An *heavy ion look* on pp collisions @ LHC : signals for MPI processes in the charm sector

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IJCLAB 31/05/2021

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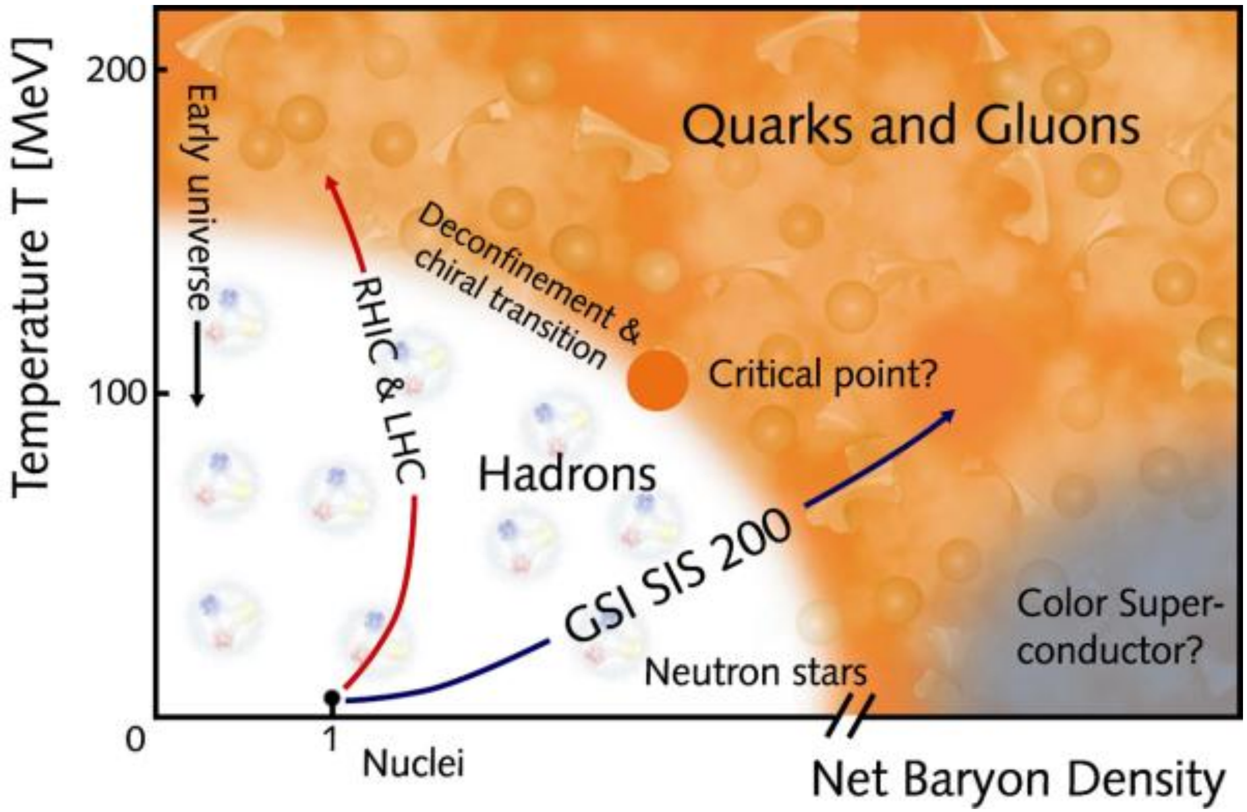
Quark-Gluon Plasma

Quark-Gluon Plasma (QGP) is a deconfined state of quarks and gluons (asymptotic freedom regime) predicted by QCD and studied in high-energy heavy-ion collisions

Credit: GSI



QGP with heavy-ion collisions

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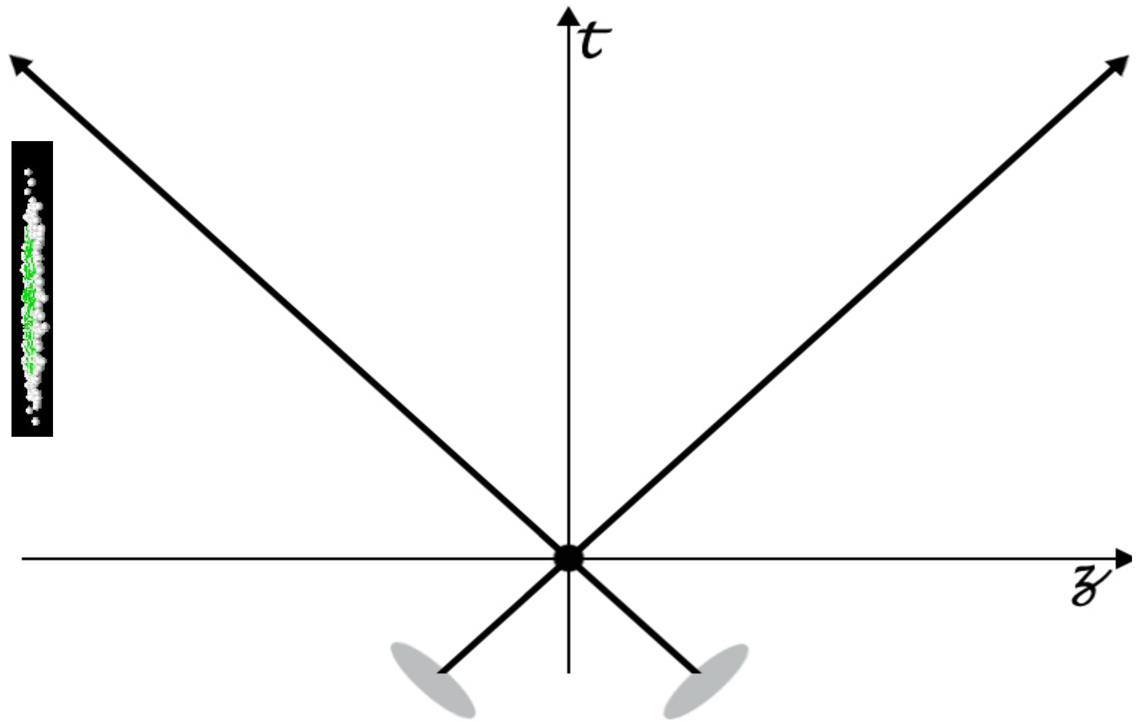

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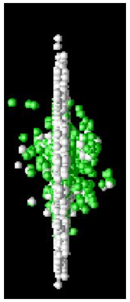

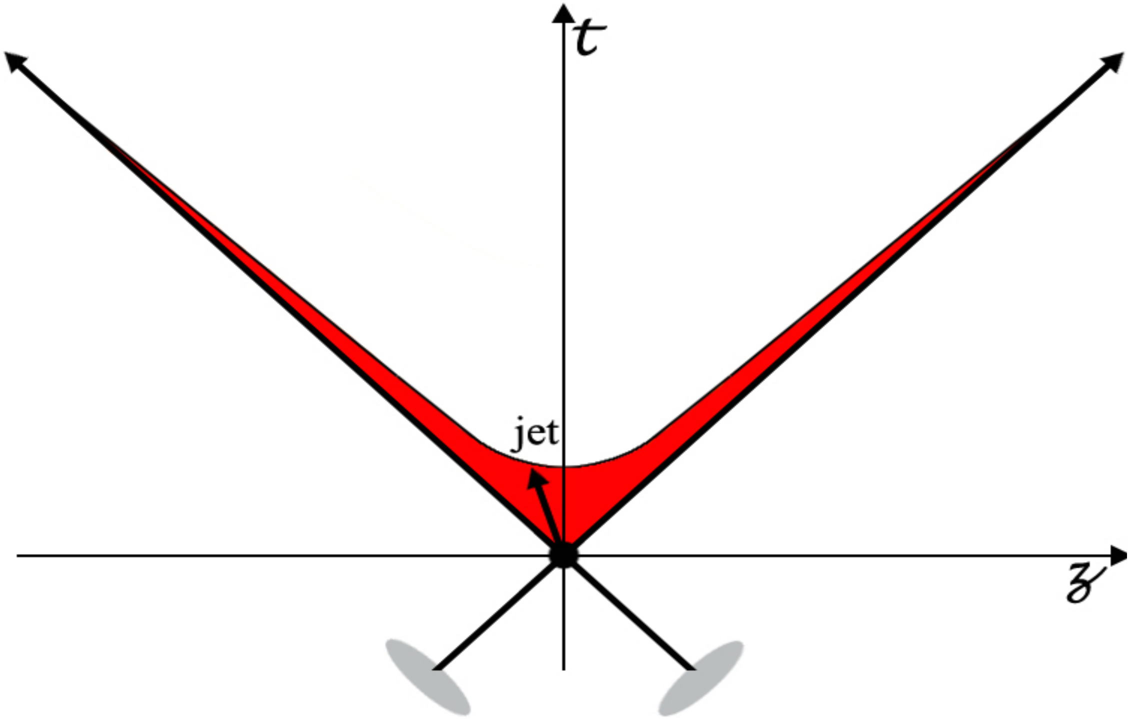

Initial-state interactions

Hard scattering: production of high-momentum particles e.g: heavy quarks, quarkonia, jets, direct photons, vector bosons

QGP with heavy-ion collisions

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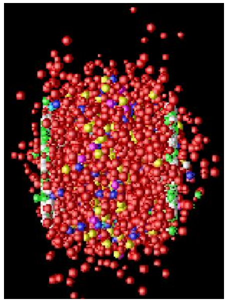
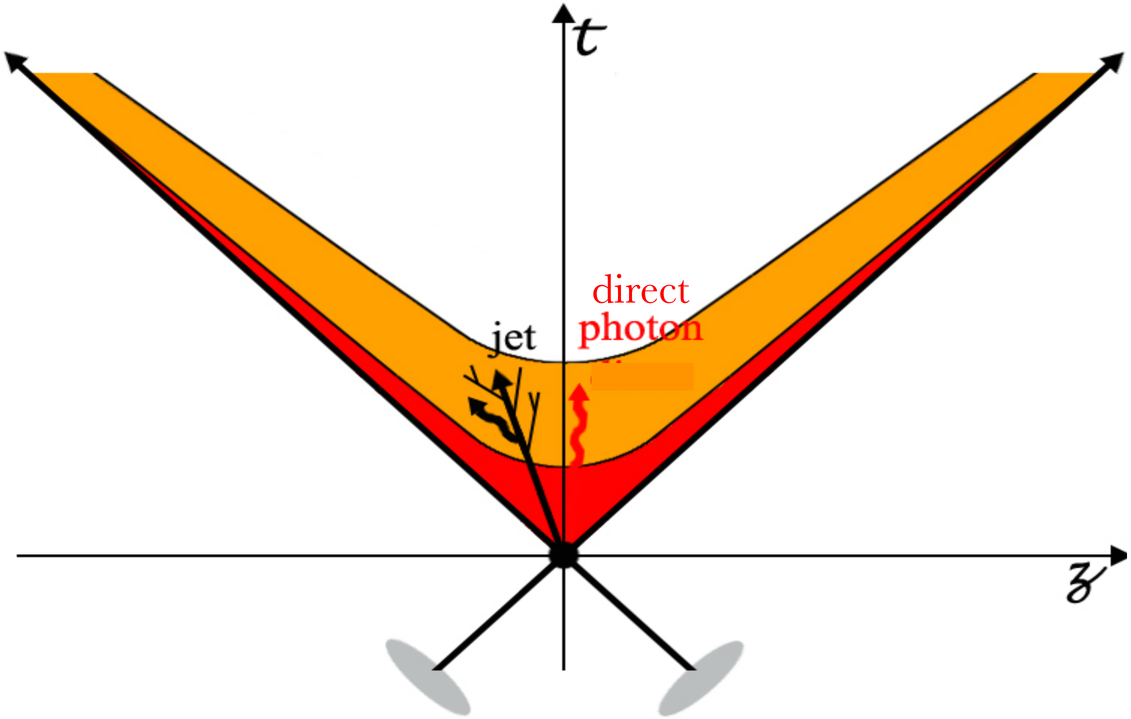
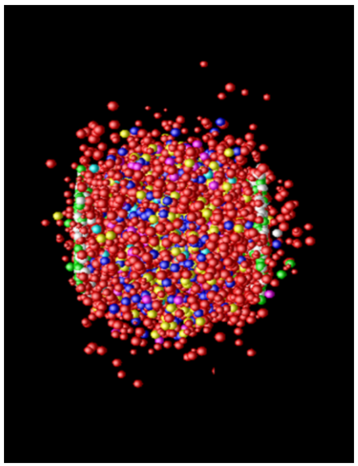


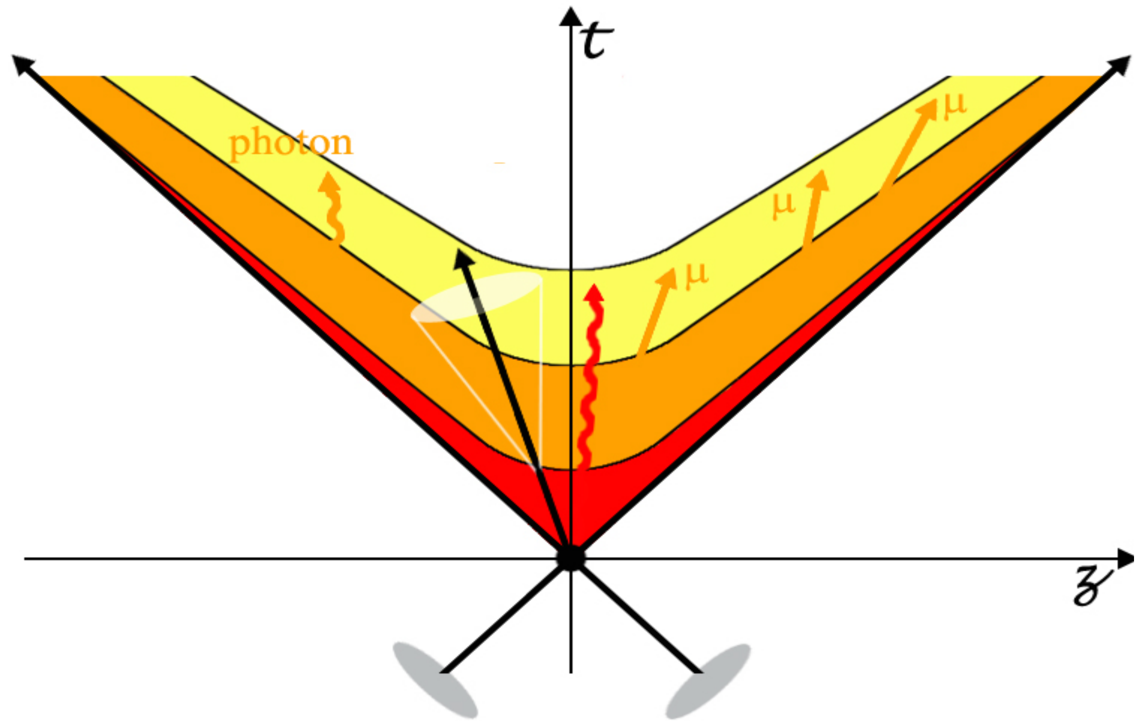


QGP ?

QGP with heavy-ion collisions

Quark-Gluon Plasma (QGP) is a deconfined state of quarks and gluons predicted by QCD and studied in high-energy heavy-ion collisions



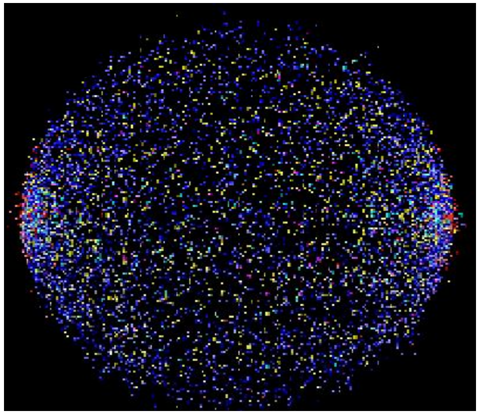


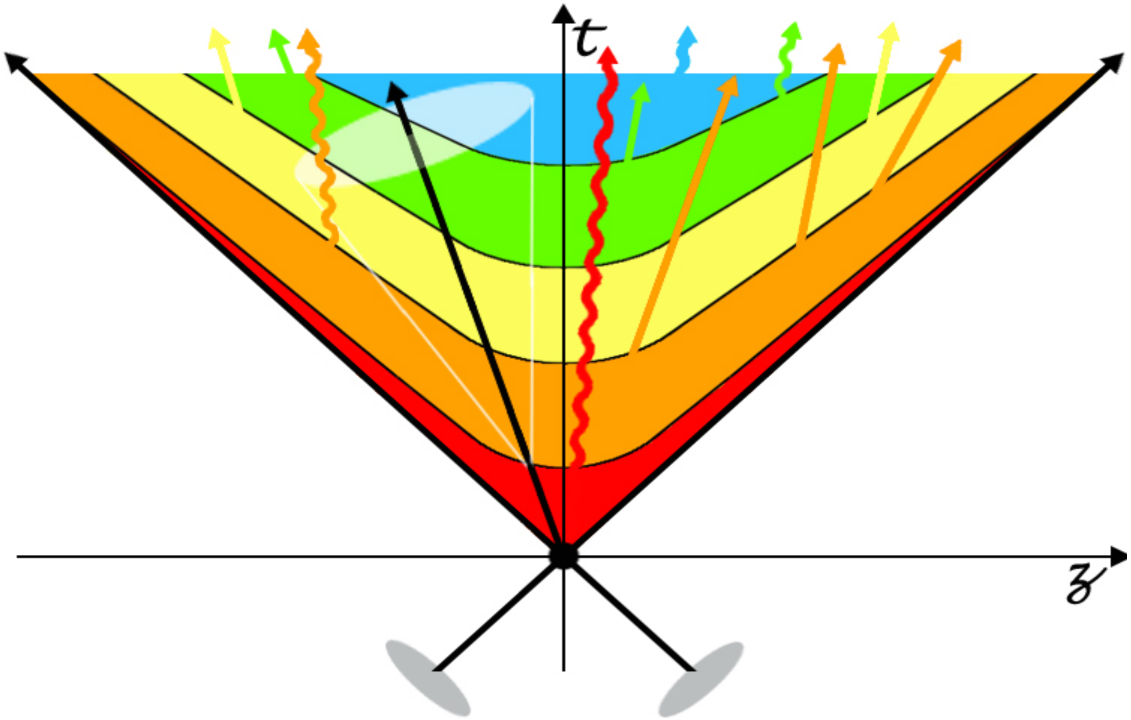
Plasma hadronization

Hadron gas

QGP with heavy-ion collisions

Quark-Gluon Plasma (QGP) is a deconfined state of quarks and gluons predicted by QCD and studied in high-energy heavy-ion collisions





Chemical freeze-out

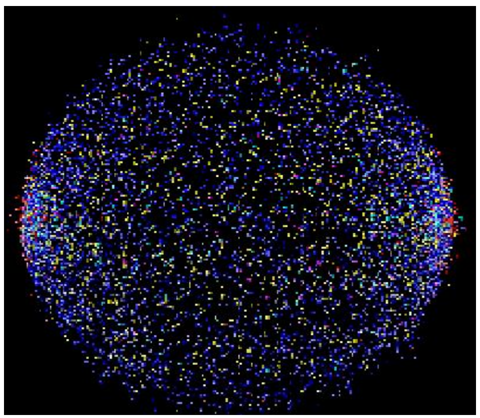
(no more inelastic collisions)

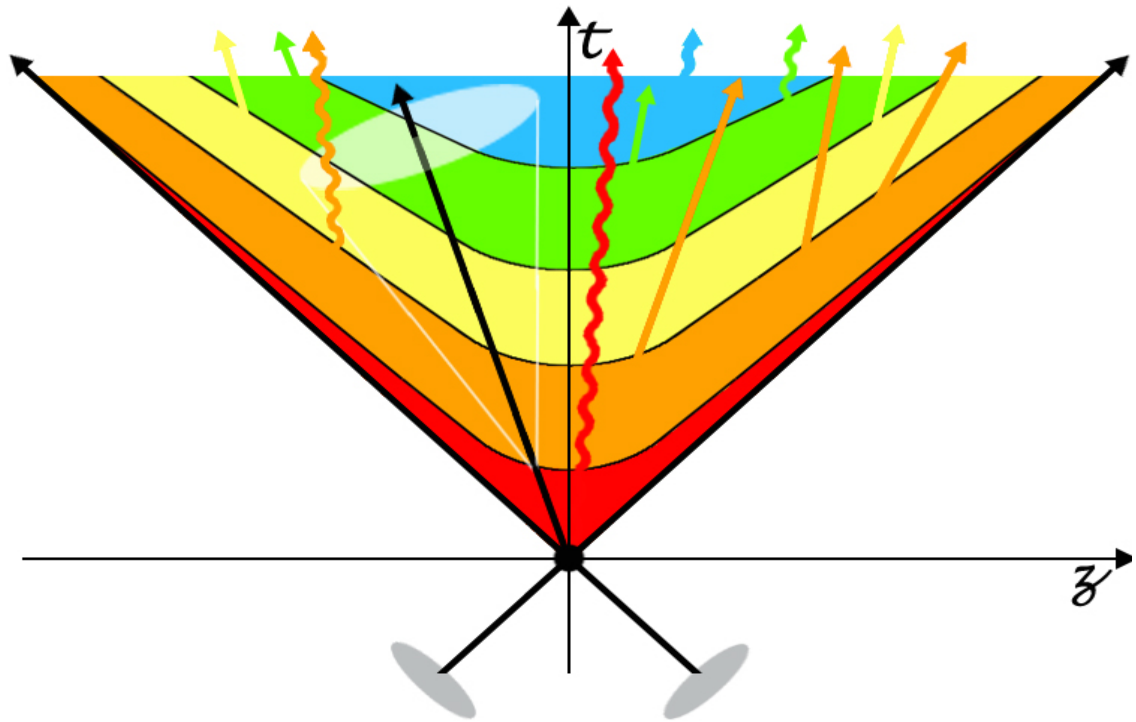
Thermal freeze-out

(no more elastic collisions)

QGP with heavy-ion collisions

Various measurements, referring to various stages of the collision

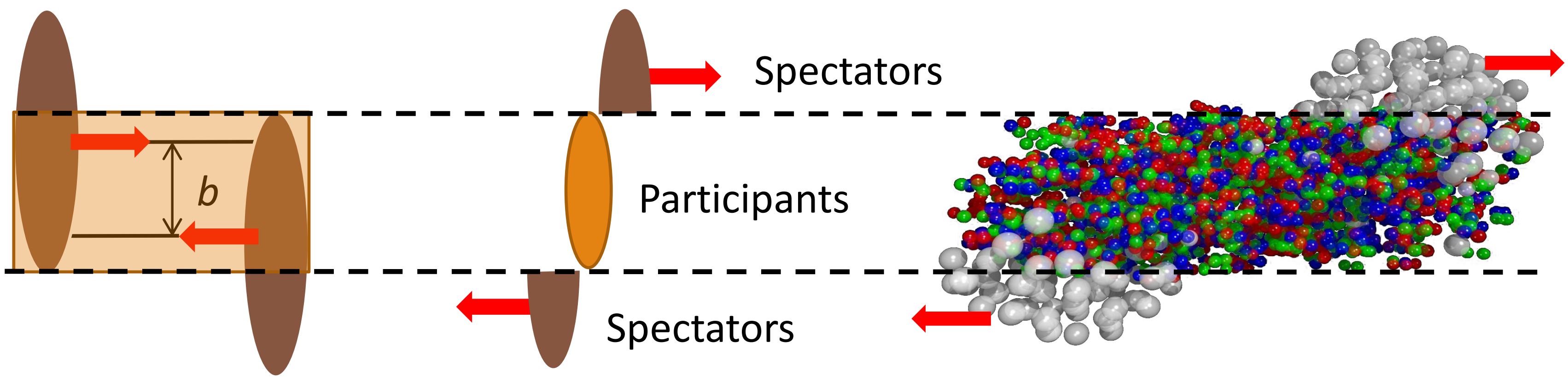




- ✓ Soft probes are produced at the QGP hadronization stage
- ✓ Hard probes are produced at the initial stage of the collision and can interact with the QGP

Strategy for QGP studies

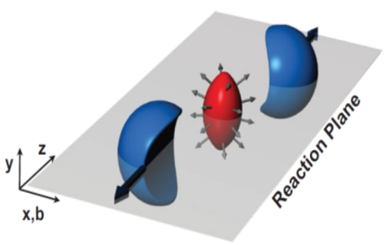
- pp collisions are considered as the vacuum reference
- p-A collisions are a control experiment to estimate cold matter effects
- AA collisions are described by a (geometrical) Glauber model defining the number of participants and the number of binary collisions (N_{coll}) for a given impact parameter *b*



- Emblematic observables for hard and soft probes

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{< N_{coll} > \times dN_{pp}/dp_T}$$

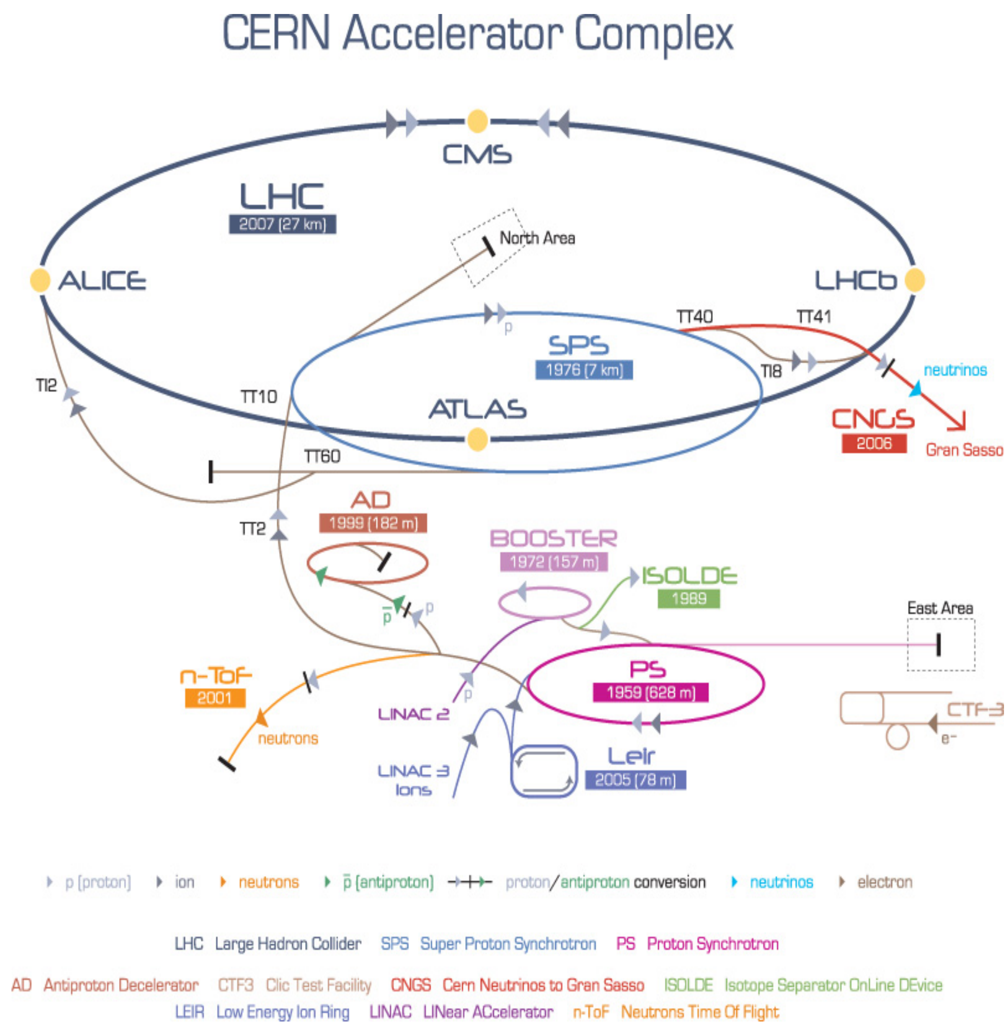


Elliptic flow

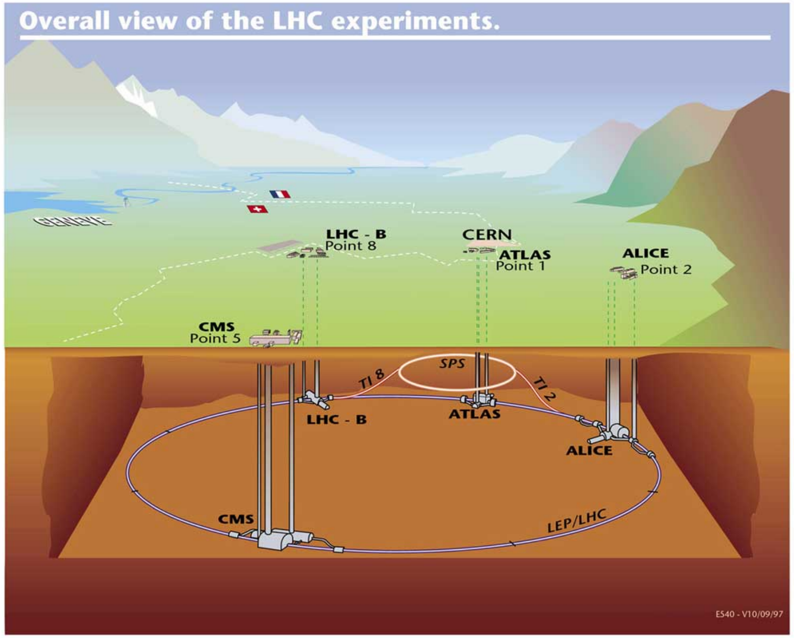
Initial spatial anisotropy transferred into a momentum anisotropy of particles

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi n))$$

The Large Hadron Collider (LHC)



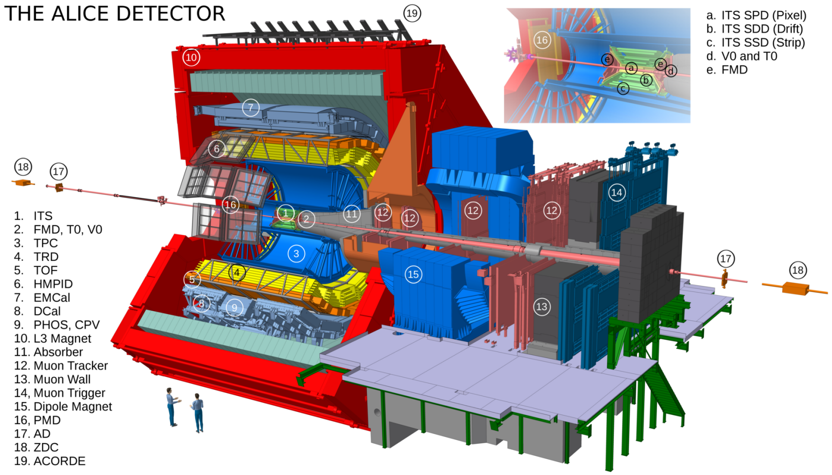
LHC 27 km circumference
50 to 175 m underground
At the French-Swiss border (Geneva area)

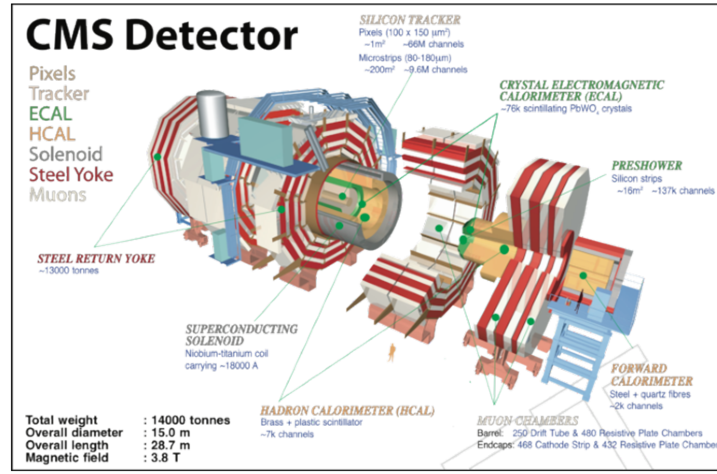


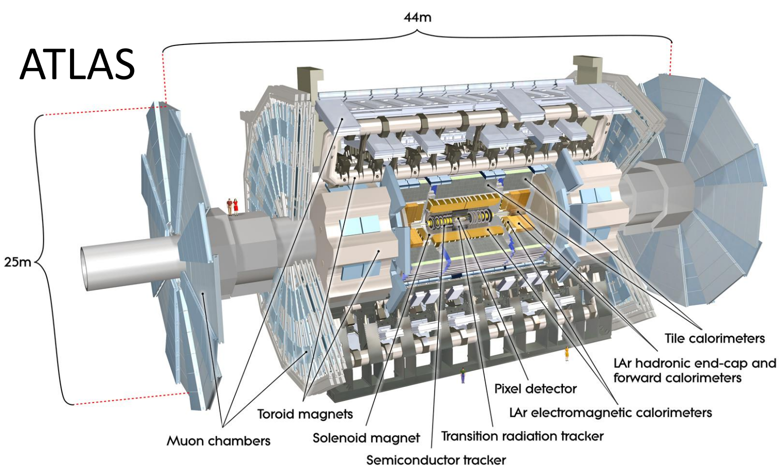
Collision systems and energies

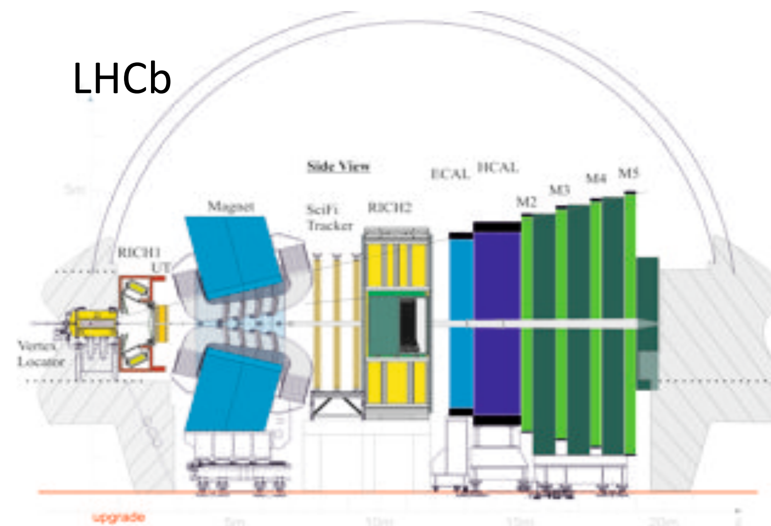
- pp $\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 8, 13 TeV
- p-Pb $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV
- Pb-Pb $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
- Xe-Xe $\sqrt{s_{NN}}$ = 5.44 TeV

QGP experiments at LHC



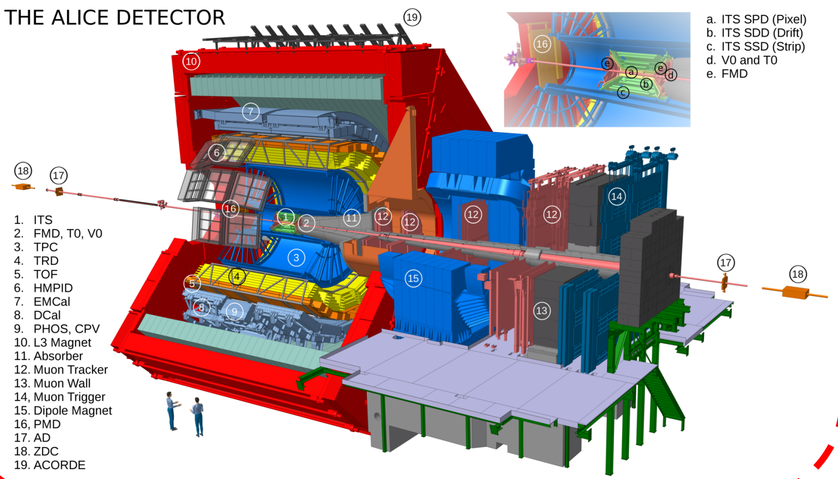




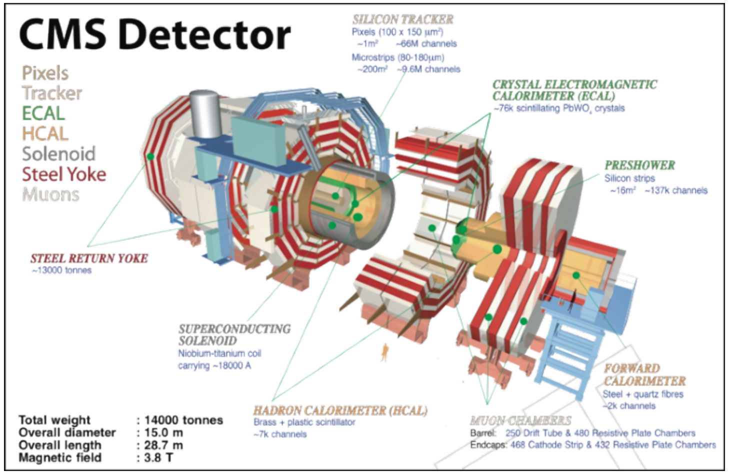


QGP experiments at LHC

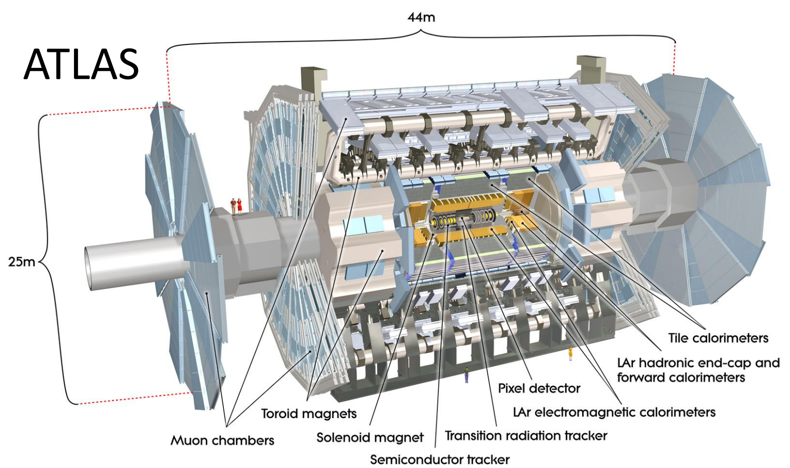
Dedicated to heavy-ion physics



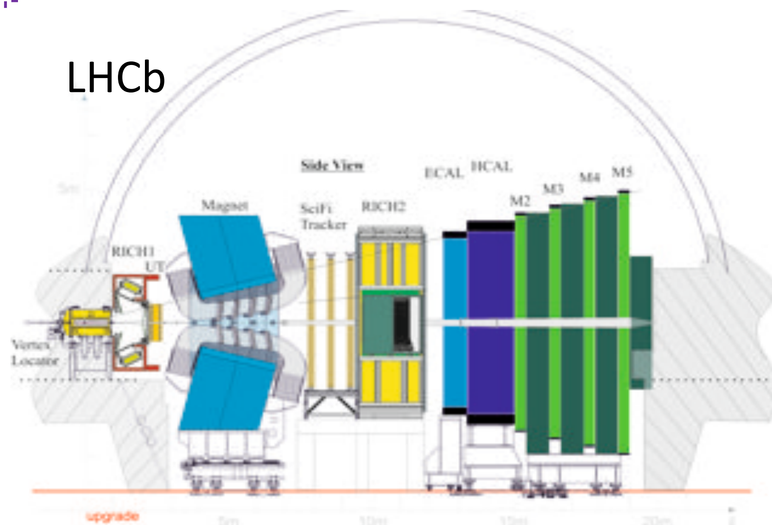
Developed an heavy-ion program



ATLAS



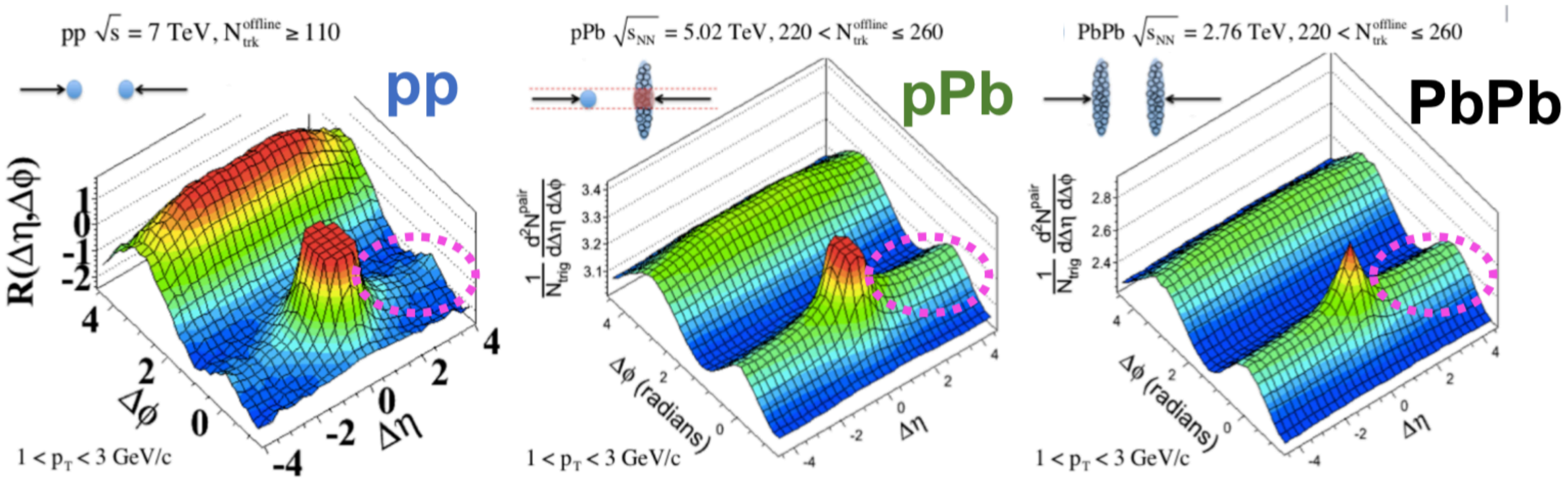
LHCb



An Heavy Ion LHC discovery
Small System Physics

An *heavy ion look* on pp collisions @ LHC : signals for MPI processes in the charm sector

Double ridge structure



CMS, JHEP09 (2010) 091

CMS, PLB 724 (2013) 213

A **long-range angular correlation** (elliptic flow) is observed for **all systems** (pp, p-A and A-A) in the **high multiplicity** regime.

Confirmed by the 4 experiments

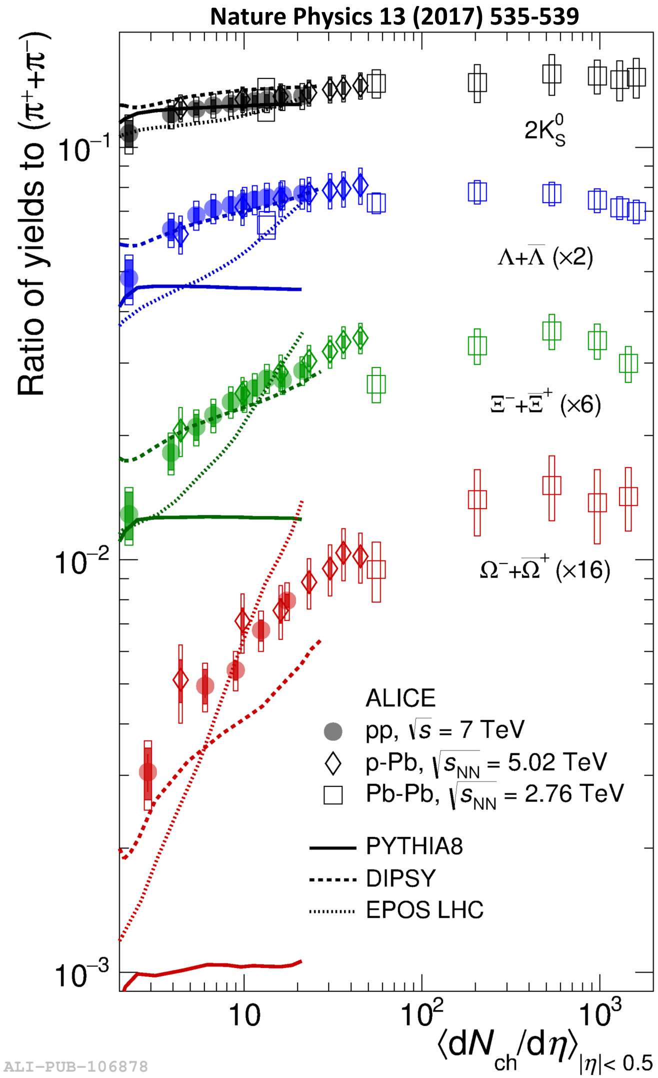
ALICE PLB 719 (2013) 29 | ATLAS PRL 110 (2013) 182302 | LHCb PLB 762 (2016) 473

In Pb-Pb collisions it is interpreted as a signature of the collective expansion of the system

Figure credit Yen-Jie Lee (MIT)

« small system» physics at the LHC

- ”small” refers to system size: protons at the initial stage
- But with sometimes a final state looking like a large system, at least for charged-particle multiplicity
- At the LHC, minimum bias pp collisions can be used as reference
- High-multiplicity events represent a small contribution to the total cross section $O(10^{-4})$ in statistics
- Role of system size in question
    - pp is smaller than p-Pb
    - nuclear environment includes cold matter effects



« small system» physics at the LHC

Table prepared by the WG small systems from the HL/E-LHC working group (~140 refs)
arXiv:1812.06772 arXiv:1602.09138

Observable of effect	Pb-Pb	pPb (high mult)	pp (high mult)
SOFT Probes			
low p_T spectra ("radial flow")	yes	yes	yes
Intermediate p_T ("recombination")	yes	yes	yes
HBT radii	R_{out}/R_{side}~1	$R_{out}/R_{side} \leq 1$	$R_{out}/R_{side} \leq 1$
Azimuthal anisotropy (v_n) (2 prt. correlations)	v_1-v_7	v_1-v_5	v_2-v_4
Characteristic mass dependence	v_2-v_5	v_2-v_3	v_2
Higher order cumulants	"4~6~8 " + higher harmonics	"4~6~8 " + higher harmonics	"4~6 "+ higher harmonics
Event by event v_n distributions	n=2-4	Not measured	Not measured
Event plane and v_n correlations	yes	yes	yes
HARD Probes			
Direct photons at low p_T	yes	Not measured	Not measured
Jet Quenching	yes	Not observed	Not measured
Quarkonia Nuclear Modification Factor	J/ψ regeneration / Y suppression	suppressed	Not measured
Heavy-flavor anisotropy	yes	yes	Not measured

Beyond the « standard model » of QGP

- Do we observe QGP droplets in small systems (Collectivity ≠ QGP) ?

  Hydro requires the Reynolds number $R_e >> 1 \Rightarrow$ small $\frac{\eta}{s}$

- What about hard probes interaction with QGP droplets ?

  Energy loss $\propto$ system size => small system = small effect

- For small systems, which mechanism in the initial state can allow to reach the energy density needed for a phase transition ?

- Is it the same mechanism for all systems ?

- Can high energy hadronic collisions be described in one single formalism ?
  Nucleon-nucleon vs. parton-parton interactions

Small systems: not a n^{th} QGP probe
But a change of paradigm

How does collectivity emerge in hadronic collisions ?

The hadronic initial state with Multi-parton interactions

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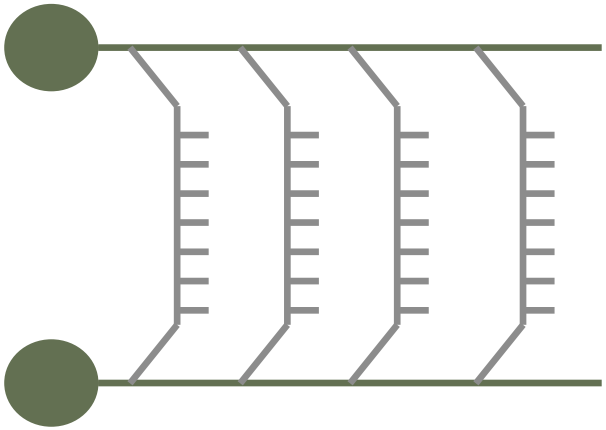
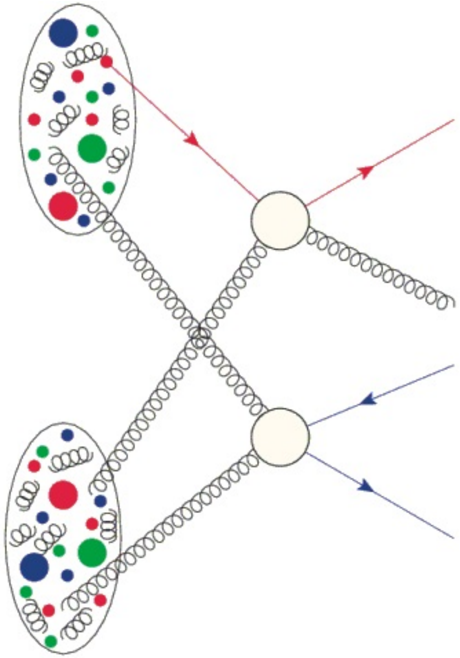
Multiple Parton Interaction (MPI)

✓ <u>A naïve picture</u>



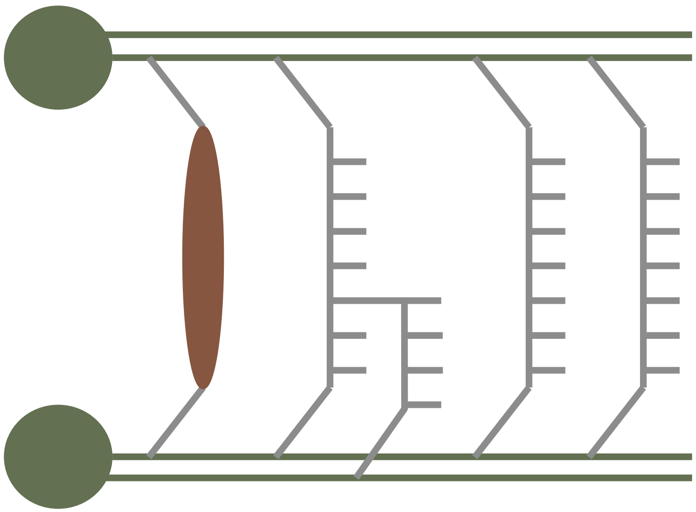
- Several interactions, soft and hard, occur in parallel
- The number of elementary interactions is connected to the multiplicity



- Several hard interactions can occur in a pp collision
- In this picture : particle yield from hard processes should increase with multiplicity

Multiple Parton Interaction (MPI)

✓ <u>A less naïve picture</u>

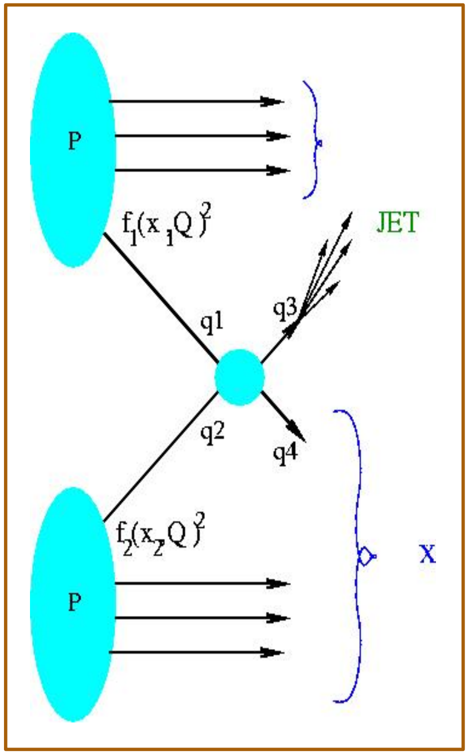


- Some of the parallel interactions are soft
- Energy and momentum conservation
- Impact parameter dependence
- Re-interaction of partons with others: ladder splitting
- Re-interaction within ladders either in initial state (screening, saturation), or in final state (color reconnections)
- Initial state radiation (ISR) and final state radiation (FSR), hadronic activity around hard processes

=> Test interaction between hard component and soft component in pp collisions : full collision description, color flow, energy sharing.

Needs for MPI

pQCD and inclusive observables



Jet production cross section:
Inclusive cross section: pp -> Jet +X

$$\sigma_{pp \to q3q4} = \iiint dx_1\, dx_2\, d\hat{t} f_1\,(x_1, Q^2) f_2\,(x_2, Q^2) \frac{d\hat{\sigma}_{q1q2 \to q3q4}}{d\hat{t}}$$

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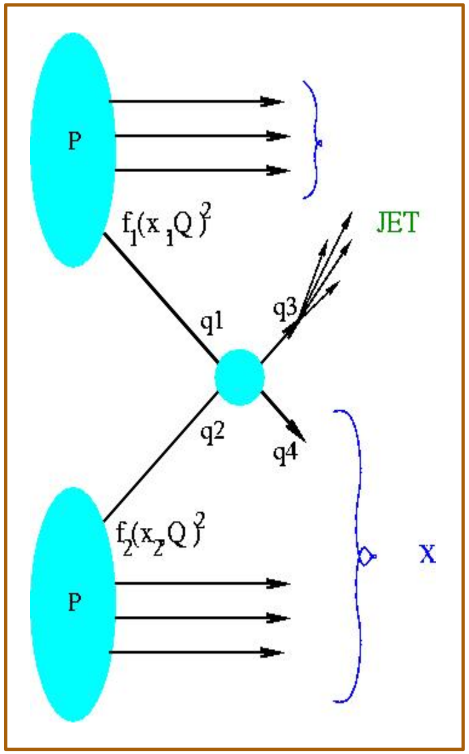

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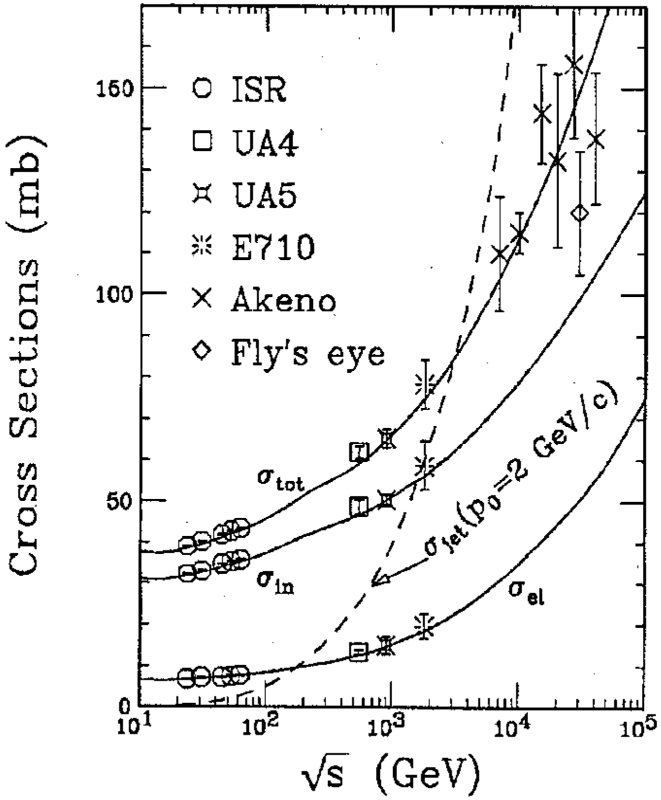
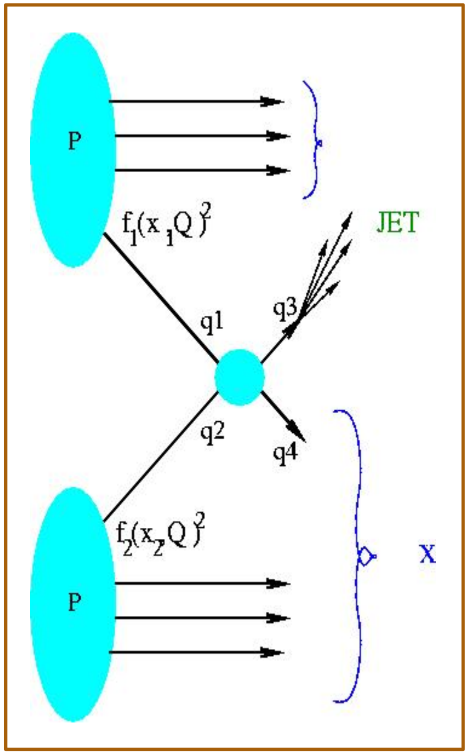


X.N.Wang, M.Gyulassy, Phys. Rev. D45 (1992) 844-856

$$< n_{\mathrm{MPI}} >= \frac{\sigma_{\mathrm{hard}}}{\sigma_{\mathrm{tot}}}$$

Needs for MPI

pQCD and inclusive observables



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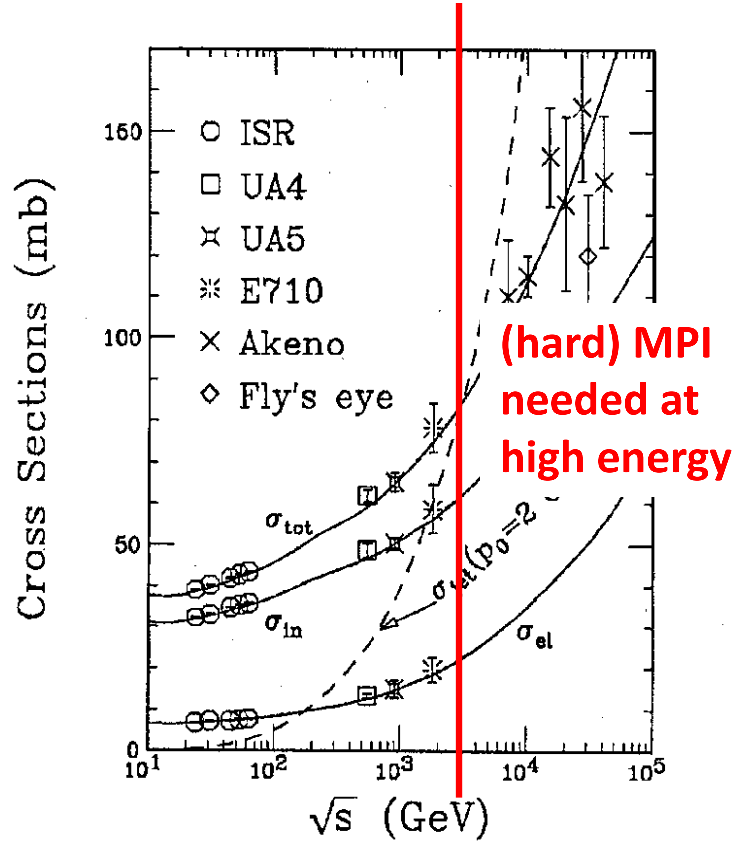
Limitation at high energy



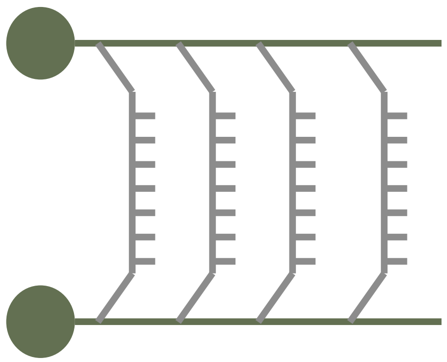
X.N.Wang, M.Gyulassy, Phys. Rev. D45 (1992) 844-856

$$< n_{\mathrm{MPI}} > = \frac{\sigma_{\mathrm{hard}}}{\sigma_{\mathrm{tot}}}$$

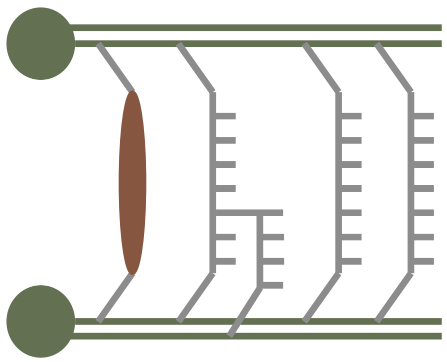
Do we understand initial conditions?
What kind of initial conditions can let pp collisions to reach high density ?

Multi Parton Interactions (MPI) are good candidates

✓ A naïve picture



✓ A less naïve picture



We have been knowing since the 90th that MPIs are necessary to describe all features of pp collisions at high energies both for soft and hard production
MPI directly connected with multiplicity

If we want to understand high multiplicity events/small systems/emergence of collectivity, it is mandatory to understand initial state and relation between soft and hard component of events

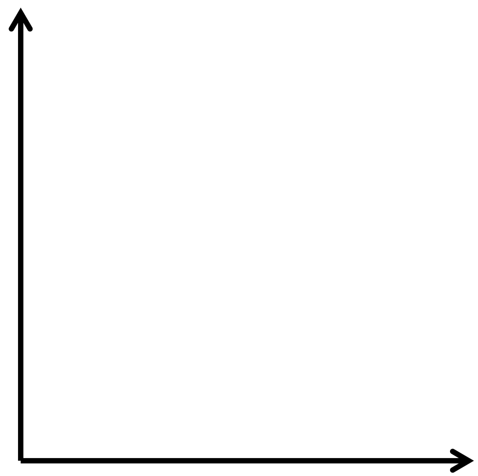
Multiplicity differential studies and exclusive measurements

Quarkonia production as a function of multiplicity
The observable

Relative quarkonium production yield as a function of relative charged multiplicity

Study of J/ψ as a function of multiplicity first proposed in 2010 (Nucl.Phys.Proc.Suppl. 214 (2011) 181-184)

$$\frac{\mathrm{d}N_Q/\mathrm{d}y}{<\mathrm{d}N_Q/\mathrm{d}y>}$$



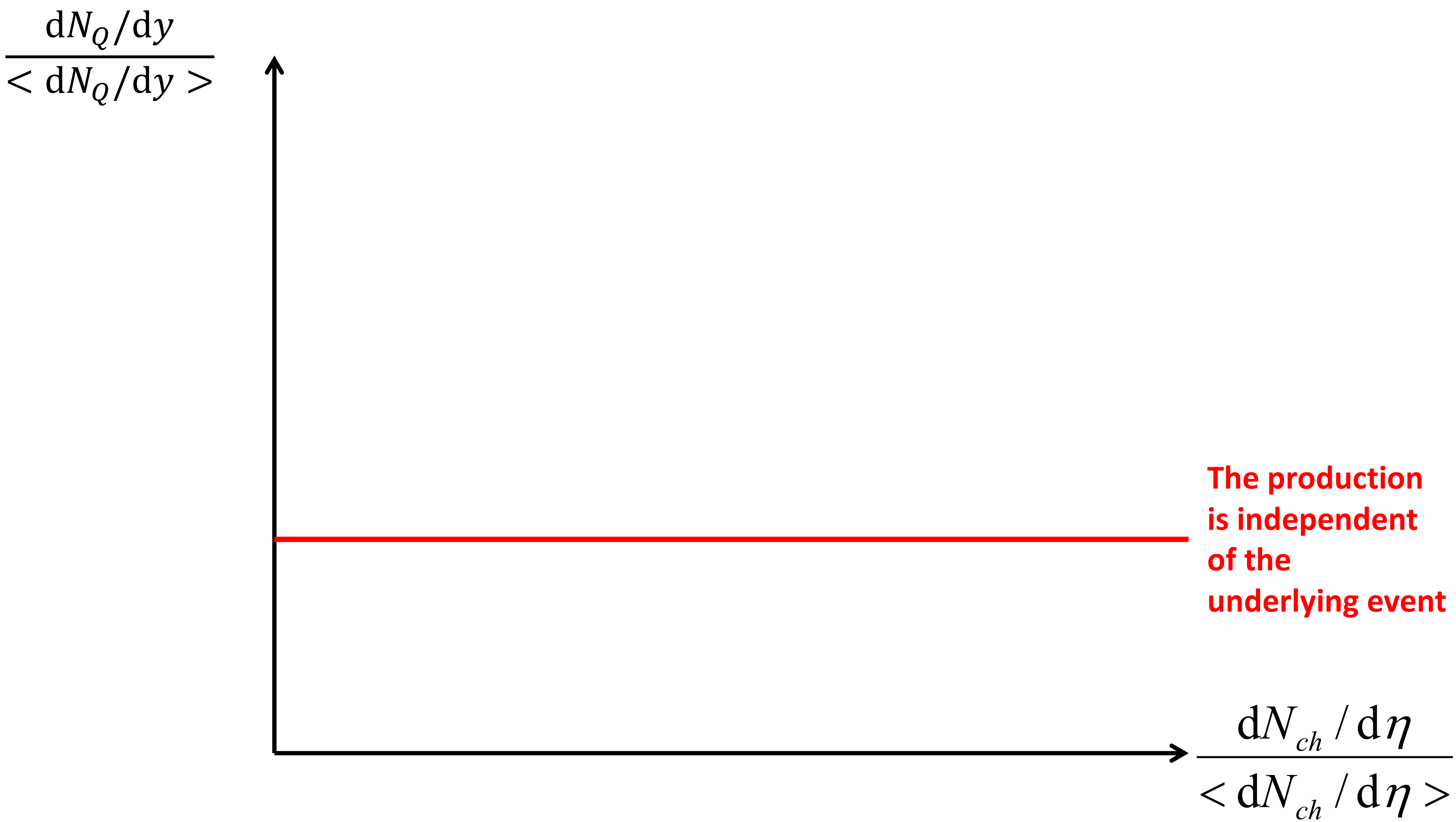
$$\frac{\mathrm{d}N_{ch}/\mathrm{d}\eta}{<\mathrm{d}N_{ch}/\mathrm{d}\eta>}$$

Self-normalized quantities, *x* label: *z* KNO variable

2 advantages :

- ✓ from analysis, various corrections cancel in the ratio
- ✓ for comparison, easier to compare various energies and systems

Quarkonia production as a function of multiplicity
The observable



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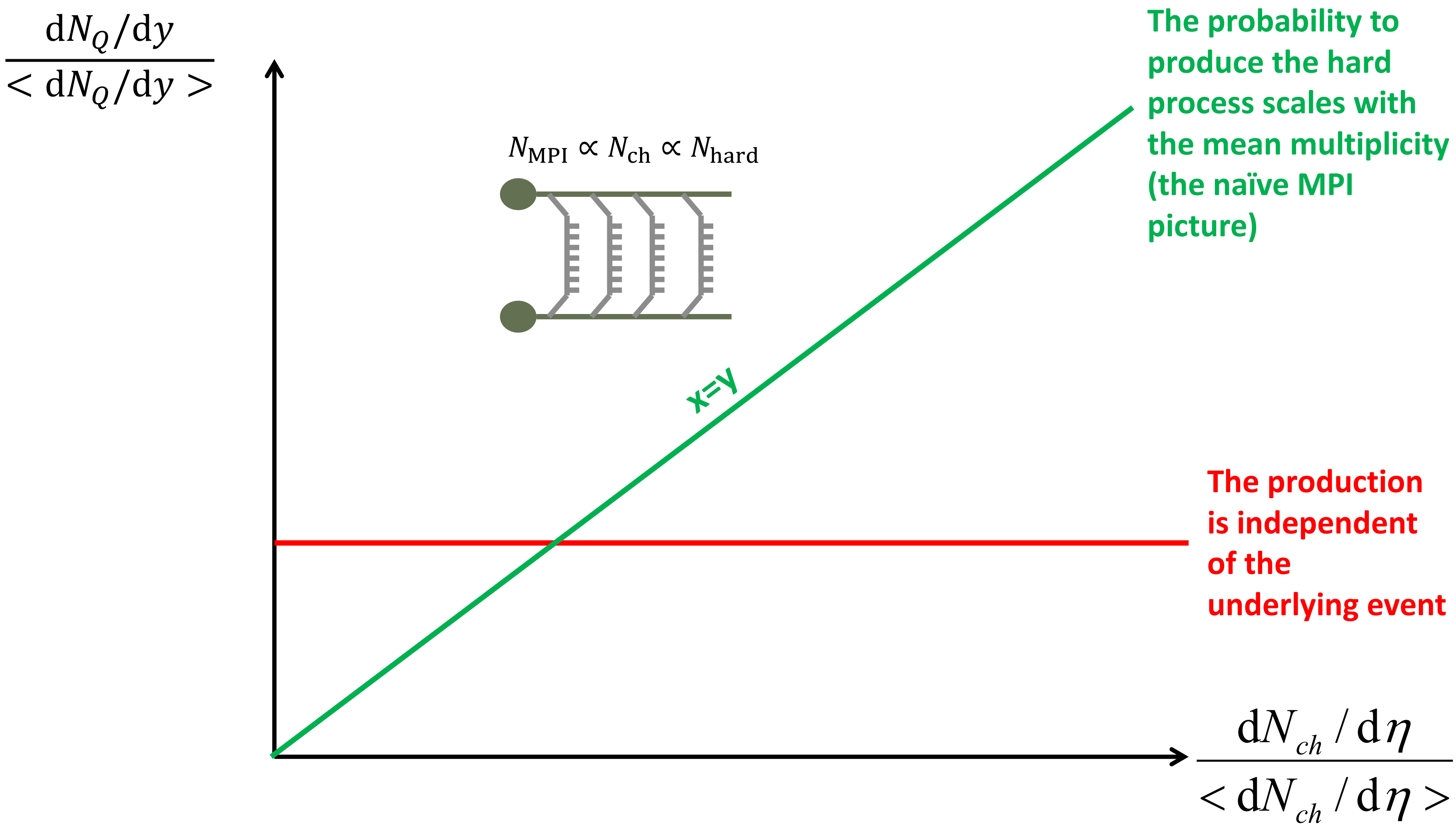

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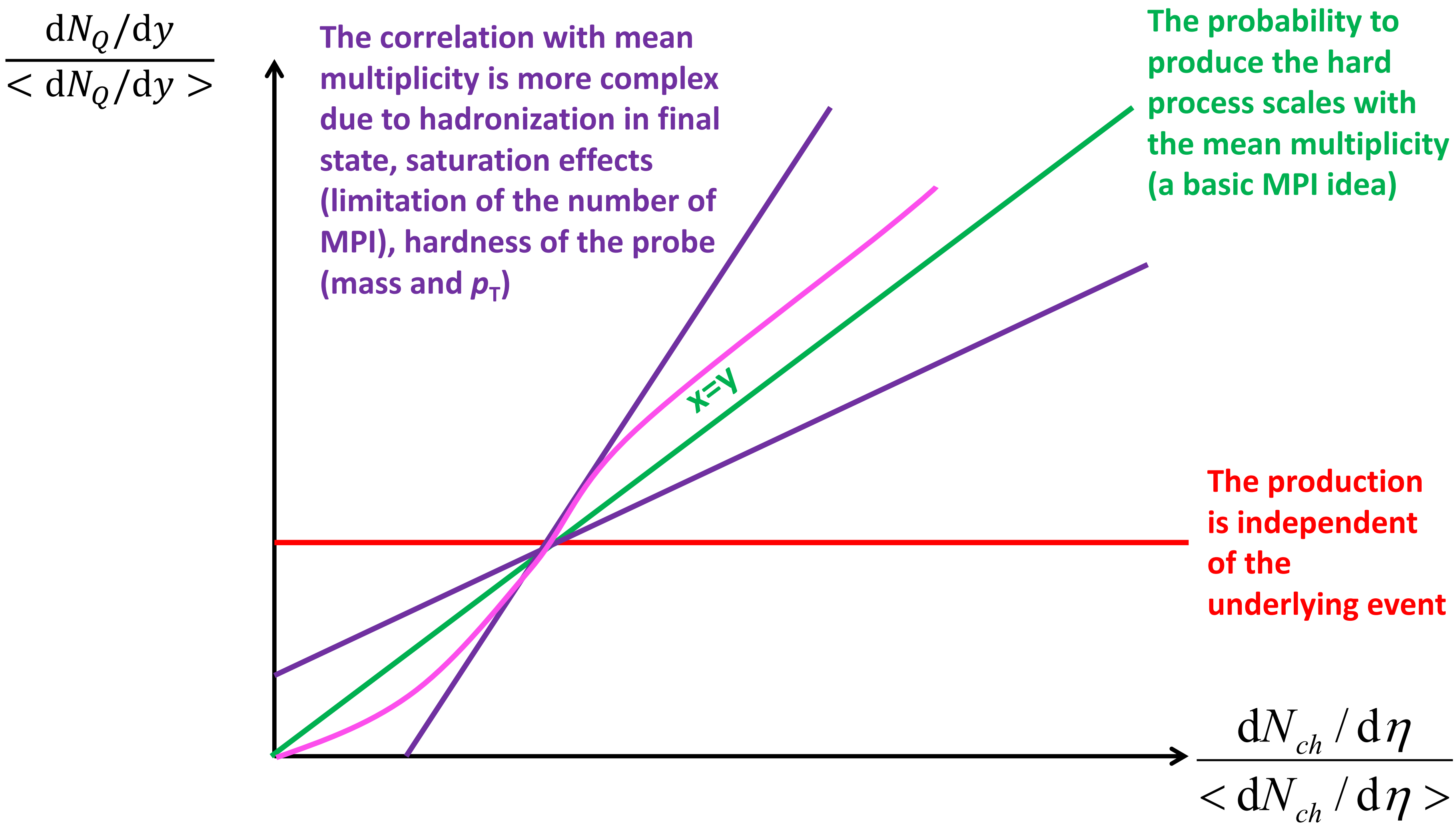

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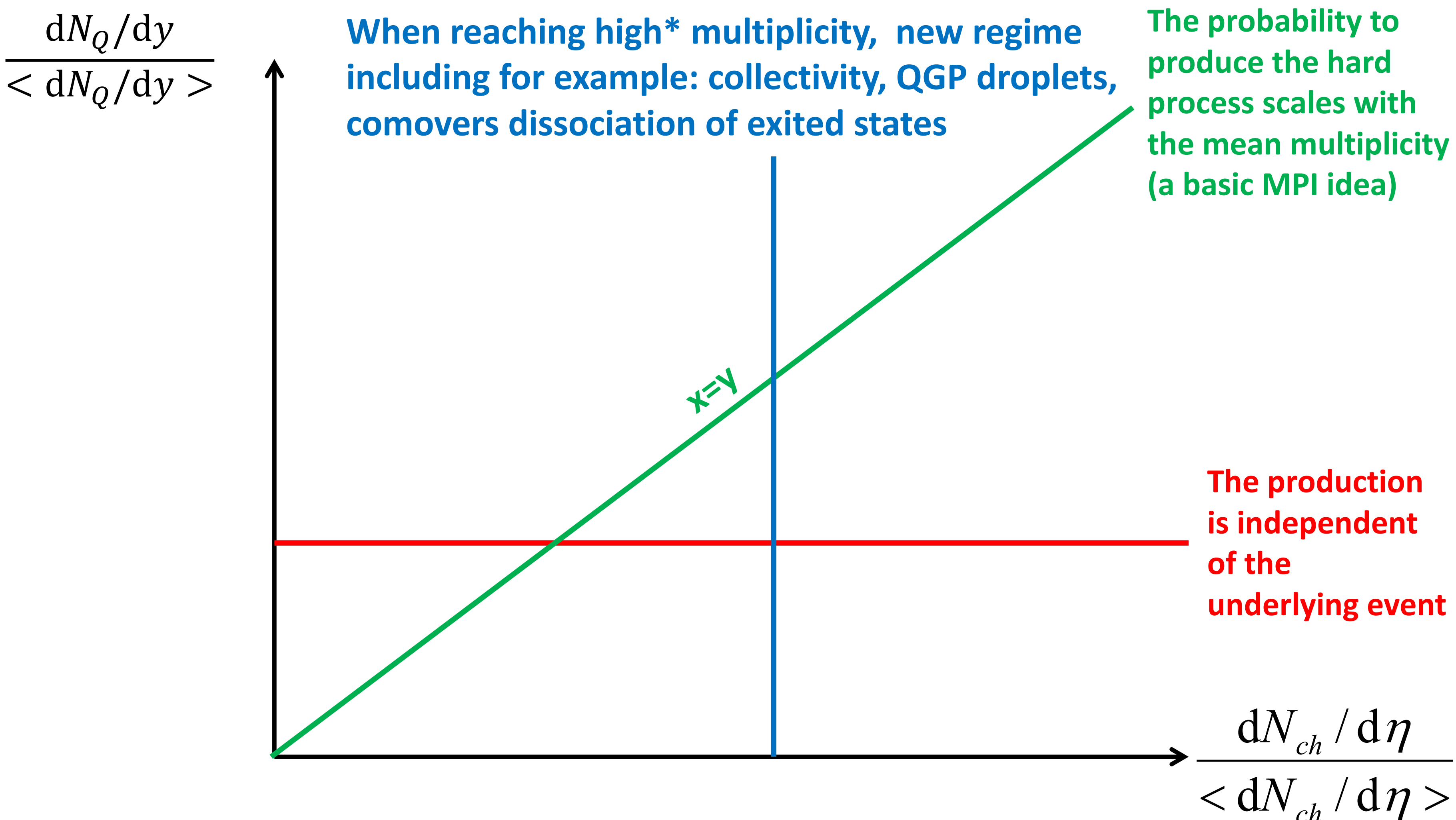

* *high* should be defined : how many times the mean mult ?

Related theory in one slide

Initial
+
Final

EPOS: EPOS3 vs. EPOS3.2

- EPOS 3 : collectivity explains qualitatively the deviation from linearity
- EPOS 3.2 : impact of collectivity in small systems is reduced and implementation of a coherent saturation scale along the model which lead to a different repartition : number of MPI vs. hardness of each =>explain STAR data at lower energy (smaller impact of collectivity)

https://indico.in2p3.fr/event/14438/contributions/18404/attachments/15245/18743/orsay.pdf

Initial
+
Final

PYTHIA

- Various production mode (hard process, MPI, ISR/FSR)
- MPI scenarios, also linked with the repartition : number of MPI vs. hardness
- Several final state mechanisms: color reconnection, string shoving

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➢ Kopeliovitch *et al.* Phys. Rev. D 88 no. 11, (2013)

- High multiplicities reached due to contribution of higher Fock states (increased number of gluons) , leading to an increase of the probability to produce a J/Ψ/ Nuclear effects in pA similar to high multiplicty pp collisions

Initial

➢ Strikman *et al.* Phys.Rev.Lett.**101**,202003(2008) Prog.Theor.Phys.Suppl.**187**,289(2011)

- Parton density in pp collisions (PDF) impact parameter dependent (centrality of a pp collisions) Enhanced effects by fluctuation of small-x gluon densities

Initial

➢ CGC Phys. Rev. D 98 no. 7, (2018) Eur. Phys. J. C 80 no. 6, (2020)

- Gluon saturation in initial state impact particle production

Related theory in one slide

Initial + Final

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CGC Phys. Rev. D 98 no. 7, (2018) Eur. Phys. J. C 80 no. 6, (2020)

- Gluon saturation in initial state impact particle production

Final

Percolation model Phys. Rev. C 86 (2012)

- Non linearity due to a reduction of the number of charged particles due to percolation of strings

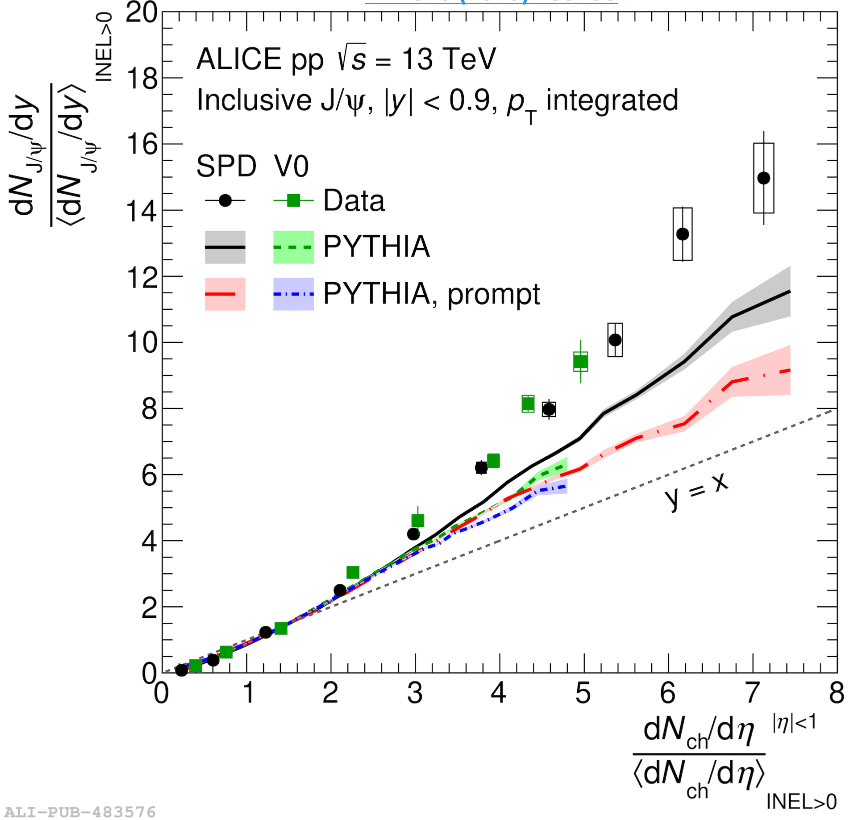
Final

Comovers Phys. Lett. B 749 (2015) arXiv:2006.15044

- High density final state environement dissociate events depending on their binding energies

J/Ψ in the central rapidity region

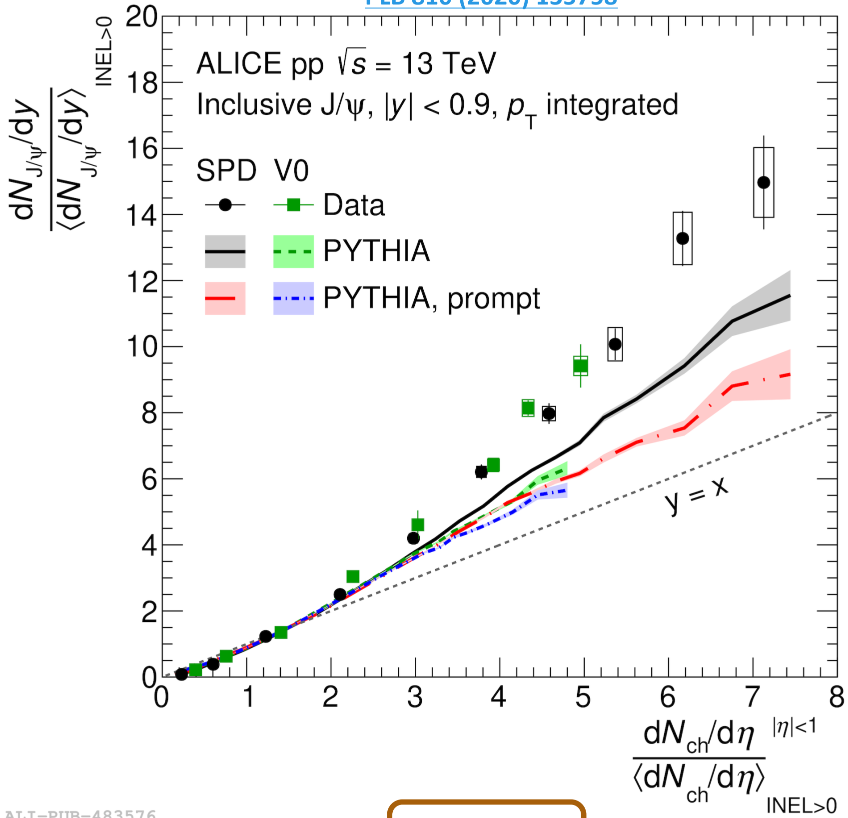
PLB 810 (2020) 135758



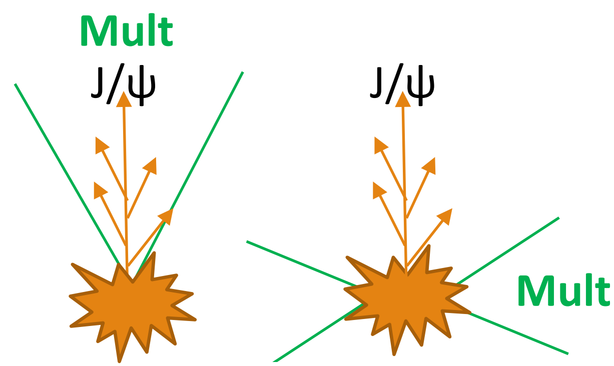
SARAH@CLERMONT.IN2P3.FR

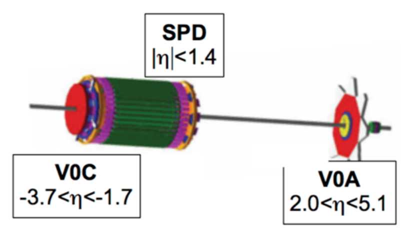
J/Ψ in the central rapidity region

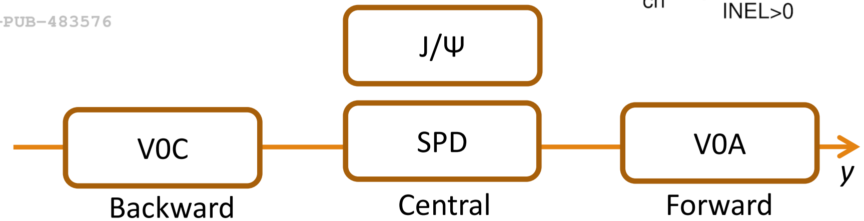
PLB 810 (2020) 135758



- J/Ψ central
- Multiplicity measurement central or forward
- Observed correlation not linear (~quadratic)
- Similar correlation, independently of the rapidity region of the multiplicity measurement

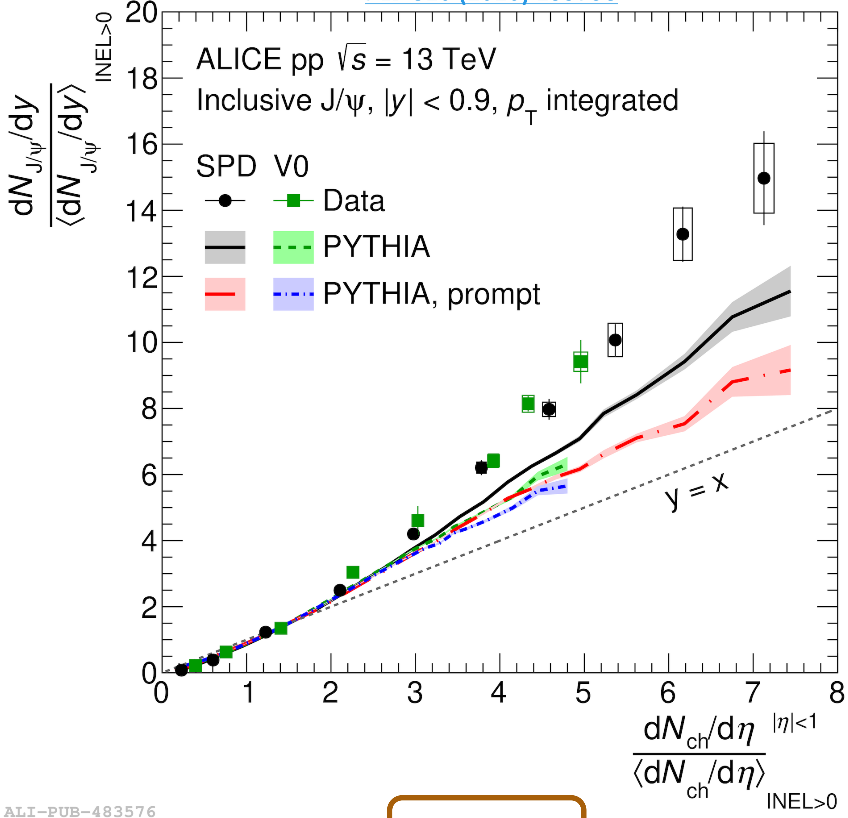


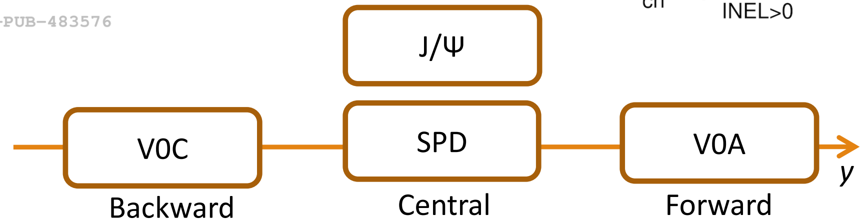




J/Ψ in the central rapidity region

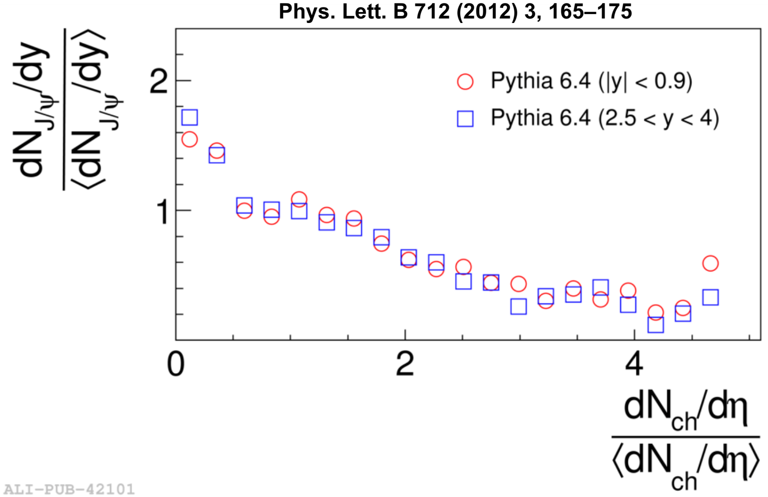
PLB 810 (2020) 135758





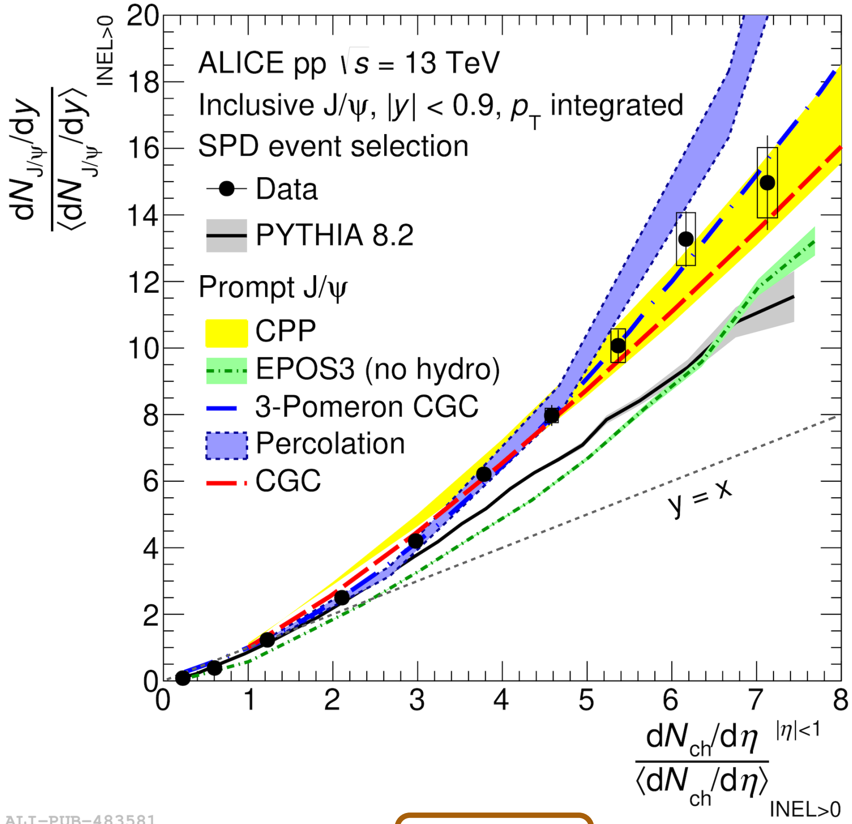
- J/Ψ central
- Multiplicity measurement central or forward
- Observed correlation not linear (~quadratic)
- Similar correlation, independently of the rapidity region of the multiplicity measurement
- Observed correlation not reproduced by PYTHIA*
- Better than PYTHIA 6.4 (MPI)

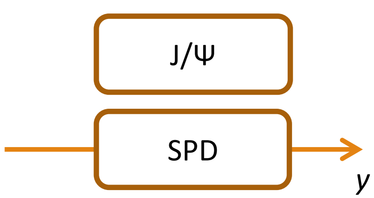
Phys. Lett. B 712 (2012) 3, 165–175



J/Ψ in the central rapidity region

PLB 810 (2020) 135758

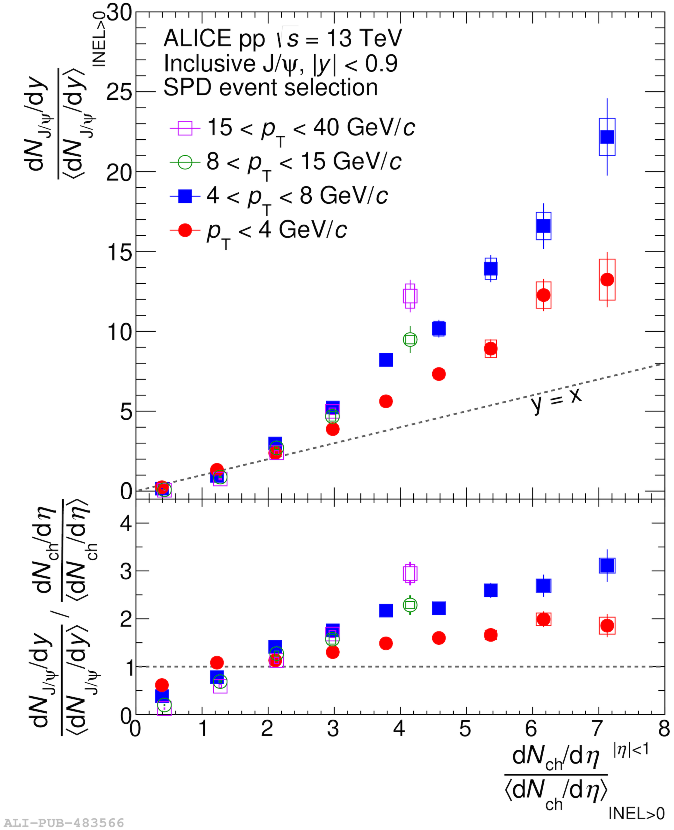


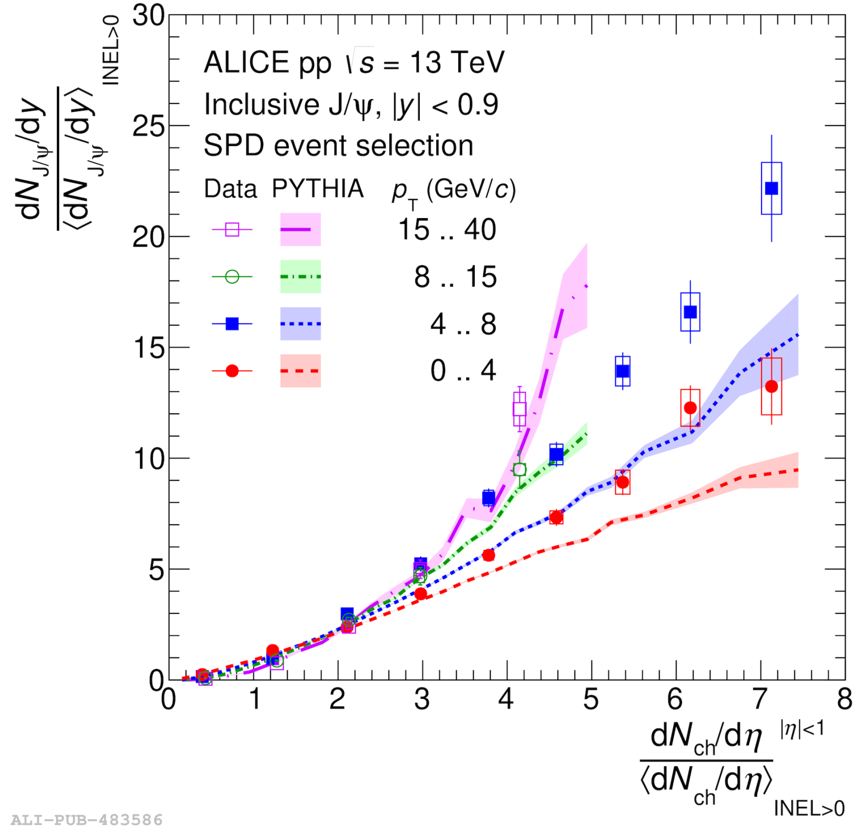


- ➢ Features catched by various approaches :
  - ➢ Initial state effects with modification of gluon distribution
  - ➢ Percolation (reduction of multiplicity)

- ➢ PYTHIA 8.2 and EPOS 3 (no hydro) show a departure from linearity, do not describe the data qualitatively

J/Ψ in the central rapidity region

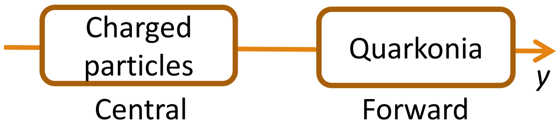


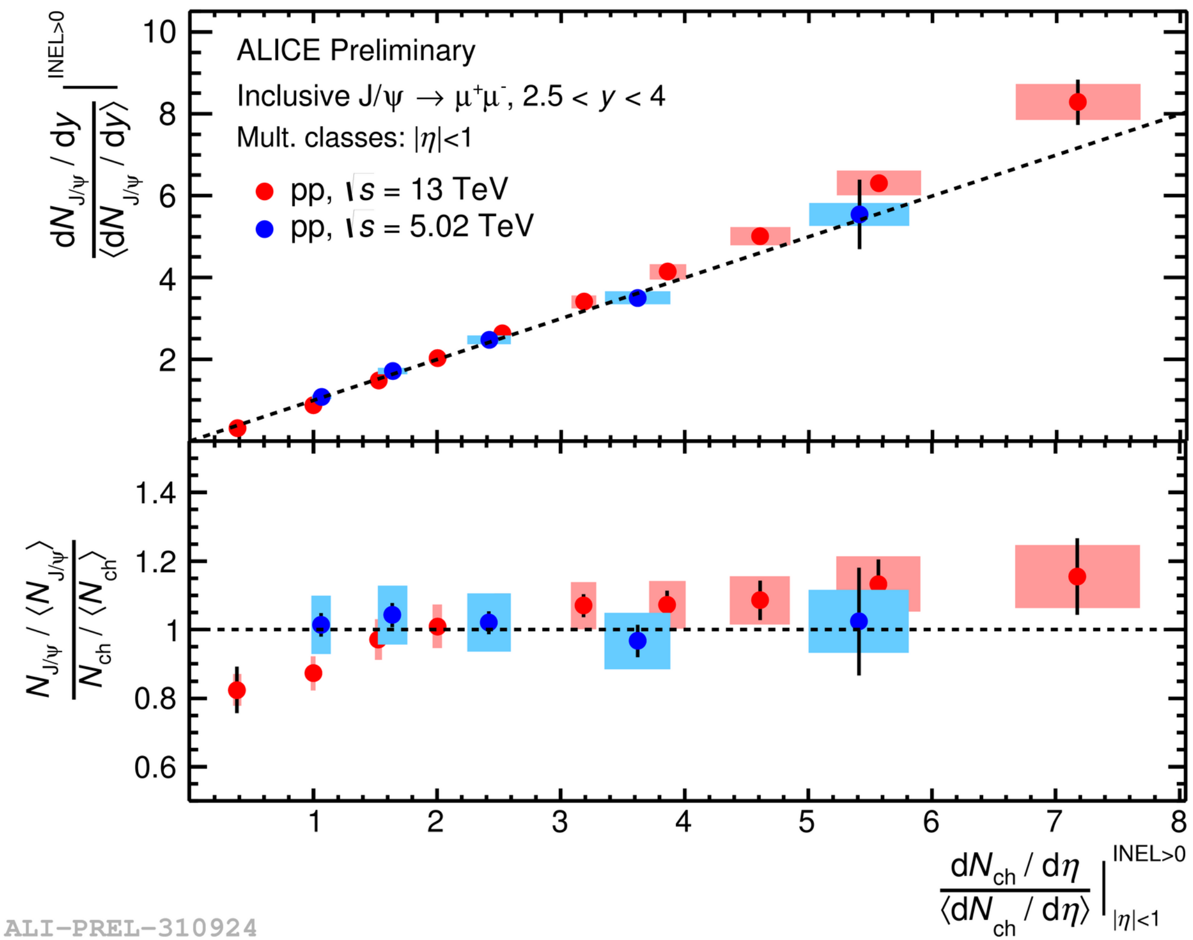


- Correlation varies with p_T ranges of the hard probe
- Number of MPI vs. hardness vs. initial state effects to built the multiplicity
- PYTHIA describes the data for p_T > 8 GeV/c

J/Ψ in the forward rapidity region

In the forward sectors for pp at 5.02 TeV and 13 TeV

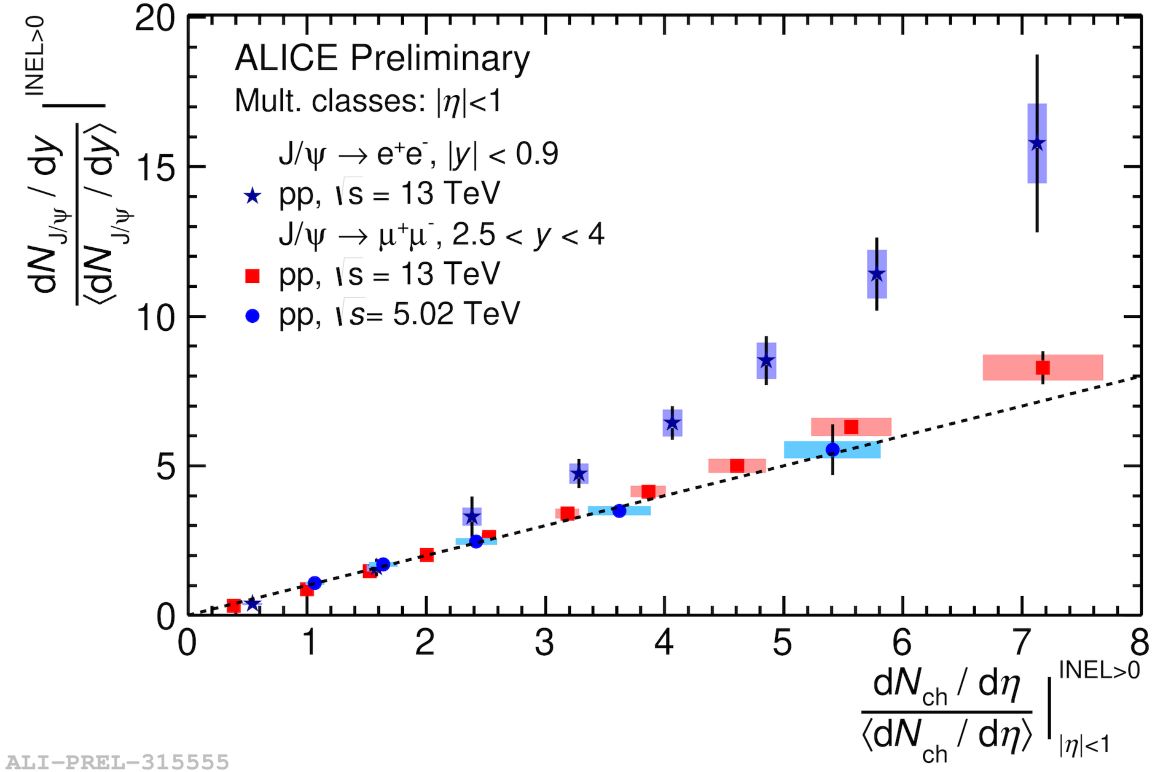


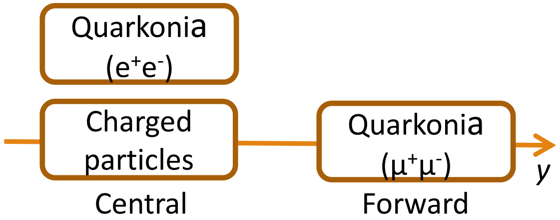


- The multiplicity is always measured in the central rapidity class
- A depletion below mean mult = 1
- Then linear increase, with slope compatible with 1, $x=y$ correlation
- No energy dependence

J/Ψ in the forward rapidity region

In the forward and central sectors for pp at 5.02 TeV and 13 TeV

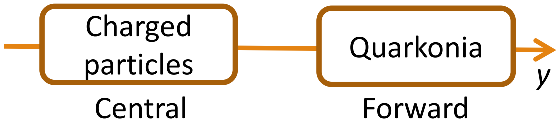


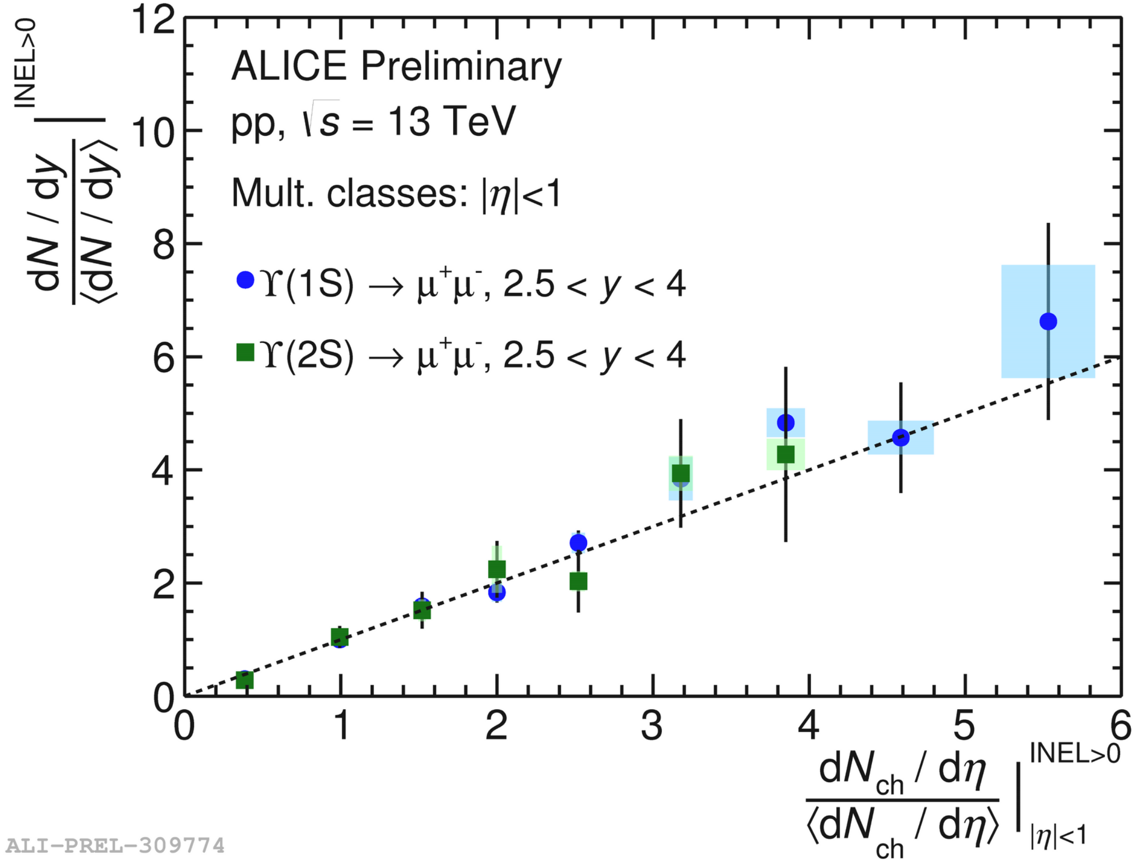


Different behavior when introducing a rapidity gap between the multiplicity estimator and the J/ψ

ϒ in the forward rapidity region

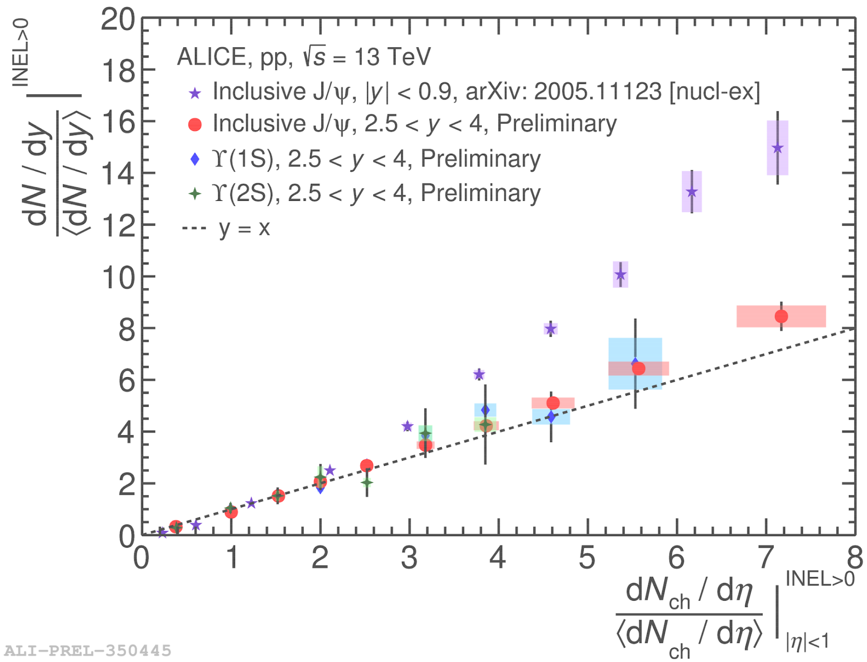
In the forward sectors for pp 13 TeV

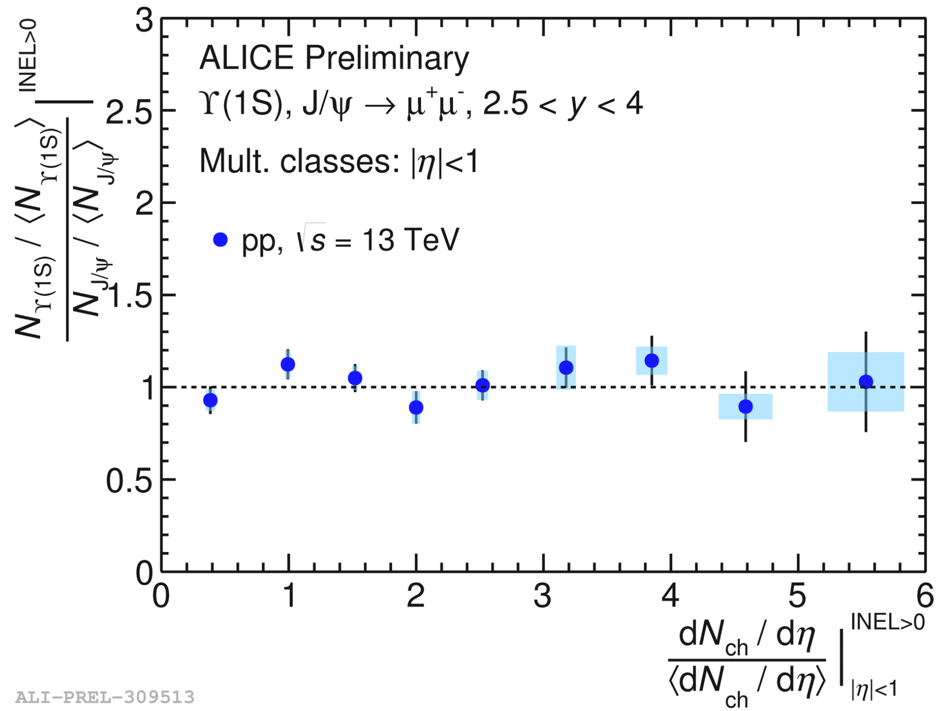




- The multiplicity is always measured in the central rapidity class
- A depletion below mean multiplicity = 1
- Then linear increase, with slope compatible with 1, *x*=*y* correlation

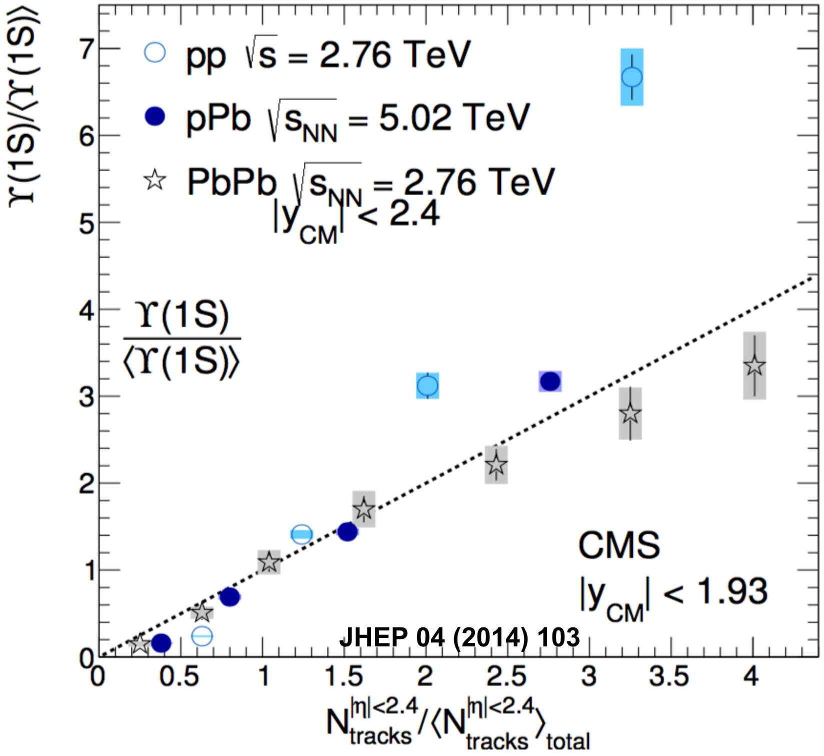
Quarkonia production as a function of multiplicity

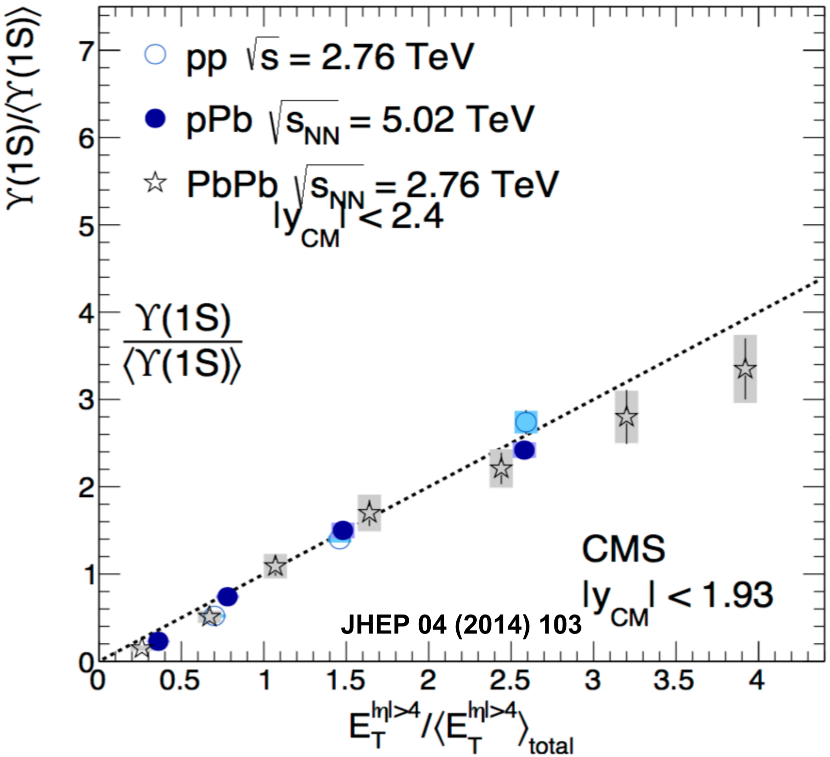




- ϒ have similar behavior as J/ψ in the forward sector within current uncertainties
- No effect seen with respect to quark content or mass

ϒ: What about rapidity gap ?

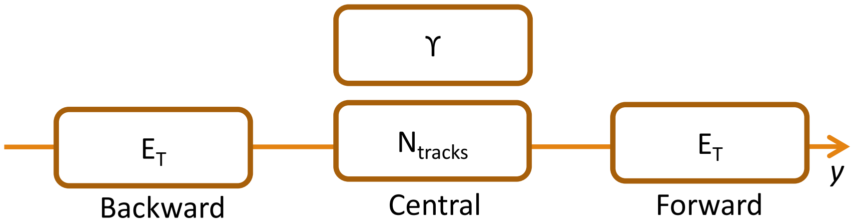




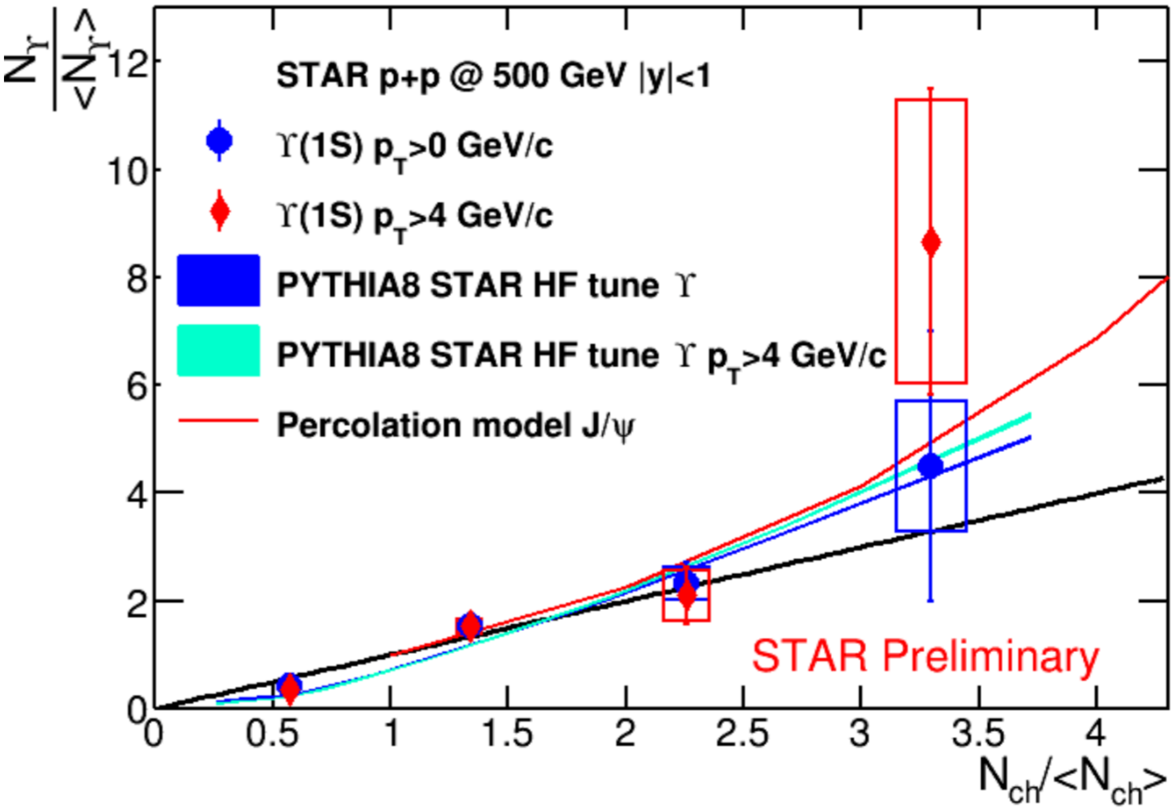
- CMS observes a strong increase of Upsilon states in the central rapidity region (pp 2.76 TeV)

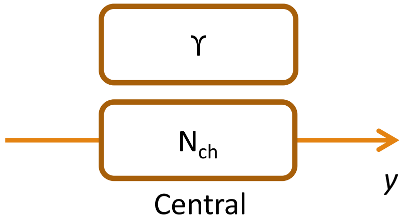
- Linear behavior measured for forward E_T

- Qualitatively similar to what we observe for J/ψ and D mesons in similar rapidity region



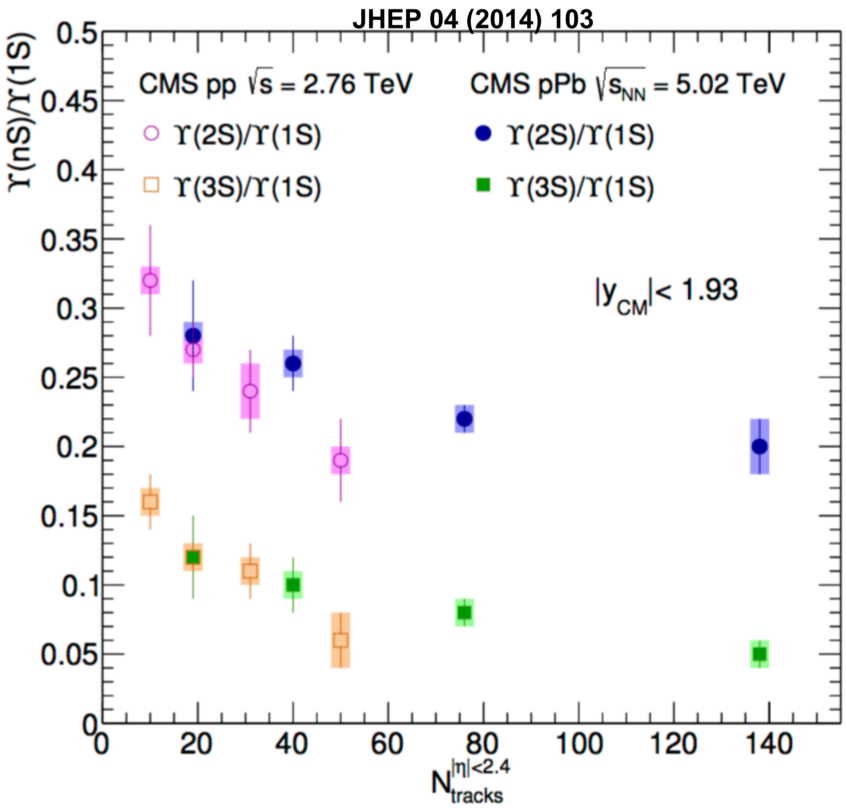
ϒ: What about rapidity gap ?

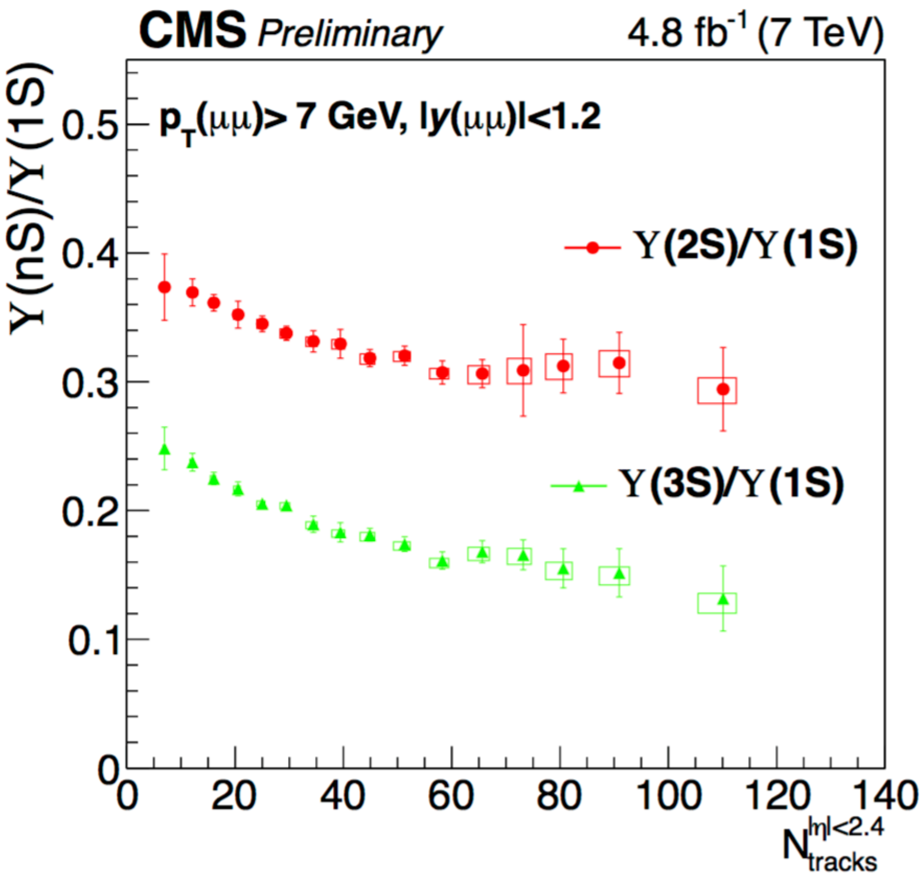




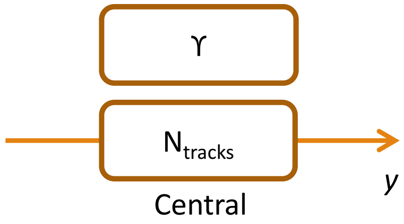
STAR observes in pp at 500 GeV in central rapidity region a deviation from linearity which is not significant with current uncertainties

ϒ: Exited to ground state ratio ?

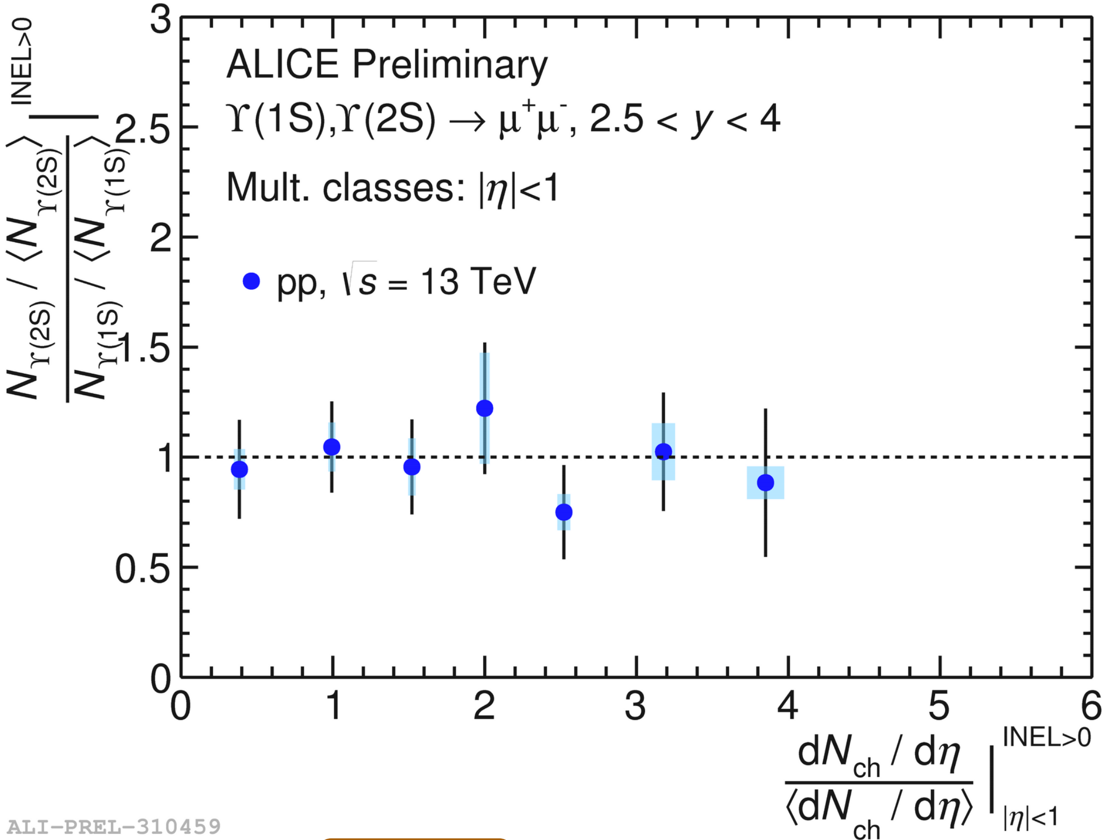


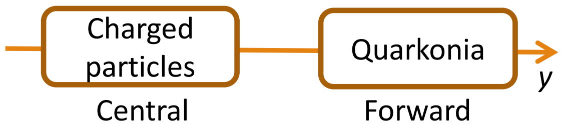


- CMS observes in pp at 2.76 TeV and 7 TeV and p-Pb at 5.02 exited to ground state disappearance in the central rapidity region, confirmed by analysis with sphericity and kinematic region of multiplicity (forward/backward/transverse)



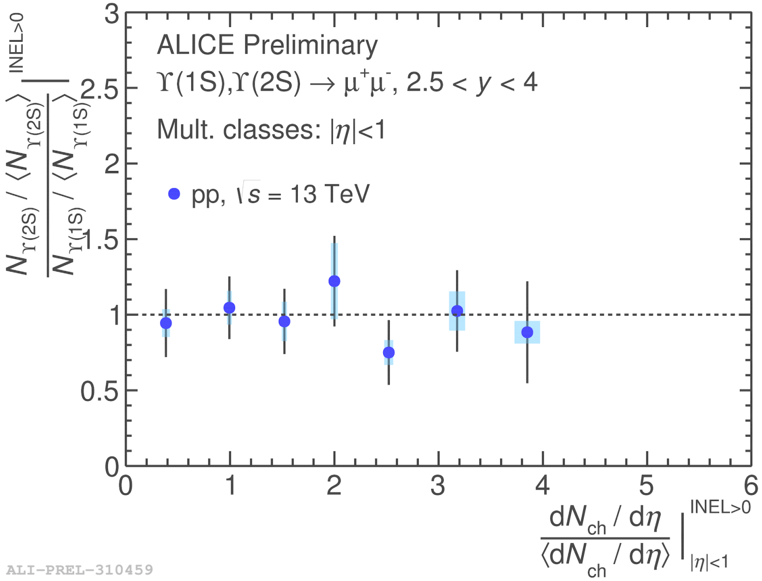
ϒ: Exited to ground state ratio ?

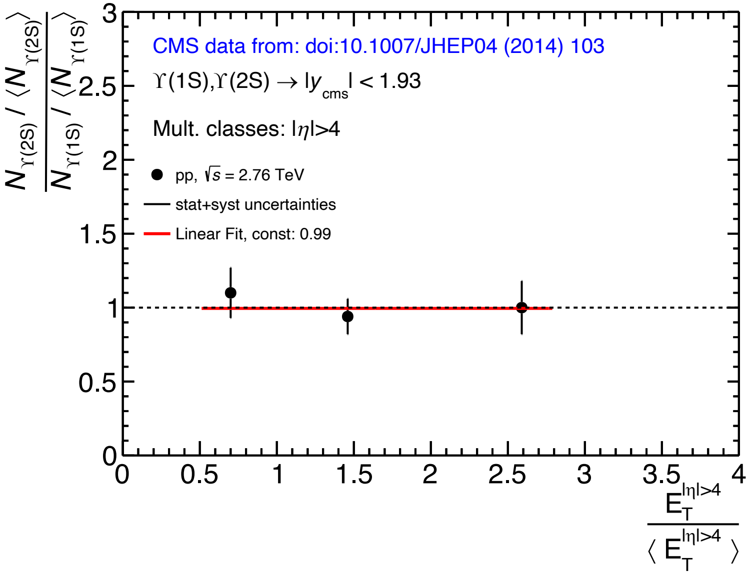


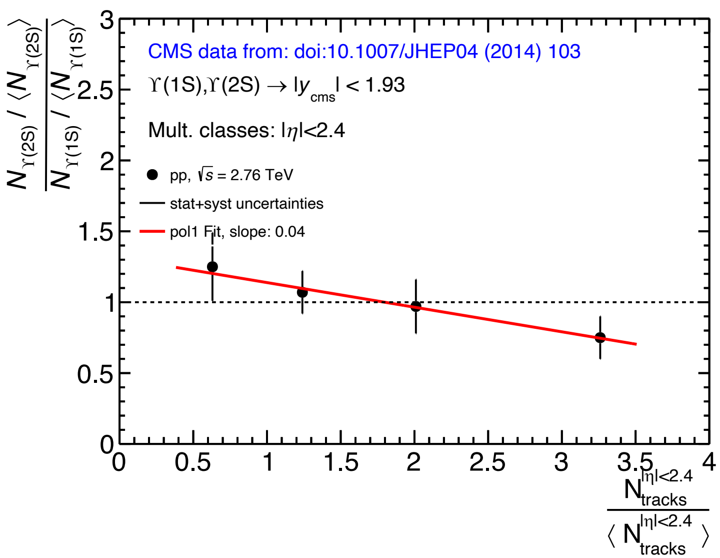


- ALICE observes same behavior as a function of multiplicity for the 1S and 2S states
- Caveats to compare to CMS: not exactly the same observables, definition of multiplicity, INEL>0
- Is the reason du to
  - a physics phenomenon: hadronization of Upsilon, dissociation in final state
  - a definition of the observable (multiplicity estimator)

ϒ: Exited to ground state ratio ?

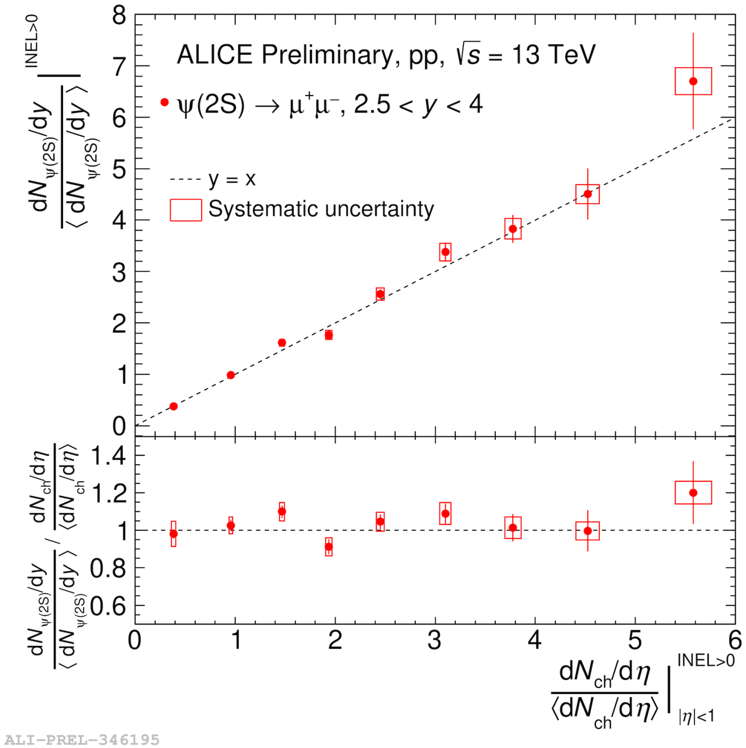


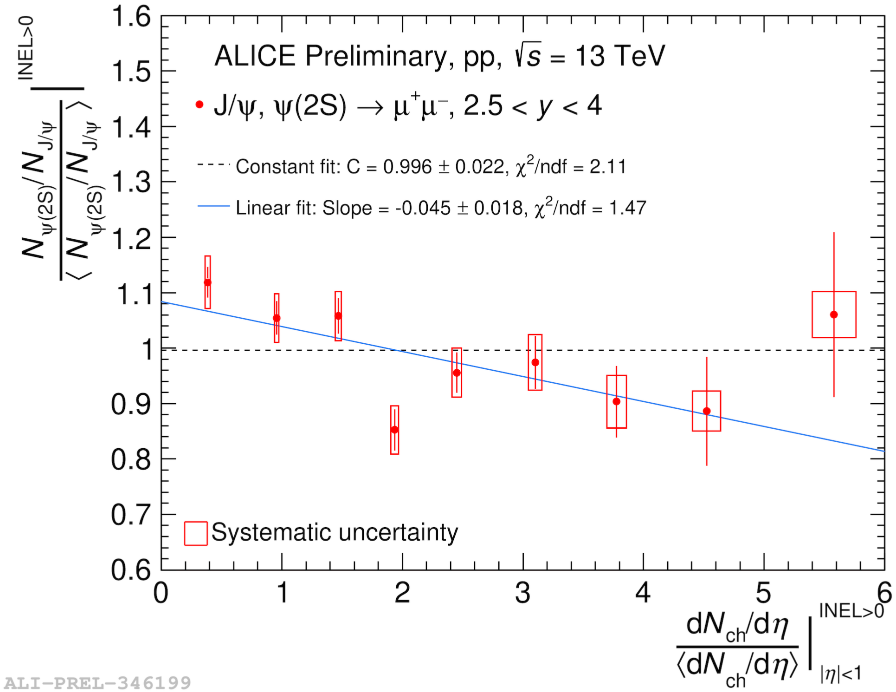




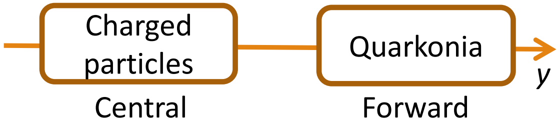
- Replotting CMS results as double ratios
- Decrease not excluded by ALICE results

Ψ(2s) in the forward rapidity region

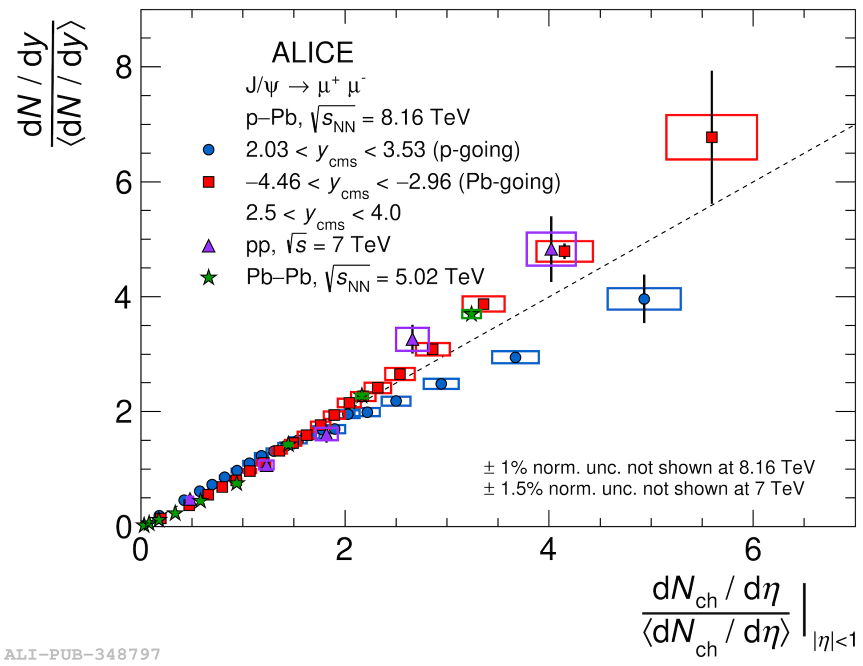


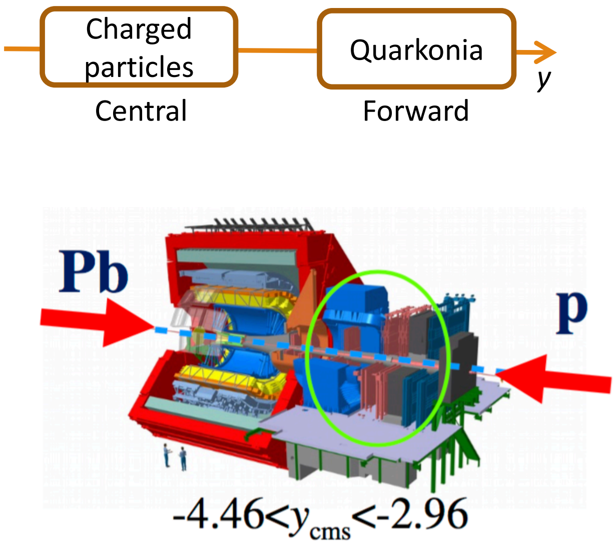


- Ψ(2s) over J/Ψ double ratio to be investigated further at RUN3
- Potential dissociation not excluded



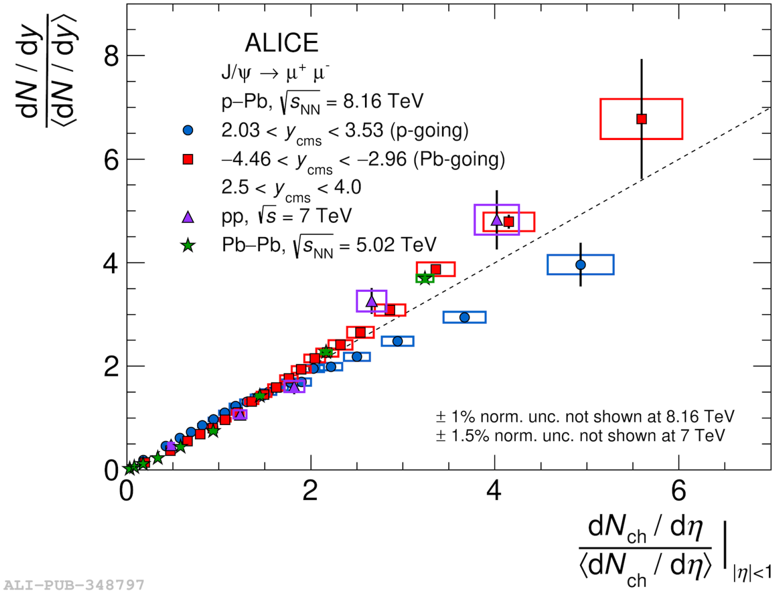
Changing system: p-Pb to Pb-Pb

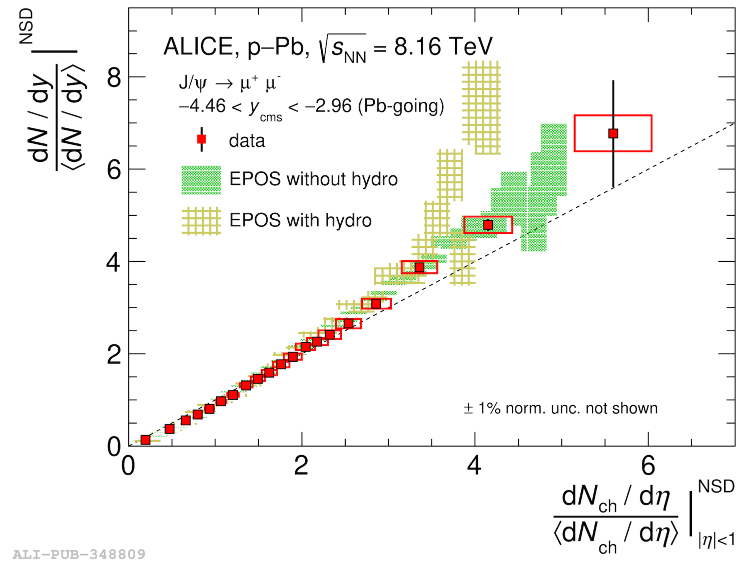


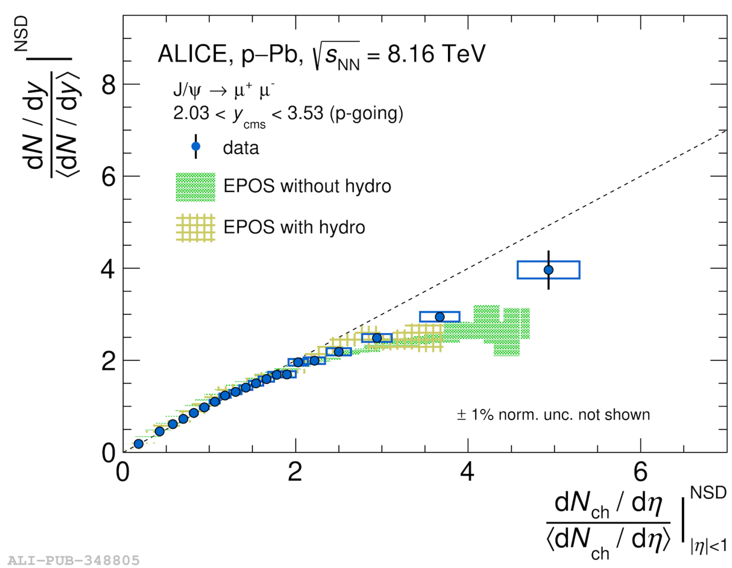


- Similar behavior from pp, to p-Pb (Pb-going) to Pb-Pb
- p-Pb (p-going) presents a different trend

Changing system: p-Pb to Pb-Pb







- EPOS3 describes this kinematical feature

Charm/beauty vs. mult

State	Channel	System	Energy	Exp.	ref
J/Ψ	- $\mu^+\mu^-$, $\|y\|<0.5$, $p_T >$ 0 GeV/c - e^+e^-, $\|y\|<1$, $p_T >$ 1.5/4 GeV/c	pp	200 GeV 500 GeV	STAR	PLB 786 (2018) 87–93
J/Ψ	- $\mu^+\mu^-$, 2.5<y<4, $p_T >$ 0 GeV/c	pp	2.76 TeV	ALICE	Preliminary
J/Ψ	- $\mu^+\mu^-$, 2.5<y<4, $p_T >$ 0 GeV/c	pp	5.02 TeV	ALICE	Paper in preparation
J/Ψ	- $\mu^+\mu^-$, 2.5<y<4, $p_T >$ 0 GeV/c - e^+e^-, $\|y\|<0.9$, $p_T >$ 0 GeV/c	pp	7 TeV	ALICE	Phys. Lett. B712 (2012) 165-175
J/Ψ	- e^+e^-, $\|y\|<0.9$, $p_T >$ 0 GeV/c - $\mu^+\mu^-$, 2.5<y<4, $p_T >$ 0 GeV/c	pp	13 TeV	ALICE	- PLB 810 (2020) 135758 - Paper in preparation
J/Ψ	- $\mu^+\mu^-$, $p_T >$ 0 GeV/c 2.03<y_{cms}<3.53 (p-going) -4.46<y_{cms}<-2.96 (Pb-going) - e^+e^- -1.37<y_{cms}<0.43 $p_T >$ 0 GeV/c	p-Pb	5.02 TeV	ALICE	Phys. Lett. B 776 (2018) 91-104
J/Ψ	- $\mu^+\mu^-$, $p_T >$ 0 GeV/c 2.03<y_{cms}<3.53 (p-going) -4.46<y_{cms}<-2.96 (Pb-going)	p-Pb	8.16 TeV	ALICE	JHEP 2009 (2020) 162
J/Ψ	- transverse energy deposition in the backward (3.1<η<4.9) - -2<y<1.5, 8 < p_T < 40 GeV/c	P-Pb	5.02 TeV	ATLAS	Eur. Phys. J. C 78 (2018) 171
Ψ(2S)	- $\mu^+\mu^-$, 2.5<y<4, $p_T >$ 0 GeV/c	pp	13 TeV	ALICE	Preliminary
D^0, D^+, D^{*+}	- Hadronic decay, $\|y\|<0.5$, 1<p_T <20 GeV/c	pp	7 TeV	ALICE	JHEP 09 (2015) 148
D^0, D^+, D^{*+}	- Hadronic decay, −0.96<y_{cms} <0.04, 2<p_T <24 GeV/c	p-Pb	5.02 TeV	ALICE	JHEP 8 (2016) 1-44
D_s^+,D+	- Hadronic decay, −0.96<y_{cms} <0.04 , 2<p_T <24 GeV/c	p-Pb	5.02 TeV	ALICE	
Non prompt J/Ψ	- e^+e^-, $\|y\|<0.9$, $p_T >$ 1.3 GeV/c	pp	7 TeV	ALICE	JHEP 09 (2015) 148

Charm/beauty vs. mult

State	Channel	System	Energy	Exp.	ref
Υ(1S)	- e^+e^-, $\lvert y \rvert<1$, $p_T > 0/4$ GeV/c	pp	500 GeV	STAR	Preliminary https://drupal.star.bnl.gov/STAR/files/Upsilon_PWRHIC_LK_2018_1_7.pdf
Υ(1/2/3S)	- $\mu^+\mu^-$, $\lvert y \rvert<1.93$, $p_T > 0$ GeV/c	pp	2.76 TeV	CMS	JHEP04(2014)103
Υ(1/2/3S) polarizations	- $\mu^+\mu^-$, $\lvert y \rvert<1.2$, $10<p_T<15$ GeV/c, $15<p_T<35$ GeV/c	pp	7 TeV	CMS	Phys.Lett. B761 (2016) 31-52
Υ(1/2/3S)	- $\mu^+\mu^-$, $\lvert y \rvert<1.2$, $p_T > 0$ GeV/c	pp	7 TeV	CMS	JHEP 11 (2020) 001
Υ(1/2S)	- $\mu^+\mu^-$, $2.5<y<4$, $p_T > 0$ GeV/c	pp	13 TeV	ALICE	Paper in preparation
Υ(1/2/3S)	- $\mu^+\mu^-$, $\lvert y \rvert<1.93$, $p_T > 0$ GeV/c	p-Pb	5.02 TeV	CMS	JHEP04(2014)103
Υ(1/2/3S)	- $\mu^+\mu^-$, $\lvert y \rvert<1.93$, $p_T > 0$ GeV/c	p-Pb	2.76 TeV	CMS	JHEP04(2014)103
HF	- Single-μ, $2.5<\eta<4$, $2<p_T<20$ GeV/c	pp	8 TeV	ALICE	
HF	- c,b->e, $\lvert y_{max} \rvert<0.8$, $0.5<p_T<30$ GeV/c	pp	13 TeV	ALICE	Paper in preparation
HF	- e^+e^-, $\lvert y_e \rvert<0.8$, $p_{T,e} > 0.2$ GeV/c, high mult	pp	13 TeV	ALICE	**Phys. Lett. B 788 (2019) 505**
HF	- e^-, $1.06<y_{cms}<0.14$, $0.5<p_T<8$ GeV/c	p-Pb	5.02 TeV	ALICE	
HF	- c,b -> e, $\lvert y_{max} \rvert<0.8$, $0.5<p_T<26$ GeV/c	P-Pb	8.16 TeV	ALICE	Paper in preparation

Open questions

- Behavior with respect to **energy and multiplicity**
  -> event with same multiplicity in final state are (or not) similar (500 GeV up to 13 TeV)?
- Behavior with respect to **systems**
  -> event with same multiplicity in final state are (or not) similar (pp vs. p-Pb vs Pb-Pb)?
- Behavior with respect to the **nature of the hard probes** (quark content, production mechanisms, closed vs. open charm/beauty)
- Behavior with respect to the **hardness of the hard probes** (invariant mass, p_T bins)
- Behavior with respect to the **multiplicity estimator**
- What is the **elementary building block of hadronic interaction**, MPI vs. nucleon-nucleon, is there a continuity from pp to AA and energy?
- Caveats, discussion should include also $< p_T >$, multiplicity studies, DPS, centrality

Conclusions

- **QGP properties** were largely studied at LHC RUN 1+2 in **heavy ion collisions**

- **A heavy-ion LHC discovery: small system physics**
  QGP signatures are observed for soft probes in high multiplicity sector of reference systems pp and p-A => unexpected!

- **Need** to **understand** the **initial state** of hadronic collisions and how the multiplicity is built up to the very high multiplicity sector (pp vs. p-A vs. A-A)

- **New observables,** soft-hard correlations in pp collisions
  - Within current uncertainties : no energy dependence, quark and mass content at forward
  - **Rapidity configuration** of the measurement (multiplicity and quarkonia) plays a role : linear or quadratic

- **Strong impact on event generators** : MPI vs. jet fragmentation vs. saturation vs. collectivity

- **To be continued in RUN3**
  - hadronic activity around quarkonia and fragmentation function
  - increase of statistics and new opportunities like sphericity, event classifier (R_T)

Possible implications for EIC

- **Study small systems / high multiplicities** at EIC : turning off sign of collectivity or not ?
  Role of saturation ?
  Could be a missing baseline for LHC
  Need to estimate expected charged particle multiplicities reached at EIC and feasibility

- **Understanding the highest multiplicity reached**: no multi-parton interactions to built the charged particle multiplicity, role of jet and fragmentation

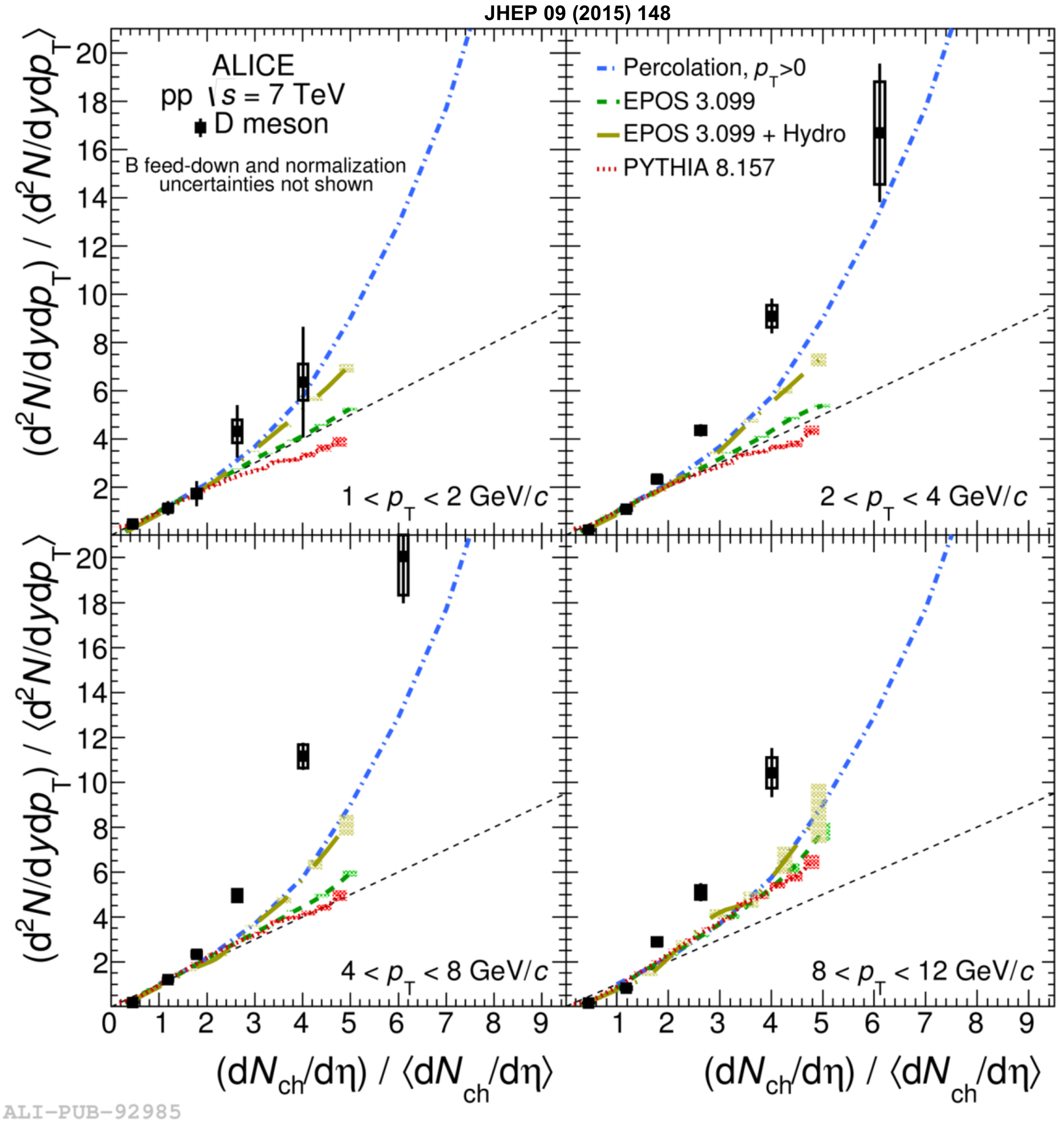
- If there is a case **for open/closed charm and beauty** at EIC, can help elucidating the building of multiplicity associated with charm and beauty and the onset of collective effects

- **To go beyond the Glauber model and finding proper scaling quantity** (N_{ch}, $R_{T, ...}$)

- **Test string fragmentation and fragmentation function in dense hadronic environment**

Thanks

HF vs. charged particle multiplicity



- **PYTHIA and EPOS wo hydro**

  Linear behavior fails to reproduce the data for the highest multiplicities

- **EPOS w hydro and percolation**

  Departure from linearity help to describe the data.
  Reduction of the number of charged particles
  - hydro evolution for EPOS

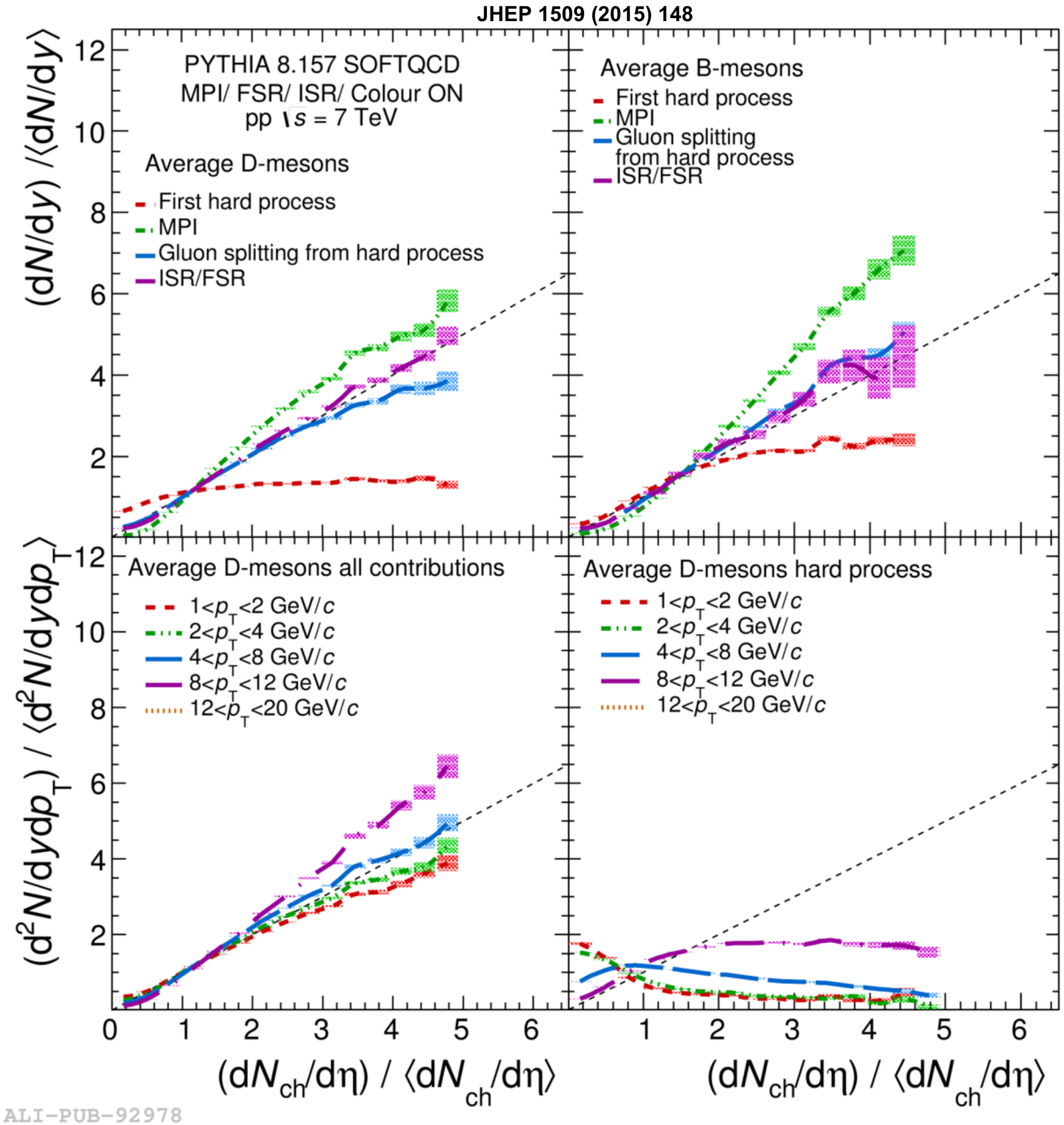
    arXiv:1602.03414
  - string percolation for the percolation model

HF vs. charged particle multiplicity

PYTHIA 8.157

- Top left : average D-mesons from different sources
- Top right : average B-mesons from different sources
- Bottom left : average D-mesons, all contributions, slices in p_T
- Bottom right : average D-mesons, slices in p_T for first hard contribution only

Tagging of D meson origin reveals implementation in PYTHIA



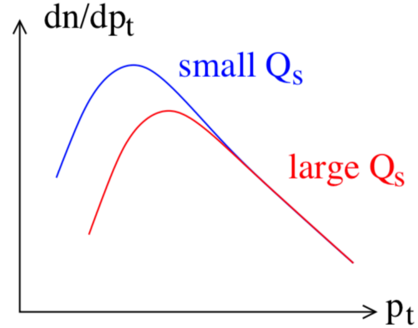
EPOS

Slides stolen from Klaus Werner

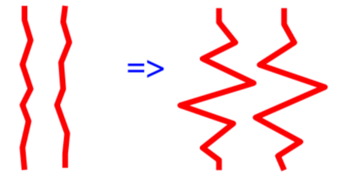
https://indico.in2p3.fr/event/14438/

- Recent development : EPOS 3.2

Parton distributions



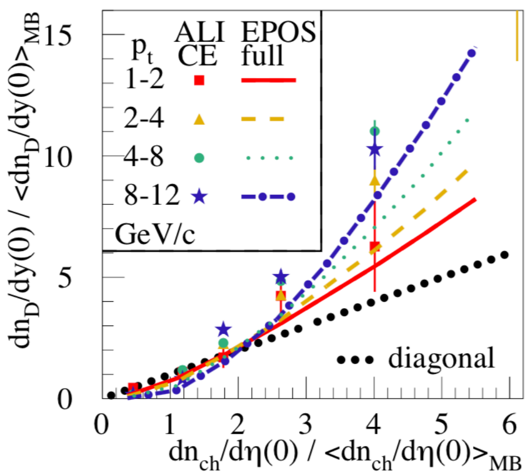
Increasing $\langle dn/d\eta(0)\rangle$ corresponds to increasing N_{Pom}. With $Q_s(N_{\mathrm{Pom}})$
=> Increasing Q_s
=> harder Pomerons
=> harder strings



=> more high pt particles

=> Strong increase of $\langle p_t\rangle$ with $\langle dn/d\eta(0)\rangle$

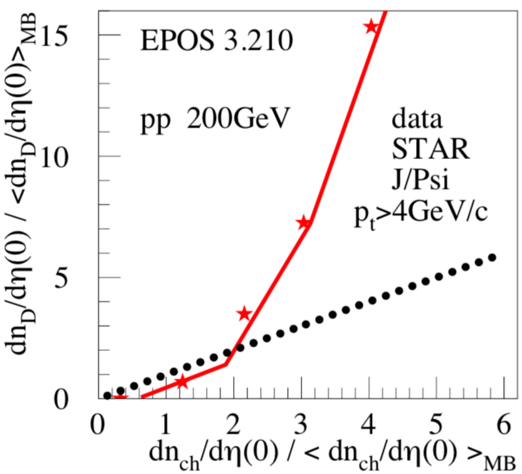
EPOS 3 compared to ALICE data



hadronic cascade on/off has no effect

hydro on/off has small effect

EPOS 3 compared to RHIC data



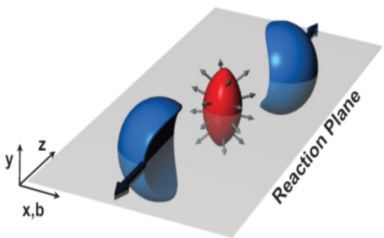
Calculations:
D mesons

Data: J/Ψ

Increase stronger than at LHC

QGP

Elliptic flow of charged particles



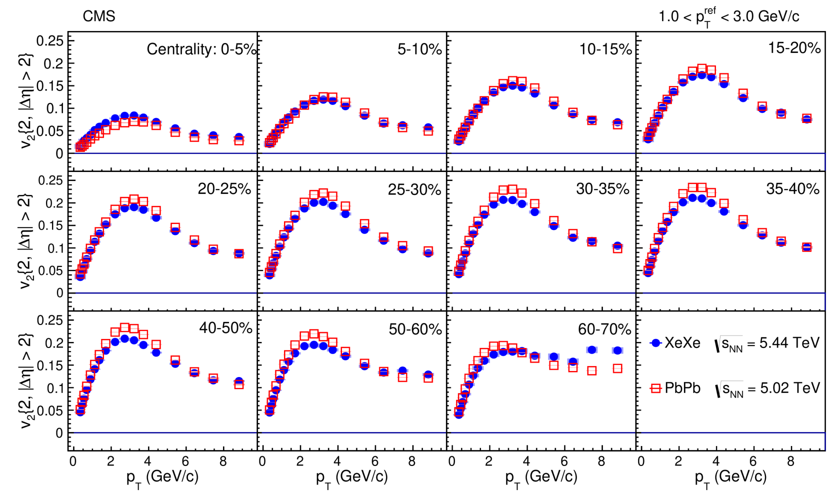
Elliptic flow

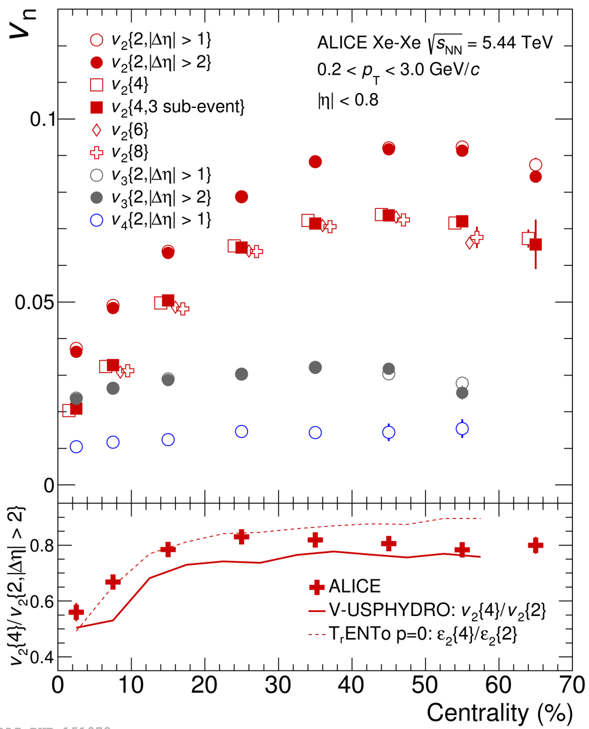
Initial spatial anisotropy transferred into a momentum anisotropy of particles

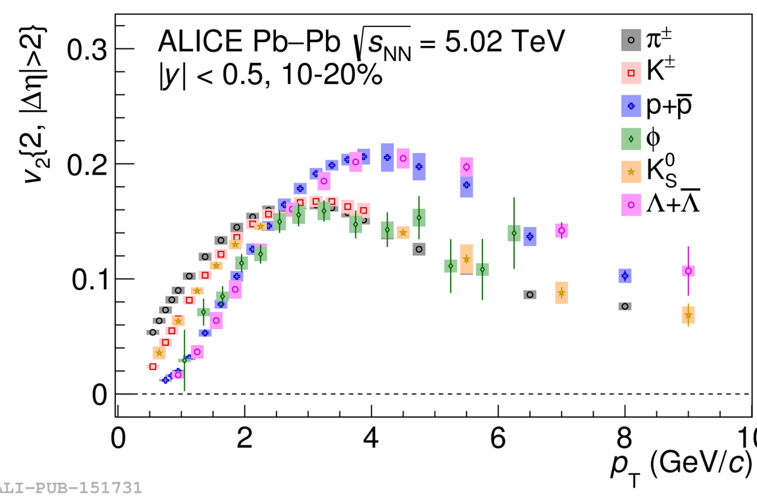
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi n))$$

The second coefficient is v_2 (elliptic flow)

$v_2 > 0$, interpreted as collective expansion of the medium





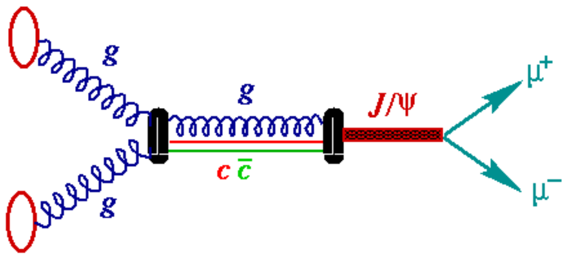


Charged particles flow in AA collisions with expected characteristics of **mass ordering**.

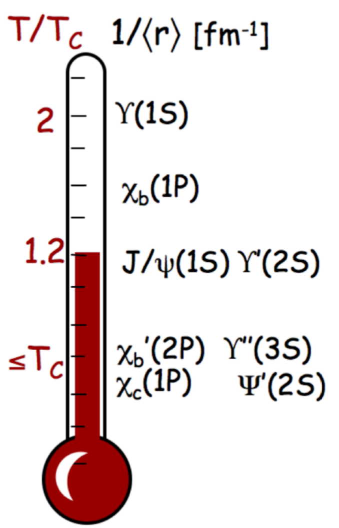
Confirmed by advanced analysis **subtracting non flow component.**

Quarkonia

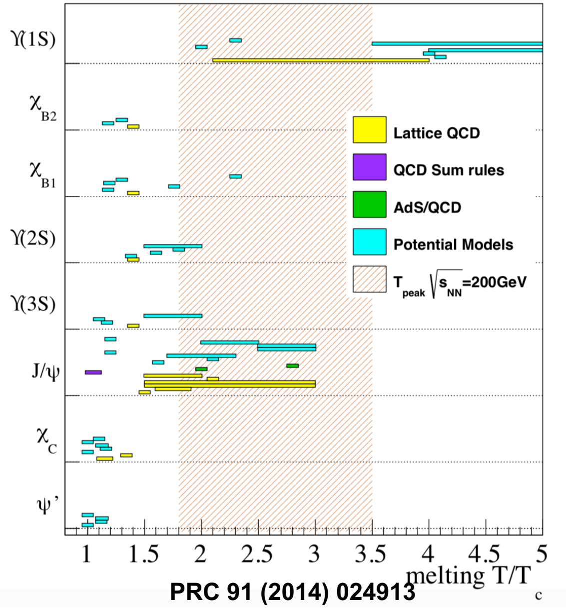
- **Quarkonia**, bound states of charm and beauty quarks,
  - Charmonia ($c\bar{c}$): e.g. J/ψ and $\Psi(2S)$
  - Bottomonia ($b\bar{b}$): e.g. $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$



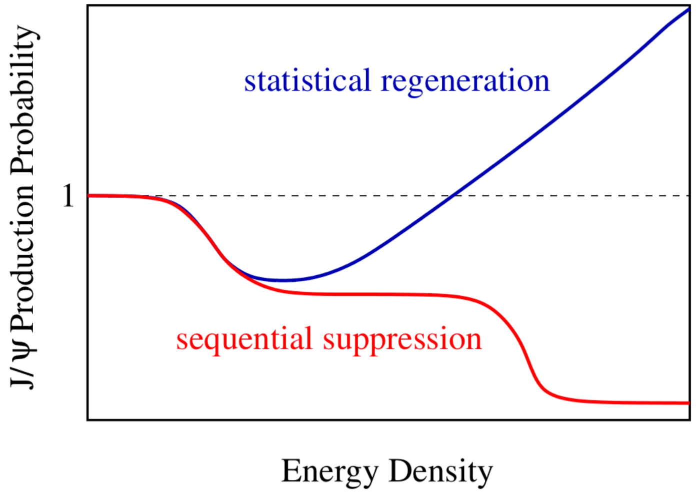
- Quarkonia, produced in first stage of AA collisions, experience the full QGP evolution:
  - **Quarkonium sequential suppression** via color screening **[Matsui and Satz, PLB178 (1986) 416]**
  - **Quarkonium regeneration**
    [Braun-Munzinger & Stachel, PLB 490 (2000) 196 ; Thews, Schroedter & Rafelski, PRC 65 (2001) 054905]



Eur Phys J C61 (2009) 705

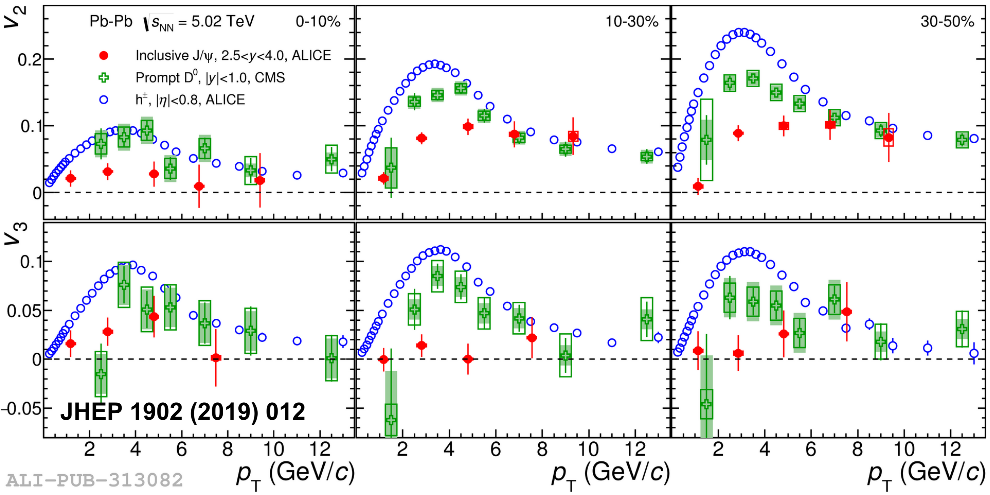


PRC 91 (2014) 024913



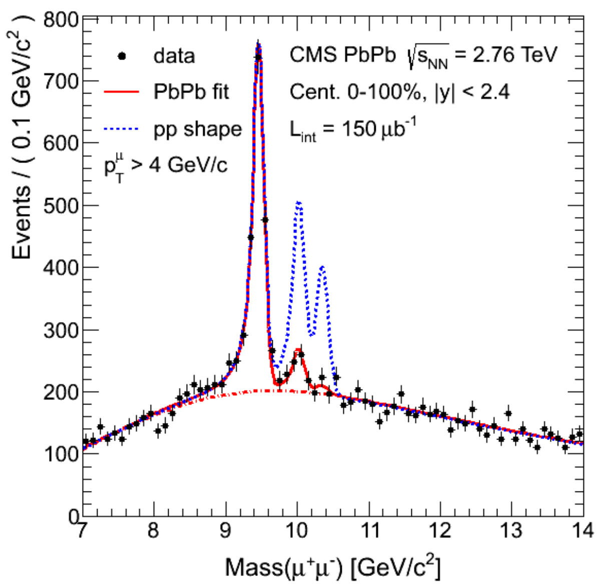
NPB 214 (2011) 3

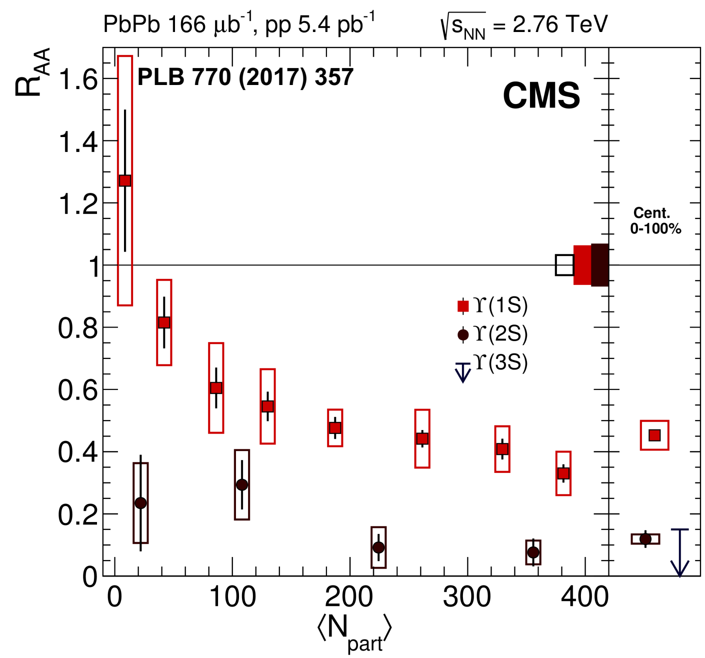
Quarkonia at Runs 1+2



- **Unambiguous observation of non-zero J/ψ v_2**
- At high p_T, stronger effect than expected: possible path-length dependence effect
- At low and intermediate p_T: $v_n(J/\psi) < v_n(D) < v_n(h)$

- **Strong ϒ suppression at the LHC**
- Exited states melting
- $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S))$





Quarkonia at Runs 1+2

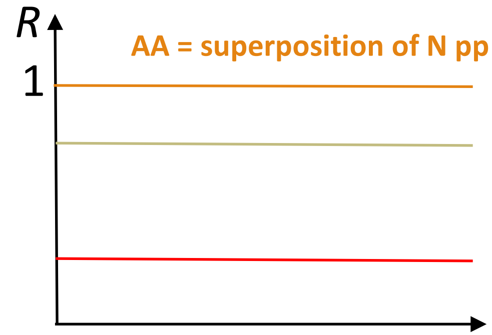
Nuclear modification factor

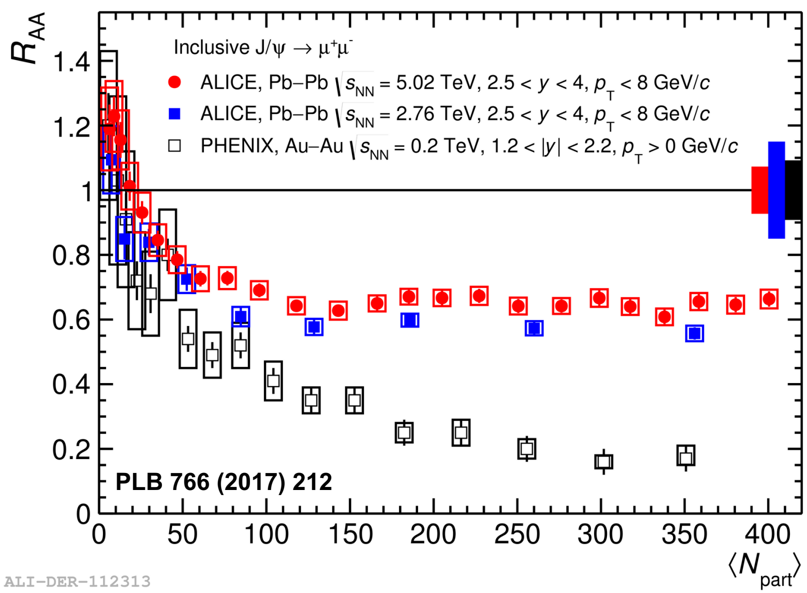
Measurement in AA

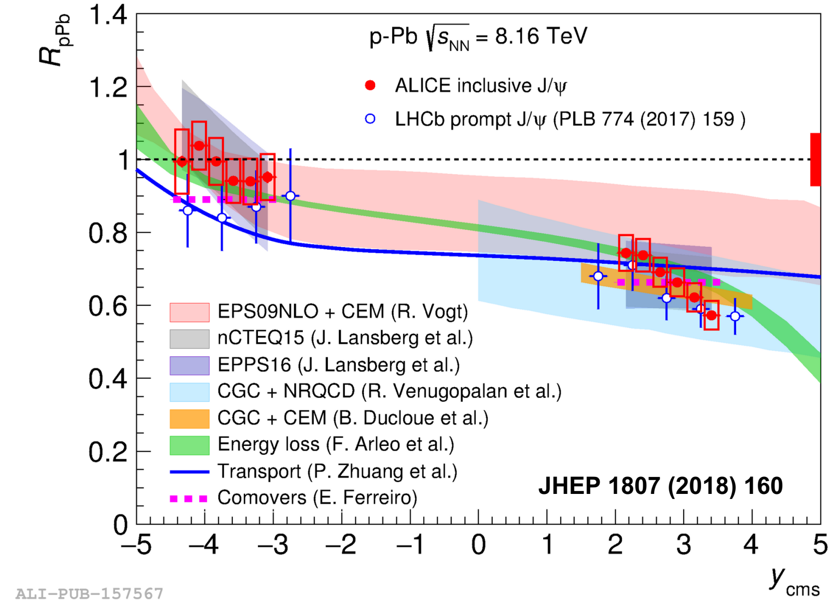
$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{< N_{coll} > \times \mathrm{d}N_{pp}/\mathrm{d}p_T}$$

Normalization by the number of collision (N_{coll})

Same measurement in pp

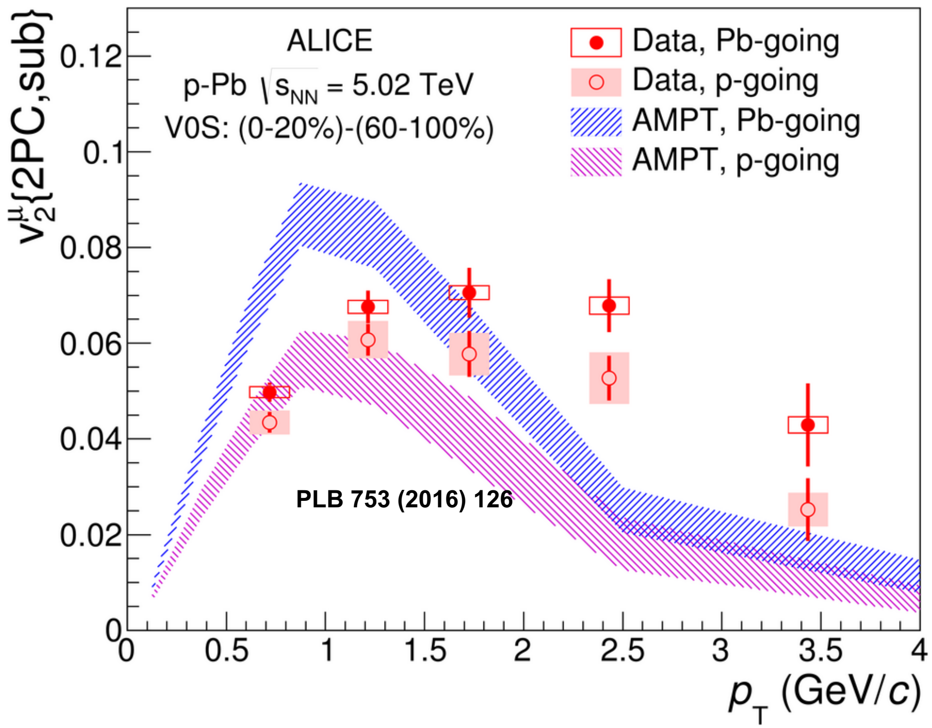


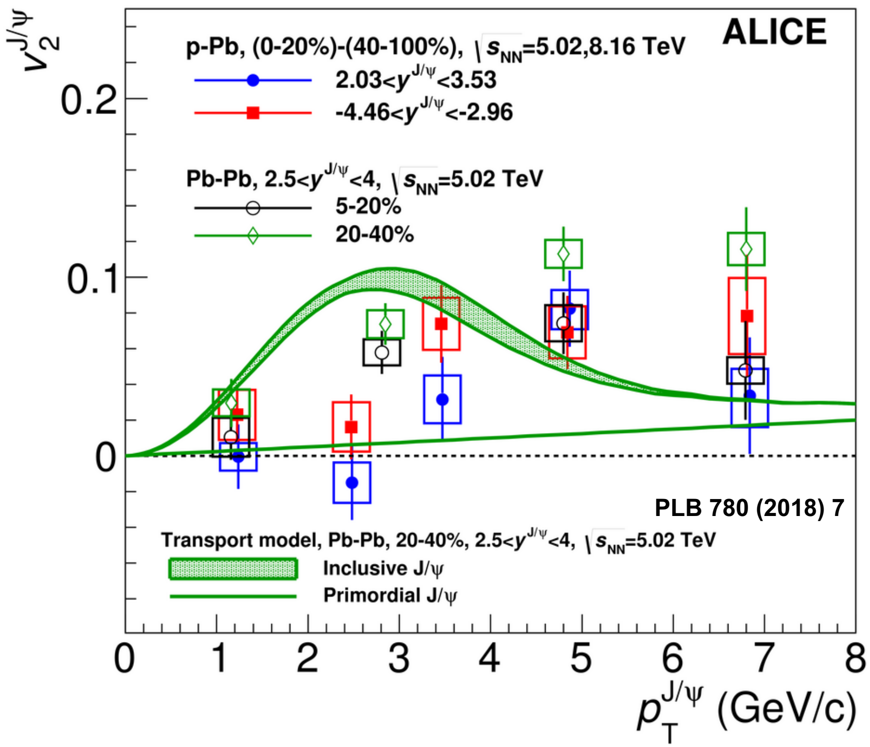




- J/ψ less suppressed at the LHC than at RHIC when varying the centrality of the collision
- Cold matter effects studied with p-Pb reference measurements
- Contribution from **regeneration** at low p_T

Collective behavior of heavy quarks in p-Pb collisions ?



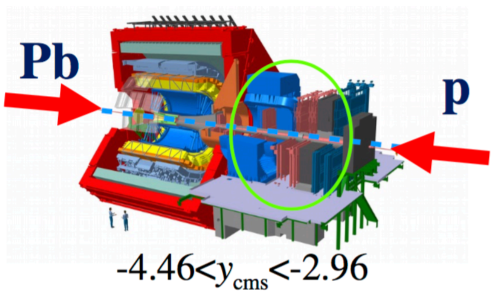


- Measurement of single-muon elliptic flow in p-Pb collisions in two rapidity regions
- Unambiguous observation of non-zero v_2 in the p_T range 0-4 GeV/c

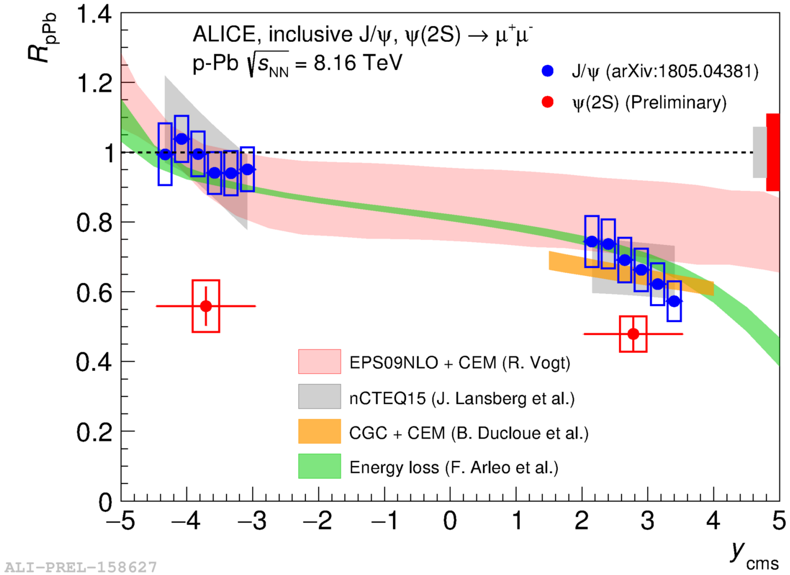
- Measurement of J/ψ elliptic flow in p-Pb collisions in two rapidity regions
- Low p_T: v_2 compatible with zero
  High p_T: positive v_2

Not yet understood

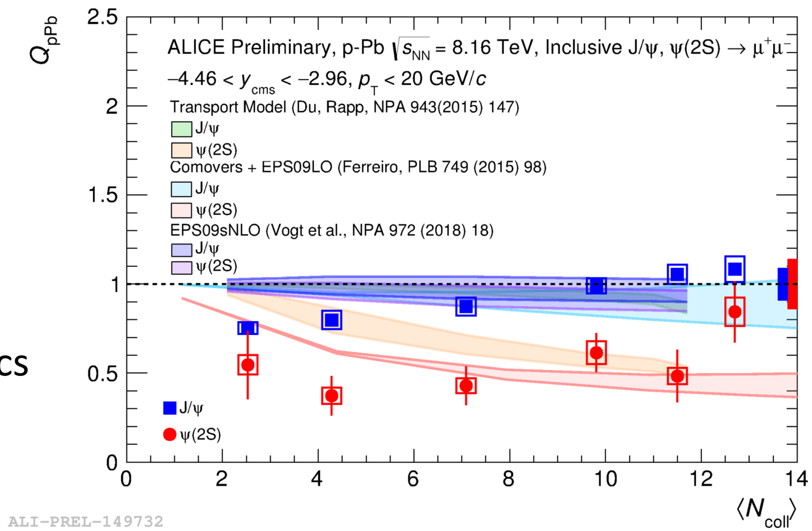
Nuclear modification factor for Ψ(2S) in p-Pb



$$R_{pPb} = \frac{dN_{pPb}/dp_T}{N_{coll} dN_{pp}/dp_T}$$



- Q_{pPb} is the nuclear modification factor as a function of multiplicity/centrality
- Ψ(2S) suppression in p-Pb not explained by cold matter effects
- Similar phenomenon seen in d-Au collisions at the RHIC **[JHEP 12 (2014) 073]**
- May require other effects: saturation or dissociation in final state
- Interpretation to be connected with small system physics and hard-soft correlations



New observables

Quark-Gluon Plasma

- Is the measurement the consequence of the evolution of a hydrodynamic fluid?
- Warning: hydro application do not necessarily imply QGP
- Hydro requires R_e >> 1 => small $\frac{\eta}{s}$, with R_e the Reynolds number:

$$R_e = \frac{\mathrm{R}v}{\nu} = \frac{\mathrm{R}v}{\eta/\rho} = \frac{\mathrm{R}vT}{\eta/s}$$

R: characteristic spatial dimension
v: characteristic velocity
$\nu = \frac{\eta}{\rho}$: kinematic velocity
η: shear viscosity
s: entropy density

- Small η/s (<0.2) is a feature of observed QGP

Looking for the proper scaling quantity

- To go **beyond the Glauber model** for heavy-ion and avoiding normalizing by N_{coll}
- To have a quantity **system and energy independent**
- **What is the best system size estimator?**
  - Multiplicity is the measured quantity (caveats: experimental estimator has to be well defined)
  - Multiplicity is protected from theoretical biases (N_{part}, N_{coll} from Glauber models ...)
  - But hard to compare to formal calculation and first principle

Bjorken estimates

$$\varepsilon \sim \frac{n\pi}{\tau_0 A} \frac{3}{2} \frac{dN_{\mathrm{ch}}}{d\eta}\bigg|_{\eta=0}$$

Multiplicity per volume unit

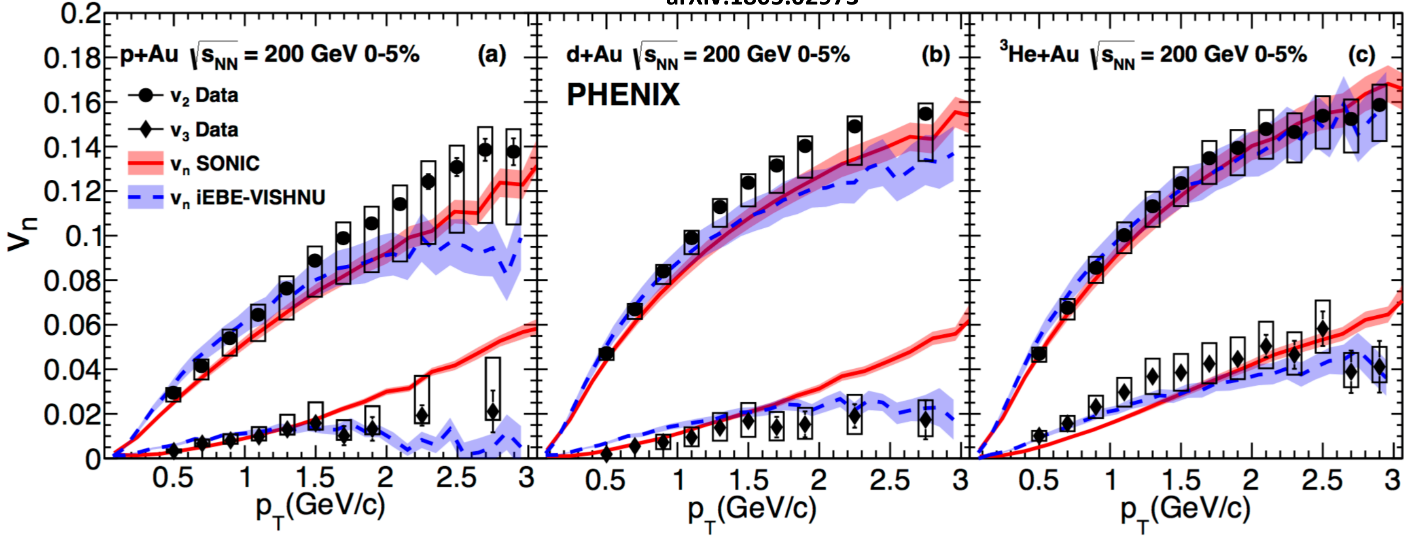
$$\frac{N_{\mathrm{ch}}}{\pi R^3}$$

Problem of the definition of the normalization size in pp and p-Pb (*A* or *R* or ?)

Turning off Collectivity: RHIC ?

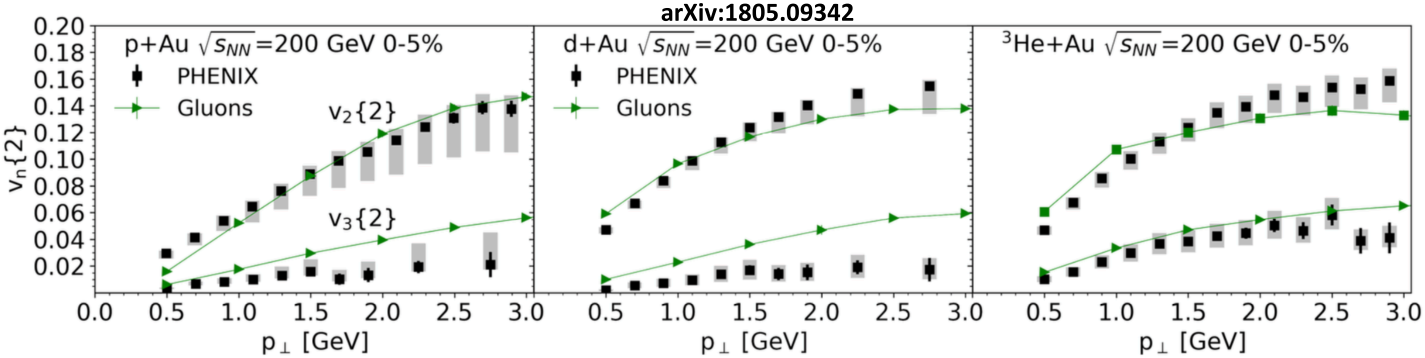
Relativistic Heavy Ion Collider, Brookhaven National Laboratory, New-York, USA
The QGP facility before LHC

arXiv:1805.02973



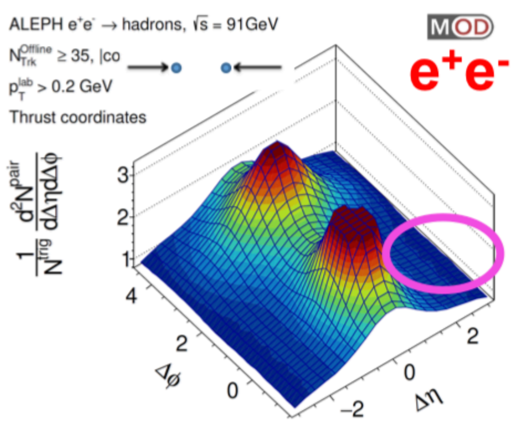
- PHENIX claim for QGP in small systems …

arXiv:1805.09342

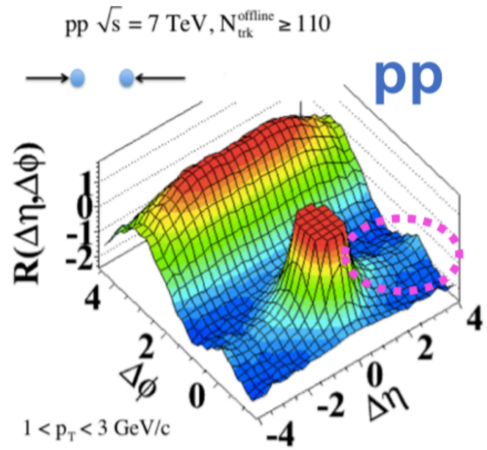


- … also explained by Color Glass Condensate.

Turning off Collectivity: e^+e^- ?



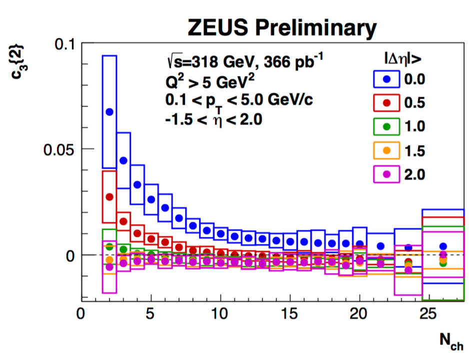
Badea et al., arXiv:1906.00489

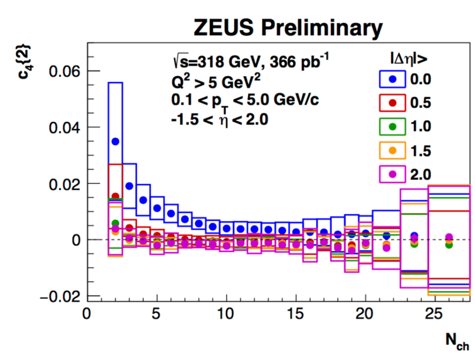


CMS, JHEP09 (2010) 091

QM2018, Yen-Jie Lee

- LEP e^+e^- $\sqrt{s}$=91 GeV
- High mult = 55 particles in $|\eta|<5$
- No ridge observed, compatible with PYTHIA





$|\Delta\eta| > 2.0$: $c_3\{2\}$ and $c_4\{2\}$ are consistent with zero.

QM2018, Jacobus Onderwaater

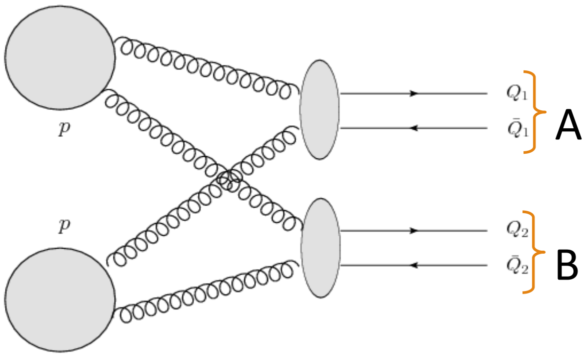
- HERA ep $\sqrt{s}$=318 GeV
- High mult = 35 particles in $-1.5<\eta<2$
- No observation of 2-particle correlations, compatible with Ariadne (dipole cascade model) and Lepto (Lund string)

Double Parton Scatterings

- Identification of events with two hard processes
- In the DPS formalism they are independent (MPI) and factorize

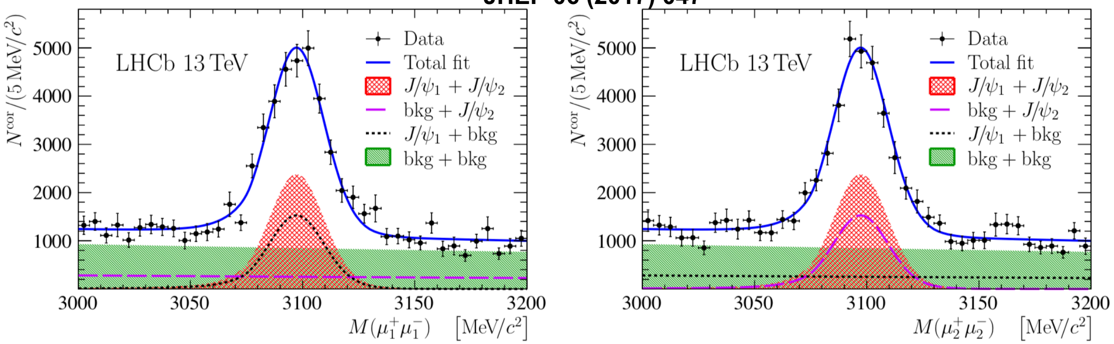
$$\sigma_{DPS}^{AB} = \frac{m}{2}\frac{\sigma_{SPS}^{A}\sigma_{SPS}^{B}}{\sigma_{eff}}$$

m=2 when A and B are distinguishable
m=1 when indistinguishable



- Universality of σ_{eff} in question
- Linked with MPI formalism and also with nucleon structure **[JHEP 10 (2016) 063]**

JHEP 06 (2017) 047

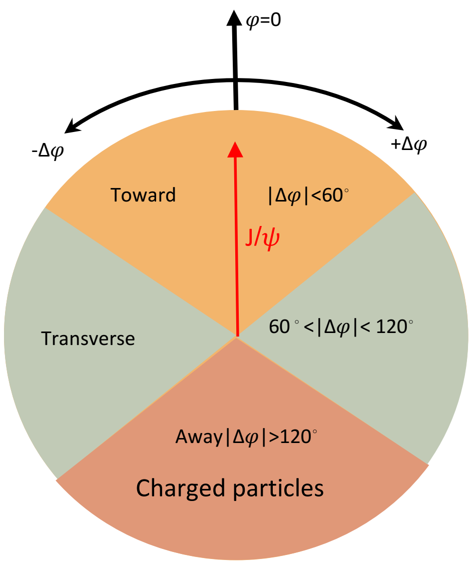


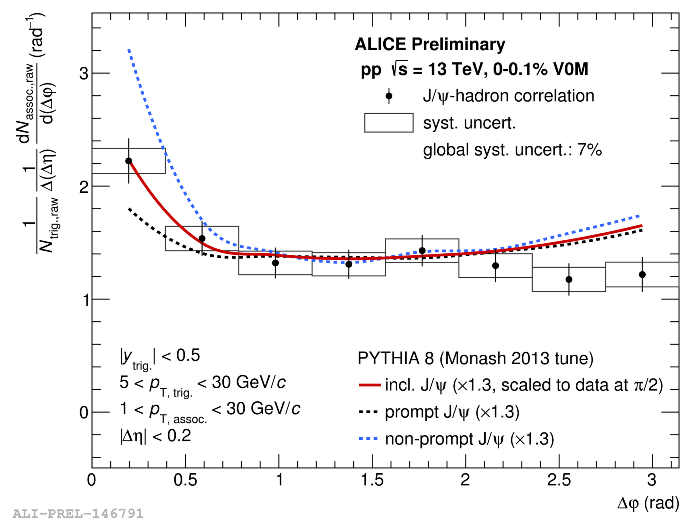
- Potential signals with 4 leptons: J/ψ + J/ψ J/ψ + Υ, J/ψ + W, J/ψ +Z, Υ + Υ
- J/ψ + D mesons, measured by LHCb with D in the hadronic channel
- Require to investigate physics potential and feasibility with ALICE in Run 3 conditions: with muons only, with muons + electrons, with muons + hadronic channels
- Possibilities should be enhanced by the continuous readout
  The MFT will specifically improve the signal/background for channels where the signal is composed of prompt muons. First study by D. Stocco and P. Bartalini

[PRD 90 (2014) 111101 , JHEP 1409 (2014) 094, EPJC 77 (2017) 76, JHEP 06 (2017) 047, JHEP 10 (2017) 068, PRL 116 (2016) 082002, JHEP 05 (2017) 013]

Opening possibilities for correlations in final states

- LHC results point to a **need of a full tomography of the final state**, understanding links between the underlying event/bulk/soft part and hard components
- First measurements performed with Run 2 data at mid-rapidity for open heavy flavours
- **Underlying event studies with a "muon" as leading particle**

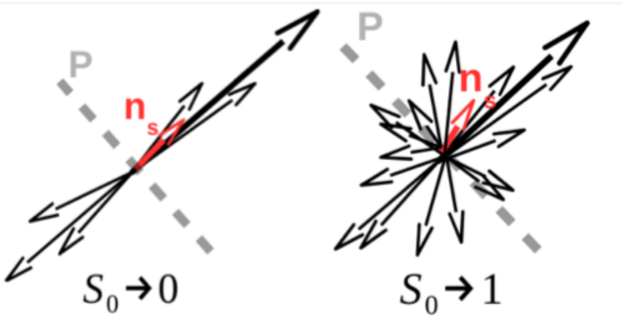




- **Opportunities to be investigated** in the muon channel with the MFT as a vertexer and a multiplicity estimator

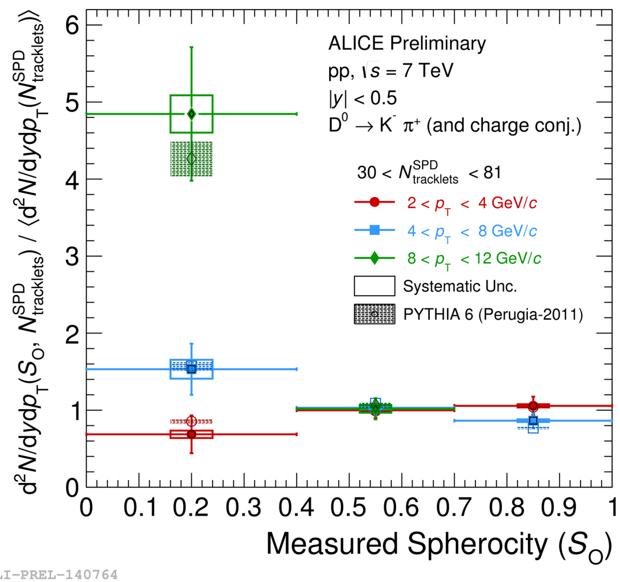
Opening possibilities for correlations in final states

- LHC results point to a **need of a full tomography of the final state**, understanding links between the underlying event/bulk/soft part and hard components
- First measurements performed with Run 2 data at mid-rapidity for open heavy flavours
- **Spherocity analysis connected with hard probes**



$$S_0 = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left(\frac{\sum_i |\vec{p}_{T_i} \times \hat{n}|}{\sum_i p_{T_i}} \right)^2$$

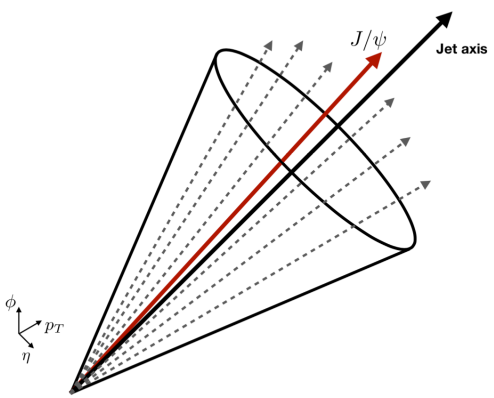
$$S_0 = \begin{cases} 0 \text{ "jetty" limit (hard events)} \\ 1 \text{ "isotropic" limit (soft events)} \end{cases}$$

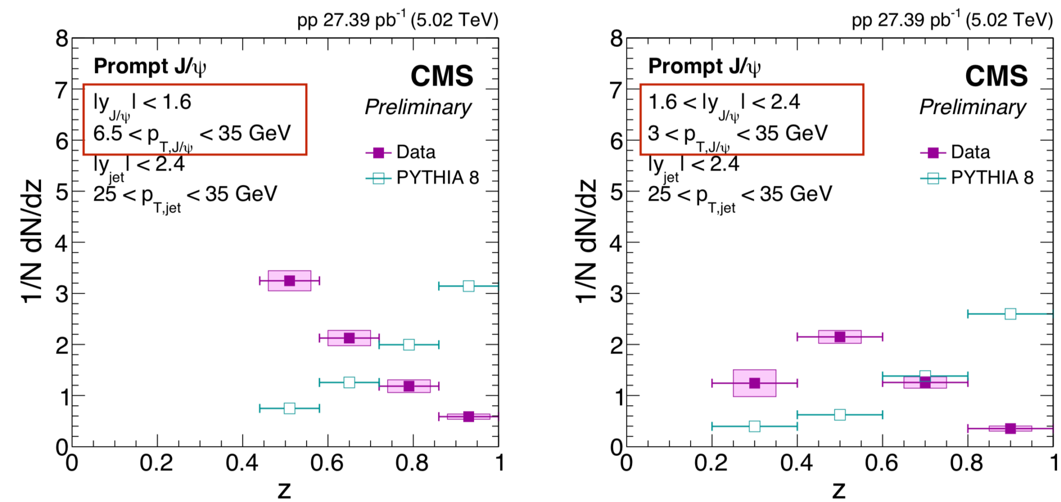


- **Opportunities to be investigated** in the muon channel with the MFT as a vertexer and a multiplicity estimator embedded into the ITS

Understanding quarkonium production in dense hadronic environment

- In the quarkonium sector a large fraction of LHC Runs 1+2 results are linked with the associated event activity
- But, quarkonium production are not yet understood and no theoretical knowledge about quarkonium fragmentation function, poor implementation in MC event generators
- **A key measurement is quarkonia in jet**, see workshop *Quarkonia as Tools**
- First measurements from CMS: J/ψ less isolated in data than in PYTHIA 8

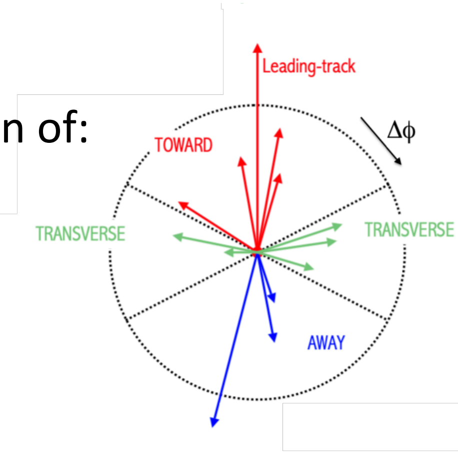


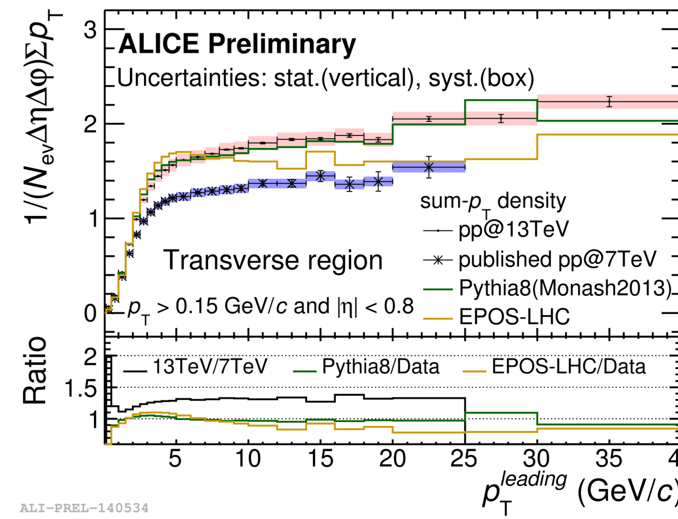


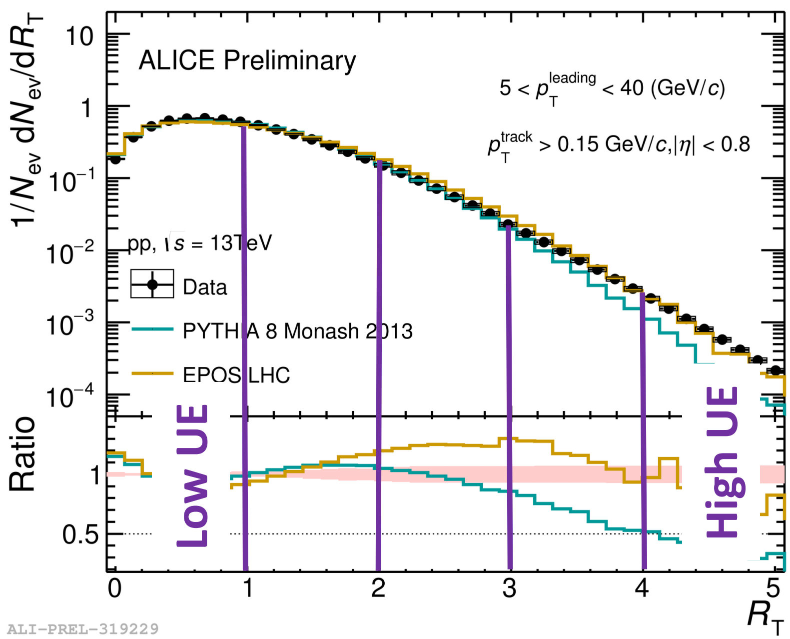
The transverse activity classifier

Events described as the association of:

- A leading hard process
- An associated Underlying Event (UE)







- ➢ The transverse activity classifier R_T built as a jet-free multiplicity estimator

$$R_T = \frac{N_{\text{inclusive}}}{\langle N_{\text{inclusive}} \rangle}\Big|_{\text{Transverse}}$$

Eur.Phys.J. C76 (2016) 299

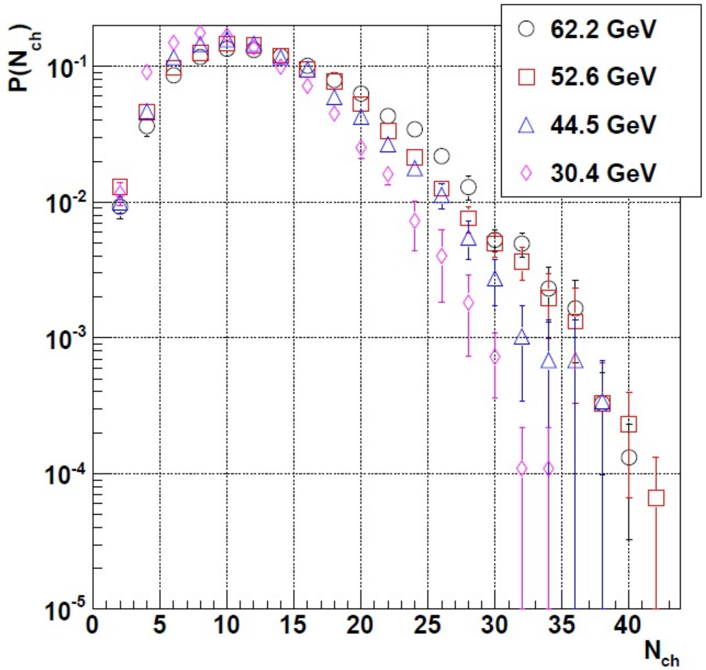
- ➢ R_T classify events in term of high or low UE

Needs for MPI

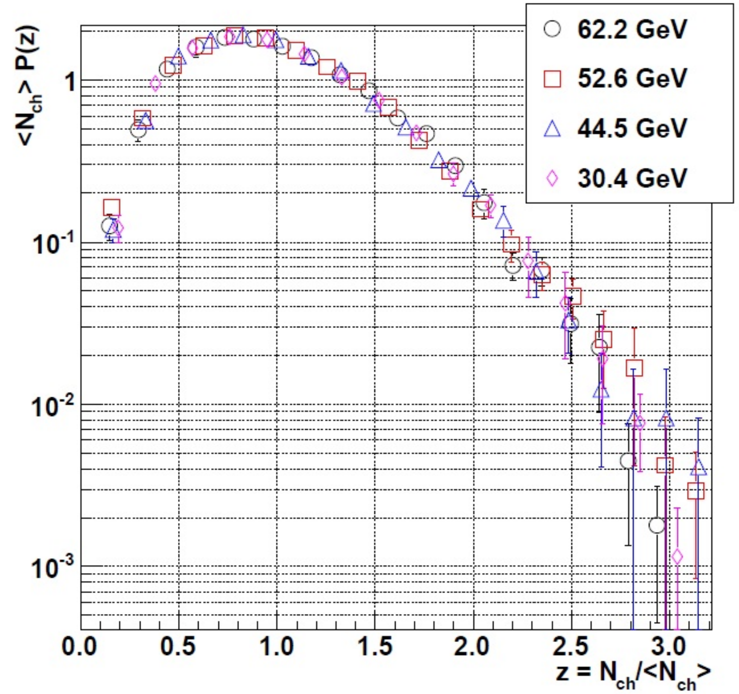
Koba-Nielsen-Oleson (KNO) scaling

Evolution of the charged particle multiplicity distribution in proton-proton collisions $P(N_{ch})$ with √s follows KNO-scaling with

Scaling variable $z = \frac{N_{ch}}{< N_{ch} >}$ and $P(N_{ch}) < N_{ch} >= \Psi(z)$ Energy independent function



Different multiplicity distributions



When self normalized : KNO scaling

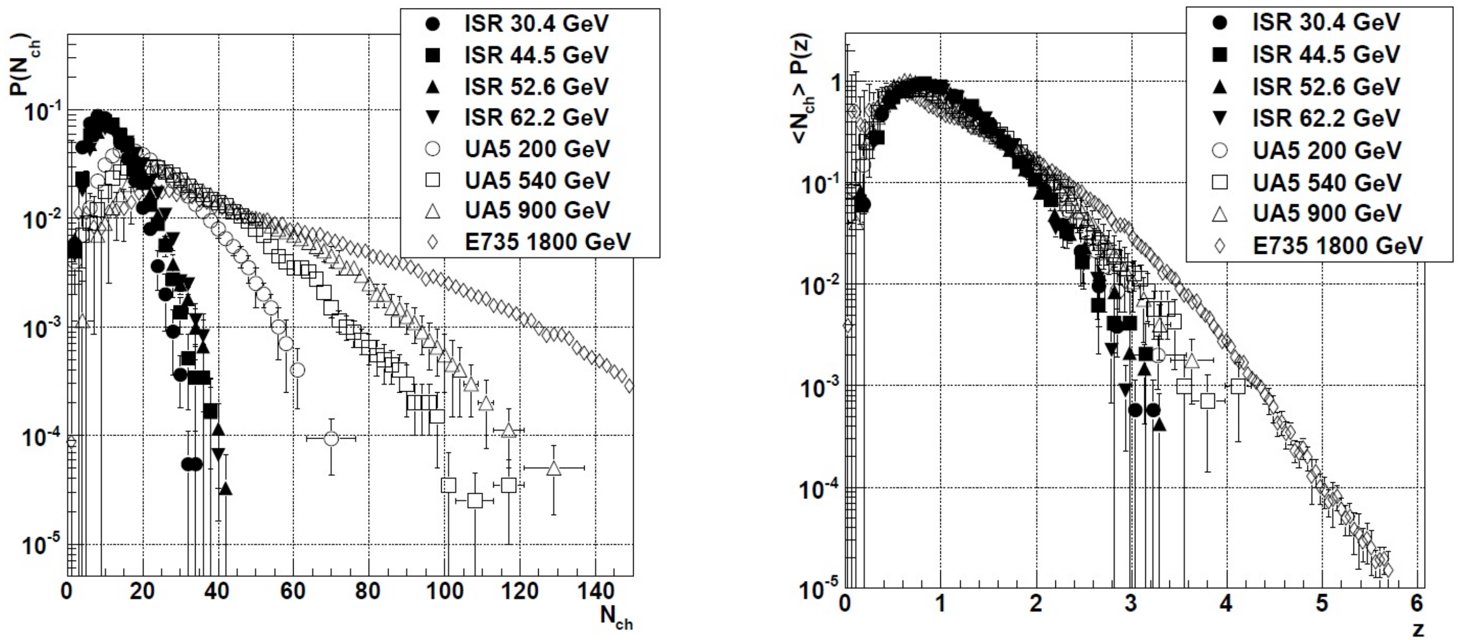
NSD events in full phase space measured by the SFM (Split Field Magnet) at ISR energies
Compilation from **J. Phys. G 37 (2010) 083001**

Up to √*s*=200 GeV, it works pretty well!

Needs for MPI

Koba-Nielsen-Oleson (KNO) scaling

At energies greater than √*s*=200 GeV in pp and $p\bar{p}$ collisions,



NSD events in full phase space
Compilation from **J. Phys. G 37 (2010) 083001**

Violation of KNO-scaling (√*s* > 200 GeV)
Phys. Lett. B 167 (1986) 476

Deviation from KNO-scaling increases with √s

Can be interpreted as a consequence of particle production through (soft) MPI

Phys. Rev. D 84 (2011) 034026 Hep-ph/1106.4959 **Phys. Rept. 349 (2001) 301 Hep-ph/0004215** **J. Phys. G 37 (2010) 083001**