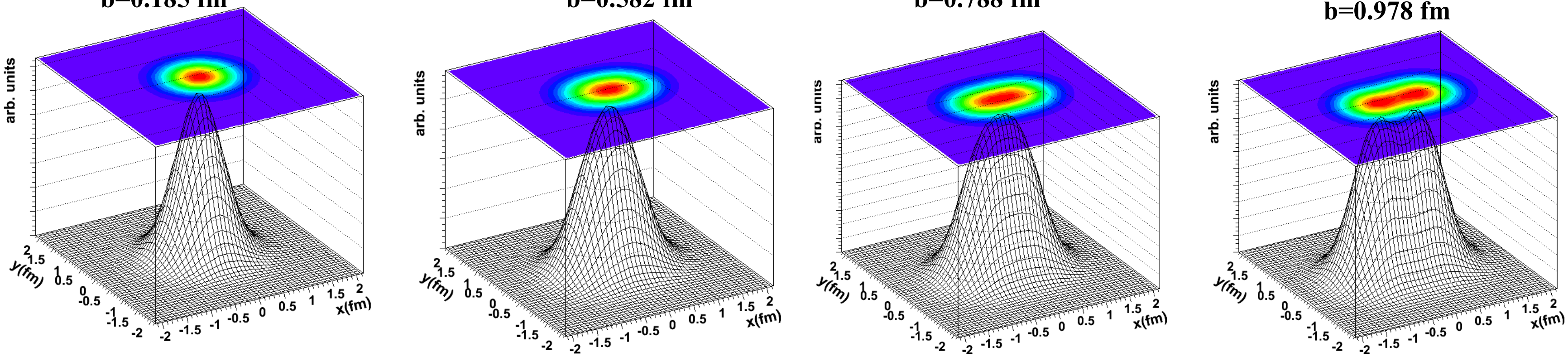
$$\rho(r) \propto \frac{1-\beta}{a_1^3} \exp\left(-\frac{r^2}{a_1^2}\right) + \frac{\beta}{a_2^3} \exp\left(-\frac{r^2}{a_2^2}\right)$$

ATLAS Monte Carlo Tunes for MC09,
ATL-PHYS-PUB-2010-002
β =0.8; a_2/a_1=0.7

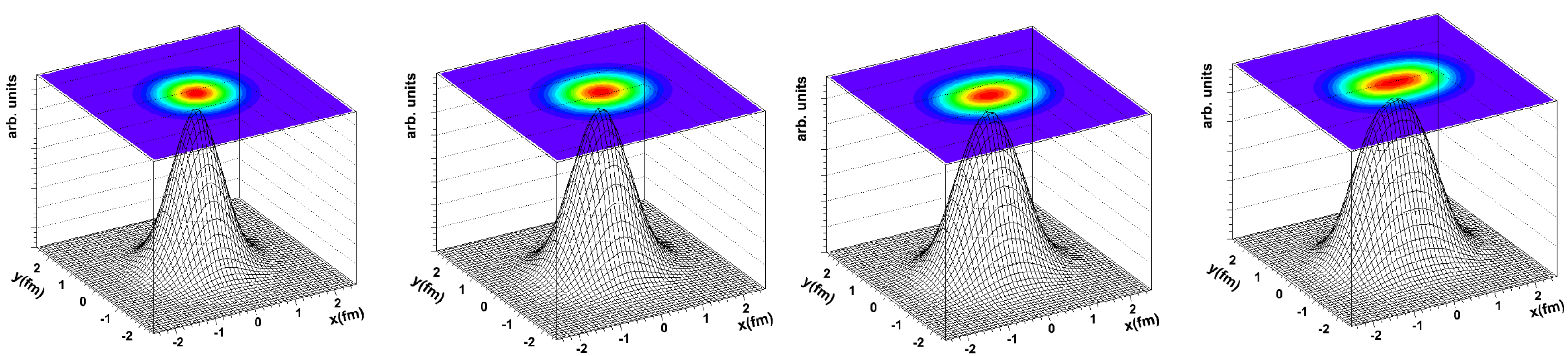


r_p=0.841 fm

b=0.185 fm **b=0.582 fm** **b=0.788 fm** **b=0.978 fm**



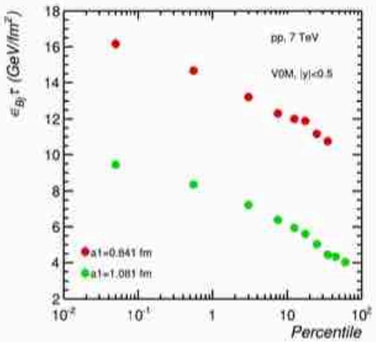
r_p=1.081 fm



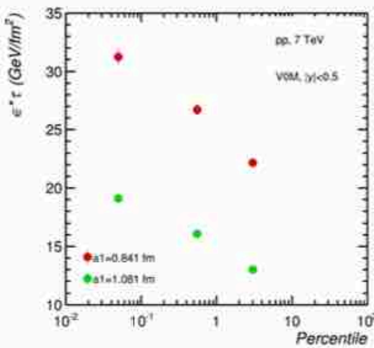
$\varepsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{S_T\tau}$ Bjorken energy density - p+p at 7 TeV

$$\frac{dE_T}{dy} \approx \frac{3}{2}(< m_T > \frac{dN}{dy})_{\pi^\pm} + 2(< m_T > \frac{dN}{dy})_{K^\pm,p,\bar{p}} \quad < m_T >= \sqrt{< p_T >^2 + m_0^2}$$

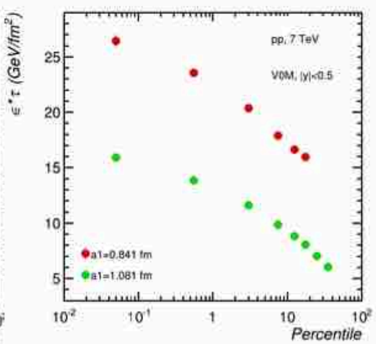
Geometrical overlap for the corresponding r_p



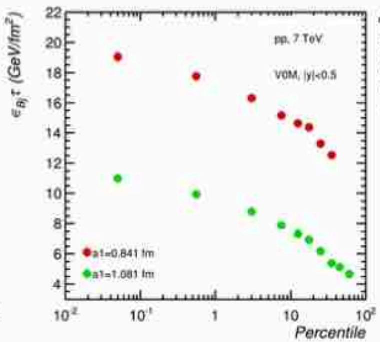
Overlapped zone corresponding r=0.25fm in each of colliding protons



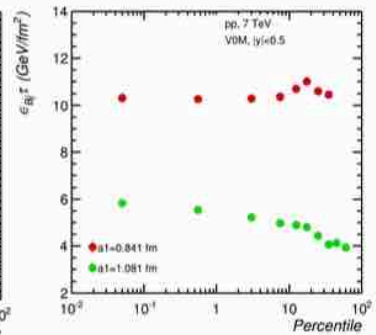
Overlapped zone corresponding to σ_{a2} complementary to r=0.25fm



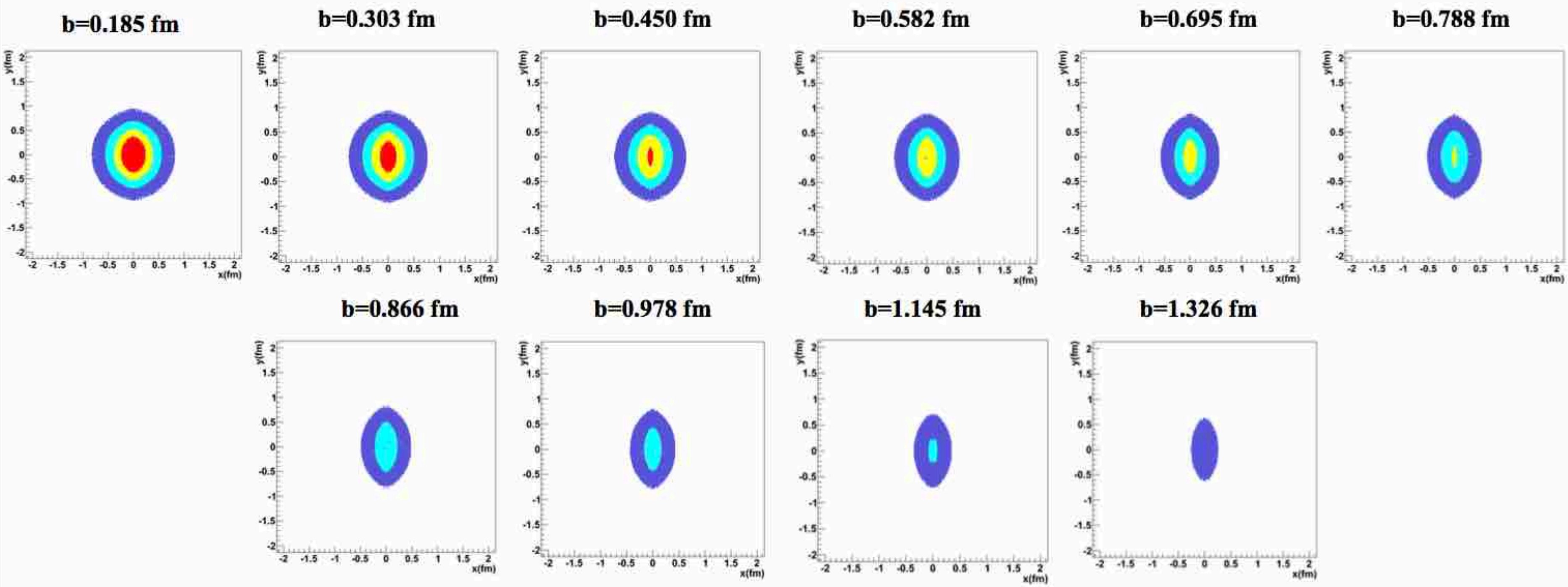
Overlapped zone corresponding to σ_{a1} complementary to σ_{a2}



Overlapped zone corresponding to r_p complementary to σ_{a1}



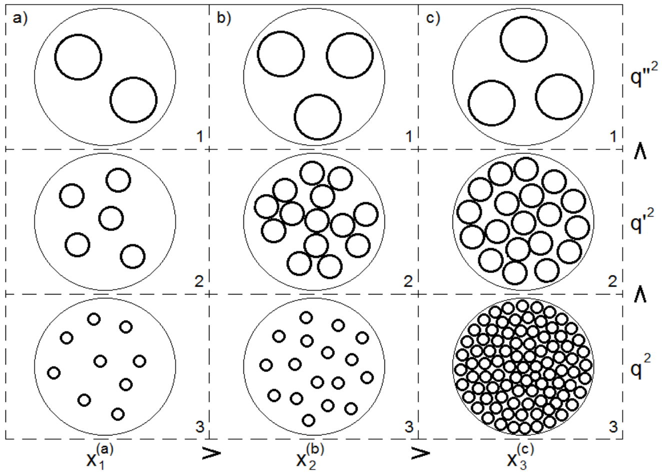
r_p = 0.841 fm



p+p high charged particle multiplicities @ LHC

Transverse flow – BGBW fits

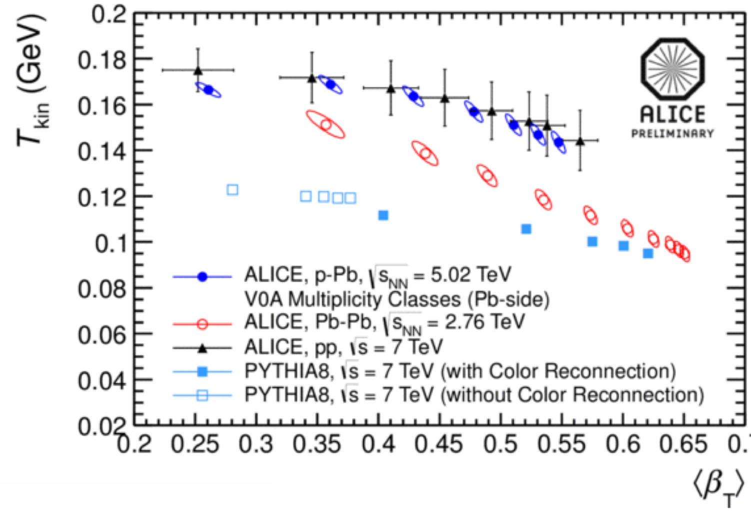
ALICE Collaboration,
Nucl.Phys. A931(2014)c888



L.V. Gribov et al, Phys.Rep. 100(1983)1

$$E\frac{d^3N}{dp^3} \sim f(p_t) = \int_0^R m_T K_1(m_T cosh\rho/T_{fo}) I_0(p_T sinh\rho/T_{fo}) rdr$$

$$\text{where } m_T = \sqrt{m^2+p_T^2};\ \beta_r(r) = \beta_s\left(\frac{r}{R}\right)^n;\ \rho = tanh^{-1}\beta_r.$$

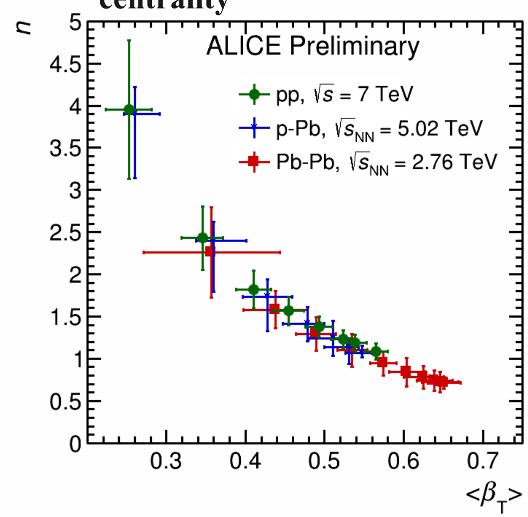


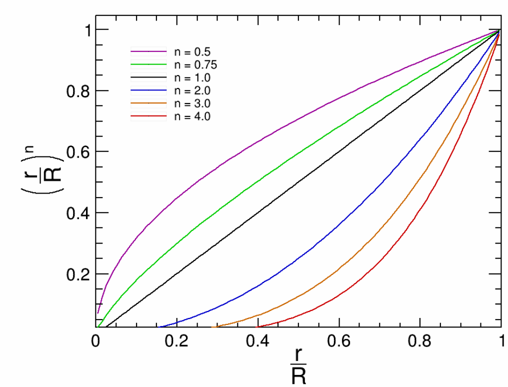
multiplicity

centrality

- *@ 7 TeV increased MPI & rescattering*
  large energy transfer in a collision volume of proton size
- *λ_{QGP} ~ 0.2 -0.3 fm*
- *close to thermalization*

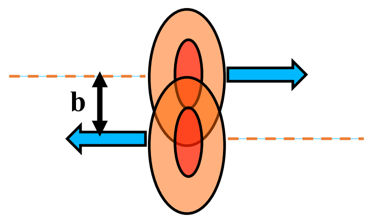
<u>*Does it follow an explosion/expansion type dynamics ?*</u>

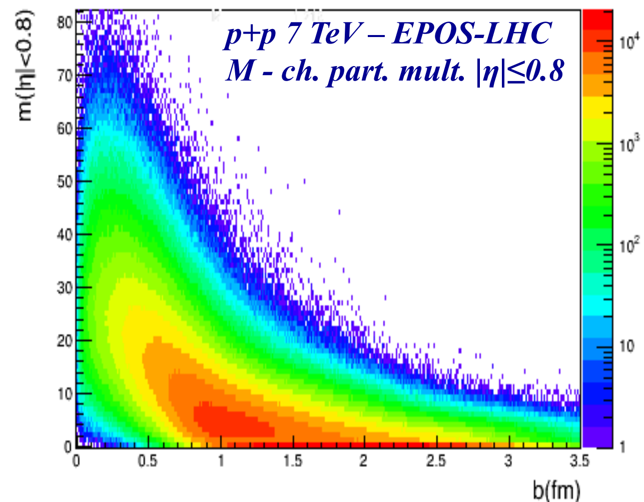


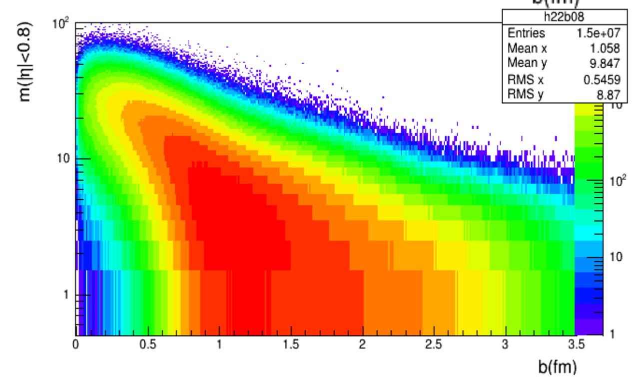


C. Andrei, ALICE Coll., QM2014

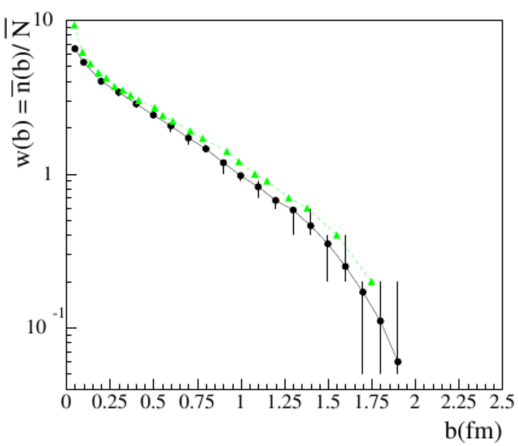
Collision geometry in p+p
N_{ch} – b correlation



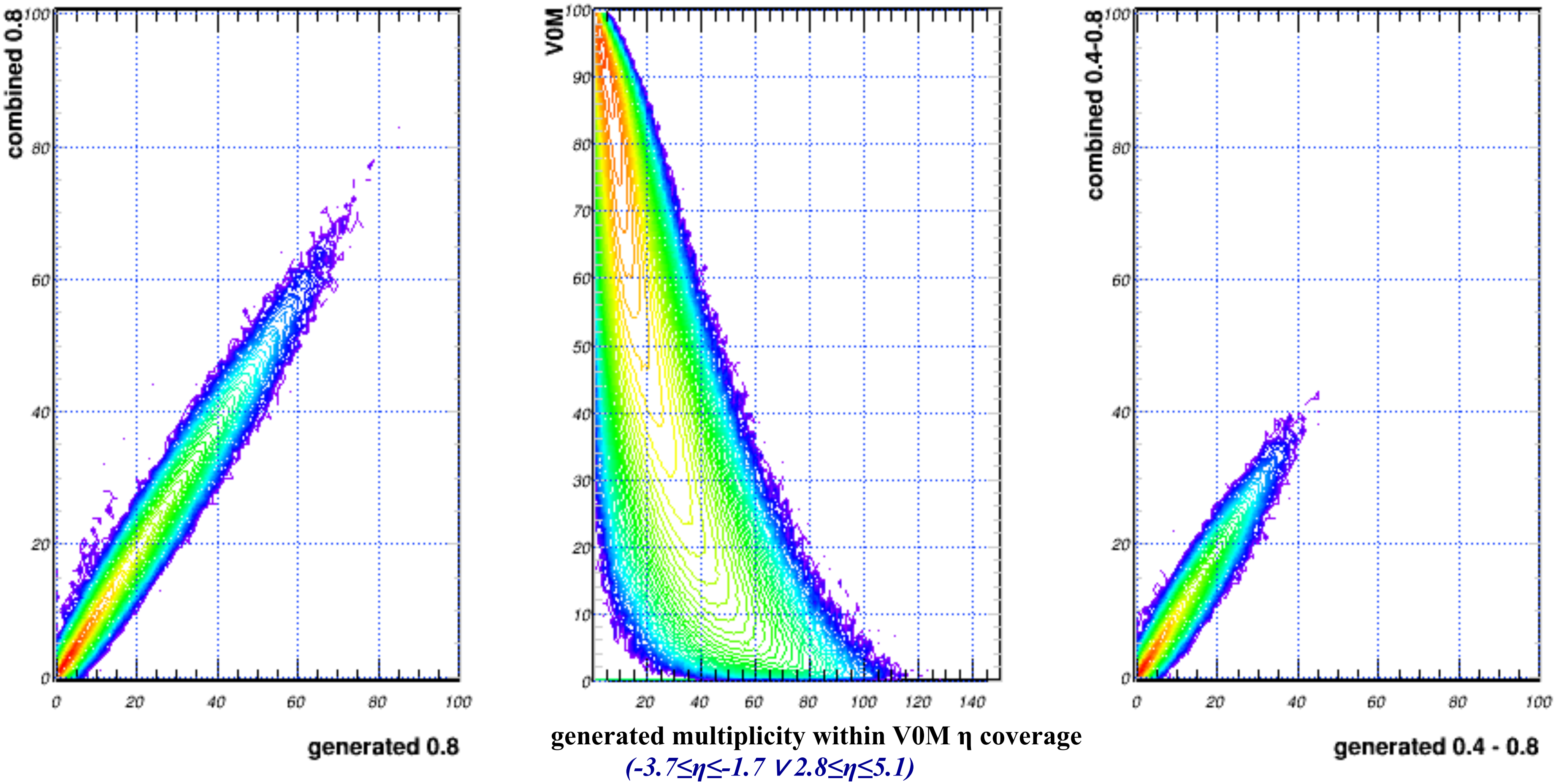




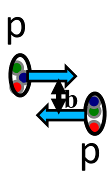
Geometrical model of particle production
A.Bialas and E.Bialas, Acta.Phys.Polonica B5(1974)373 and references therein

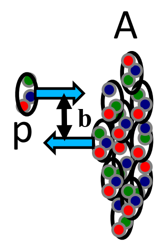


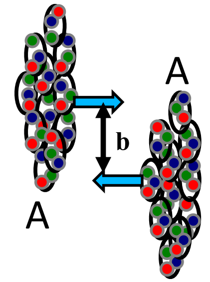
Collision geometry - p + p
correlation between measured and real observables
PYTHIA

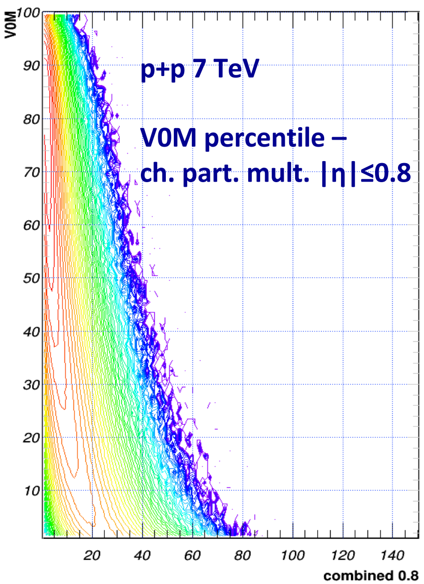


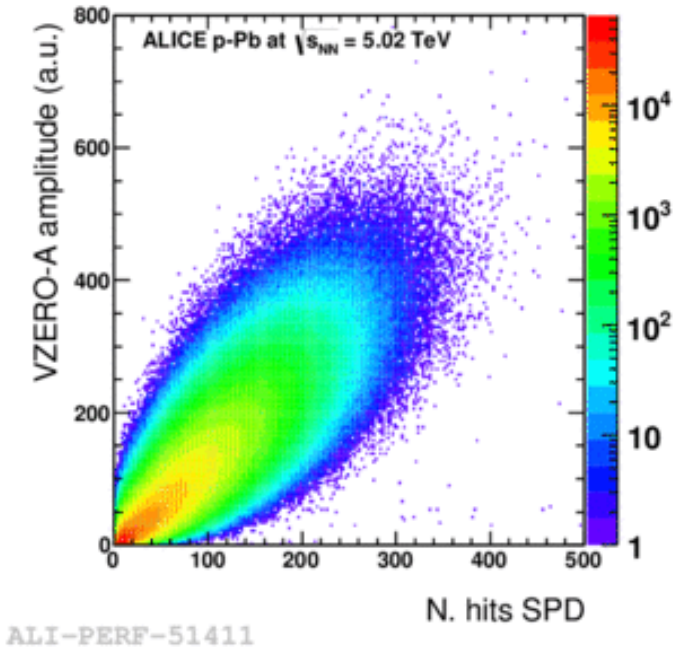
Collision geometry - A+A vs. p+p based on measured observables

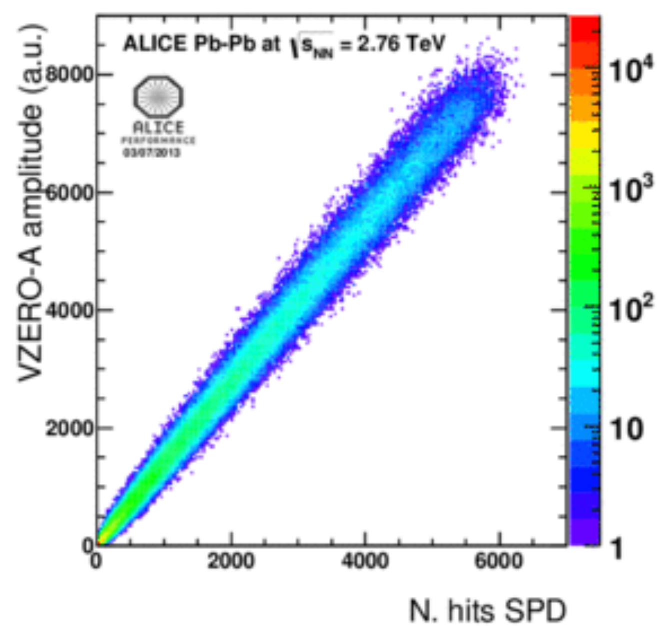




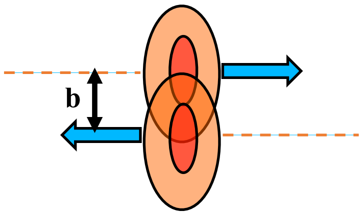




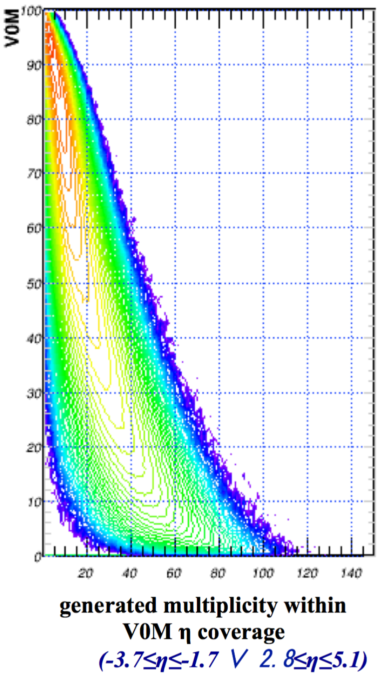


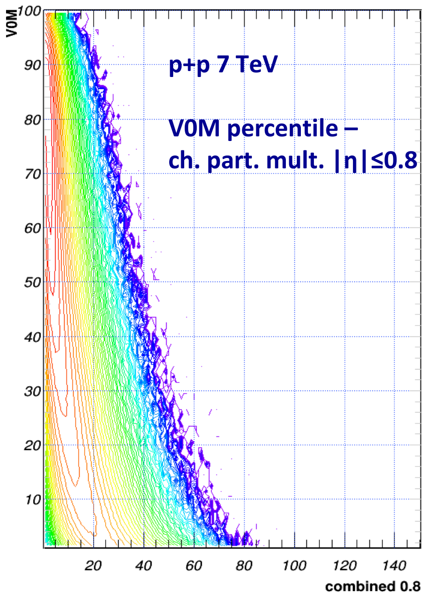


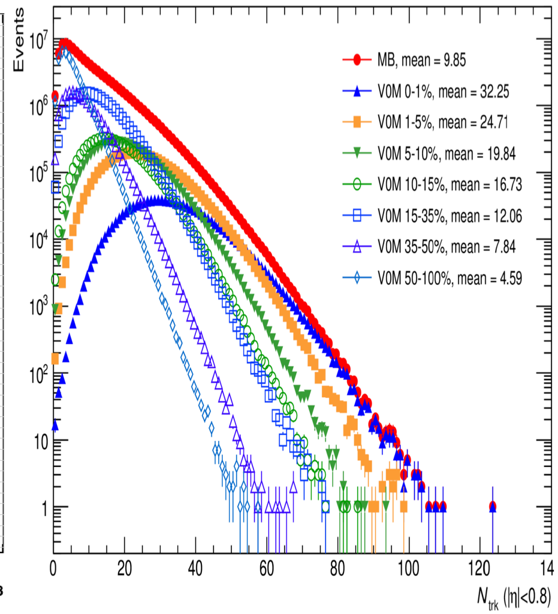
Collision geometry p+p based on measured observables

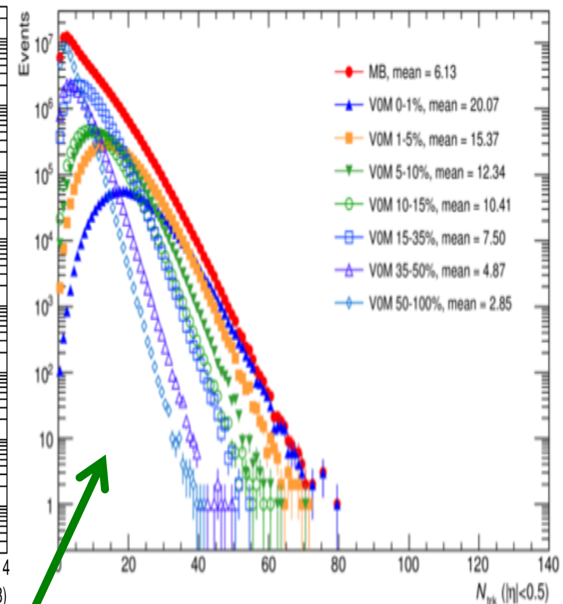


We face problems in comparing with theory predictions !







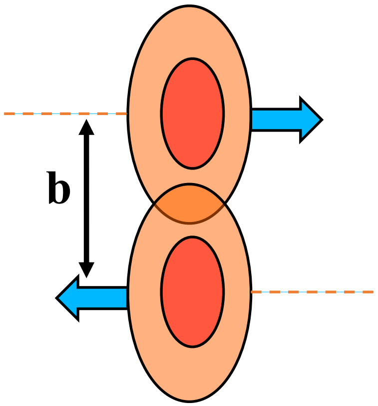


They consider $\langle dN_{ch}/d\eta \rangle$

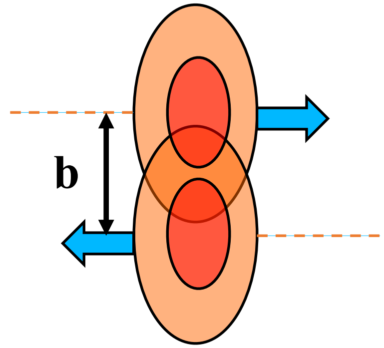
In reality we select this

V0M	$\langle dN_{ch}/d\eta \rangle$	V0M	$\langle dN_{ch}/d\eta \rangle$
0-0.1%	25.3 ± 0.8	0.1-1%	20.8 ± 0.6
1-5%	16.5 ± 0.5	5-10%	13.5 ± 0.4
10-15%	11.5 ± 0.3	15-20%	10.1 ± 0.3
20-30%	8.4 ± 0.3	30-40%	6.7 ± 0.2
40-50%	5.4 ± 0.2	50-70%	3.9 ± 0.1
70-100%	2.3 ± 0.1	0-100%	6.0 ± 0.2

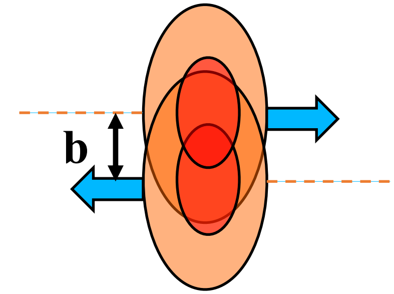
D. A few considerations on multiplicity selectors in p+p collisions



Large impact parameter
soft partons overlap

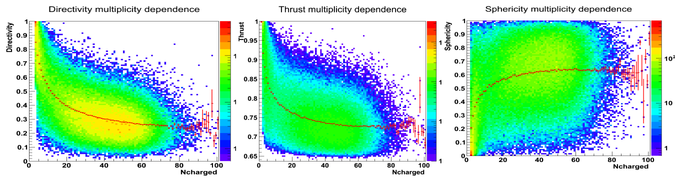


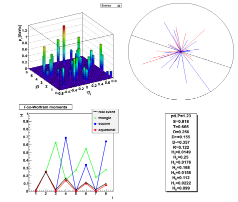
Intermediate impact parameter
soft & soft –hard partons overlap

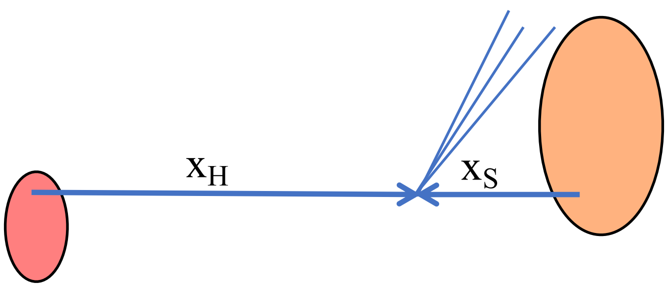


Small impact parameter
soft, soft-hard and hard partons overlap
The largest no. of parton interactions (<u>MPI</u>)
&
<u>re-scatterings</u>

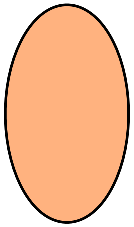
How to select them?
=> multiplicity & event shape



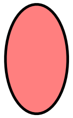




Hadron production in the
forward-backward rapidity regions
(<u>preferentially selected by "V0M"</u>)

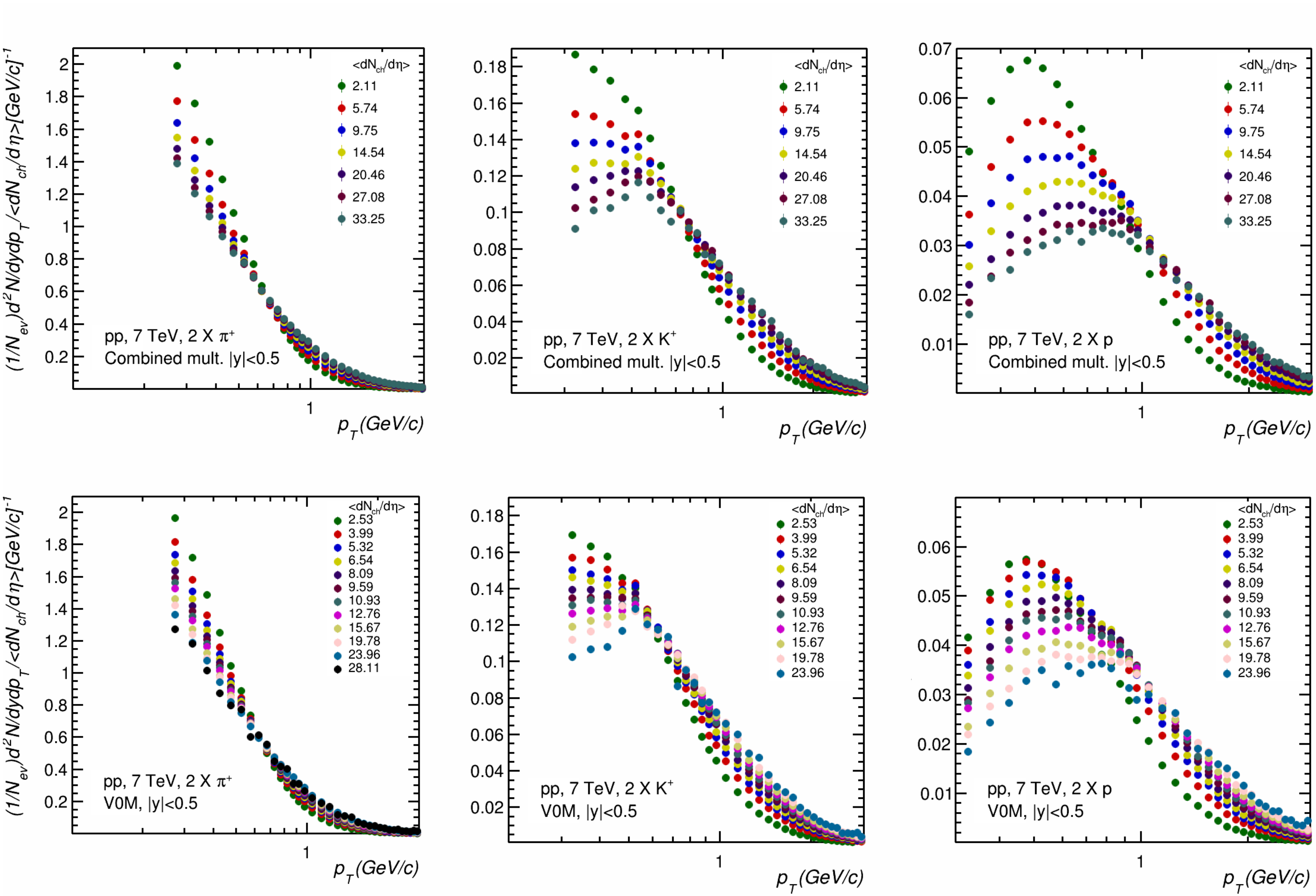


Transverse spatial distributions of the soft partons ($x<<10^{-2}$)

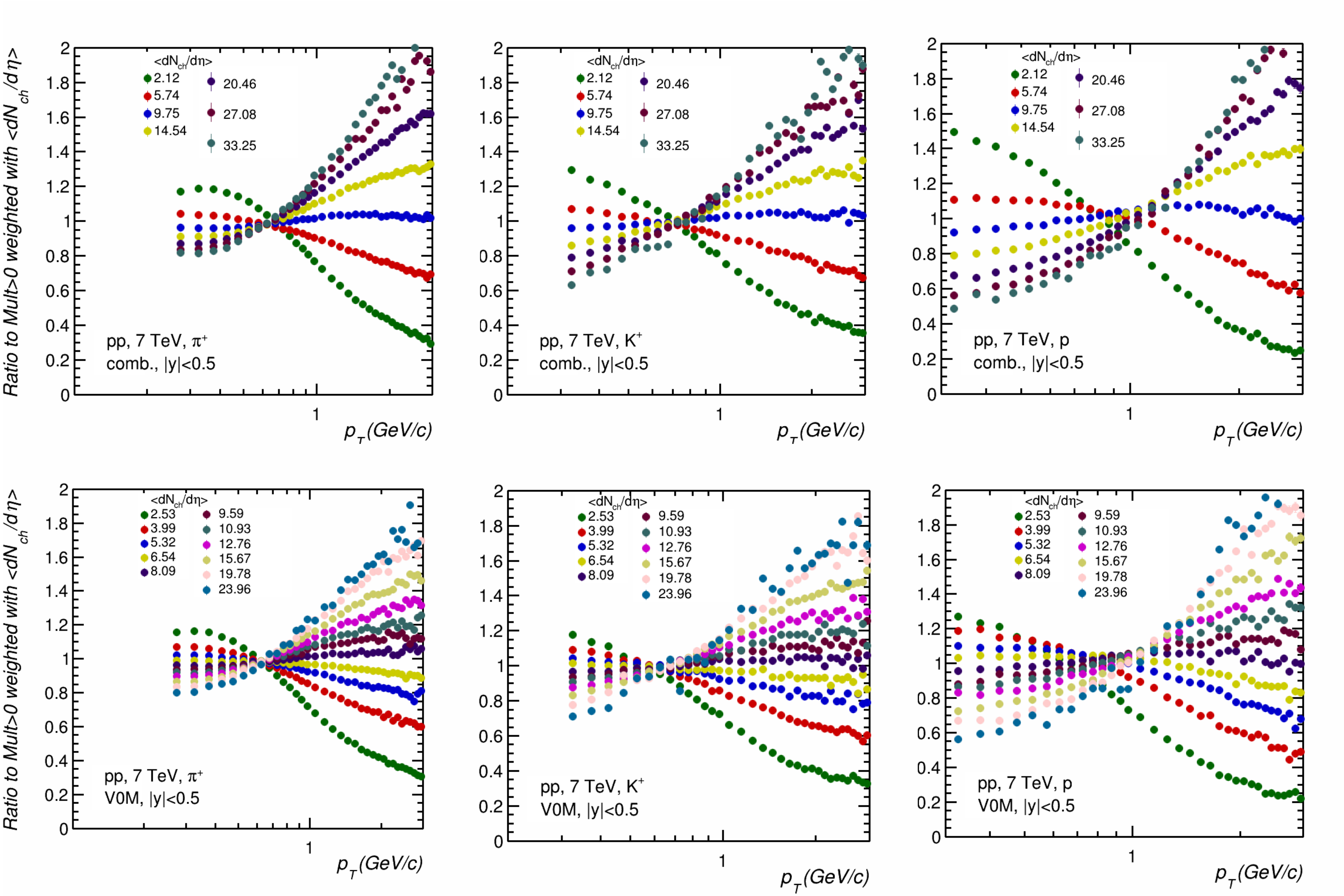


Transverse spatial distributions of the hard partons ($x\geq10^{-2}$)

Normalized p_T spectra - identified charged hadrons

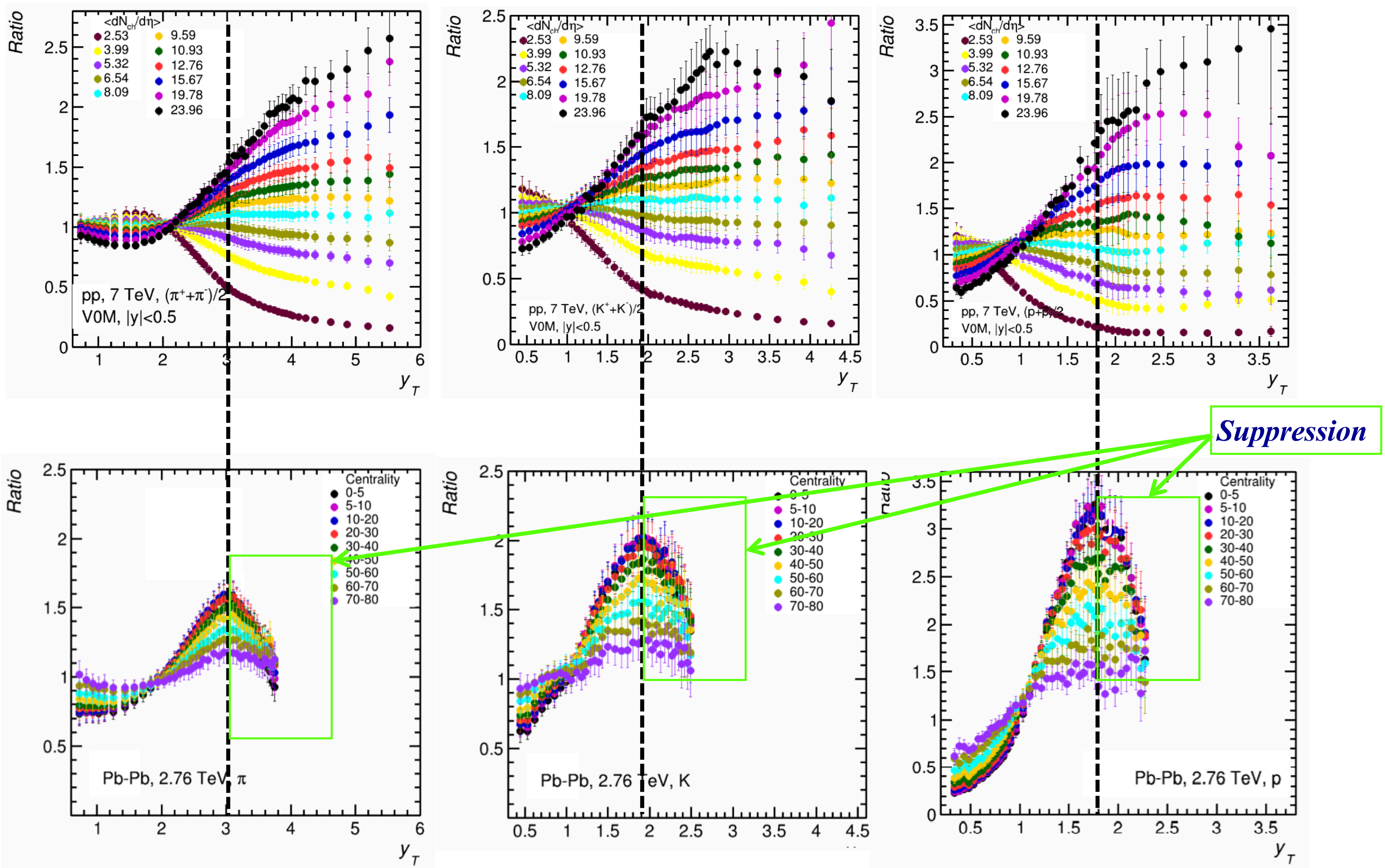


Ratios of normalized p_T spectra to Mult>0 identified charged hadrons



Ratio of normalized y_T distributions to normalized V0M 0-100% p+p (7 TeV) and Pb+Pb (2.76 TeV))

$$y_T = ln\{(m_T + p_T)/m_o\} \quad m_T = \sqrt{p_T^2 + m_0^2}$$



Ratios of normalized charged particles p_T distributions relative to MB p+p as a fuction of charged particle multiplicity-centrality for Au+Au (0.2 TeV), Pb+Pb (2.76 TeV) compared with R_{AA}

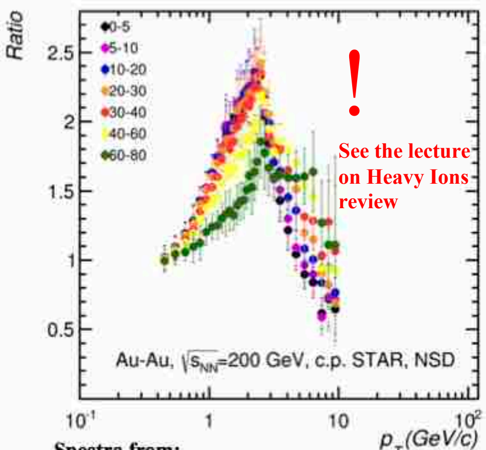
$$\frac{\left[\frac{d^2\sigma}{dy\,dp_T} / < dN_{ch}/d\eta > \right]^{(\%bin)}}{\left[\frac{d^2\sigma}{dy\,dp_T} / < dN_{ch}/d\eta > \right]^{(p+p)MB}}$$

- based only on measure observables

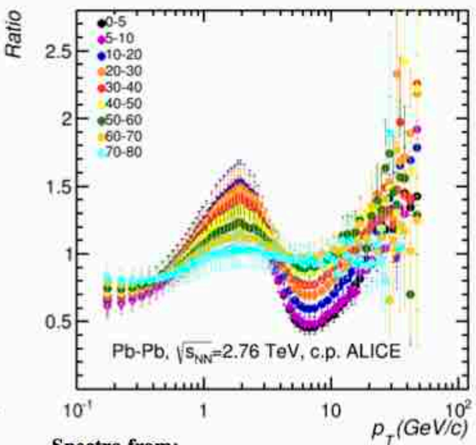
$$R_{AA} = \frac{1}{\langle T_{AA}\rangle} \frac{1/N_{\rm evt}\; d^2N_{\rm Pb+Pb}/d\eta dp_T}{d^2\sigma_{pp}/d\eta dp_T}$$

- based on Glauber approach

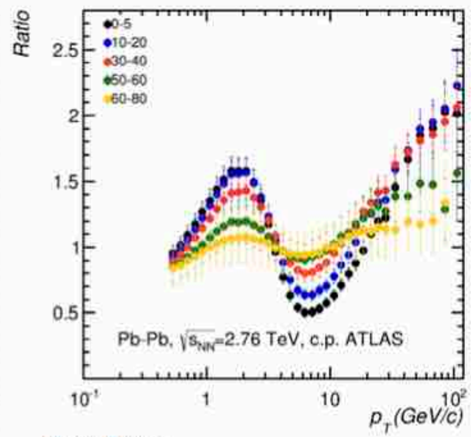
$<T_{AA}>$ - the no. of N–N collisions (Glauber approach) over their cross section



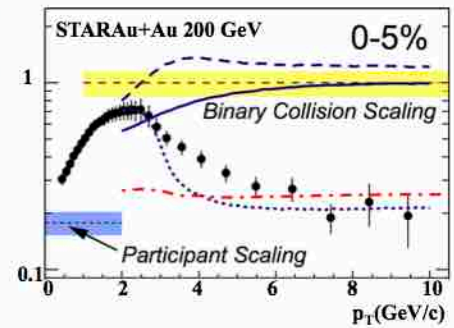
Spectra from:
J.Adams et al., STAR arXiv:[nucl-ex]0305015



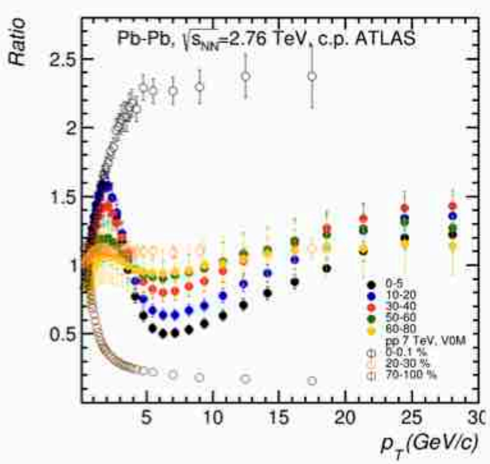
Spectra from:
B.Abelev et al., ALICE Phys.Lett.B720(2013)52

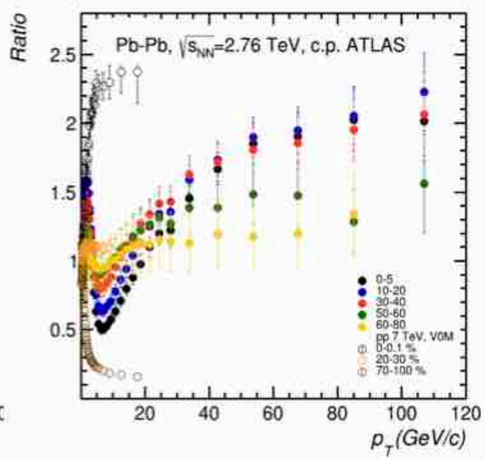


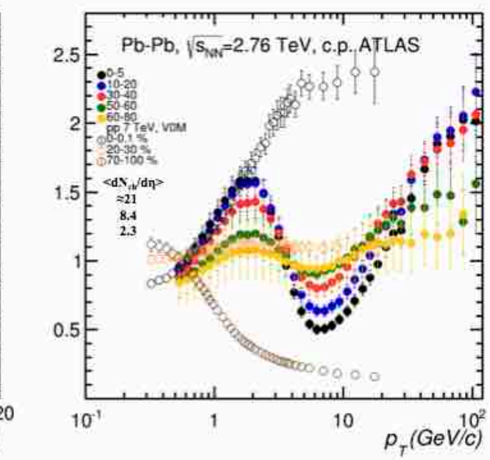
Spectra from:
G.Aad et al., ATLAS arXiv:[hep-ex]1504.04337

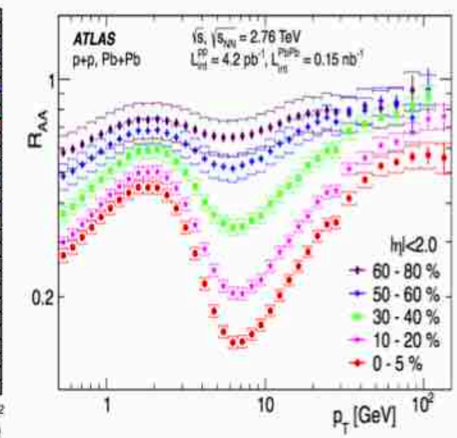


J.LKlay, UCRL-PROC-207407(2004)





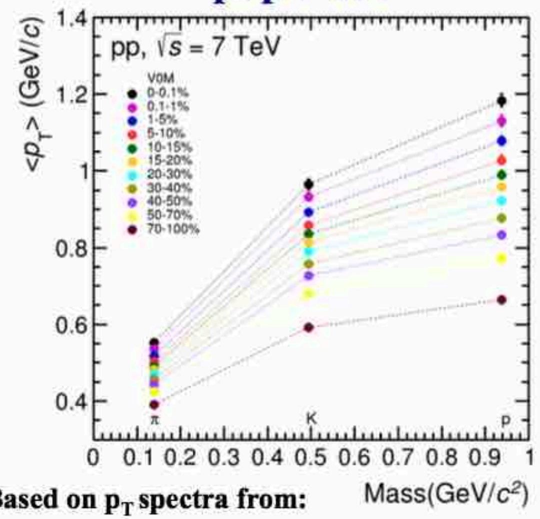




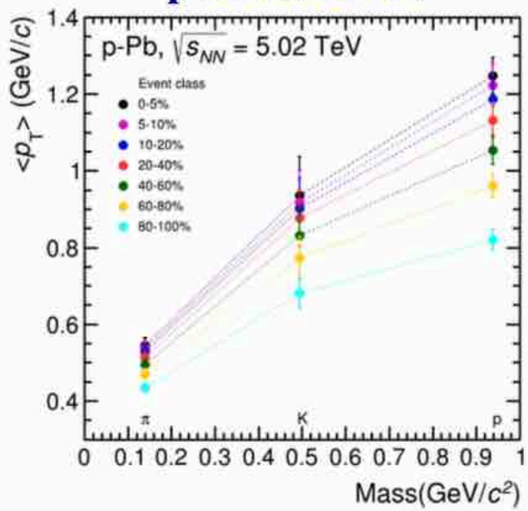
G.Aad et al., ATLAS arXiv:[hep-ex]1504.04337

$\langle p_T \rangle$ as a function of mass - different charged particle multiplicities (centralities) for p+p (7 TeV), p+Pb (5.02 TeV) and Pb+Pb (2.76 TeV)

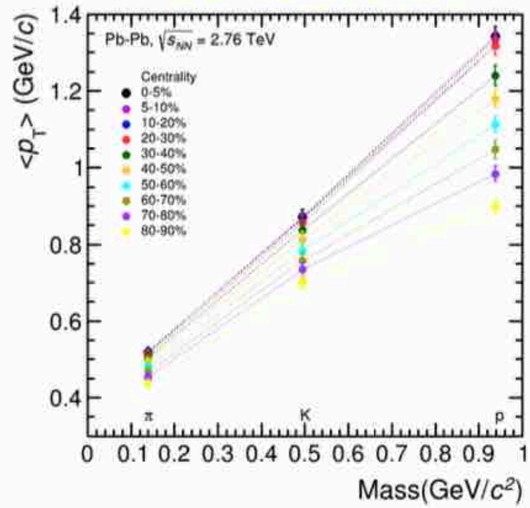
p+p 7 TeV



p+Pb 5.02 TeV



Pb+Pb 2.76 TeV

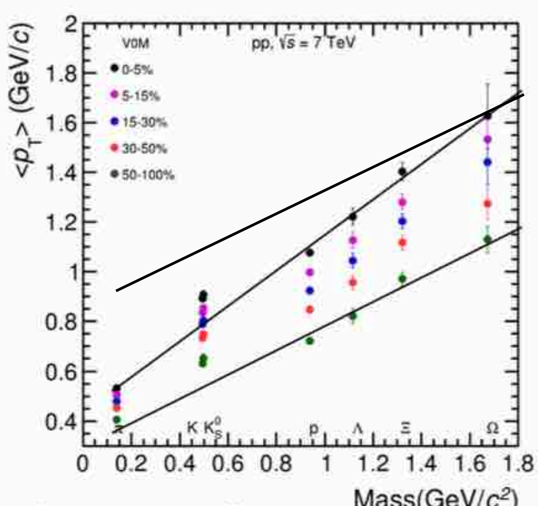


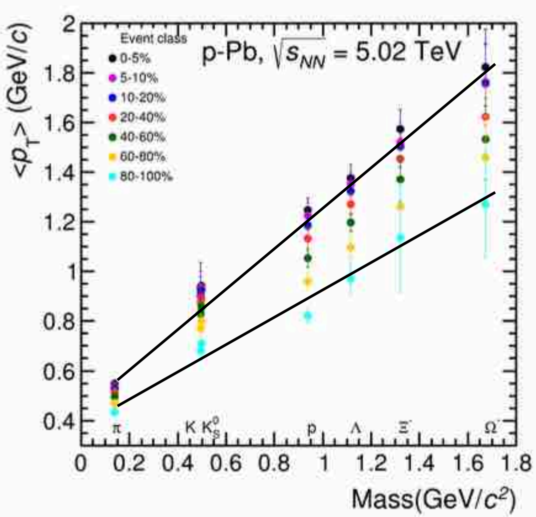
Based on p_T spectra from:

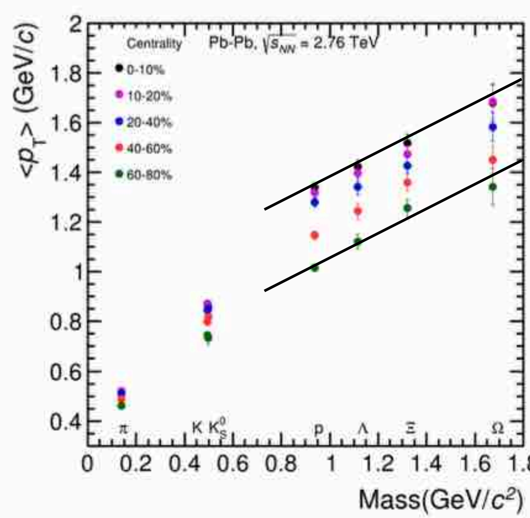
V.Vislavicius , ALICE Coll. QM2015

J.Adam et al., ALICE arXiv:[nucl-ex]1601.03658

B.Abelev et al., ALICE Phys.Lett. B720(2013)52







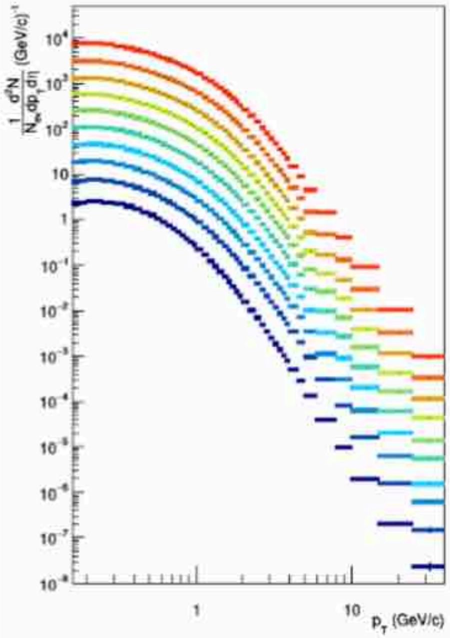
Based on p_T spectra from:

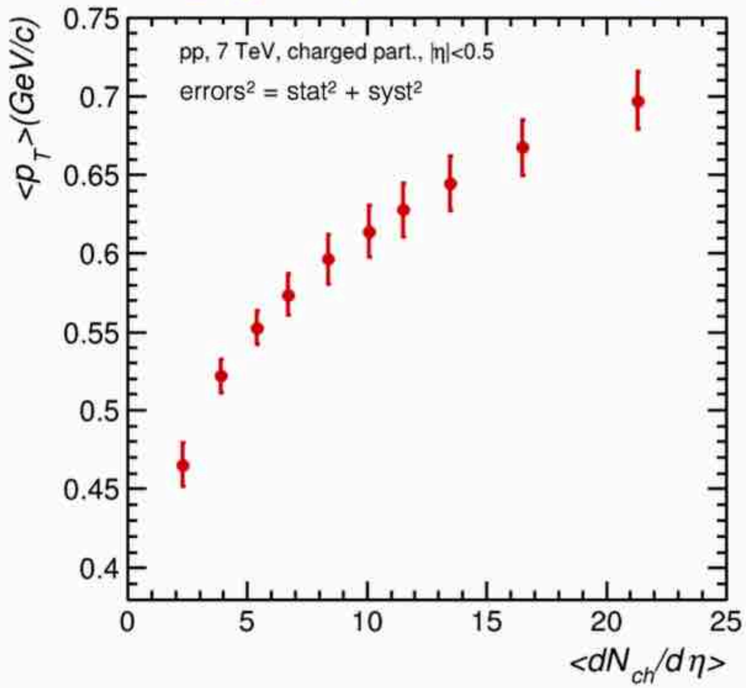
L.Bianchi , ALICE Coll. QM2015

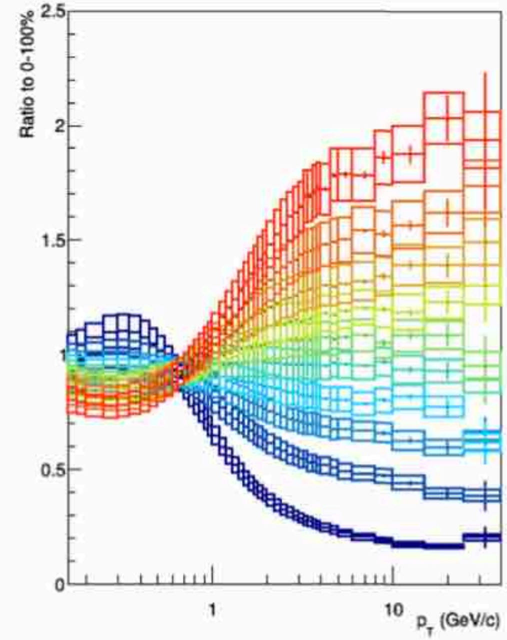
J.Adam et al.,ALICE Coll. Phys.Lett. B758(2016)389
B.Abelev et al.,ALICE Coll. Phys.Lett. B728(2014)25

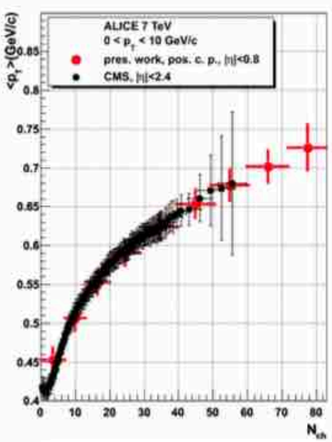
L.Hanratty, ALICE Coll. J. of Physics Conf. Series 509(2014)0120
B.Abelev et al.,ALICE Coll. Phys.Lett. B734(2014)409

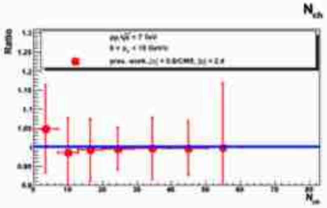
p_T spectra, ratios, $\langle p_T \rangle$ of unidentified charged hadrons

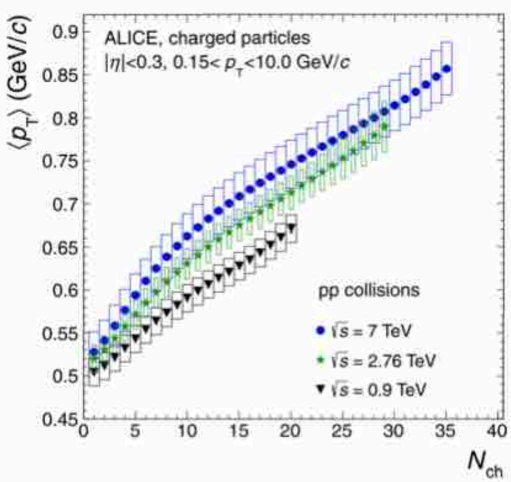


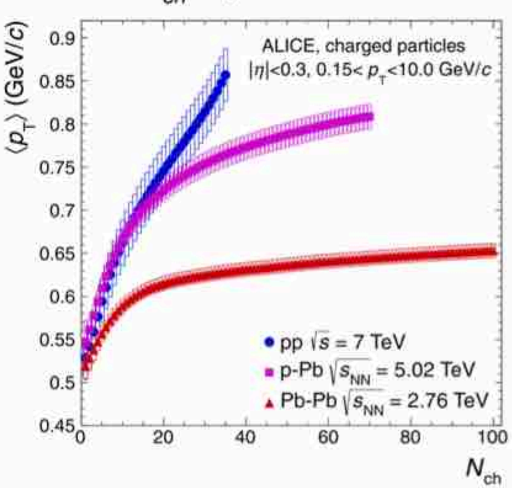










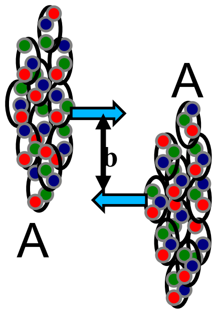


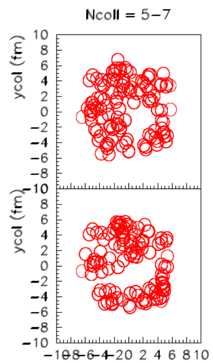
?

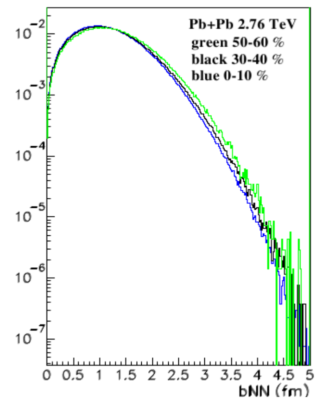
p+p high charged particle multiplicities @ LHC

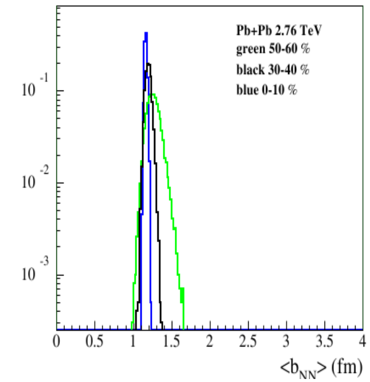
A-A, p-A, pp collision geometry

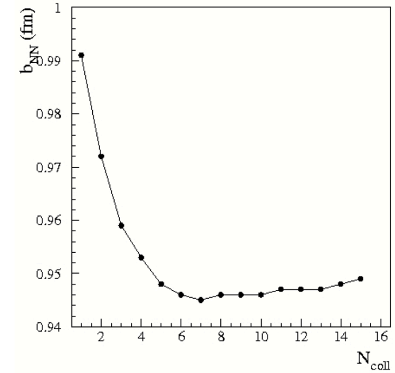
Glauber MC



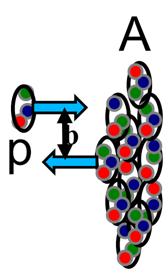


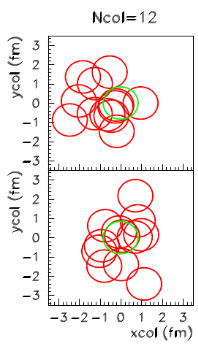


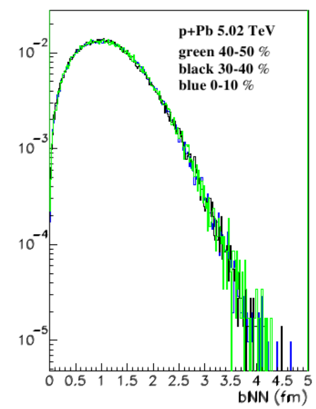


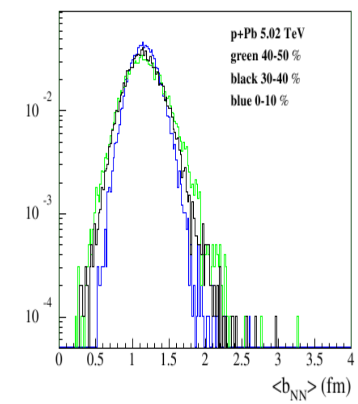


Pb+Pb 2.76 TeV, b=0

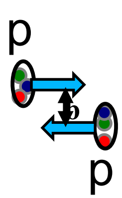


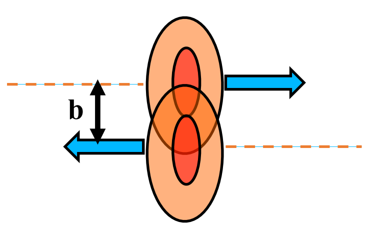


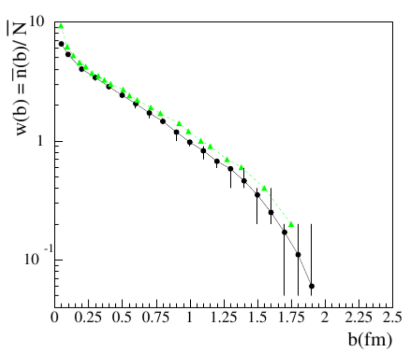




p+Pb 5.02 TeV, b=0



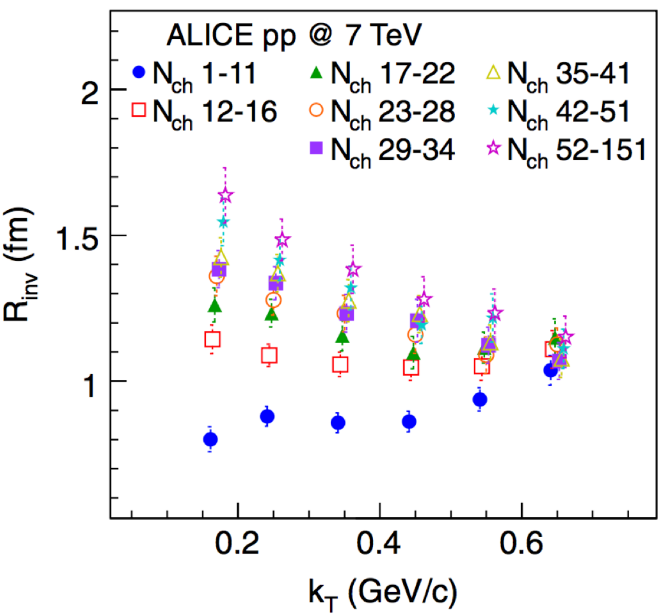




M.Petrovici, Carpathian Summer School of Physics
July 23, 2014 - Sinaia, Romania

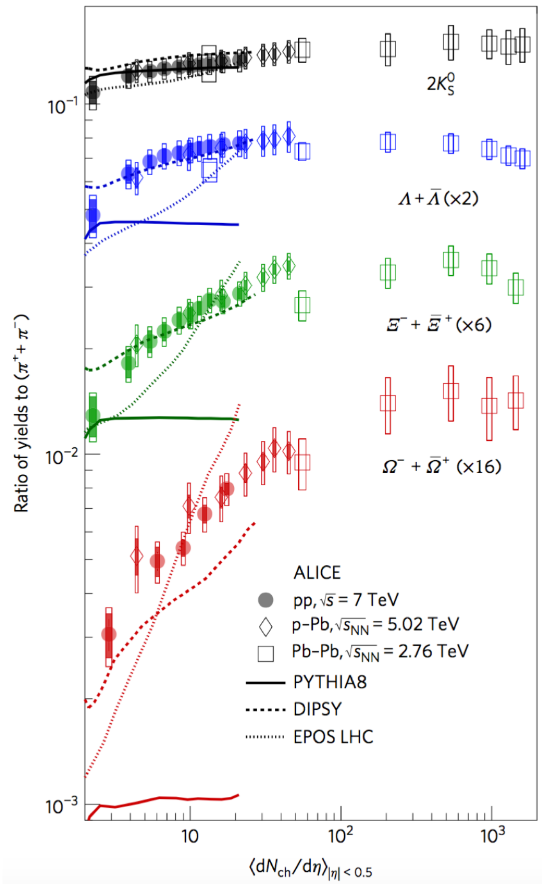
p+p high charged particle multiplicities @ LHC

Bose-Einstein correlations



K.Aamodt et al., ALICE Collaboration, Phys.Rev. D84(2011)112004

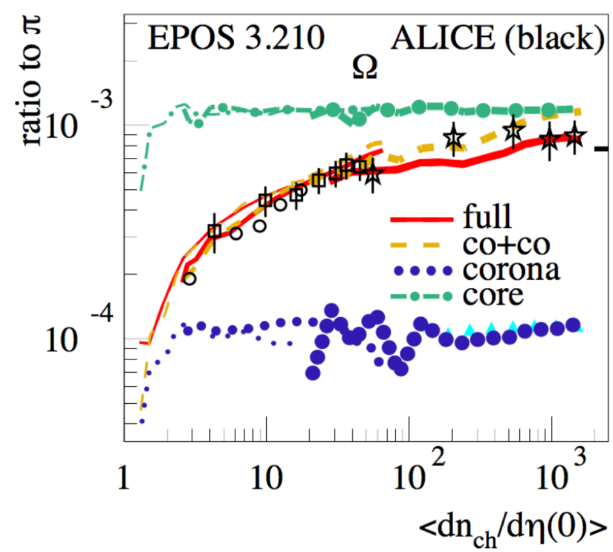
Strangeness enhancement ?



ALICE Collaboration, Nat.Phys. 13(2017)535

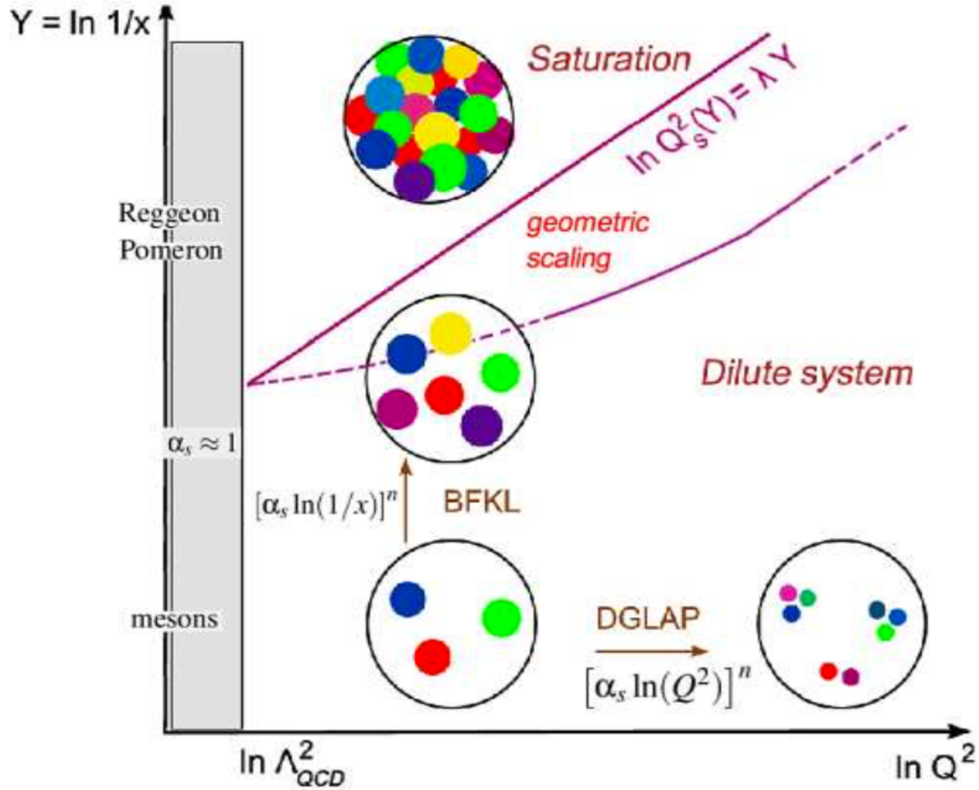
Core-Corona

thin lines = pp (7TeV)
intermediate lines = pPb (5TeV)
thick lines = PbPb (2.76TeVVV)
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

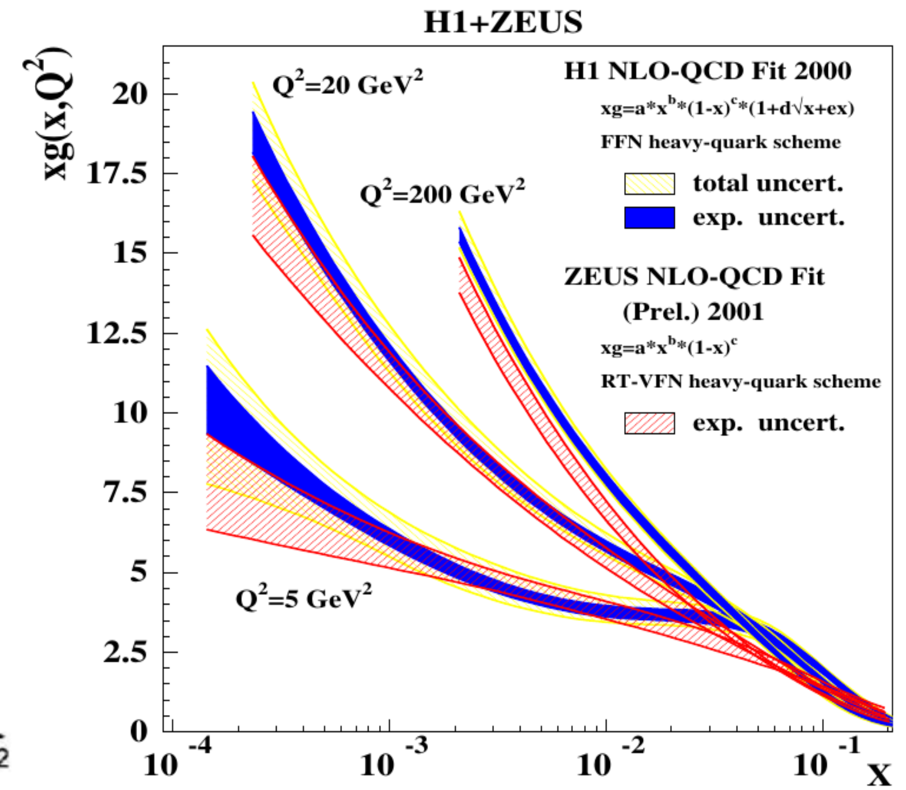


K. Werner, SQM 2017, July 10-15 2017, Utrecht

Physics motivation



D. d'Enterria, Eur.Phys.J. A31(2007)816)

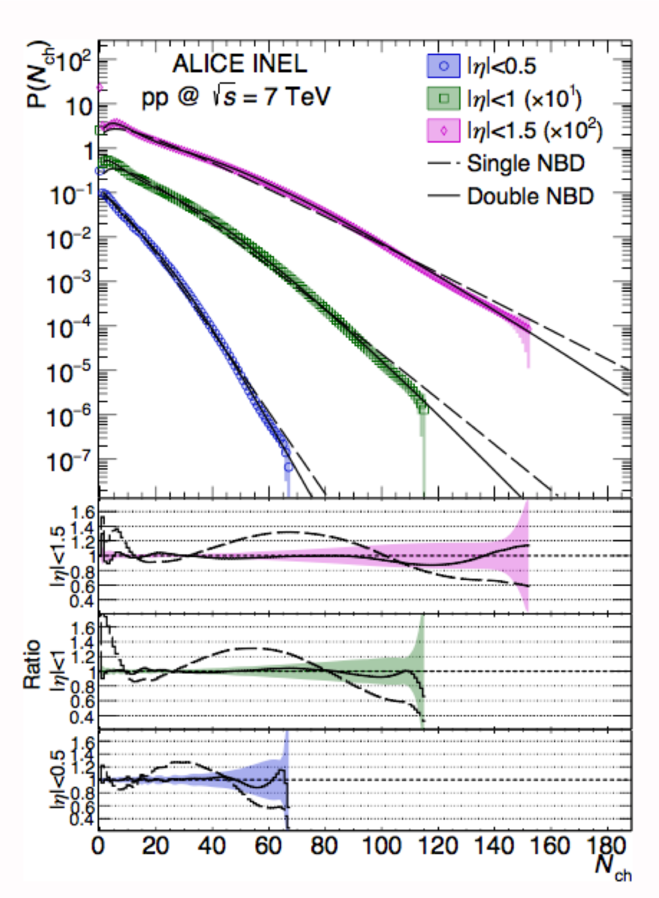


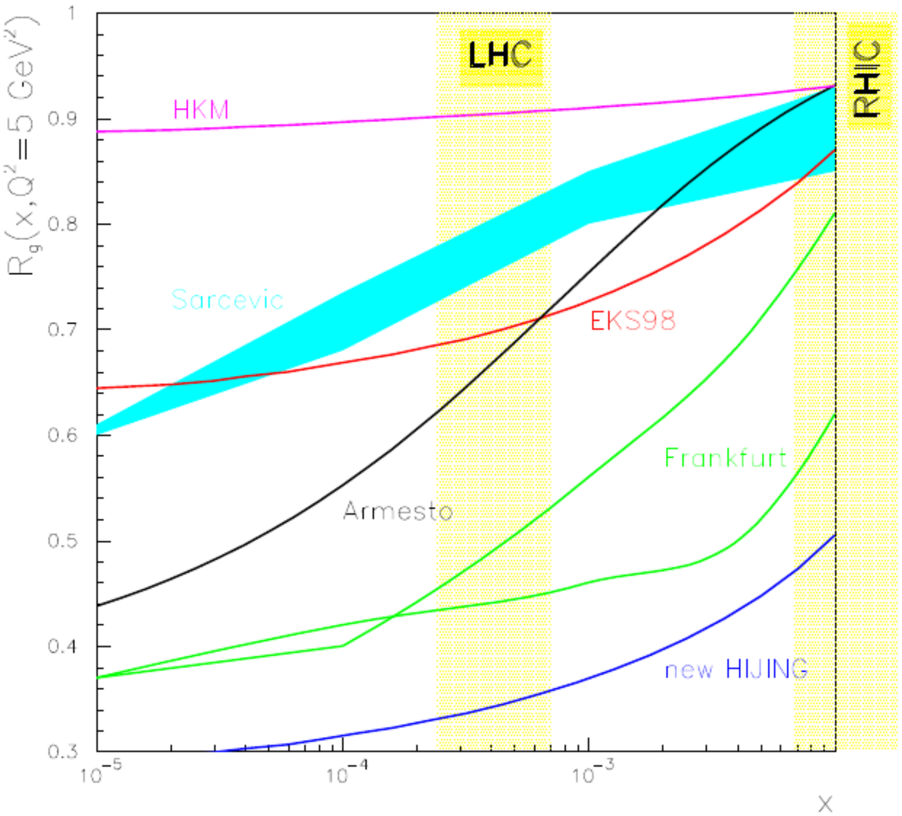
M.Dittmar et al., Proceedings HERA-LHC Workshop arXiv:[hep-ph]0511119

Following A.H. Mueller approximations
Nucl.Phys A715(2003)20

System	*Au-Au*	*Pb-Pb*	*Pb-Pb*	*pp*
$\sqrt{s}(GeV)$	*200*	*2700*	*5020*	*7000*
$\frac{dN_g^{in}}{dyd^2b}(fm^{-2})$	≈4.7	≈11.8	≈15.9	≈18.7
f_{in}^g	≈0.9	≈2.3	≈3.1	≈3.6

Physics motivation





A.Accardi et al., arXiv:[hep-ph]0308248

Geometrical scaling

Local parton-hadron duality picture and dimensionality argument

$$\langle p_T \rangle / \sqrt{\frac{dN}{dy} / S_\perp} \sim \frac{1}{n\sqrt{n}}$$

n - *no. of charged part. from a gluon fragmentation*

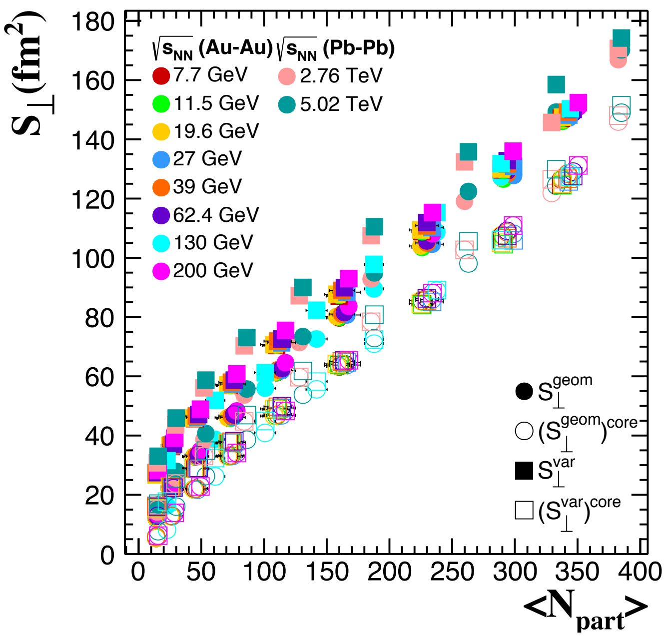
- Y.L.Dokshitzer, V.A.Khoze and S.Troian, J.Phys.G 17 (1991) 1585
- T. Lappi, Eur.Phys.J. C71 (2011) 1699
- E. Levin and A.H. Rezaeian, Phys.Rev.D 83 (2011) 114001

$$\langle p_T \rangle / \sqrt{\frac{dN}{dy} / S_\perp}$$

decreases as a function of:
- **collision energy**
- **centrality**

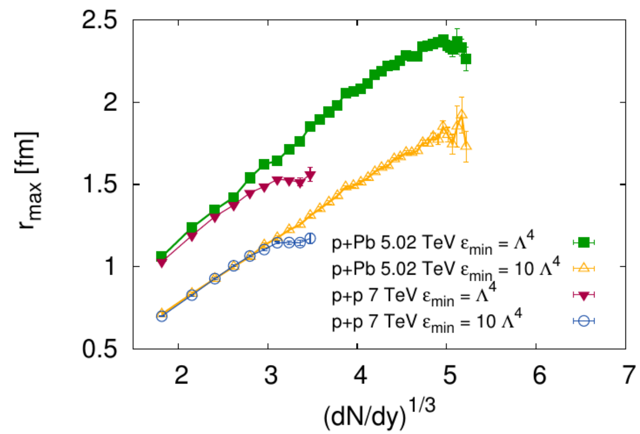
S_{perp} & dN/dy estimates

Glauber Monte Carlo approach



$$S_\perp^{var} \sim \pi \sqrt{\sigma_x^2 \sigma_y^2 - \sigma_{xy}^2}$$

A.Bzdac et al., Phys.Rev. C87(2013)064906



McLarren etal., Nucl.Phys. A916(2013)210

$S_\perp^{pp} = \pi R_{pp}^2$ $\quad R_{pp} = 1fm \cdot f_{pp}$ - **maximal radius for which the energy density of the Yang-Mill fields is larger than** $\varepsilon = \alpha \Lambda_{QCD}^4$ $(\alpha \in [1, 10])$

α=1 $\quad f_{pp} = \begin{cases} 0.387 + 0.0335x + 0.274x^2 - 0.0542x^3 & \text{if } x < 3.4 \\ 1.538 & \text{if } x \geq 3.4 \end{cases}$

$x = (dN_g/dy)^{1/3}$

$dN_g/dy \approx dN/dy$

α=10 $\quad f_{pp} = \begin{cases} -0.018 + 0.3976x + 0.095x^2 - 0.028x^3 & \text{if } x < 3.4 \\ 1.17 & \text{if } x \geq 3.4 \end{cases}$

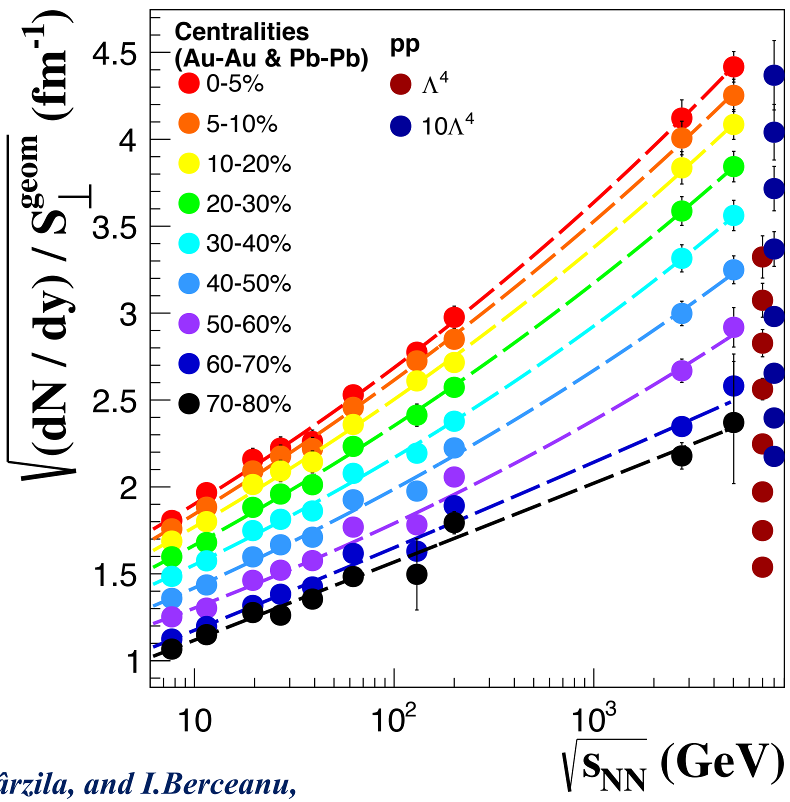
Geometrical scaling

dN/dy estimates

BES $$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2\frac{dN}{dy}^{(K^+ + K^-, p+\bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(\Lambda + \bar{\Lambda})}$$

RHIC 62.4; 130; 200 GeV $$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2\frac{dN}{dy}^{(K^+ + K^-, p+\bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(\Lambda + \bar{\Lambda}, \Omega^- + \bar{\Omega}^+)}$$

LHC $$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2\frac{dN}{dy}^{(p+\bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(K^+ + K^-, K_S^0 + \bar{K}_S^0, \Lambda + \bar{\Lambda}, \Omega^- + \bar{\Omega}^+)}$$

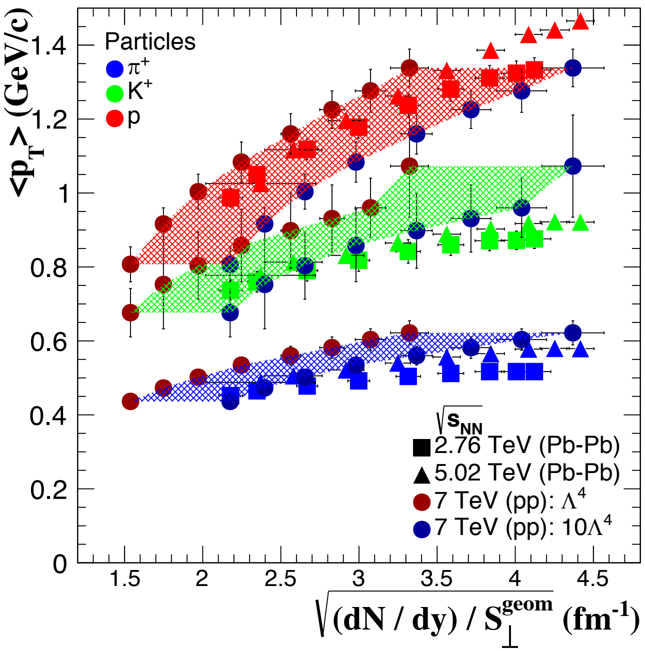


M. Petrovici, A.Lindner, , A. Pop, M. Târzila, and I.Berceanu, Phys.Rev. C98(2018)024904

Geometrical scaling

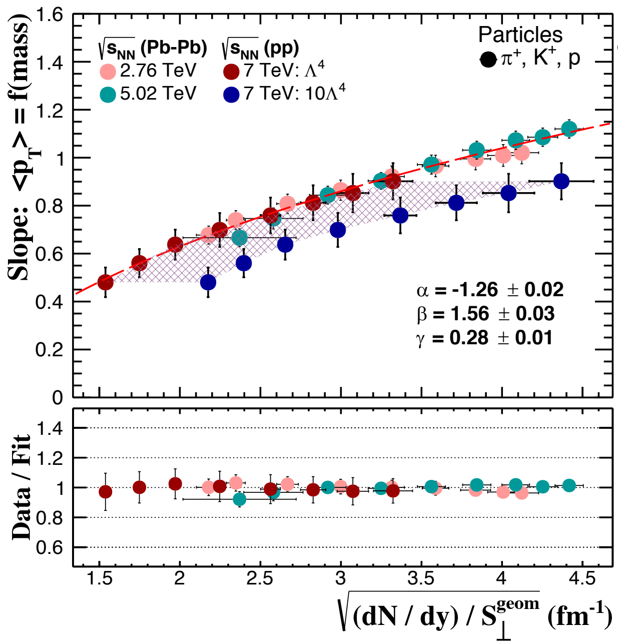
p+p vs. Pb+Pb @ LHC

$\langle p_T \rangle$ vs. $[(dN/dy)/S_{perp}]^{1/2}$



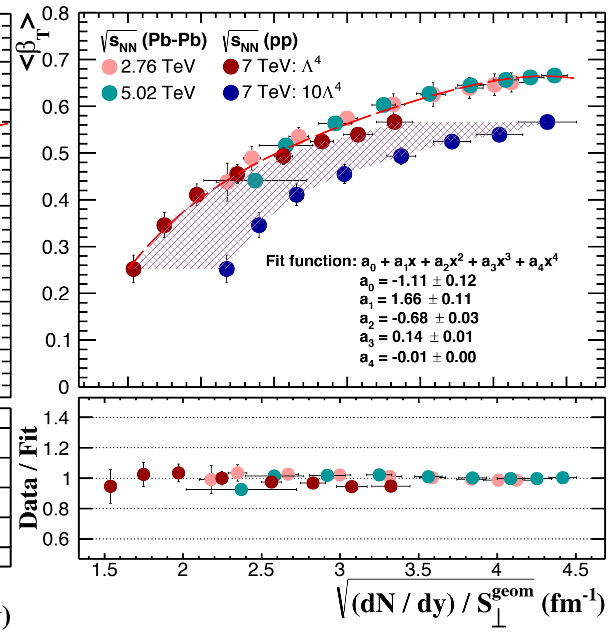
ALICE Collaboration, Nucl.Phys. A931(2014)c888

The slope of $\langle p_T \rangle = f(\mathrm{mass})$ vs. $[(dN/dy)/S_{perp}]^{1/2}$



$$Slope_{\langle p_T \rangle = f(mass)} = \alpha + \beta \left(\sqrt{\frac{dN}{dy} / S_\perp^{geom}} \right)^\gamma$$

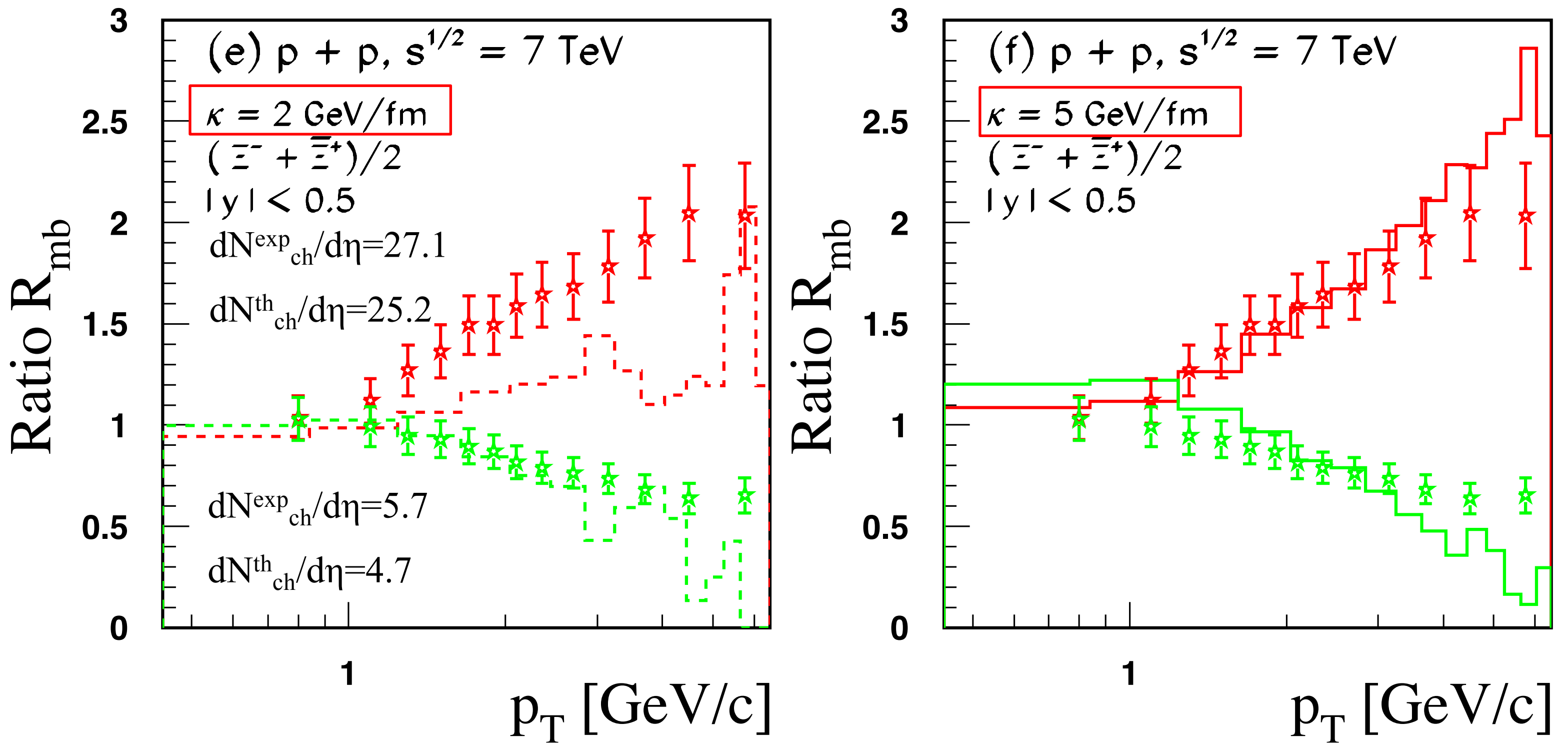
$\langle \beta_T \rangle$ from BGBW fits vs. $[(dN/dy)/S_{perp}]^{1/2}$



M. Petrovici, A.Lindner, , A. Pop, M. Târzila, and I.Berceanu, Phys.Rev. C98(2018)024904

pp - Pb+Pb similarities @ LHC within HIJING/BB v2.0 model

$$R_{mb}\,(cen) = \left(\frac{\frac{d^2N}{dydp_T}}{\langle\frac{dN_{ch}}{d\eta}\rangle}\right)_i^{cen} \Big/ \left(\frac{\frac{d^2N}{dydp_T}}{\langle\frac{dN_{ch}}{d\eta}\rangle}\right)_i^{ppMB}$$

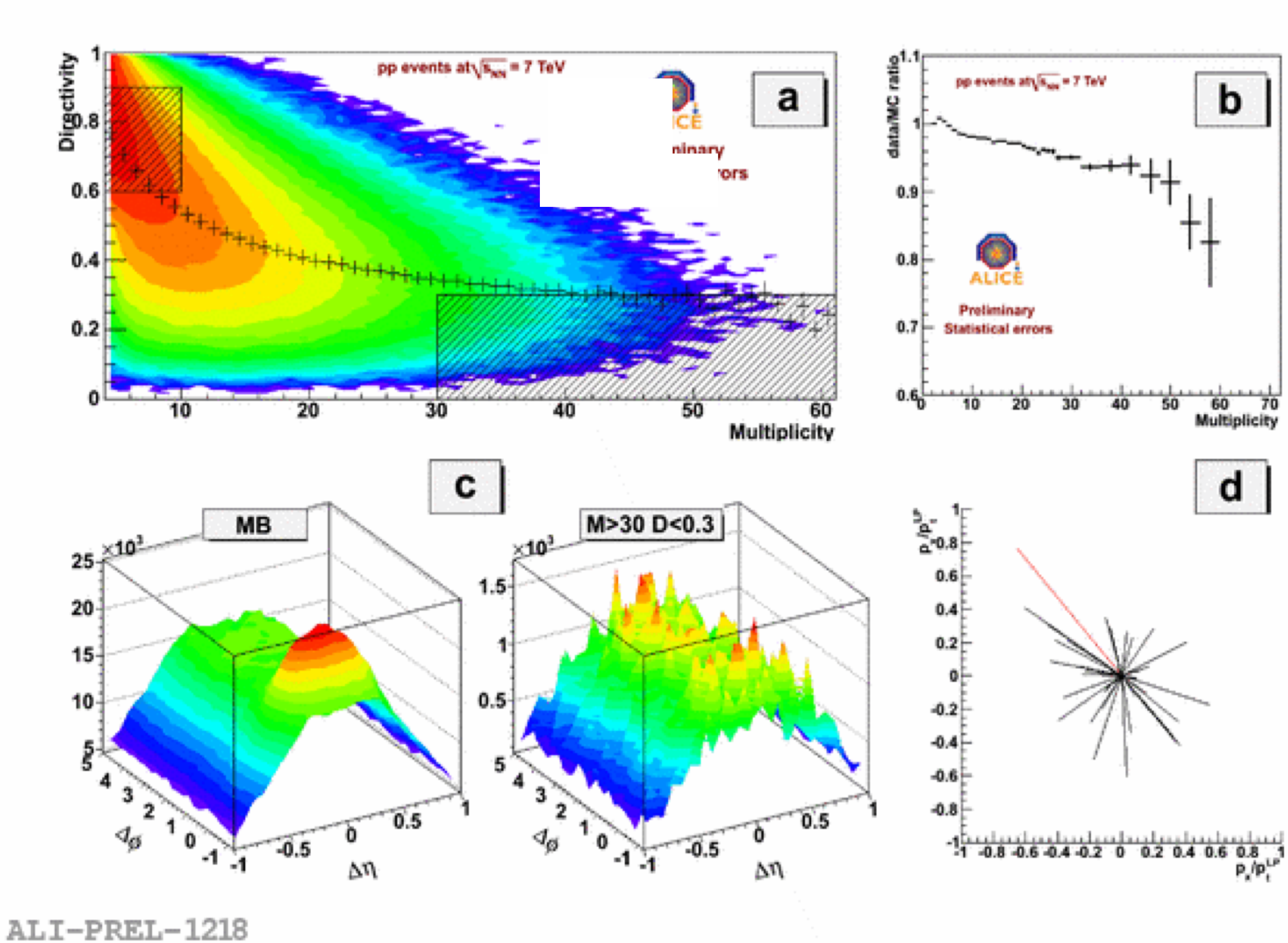


ALICE Coll., Phys.Lett. 712B(2012)309
R. Derradi de Souza, ALICE Coll., J.Phys.Conf.Ser. 779, no.1(2017)012071
V.Topor Pop and M.Petrovici, Phys.Rev. 98C(2018)064903

In progress

Multiplicity - Event shape analysis in p+p collisions

Directivity, Sphericity, Thrust



$D=(D^{+}+D^{-})/2$

$$D^{\pm} = \frac{|\sum_i \vec{p}_{t,i}|}{\sum_i |\vec{p}_{t,i}|}\Big|_{\eta^{pos/neg}}$$

C. Andrei – PhD thesis
https://niham.nipne.ro/THESIS_CA.pdf

In progress

Multiplicity - Event shape analysis in p+p collisions

Directivity, Sphericity, Thrust

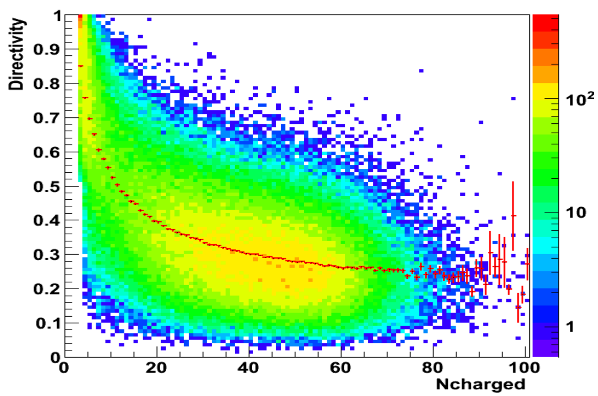
$$D^{\pm} = \frac{|\sum_i \vec{p}_{t,i}|}{\sum_i |\vec{p}_{t,i}|}\Big|_{\eta^{pos/neg}}$$

$$T = \underbrace{max}_{\vec{n}_T} \frac{\sum_i |\vec{p}_{t,i} \cdot \vec{n}_T|}{\sum_i |\vec{p}_{t,i}|}$$

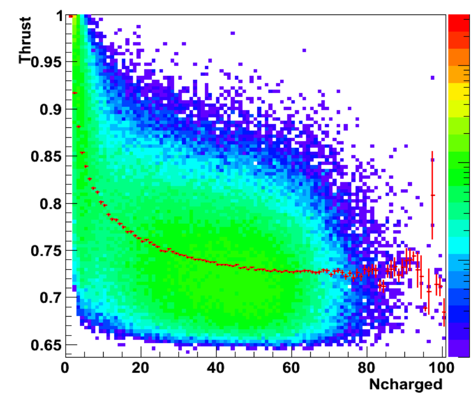
$$S_{xy} = \sum_i \begin{pmatrix} p_x^{(i)^2} & p_x^{(i)} p_y^{(i)} \\ p_x^{(i)} p_y^{(i)} & p_y^{(i)^2} \end{pmatrix}$$

$$S_{\perp} \equiv \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$

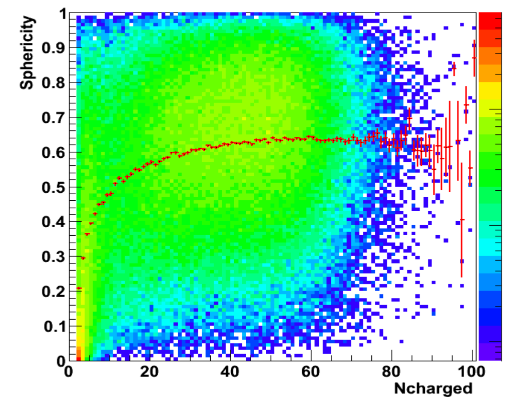
Directivity multiplicity dependence

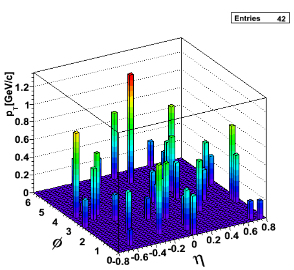


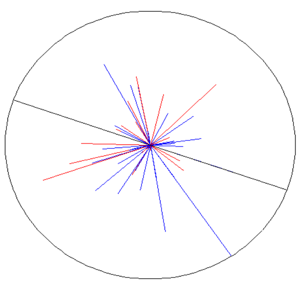
Thrust multiplicity dependence

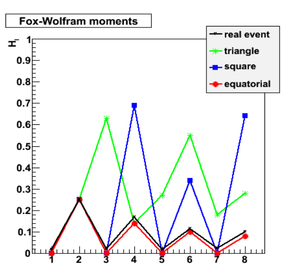


Sphericity multiplicity dependence



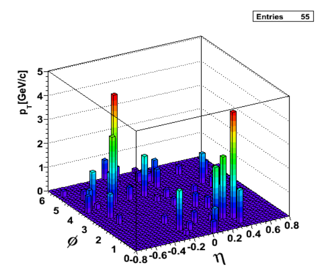


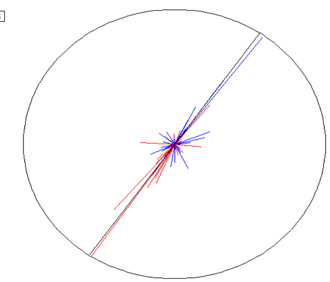


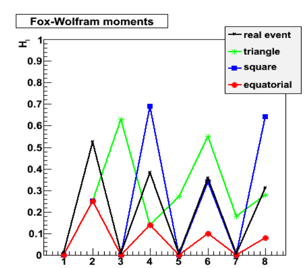


ptLP=1.23
S=0.918
T=0.665
D=0.256
D+=0.155
D-=0.357
R=0.122
H_1=0.0149
H_2=0.25
H_3=0.0176
H_4=0.168
H_5=0.0158
H_6=0.112
H_7=0.0222
H_8=0.099

$$H_l = \frac{\sum_{i,j} p_i p_j P_l(cos\phi_{ij})}{\sum_{i,j} p_i p_j}$$







ptLP=4.57
S=0.132
T=0.865
D=0.446
D+=0.338
D-=0.553
R=0.0998
H_1=0.00996
H_2=0.525
H_3=0.00624
H_4=0.381
H_5=0.00498
H_6=0.357
H_7=0.00379
H_8=0.31

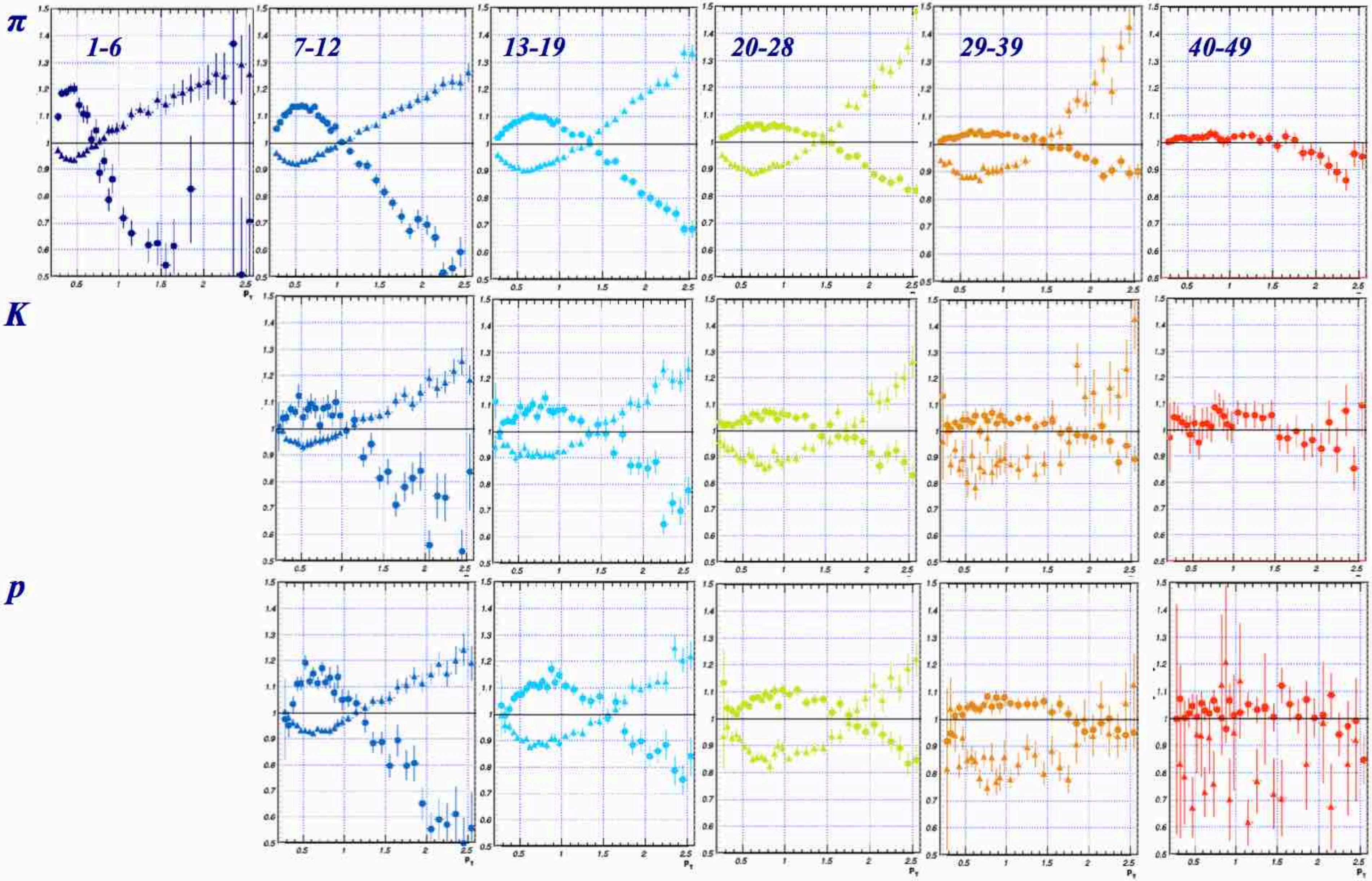
A. Herghelegiu – PhD thesis
https://niham.nipne.ro/THESIS_AH.pdf

p_T spectra of identified charged hadrons as a function of combined charged particle multiplicity and Directivity (ratio to the spectra for the corresponding cmul)

□ $0<D^+\&D^-<0.3$

△ $0.6<D^+\&D^-<1.0$

cmul



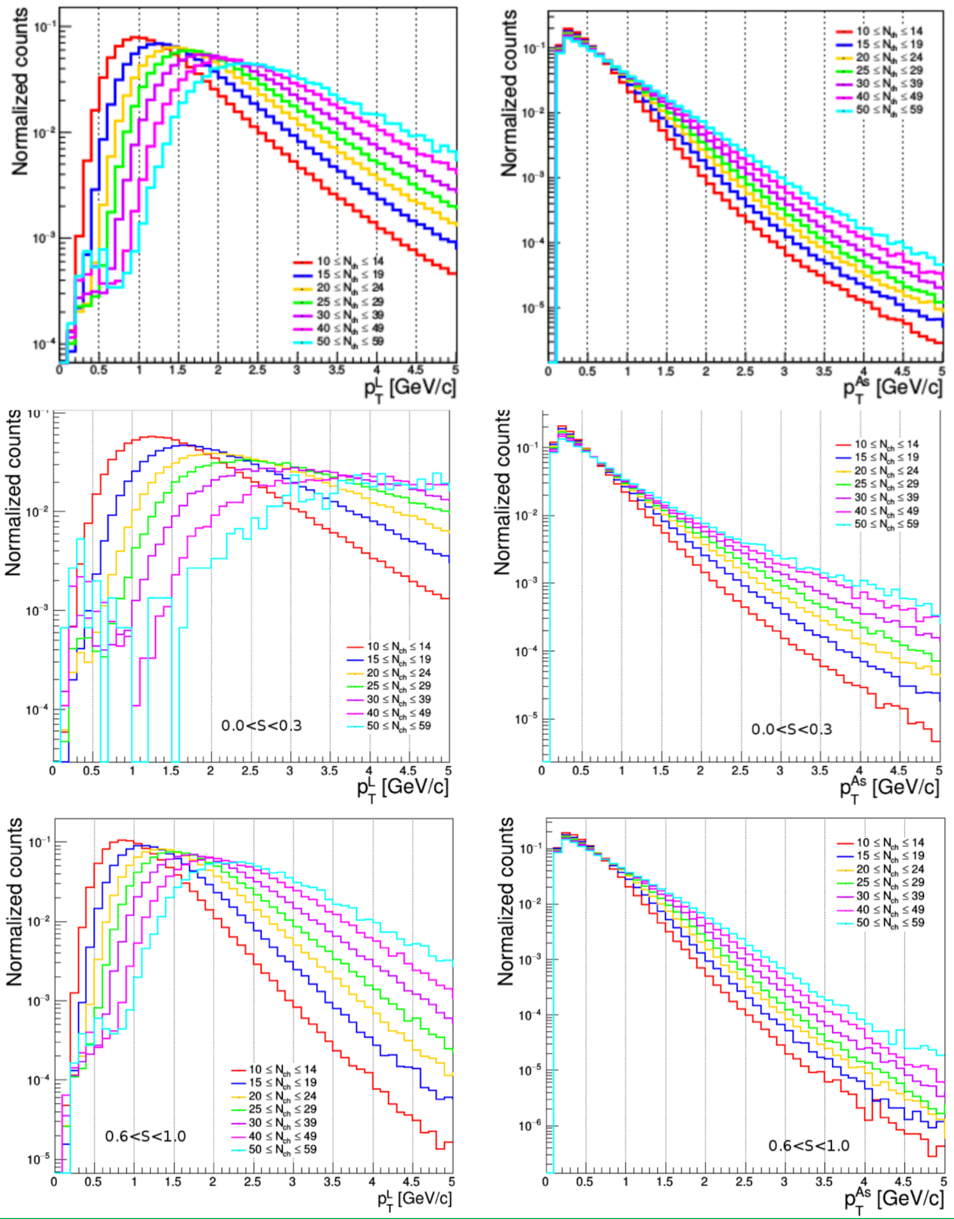
Two particle correlations

Leading particles **Associated particles**

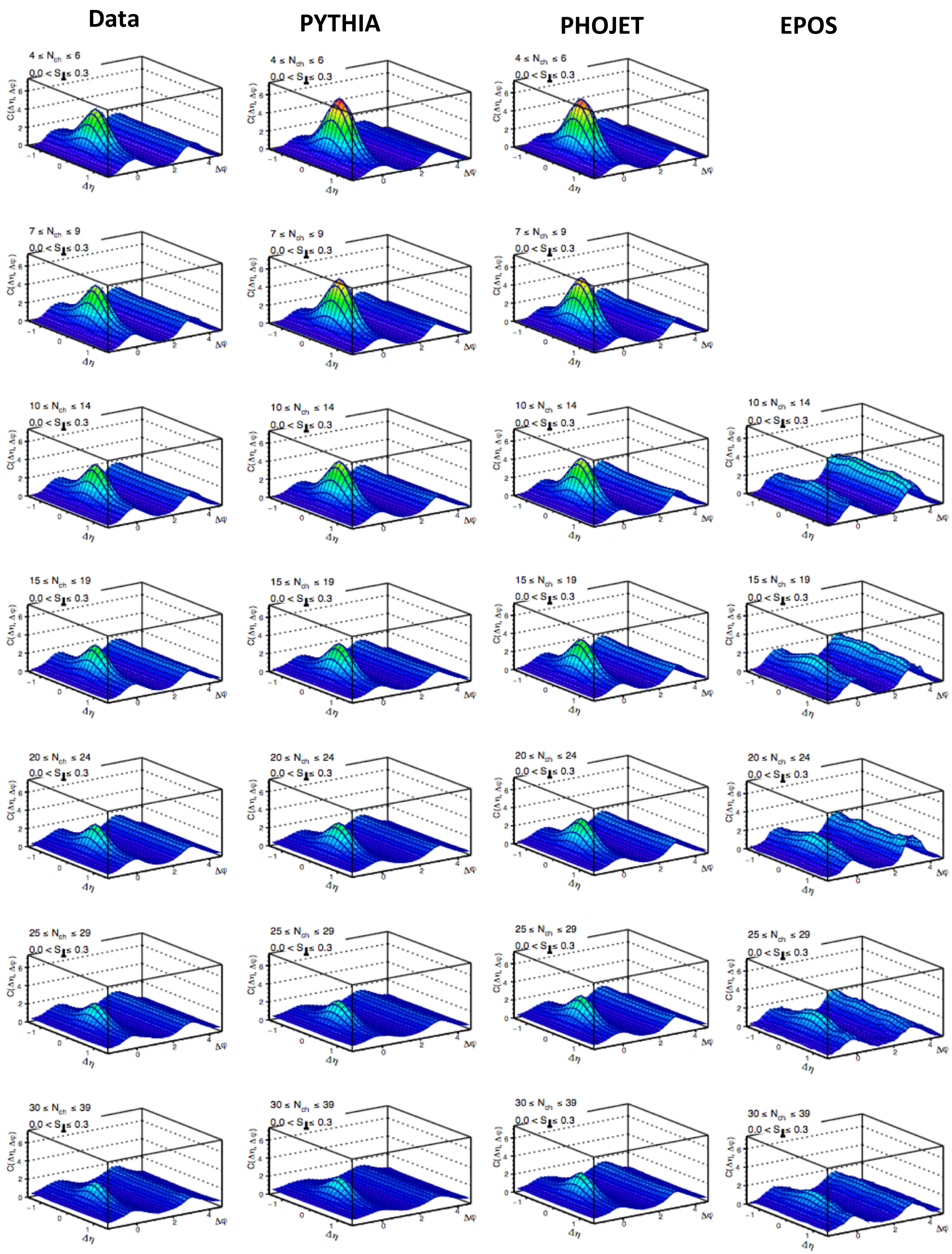
No event shape selection

$0 \leq S_{\perp} \leq 0.3$

$0.6 \leq S_{\perp} \leq 1.0$

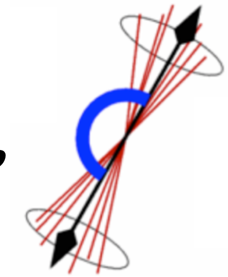


The present results are based on 1 GeV/c $\leq p_{\perp,assoc} < p_{\perp,lead} \leq$ 2 GeV/c



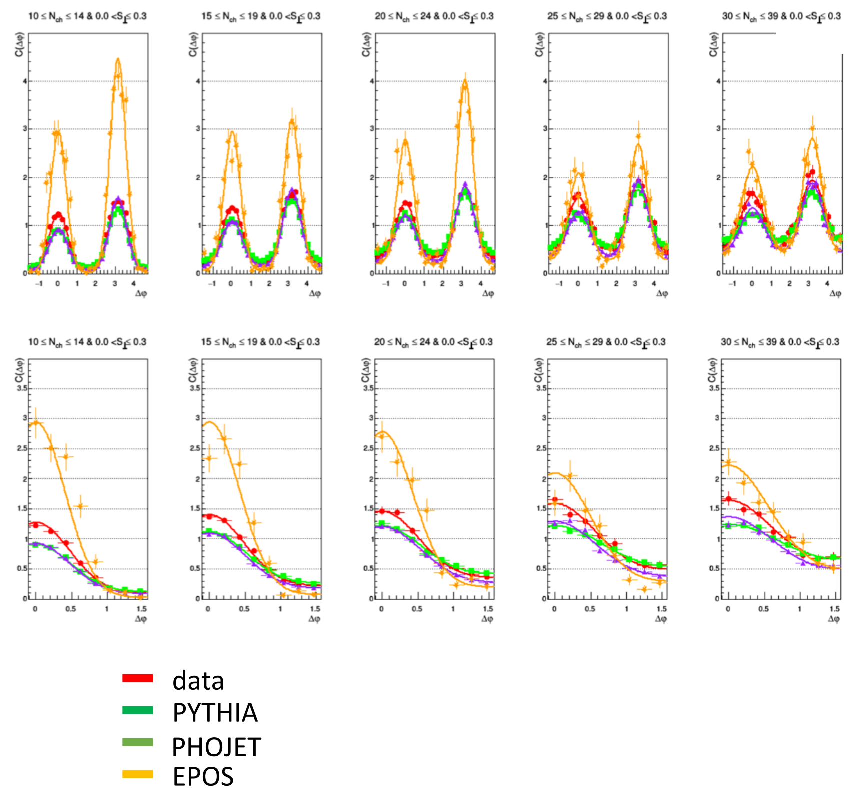
Two particle correlations

Near-side peak normalization



1 GeV/c≤p$_{\perp,assoc}$<p$_{\perp,lead}$ ≤2 GeV/c
0≤S$_{\perp}$≤0.3
1.25< |Δη| <1.5 - projection on Δφ
multiplicity dependence

$$G(\Delta\varphi) = \frac{Y_{near}}{\sqrt{2\pi}\sigma_{near}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi}{\sigma_{near}}\right)^2} + \frac{Y_{away}}{\sqrt{2\pi}\sigma_{away}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi-\pi}{\sigma_{away}}\right)^2} + B$$

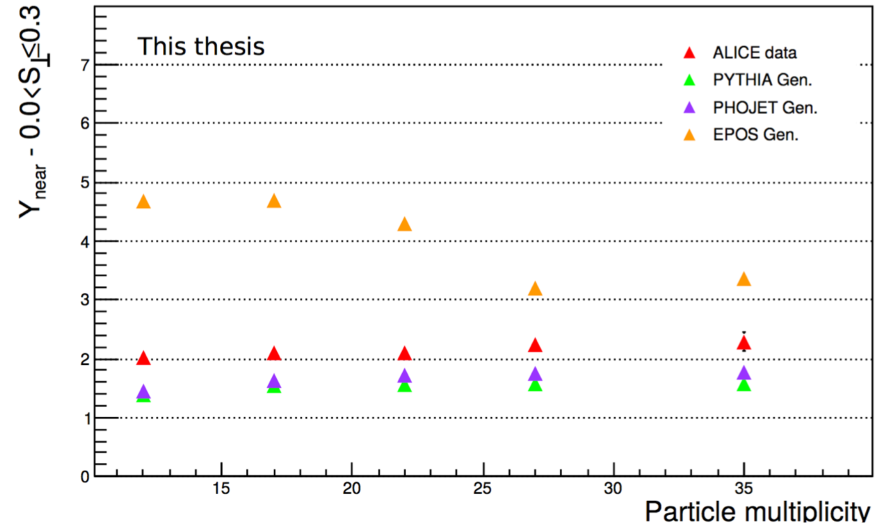


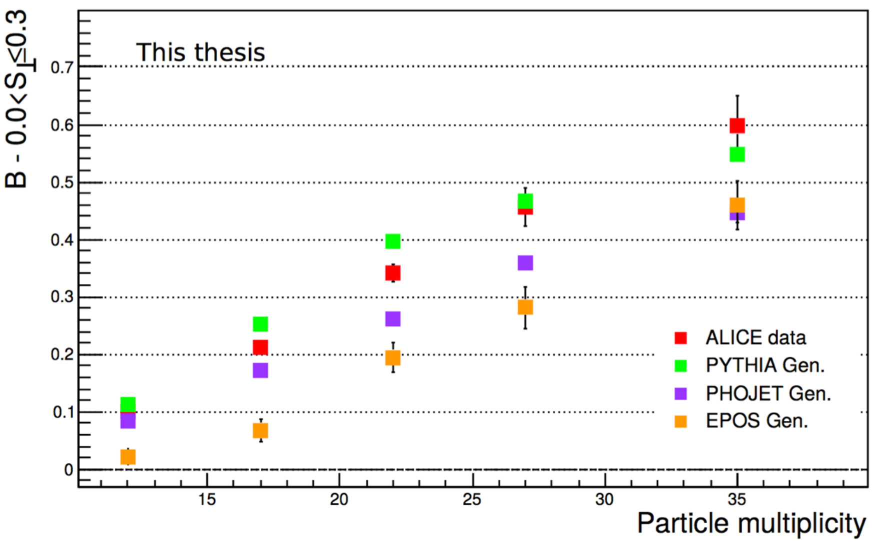
Two particle correlations

1 GeV/c≤$p_{\perp,assoc}$<$p_{\perp,lead}$≤2 GeV/c
0≤$S_\perp$≤0.3
1.25< |Δη| <1.5 – projection on Δφ
multiplicity dependence

$$G(\Delta\varphi) = \frac{Y_{near}}{\sqrt{2\pi\sigma_{near}}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi}{\sigma_{near}}\right)^2} + \frac{Y_{away}}{\sqrt{2\pi\sigma_{away}}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi-\pi}{\sigma_{away}}\right)^2} + B$$

data
PYTHIA
PHOJET
EPOS

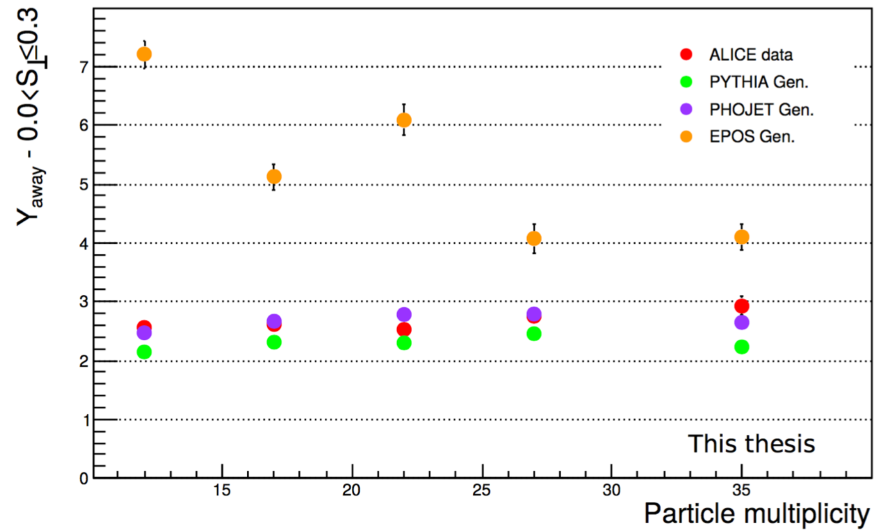




- underlying event activity increases with multiplicity

- EPOS and PHOJET underestimate the data

- PYTHIA describes better the data



-Y_{away} are slightly larger than Y_{near}

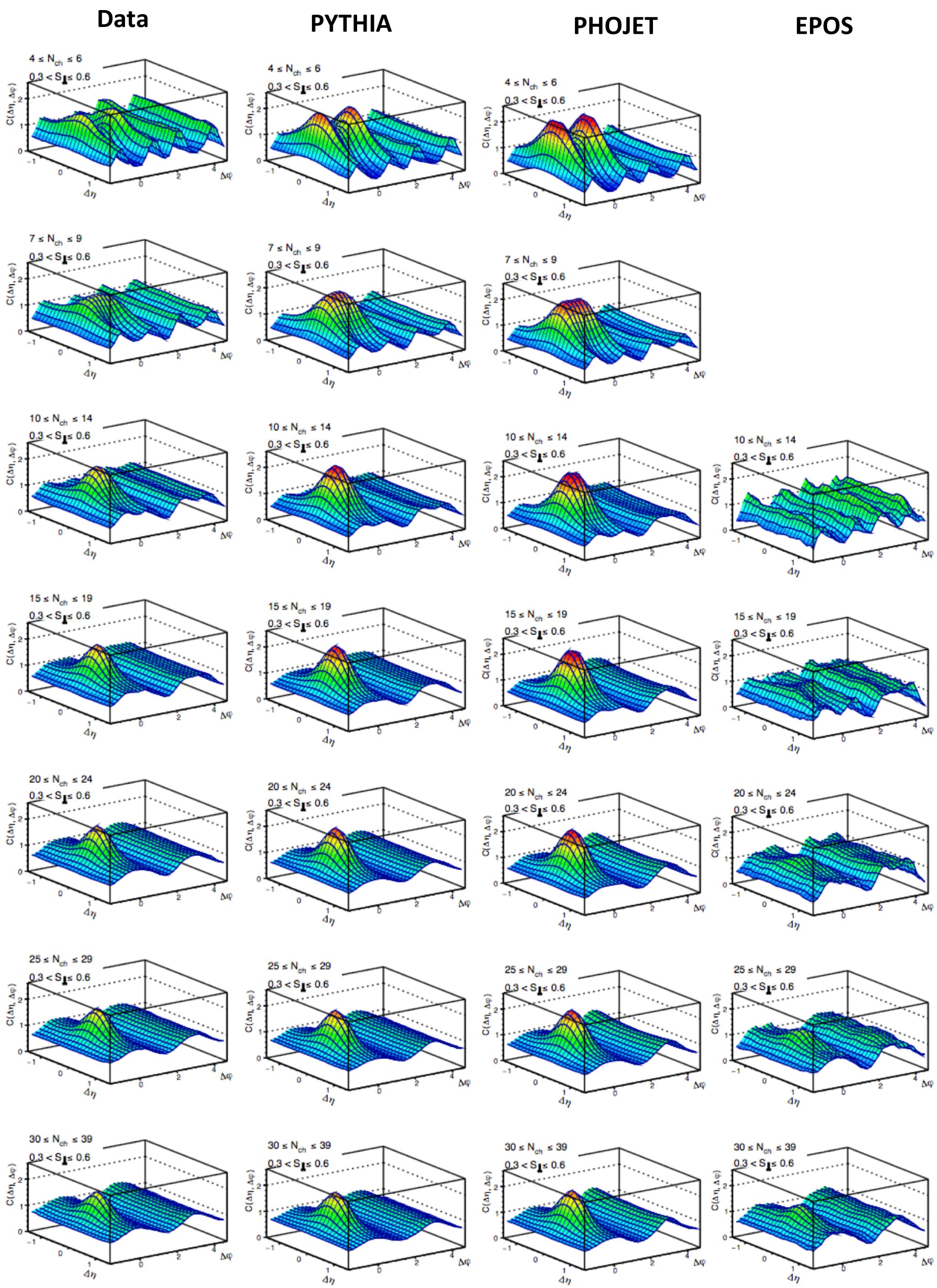
-Y_{away} have a similar behavior as Y_{near} as a function of multiplicity

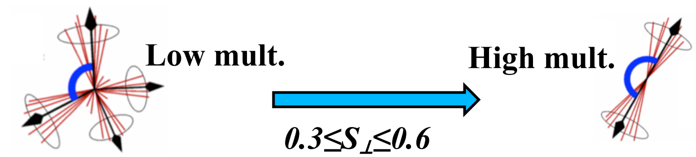
-PYTHIA and PHOJET models systematically underestimate the data on the near side

- EPOS shows much larger values at lower charged particle multiplicity, decreasing towards larger multiplicity, but still remaining above data by a factor of ~1.5

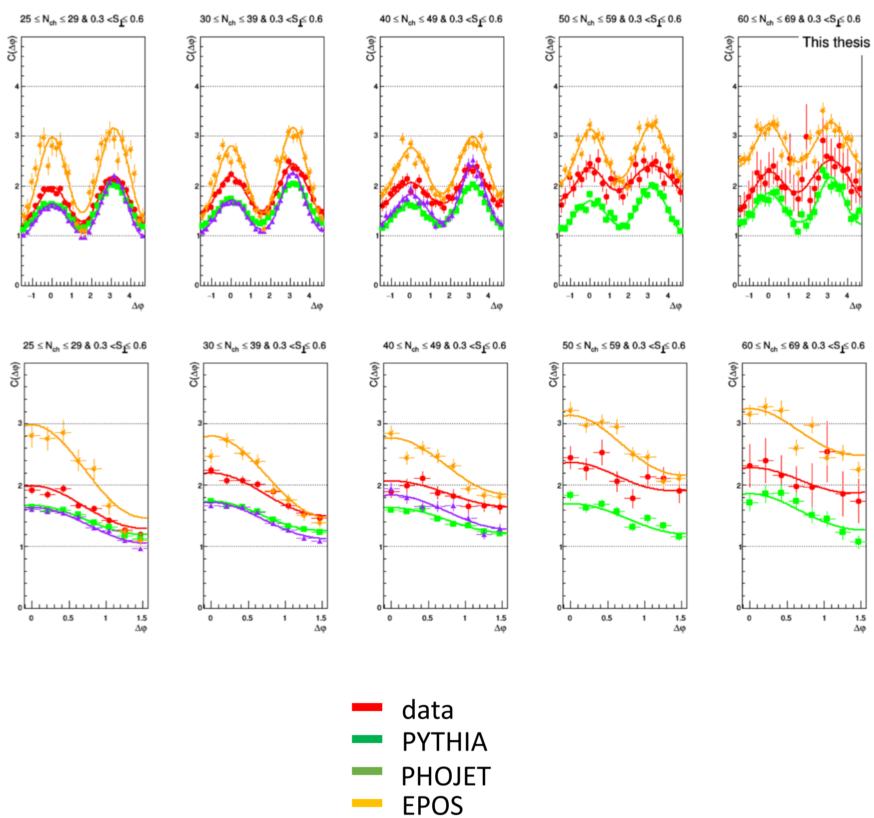
Two particle correlations

$1\ GeV/c \leq p_{\perp,assoc} < p_{\perp,lead} \leq 2\ GeV/c$
$0.3 \leq S_{\perp} \leq 0.6$
$1.25 < |\Delta\eta| < 1.5$ – projection on $\Delta\varphi$
multiplicity dependence





$$G(\Delta\varphi) = \frac{Y_{near}}{\sqrt{2\pi}\sigma_{near}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi}{\sigma_{near}}\right)^2} + \frac{Y_{away}}{\sqrt{2\pi}\sigma_{away}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi-\pi}{\sigma_{away}}\right)^2} + B$$

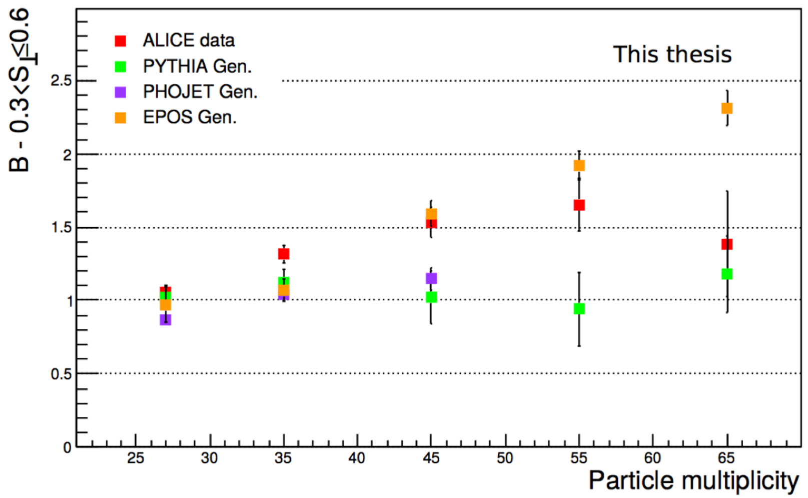


Two particle correlations

1 GeV/c $\leq p_{\perp,assoc} < p_{\perp,lead} \leq$ 2 GeV/c
$0.3 \leq S_{\perp} \leq 0.6$
$1.25 < |\Delta\eta| < 1.5$ – projection on $\Delta\varphi$
multiplicity dependence

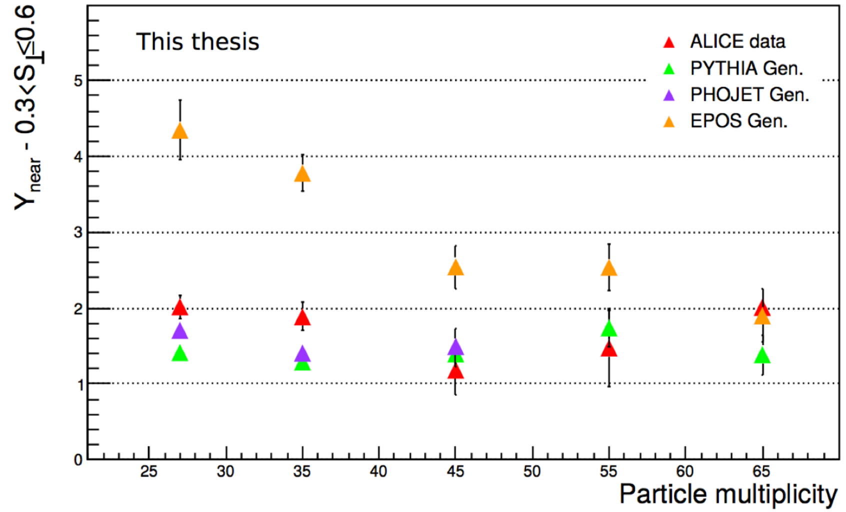
$$G(\Delta\varphi) = \frac{Y_{near}}{\sqrt{2\pi}\sigma_{near}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi}{\sigma_{near}}\right)^2} + \frac{Y_{away}}{\sqrt{2\pi}\sigma_{away}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi-\pi}{\sigma_{away}}\right)^2} + B$$

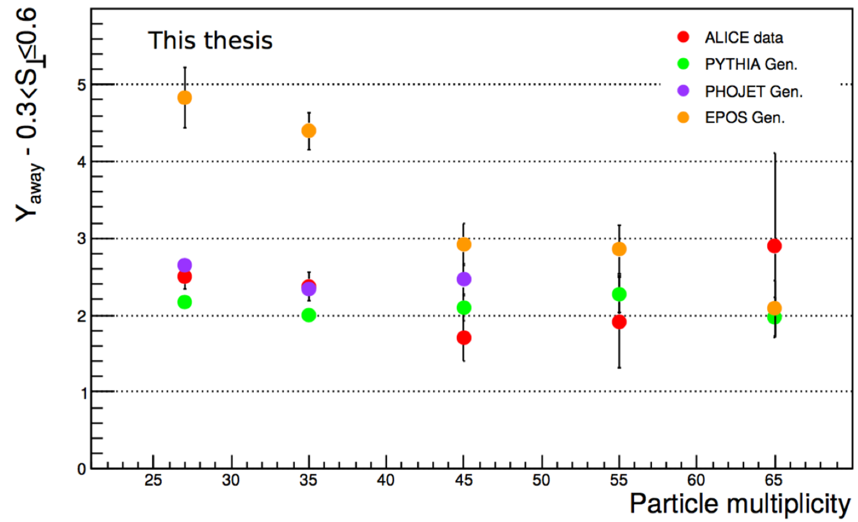
data
PYTHIA
PHOJET
EPOS



- PYTHIA and PHOJET have an almost flat underlying event contribution as a function of charged particle multiplicity

- data and EPOS the underlying event rises with increasing charged particle multiplicity being in a rather good agreement (except the last bin in multiplicity – to be cross-checked)



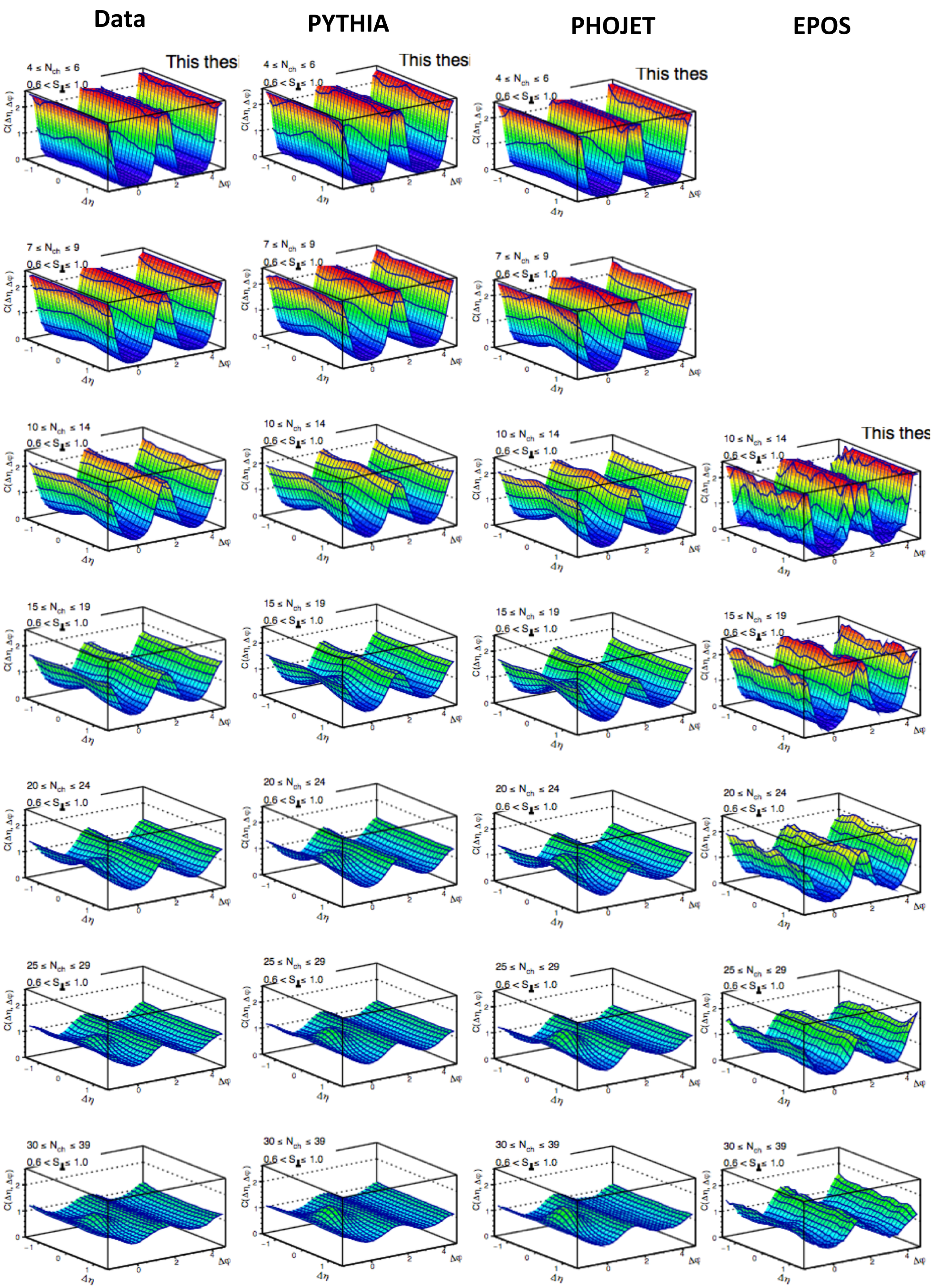


- similar trend for both the near and away-side long-range regions

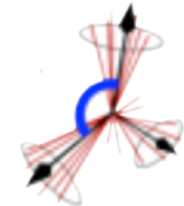
- Y_{near} and Y_{away} have rather similar values for data, PYTHIA and PHOJET

- EPOS clearly overestimates both regions

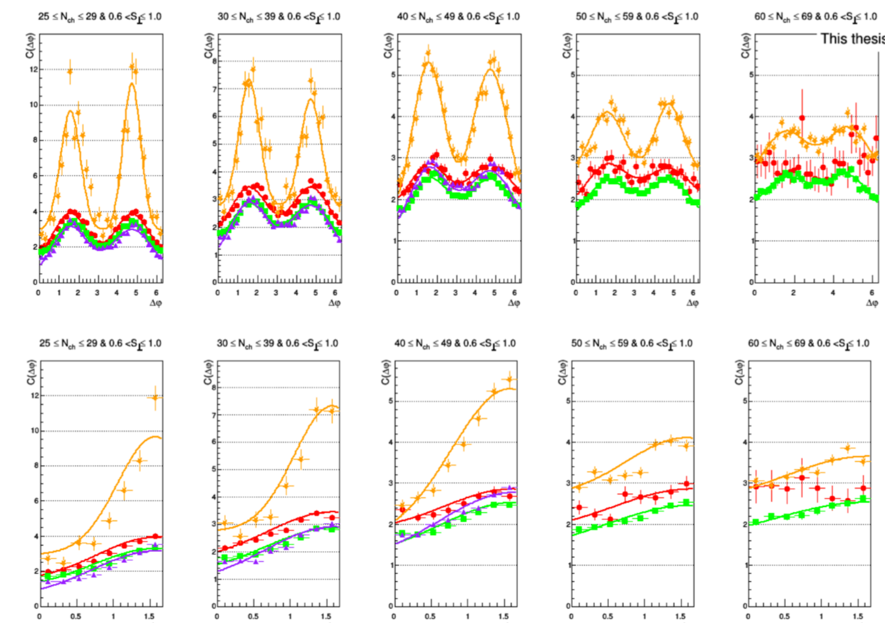
Two particle correlations



$1\ GeV/c \leq p_{\perp,assoc} < p_{\perp,lead} \leq 2\ GeV/c$
$0.6 \leq S_{\perp} \leq 1.0$
$1.25 < |\Delta\eta| < 1.5$ – projection on $\Delta\varphi$
multiplicity dependence



$$G(\Delta\varphi) = \frac{Y_{near}}{\sqrt{2\pi}\sigma_{near}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi}{\sigma_{near}}\right)^2} + \frac{Y_{away}}{\sqrt{2\pi}\sigma_{away}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi-\pi}{\sigma_{away}}\right)^2} + B$$



data
PYTHIA
PHOJET
EPOS

- the $C(\Delta\varphi)$ values for $\Delta\varphi < 0$ were shifted to values larger than $3\pi/2$

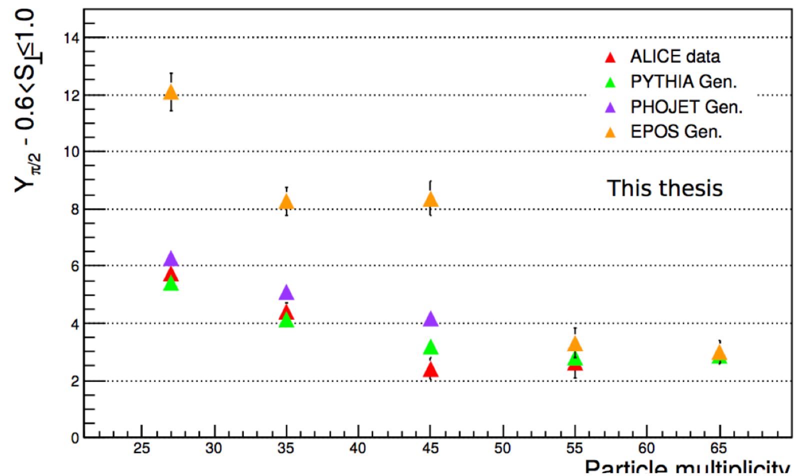
- at the largest charged particle multiplicity the data presents a rather flat $C(\Delta\varphi)$ while an azimuthal anisotropy is still evidenced in the models

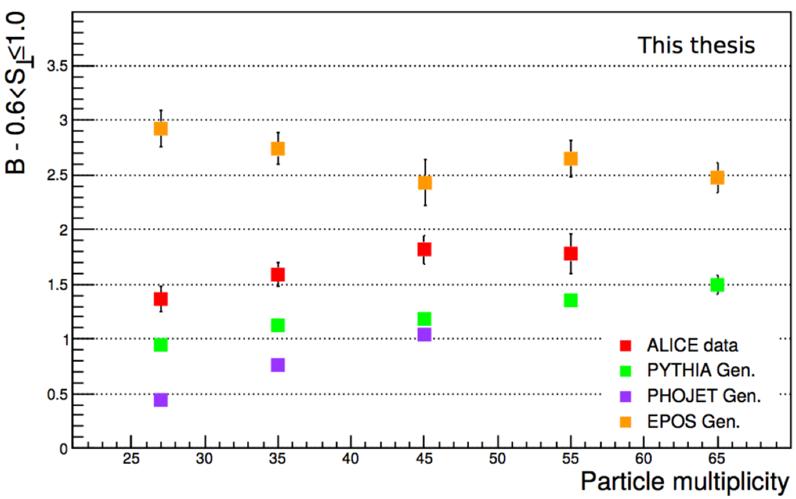
Two particle correlations

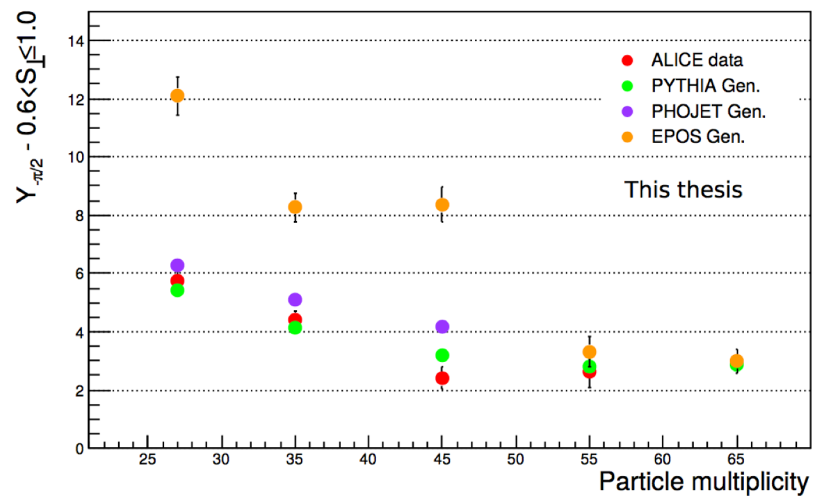
$1\ GeV/c \le p_{\perp,assoc} < p_{\perp,lead} \le 2\ GeV/c$
$0.6 \le S_{\perp} \le 1.0$
$1.25 < \Delta\eta < 1.5$ – projection on $\Delta\varphi$
multiplicity dependence

$$G(\Delta\varphi) = \frac{Y_{near}}{\sqrt{2\pi\sigma_{near}}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi}{\sigma_{near}}\right)^2} + \frac{Y_{away}}{\sqrt{2\pi\sigma_{away}}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi-\pi}{\sigma_{away}}\right)^2} + B$$

data
PYTHIA
PHOJET
EPOS







- the underlying event activity shows an ascending trend with multiplicity for the data, PYTHIA and PHOJET, the two models underestimating the experiment

- in EPOS it slightly decreases with charged particle multiplicity, overestimating the data

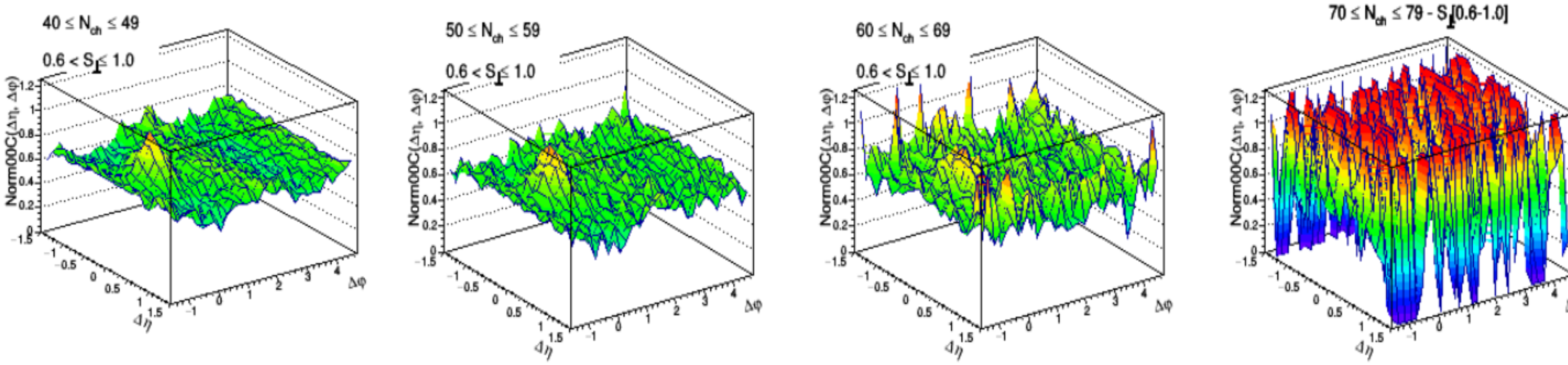
-the yields at π/2 and 3π/2 decrease going towards higher multiplicities

- $Y_{\pi/2}$ and $Y_{3\pi/2}$ are the same within the error bars in both regions

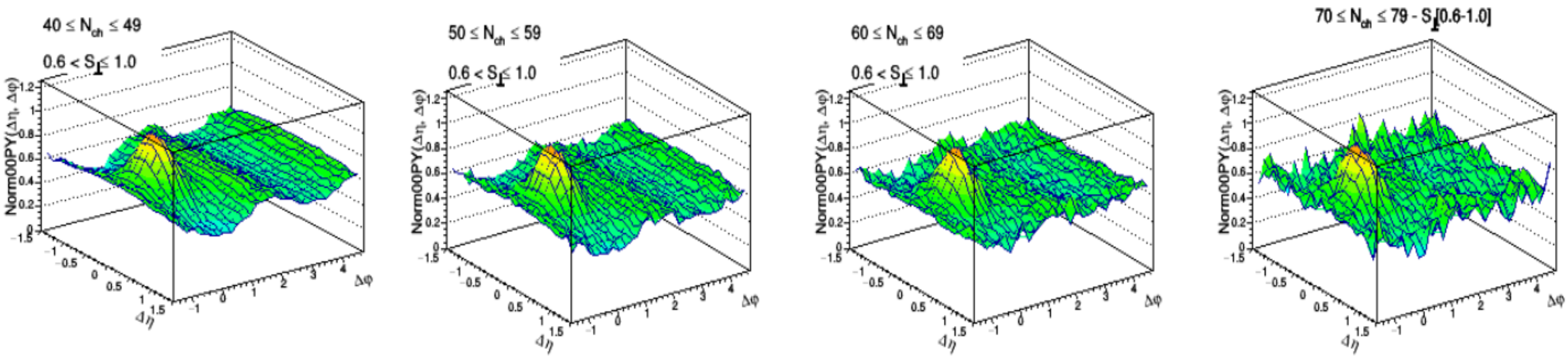
- EPOS largely overestimates the data up to charged particle multiplicity ~ 45, the difference decreasing with increasing multiplicity

Two particle correlations

Data

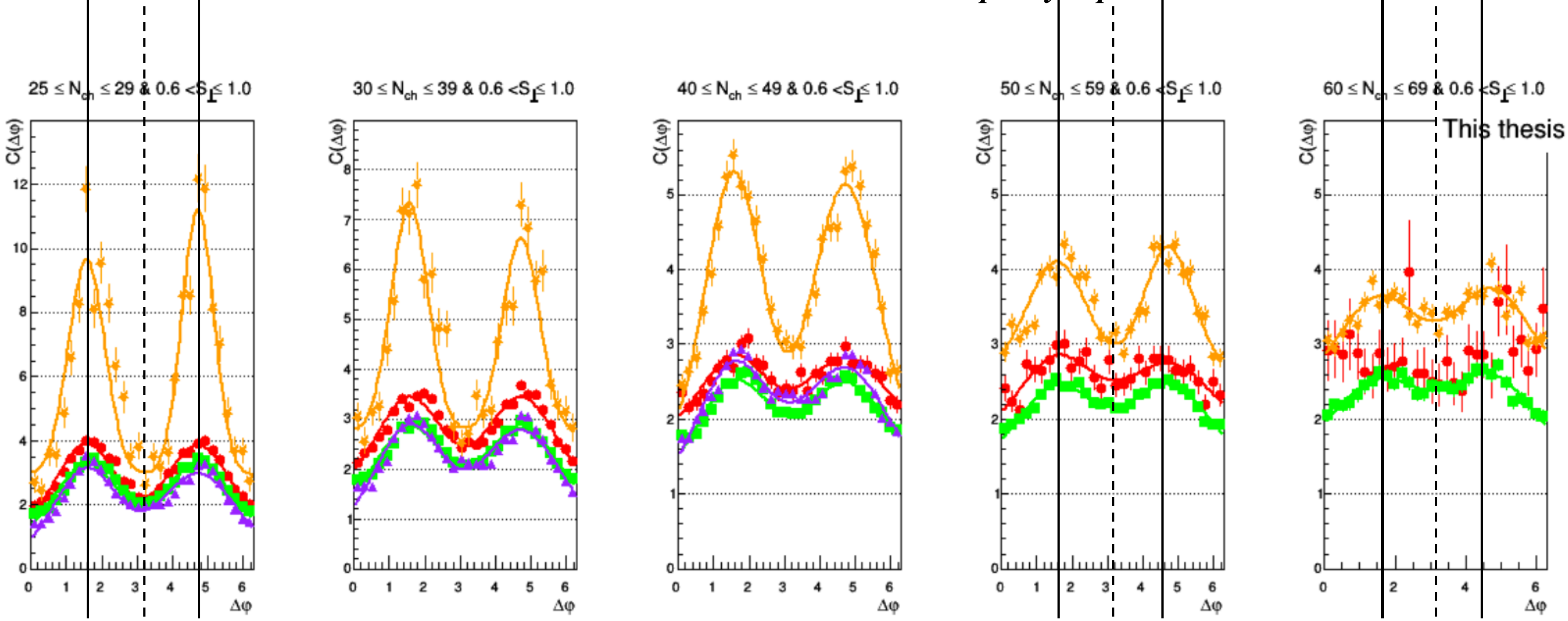


PYTHIA



Two particle correlations

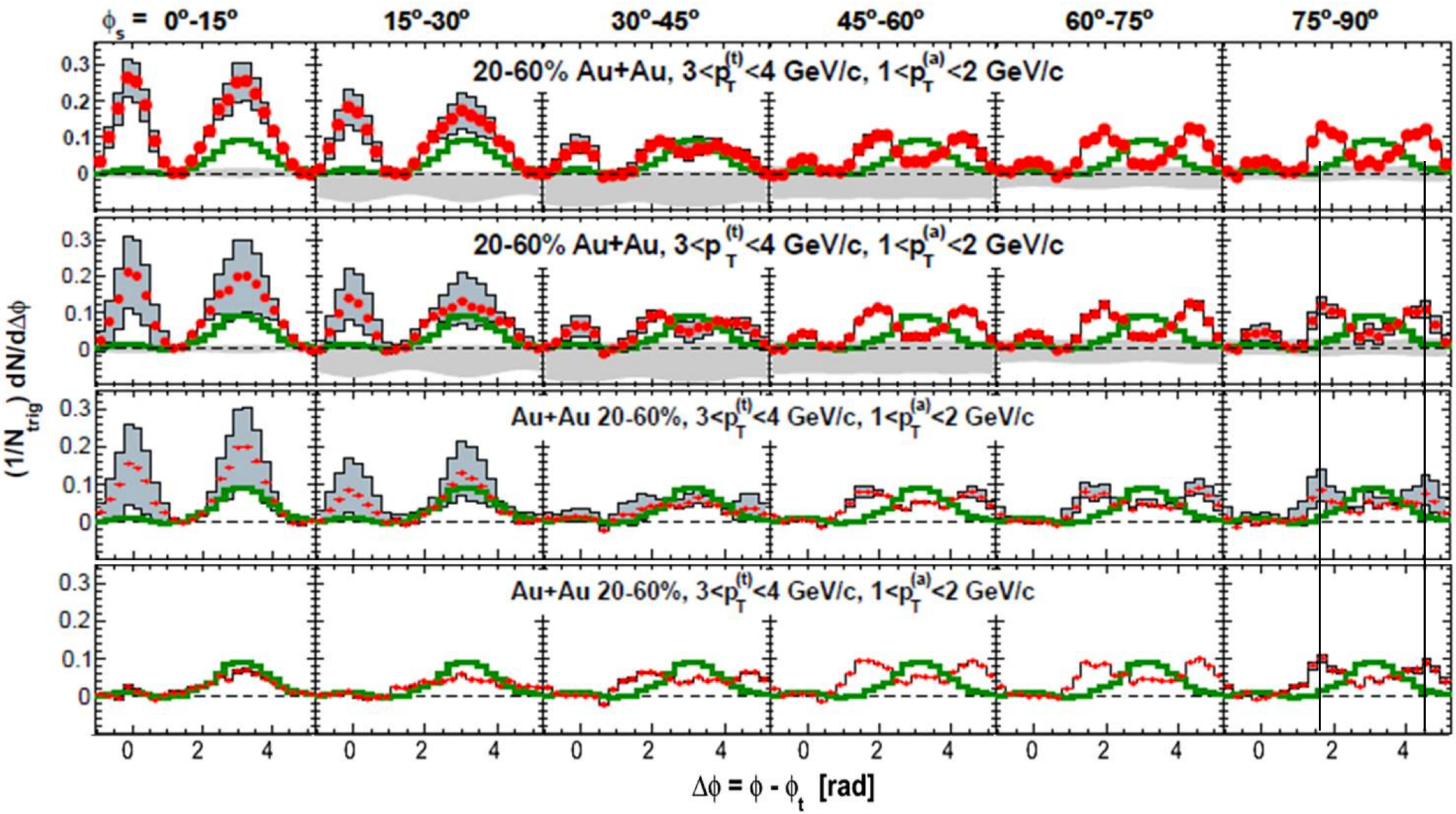
1 GeV/c≤$p_{\perp,assoc}$<$p_{\perp,lead}$≤2 GeV/c
0.6≤$S_\perp$≤1.0
1.25< |Δη| <1.5 – projection on Δφ
multiplicity dependence



$$G(\Delta\varphi) = \frac{Y_{near}}{\sqrt{2\pi\sigma_{near}}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi}{\sigma_{near}}\right)^2} + \frac{Y_{away}}{\sqrt{2\pi\sigma_{away}}} e^{-\frac{1}{2}\left(\frac{\Delta\varphi-\pi}{\sigma_{away}}\right)^2} + B$$

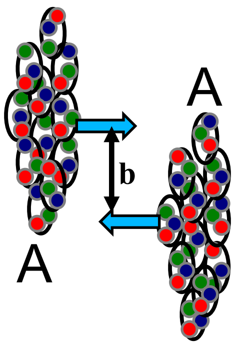
data
PYTHIA
PHOJET
EPOS

Two particle correlations

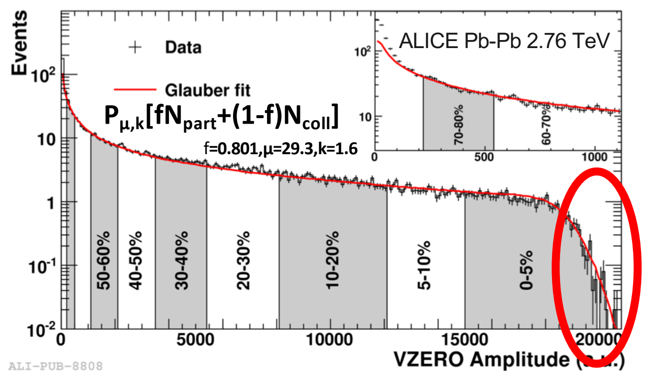


F.Wang, STAR Collaboration, arXiv:[nucl-ex]1309.4515

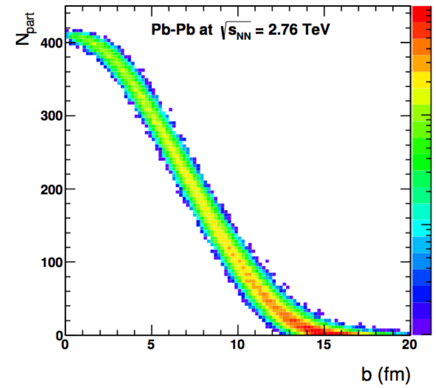
Similar studies in A-A ???

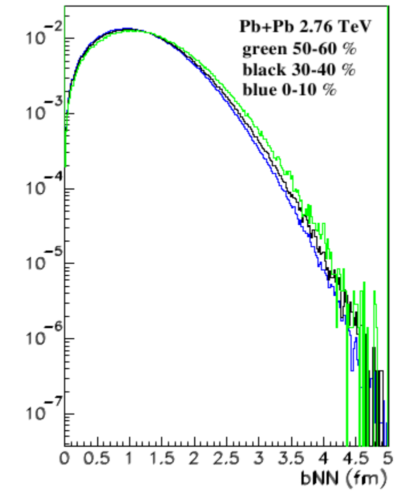


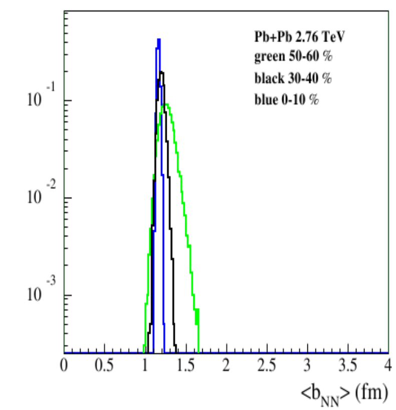
Experimental Multiplicity

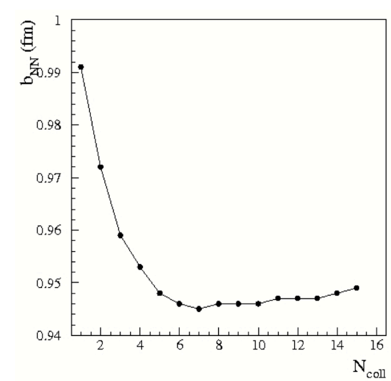


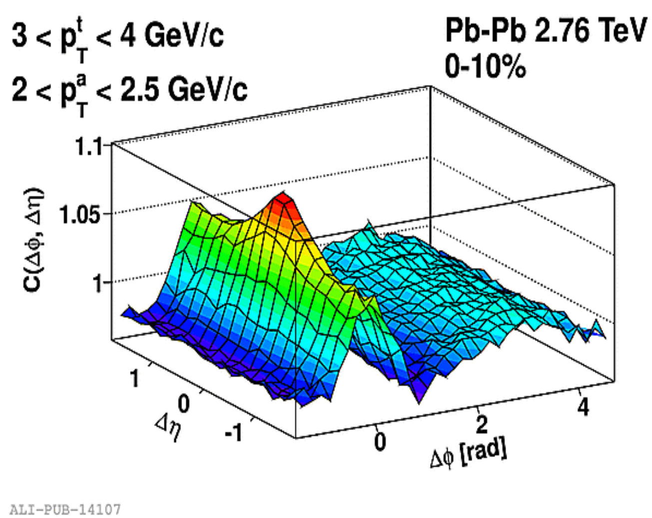
ALICE Collaboration, Phys. Rev. Lett. 106, 032301











Phys.Lett. B708(2014)249

Theoretical approaches - short list of references

HIJING *- Heavy-Ion Jet Interaction Generator*

X.N.Wang et al., Phys.Rev. D44(2011)3501
M.Gyulassy et al., Comp.Phys.Com. 83(1994)307
X.N.Wang et al., Phys.Reo. 280(1997)287
W.T.Deng et al., Phys.Rev. C83(2011)014915

HERWIG *- Monte Carlo implementation of the two-component Dual Parton Model*

S.Moretti et al., arXiv:[hep-ph]0205105

PHOJET *- Monte Carlo event generator for high-energy processes*

F.W.Bopp et al., arXiv:[hep-ph]9803437

PYTHIA *- review, Thermodynamical String Fragmentation, Color Reconnection, Shoving*

C.Bierlich et al., arXiv:[hep-ph]1412.6259
C.Bierlich et al., arXiv:[hep-ph]1612.05132
N.Fischer et al., arXiv:[hep-ph]1610.09818

Theoretical approaches - short list of references

CGC *- Color Glass Condensate - a state of high density gluonic matter which controls the high energy limit of hadronic matter.*

L. McLerran, arXic:[hep-ph]0104285 and references therein

*- **GLASMA** - a system where the the interaction of classical field with itself and the interaction of classical fields with the hard fields become important*

T.Lappi et al., arXiv:[hep-ph]0602189

- Expanding color flux tubes and instabilities

H.Fujii et al., arXiv:[hep-ph]0803.0410

- Simulation collisions of thick nuclei in CGC framework

D.Gelfand et al., arXiv:[hep-ph]1605.0718

More details in Dana Avramescu lecture

Theoretical approaches - short list of references

KøMPøST *- a practical tool to bridge between early time dynamics of strong color fields*
and
successful hydrodynamical simulations at late times

A.Kurkela et al., arXiv:[hep-ph]1805.01604

$\langle \tau s \rangle$ - the average entropy density per unit of rapidity

$\langle \tau s \rangle \approx (S/N_{ch})(1/A_{\perp})dN_{ch}/d\eta$

$(S/N_{ch}) \approx 7$ - for a hadron resonance gas

$\tau_{hydro}/R \simeq [4\pi(\eta/s)/2]^{3/2}[(dN_{ch}/d\eta)/63]^{-1/2}[(S/N_{ch})/7]^{-1/2}(\nu_{eff}/40)^{1/2}$ - **is independent on the system size R depends only on the charged particle multiplicity**

$\Rightarrow$ **In an optimistic scenario the minimum requirement for hydrodynamic phase, $\tau_{hydro}/R \approx 1$ is reached if <u>$dN_{ch}/d\eta \gtrsim 8$ for small $\eta/s = 1/(4\pi)$</u>**
For a larger value of specifics shear viscosity <u>$\eta/s = 2/(4\pi) \Rightarrow dN_{ch}/d\eta \gtrsim 63$</u>

Outlook

- *larger statistics => multi-differential analysis*
  - *very good PID as low as possible in p_T*
  - *event-shape*
  - *different ranges in $\Delta\eta$ and $\Delta\Phi$ relative to L(T)P*

- *Core-corona interplay in A-A and pp - plays an important role in understanding the origin of different experimentally evidenced trends*

- *pp as high as possible in charged particle multiplicity*

- *Understanding the similarities and differences between pp and A-A at high f_g^{in}*

- *lower mass A-A collisions ?*