MPI in collisions with nuclei: selected highlights

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***NPQCD 2015**, Cortona 19-22 April 2015*

Outline

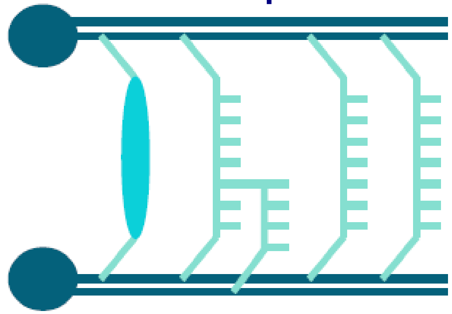
- MPI: basic concepts
- MPI in different collision systems
- Centrality determination (example from ALICE)

- Selected highlights from heavy-ion collisions:
  - Heavy flavour
  - $\langle p_T \rangle$
  - Long range correlations
  - Di-hadron azimuthal correlations

- Summary

Multiple Parton Interactions

- Basic concepts:



- Several hard interactions can occur in a pp collision
- Some of the parallel interactions can be soft
- Re-interaction of partons with others: ladder splitting
- Re-interaction within ladders either in initial state: screening, or in final state
- Initial / Final State Radiation (ISR/FSR)

- Modelling MPI in Monte Carlo → examples

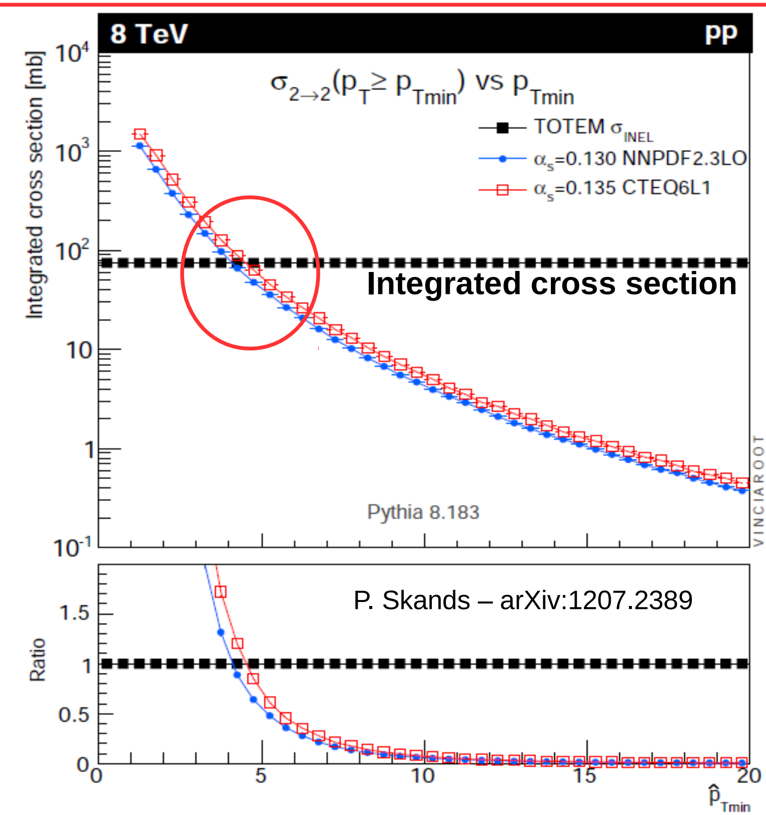
Pythia (pQCD based model)

- "Naive" factorization approach:
  - ✔ Mean number of hard 2 → 2 collisions given by the ratio of σ_{hard} (computed from pQCD, LO) over σ_{inel} (measured)
  - ✔ Poissonian fluctuations for the number of 2→ 2 collisions per event

$$\langle n_{hard} \rangle = \frac{\sigma_{\text{hard}}}{\sigma_{\text{inel}}};\ \mathrm{P}_n = \frac{\langle n_{hard} \rangle^n}{n!} \exp - \langle n_{hard} \rangle$$

- Regularization of the increase of σ_{hard} cross section at low pT
- impact parameter dependence
- coherence between MPI (Color Reconnection)

σ_{hard} > σ_{TOT} (~4 GeV/c)→ Straightforward interpretation: each pp collision contains several parton-parton collisions



Multiple Parton Interactions

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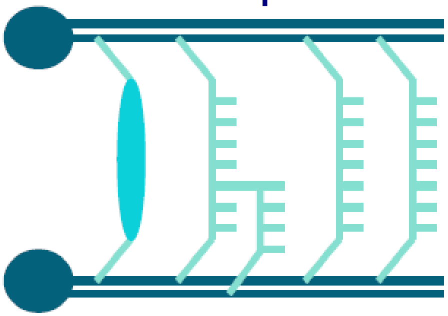

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EPOS (Gribov-Regge multiple scattering framework)

- Individual scatterings referred to as Pomerons, identified with parton ladders
- Each parton ladder is composed of a pQCD hard process with ISR/FSR
- Non-linear effects are considered by means of a saturation scale
- hadronisation performed with a string fragmentation procedure
- hydrodynamical evolution applied on the dense core of the collision (also in pp)

Multiple Parton Interactions

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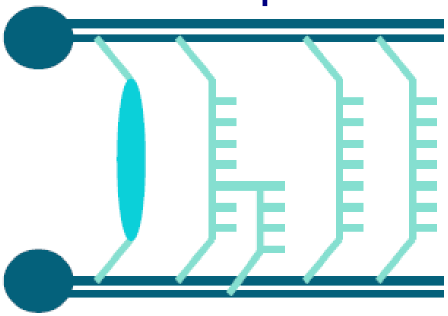

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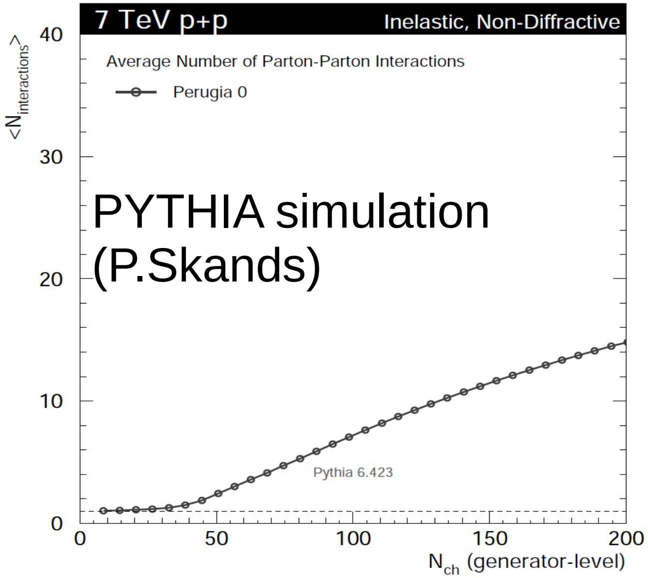
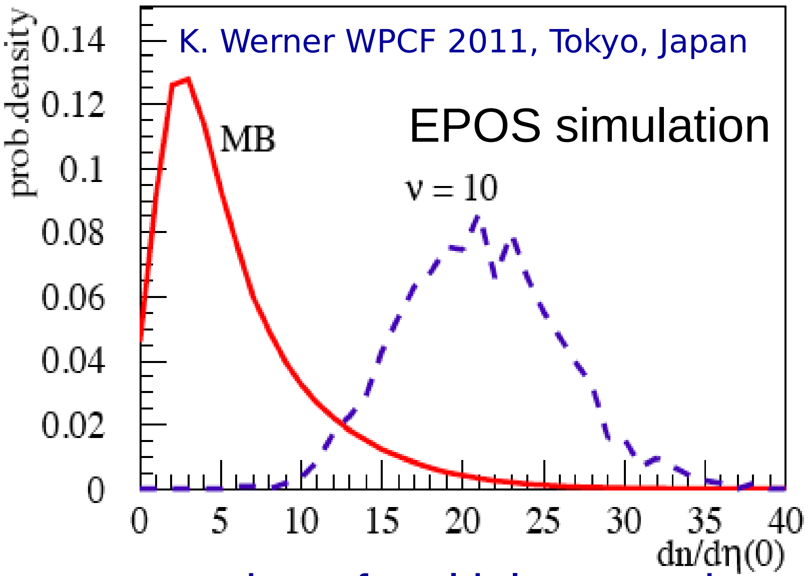


$<N_{MPI}>$ as a function of charged particle multiplicity

EPOS (Gribov-Regge multiple scattering framework)



υ: number of multiple scatterings

$<\upsilon>$(MB) << 10

Larger number of multiple scatterings ≡ High event multiplicity

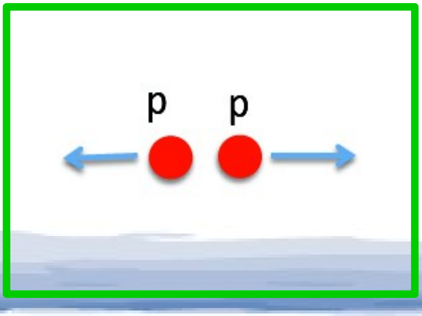
MPI in different collision systems

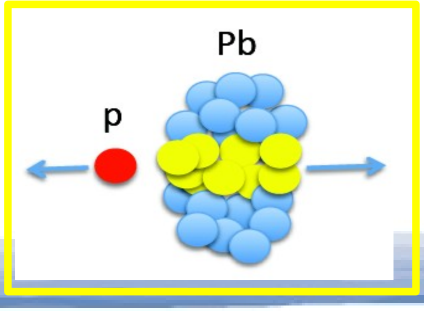
- High-multiplicity (HM) pp, p-A and A-A collisions → commonality: possible presence of large number of (initial) hard parton-parton scattering (MPI) and overlapping strings (CR)

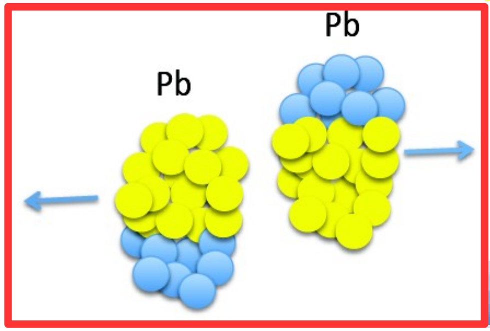
- HM proton-proton collisions:
  - arise from low-impact parameter collisions and statistical upward fuctuations of the number of MPIs per event
  - are expected to contain harder than average partonic collisions (larger $\langle Q^2 \rangle$) and partons fragmenting into a larger than average number of hadrons (fragmentation bias).

- A-A collisions →the mean number of MPI is almost dominated by the collision centrality (large N_{coll}) → additional biases are weak

- p-A → lie in between the two extreme cases: p-A centrality dominates, however when N_{coll} is small the p-N geometry can became important
  - In models that treat p-Pb collisions as independent p-N collisions, the number of parton-parton scatterings is expected to be determined by the p-A and p-N centralities







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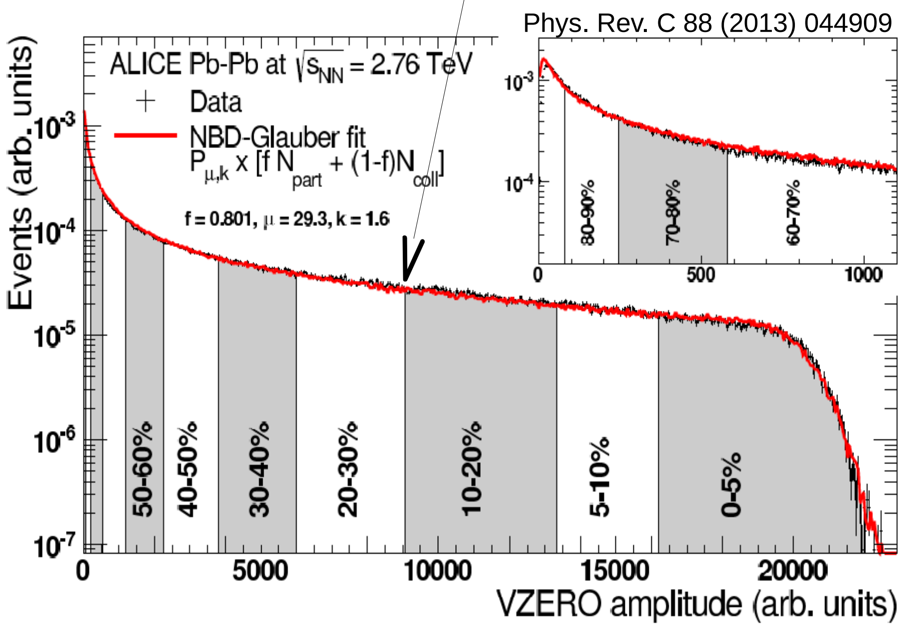
Furthermore:

- **<u>FINAL STATE EFFECTS in A-A</u>** → Thermal production, flow, recombination, jet quenching and fragmentation in the quark-gluon-plasma (QGP)
- **<u>INITIAL STATE EFFECTS in p-A</u>** → shadowing/gluon saturation, Cronin effect (Cold Nuclear Matter Effects)

Centrality determination

- Similar approach used in Pb-Pb and p-Pb in ALICE: multiplicity distribution of a given “estimator” (i.e. V0A multiplicity) fitted by Negative Binomial Distribution(NDB)(*) + Glauber MC
- Ingredients:
  - Glauber MC: given the σ_{NN} and assuming dP/db ~ b → this gives N_{part}, N_{coll}, T_{pA} (T_{AA}) event-by-event basis (b randomly changed and NN interaction happens if $b_{NN} < \sqrt{\sigma_{NN}/\pi}$)
  - NBD function used to represent the multiplicity distribution for the “estimator” (e.g. V0A) for a given N_{part}
  - convolution N_{part} from Glauber + NBD → used to fit the reconstructed multiplicity distribution (e.g. VZERO amplitude in Pb-Pb)

Phys. Rev. C 88 (2013) 044909



- Centrality classes are defined as percentiles of the multiplicity/summed-amplitude distributions
- For a given centrality class the information from the Glauber MC in the corresponding generated distribution is used to calculate the mean number of participants <N_{part}>, the mean number of collisions <N_{coll}>, and the average nuclear overlap function < T_{pA}> (< T_{AA}>)
- <u>Bias observed in p-Pb collisions!</u>
  (→ more details in back-up)

(*) Similar procedure but coupled with a model for slow nucleon emission (SNM) for ZNA

Selected highlights from LHC

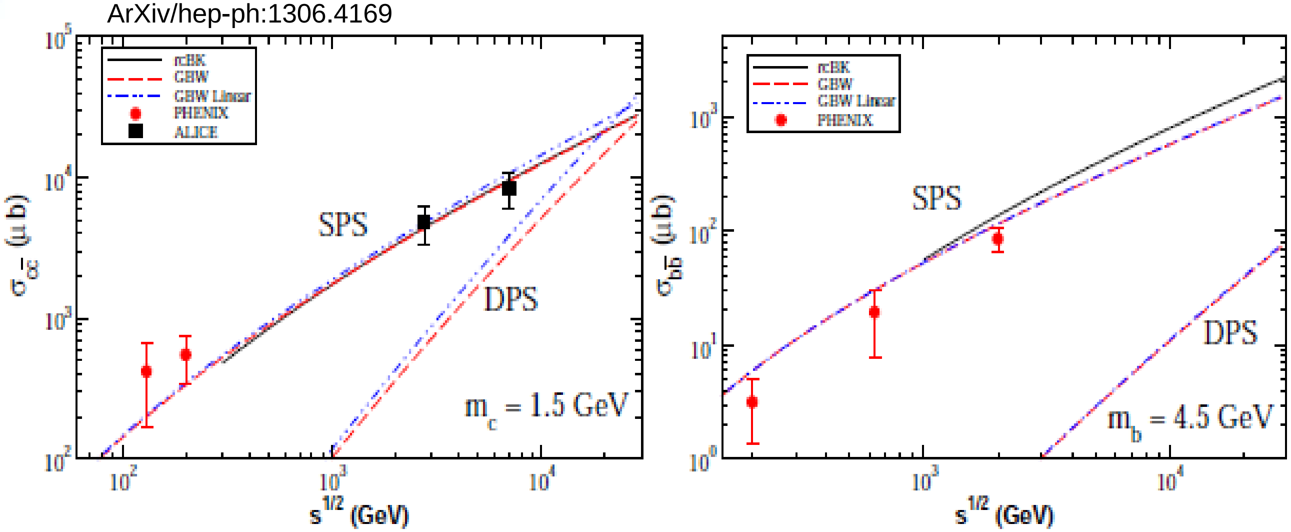
Heavy-flavour and MPIs

- Heavy-quarks (c,b) created in hard processes with a minimum momentum transfer $Q>2m_Q>>\Lambda_{QCD}$ → assuming
  - Soft particle production scales with the number of MPIs
  - MPIs proportional to the hard cross section

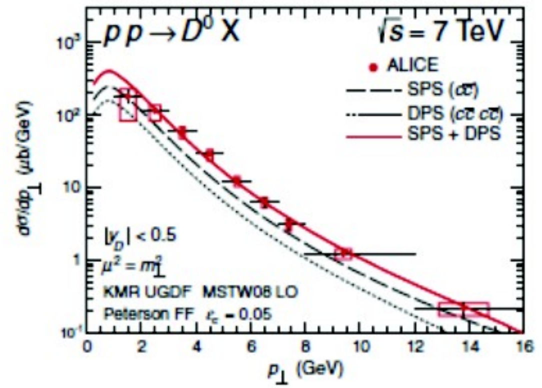
    → yields from any hard sub-process should increase with multiplicity
  - CNM effects in p-Pb can modify increasing pattern w.r.t to pp

- Direct comparison of open charm and beauty production yields with theory would give the possibility to extract the cross section of HF production from DPS:
  - Possible impact of DPS on charm and bottom production at the LHC

ArXiv/hep-ph:1306.4169



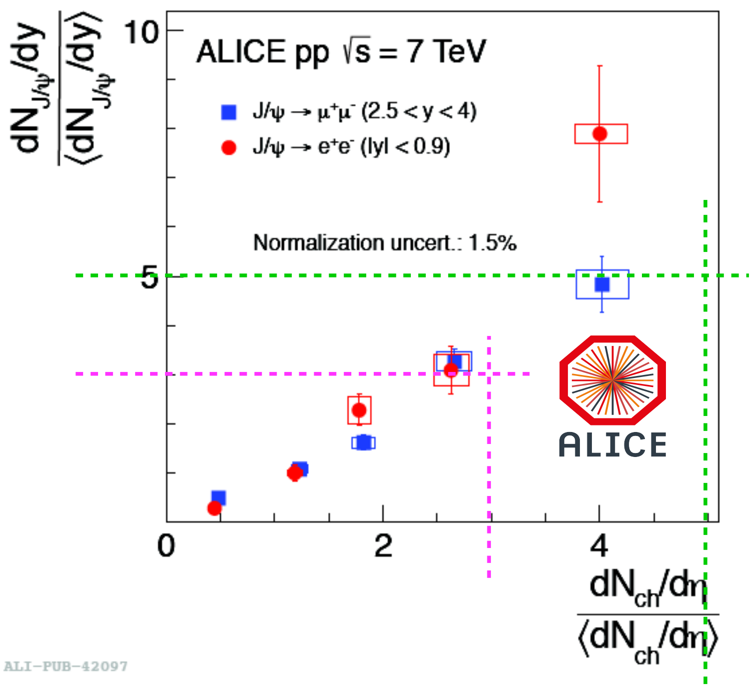
R.Maciula and Szczurek, Phys. Rev. D 87, 074039

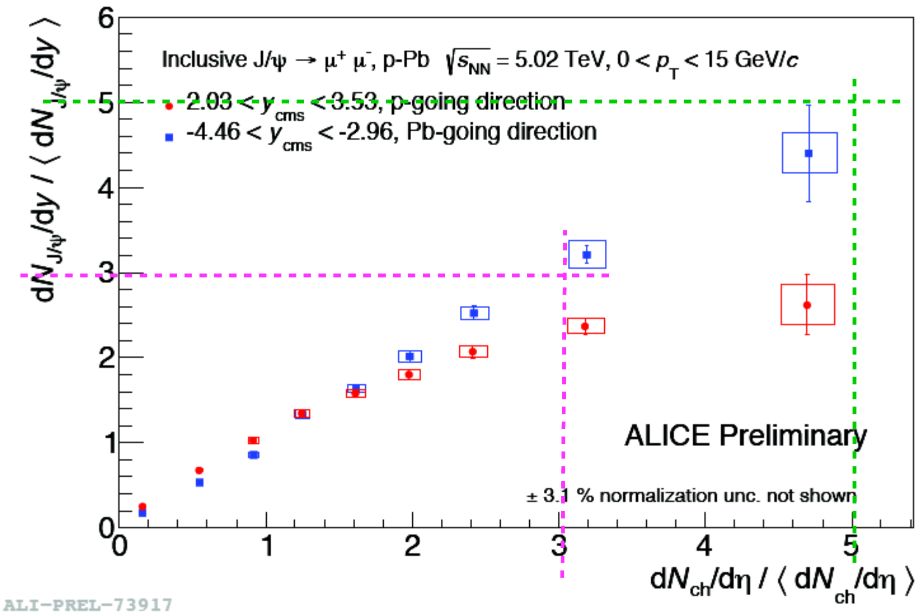


- In p-Pb CNM effects should be taken into account!

Heavy-flavour vs multiplicity (pp / p-Pb)

- ALICE: J/ψ yields self normalized to their integrated values as a function of particle multiplicity at mid rapidity normalized to the average number



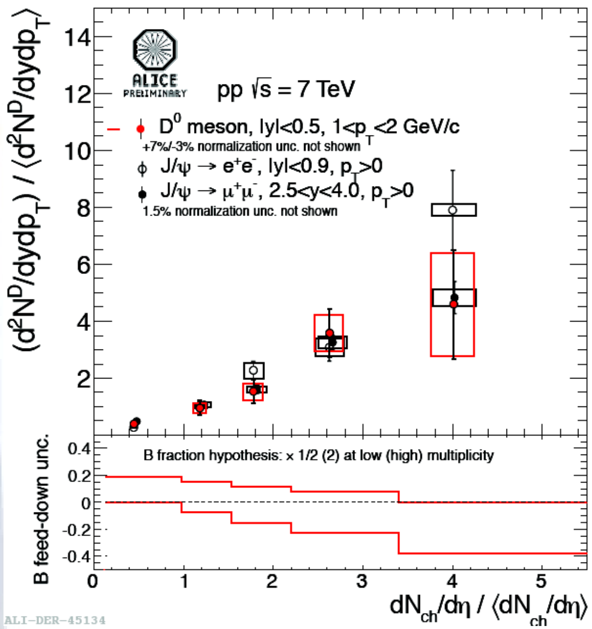


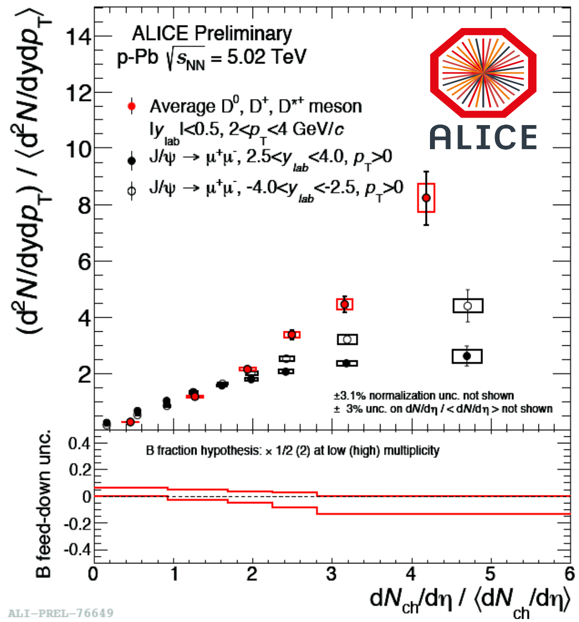
- Increasing J/ψ yields vs multiplicity observed both in pp and p-Pb → similar pattern in pp and p-Pb suggests that also in pp high-multiplicity events would come from MPIs

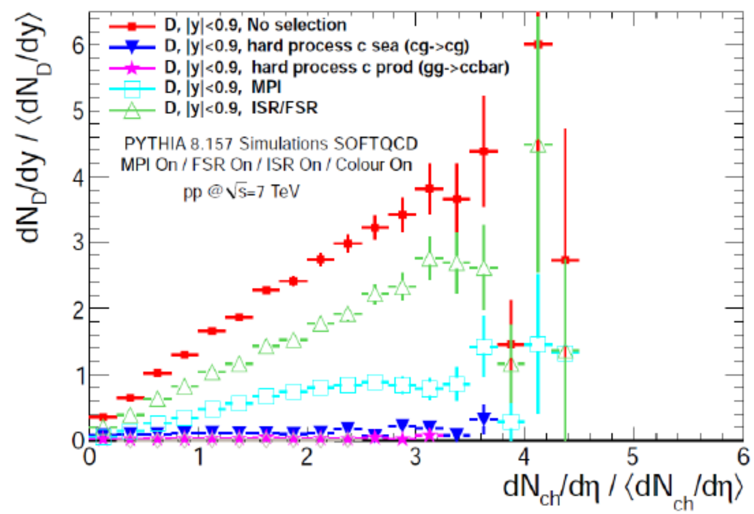
- Clear difference between pp and p-Pb in the forward region (2 < y < 4) → CNM ?

Heavy-flavour vs multiplicity (pp / p-Pb)

- ALICE: D meson yields self normalized to their integrated values as a function of particle multiplicity at mid rapidity normalized to the average number





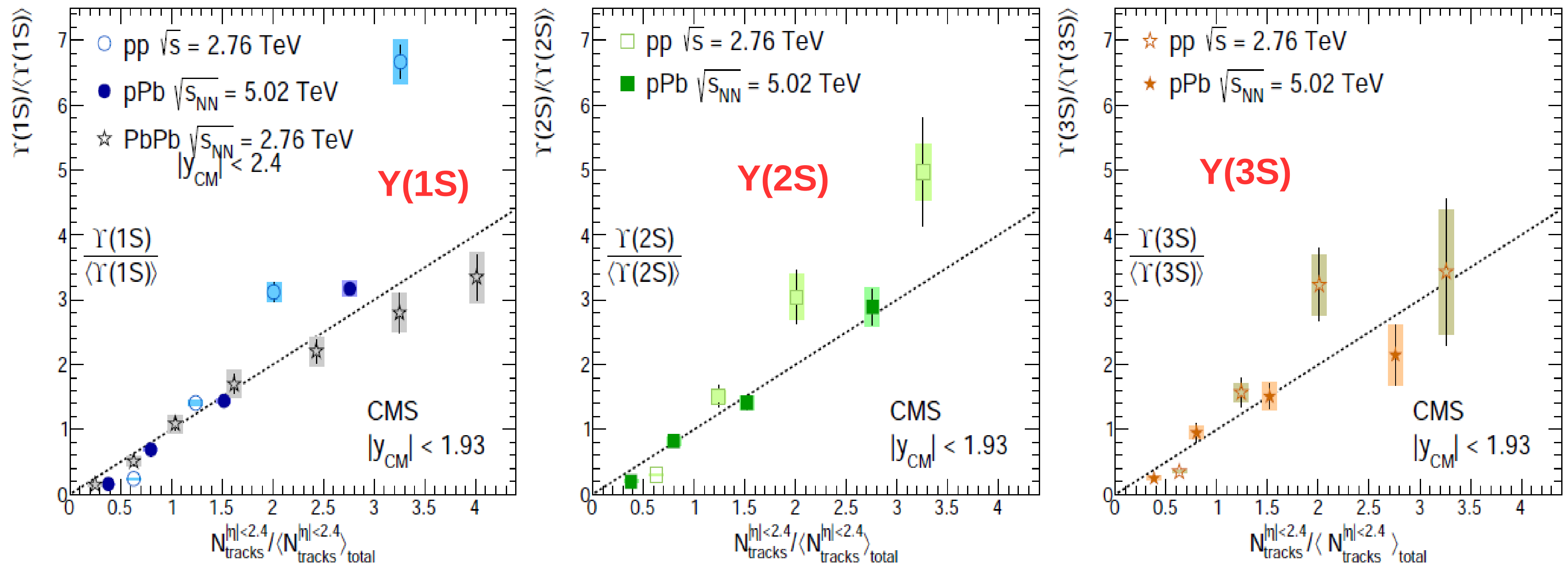


- Increasing D meson yields vs multiplicity observed both in pp and p-Pb → similar pattern in pp and p-Pb suggests that also in pp high-multiplicity events come from MPIs
  - → In pp PYTHIA8 (with HF production in MPIs) reproduced the observed trend vs multiplicity
- Different magnitude between D mesons and J/ψ observed in p-Pb → different CNM ? (different y and pT ranges)

Heavy-flavour vs multiplicity (pp / p-Pb / Pb-Pb)

- CMS: Y(nS) yields self-normalized to their integrated values as a function of particle multiplicity at mid rapidity normalized to the average number

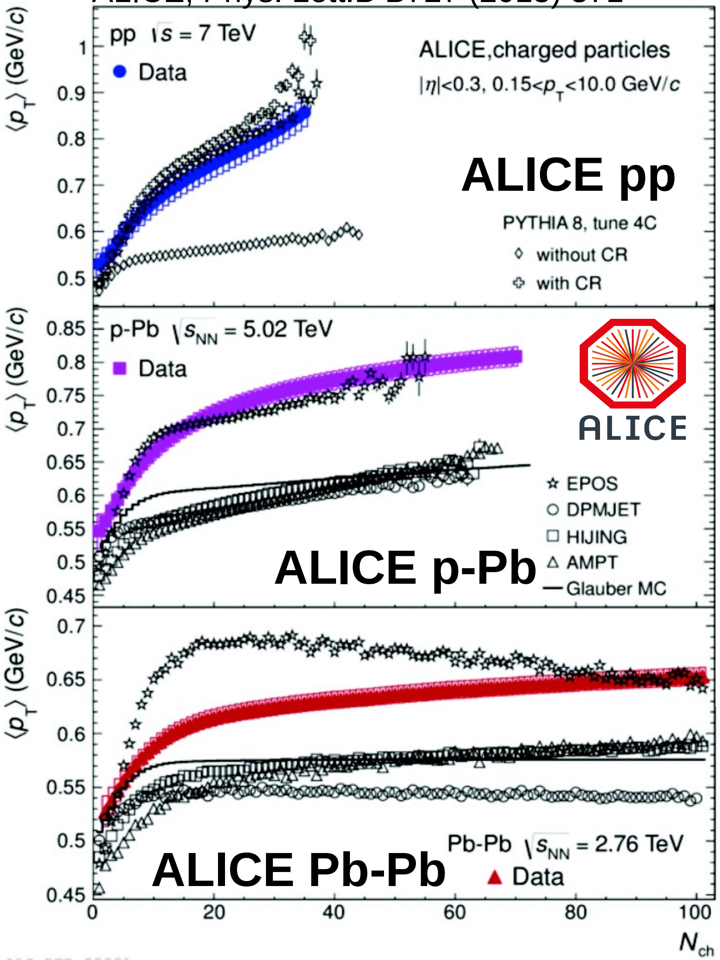
JHEP 04 (2014) 103



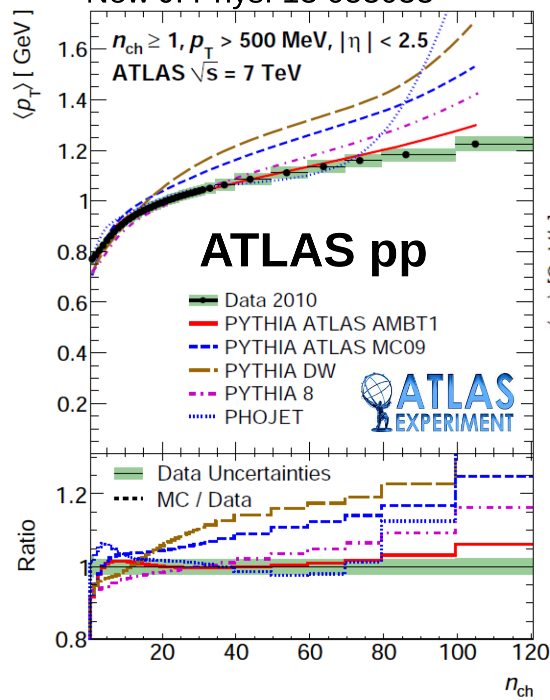
- Y(nS) yields increase with multiplicity: different patterns observed in the three collision systems (CNM and final state effects may change the trends)

<pT> vs Nch: data vs MC models

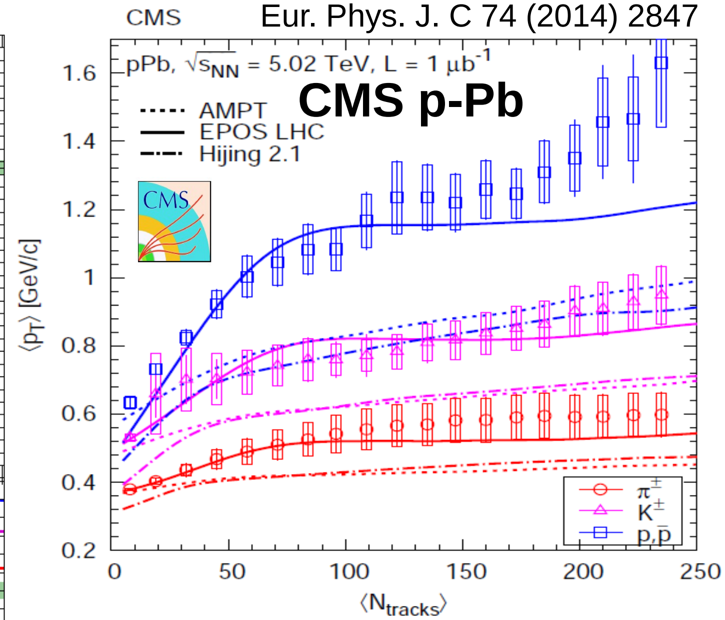
ALICE, Phys. Lett.B B727 (2013) 371



New J. Phys. 13 053033



Eur. Phys. J. C 74 (2014) 2847



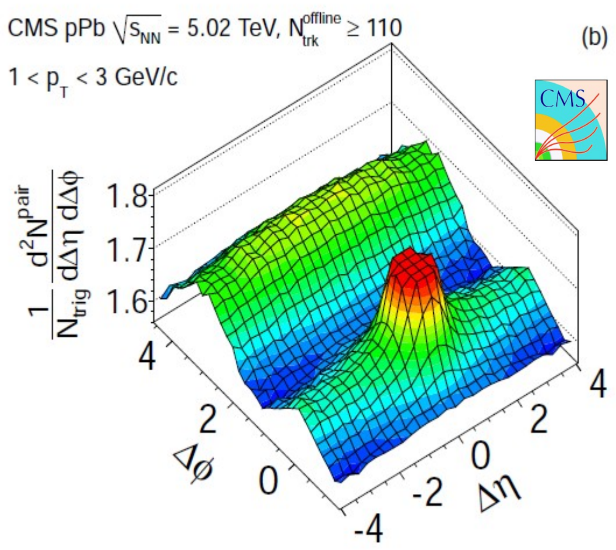
- pp: rise of <p_T> cannot be reproduced by a superposition of independent parton-parton scatterings → Color Reconnection (CR) looks indispensable for the description of the data

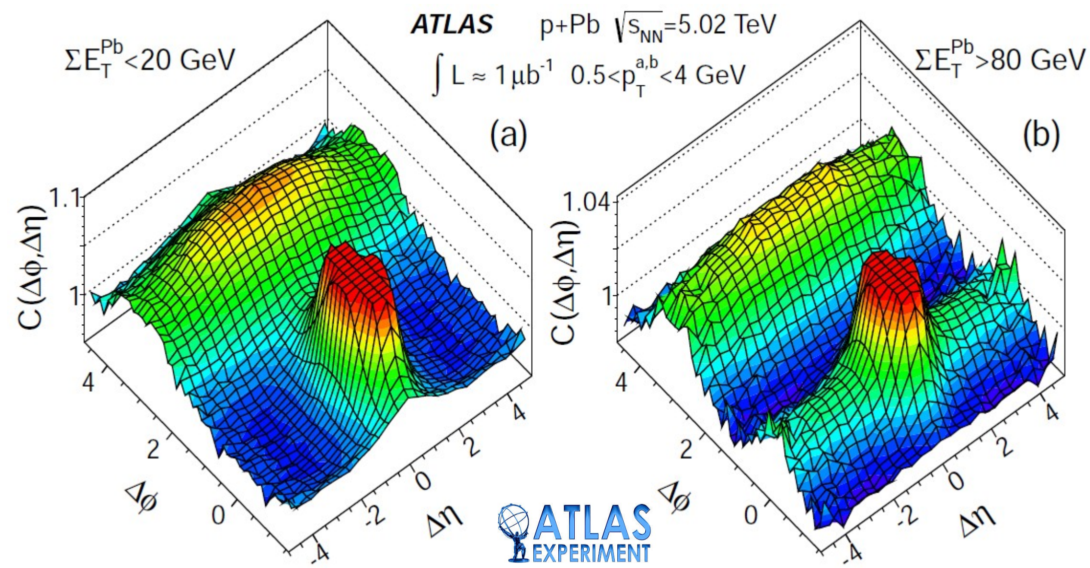
- p-Pb: the EPOS model, which includes a mechanism of collective string hadronization, shows a good agreement (but fails to describe Pb-Pb data) → calculation from a Glauber approach underestimate the measured <p_T>

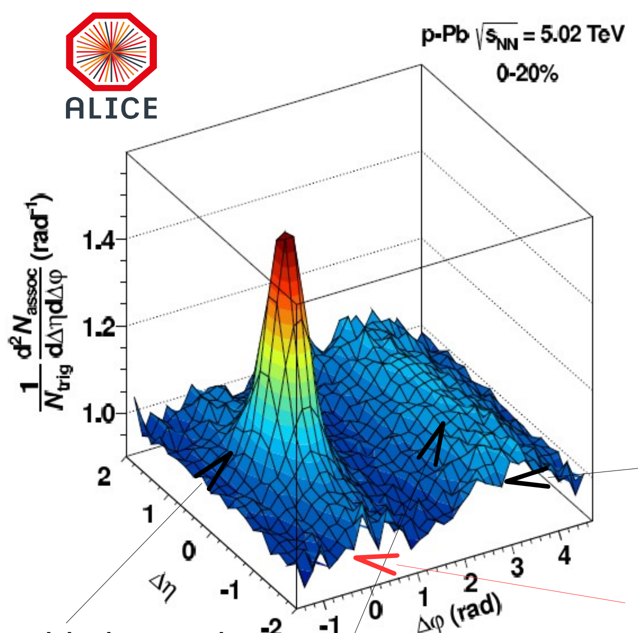
  - Would CR mechanism also reproduce the data ?
  - Do CNM effects play a role ?

→ To be further investigated

Long range correlations in p-Pb







Near side jet peak

Away side rencoil-jet peak

+away side ridge

+near side RIDGE!

- Overview of 2-particle angular correlations → distribution of (Δφ,Δη) between triggered-associated particles in p-Pb
- Same near (Δφ=0) side "ridge" structure, elongated in Δη, in high multiplicity p-Pb events similarly as observed in HM pp collisions by CMS (JHEP 09 (2010) 091)

Mechanisms proposed to explain the same-side "ridge":

- Multiparton interactions

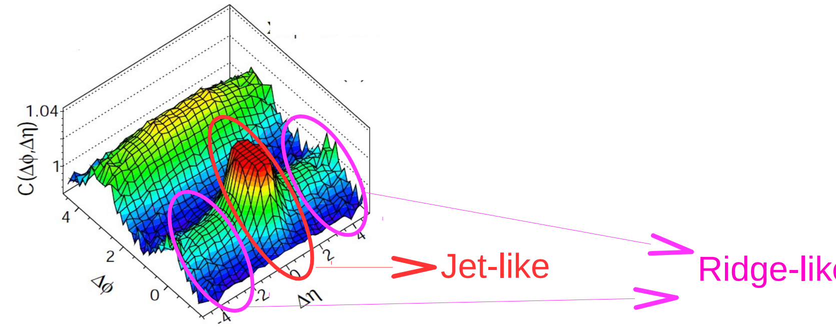
S. Alderweireldt and P. Van Mechelen, arXiv:1203.2048 [hep-ph]

- Collective effects

K. Werner, I. Karpenko, and T. Pierog, P.R.L. 106 (2011) 122004

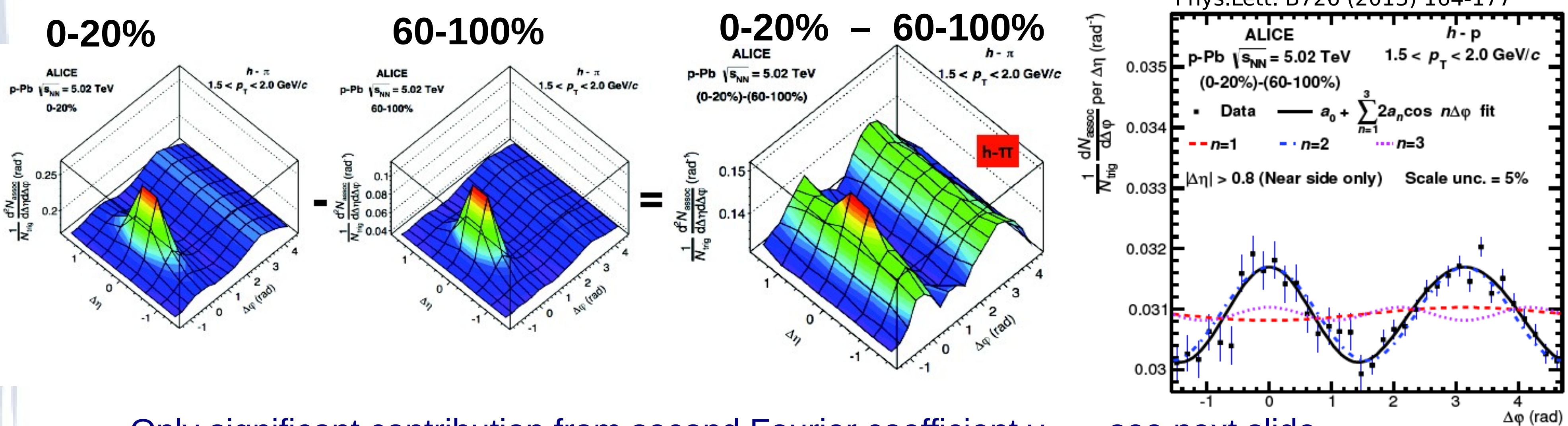
v_2 from h-(π, K, p) long range correlations in p-Pb

- Two particle correlation function:
  - Trigger particle → unidentified hadron
  - Associated particle → identified hadron (π, K, p)
  - Same p_T interval for trigger / associated particles



- Ridge like component isolated by subtracting low multiplicity correlations (60-100%) from high multiplicity correlations(0-20%):
  - Mostly jet contribution (i.e. no significant ridge) in low multiplicity p-Pb events

Phys.Lett. B726 (2013) 164-177



- Only significant contribution from second Fourier coefficient v_2 → see next slide
  - First coefficient smaller w.r.t. the case without subtraction (up to ~10 times smaller)
  - Third coefficient still small

v_2 from h-(π, K, p) long range correlations in p-Pb

- Two particle correlation function:
  - Trigger particle → unidentified hadron
  - Associated particle → identified hadron (π, K, p)
  - Same p_T interval for trigger / associated particles

Associated yield per trigger particle

$$\frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\eta d\Delta\varphi} = \frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)}$$

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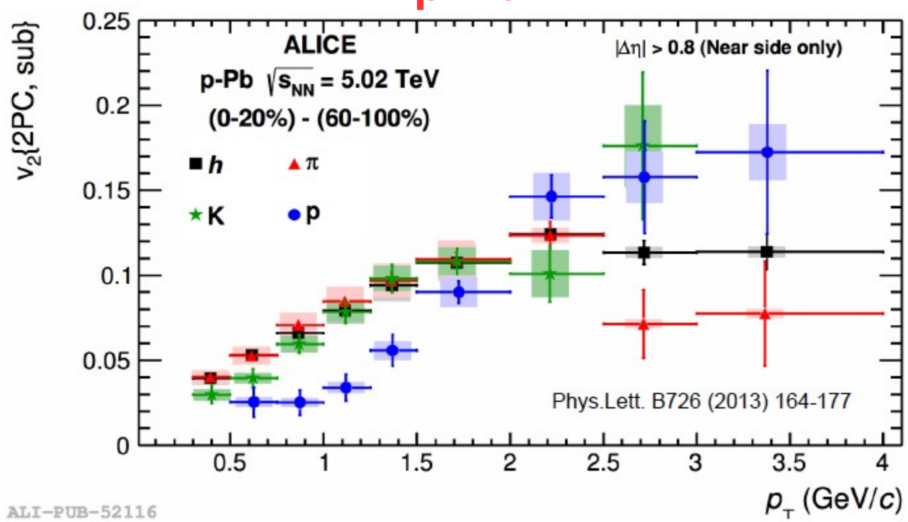
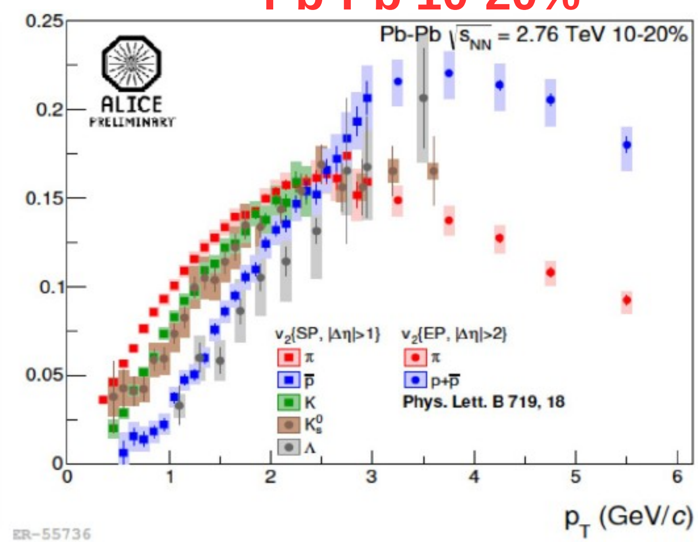
p-Pb



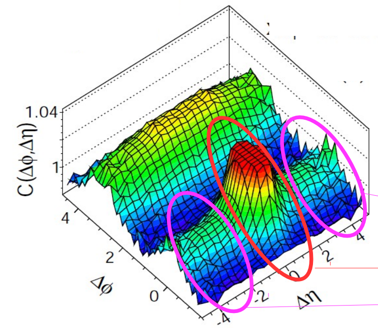
Pb-Pb 10-20%



- Similar behaviour as in Pb-Pb collisions → mass ordering at low pT qualitatively consistent with hydro models
  - MPI + Color Reconnection also at the origin of flow-like pattern in p-Pb ? → still open question

Di-hadron azimuthal correlation in p-Pb

- Two particle correlation function:
  - Trigger particle → unidentified hadron
  - Associated particle → unidentified hadron
  - $0.7 < p_T,ass < p_T,trigg < 5$ GeV/c



- Double "ridge" like structures observed → in order to study the jet-like component, the ridge structures have been subtracted

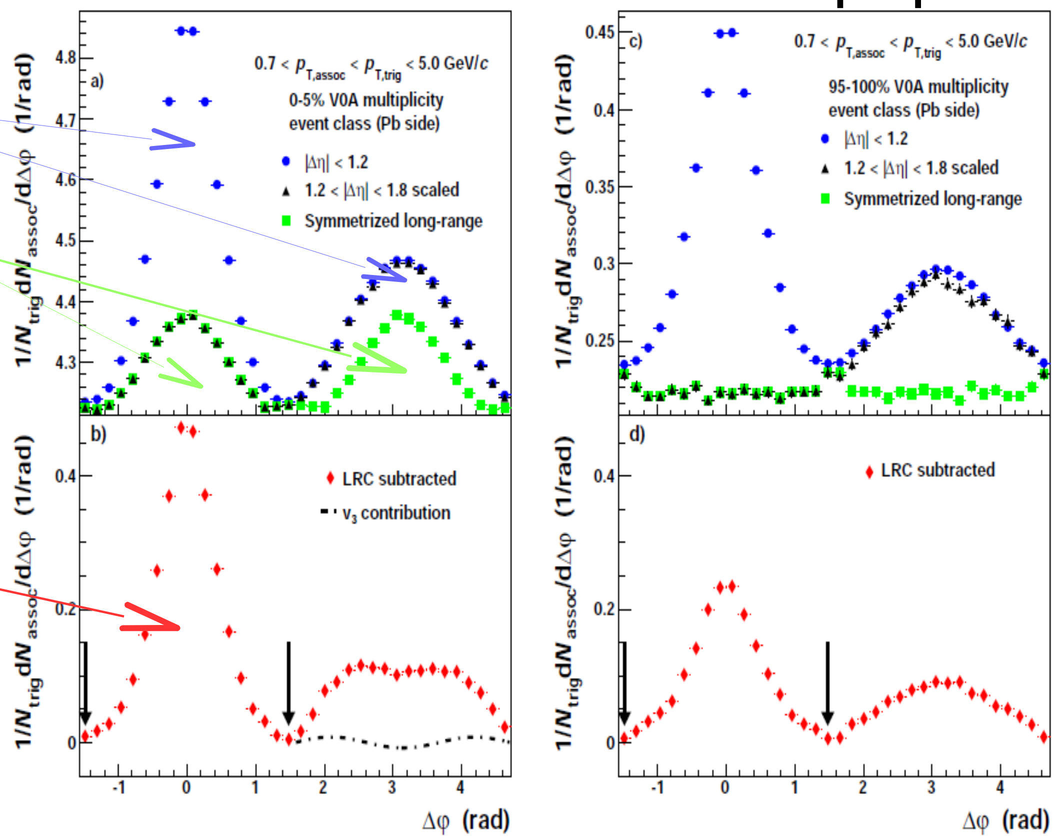
Phys. Lett. B 741 (2015) 38-50

5% more central **5% more peripheral**

Short range (|Δη|<1.2) near (away) side at Δφ=0 (Δφ=π)

Long range (1.2<|Δη|<1.8) near side (Δφ=0) and away side (Δφ=π) simmetrized

Subtraction: short range – long range (symmetrized) correlations



Number of associated particles in the near ($<N_{ass,nearside}>$) and away ($<N_{ass,awayside}>$) side calculated by integrating the subtracted Δφ projection

Di-hadron azimuthal correlation in p-Pb

- Near and away side per-trigger yields vs V0A mulitplicity → more sensitive to the fragmentation properties
  - The presence of more MPIs should dilute the back-to-back correlation pattern resulting in an increasing of combinatorial background in the correlation function

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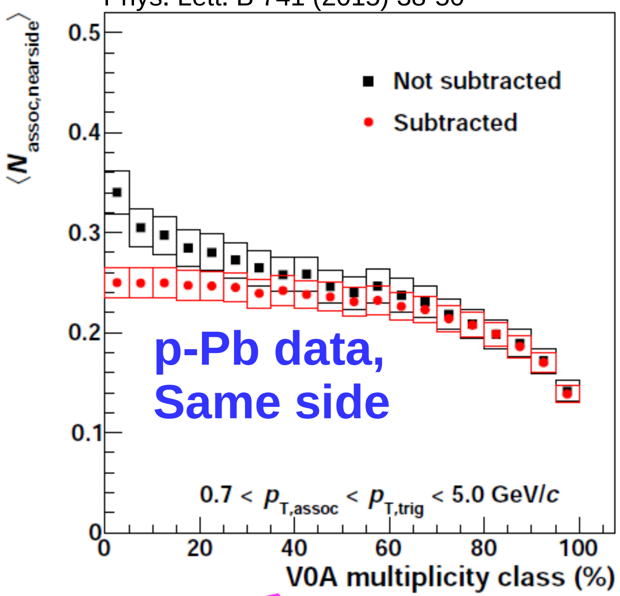
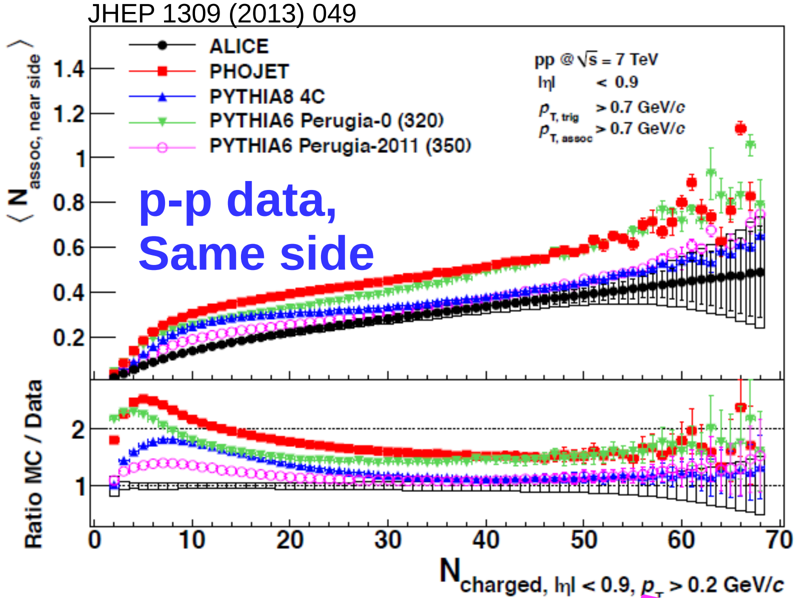


JHEP 1309 (2013) 049



Increasing multiplicity

Increasing multiplicity

- Similar results in the away side

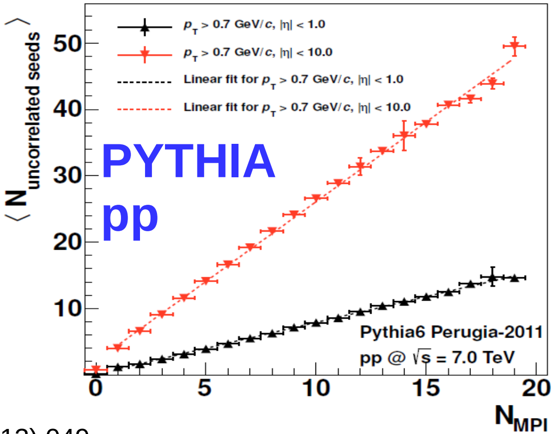
- After long-range correlation subtraction:
  - At high multiplicity the associated yield per trigger particle is independent on multiplicity
    → high multiplicity events are not built by a large number of particles in the jet peak
    → consistent with the picture that they originate from “inchoerent” fragmentation of multiple-parton scatterings
    - The absence of coherence effects for large number of MPI might strong constraint for models implementing such effects
  - In pp the yield increases with multiplicity

Di-hadron azimuthal correlation in p-Pb

- Number of "**uncorrelated seeds**":

$$\langle N_{\mathrm{uncorrelated\ seeds}}\rangle = \frac{\langle N_{\mathrm{trig}}\rangle}{\langle N_{\mathrm{correlated\ triggers}}\rangle} = \frac{\langle N_{\mathrm{trig}}\rangle}{1+\langle N_{\mathrm{assoc,nearside}}\rangle+\langle N_{\mathrm{assoc,awayside}}\rangle}$$

  – provides the number of independent source of particle production → in PYTHIA6 the uncorrelated seeds are found to be proportional to the number of the MPIs



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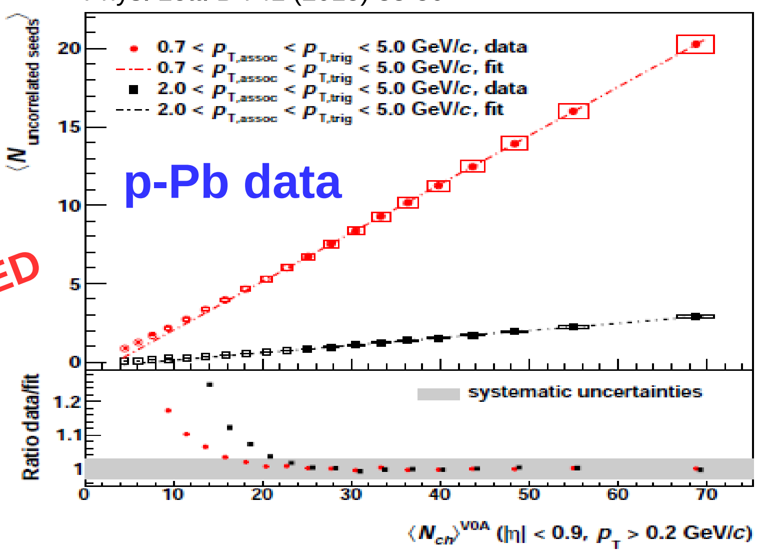
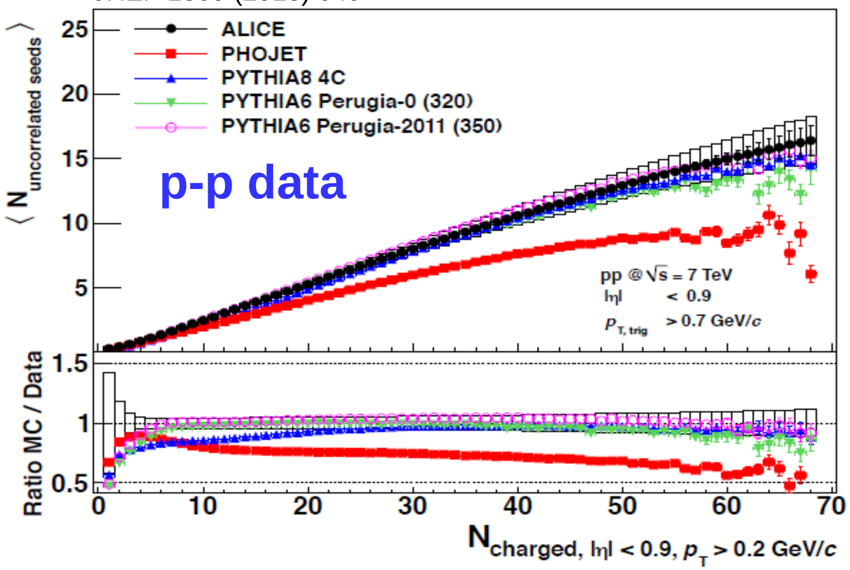


FIRST INTRODUCED BY ALICE!

JHEP 1309 (2013) 049



  – increases almost linearly with multiplicity (deviation observed at low multiplicity) → there is no evident saturation of nMPIs at high multiplicities in p-Pb

  – In pp there is an indication of a limit in the increasing of the MPIs → consistent with the previous observation of increasing yields in pp (w.r.t. p-Pb) at higher multiplicity

Di-hadron azimuthal correlation in p-Pb

- Number of "**uncorrelated seeds**":

$$\langle N_{\text{uncorrelated seeds}} \rangle = \frac{\langle N_{\text{trig}} \rangle}{\langle N_{\text{correlated triggers}} \rangle} = \frac{\langle N_{\text{trig}} \rangle}{1 + \langle N_{\text{assoc,nearside}} \rangle + \langle N_{\text{assoc,awayside}} \rangle}$$

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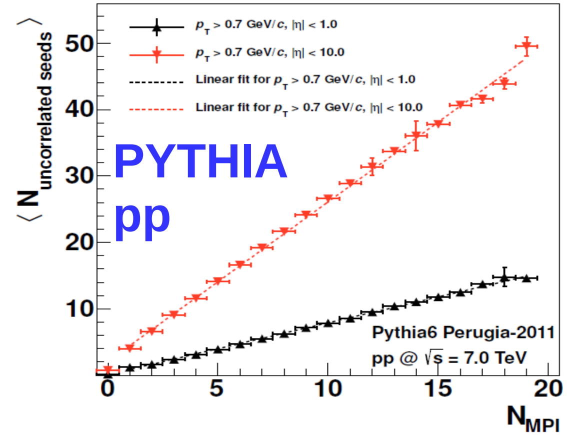

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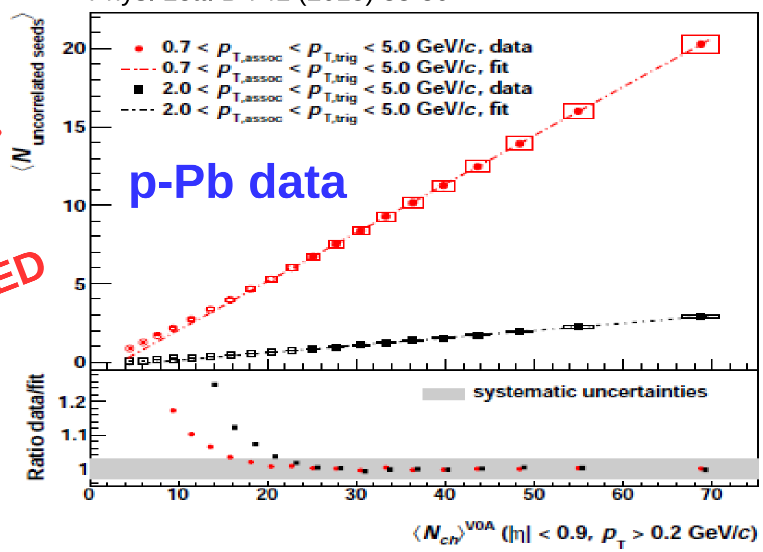
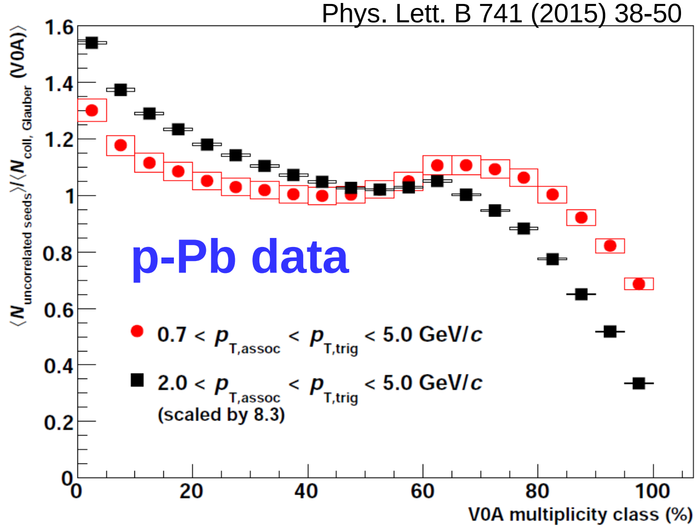


FIRST INTRODUCED BY ALICE!

Phys. Lett. B 741 (2015) 38-50



  – increases almost linearly with multiplicity (deviation observed at low multiplicity) → there is no evident saturation of nMPIs at high multiplicities in p-Pb

  – Number of uncorrelated seeds scales at intermediate multiplicity with $N_{\text{coll,Glauber}}$: important deviations for low and high Ncoll → less / more semi-hard scatterings per p-N collision ?

    - Resembles centrality bias observed in p-Pb (see slide 25)

Summary

- Rich phenomenology of MPI in pp used to constrain models (not shown in this talk)

  → Interest in MPIs in p-A

- Increasing of quarkonium and open-charm yields vs multiplicity observed both in pp and p-Pb by ALICE and CMS

- Signs of Collectivity in p-Pb:
  - $\langle p_T \rangle$
  - Double ridge structure in di-hadron (long range) correlations
  - Mass ordering in v_2 of π, K, p

  → Intriguing: Several trends as function of multiplicity seen in p-Pb (and pp) reproduced by PYTHIA8 with MPIs + Color Reconnection included

- Linearity of "uncorrelated seeds" (i.e. MPIs) with multiplicity studied with di-hadron correlations in p-Pb

Back-up

Run II perspectives - ALICE

- Actually a large part of Run II program for MPI studies is concentrated on proton-proton foreseen on a short time scale w.r.t. p-Pb
- Several measurements already performed in pp @ 7 TeV: multiplicity distributions, Average transverse momentum vs. Nch, Underlying event, Two-particle azimuthal correlations vs. Nch, Average transverse sphericity vs. Nch.
- Near side "Ridge" in HM pp collisions observed by CMS (at 10 times the average multiplicity, i .e. $10^{-5} x \sigma_{INEL}$) inspire new studies related to MPI for Run II at HM pp:

→ in general all pp studies at higher energies 13 TeV should be repeated: the goal is to reach very high multiplicity (up to now ~4-6 times average multiplicity for HF studies, up to ~8 times for <pT> vs multiplicity) and perform more "differential" measurements (e.g. transverse sphericity studies in pTbins, etc.)

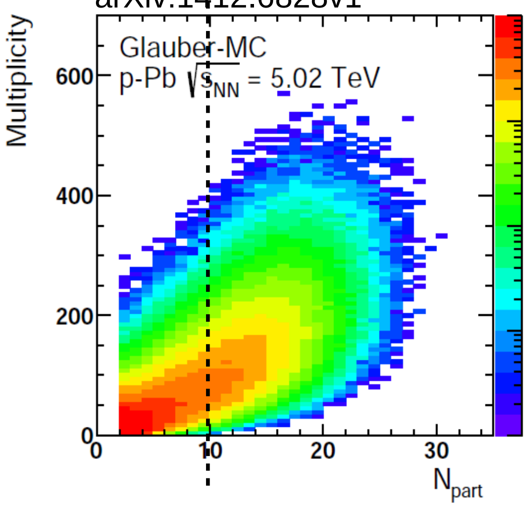
→ benefit from higher statistics of RunII as well as from Run I experience (true also for p-Pb)

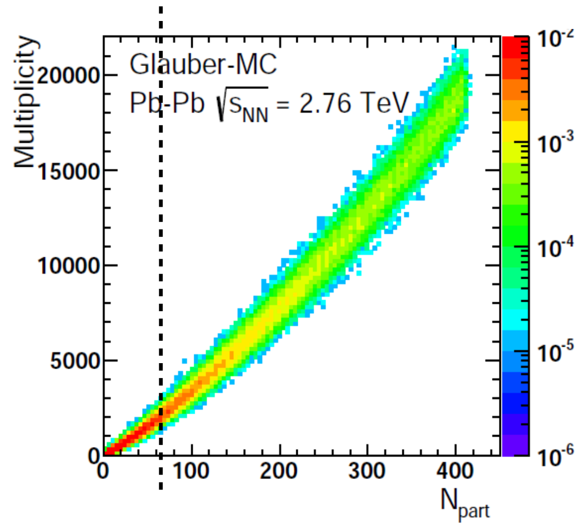
- Some examples of benchmark analyses in (HM) pp:
  - Multi-strange at HM pp
  - "Minijet" and long range correlations
  - Heavy-flavour vs multiplicity
  - Sphericity analysis (in RunI it has shown that at high multiplicities there are less jets than predicted by the models) → It may help to disentangle the jetty / not-jetty components at HM pp,
- Ideas for future MPI analysis in pp and p-Pb (still under discussion)
  - DPS with multiple HF production (pp, pPb) → starting at Grenoble-CCNU
  - Underlying Event measurement in pPb (this could be already performed with RUN I data)
  - DPS with W production + jets (or high pT tracks) in pPb

Biases on centrality determination in p-Pb

- Multiplicity bias: compared to Pb-Pb collisions, in p-Pb collisions the correlation between the centrality estimator and N_{coll} is very loose
  - Same N_{part} (N_{coll}) can contribute to several adjacent centrality classes

arXiv:1412.6828v1





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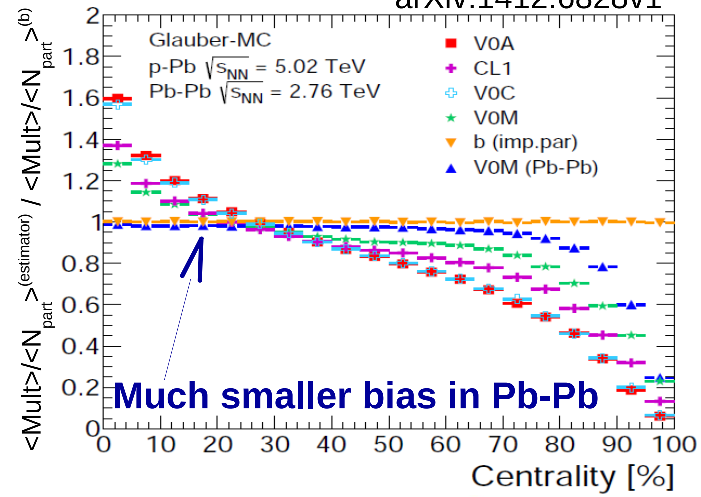
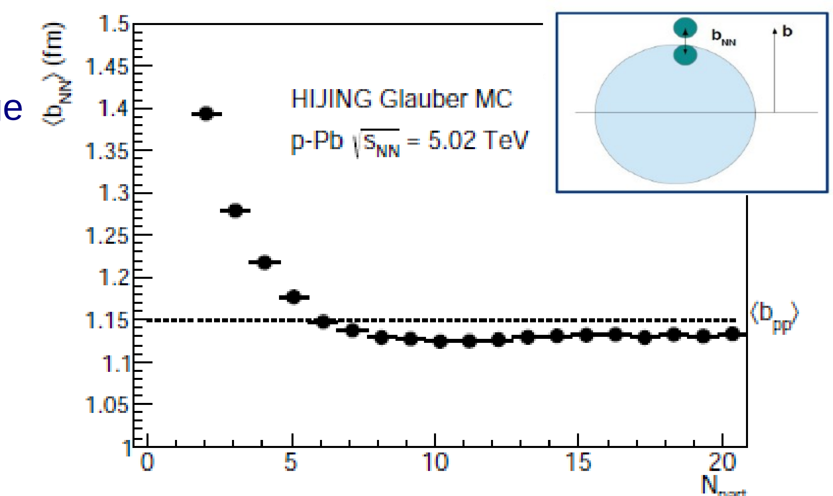


- Geometric bias: for a given p-A impact parameter (b), the mean number of hard scattering $\langle n_{hard} \rangle$ depends on the average p-n impact parameter (b_{NN})
(first studies in Jiangyong Jia, Phys.Lett. B681 (2009) 320–325, arXiv:0907.4175 [nucl-th].)
  - This is mainly important for peripheral collisions

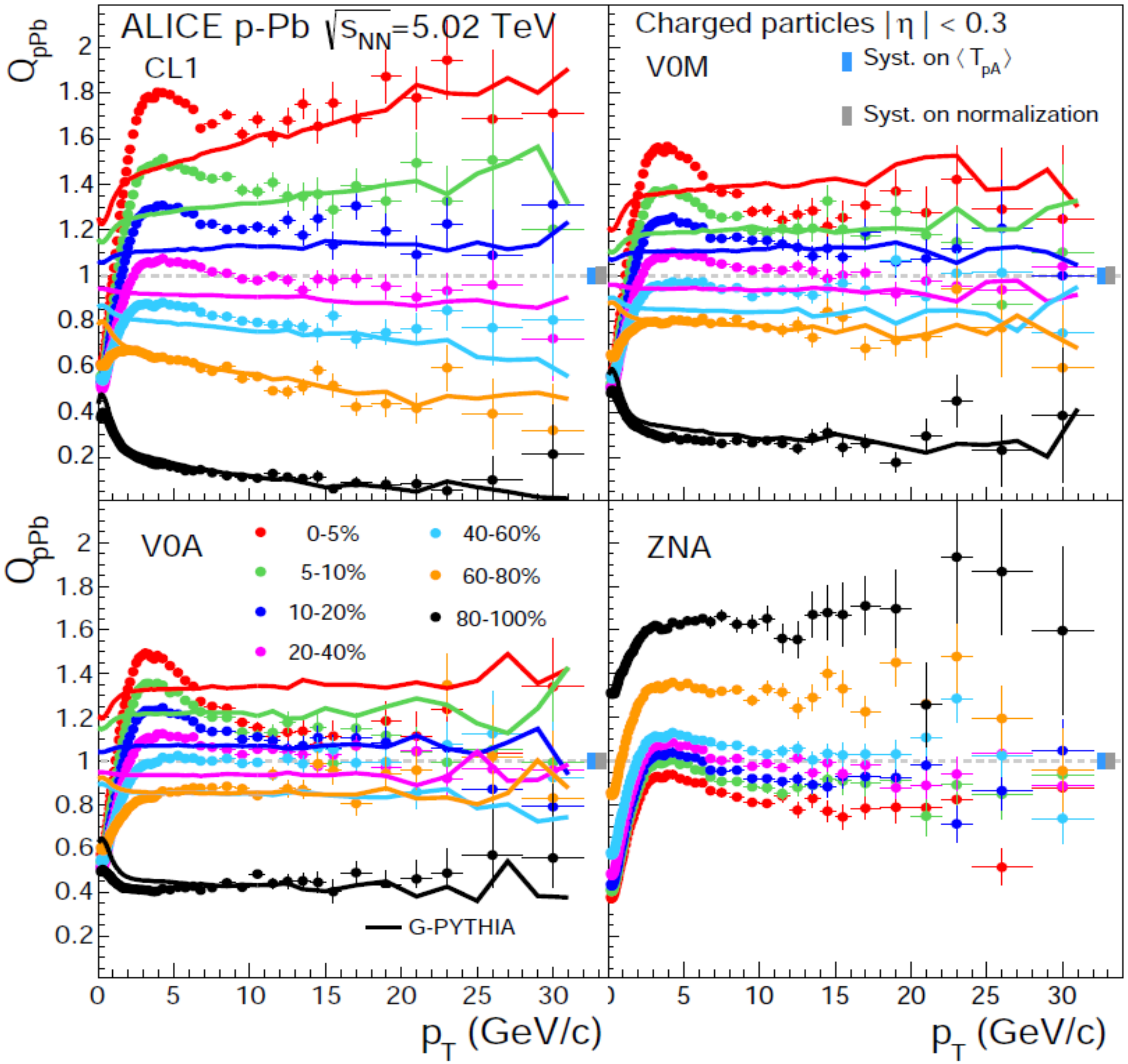
$$\langle n_{\mathrm{hard}} \rangle (b_{\mathrm{NN}}) = \sigma_{\mathrm{hard}} T_{\mathrm{N}} (b_{\mathrm{NN}})$$



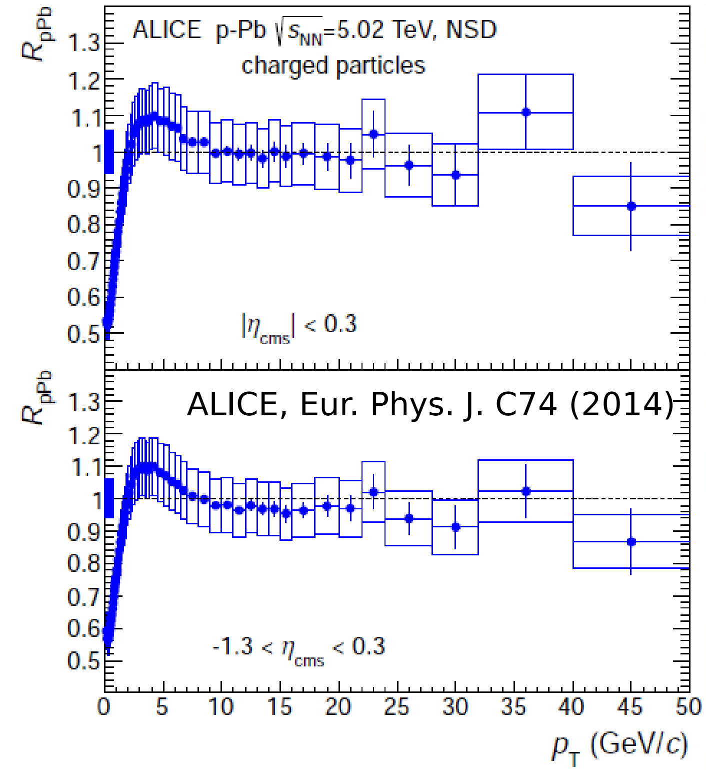
- Jet-veto bias: correlation between centrality estimator and high-pT particles → very peripheral collisions can represent an effective “veto” for high pT particles

Biased Nuclear Modification Factor in p-Pb

arXiv:1412.6828v1



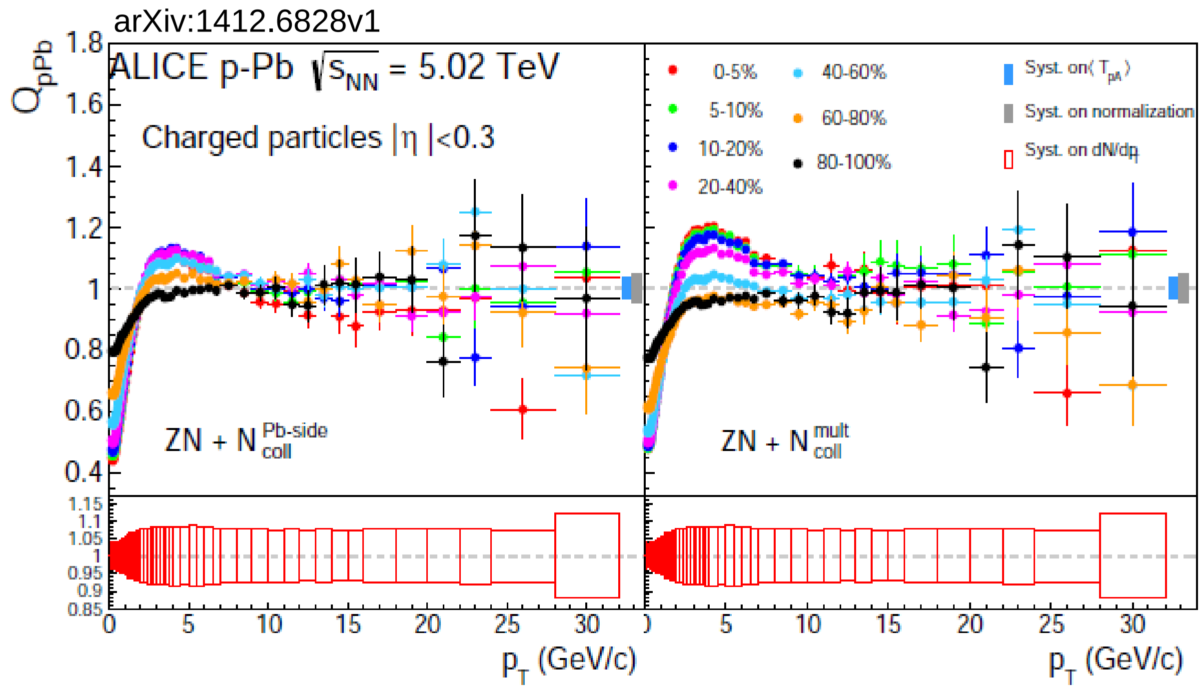
Minimum Bias (data)

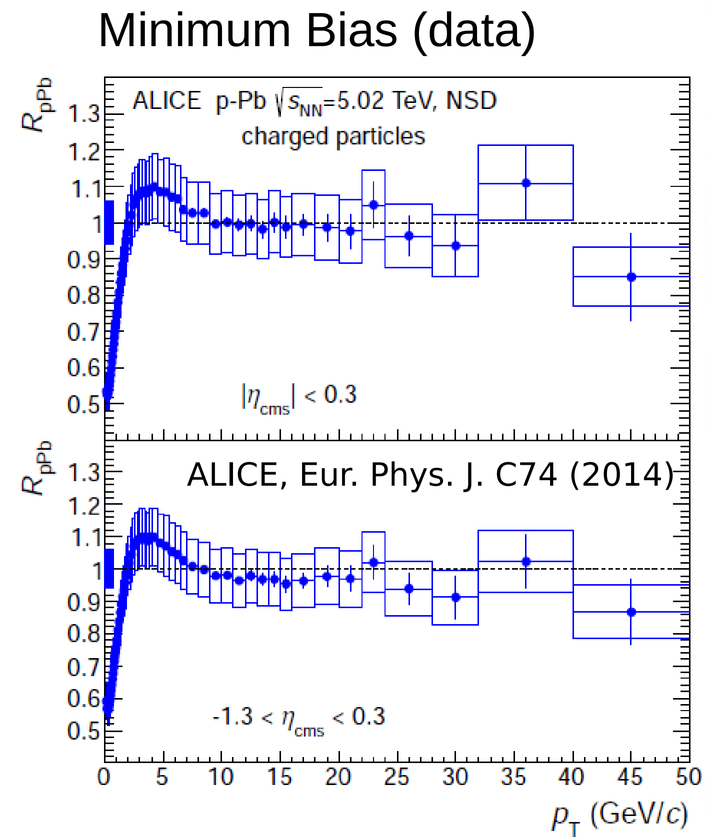


$$Q_{pA}(p_T; cent) = \frac{dN^{pA}/dp_T}{N_{coll}^{Glauber} \cdot dN^{pp}/dp_T}$$

- Bias at high p_T described by incoherent superposition of pp collisions (G-PYTHIA)
- For most peripheral p-Pb, good agreement also at low and intermediate p_T
- Strong deviations for all other centrality bins → spread between centrality classes reduces with increasing rapidity gap between the regions used for measurements or centrality estimation

Biased Nuclear Modification Factor in p-Pb





- Hybrid method:
  - centrality classes determined using energy deposit in ZNA (Pb-going side) calorimeter
  - Number of binary collisions $\langle N_{coll} \rangle$ determined by studying correlation of various pairs of observables, in ZNA centrality classes, that are expected to scale linearly with Ncoll or Npart
  - R_{pPb} consistent with unity at high pT
  - Cronin enhancement clearly visible (stronger in more central collisions)

$$Q_{pA}(p_T; cent) = \frac{dN^{pA}/dp_T}{N_{coll}^{Glauber} \cdot dN^{pp}/dp_T}$$

Heavy-flavour vs multiplicity (pp / p-Pb / Pb-Pb)

- CMS: Y(nS) yields self-normalized to their integrated values as a function of particle multiplicity at mid rapidity normalized to the average number

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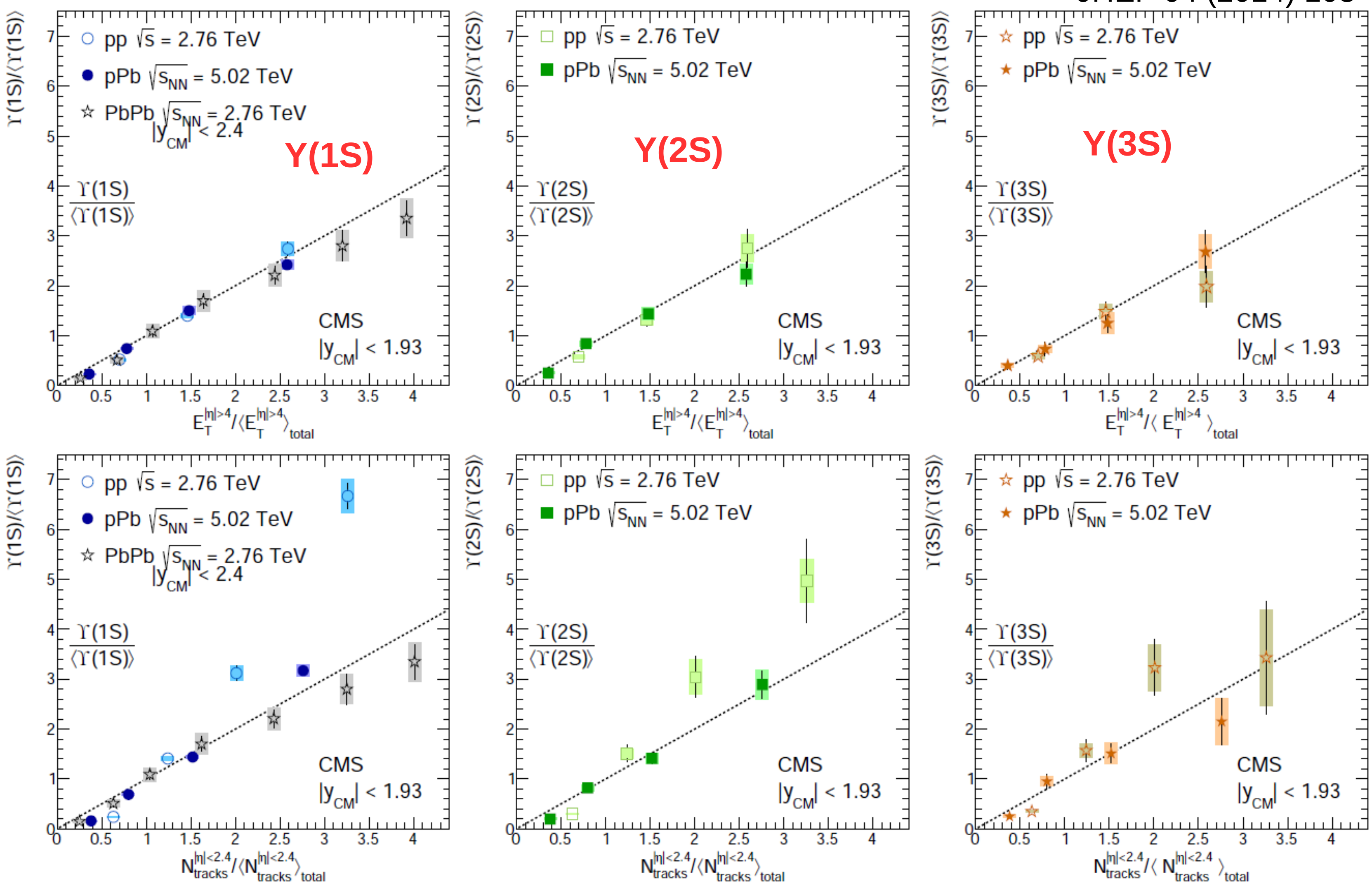


Jet studies in HM pp collisions

- Several studies performed by ALICE and CMS in pp@7TeV show that high mltiplicity pp collisions are less “jet-like” than what is predicted by some Monte Carlo, e.g. Pythia:

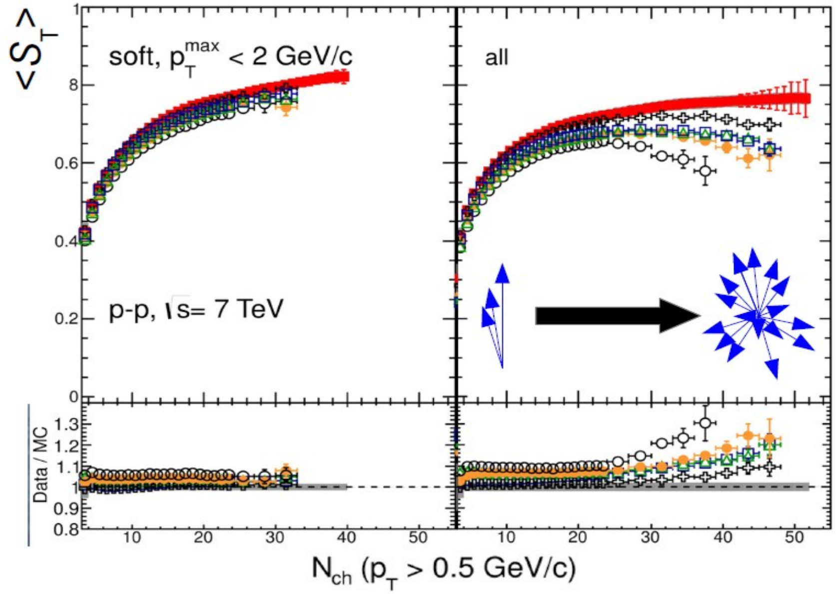
ALICE: Transverse Sphericity [Eur. Phys. J. C (2012) 72:2124]

$$\mathbf{S}^{\mathbf{L}}_{\mathbf{xy}} = \frac{1}{\sum_i p_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$$

Eigenvectors λ_1, λ_2

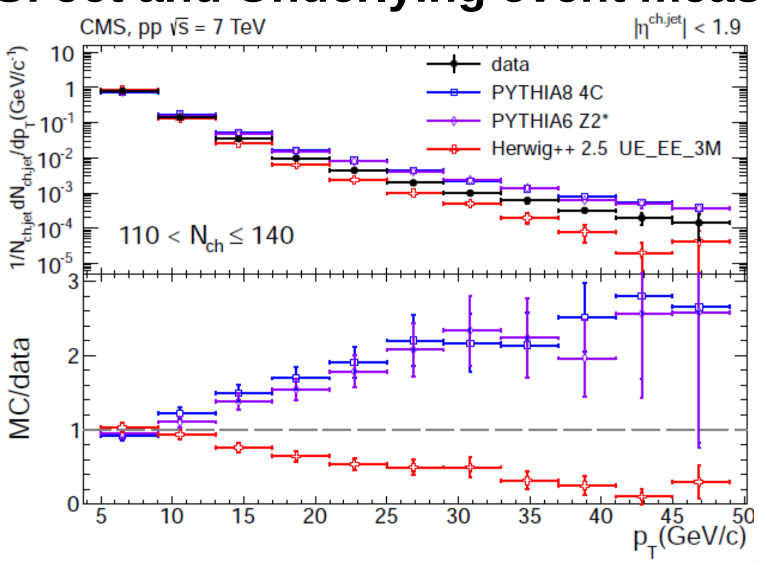
$$S_T \equiv \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$

1 isotropic
0 jet like



- Increase of multiplicity due to MPI increases sphericity
- Turning point in MC towards more “jettiness” at high multiplicity not seen in data

CMS: Jet and Underlying event measurements [http://arxiv.org/pdf/1310.4554v2.pdf]



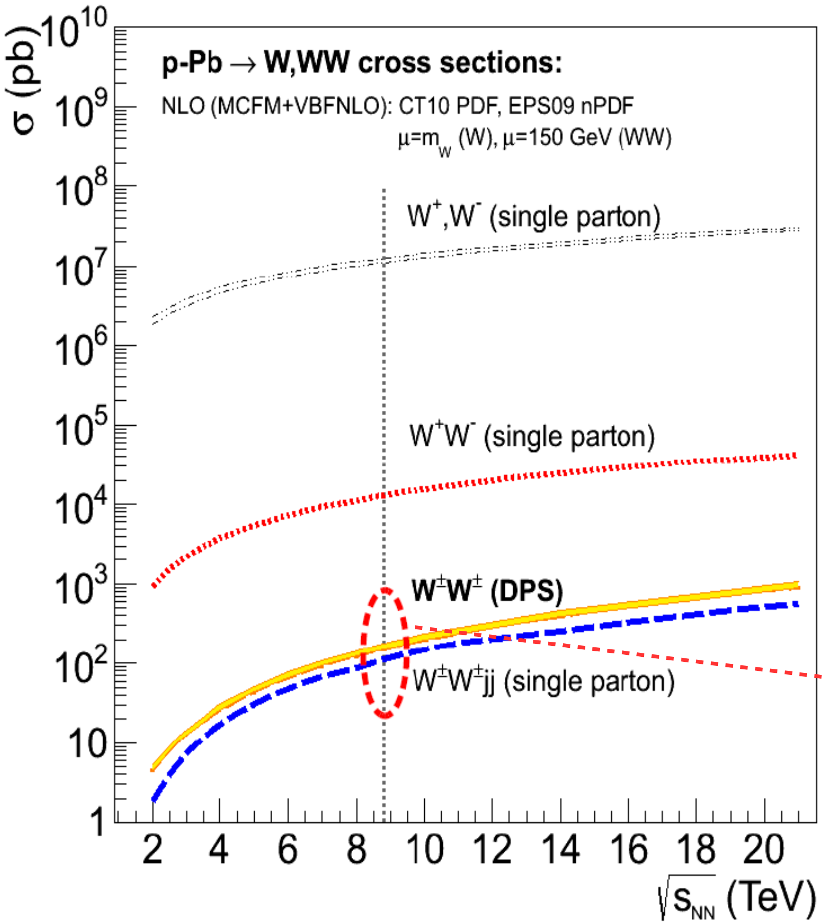
- At high multiplicity jets are softer, and less abundant than predicted by PYTHIA
  - Stronger jet bias in Pythia ?
  - Or softening of jet spectrum due to further mechanisms in HM pp ?

  → Comparison of HM pp results with similar results from p-Pb collisions would be helpful to understand this behaviour

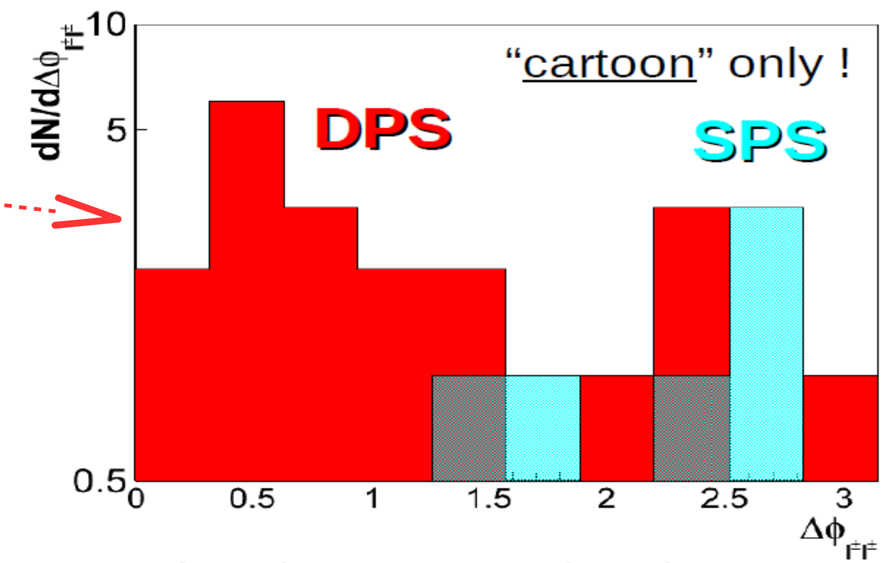
A look to the future: DPS in same sign W pair in p-Pb collisions

[DdE,Snigirev, arXiv:1211.0197]

Cross section for all relevant processes in SPS and DPS vs √s



- Measurable final states:
  - W's branching ratios: BR(W →lν) ~ 3 x 1/9
  - Typical ATLAS/CMS acceptances & efficiencies → leptons: |y|<2.5, pT >15 GeV ε_{WW} ~ 40%
- LHC p-Pb luminosities: 0.2-2 pb^{-1}
- Expected rates: $\sigma^{DPS}_{p\text{-}Pb\to WW}/(\varepsilon\cdot L_{int})$ ~ **1-10 same-sign W pairs/year**



N(DPS)≈10 evts N(SPS)≈ 6 evts

- Enhanced DPS p-Pb cross sections: $\sigma_{eff,pp}/\sigma_{eff,pA}$~ 600

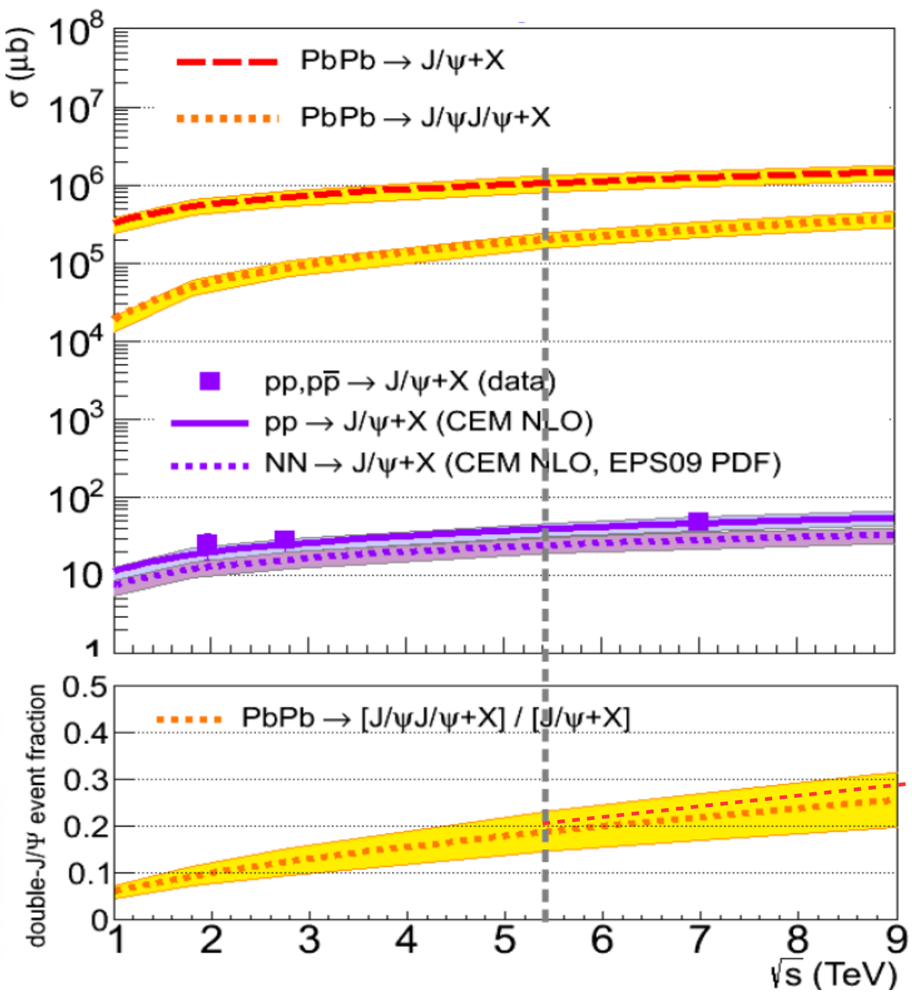
  p-Pb @ 8 TeV: σ(WW,DPS)~150pb / σ(WWjj)~100pb

  ±18% uncert.:±15% for $\sigma_{eff,pp}$,±10% for scales&PDFs

A look to the future: DPS in double J/Ψ production in Pb-Pb collisions

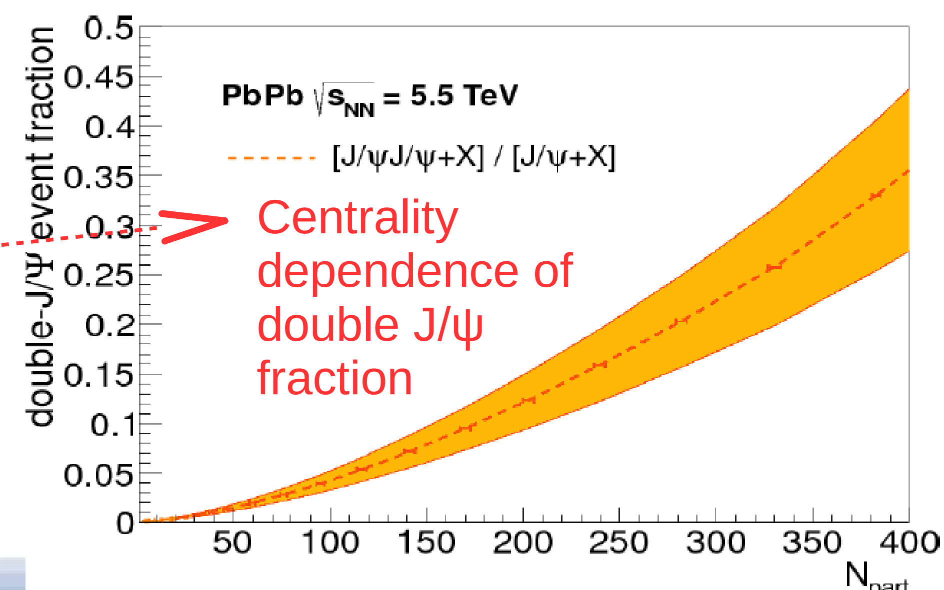
[DdE,Snigirev, arXiv:1301.5845]

Cross section for single and double J/ψ production in Pb-Pb vs √s



Many double hard scattering processes visible in p-Pb and Pb-Pb!

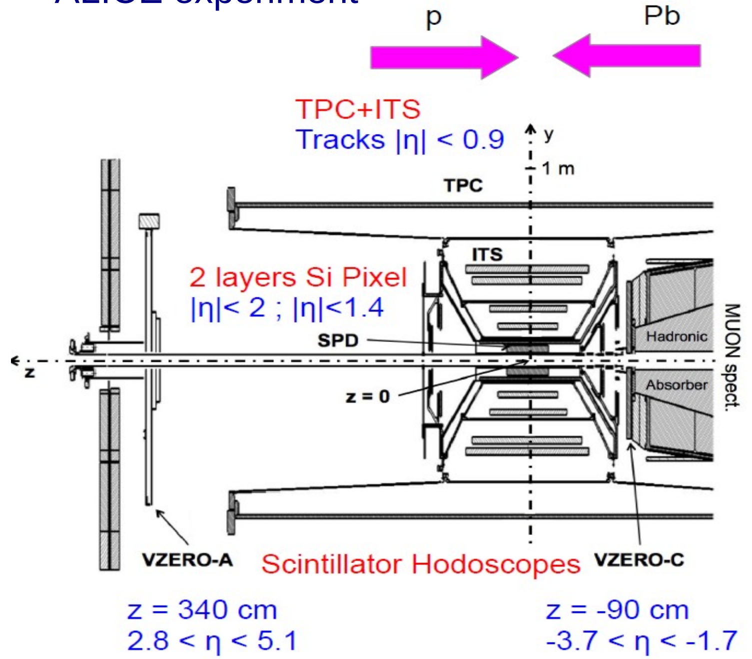
		$J/\psi\ J/\psi$	J/ψ+W	J/ψ+Z	ss WW
Pb-Pb 5.5 TeV	σ^{DPS}	200 mb	500 μb	330 μb	630 nb
	$N^{DPS}(1\ nb^{-1})$	~240	~80	~10	~20
p-Pb 8.8 TeV	σ^{DPS}	45 μb	120 nb	70 nb	140 pb
	$N^{DPS}(1\ pb^{-1})$	~60	~15	~2	~5



- Enhanced DPS p-Pb cross sections: $\sigma_{eff,pp}/\sigma_{eff,AA} \sim 9{\cdot}10^6$

Biased Nuclear Modification Factor in p-Pb

- Dependence introduced also by the centrality estimator → example: several estimator used by the ALICE experiment



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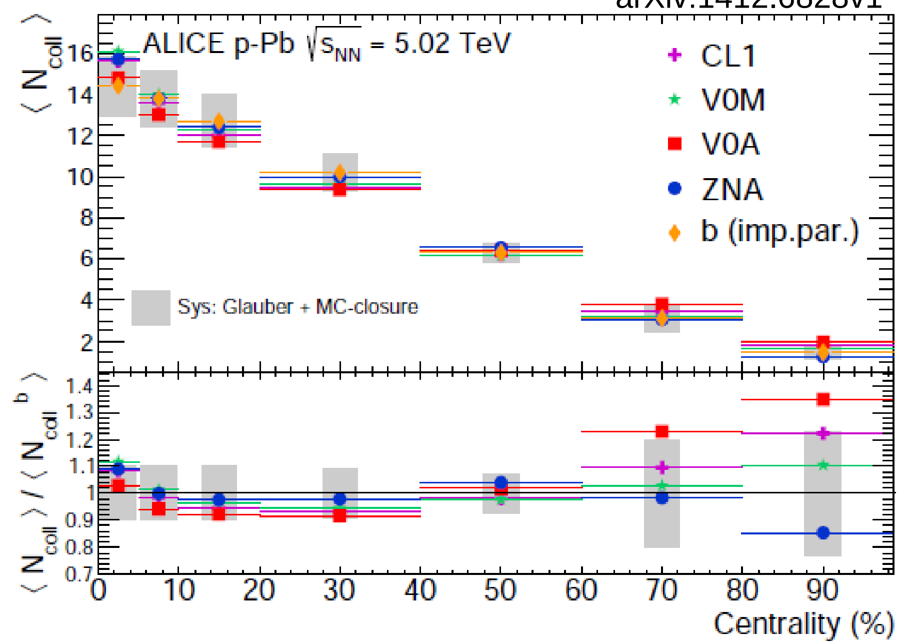
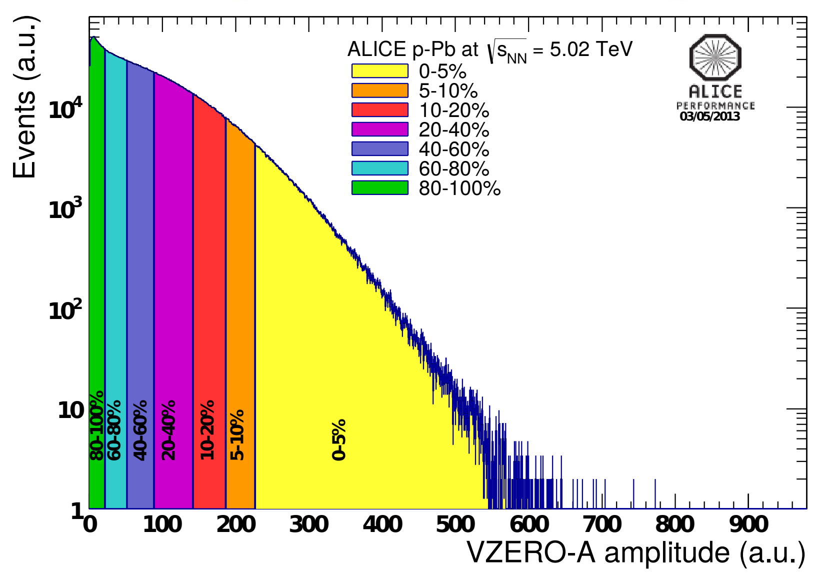




- Detectors used for multiplicity estimation in ALICE:
  - Silicon Pixel Detector (two innermost layers of inner tracking systems)
  - VZERO scintillators hodoscopes
  - ZDC: Zero Degree Calorimeters (located at z = ±112.5m,|η|>8.7)

- Examples of multiplicity estimators:
  - CL1 → number of reconstructed cluster in the second layer of SPD
  - V0A → VZERO-A multiplicity
  - V0M → VZERO-A + VZERO-C multiplicity
  - ZNA → energy deposition in ZNA

Scaling of hard processes in p-A

- In p-A collisions the number of hard processes (i.e. MPIs) is proportional to the number of binary collisions (i.e. N_{coll})

- Factorization approach (as used in pp) → mean number of MPIs in p-A (assuming p-A collision described by an independent superposition of pp collisions) is given by:

$$\langle n_{hard} \rangle_{pA} = \langle N_{coll} \rangle_{MB} \langle n_{hard} \rangle_{pp}$$

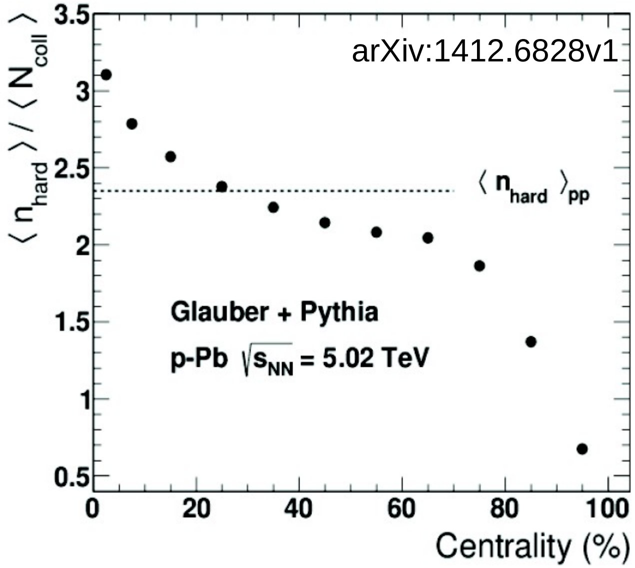
→ particle yields for hard processes would scale like

$$\frac{Y_{hard}}{\langle N_{coll} \rangle_{cent}} \propto \frac{\langle n_{hard} \rangle_{pN}^{cent}}{\langle n_{hard} \rangle_{pp}} \longrightarrow \frac{\langle n_{hard} \rangle_{pN}}{\langle n_{hard} \rangle_{pp}}$$

Is unity for centrality-integrated p-A, but can be ≠ 1 for event centrality classification based on multiplicity → bias introduced for the binary scaling of hard processes in centrality bins

- Influence of the centrality selection on MPIs in a coherent superposition of pN collisions studied by PYTHIA6 event generator coupled to a p-Pb Glauber MC calculation (G-PYTHIA): for each MC Glauber event, PYTHIA6 is used N_{coll} times to generate N_{coll} independent pp collisions

Number of hard scatterings per pN collision →

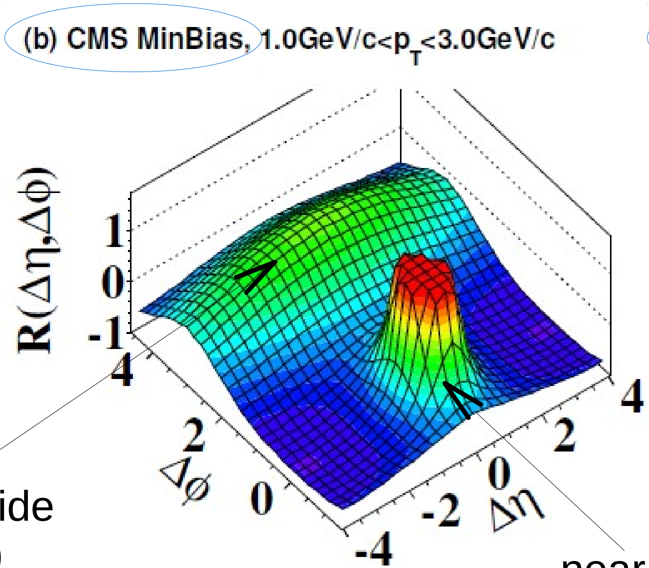


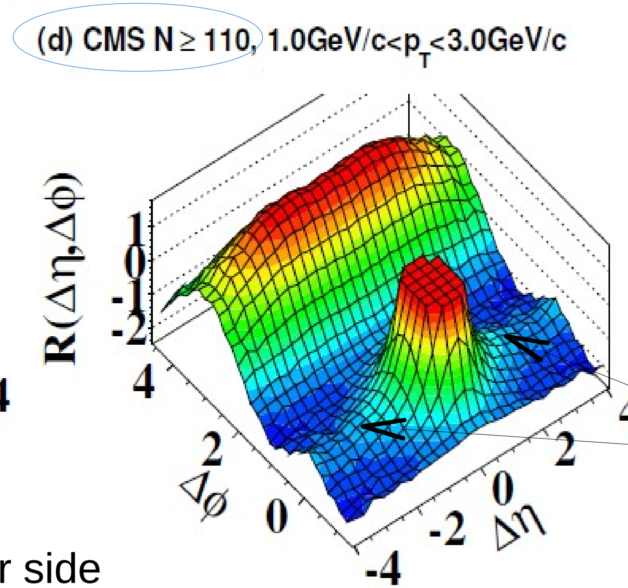
- multiplicity can bias the number of hard scatterings per binary collisions

Long range correlations: pp – Pb-Pb

2 particle correlations in (η-φ) between “trigger” and associates particles

- pp:





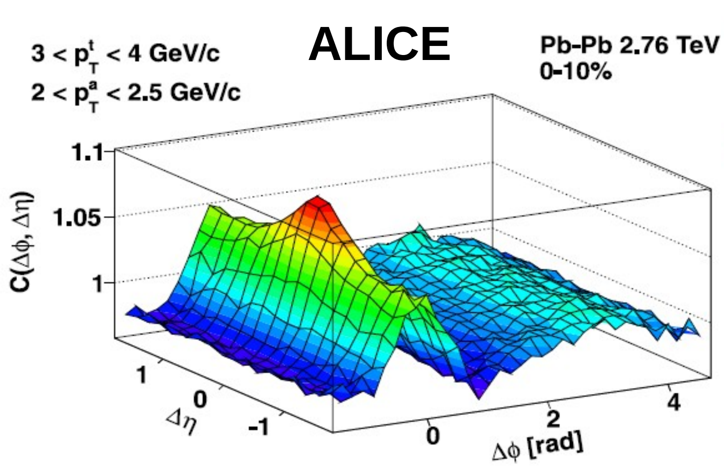
away side (Δφ=π)

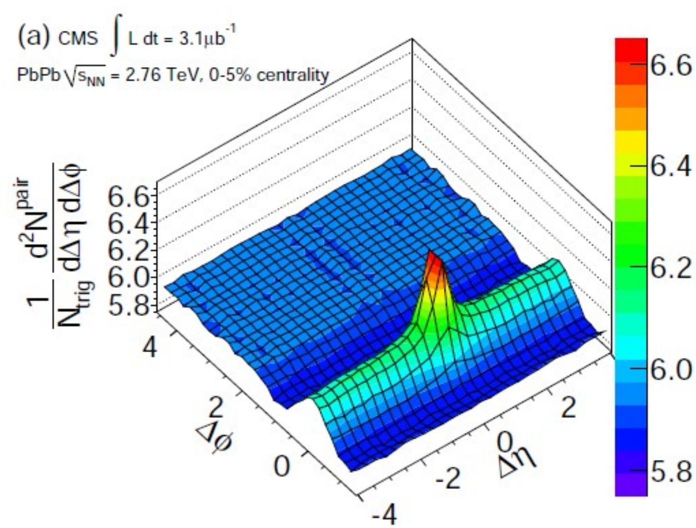
near side (Δφ=0)

Min. Bias:
- Near side: “collimated” jet peak
- Away side: rencoil jet (“ridge structure” expected from momentum conservation)

HM: near side ridge → origin not yet fully understood

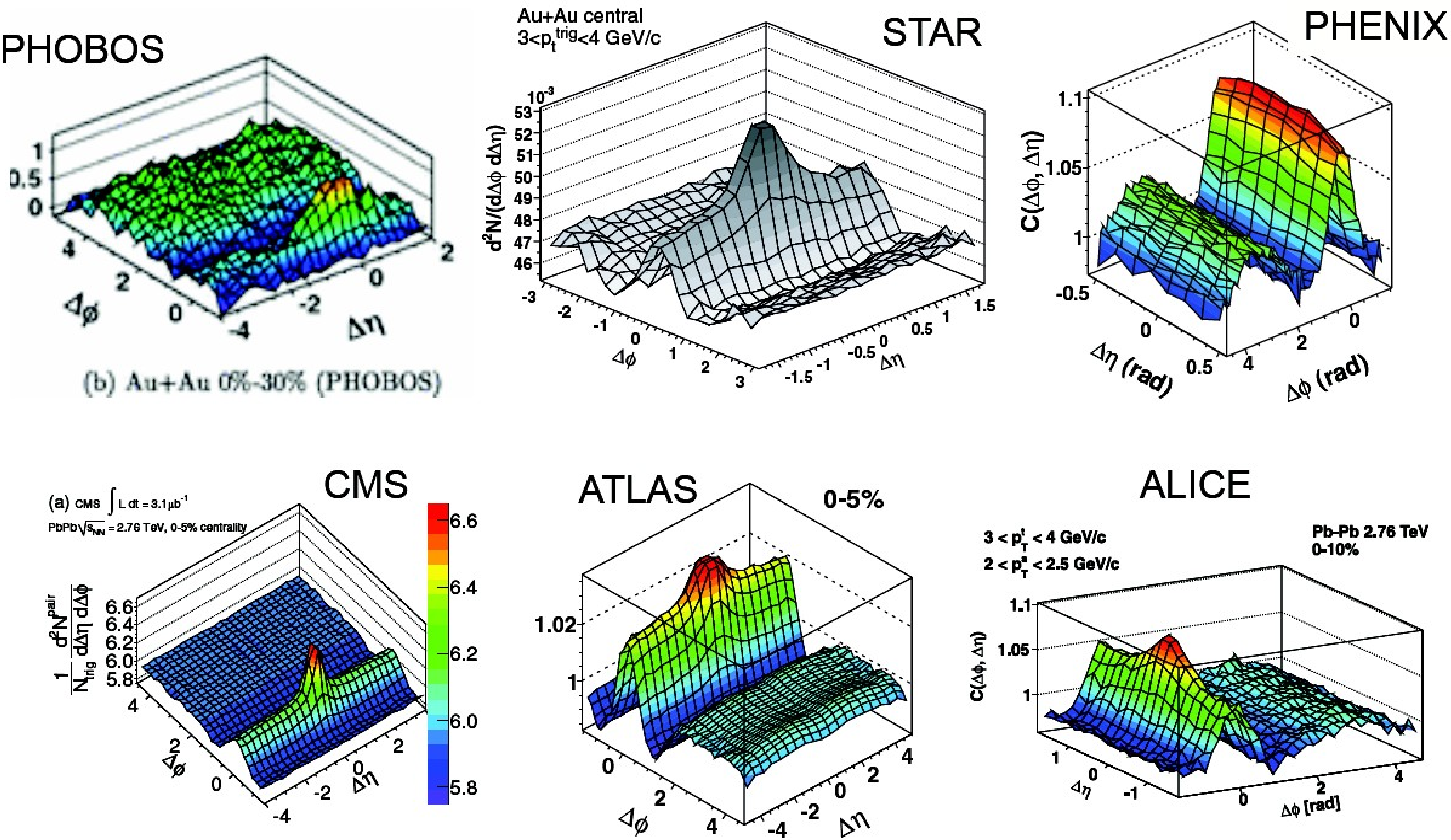
- Pb-Pb:





- near side ridge structure, typical of collective systems
- long range in Δη reproduced by hydromodels

Long range correlations: the “ridge” in A-A collisions

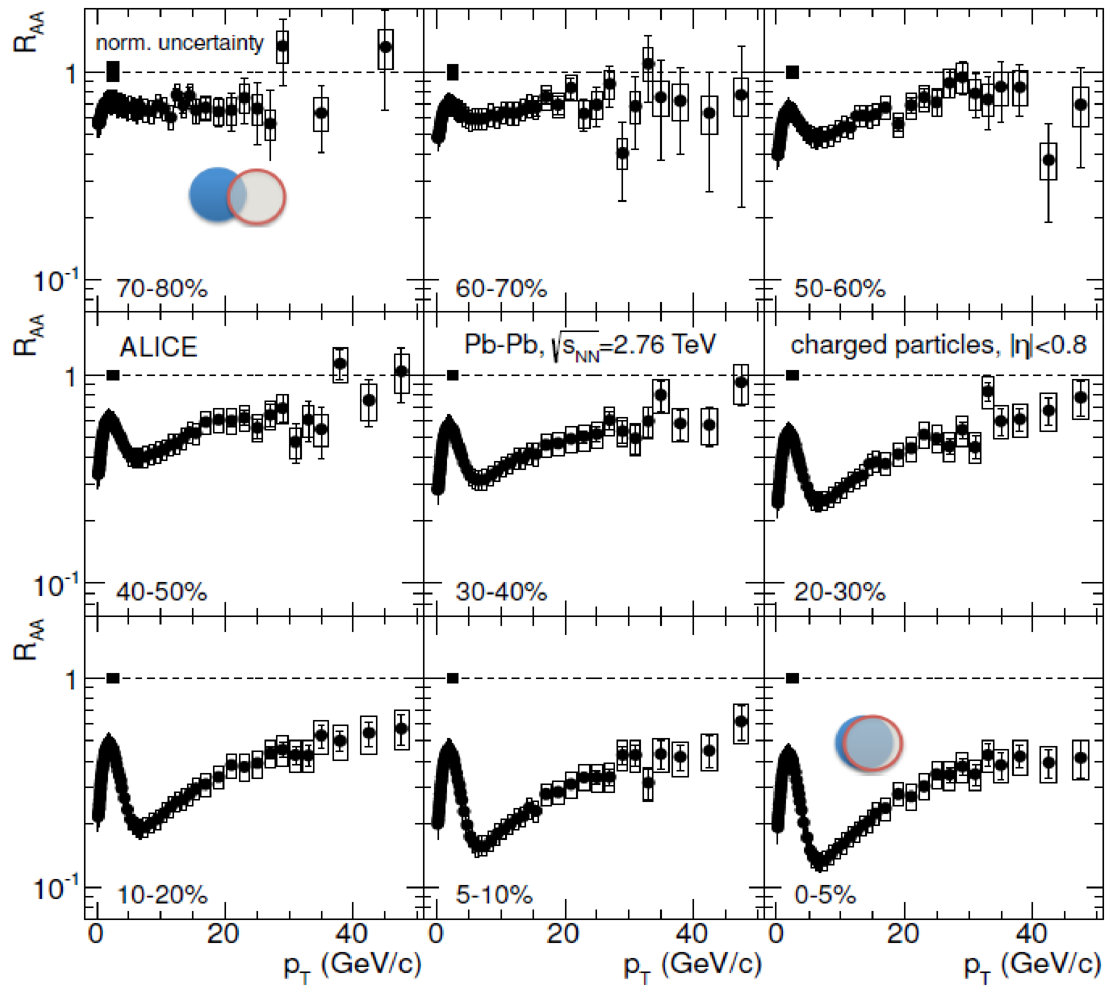


RAA centrality dependence

Suppression depends on centrality: stronger for more central collisions

- Strongest suppression around 7 GeV/c for all centralities
- Suppression non-zero up to high transverse momenta

More central collisions: longer path length, denser medium lead to more suppression



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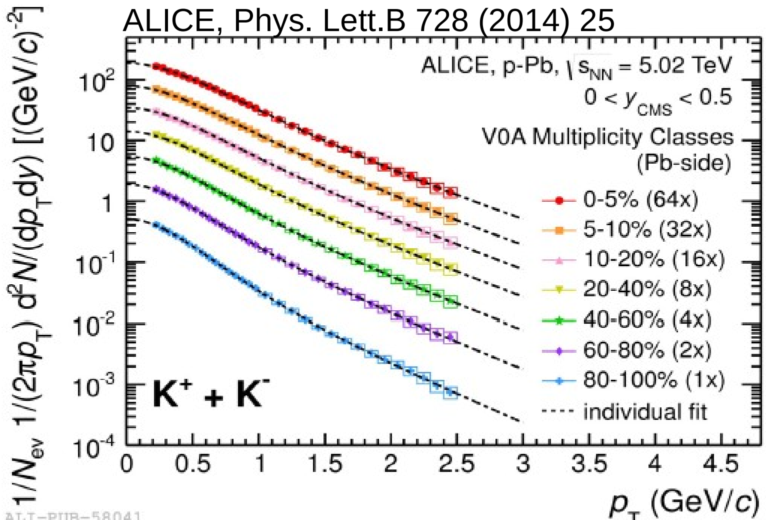
Identified hadrons at low-pT vs multiplicity

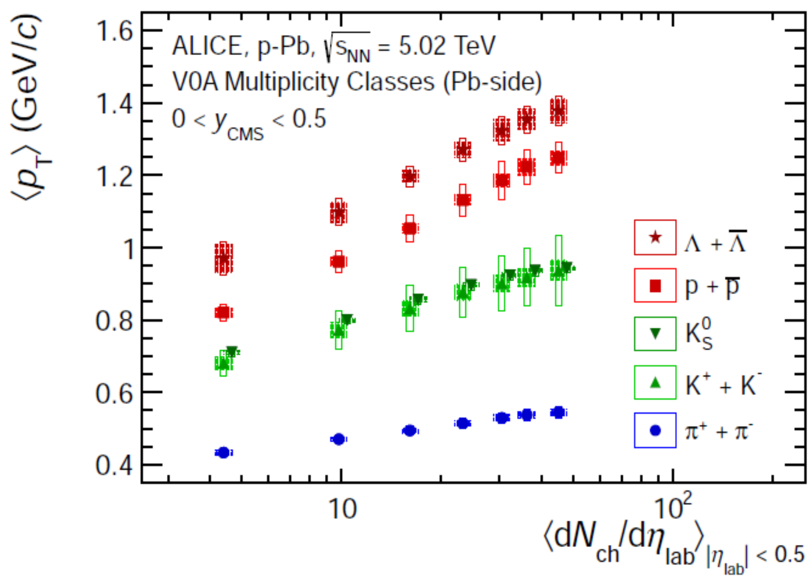


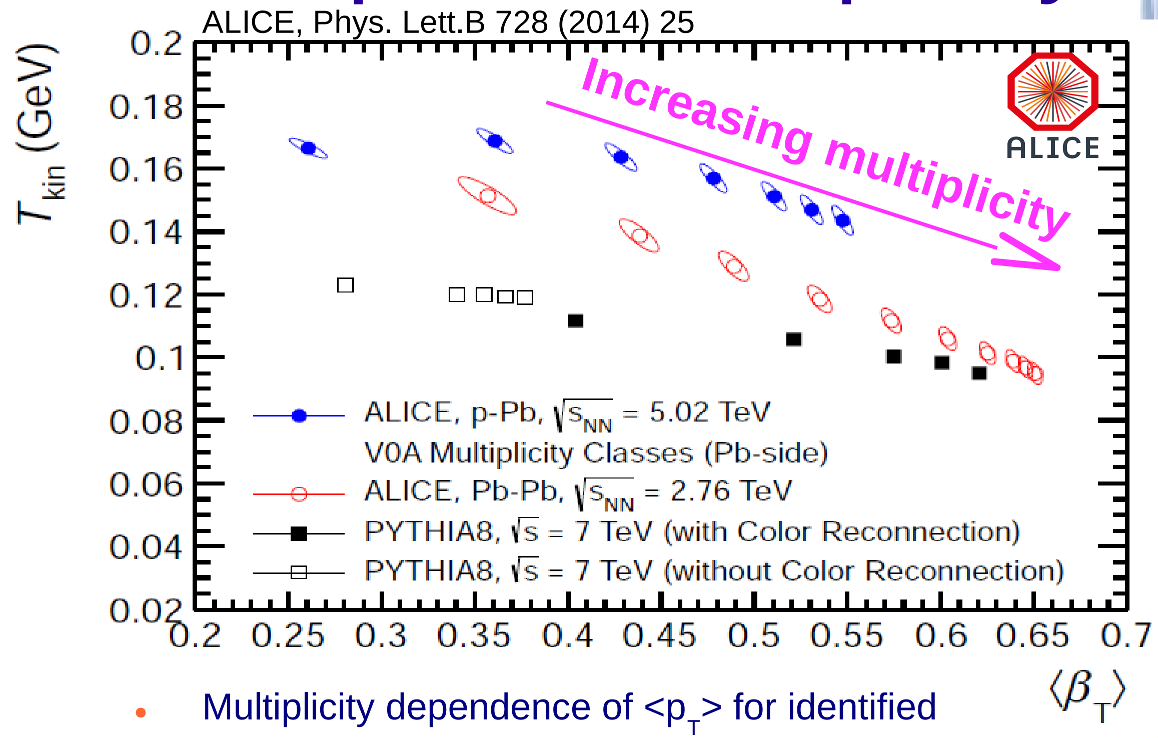
ALICE: Blast-wave model fit (thermal+collective)

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\, m_T I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

$$\rho = \tanh^{-1}\beta_T$$

T_{kin} – kinetic freeze-out
β_T – transverse velocity





- Multiplicity dependence of $<p_T>$ for identified particles:clear mass ordering → indication for a collective expansion with a common velocity field.
  - The same kind of mass ordering is also qualitatively expected from colour re-connections [A. Ortiz Velasquez et al. Phys. Rev. Lett. 111 (2013) 4, 042001]
- Similar evolution of the blast–wave parameters with increasing multiplicity in p-Pb and Pb-Pb
- PYTHIA8 pp events (no hydrodynamic evolution) also show the same trend (albeit at a 30% smaller T_{kin})
  - MPI + Color Reconnection causes similar effect as radial flow

Run 2 schedule

Year	System	E [TeV]	Lumi [$cm^{-2}s^{-1}$]	Rate [kHz]	Time
2015	pp 50ns	13	$1x10^{31}$	600	3w
	pp	13	$5x10^{30}$	300	11w
	PbPb	5.02	$1x10^{27}$	8	4w
	pp-ref	5.02	$5x10^{30}$	300	4d
2016	pp	13	$5x10^{30}$	300	22w
	pPb	5.02	$1x10^{29}$	200	4w
	pp-ref	5.02	$5x10^{30}$	300	7d
2017	pp	13	$5x10^{30}$	300	22w
2018	pp	13	$5x10^{30}$	300	6w
	PbPb	5.02	$1x10^{27}$	8	4w
	pp-ref	5.02	$5x10^{30}$	300	7d

- p-Pb in 2016 → ALICE Preference