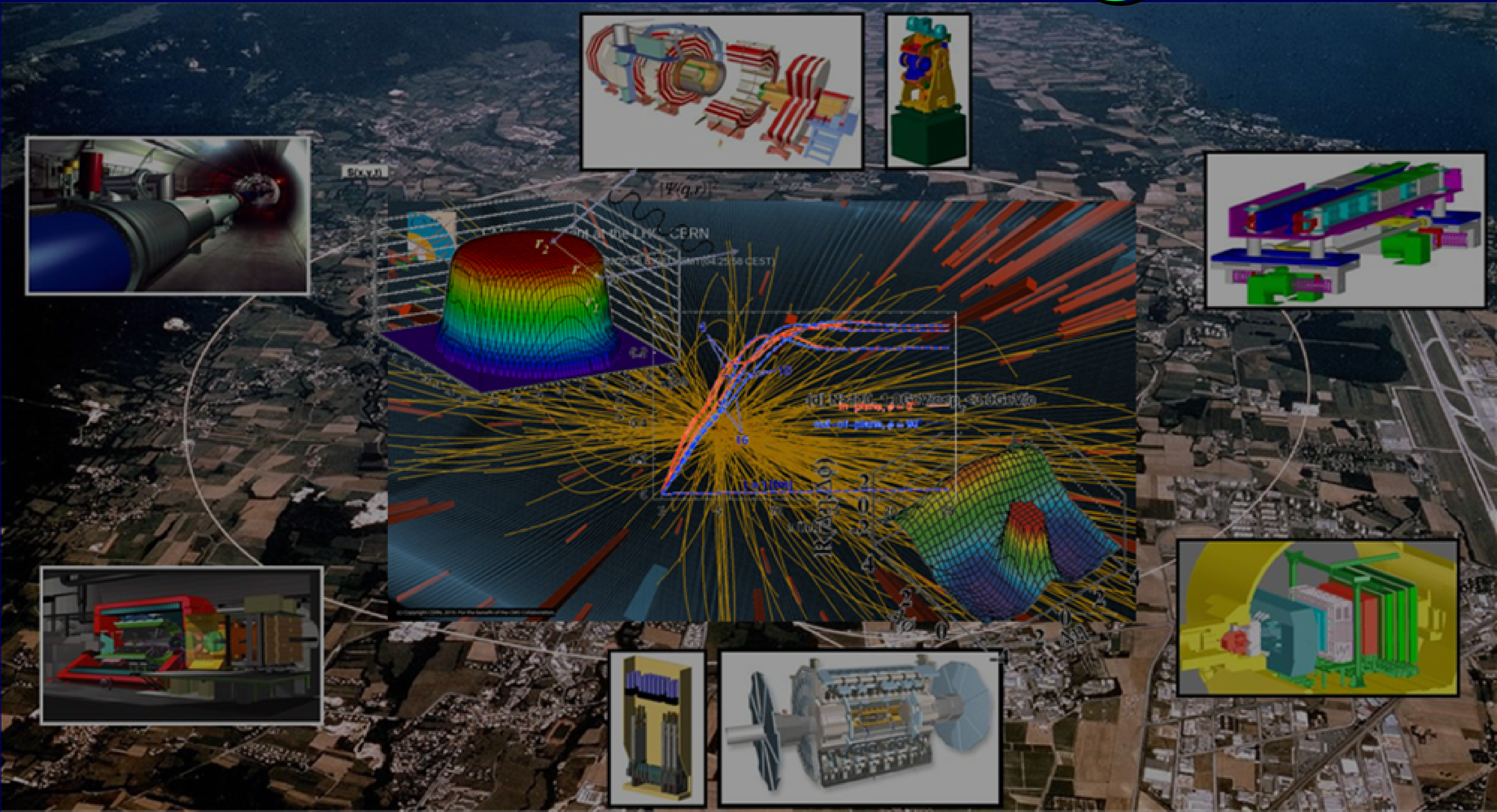
Particle correlations @ LHC



Luca Perrozzi (INFN & Universita' di Padova - CERN)

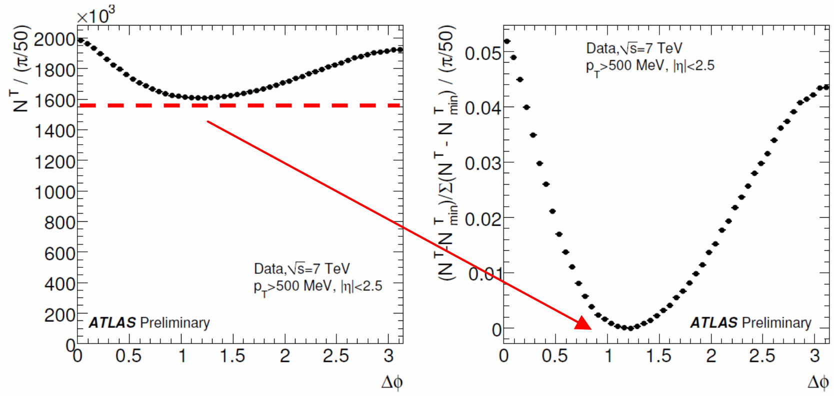
Standard Model @ LHC - Durham, 11th-14th April 2011

Particle correlations @ LHC

- Correlations represent multipurpose tools to extract several useful information from data and give feedback to theoreticians/MC developers to overcome the non-perturbative nature of QCD
  - MC tuning
    - $\Delta\phi$
  - Characterize QCD @ LHC energies, study mechanism of hadronization and possible collective effects due to the high particle densities reached
    - $\Delta\eta$ vs $\Delta\phi$
  - Study the creation and characteristics of the collective effects
    - Elliptic Flow
  - Study effective space-time structure of the hadron emission region
    - Bose-Einstein correlations

MC tuning: Δφ correlations

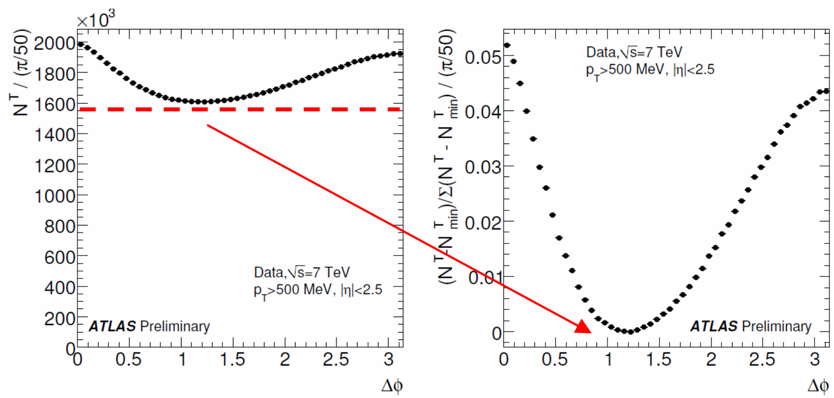
ATLAS-CONF-2010-082

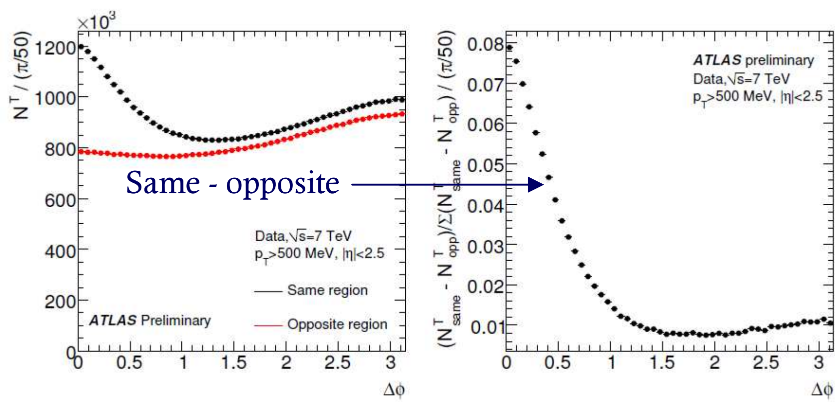


- Δφ "crest shape"
  - Background subtracted distribution of azimuthal angular difference Δφ, between the leading p_T particle and all the others

MC tuning: Δϕ correlations

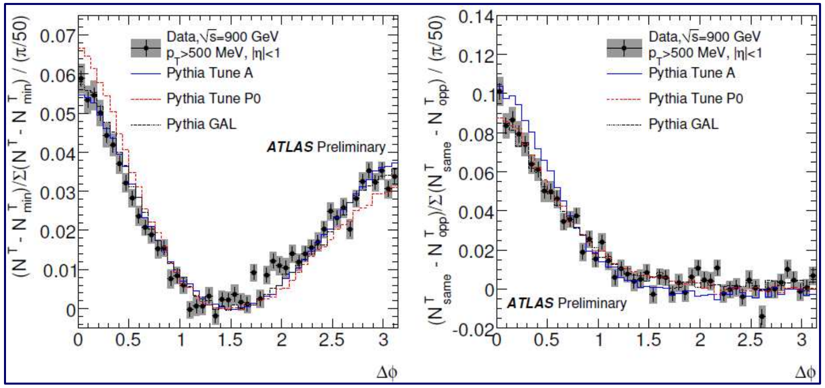
ATLAS-CONF-2010-082

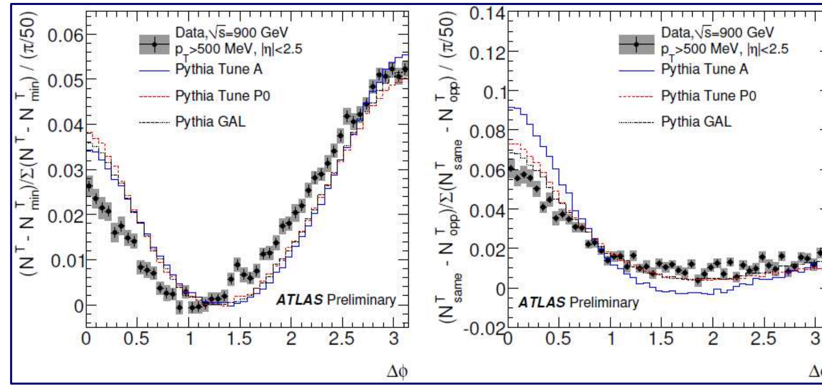




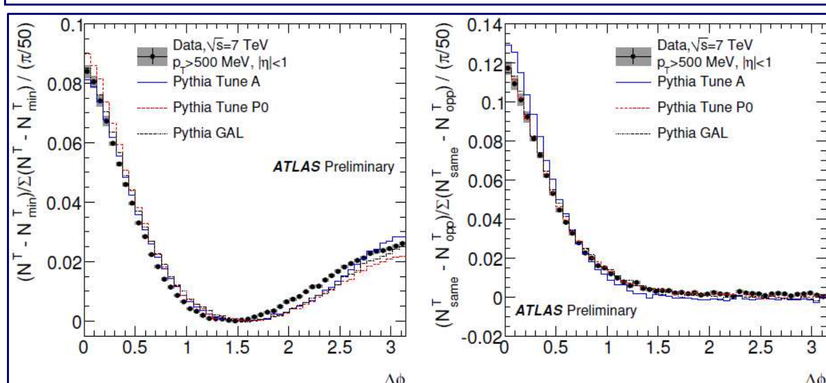
- Δϕ "crest shape"
  - Background subtracted distribution of azimuthal angular difference Δϕ, between the leading p_T particle and all the others
- Δϕ "same minus opposite"
  - Each event is divided into two η regions according to the η of the leading particle to create the Δϕ "same minus opposite" observable.
  - Δϕ is divided for particles with η of the same sign as the leading particle and for particles with η of the opposite sign. The "opposite region" distribution is subtracted from the "same region" distribution and the resulting distribution is normalised to unit area.

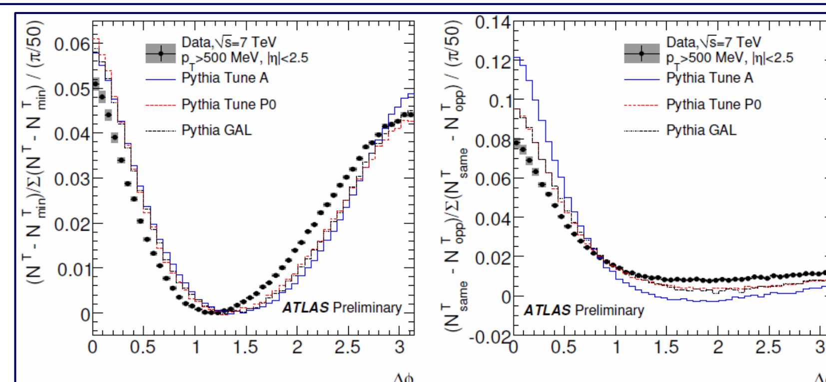
Δφ correlations



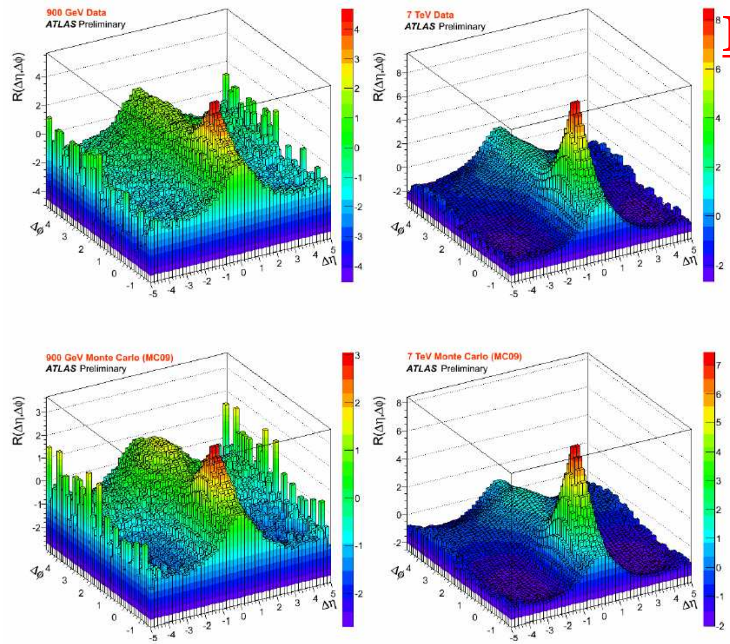


- The best agreement between data and theory curves in the region |η| < 1.0
  - Not surprising since a lot of tunes use TeVatron data from CDF as input, which is limited to this range.
- The agreement is not perfect, especially in the crest shape at 7 TeV where the recoil peak shape is not well-modelled.
- The further the η range is extended, the worse the match between data and theory

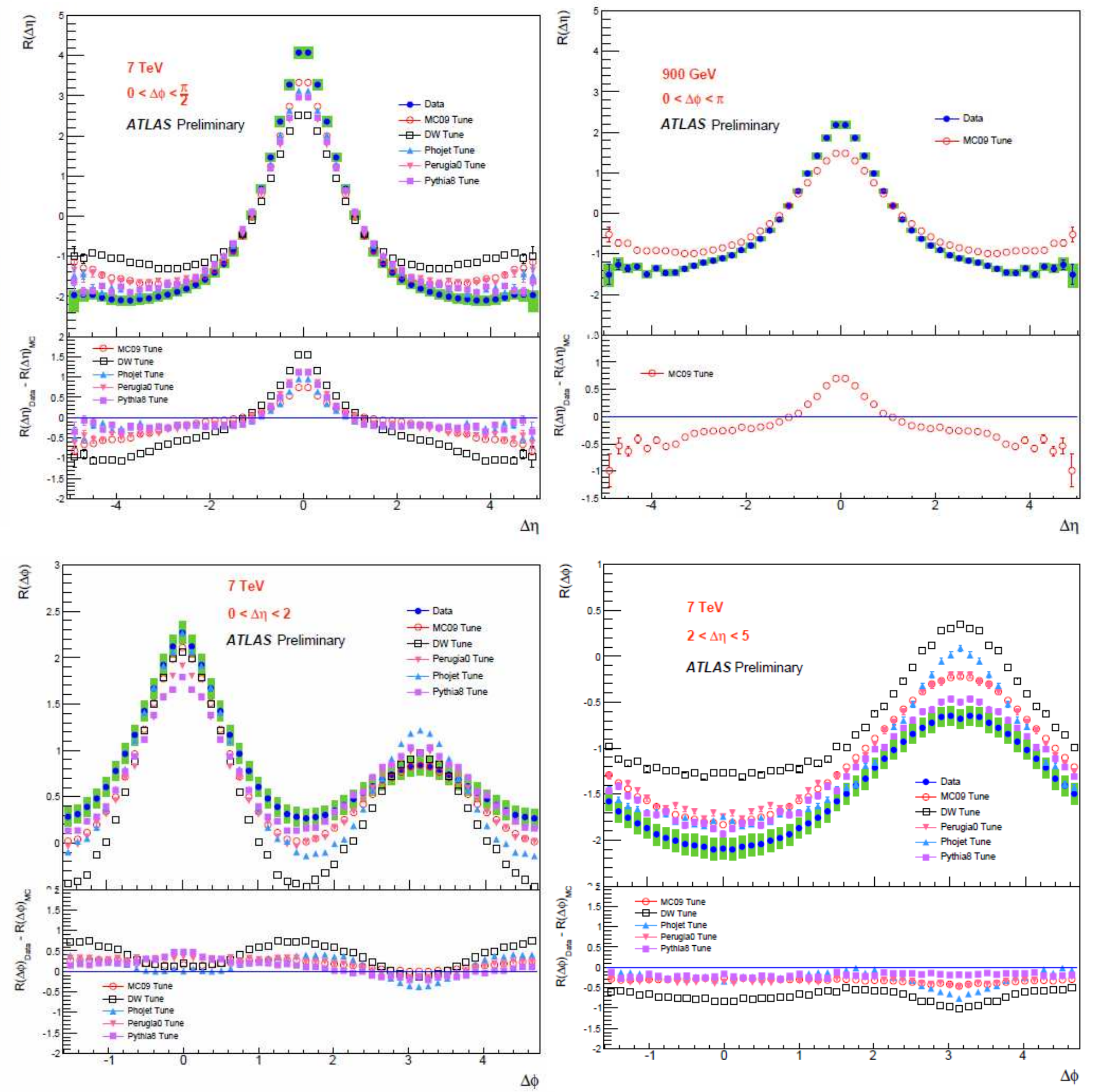




MC tuning: Δη vs. Δϕ correlations



LAST SECOND UPDATE: ATLAS-CONF-2011-055



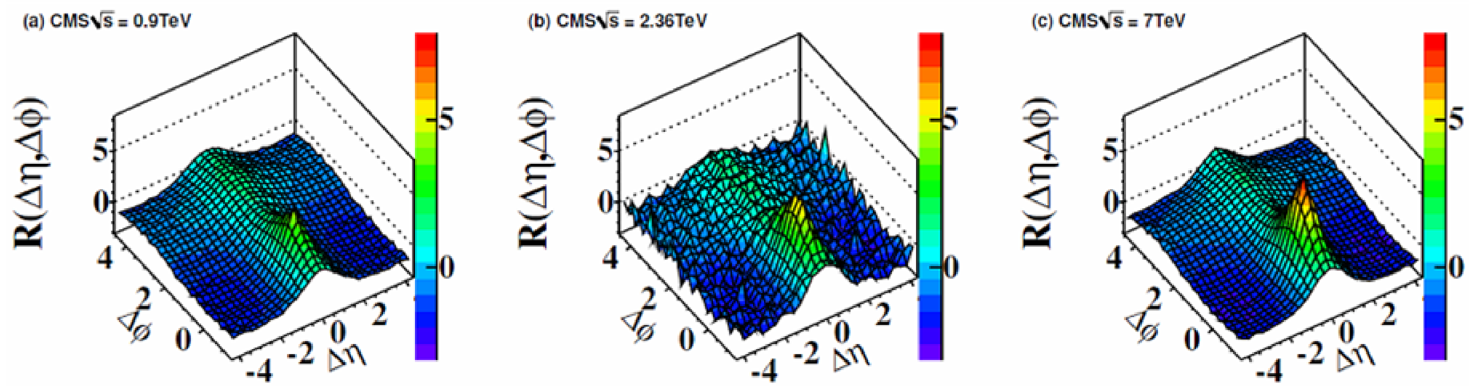
- "The structure of the correlation was explored in more detail by projecting the two-dimensional distribution into both Δη and Δϕ."
- "The results have been compared to Monte Carlo samples which show a similar complex structure in Δη and Δϕ but fail to reproduce the strength of the correlations seen in data."

Characterize QCD: $\Delta\eta$ vs $\Delta\phi$ correlations

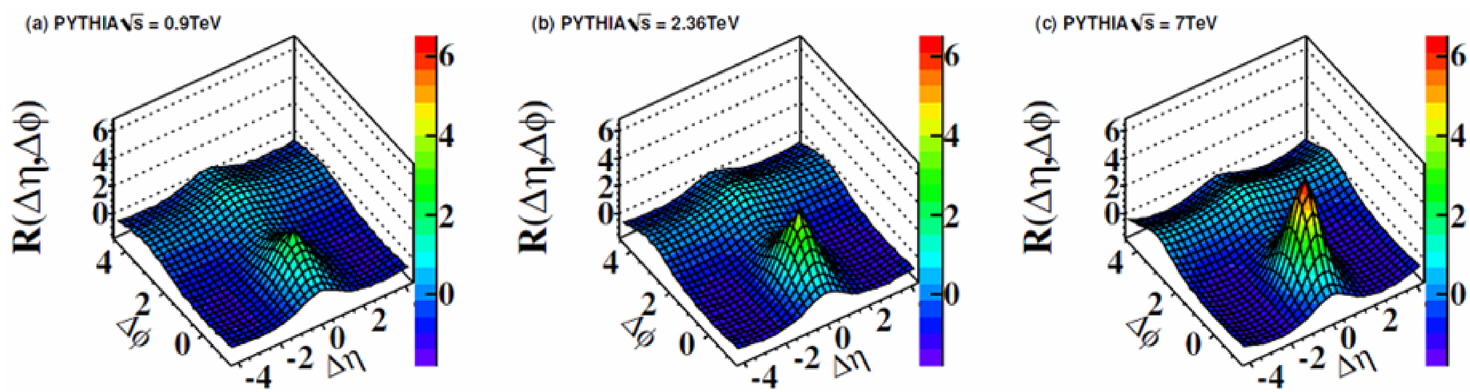
- Multiparticle correlations have been measured for a broad range of collision energies and colliding systems with the goal of understanding the underlying mechanism of particle production

CMS - JHEP 1009:091,2010

CMS pp data



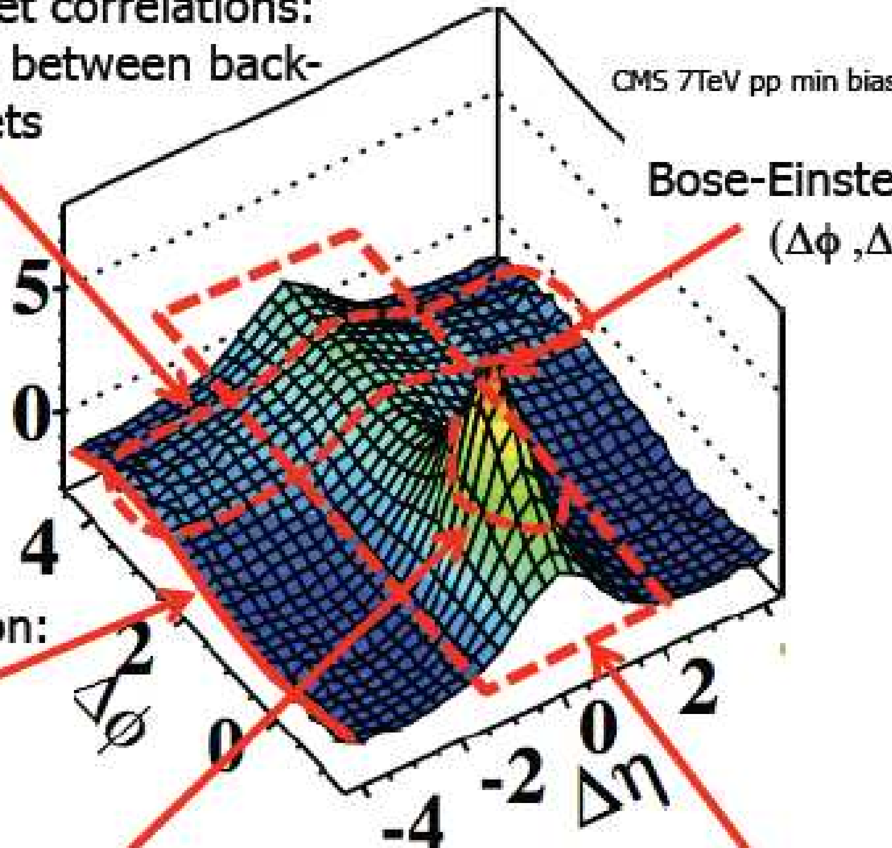
Pythia D6T MC



Δη vs Δϕ correlations

"Away-side" (Δϕ ~ π) jet correlations: Correlation of particles between back-to-back jets

$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$



Bose-Einstein correlations: (Δϕ ,Δη) ~ (0,0)

Momentum conservation: ~ -cos(Δϕ)

"Near-side" (Δϕ ~ 0) jet peak: Correlation of particles within a single jet

Short-range correlations (Δη < 2): Resonances, string fragmentation, "clusters"

Δη vs Δϕ correlations

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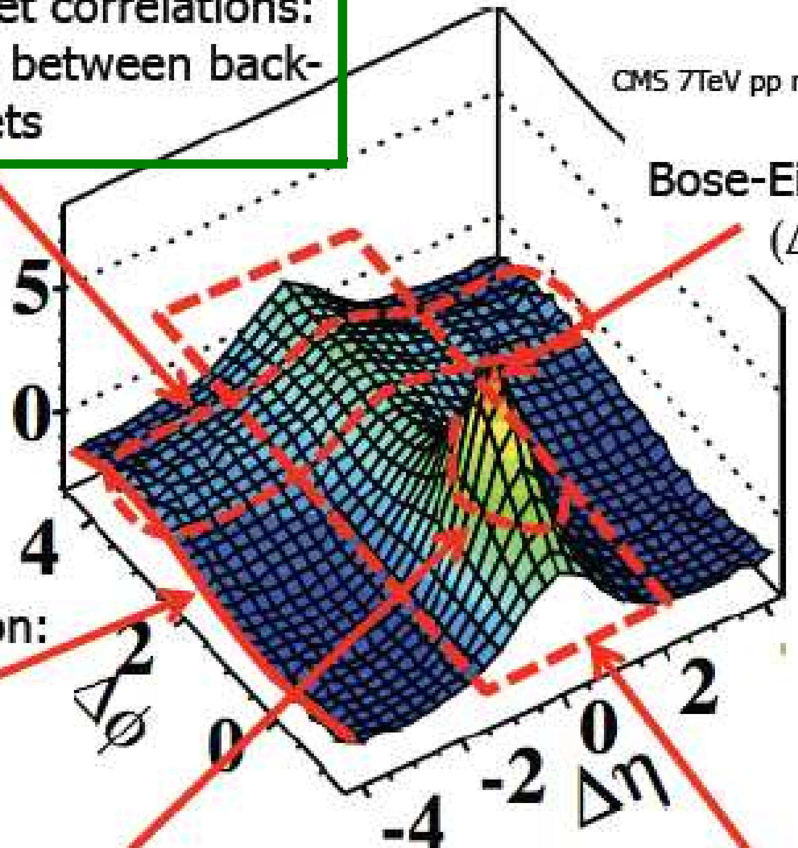

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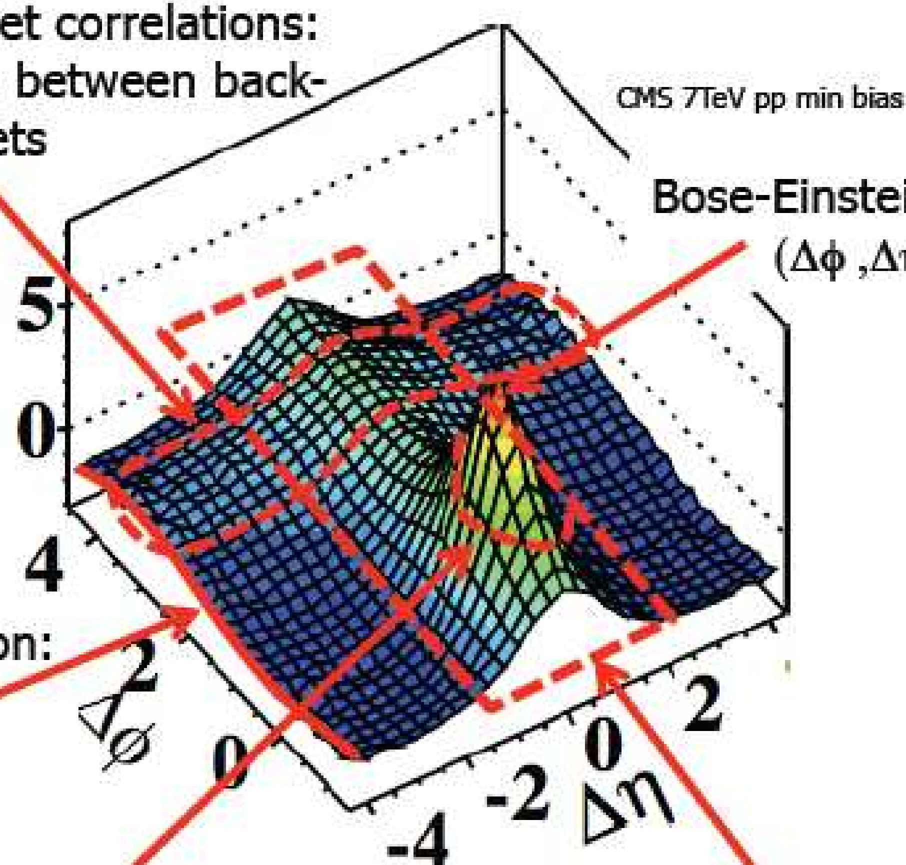

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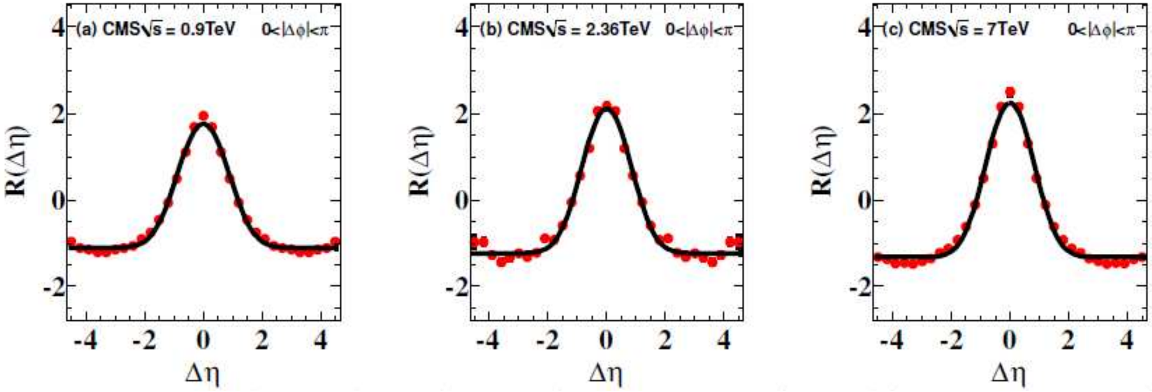
Δη vs Δϕ correlations

- Short-range correlations in Δη, studied in MinBias events, are characterized using a simple "independent cluster" parametrization $R(\Delta\eta) = \alpha \left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1 \right]$ in order to quantify their strength (cluster size) and their extent in η (cluster decay width).

CMS - JHEP 1009:091,2010



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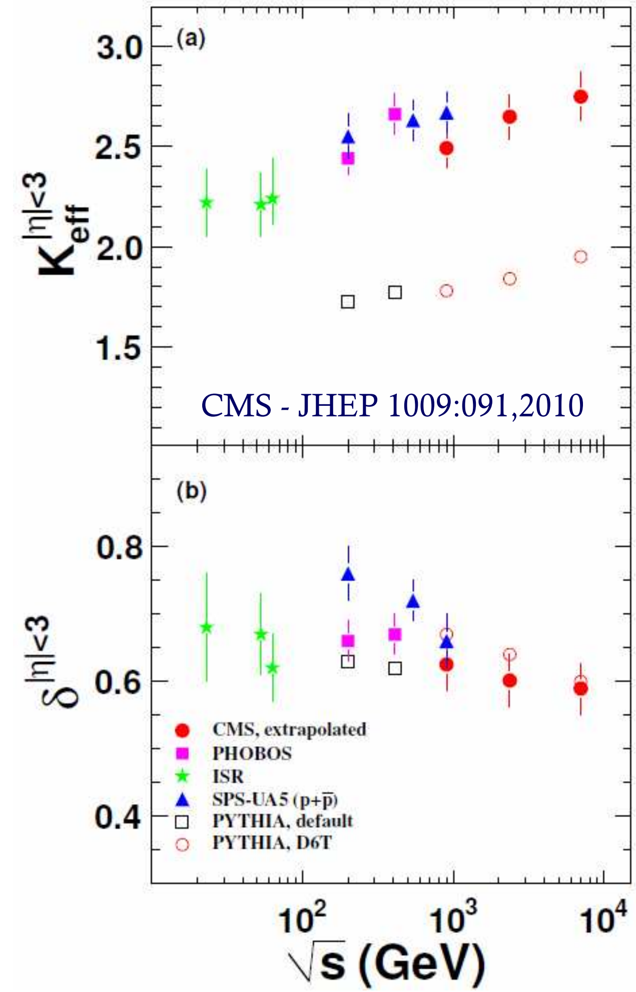
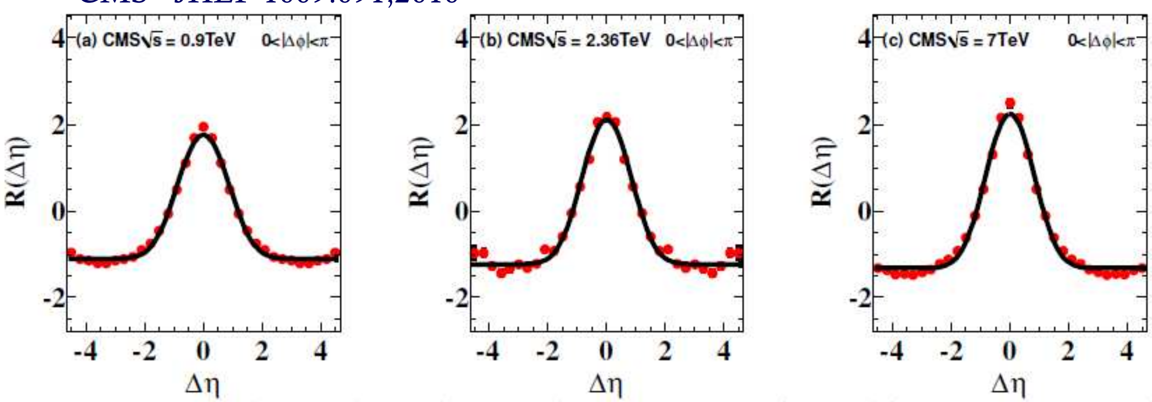


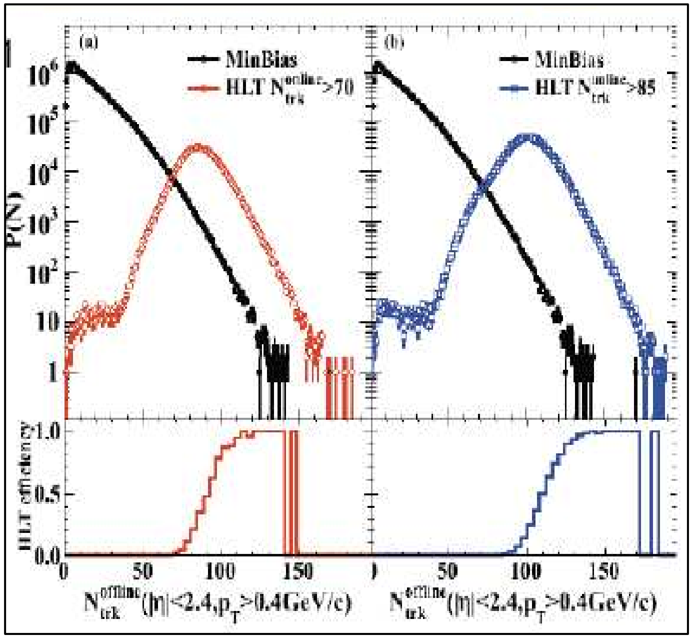
CMS - JHEP 1009:091,2010

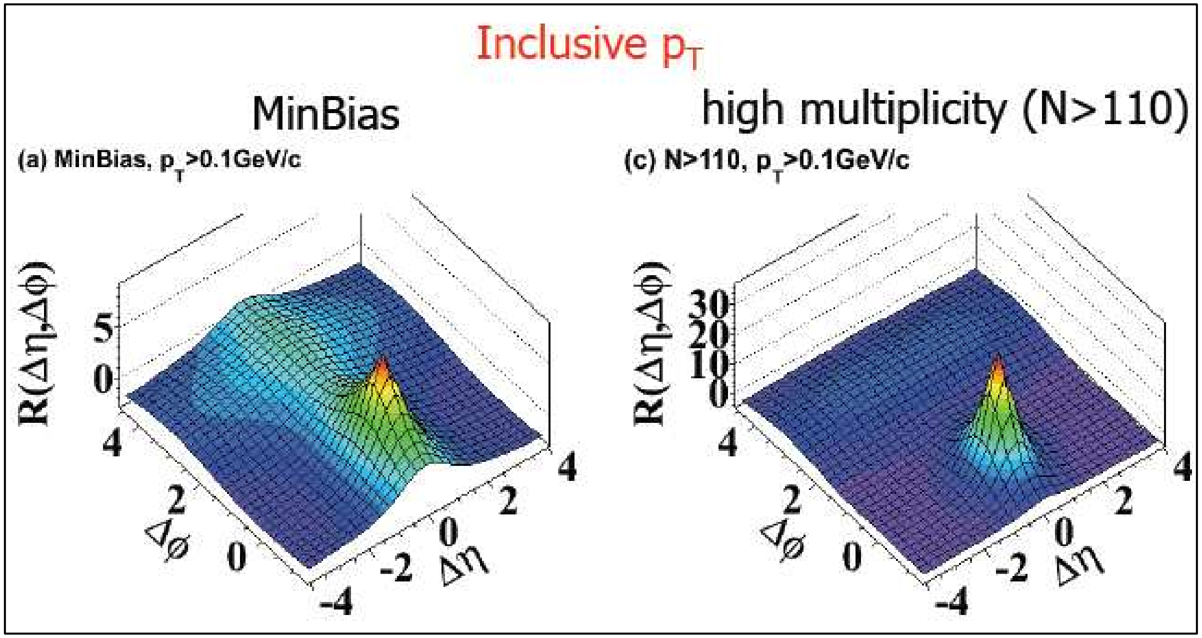


PYTHIA reproduces the energy dependence, matches the cluster width δ in data, underestimates the cluster size K_{eff}

High multiplicity trigger

- Thanks to the very flexible CMS trigger system it was possible to collect a sizeable sample of very high multiplicity events
- In these events:
  - There is abundant jet production
  - The jet peak/away-side correlations are enhanced

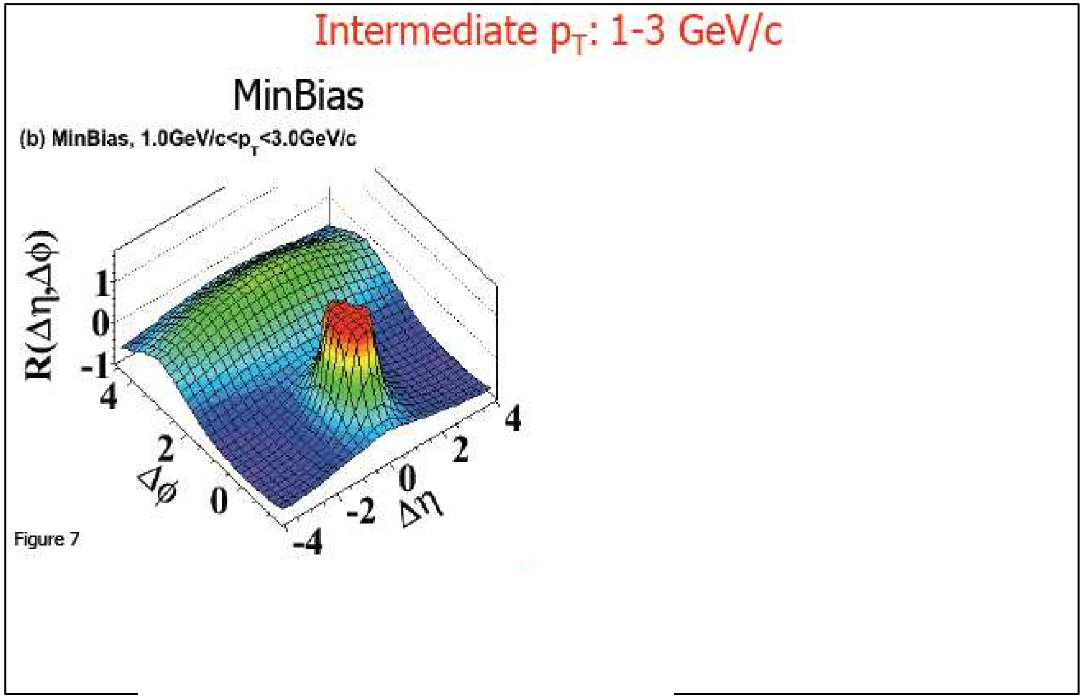




MinBias vs high multiplicity events

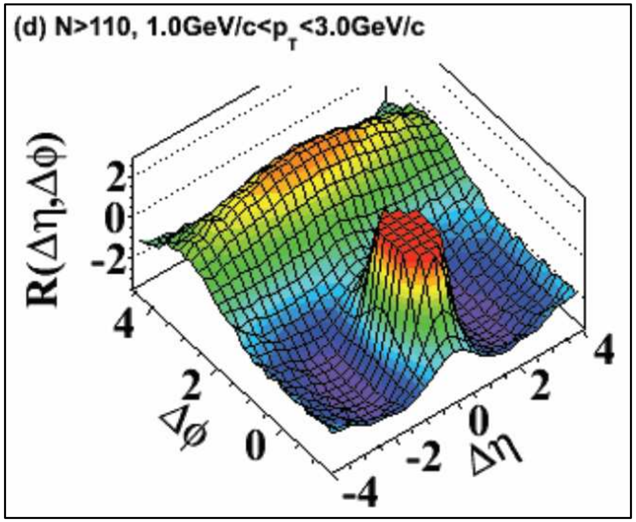
- Cut off peak at (0,0) shows structure of away-side ridge (back-to-back jets)

CMS - JHEP 1009:091,2010



MC (Pythia8 ver.135)

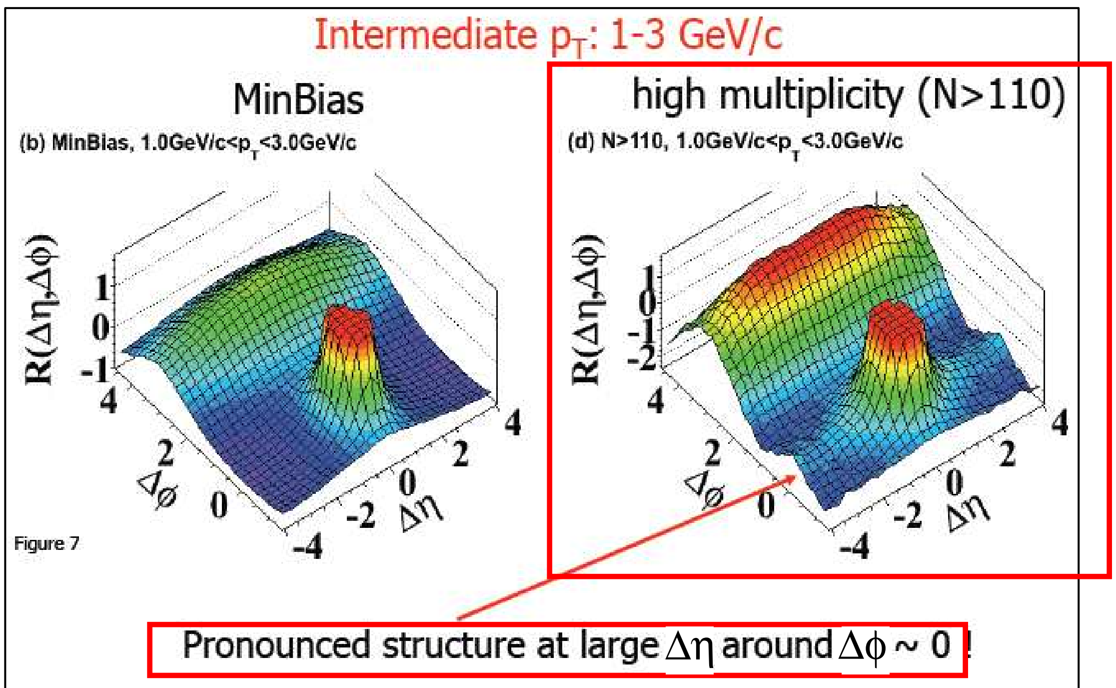
High multiplicity (N>110)



MinBias vs high multiplicity events

- Cut off peak at (0,0) shows structure of away-side ridge (back-to-back jets)
- Intermediate p_T range exhibit a pronounced structure at large $\Delta\eta$ around $\Delta\phi \sim 0$
- No such a structure is reproduced by MC (Pythia, Herwig, Madgraph)

CMS - JHEP 1009:091,2010



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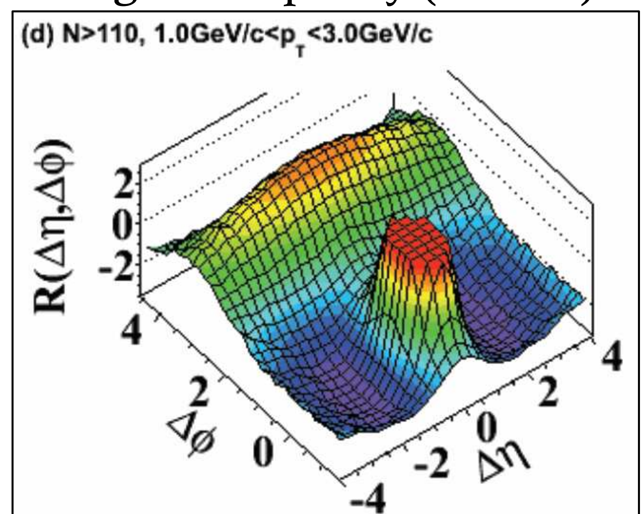
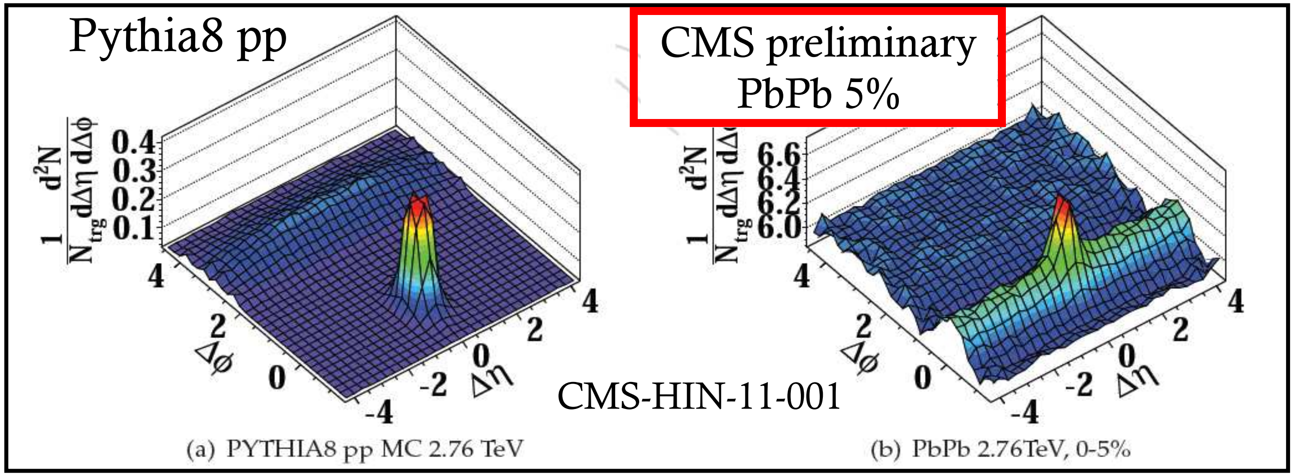
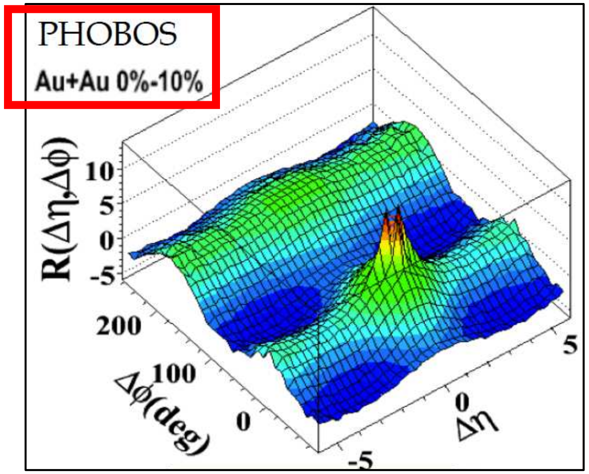


The "ridge" in PbPb collisions

- The pronounced structure at large Δη around Δϕ~0, usually called "ridge", was discovered in long-range pseudorapidity correlations in central AuAu collisions at RICH.
- In that case is expected to be an evidence of the development of collective motion, where matter is strongly interacting.





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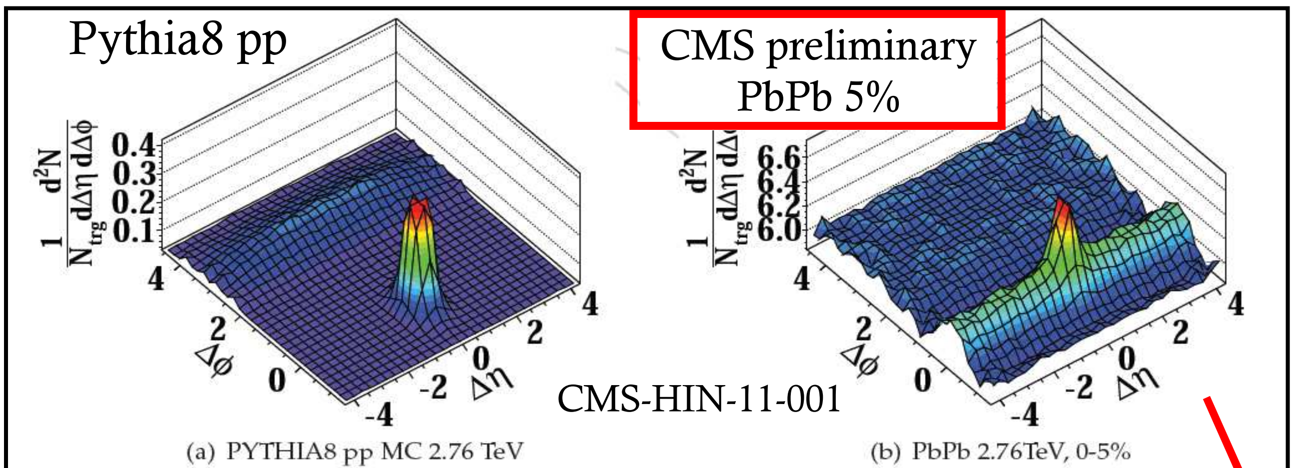
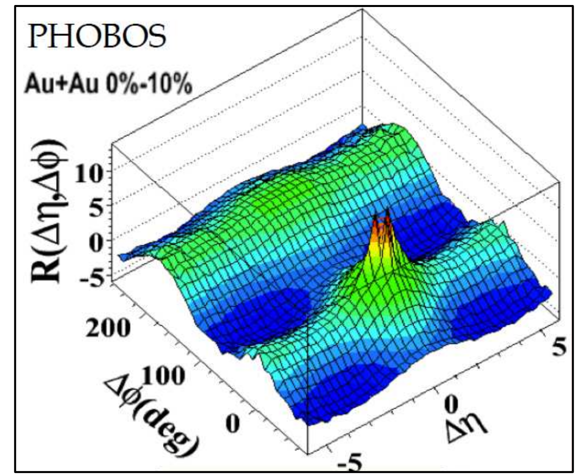
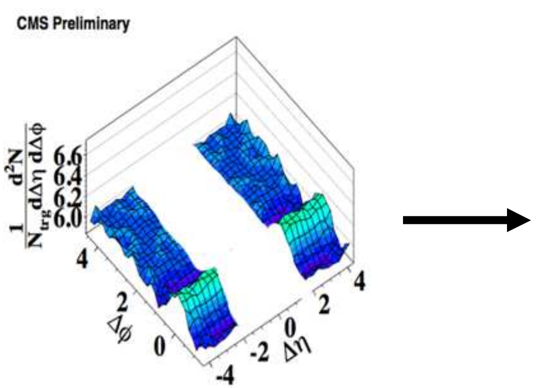
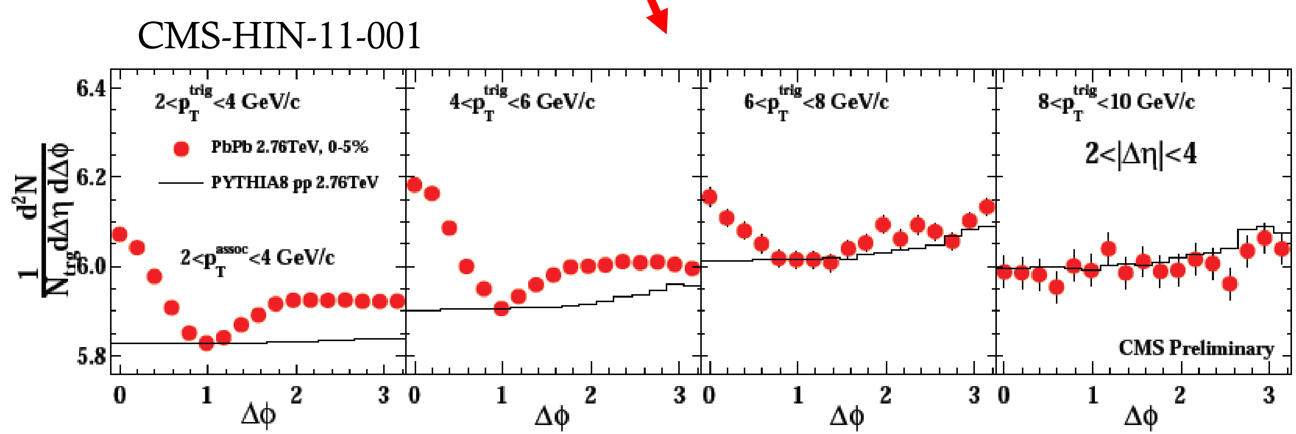


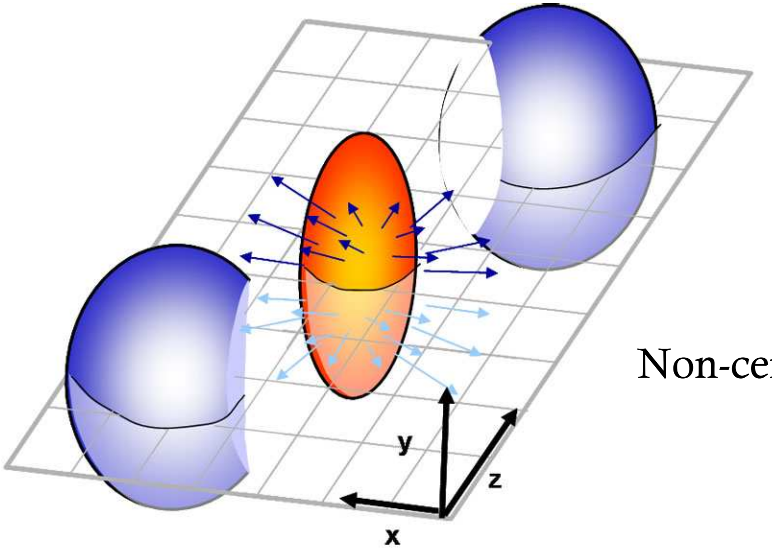






Describing collectivity: hydrodynamics

- Hydrodynamics approach describes collective flow
  - common velocity of all particles
- The process drives the space-time evolution of the system
- The observables in the momentum sector: particle spectra, elliptic flow are well described with a variety of model parameters.



Non-central collision sketch

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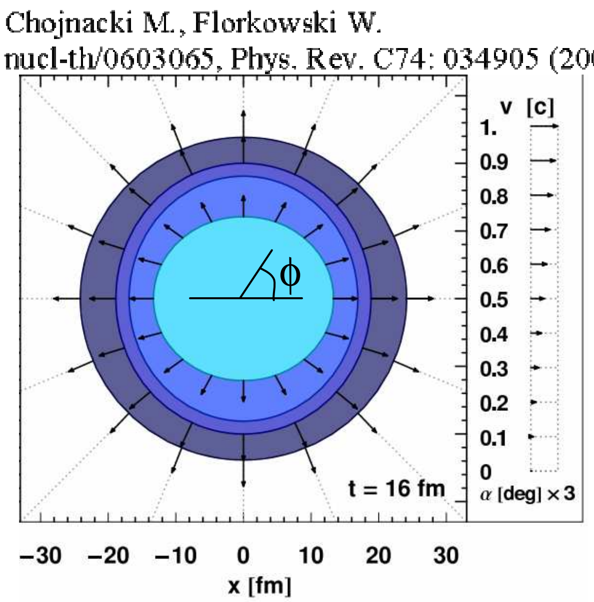
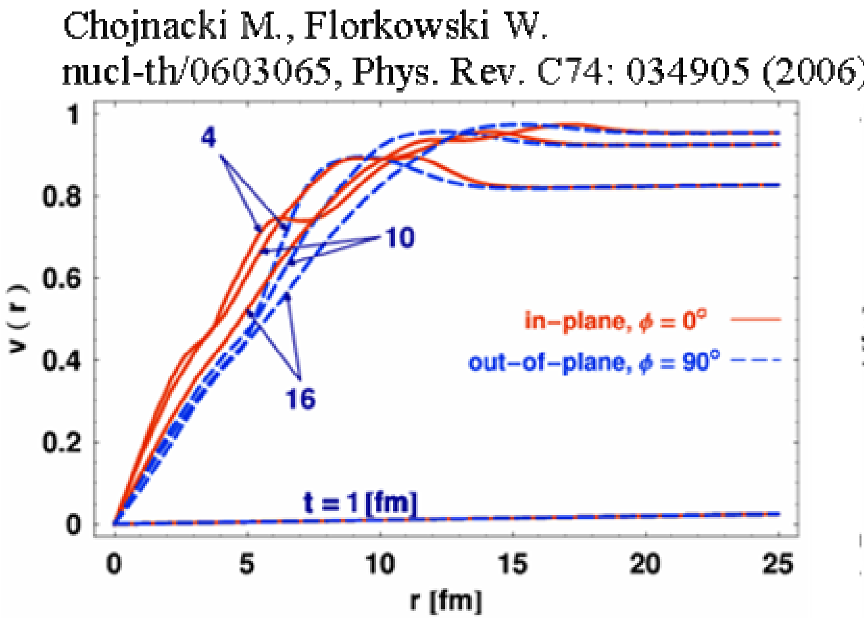




Elliptic flow

- The second moment of the final state hadron azimuthal distribution is called elliptic flow
  - it is a response of the dense system to the initial conditions and therefore sensitive to the early and hot, strongly interacting phase of the evolution.

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_R)]\right)$$

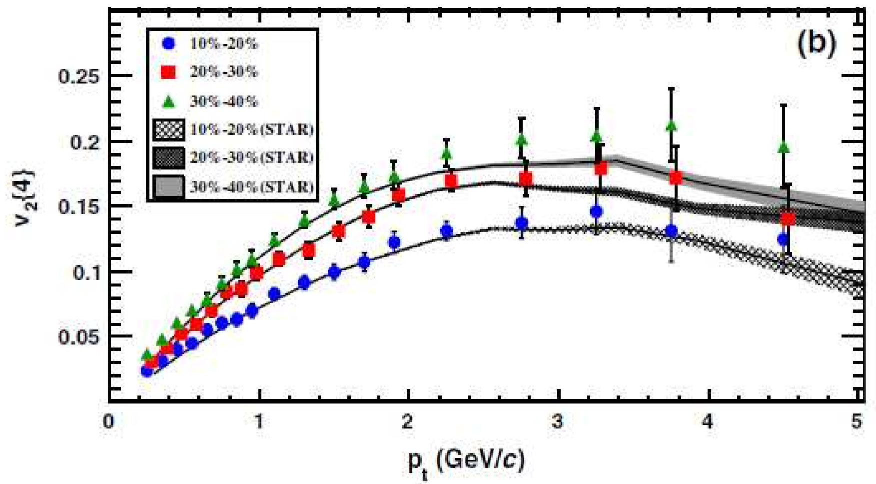
where E is the energy of the particle, p the momentum, p_t the transverse momentum, ϕ the azimuthal angle, y the rapidity, and Ψ_R the reaction plane angle. The reaction plane is the plane defined by the beam axis z and the impact parameter direction.

- Using a 4-particle correlation method, (averaged over transverse momentum and pseudorapidity) the elliptic flow signal v_2 is found to be $v_2 = 0.087 \pm 0.002(stat) \pm 0.003(syst)$ in the 40%–50% centrality class.

- The differential elliptic flow $v_2(p_t)$ reaches a maximum of 0.2 near p_t=3 GeV/c.

- Compared to RHIC Au-Au collisions at sqrt(s)_{NN}=200 GeV, the elliptic flow increases by about 30% due to harder p_t spectrum, differential results are found to be consistent

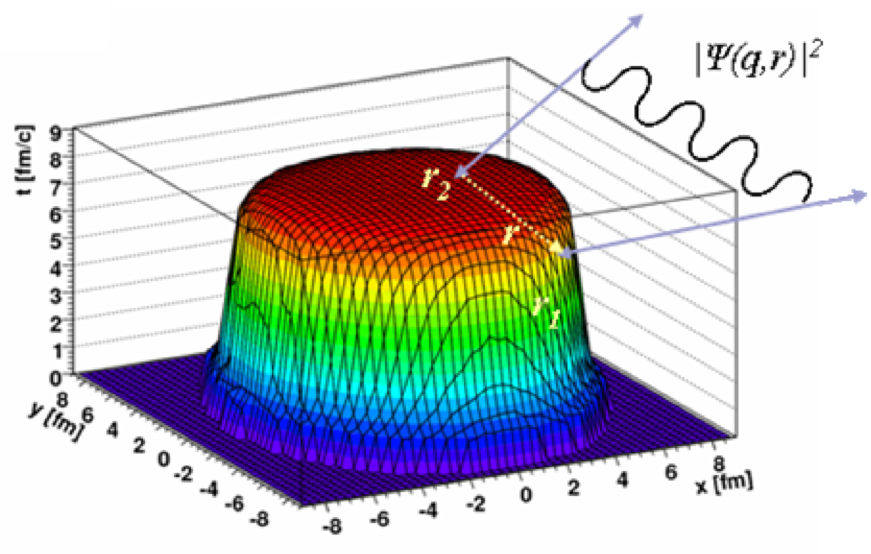
ALICE - arXiv:1011.3914



(b) $v_2\{4\}(p_t)$ for various centralities compared to STAR measurements. The data points in the 20%–30% centrality bin are shifted in p_t for visibility.

Measuring space-time extent: femtoscopy

- Femtoscopy uses the correlation between two particles which arises from quantum statistics symmetrization (Bose-Einstein correlation, BEC or HBT)
- The correlation is reflected in the pair wave function Ψ as an enhancement of same-sign charged particles with small relative four-momentum.



- Is it possible to learn about the space-time structure of the source by measuring the correlation function of the particles.

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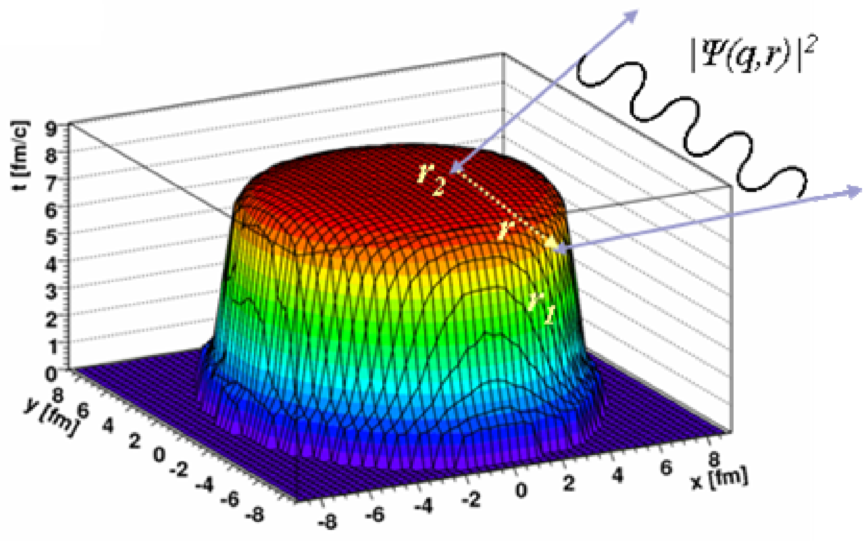
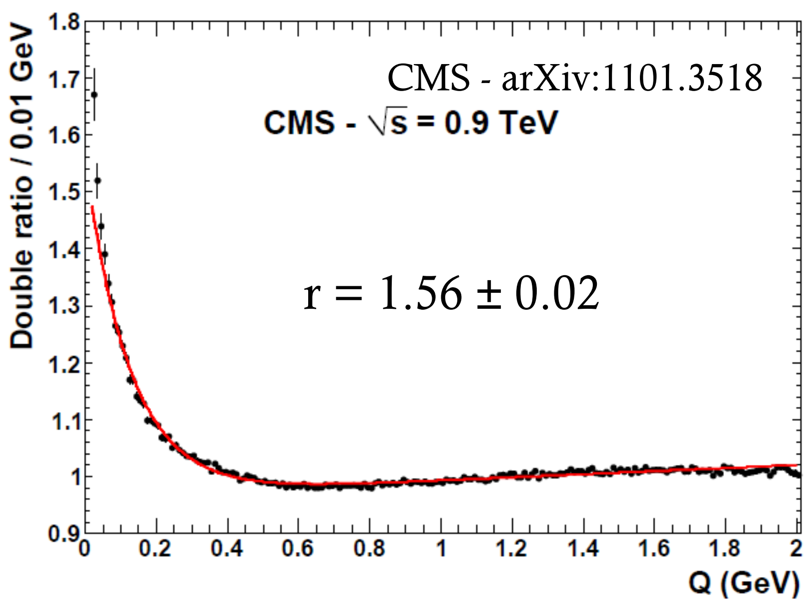


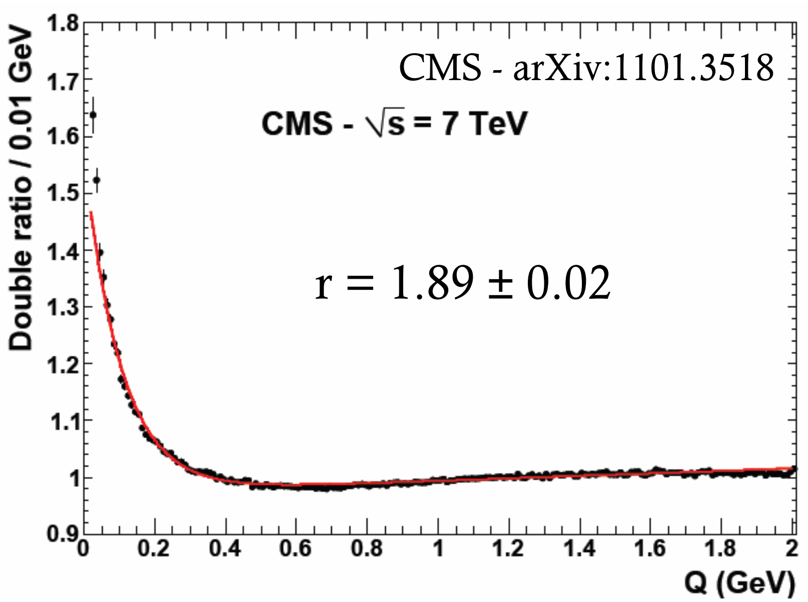
- Is it possible to learn about the space-time structure of the source by measuring the correlation function of the particles.
- Experimentally the proximity in phase space between final-state particles is quantified by the Lorentz-invariant quantity $Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M^2 - 4m_\pi^2}$ which is then fitted with the parametrization $R(Q) = C \cdot [1 + \lambda\Omega(Qr)] \cdot (1 + \delta Q)$
  - Ω is often phenomenologically parameterized as $\Omega(Qr) = e^{-(Qr)^2}$ or $\Omega(Qr) = e^{-(Qr)}$
    - r is the effective size of the source
    - λ measures the "strength" of BEC
    - δ accounts for long-distance correlations
    - C is a normalization factor.

Determination of BEC parameters

- Fits to the correlation function (using exponential Ω form) performed on CMS data at different energies lead to different r values

$\sqrt{s}$	χ^2/N_{dof}	C	λ	r (fm)	δ (10^{-2} GeV^{-1})
0.9 TeV	2.5	0.965 ± 0.001	0.616 ± 0.011	1.56 ± 0.02	2.8 ± 0.1
7 TeV	3.8	0.971 ± 0.001	0.618 ± 0.009	1.89 ± 0.02	2.2 ± 0.1





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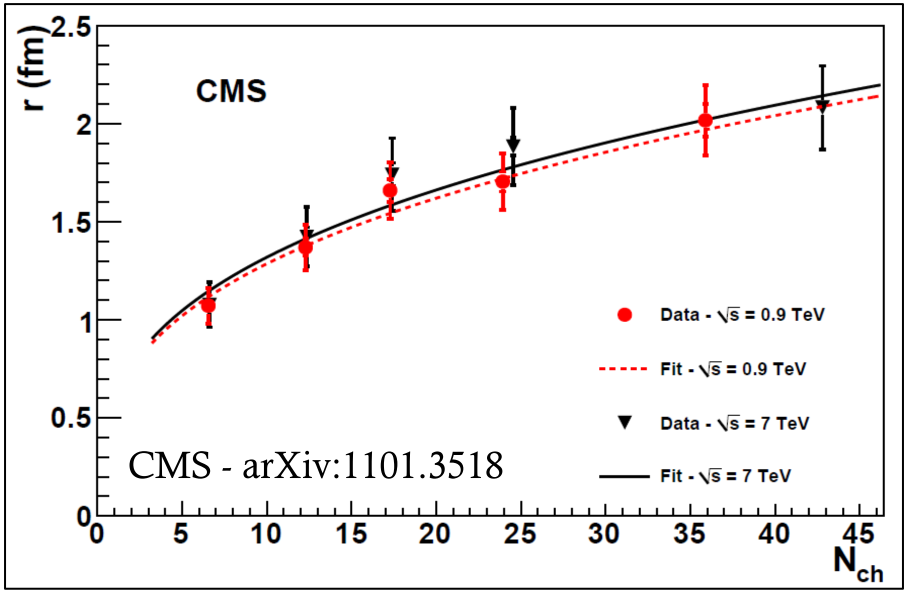
7 TeV	3.8	0.971 ± 0.001	0.618 ± 0.009	1.89 ± 0.02	2.2 ± 0.1

- However both CMS and ALICE show that the scaling of r is dominated by the different mean values of the charged-particle multiplicities in the event (N_{ch}) and k_T (pair momentum), defined as $k_T = |\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|/2$.
  - The scaling as a function of N_{ch} is well dsecribed by the function $r(N_{ch}) = a \cdot (N_{ch})^{1/3}$
  - Inside the N_{ch} and k_T bins the results are consistent



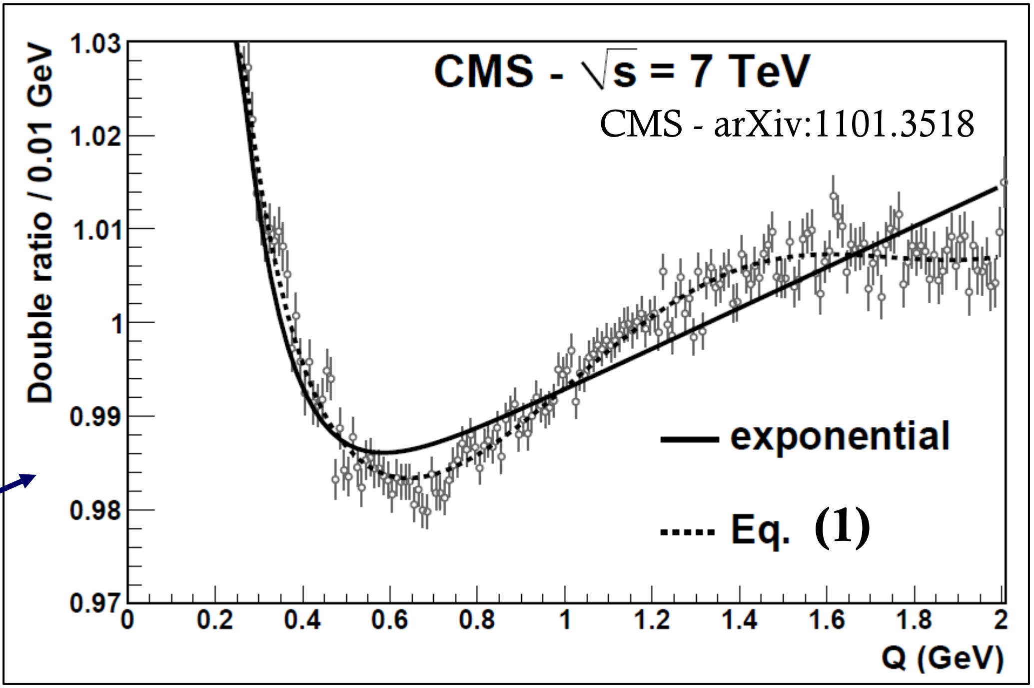
BEC fitting functions

- The Ω functions used in literature to fit the BEC distribution, are not able to provide a good description of the ***R*** distributions
  - mainly due to an anticorrelation effect in the Q distribution just above the signal region (dip with R<1)
- Such a dip was observed in e^+e^- collisions at LEP by the L3 collaboration.
  - an alternative parameterization for R(Q) has been proposed:

$$R(Q) = C \cdot \left[1 + \lambda \left(\cos[(r_0 Q)^2 + \tan(\alpha\pi/4)(Qr)^\alpha] \cdot e^{-(Qr)^\alpha} \right)\right] \cdot (1 + \delta Q) \quad (1)$$

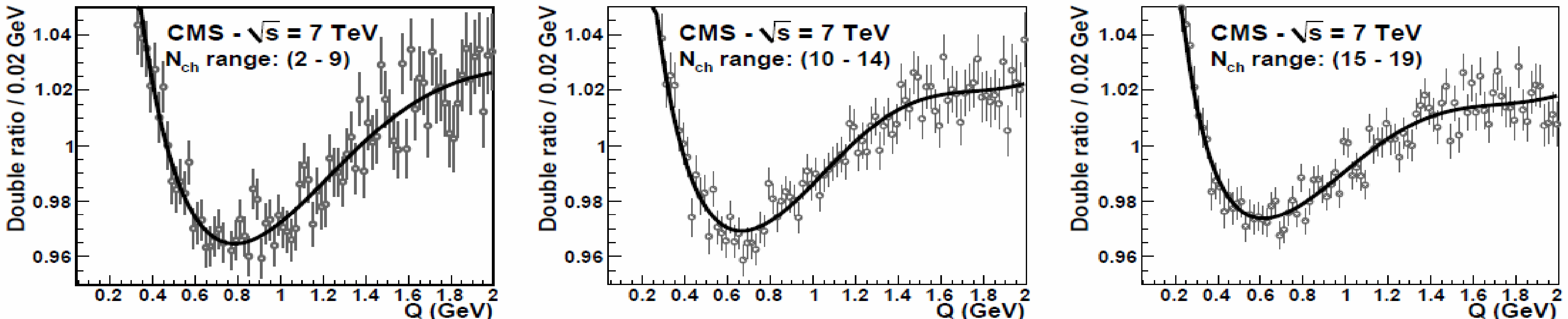
- r_0 is related to the proper time of the onset of particle production, r enters in both the exponential and the oscillation factors.
- Fits with Eq. (1) are of very good quality, ($\chi^2/N_{dof} \sim 1$) at both energies (0.9 and 7 TeV)

PS: note the enlarged Y scale

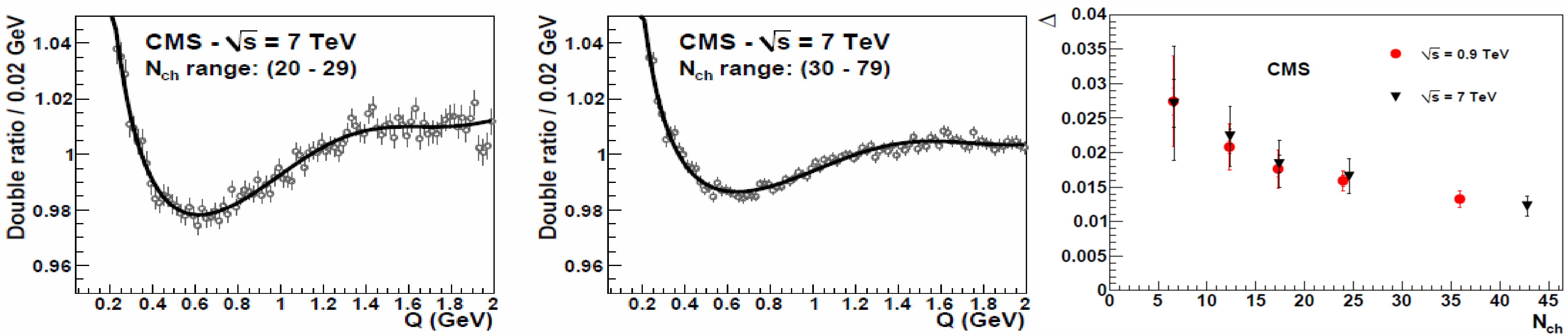


BEC fitting functions

- The depth of the dip in the anticorrelation region is measured as the difference Δ between the baseline curve defined as $C\cdot(1+\delta Q)$ and the minimum of R fitted with Eq. (1).
- The depths are found to decrease with N_{ch} consistently for the two centre-of-mass energies.



CMS - arXiv:1101.3518



N_{ch} and k_T dependence with exponential Ω

- The BEC is studied as a function of both charged-particle multiplicity in the event, N_{ch}, and of the pair average transverse momentum k_T
  - a dependence on k_T has been observed at the Tevatron and at RHIC in Heavy Ion collisions, where it is associated with the system collective expansion.

N_{ch} and k_T dependence with exponential Ω

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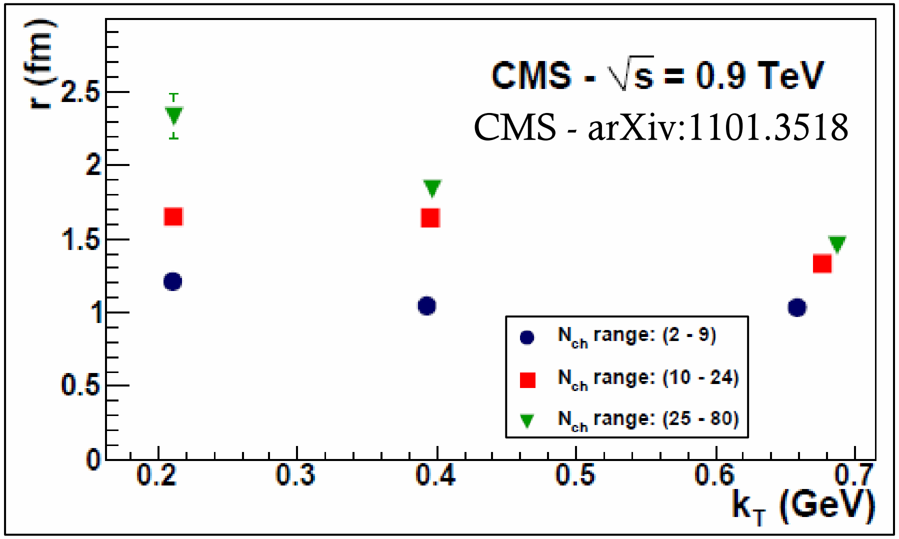
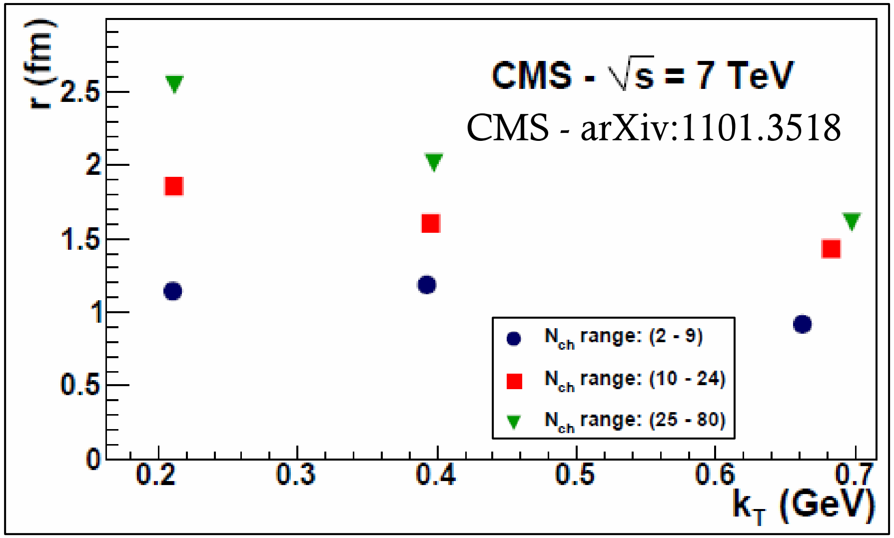
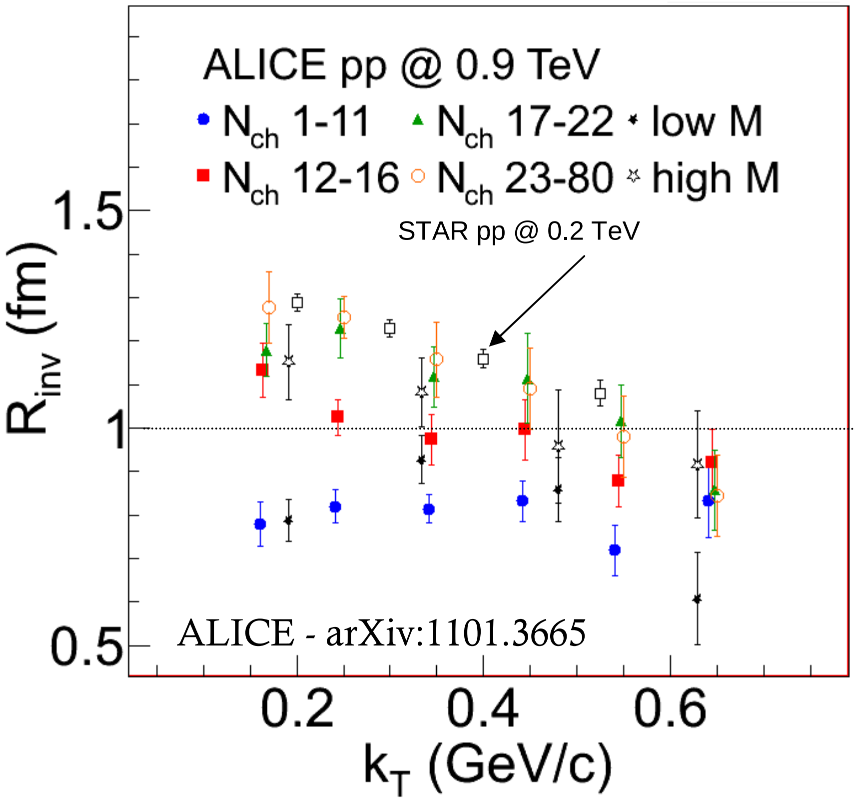
  - a dependence on k_T has been observed at the Tevatron and at RHIC in Heavy Ion collisions, where it is associated with the system collective expansion.
- Using the usual exponential Ω parameterization, the effective radius r:
  - is observed to increase with multiplicity
  - at low multiplicity, is approximately independent of k_T
  - decreases with k_T as N_{ch} increases
- Alternative fitting functions give consistent trend results

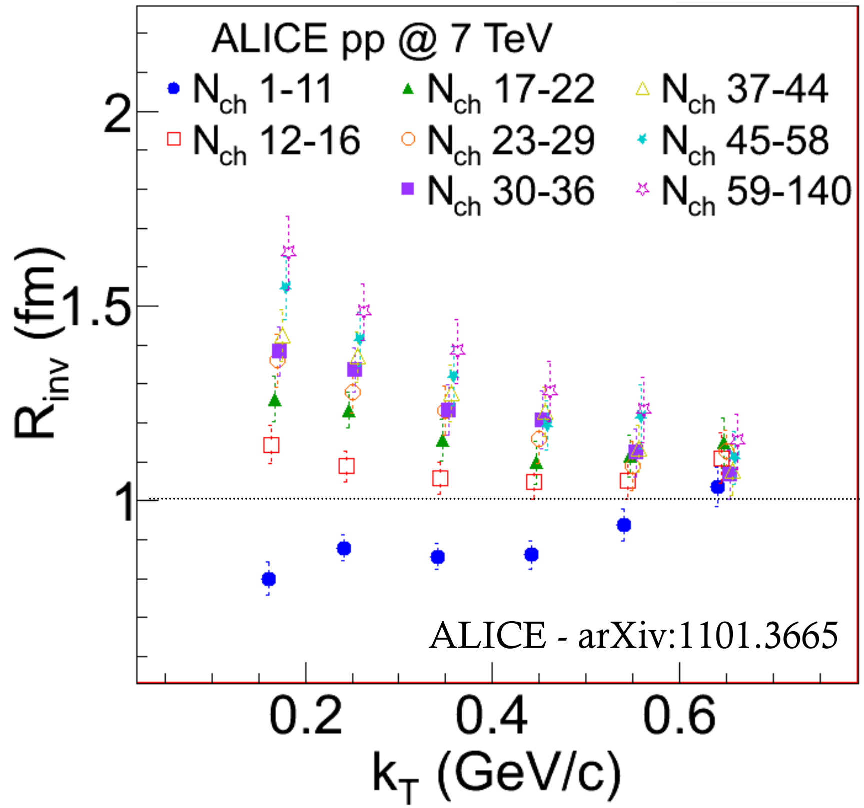




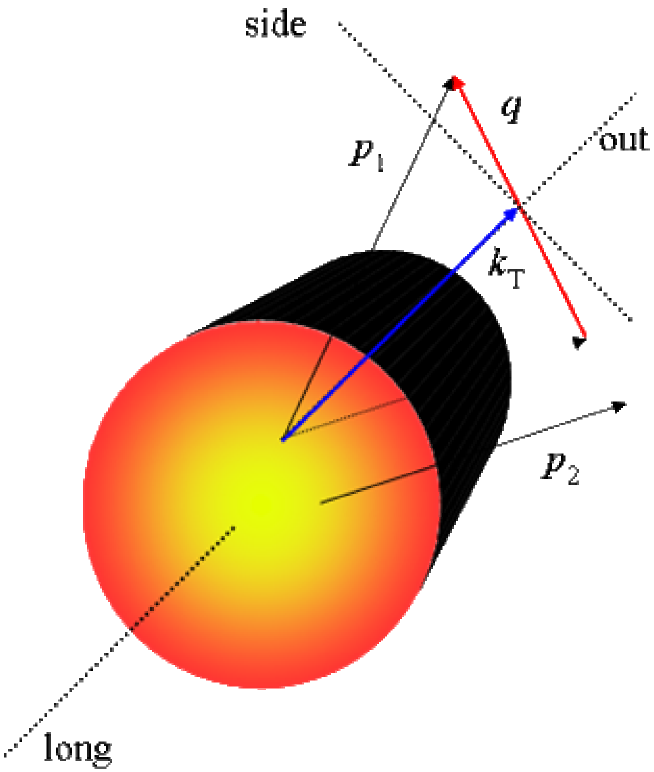
N_{ch} and k_T dependence with Gaussian Ω

- Using Gaussian Ω form
  - At low multiplicity, r is approximately independent of k_T
  - r decreases with k_T as N_{ch} increases
    - consistent with CMS measurement





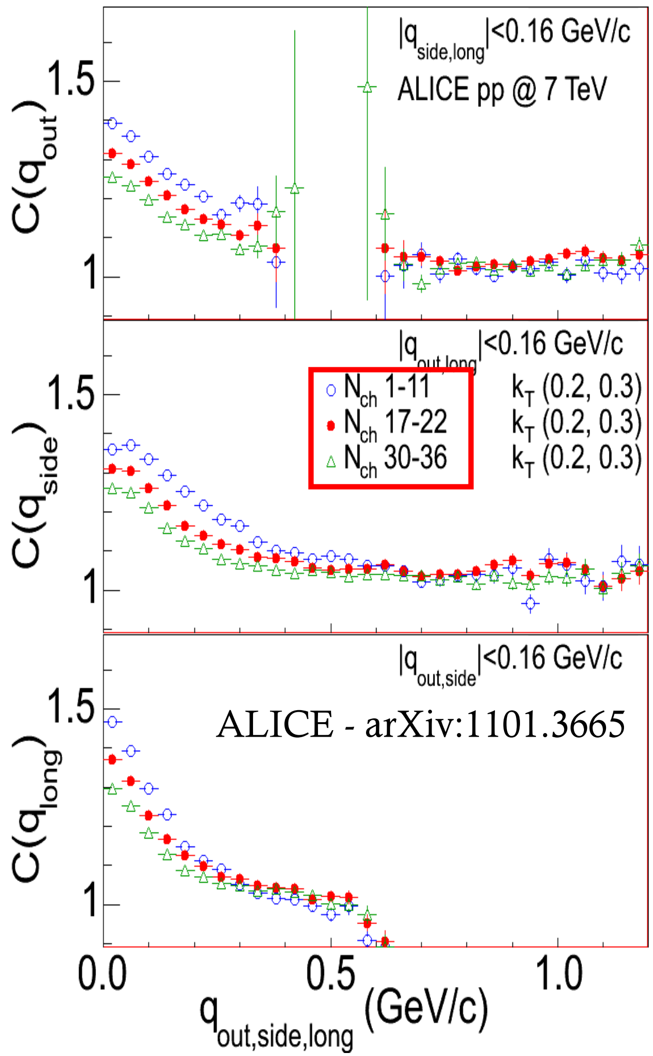
BEC 3D: directions and reference frames



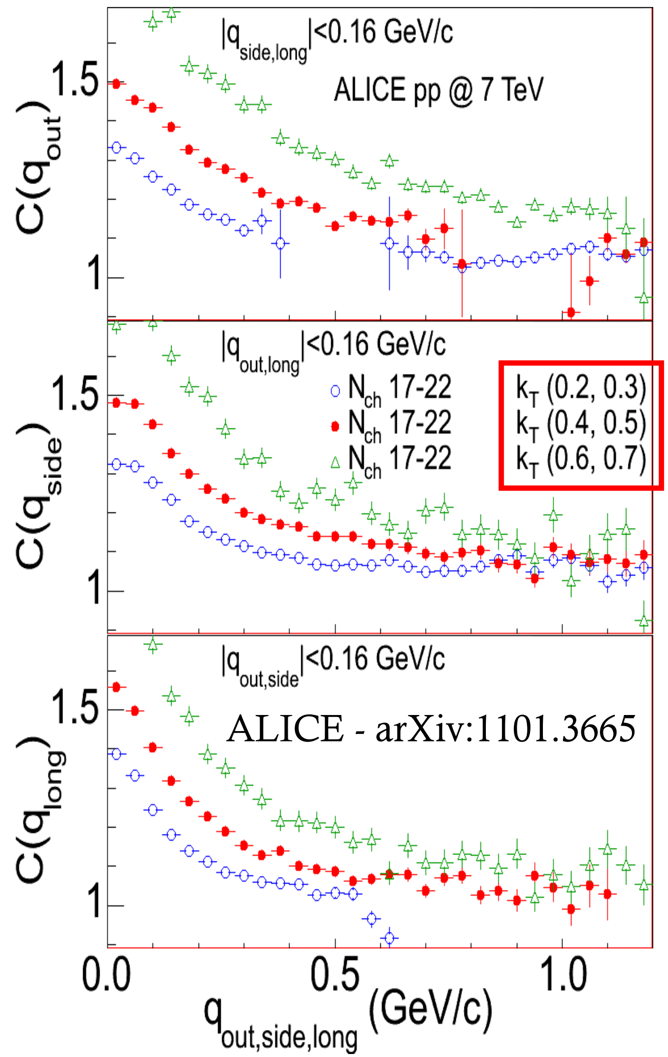
- 1-dimensional BEC analysis vs. the invariant relative momentum Q (or q_{inv}) can only extract system size averaged over all directions.
- In the Longitudinally Co-Moving System in 3 directions: *long* – the beam axis, *out* – the pair momentum, *side* – orthogonal to the others.
  - In LCMS the pair momentum in *long* vanishes.
  - Gives access to three system sizes in these directions separately.
  - Focus is on the transverse direction, where *side* is interpreted as "geometrical size" while *out* has additional components from emission duration.
  - *Long* is used to extract total evolution time.
- The 3-dimensional correlation is usually shown either as 1-dimensional slices along the axes
  - can be also shown as a set of spherical harmonics components

N_{ch} and k_T dependence of the correlation function

Dependence of the radii on multiplicity visible, not strong



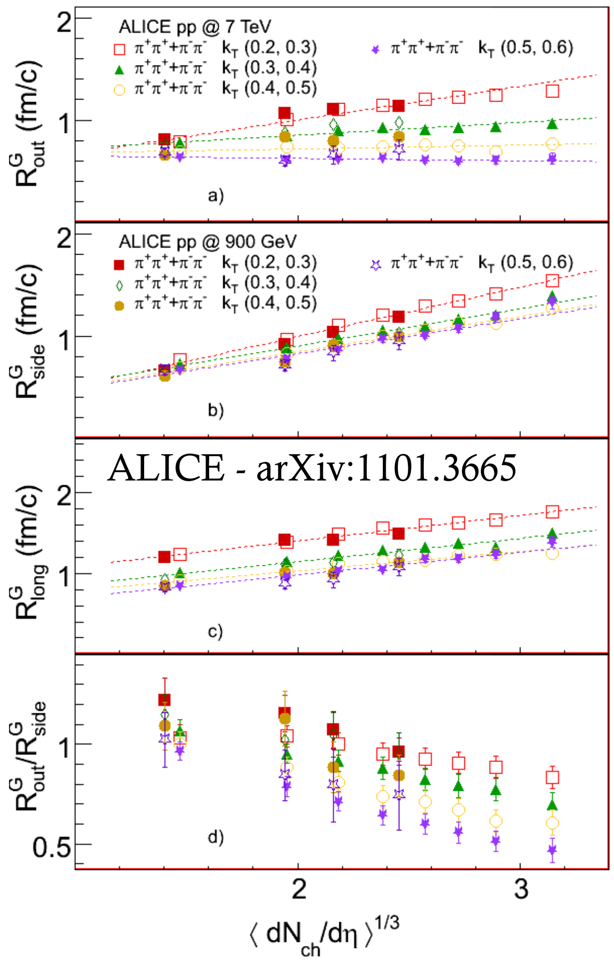
Dependence on k_T visible, stronger



BEC radii in pp at 0.9 and 7 TeV

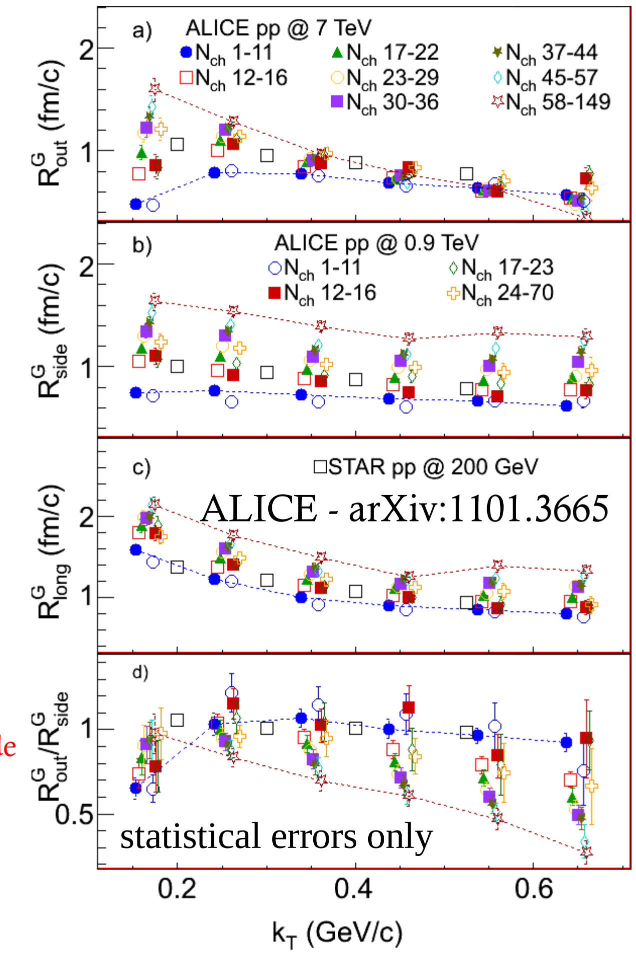
- Grow with multiplicity for all energies,
  - scaling linearly for each k_T bin

- Fall with k_T
  - develops with multiplicity for R_{out}
  - less pronounced for R_{side}
  - very prominent for R_{long}



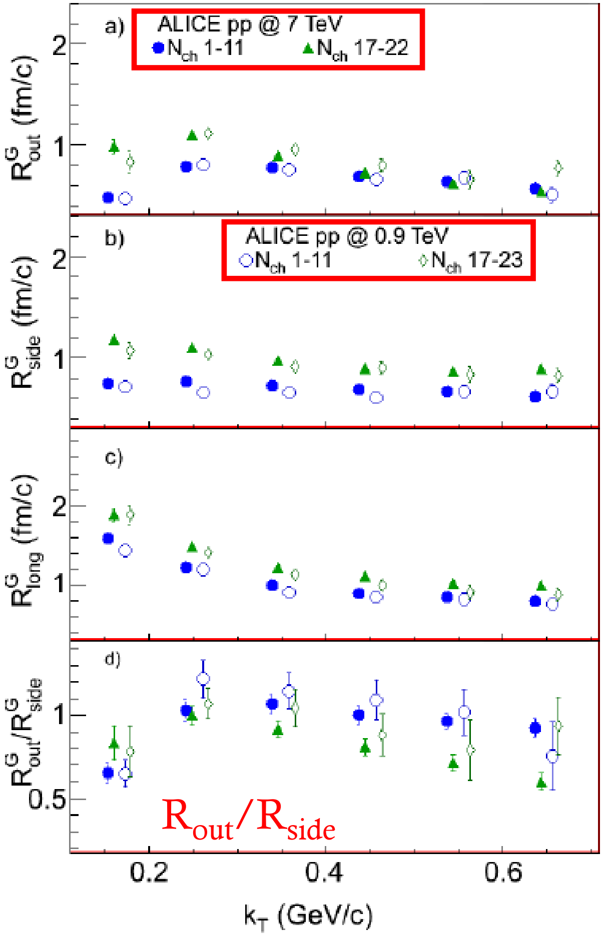
R_{out}/R_{side}

R_{out}/R_{side}



Summary of lessons learnt @ LHC

Collision energy independence



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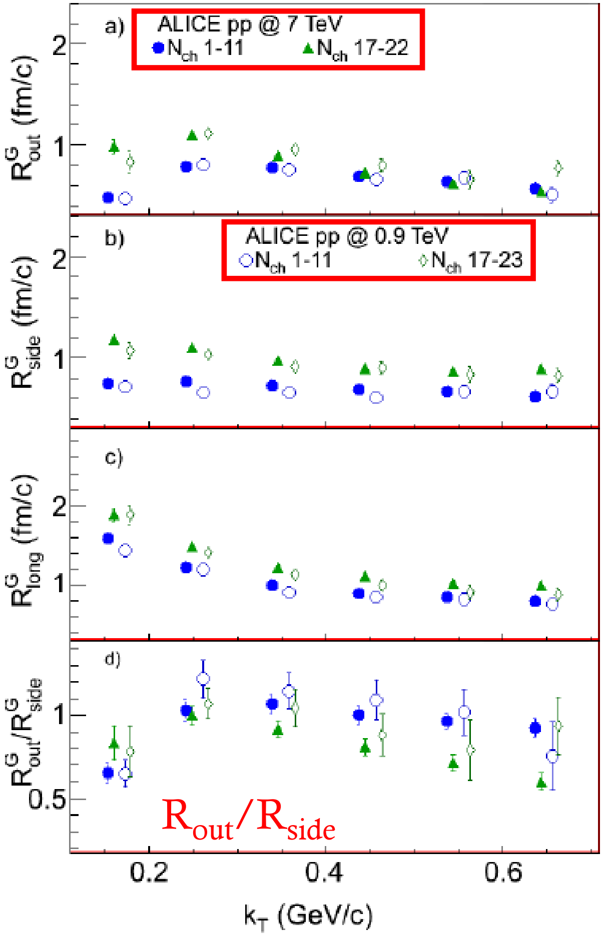
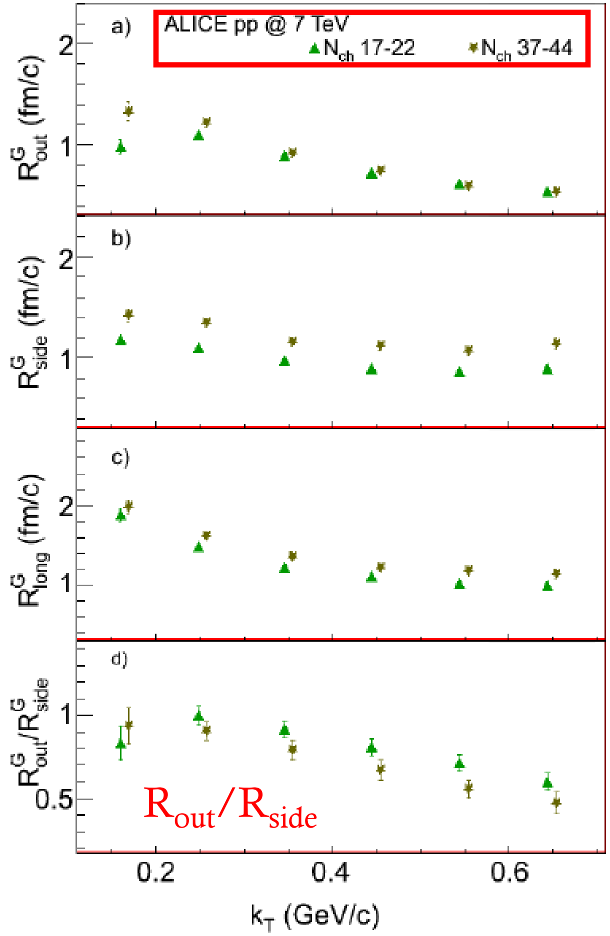


Radius decreasing with pair momentum



Summary of lessons learnt @ LHC

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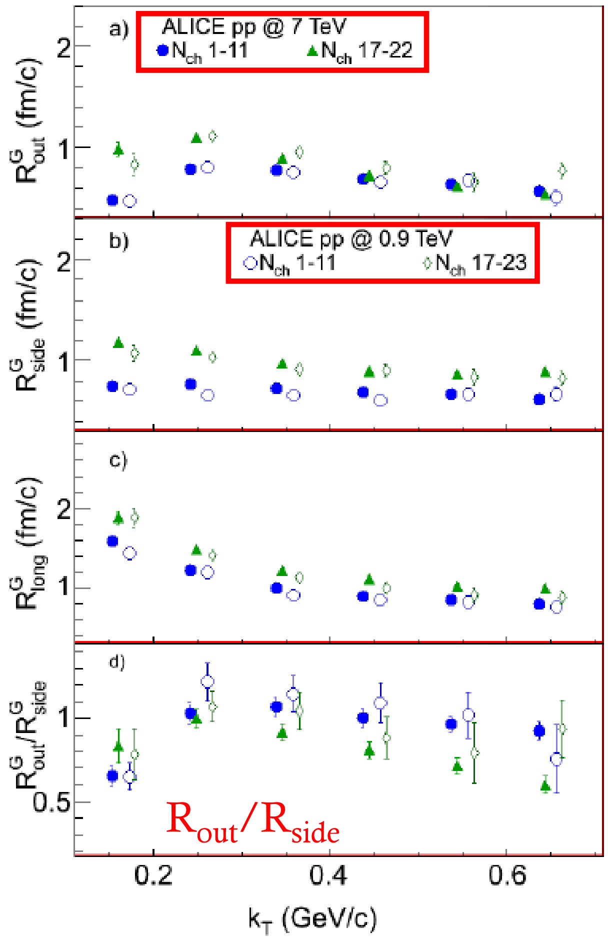

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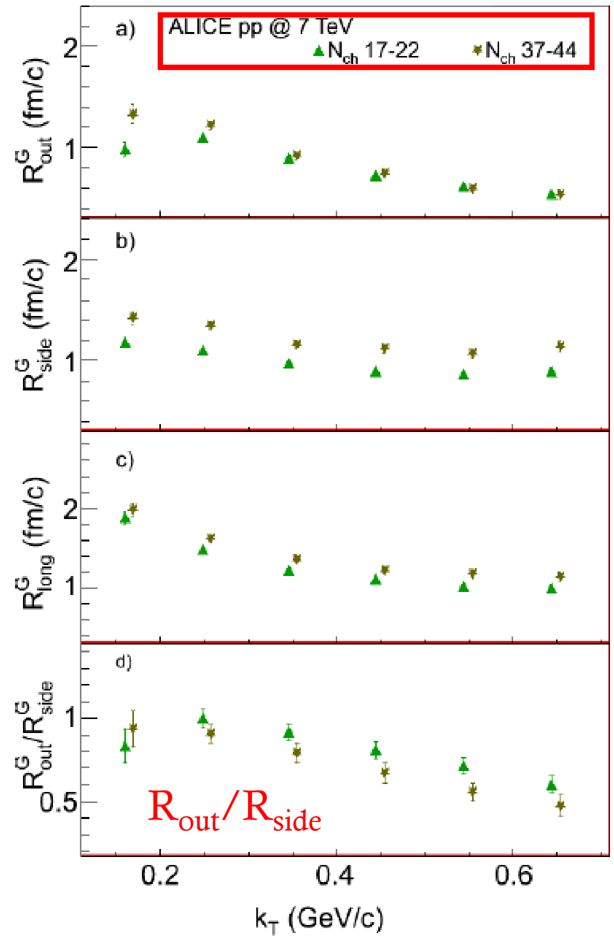
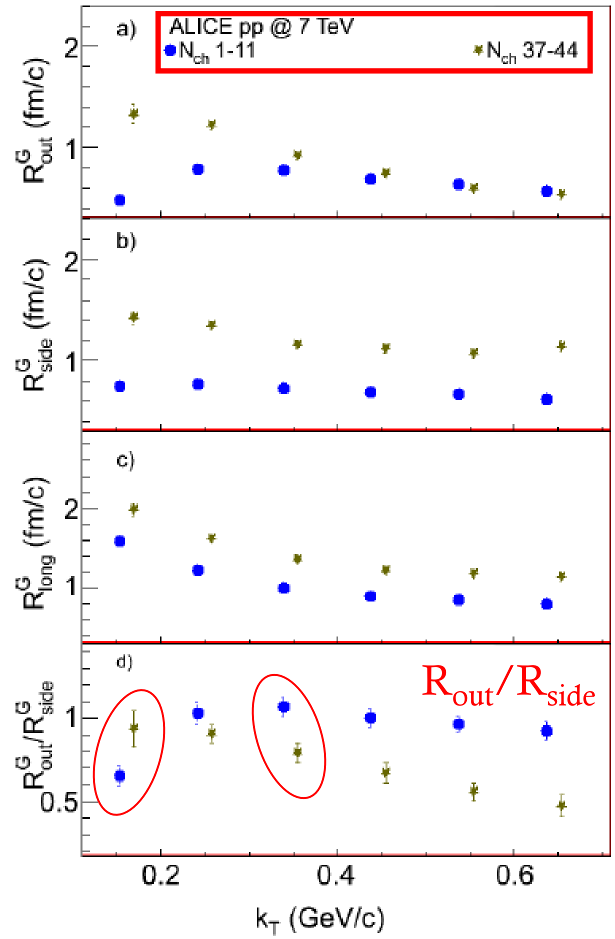


Change of behavior with multiplicity



The different evolution of R_{out} and R_{side} wrt k_T is reflected in low R_{out}/R_{side} values

- this evolution was not observed in Heavy Ions collisions (no high multiplicity events)
- p+p vs. Heavy Ions scaling not obvious anymore

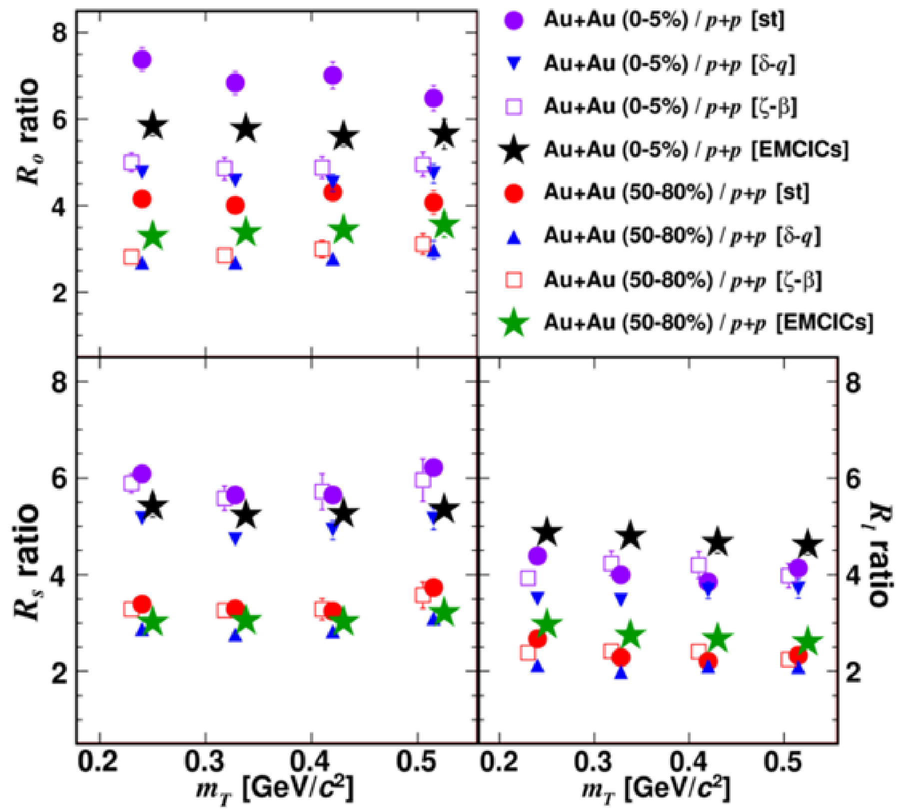
pp vs. AuAu: puzzling scaling …

- At RIHC in AuAu collisions, 3D radii are strongly dependent on m_T(~k_T)
  - This is taken as a signature of a flowing medium

pp vs. AuAu: puzzling scaling ...

- At RIHC in AuAu collisions, 3D radii are strongly dependent on m_T(~k_T)
  - This is taken as a signature of a flowing medium
- STAR reports that 3D BEC radii scale in pp in a way very similar to AuAu
  - They could not check the N_{ch} scaling dependence
- Is the scaling between pp and AuAu a signature of the universal underlying physics mechanism or a coincidence?

STAR - arXiv:1004.0925



NB: STAR scaling is measured by comparing different charged multiplicity bins between pp and Heavy Ions!!!

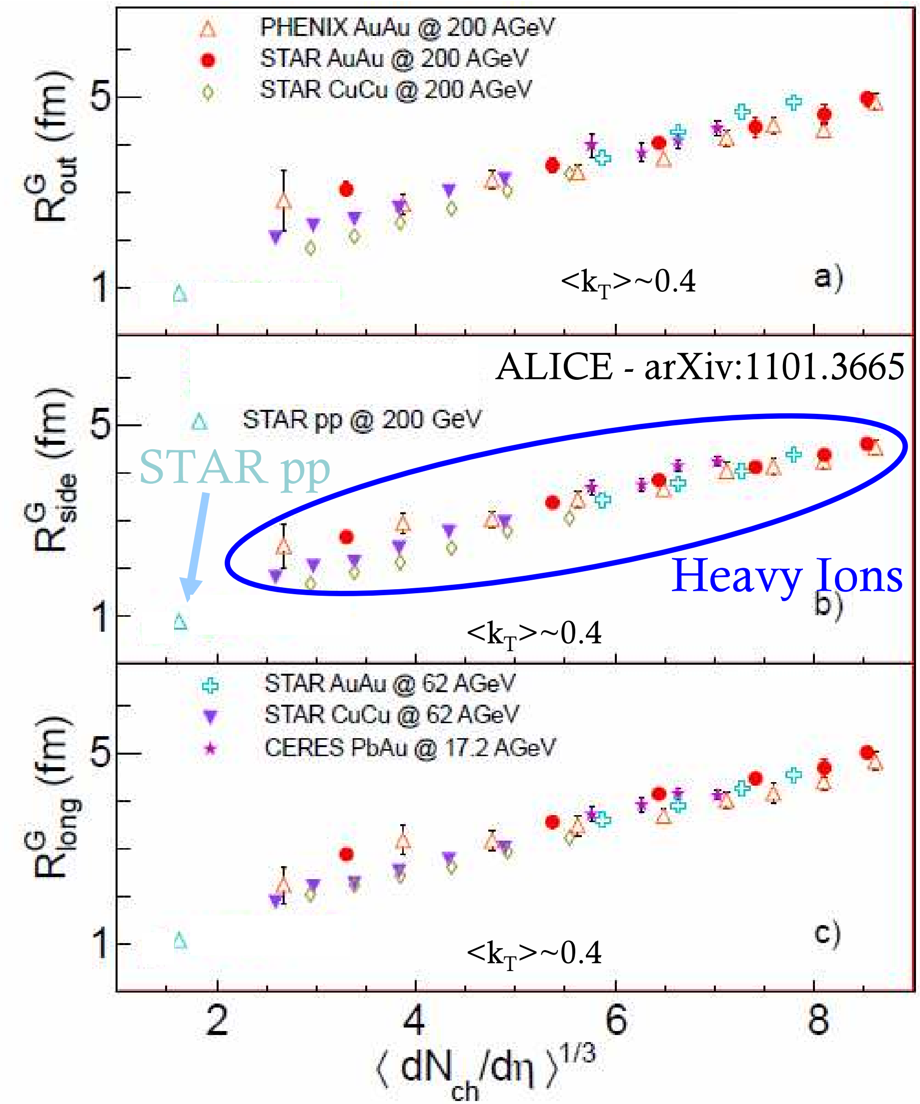
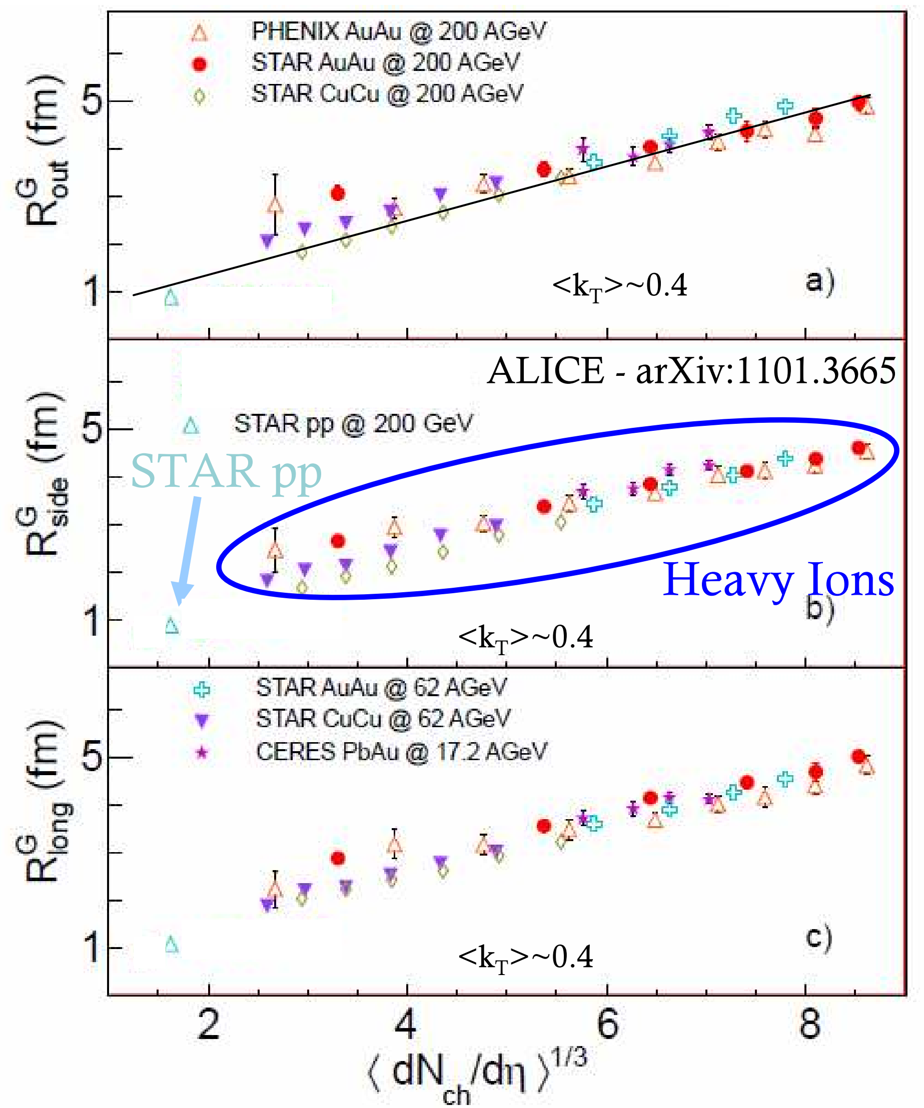


FIG. 13. Gaussian radii as a function of $\langle dN_{ch}/d\eta\rangle^{(1/3)}$, for $\sqrt{s} =$ 0.9 TeV and 7 TeV, compared to the results from (heavy-)ion collisions at RHIC [32, 33] and SPS [34]. Panel a) shows R^G_{out}, b) shows R^G_{side}, c) shows R^G_{long}. All results are for $\langle k_T\rangle = 0.4$ GeV/c, except the values from the PHENIX experiment, which are at $\langle k_T\rangle =$ 0.45 GeV/c.

pp vs. Heavy-Ions

- Both p+p and Heavy-ion RIHC data show a linear scaling with $dN/d\eta^{1/3}$

pp vs. Heavy-Ions



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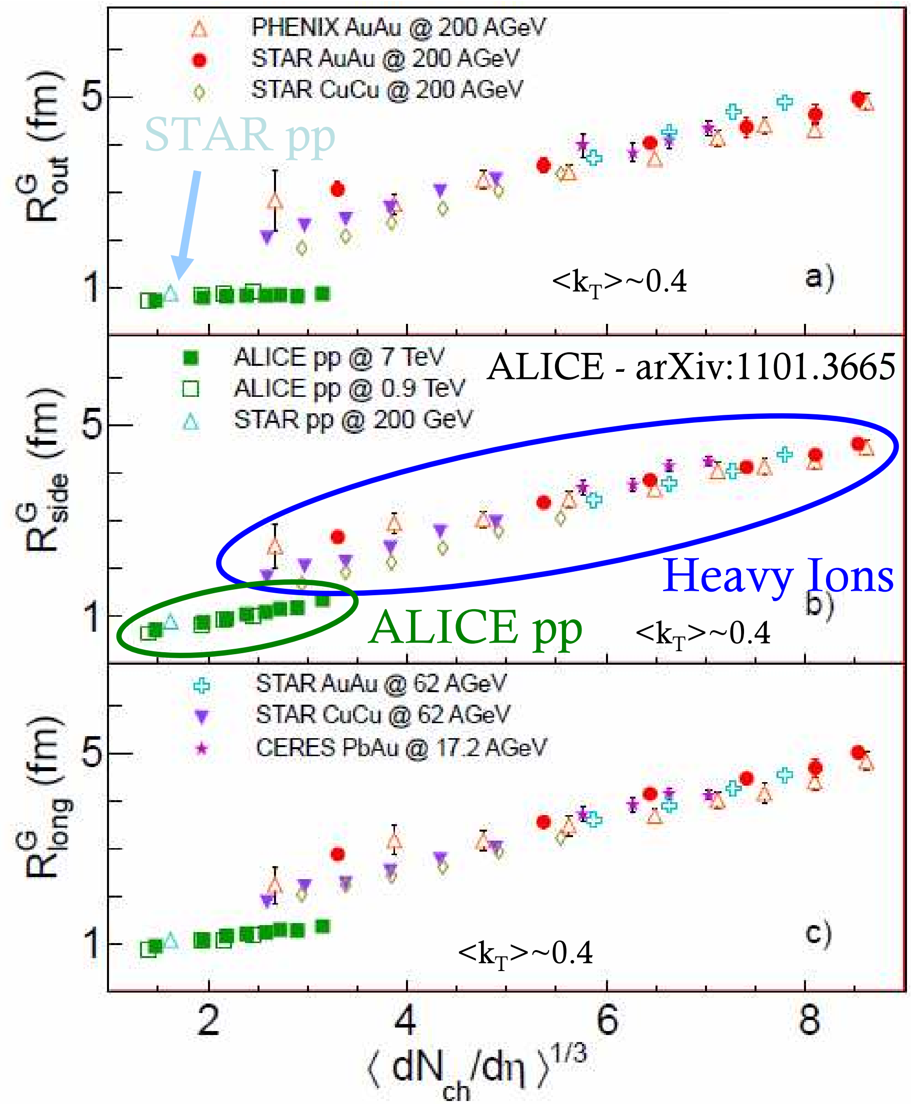
- Both p+p and Heavy-ion RIHC data show a linear scaling with $dN/d\eta^{1/3}$
  - They seem to have the same offset and slope



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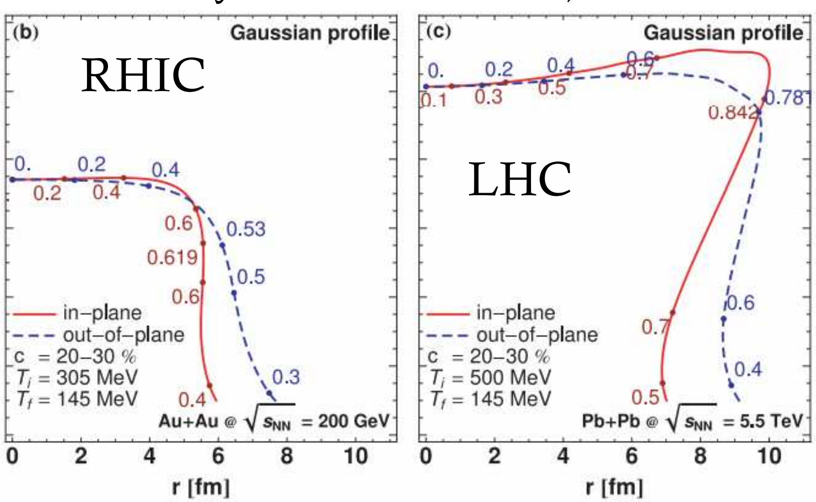
pp vs. Heavy-Ions

- Both p+p and Heavy-ion RIHC data show a linear scaling with $dN/d\eta^{1/3}$
  - They seem to have the same offset and slope
- Using LHC data is it possible to compare pp and Heavy Ions at same $dN_{ch}/d\eta$ for the first time
  - The scaling seems to be violated especially in the out direction
- Initial geometry ($N_{nucleons}$) seem to play a role in the final freeze-out shape
- Final answer (?) with ratio of pp @ LHC with Heavy Ions @ LHC
  - Same detector
  - Same systematics

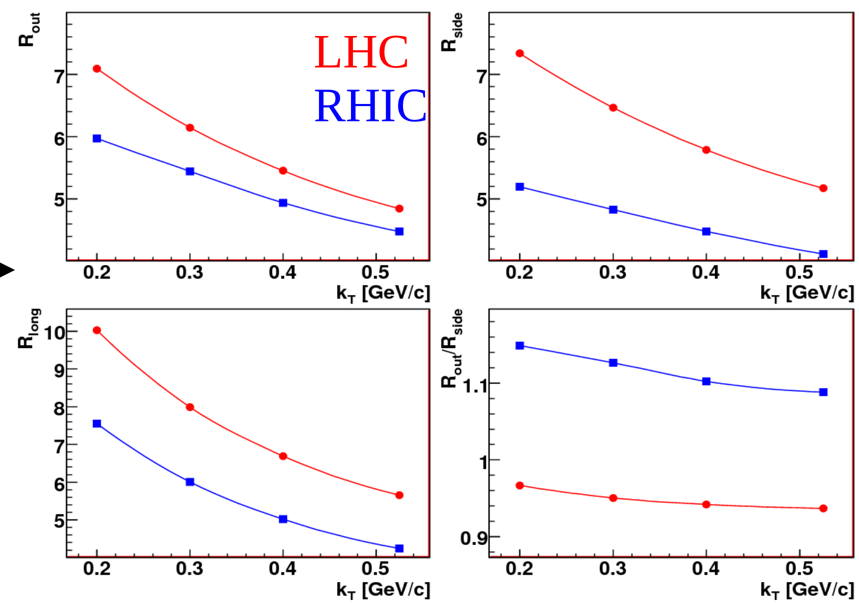
Predictions for Heavy Ions at LHC

- Specific predictions for LHC in Heavy Ions (PbPb @ 2.76 TeV):
  - steeper m_T dependence of the system size from larger flow,
  - longer evolution gives larger size and the reversal of the azimuthal anisotropy in space-time.
  - R_{out}/R_{side} ratio smaller than at RHIC
    - due to a longer evolution time the freeze-out shape changes from inside-out to outside-in.

Phys.Rev.C79:014902,2009

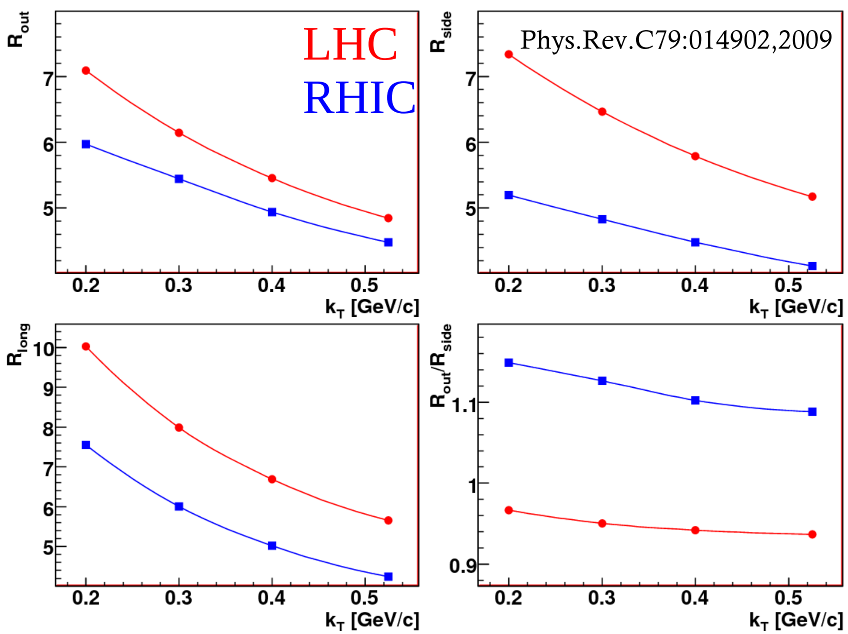


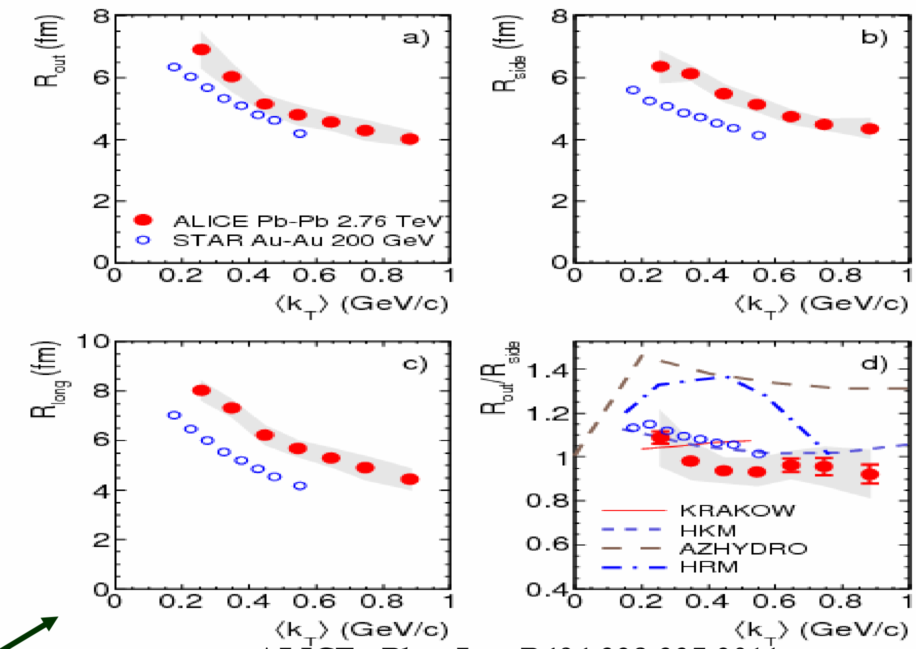
Phys.Rev.C79:014902,2009



First results with Pb+Pb @ LHC

- First analysis performed in Pb+Pb at LHC with top 5% central events
  - limited sample of events recorded at the beginning of November 2010
- All the expected trends are observed:
  - Overall increase of the radii as compared to RHIC
  - Strong dependence of the radii on k_T
  - R_{out}/R_{side} ratio smaller than the one at RHIC





ALICE - Phys.Lett.B696:328-337,2011

Figure 2: Pion HBT radii for the 5% most central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, as function of $\langle k_T \rangle$ (red filled dots). The shaded bands represent the systematic errors. For comparison, parameters for Au–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [30] are shown as blue open circles. (The combined, statistical and systematic, errors on these measurements are below 4%.) The lines show model predictions (see text).

From predictions to data

Energy dependence in Pb+Pb at LHC

- Clear increase of the emitting region size and the system lifetime between the largest system to date (central full energy RHIC) and the central LHC.
  - The "quark-gluon plasma", if produced, lives longer and in a significantly bigger volume.
- The dependence with energy follows the multiplicity scaling
  - Will be tested in more detail with the full centrality dependence

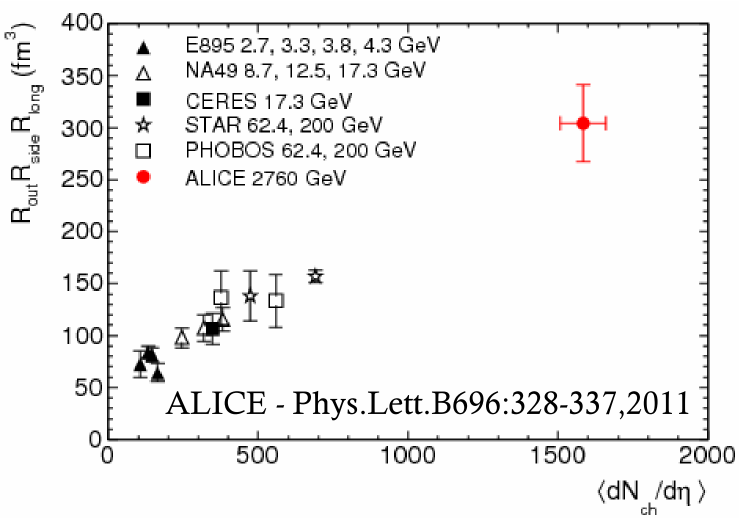


Figure 4: Product of the three pion HBT radii at $k_T = 0.3$ GeV/c. The ALICE result (red filled dot) is compared to those obtained for central gold and lead collisions at lower energies at the AGS [35], SPS [36, 37, 38], and RHIC [39, 40, 41, 42, 30, 43].

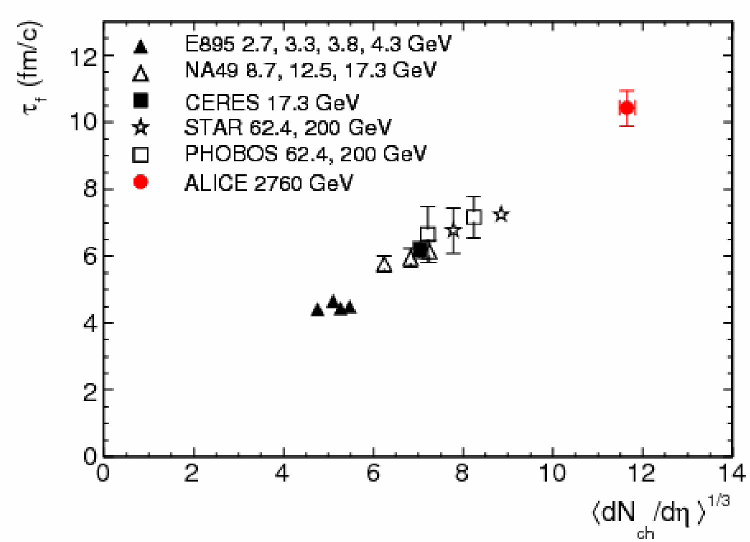


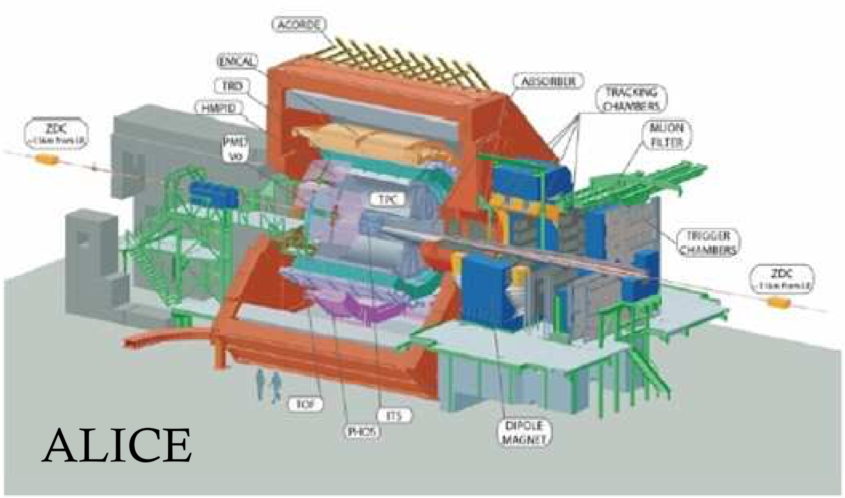
Figure 5: The decoupling time extracted from $R_{long}(k_T)$. The ALICE result (red filled dot) is compared to those obtained for central gold and lead collisions at lower energies at the AGS [35], SPS [36, 37, 38], and RHIC [39, 40, 41, 42, 30, 43].

Conclusions

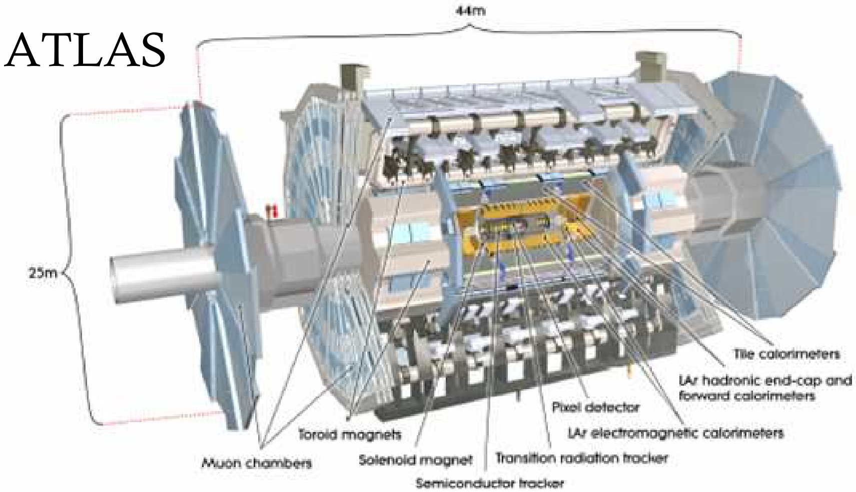
- LHC experiments are able to measure a variety of particle correlations with both pp and PbPb collisions at very high energies:
  - $(\Delta\eta, \Delta\phi)$
  - Elliptic flow
  - Bose-Einstein correlations
- These measurements are providing several piece of informations necessary to study the properties of formation and evolution of hadron source
- Very high multiplicity events in pp collision show features that are somehow similar to Heavy Ions collisions
  - More studies are needed to better establish the real nature of the underlying processes
  - The comparison of LHC data recorded with pp and Heavy Ions at the same energy (2.76 TeV) could bring some further light to answer this question

Backup

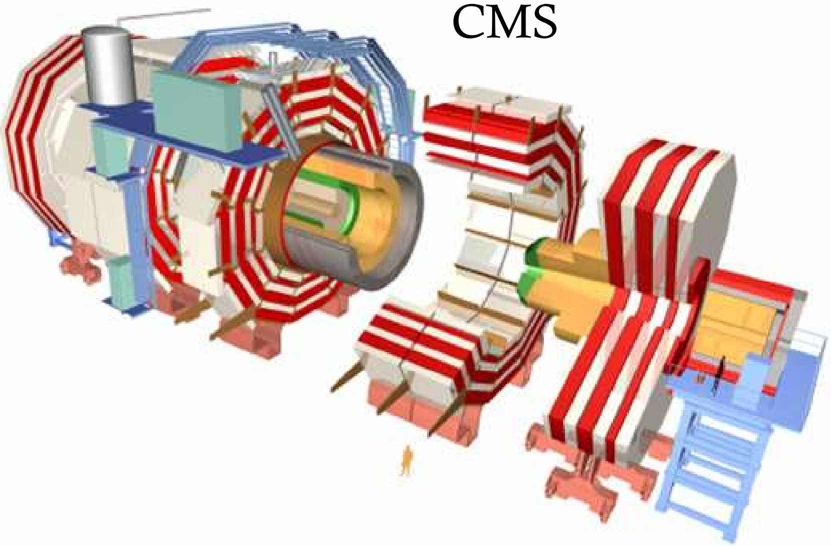
LHC detectors



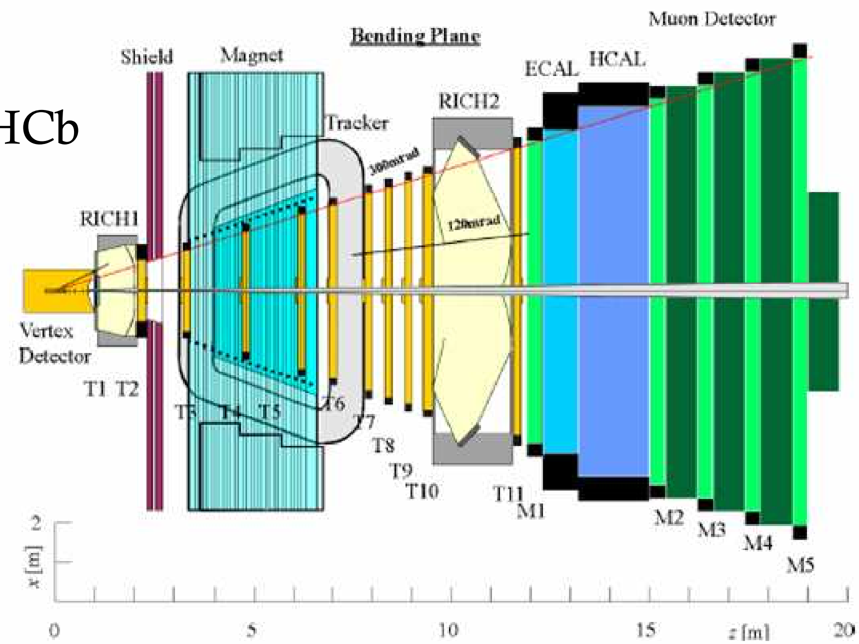
ATLAS



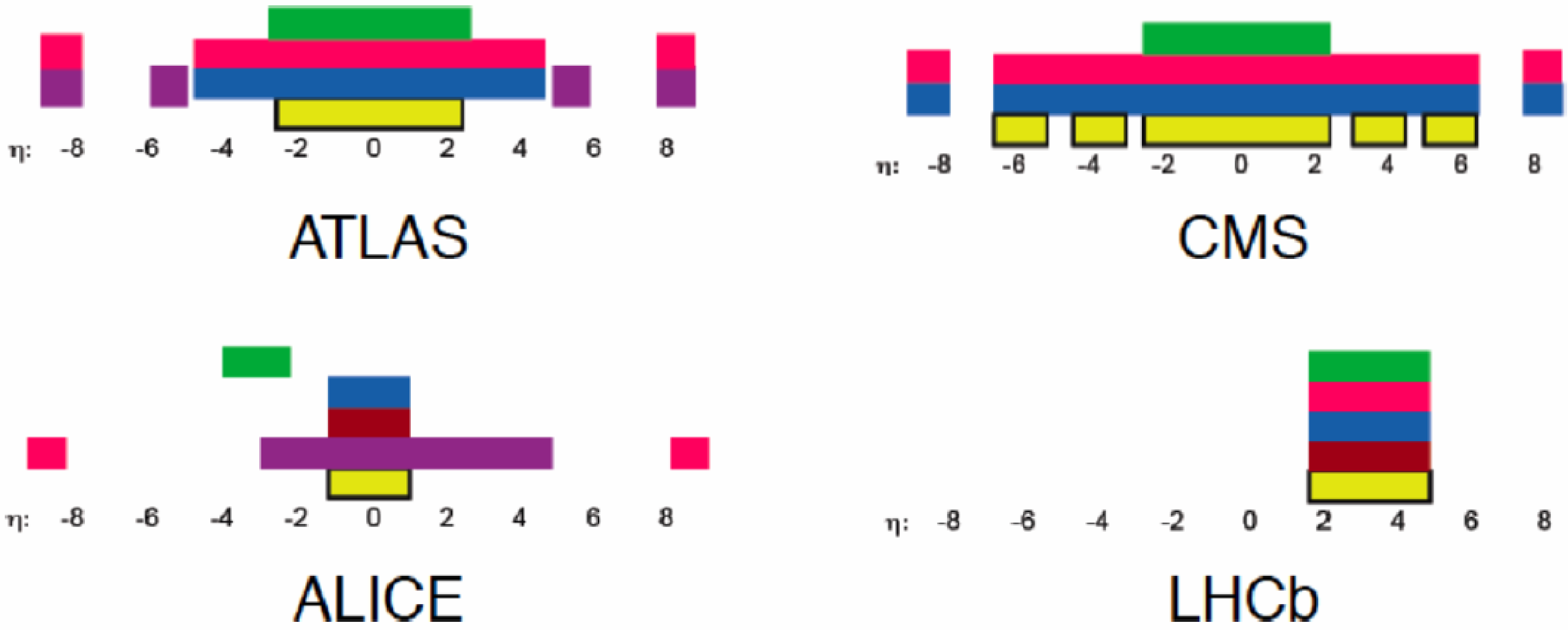
CMS



LHCb



LHC detector acceptances



ATLAS and CMS are general-purpose, fully 4π detectors.

ALICE has a central tracker comparable in η range to ATLAS and CMS.

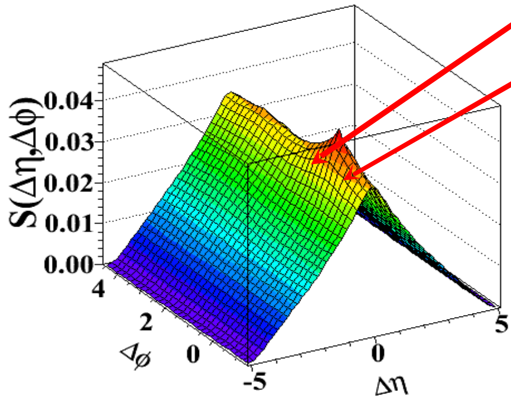
LHCb is an entirely forward, one-sided detector, with a forward-facing tracker geometry.

CMS - JHEP 1009:091,2010

Inclusive Correlation Technique –Wei Li

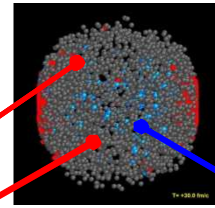
Signal distribution:

$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$

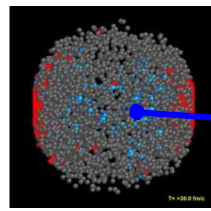


same event pairs

Event 1



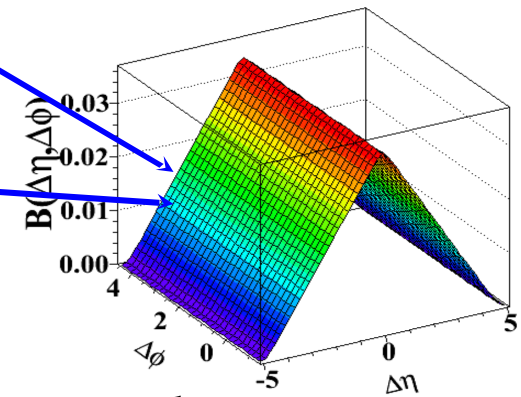
Event 2



€

Background distribution:

$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2}\frac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi}$$

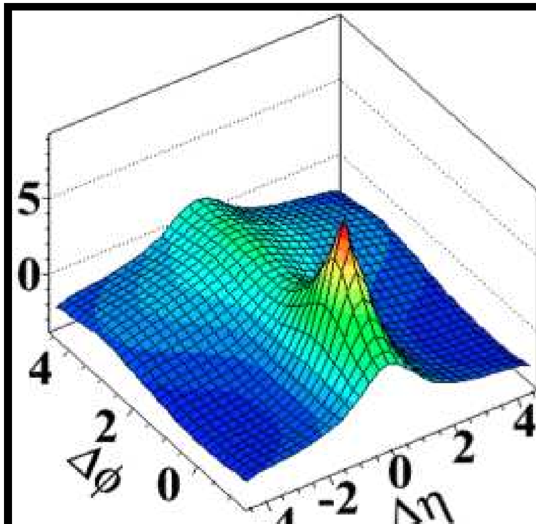


mixed event pairs

$\Delta\eta = \eta 1 - \eta 2$

$\Delta\phi = \phi 1 - \phi 2$

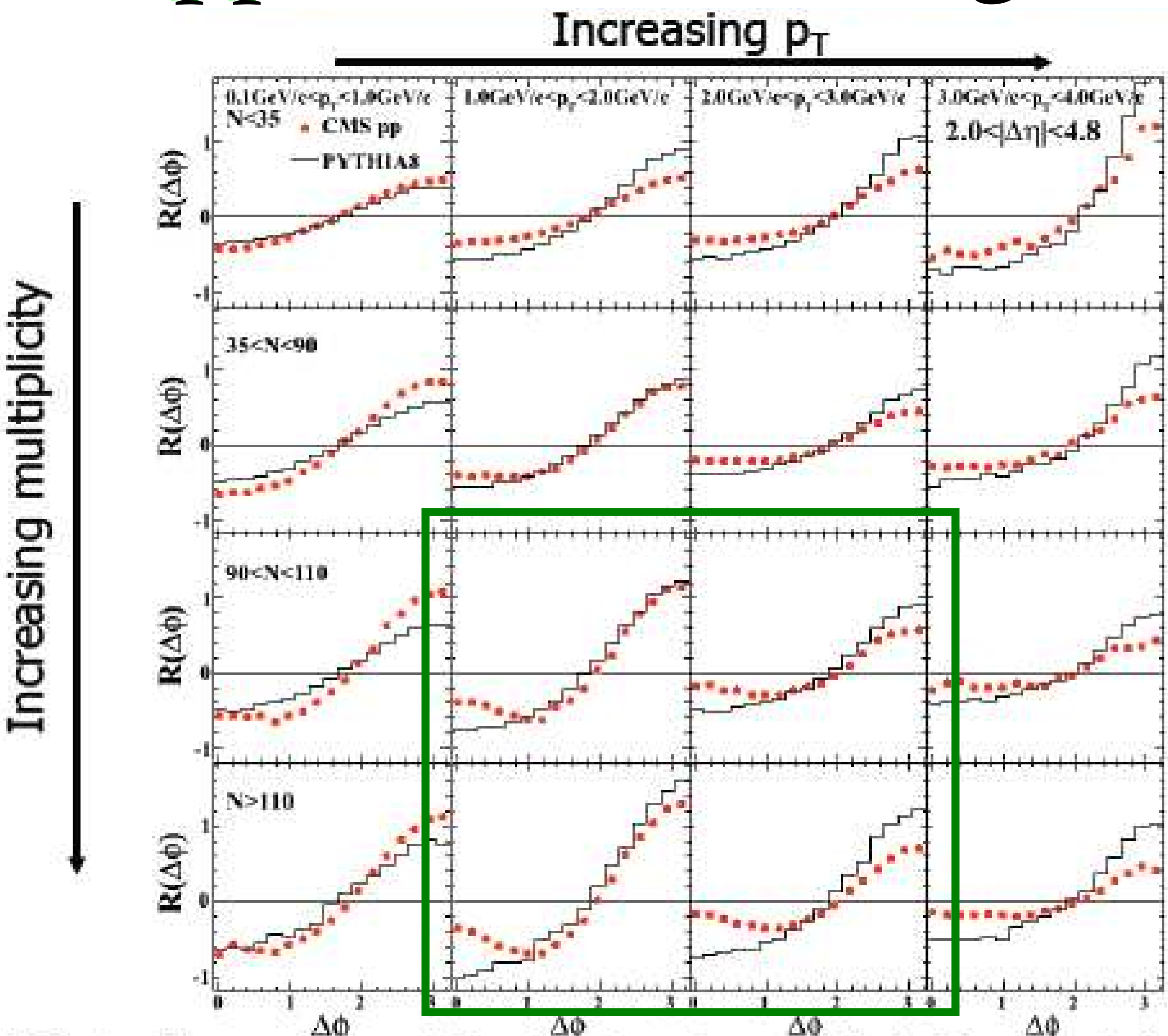
CMS 7 TeV pp



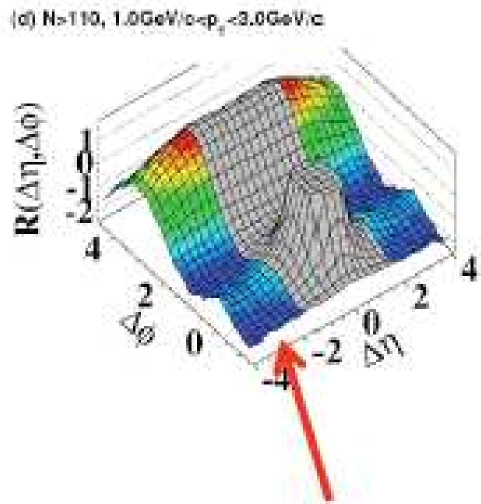
pT-inclusive two-particle angular correlations in Minimum Bias collisions

$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$

pp: Characterizing the ridge



CMS 7 TeV pp



Project |Δη| > 2 onto Δφ

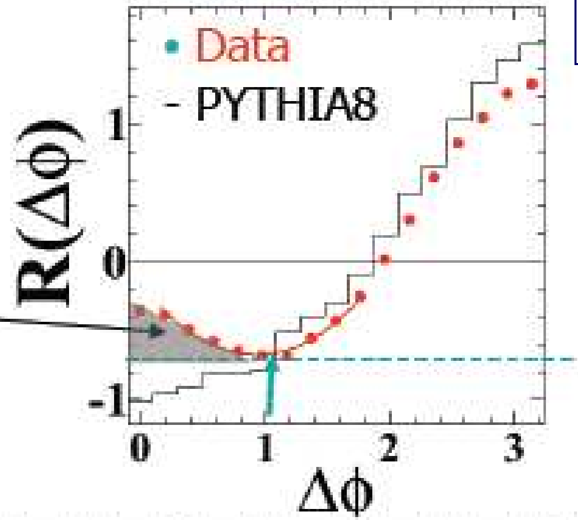
CMS - JHEP 1009:091,2010

"Ridge" maximal for highest multiplicity and 1 < p_T < 3 GeV/c

pp: Characterizing the ridge

Zero Yield At Minimum (ZYAM)

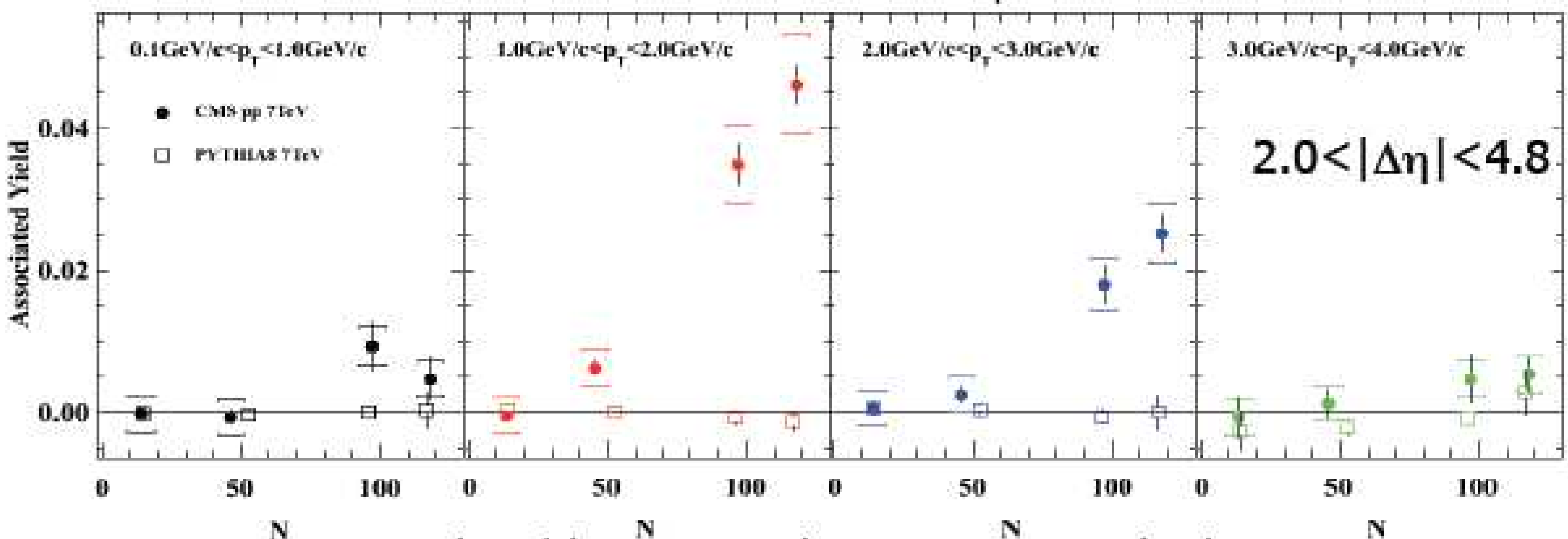
Associated yield:
correlated multiplicity per particle



CMS - JHEP 1009:091,2010

N>110
$2.0<|\Delta\eta|<4.8$
$1GeV/c<p_T<2GeV/c$

CMS 7 TeV pp



Associated yield grows with increasing multiplicity

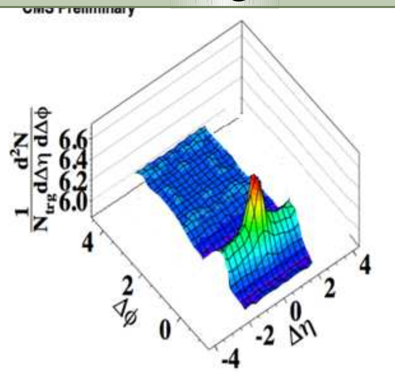
CMS pp ridge interpretations

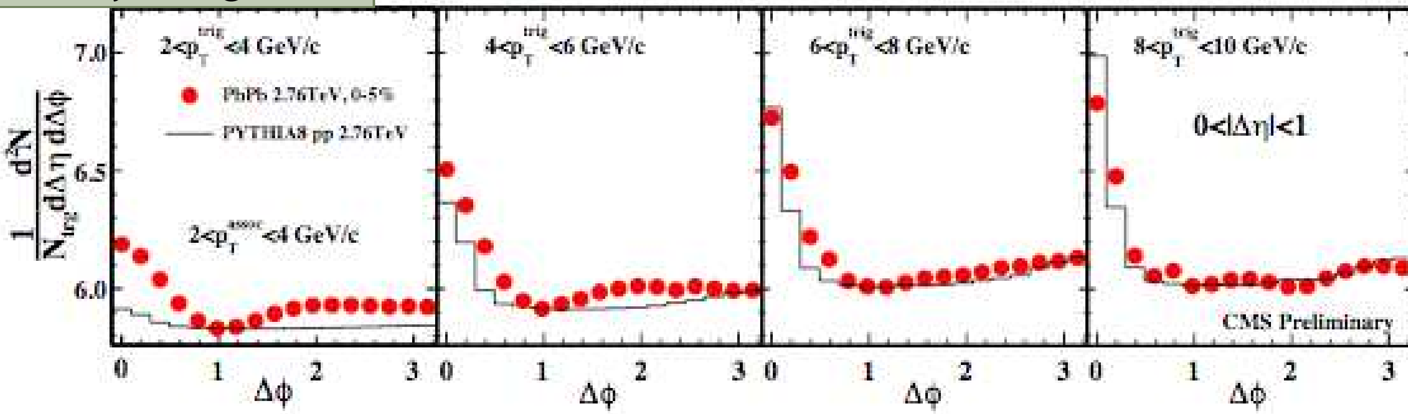
- Comments on the CMS discovery of the "Ridge" in High Multiplicity pp collisions at LHC [arXiv:1009.4635]
- On the ridge-like structures in the nuclear and hadronic reactions [arXiv:1009.5229]
- The ridge in proton-proton collisions at the LHC [arXiv:1009.5295]
- Elliptic flow in proton-proton collisions at 7 TeV [arXiv:1010.0405]
- Towards a common origin of the elliptic flow, ridge and alignment [arXiv:1010.0918]
- Comparing the same-side "ridge" in CMS p-p angular correlations to RHIC p-p data [arXiv:1010.3048]
- On correlations in high-energy hadronic processes and the CMS ridge: A manifestation of quantum entanglement? [1010.4463]
- Angular Correlations in Gluon Production at High Energy [arXiv:1012.3398]
- The "Ridge" in Proton-Proton Scattering at 7 TeV [arXiv:1011.0375]
- Soft ridge in proton-proton collisions [arXiv:1102.3258]
- Ridge Formation Induced by Jets in pp Collisions at 7 TeV [arXiv:1011.0965]
- Elliptic flow in pp-collisions at the LHC [arXiv:1103.0626]
- CMS ridge effect at LHC as a manifestation of bremstralung of gluons due to the quark-anti-quark string formation [arXiv:1104.1283]

PbPb Ridge – Integrated associated Yeld

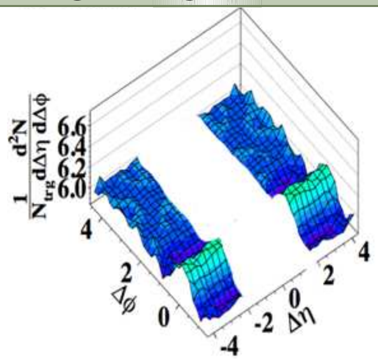
CMS – HIN-11-001

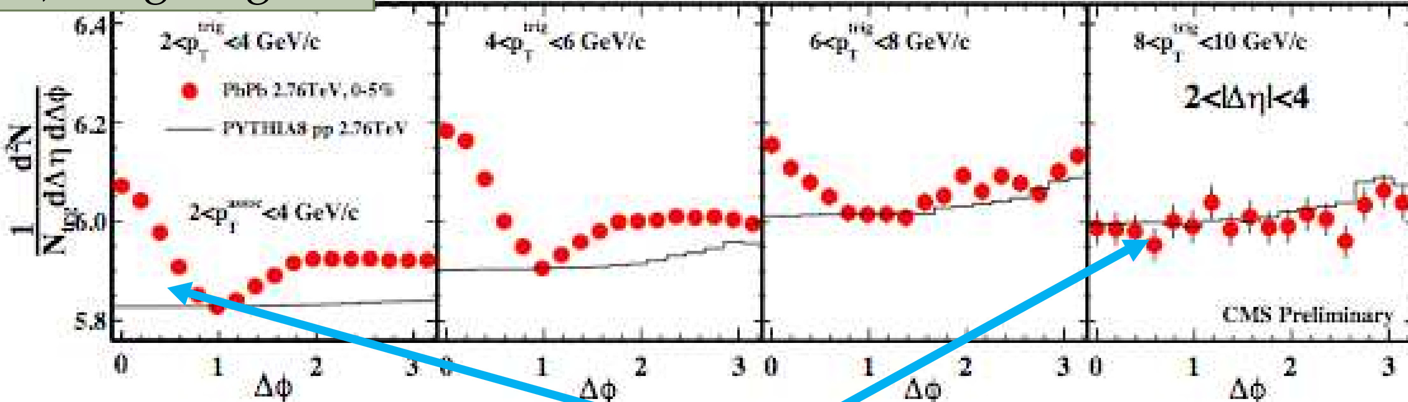
Short-range (0<|Δη|<1): jet region





Long-range (2<|Δη|<4): ridge region



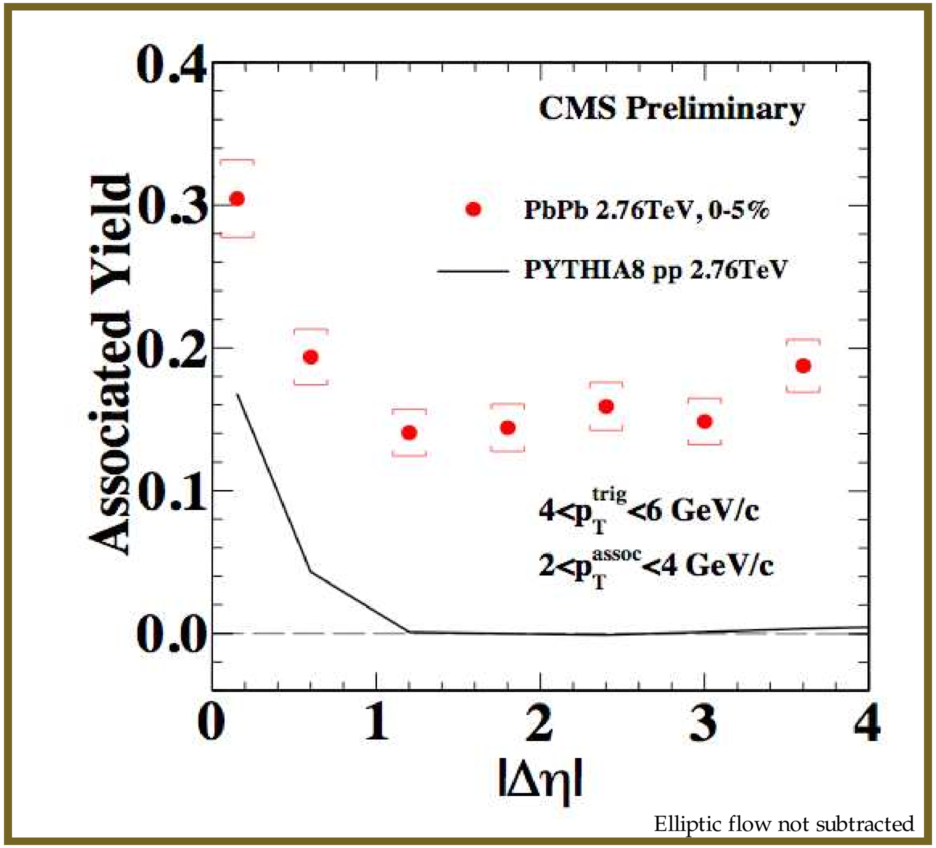


- ✓ Enhancement seems to disappear at high pT

PbPb Ridge – Integrated associated Yeld

Elliptic flow not subtracted

CMS – HIN-11-001



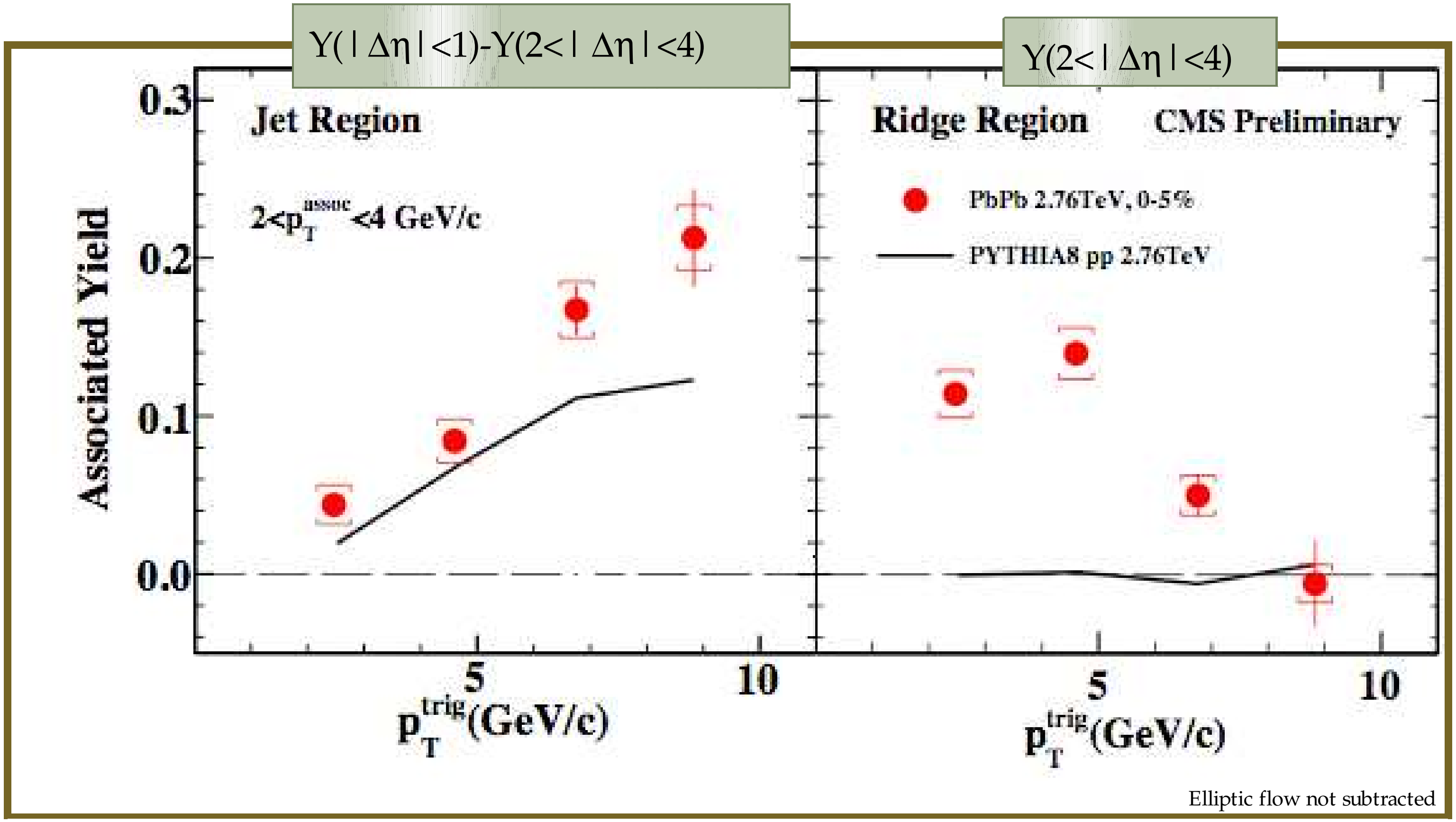
Δη dependence of the near-side yield

(measured in Δη slices of 0.6)

- Flat near-side ridge structure in PbPb for |Δη| > 1
- Similar jet peak between PYTHIA8 and PbPb

PbPb Ridge – Integrated associated Yeld

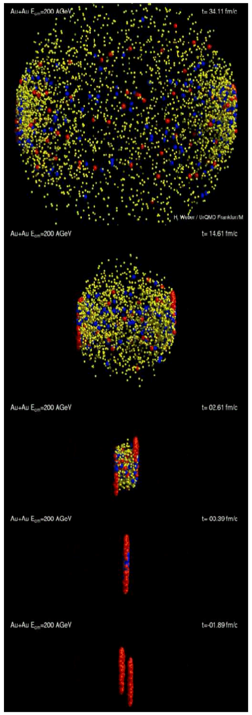
Associated Yield (Y) vs trigger pT in jet and ridge region

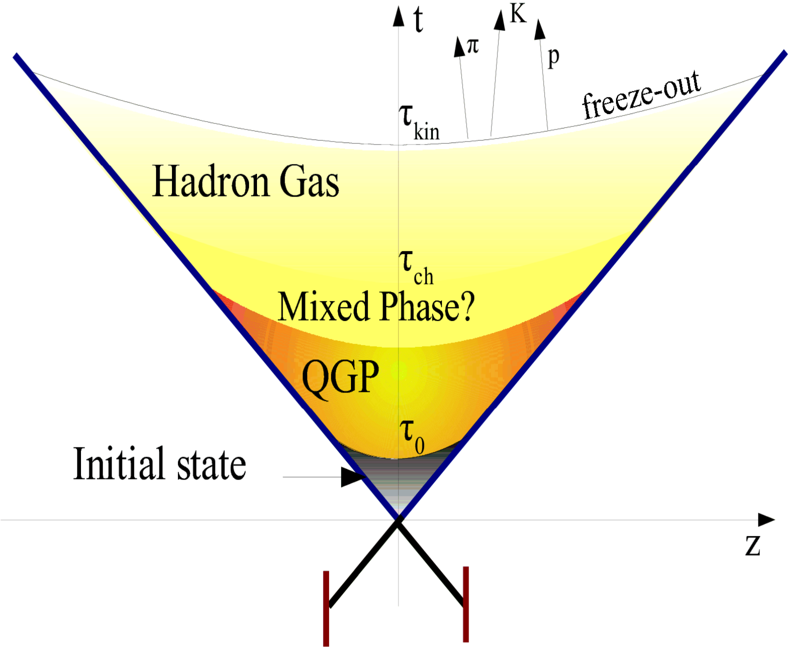


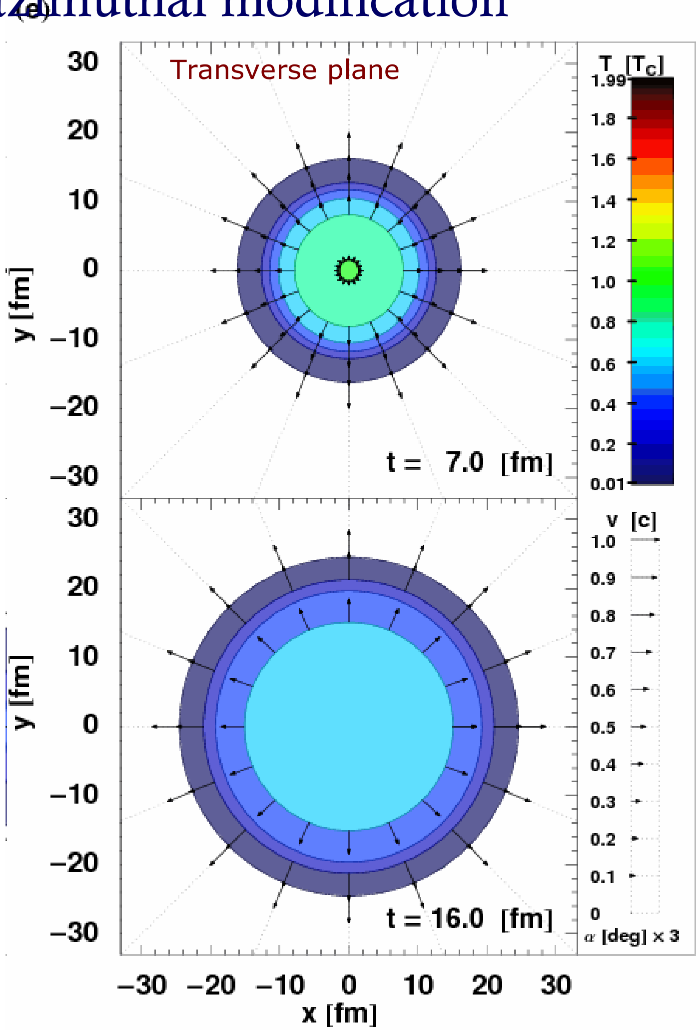
CMS – HIN-11-001

Heavy Ion collision evolution

- HIC is expected to go through a Quark Gluon Plasma phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification

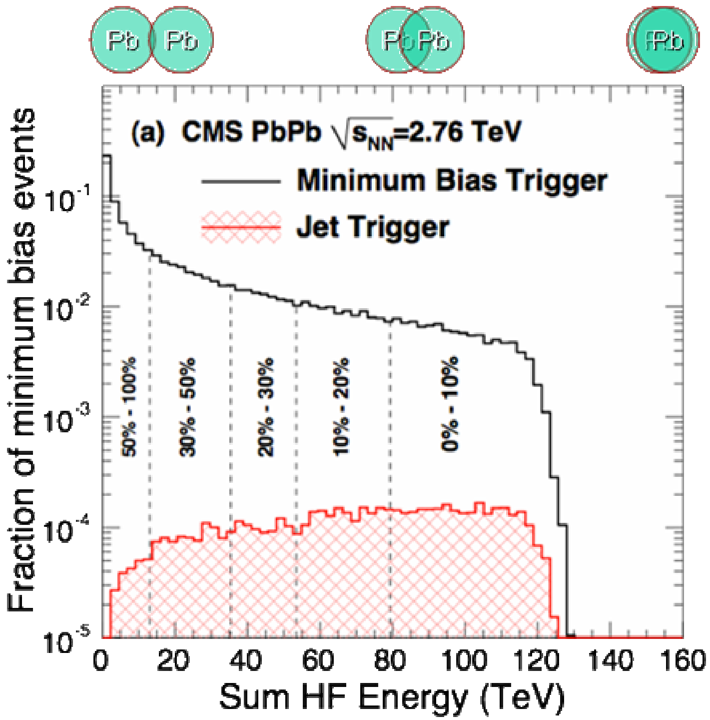


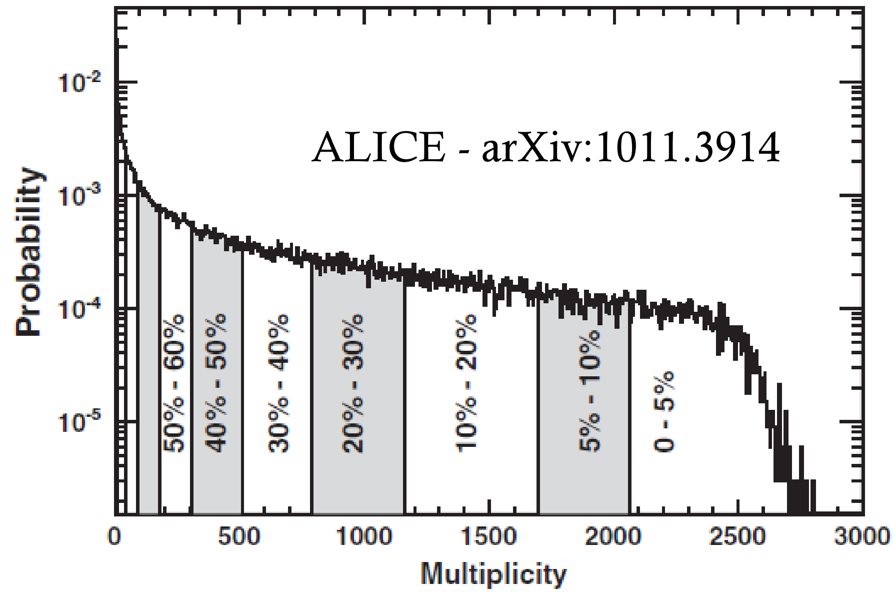


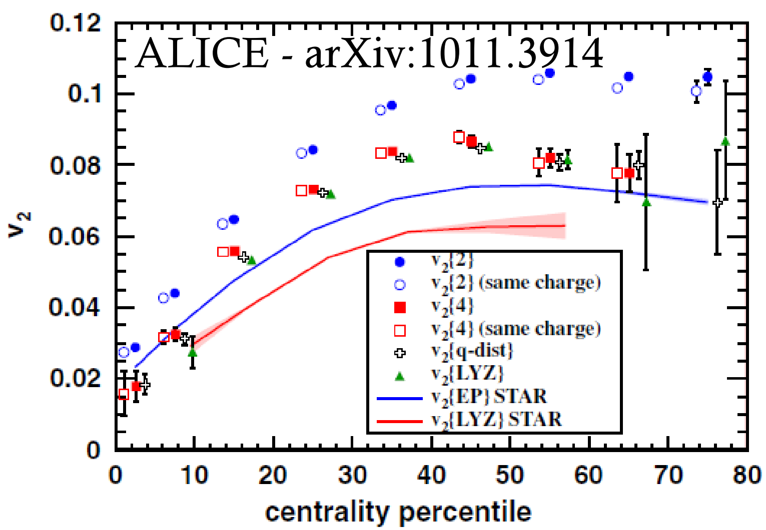


M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905

Centrality and v_2







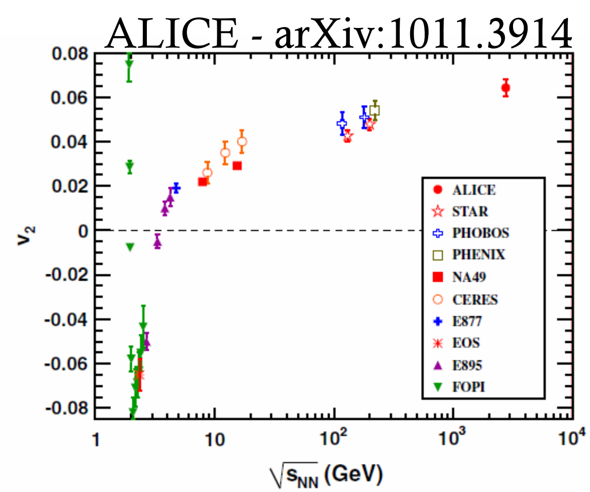
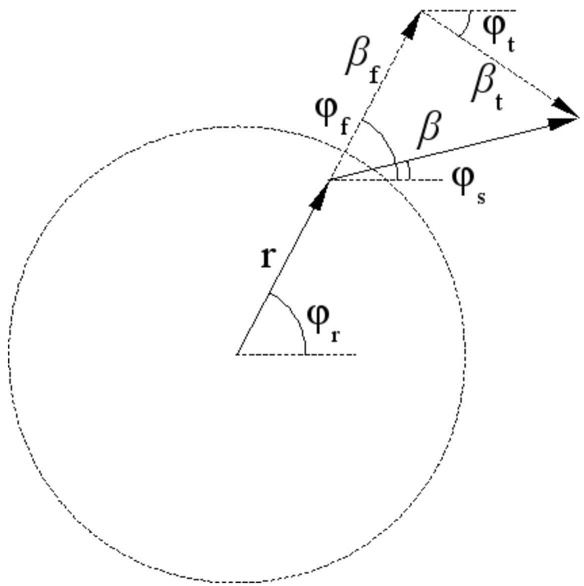
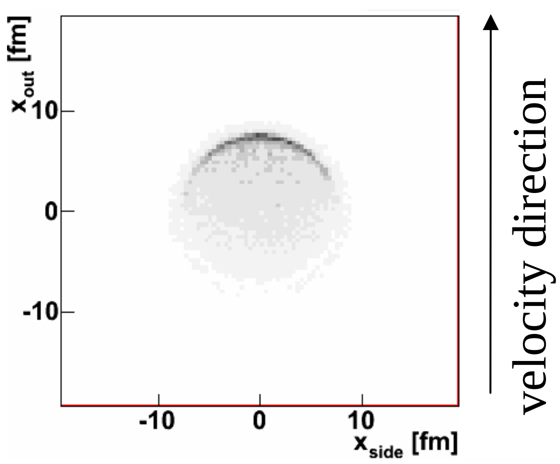


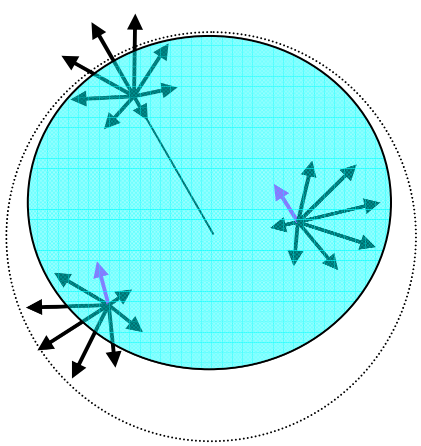
FIG. 4 (color online). Integrated elliptic flow at 2.76 TeV in Pb-Pb 20%–30% centrality class compared with results from lower energies taken at similar centralities [40,43].

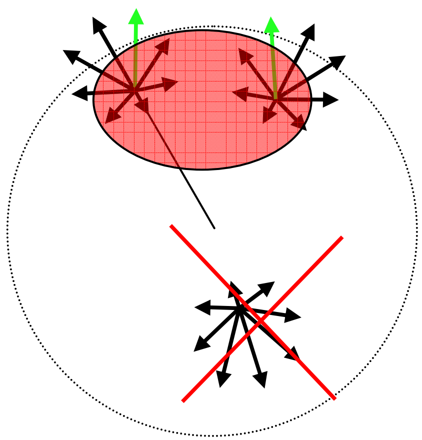
Dynamics via momentum dependence



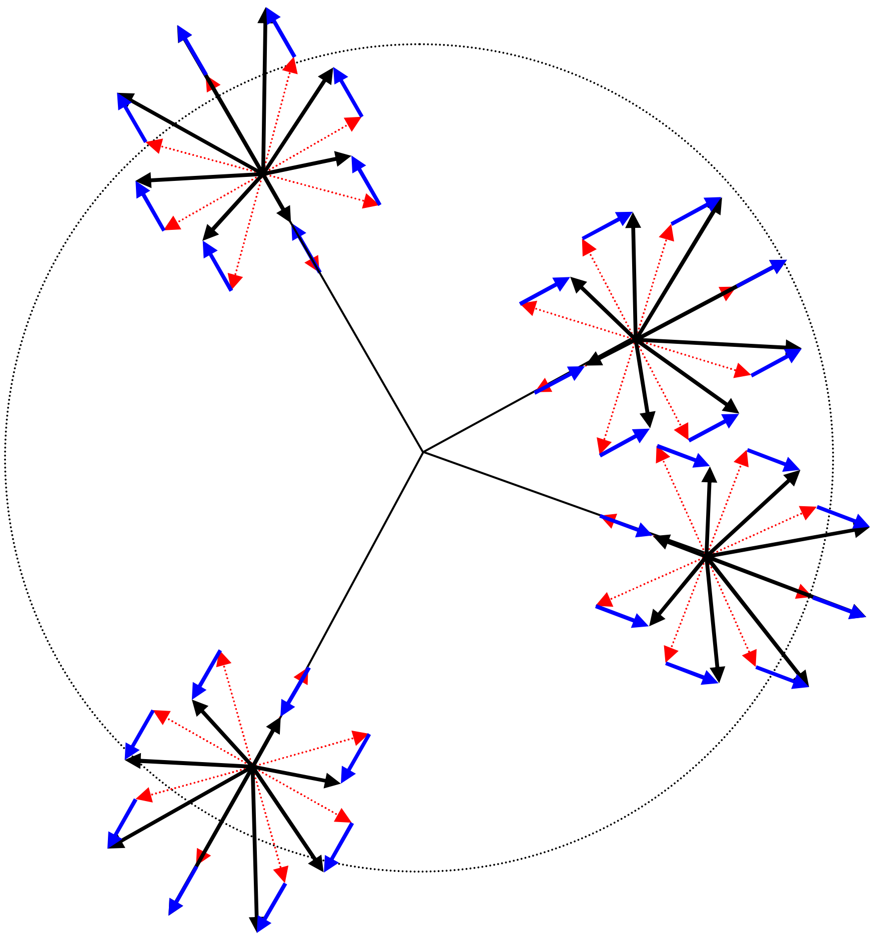
- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where such particles can be emitted gets smaller and shifted to the outside of the source







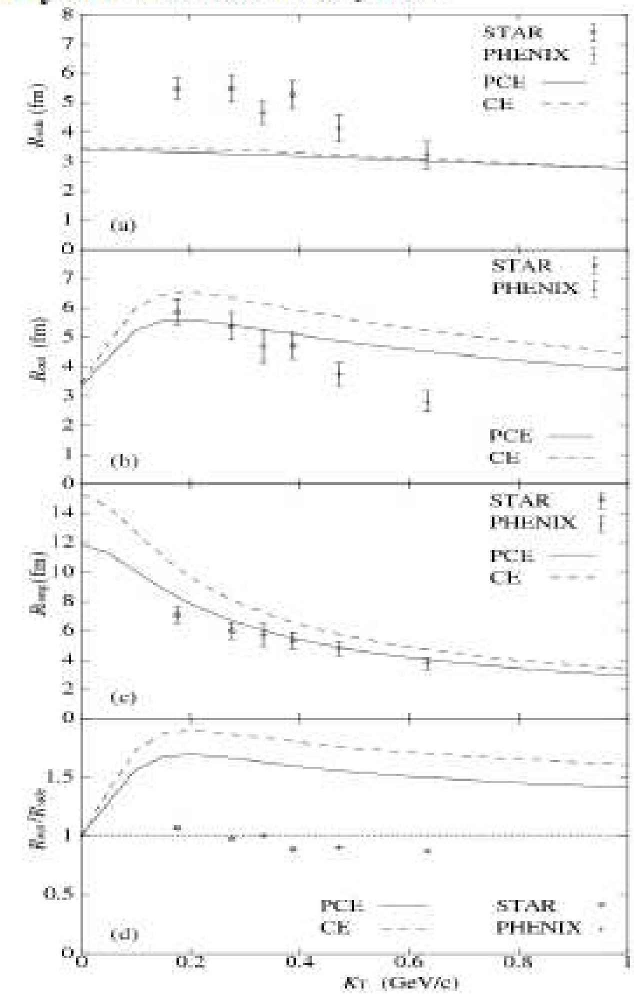
Which collectivity do we seek?



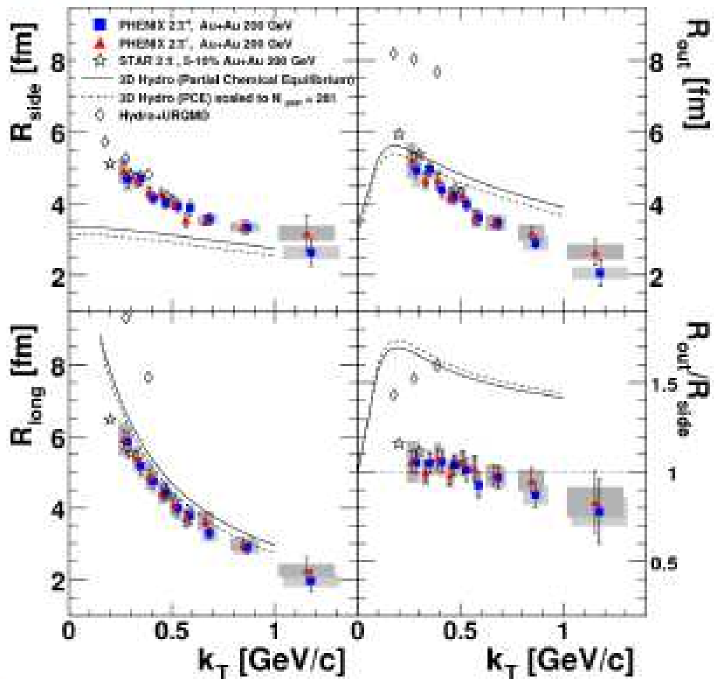
- A collective component is a "common" velocity for all particles emitted close to each other
- To that one adds "thermal" (random) velocity
- We expect specific "common" velocity – radial direction, pointing outwards from the center

RHIC Hydro-HBT puzzle

T. Hirano, K. Tsuda, nucl-th/0205043
Phys.Rev.C66:054905,2002.



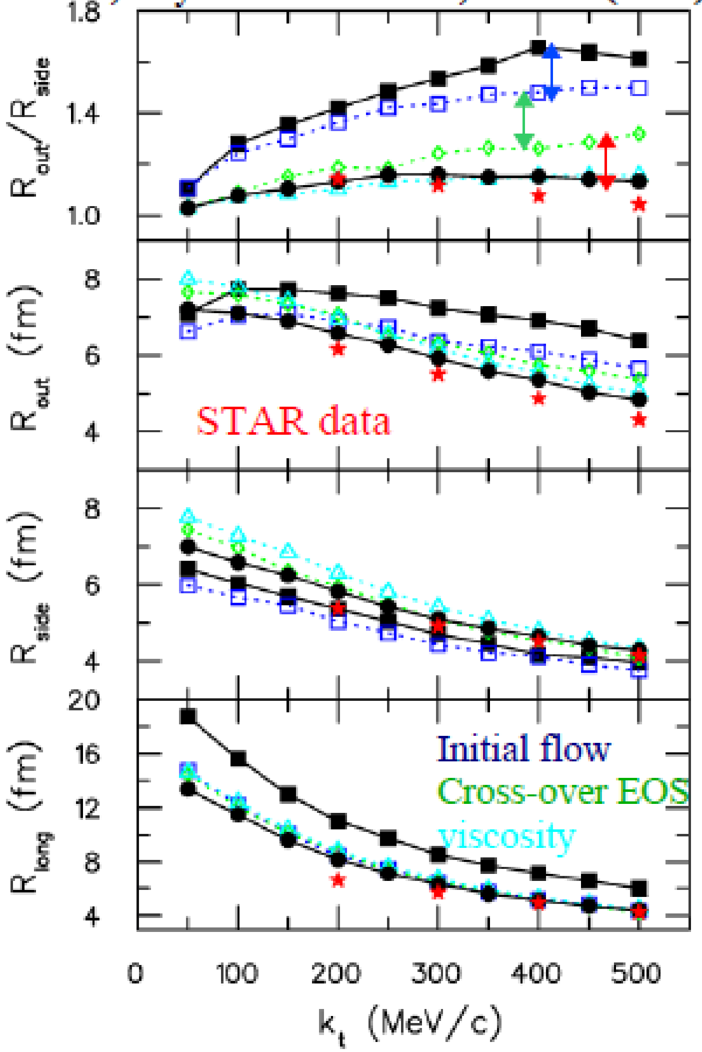
- First hydro calculations struggle to describe femtoscopic data: predicted too small R_{side} , too large R_{out} – too long emission duration
- No evidence of the first order phase transition



U. Heinz, P. Kolb, hep-ph/0204061

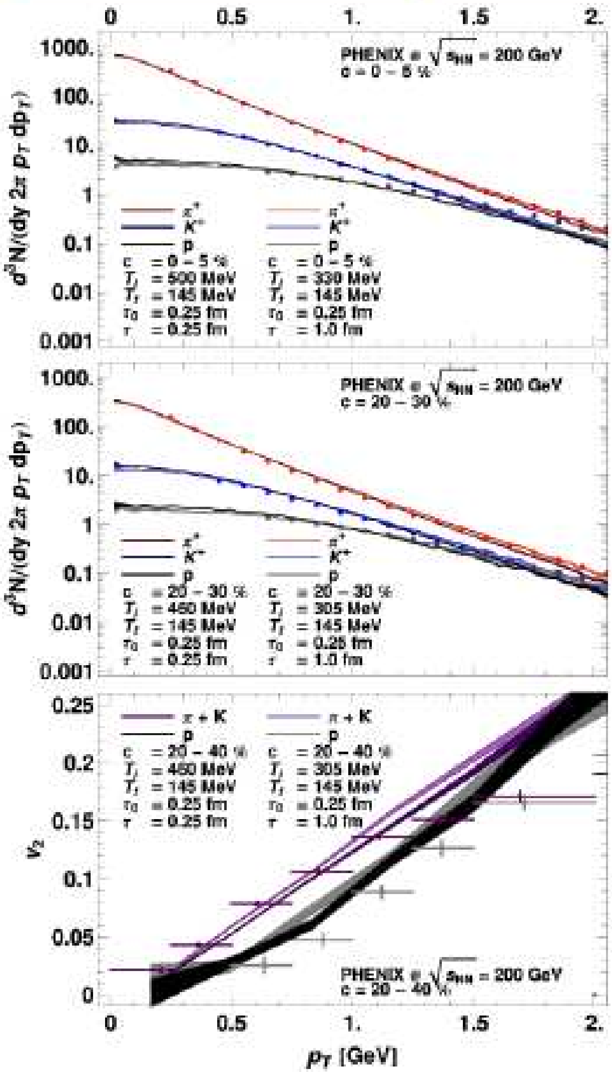
Revisiting hydrodynamics assumptions

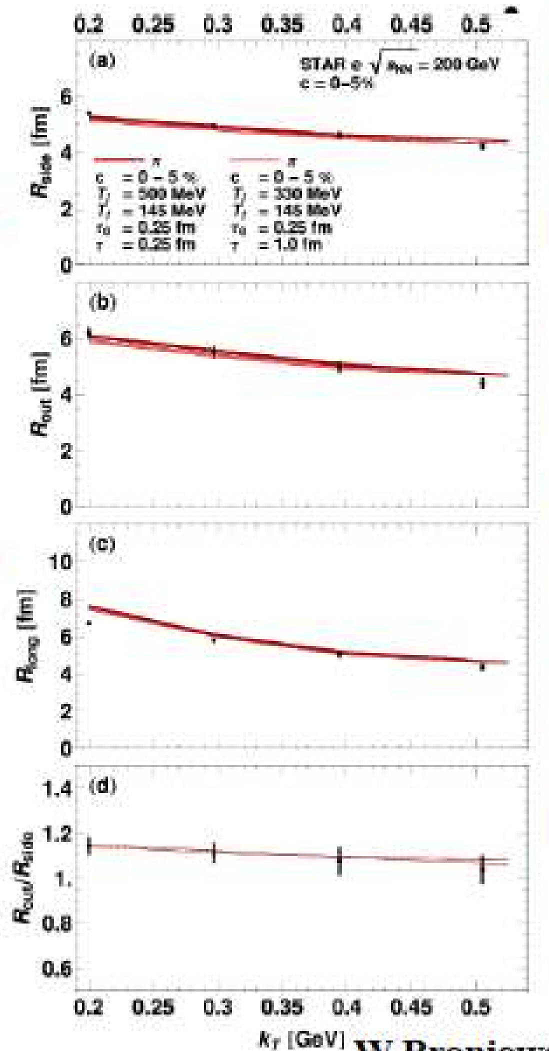
S. Pratt, Phys. Rev. Lett. 102, 232301 (2009)



- Data in the momentum sector (p_T spectra, elliptic flow) well described by hydrodynamics, why not in space-time?
- Usually initial conditions do not have initial flow at the start of hydrodynamics (~1 fm/c) – they should.
- Femtoscopy data rules out first order phase transition – smooth cross-over is needed
- Resonance propagation and decay as well as particle rescattering after freeze-out need to be taken into account: similar in effects to viscosity

Description of the soft sector at RHIC





Dynamical model with hydrodynamical evolution, propagation of strong resonances

Reproduces spectra, elliptic flow and femtoscopy

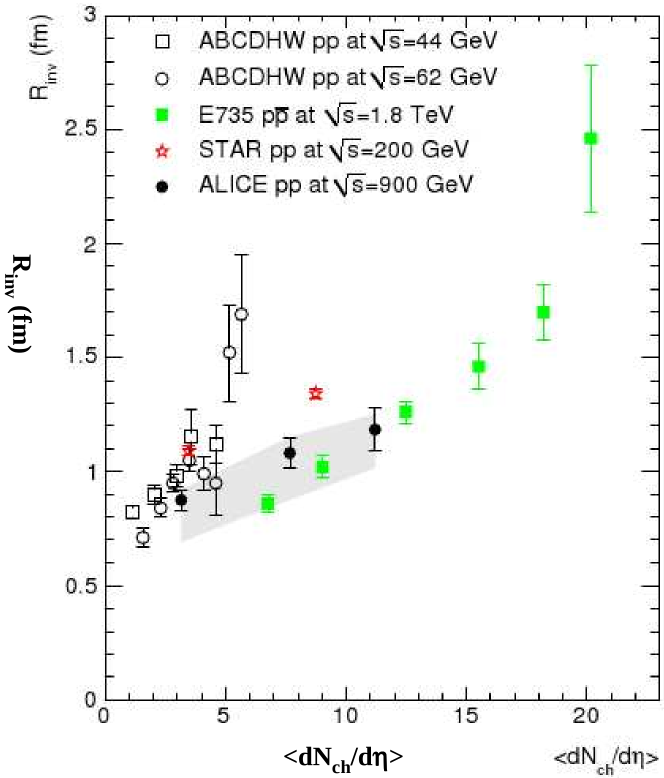
Initial flow, smooth cross-over phase transition, resonance treatment naturally included

RHIC HBT puzzle solved: soft sector data at RHIC understood in detail

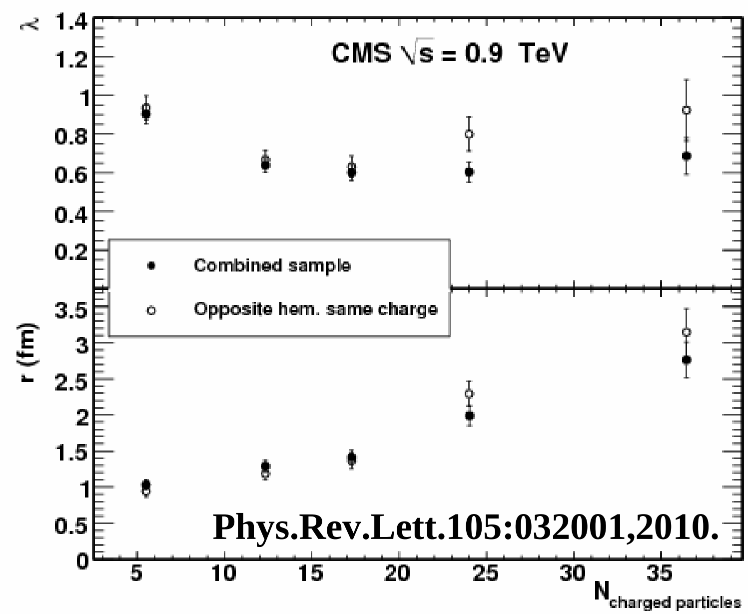
W.Broniowski, W.Florkowski, M.Chojnacki, AK
nucl-th/0801.4361; nucl-th/0710.5731

First look at system size at 0.9 TeV

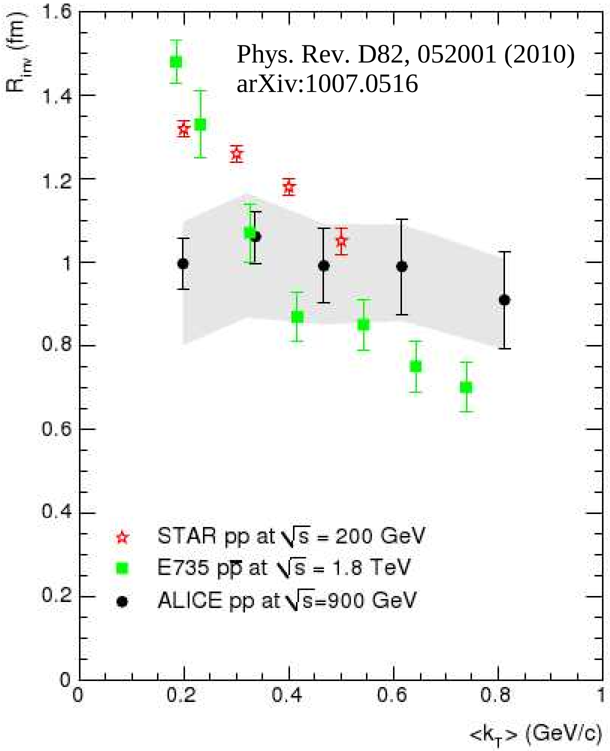
Phys. Rev. D82, 052001 (2010)
arXiv:1007.0516

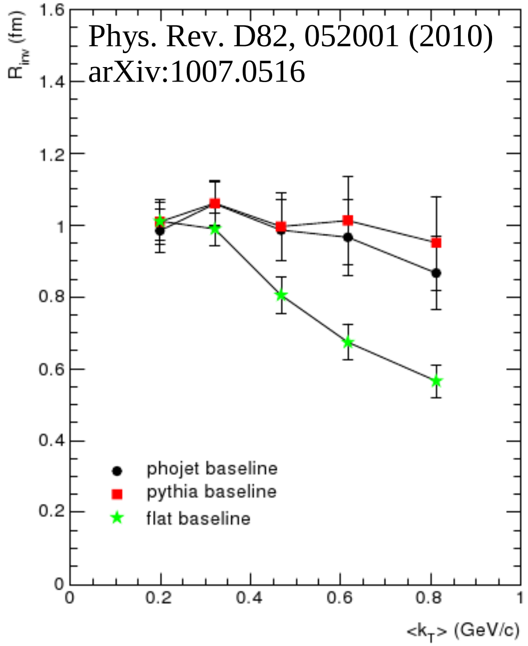


- Only ~250k minimum-bias triggered events
- growth of the system size with multiplicity observed
- ALICE results are given as a function of pseudorapidity density and can be compared to world systematics
- The observed trend is qualitatively similar to world data, but quantitative comparisons are complicated by large differences in experimental acceptances and analysis methods



Firtst look at pair momentum dependence

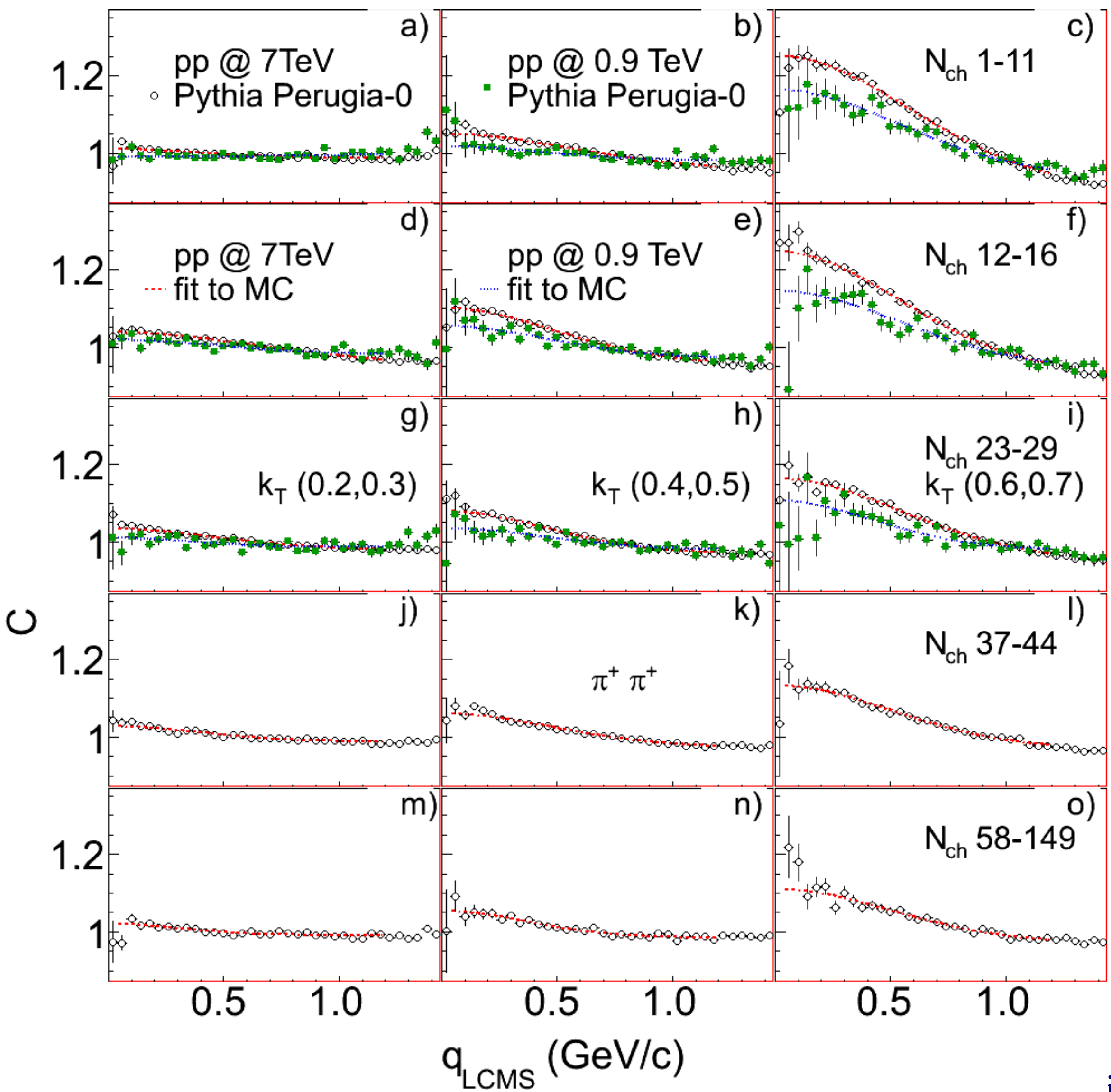




- First attempt in measuring pair momentum dependence limited by statistics and systematics
- Dominating systematic effect: appearance of "mini-jet" non-femtoscopic correlations at large p_T
- Integrated R_{inv} shows flat behaviour, but only if the systematic effects are treated properly
- Discrepancy with data at lower (STAR) and higher (E735) energy is apparent, but acceptance (in particle momenta and event multiplicities) differs significantly

BEC baseline in Pythia (Perugia-0)

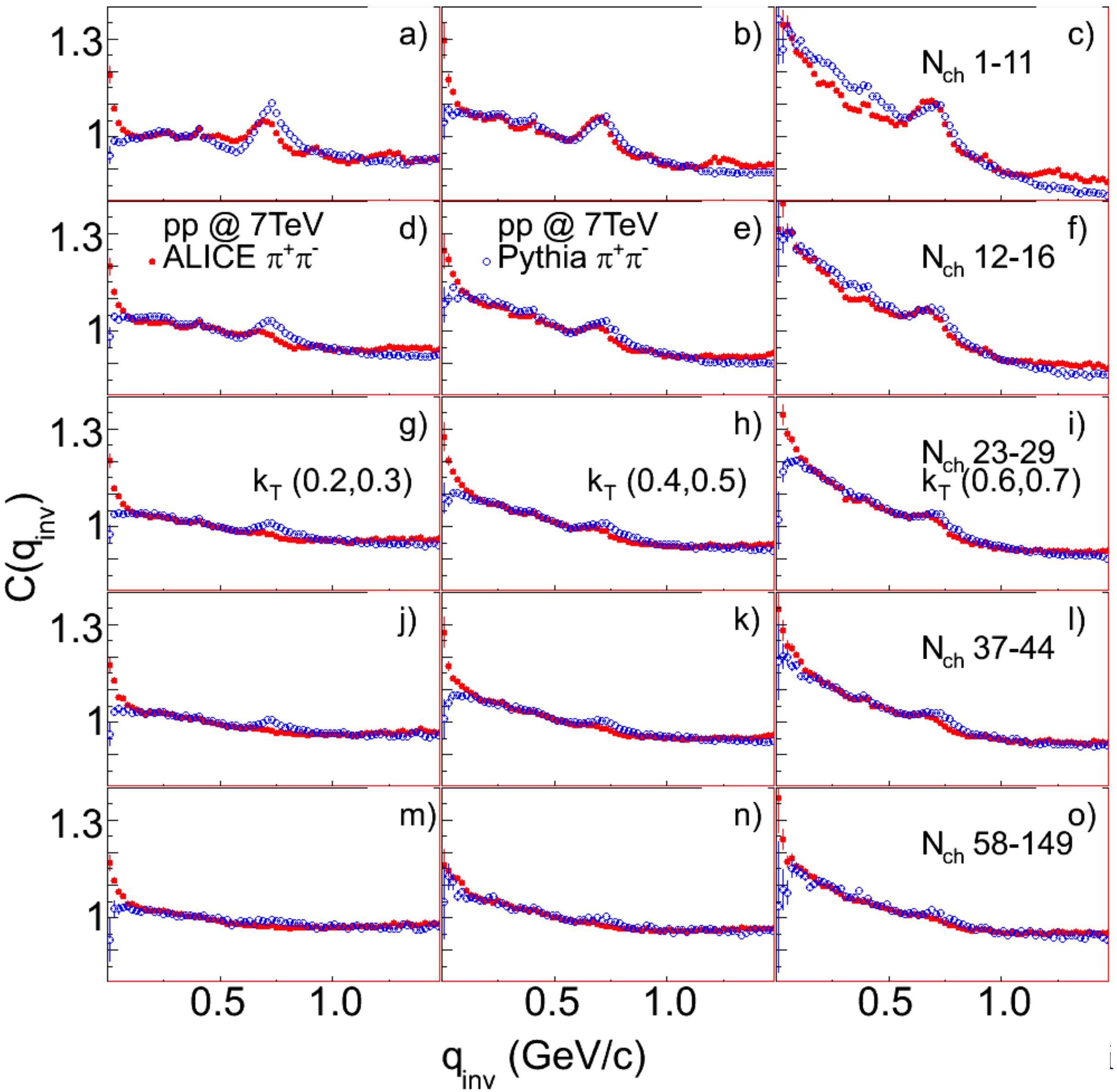
ALICE - CERN-PH-EP-2010-083



- Pythia Perugia-0 tune background fitted a 3D Gaussian peak with equal radii in LCMS
- Width of the peak varies by only 10% between multiplicity, k_T bins
- Height of the peak grows with k_T, falls with multiplicity
- Background at 0.9 TeV smaller than at 7 TeV

Pythia baseline for unlike sign pairs

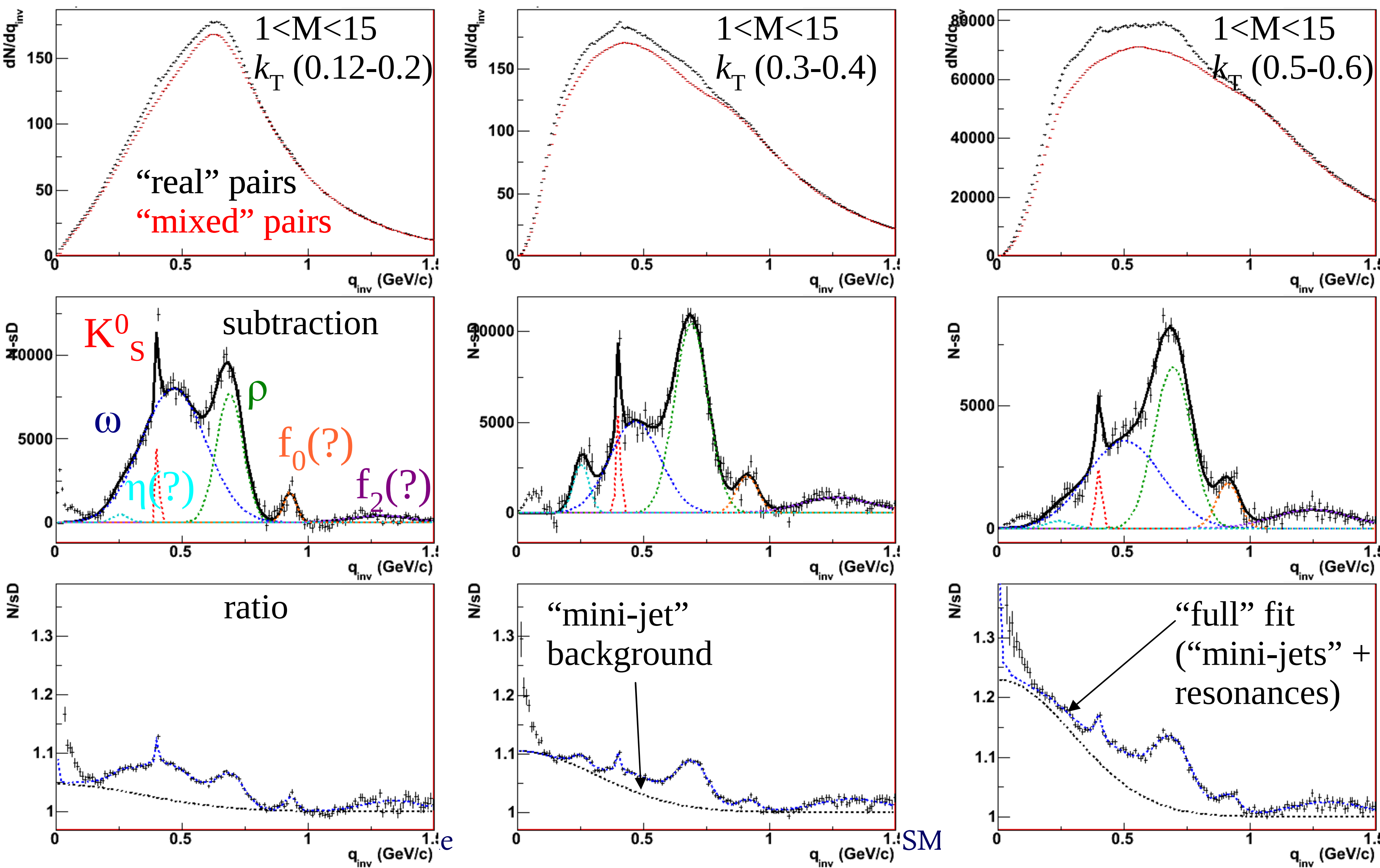
ALICE - CERN-PH-EP-2010-083



- Reasonable match between Pythia and data across multiplicity and k_T bins
- Visible resonance structures (non-id **not** a suitable background for identical pairs, and vice-versa)
- Details of resonance structure not reproduced – a limitation of resonance treatment in Pythia.

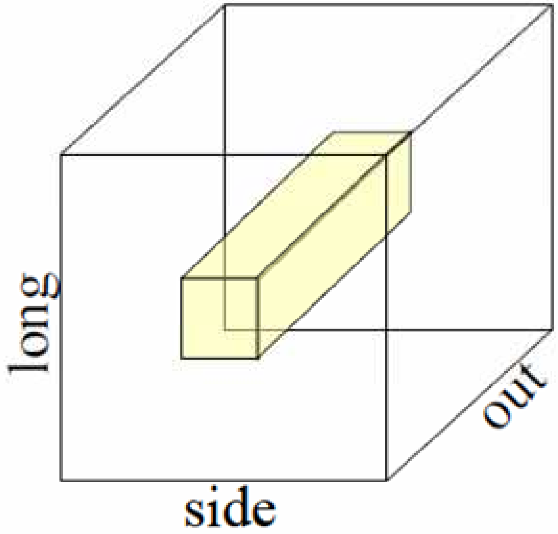
Resonance structure in detail (data)

ALICE



e

SM



Representations of the correlation

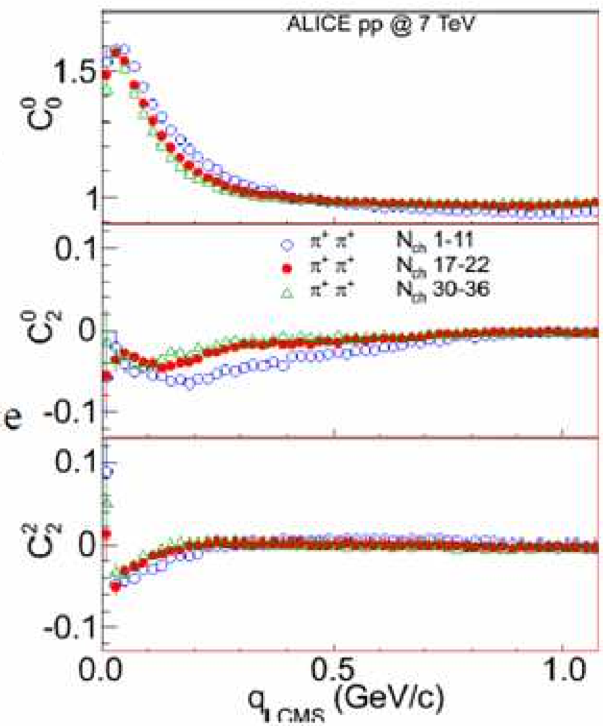
- 3D space can be viewed via 1D projections or spherical harmonics
- Projections used traditionally
- Spherical harmonics have synergy with symmetries of the correlation

$$C_l^m = \int C(\vec{q}) Y_l^m(\vec{q})$$

C_0^0 - angle averaged similar to 1D CF

C_2^0 - $\cos^2\theta$ weight longitudinal vs. transverse difference

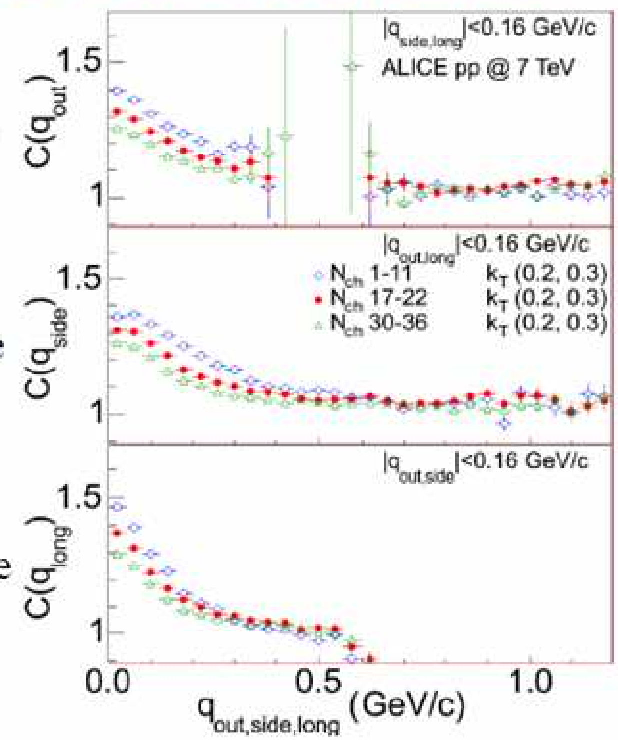
C_2^2 - $\cos^2\varphi$ weight out vs. side difference



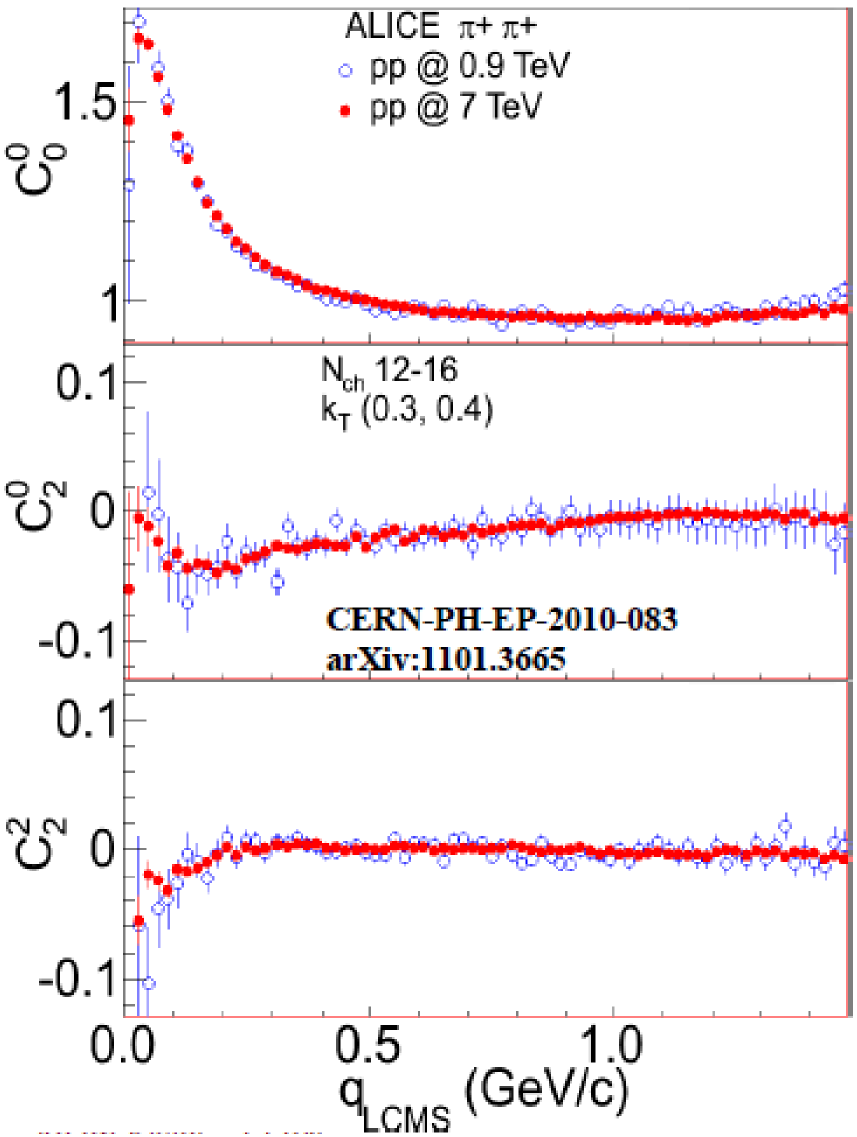
$C(q_{out})$ out size

$C(q_{side})$ side size

$C(q_{long})$ long size

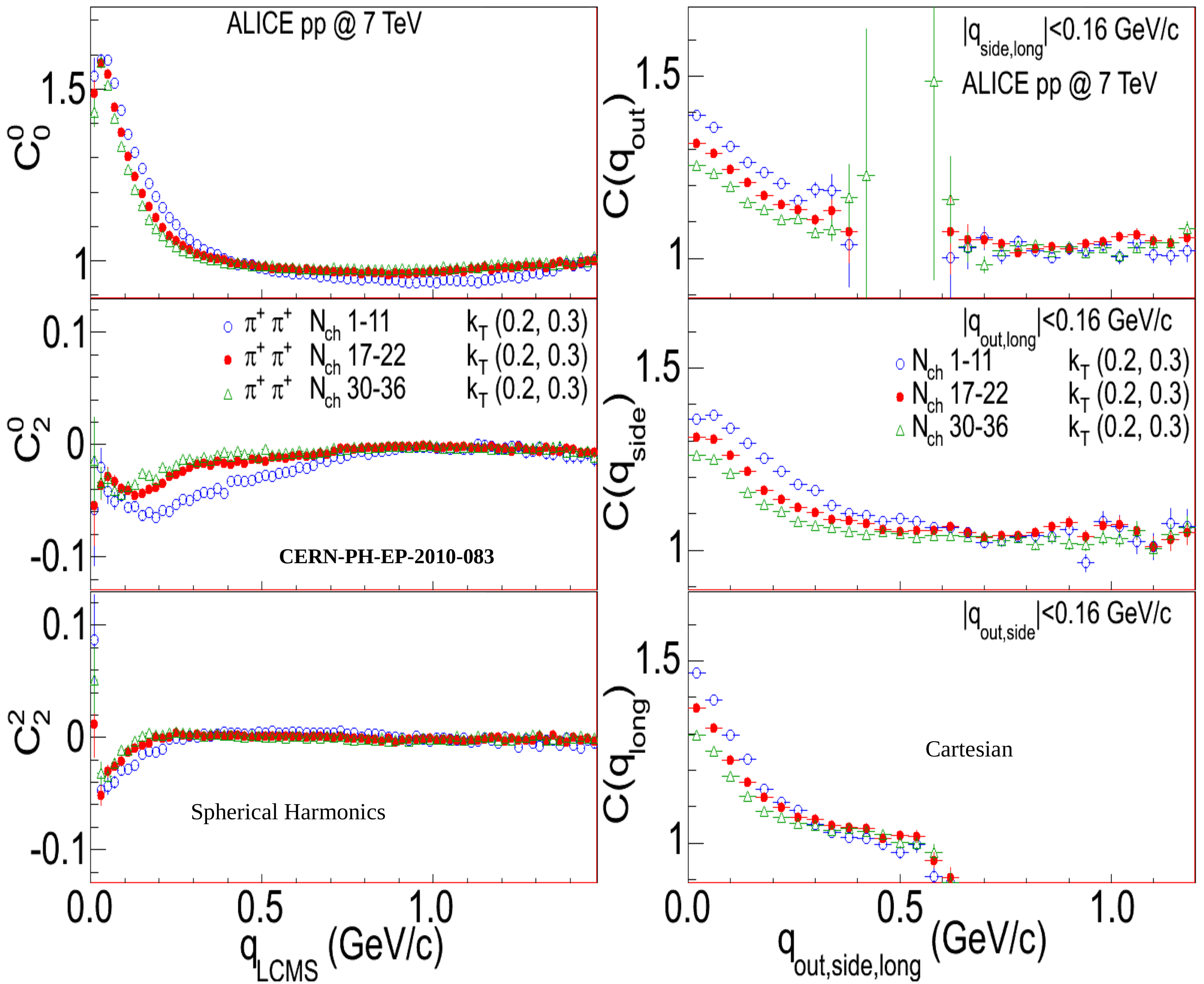


Energy dependence of the correlation function



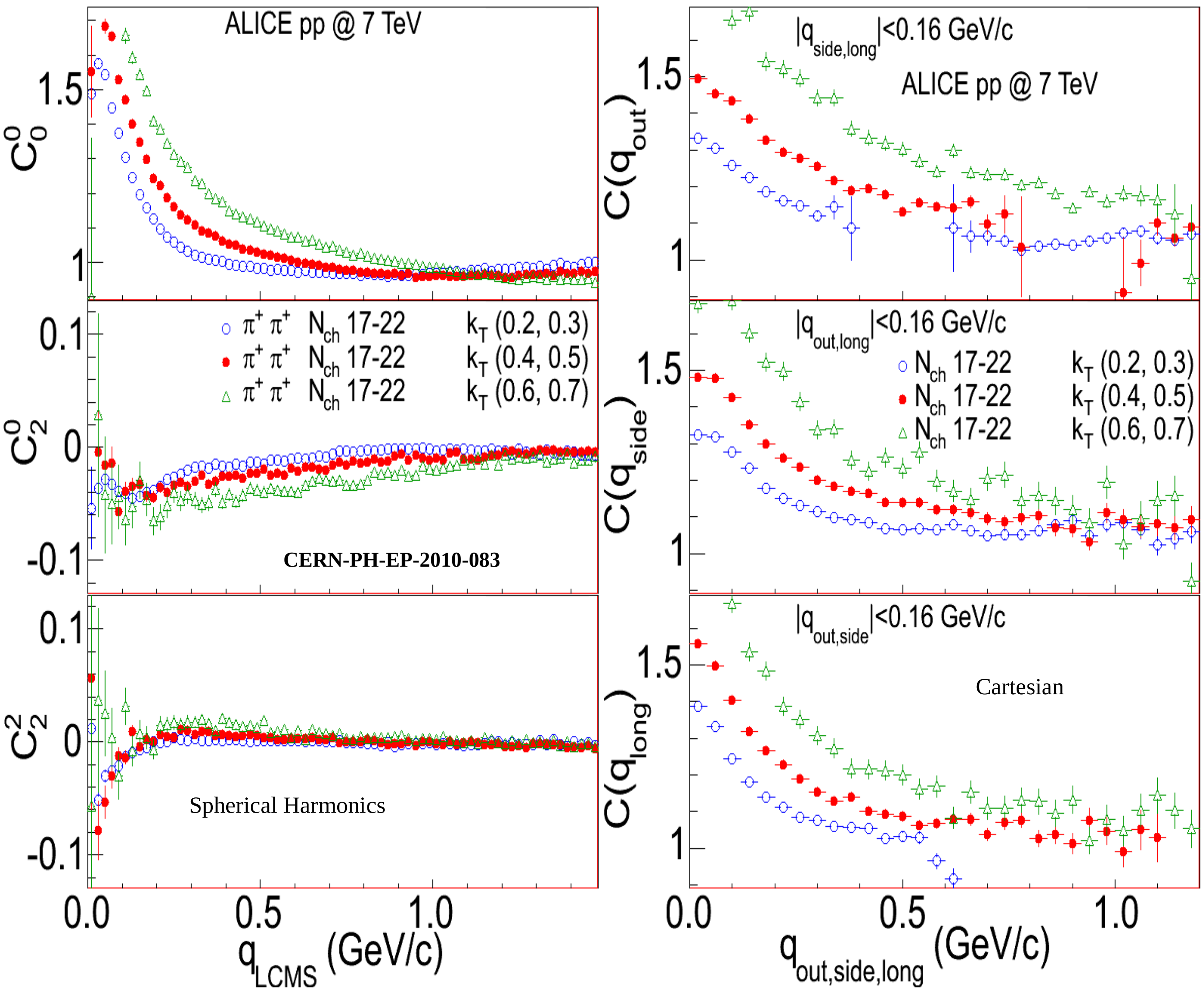
- Correlation functions for 0.9 TeV and 7 TeV, for same multiplicity and k_T bins similar
- 3D shape ($C_2^{\,0}$ and $C_2^{\,2}$ components) also consistent
- Checked all multiplicity/k_T bins - all show comparable similarity
- First important finding: the scaling variables are the total event multiplicity and pair momentum. Dependence on collision energy is small in comparison.

Multiplicity dependence of the correlation function



- Dependence of the CF on multiplicity visible, not strong
- Large holes in the acceptance in certain k_T bins
- Consistent behavior for Spherical Harmonics and cartesian CFs

k_T dependence of the correlation function



- Dependence on k_T visible, stronger
- Acceptance holes in the CF depend directly on k_T (kinematics cut effect)
- Additional structures appear in the correlation at higher k_T ranges
- Extraction of the k_T dependence of the radii complicated by the need to account for the background

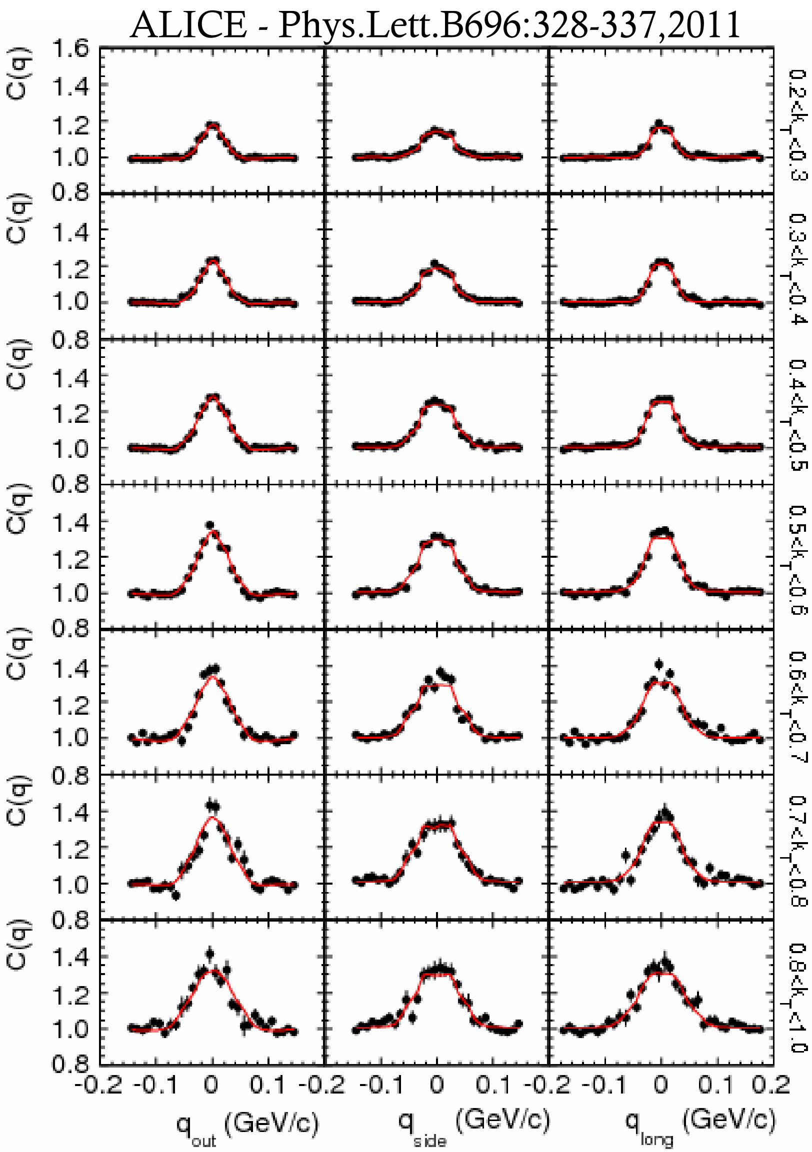
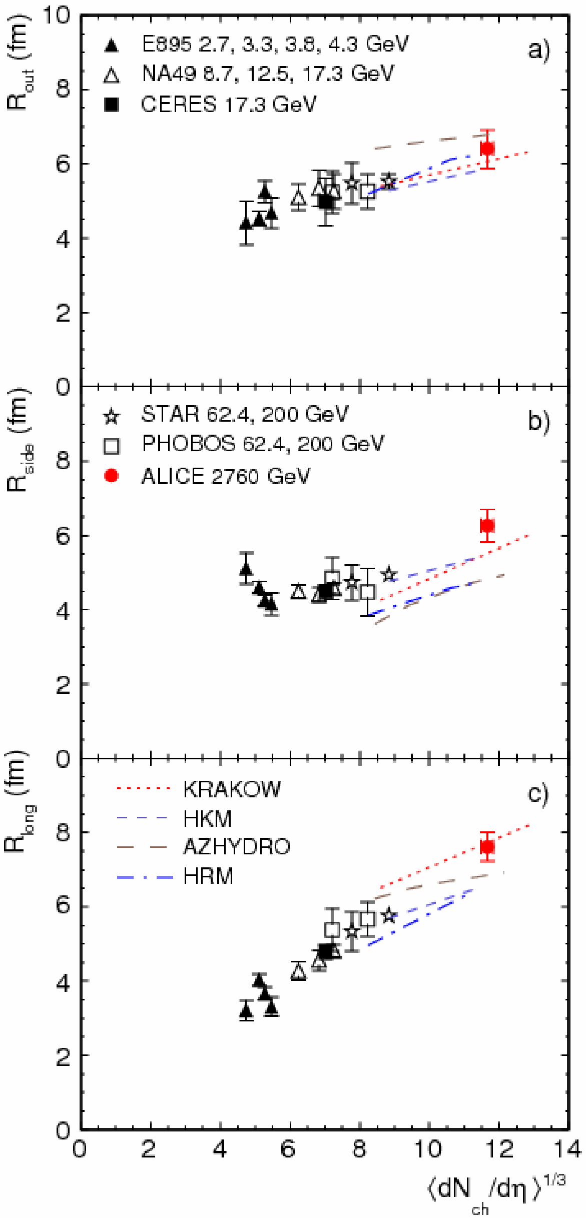


Figure 1: Projections of the three-dimensional $\pi^-\pi^-$ correlation function (points) and of the respective fits (lines) for seven k_T intervals. When projecting on one axis the other two components were required to be within (-0.03,0.03) GeV/c. The k_T range is indicated on the right hand side axis in GeV/c.

BEC Correlations in Pb+Pb

- The correlation functions in Pb+Pb have been measured in the limited sample of events recorded at the beginning of November 2010
- First analysis was performed only for top 5% central events
- The pair momentum dependence was the main focus of the paper
- Specifically the fall of radii with pair momentum as well as the overall increase of radii as compared to RHIC was expected

Comparing to models



ALICE - Phys.Lett.B696:328-337,2011

Figure 3: Pion HBT radii at $k_T = 0.3$ GeV/c for the 5% most central Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV (red filled dot) and the radii obtained for central gold and lead collisions at lower energies at the AGS [35], SPS [36, 37, 38], and RHIC [39, 40, 41, 42, 30, 43]. Model predictions are shown as lines.

- The hydrodynamic models which were extensively tuned to reproduce the RHIC data work also at the LHC
- It is still not trivial to simultaneously reproduce the overall magnitude of the radii and the change between RHIC and the LHC.
- Only the models which introduce all the features important at RHIC (initial flow, cross-over phase transition, realistic equation of state, full inclusion of resonances) continue to work at the LHC.

BEC@LHC feedback

- The results from p+p collisions were received with considerable interest by the community:

  K.Werner et al., "*Evidence for Hydrodynamic Evolution in Proton-Proton Scattering at LHC Energies.*", arXiv:1010.0400 [nucl-th]

  AK, "*Signatures of collective flow in high multiplicity pp collisions.*", arXiv:1012.1517 [nucl-th]

  V.A. Schegelsky, A.D. Martin, M.G. Ryskin, V.A. Khoze, "*Pomeron universality from identical pion correlations*", arXiv:1101.5520

- Interest in high-multiplicity measurements: interpreted as a collective system with strong expansion. Should be combined with other measurements for a stronger case.

- Energy independence interpreted as a signature of the Pomeron exchange mechanism.