Quarkonia production in high multiplicity environment

SARAH PORTEBOEUF-HOUSSAIS

GDR QCD

21 JUNE 2021

Let’s define ”high multiplicities”

QGP

Final state

Collective effects

Heavy ions

Quarkonia dissociation

High multiplicities

Quarkonia regeneration

Let’s define ”high multiplicities”

Final state

QGP

Collective effects

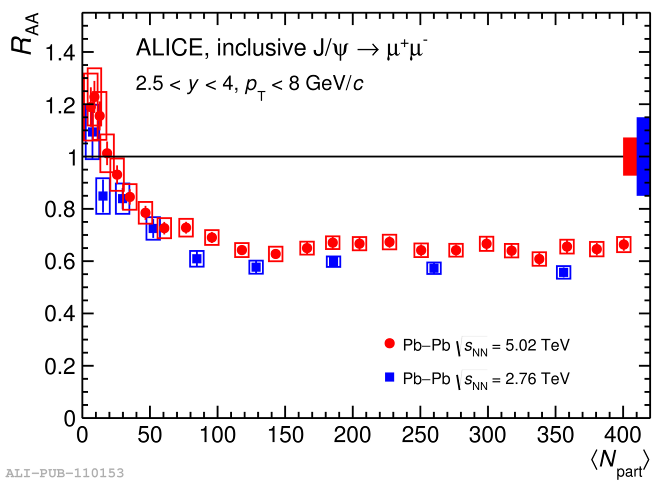
Heavy ions

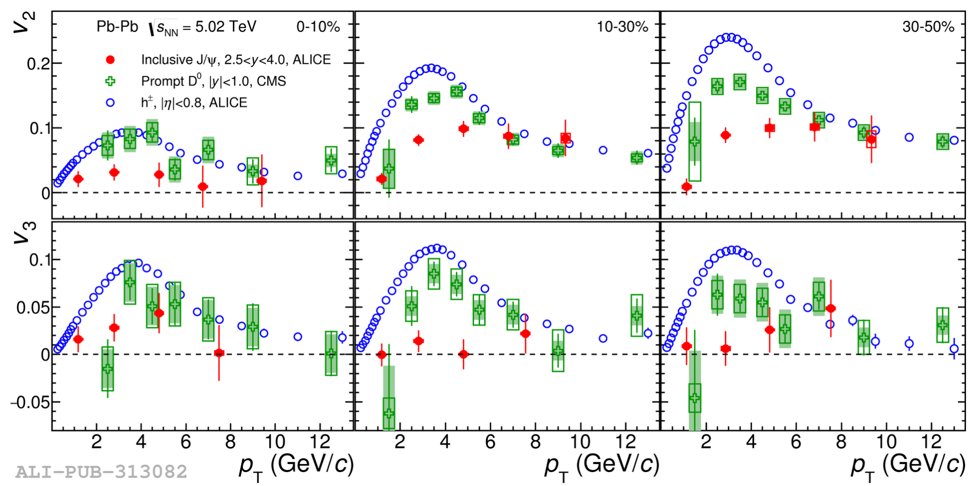
Quarkonia dissociation

High multiplicities

- High multiplicities refers initially to heavy ion physics and the study of QGP via probes such as quarkonia

Quarkonia regeneration





Let’s define ”high multiplicities”

QGP

Final state

Collective effects

Heavy ions

Quarkonia dissociation

p-Pb

High multiplicities

Quarkonia regeneration

Initial state

Cold matter effect

Let’s define ”high multiplicities”

Final state

QGP

Collective effects

Heavy ions

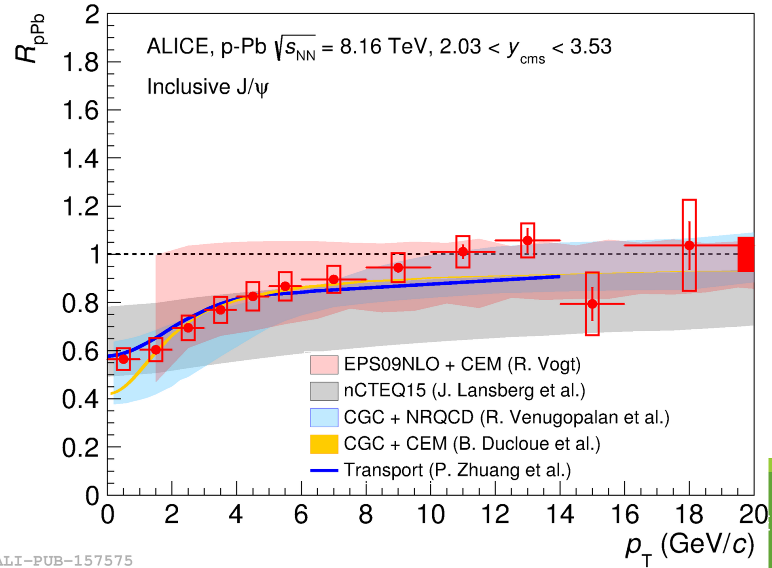
Quarkonia dissociation

p-Pb

High multiplicities

- For quarkonia study, the knowledge of initial state and cold matter effect is a requirement!
- It is “controlled” by studying p-Pb systems

Quarkonia regeneration



Initial state

Cold matter effect

Let’s define ”high multiplicities”

QGP

Final state

Collective effects

Heavy ions

Quarkonia dissociation

p-Pb

High multiplicities

Quarkonia regeneration

pp

Initial state

Small systems

Cold matter effect

- Since the LHC era, high multiplicities are also linked to smaller systems than heavy ions

What is a small system for QGP physics?

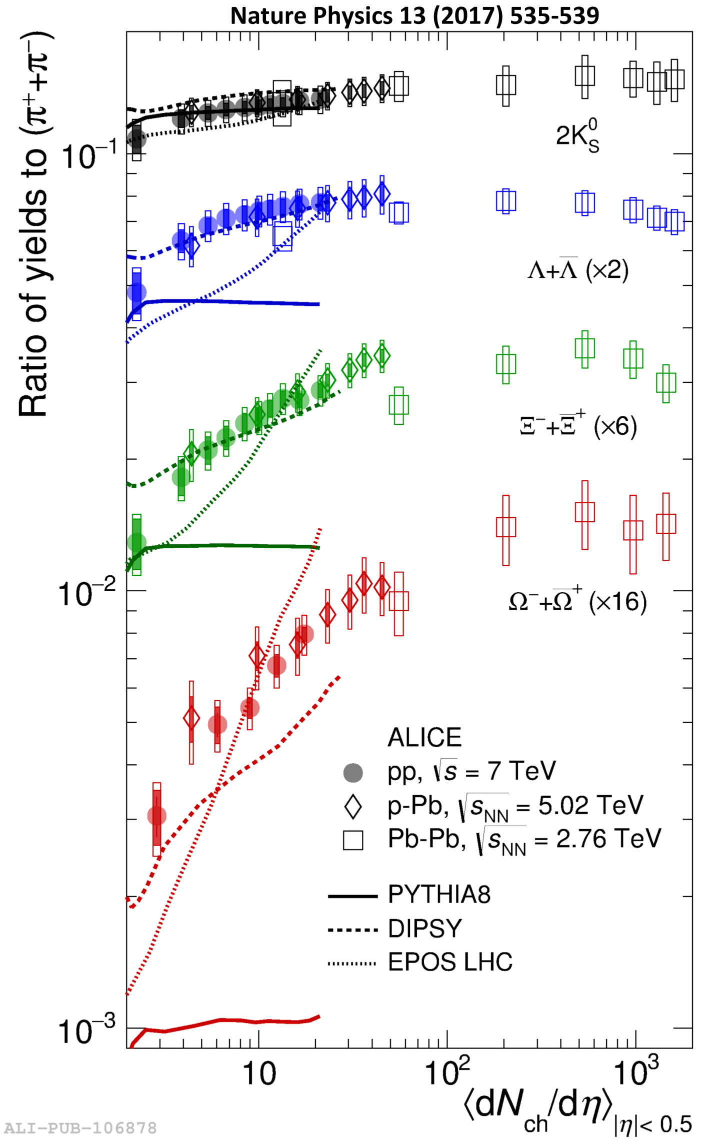
- Small refers to system size: protons in initial stage
- But with sometimes a final state looking like a large system, at least for charged particle multiplicity
- For LHC RUN 1+2 energies, idea of reference system still valid for pp minimum bias. High multiplicity events represent a small contribution to the total cross section
  O(10^{-4}) in statistics

pp/pA/AA at the same multiplicity, is it the same behavior, role of geometry, role of collectivity?

How is done the transition from small to large ?

How does the collectivity emerge ?

Quarkonia and small systems ?



Let’s define ”high multiplicities”

Final state

QGP

Collective effects

Heavy ions

Quarkonia dissociation

p-Pb

High multiplicities

Quarkonia regeneration

pp

Initial state

Small systems

Cold matter effect

In this talk high multiplicities refers to charged particle multiplicity in the final state, independently of initial state and/or energy

Quarkonia in "high multiplicity" environment

Final state

QGP

Collective effects

Heavy ions

Quarkonia dissociation

p-Pb

High multiplicities

Comovers

Quarkonia regeneration

fragmentation

pp

saturation

Initial state

Small systems

Cold matter effect

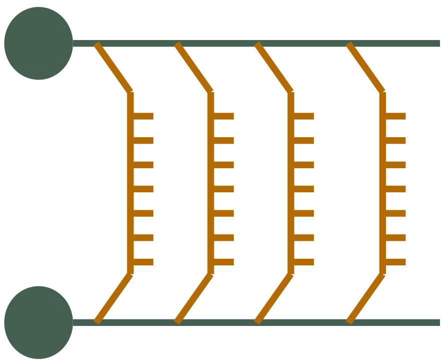
Multi-parton interactions

Quarkonia is a rich tool for high multiplicity studies being as well linked to initial and final state

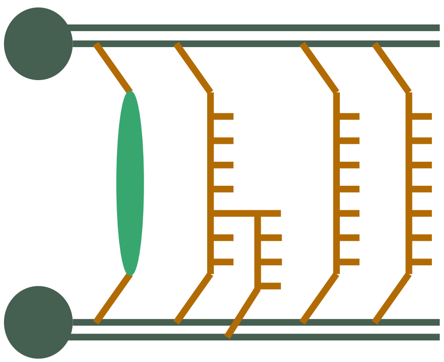
Do we understand initial conditions?
What kind of initial conditions can let pp collisions to reach high density ?

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

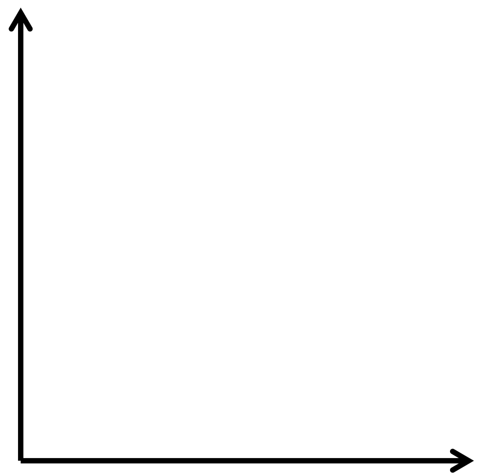
Multiplicity differential studies and exclusive measurements

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)

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



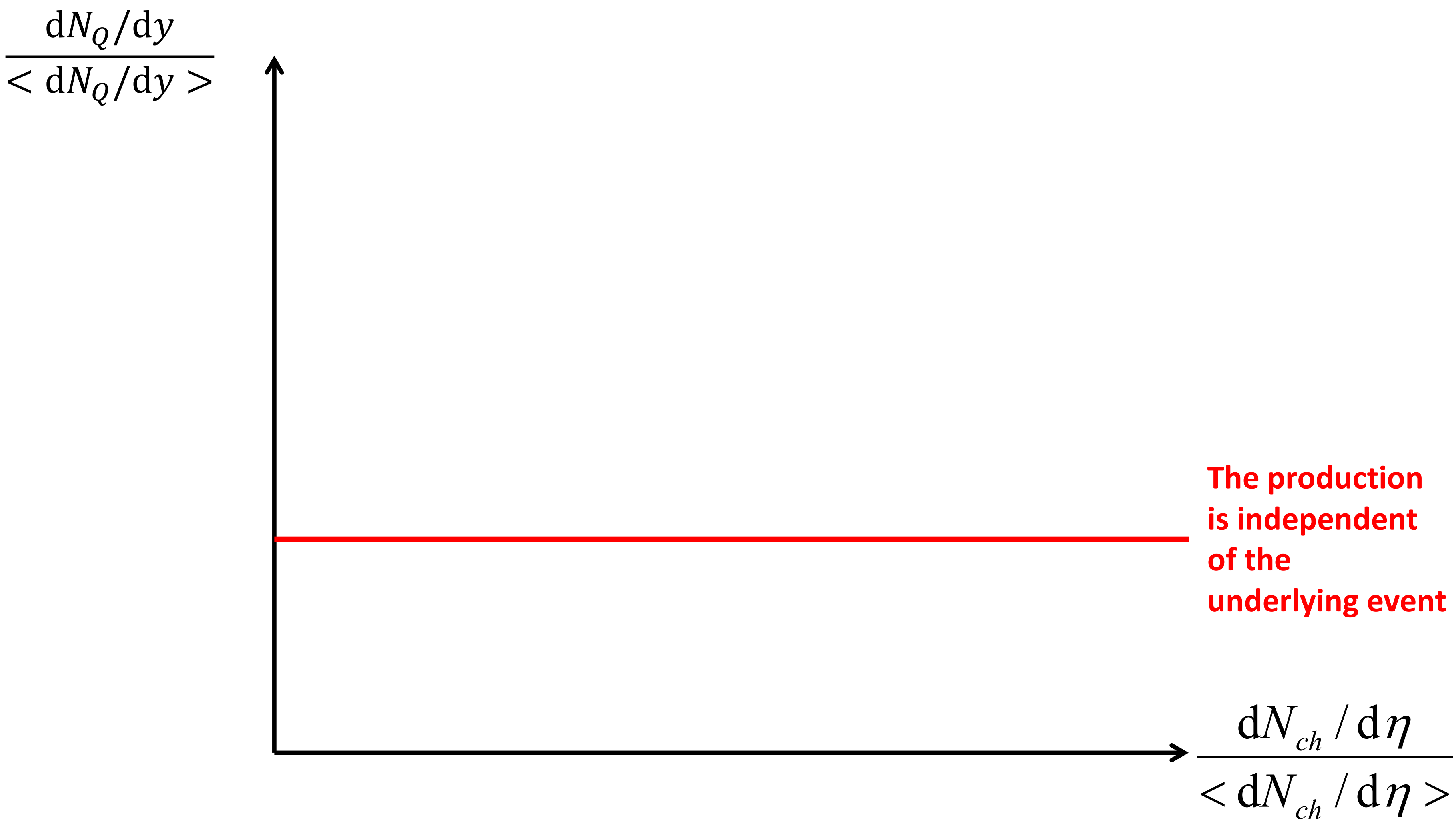
$$\frac{\mathrm{d}N_{ch}/\mathrm{d}\eta}{<\mathrm{d}N_{ch}/\mathrm{d}\eta>}$$

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

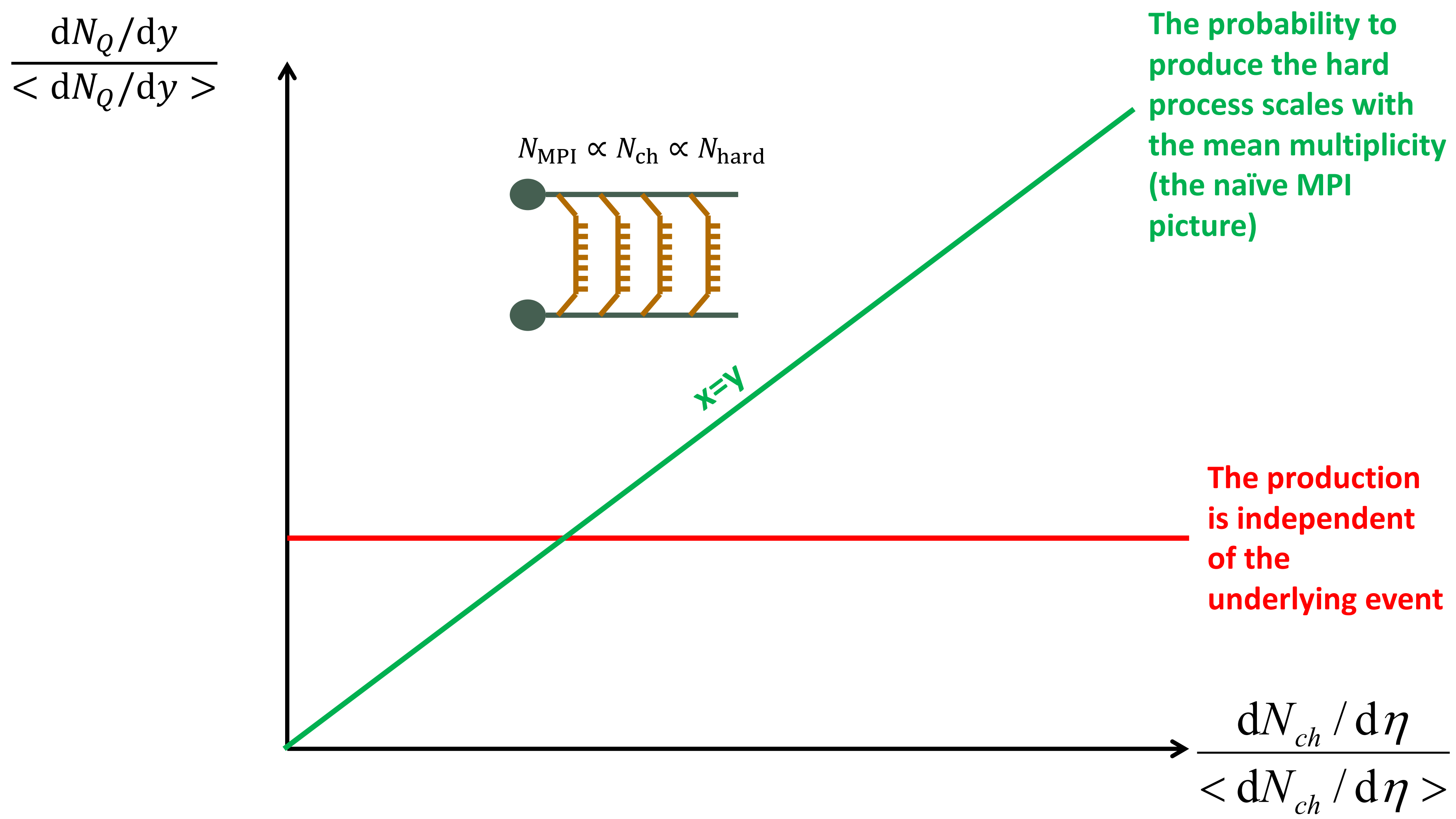
2 advantages :

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

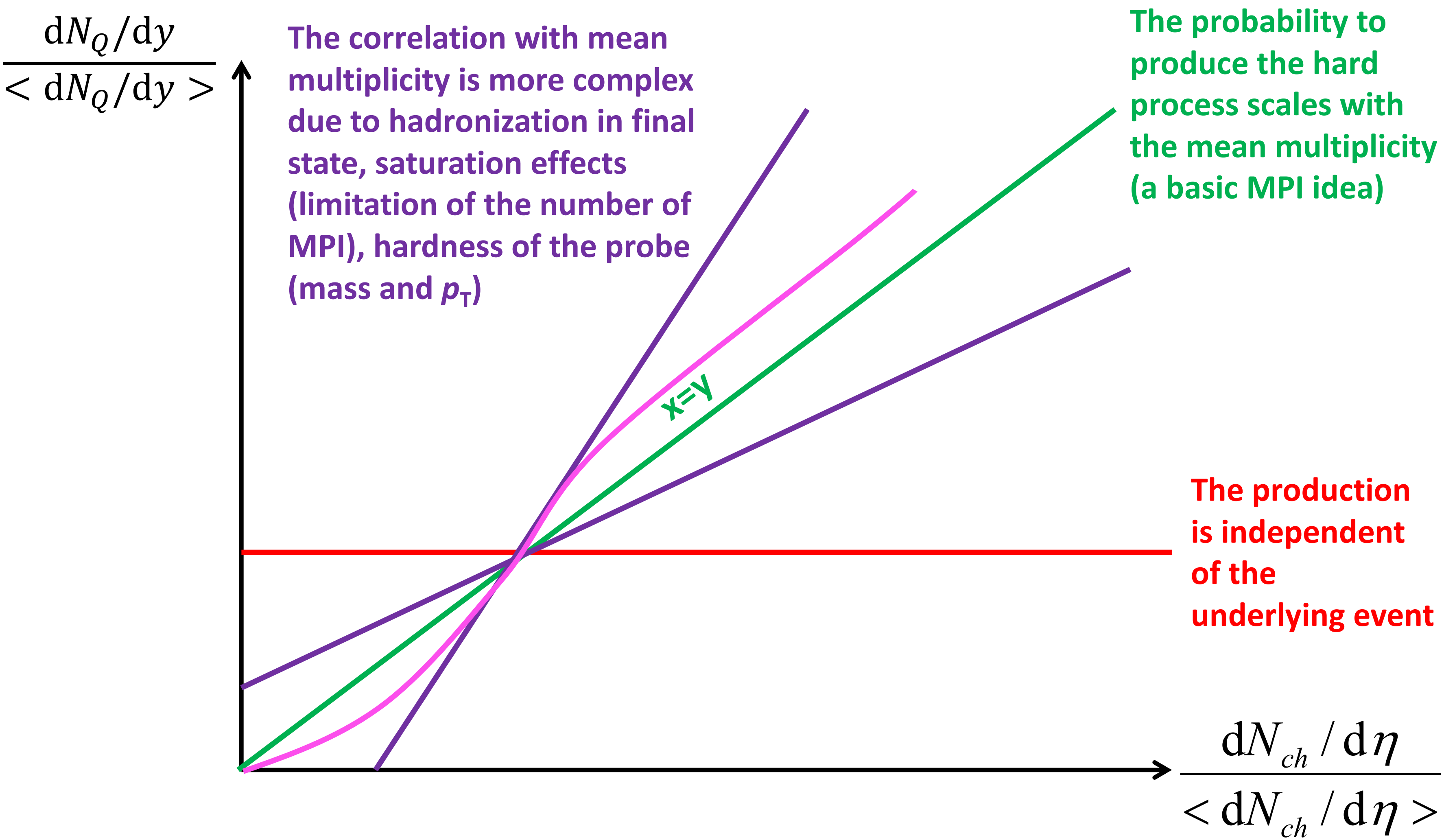
Quarkonia production as a function of multiplicity
The observable



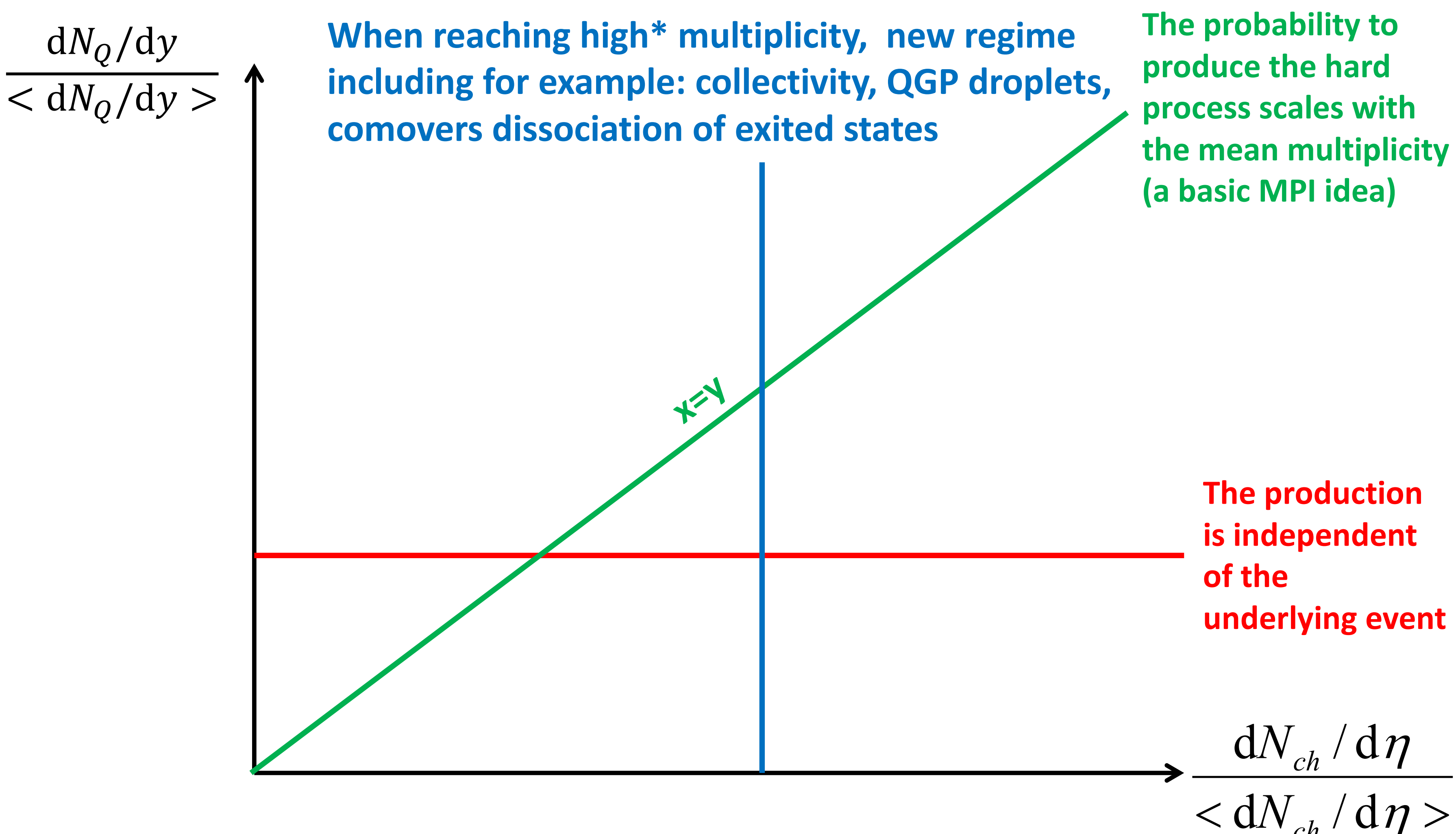
Quarkonia production as a function of multiplicity
The observable



Quarkonia production as a function of multiplicity
The observable



Quarkonia production as a function of multiplicity
The observable



* *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

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

Initial

➢ 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

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

Initial

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

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

Charm/beauty vs. mult

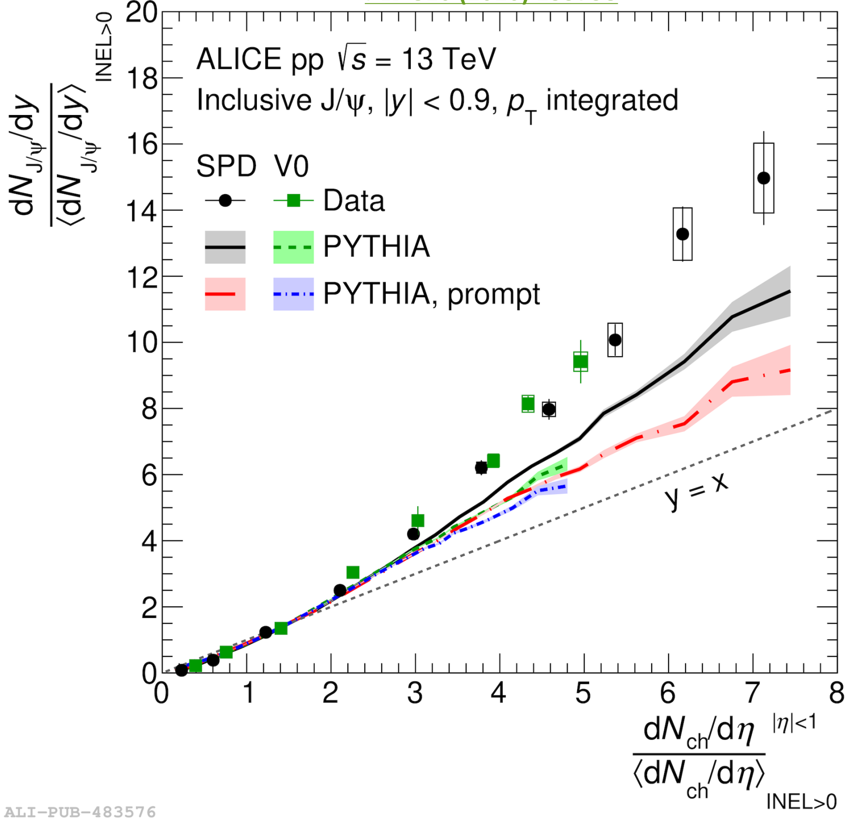
State	Channel	System	Energy	Exp.	ref
J/Ψ	- $\mu^+\mu^-$, $\|y\|<0.5$, $p_T >$ 0 GeV/c - e^+e^-, $\|y\|<1$, $p_T >$ 1.5/4 GeV/c	pp	200 GeV 500 GeV	STAR	PLB 786 (2018) 87–93
J/Ψ	- $\mu^+\mu^-$, 2.5<y<4, $p_T >$ 0 GeV/c	pp	2.76 TeV	ALICE	Preliminary
J/Ψ	- $\mu^+\mu^-$, 2.5<y<4, $p_T >$ 0 GeV/c	pp	5.02 TeV	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^-, $\|y\|<1$, $p_T > 0/4$ 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)	- $\mu^+\mu^-$, $\|y\|<1.93$, $p_T >$ 0 GeV/c	pp	2.76 TeV	CMS	JHEP04(2014)103
Υ(1/2/3S) polarizations	- $\mu^+\mu^-$, $\|y\|<1.2$, $10<p_T<15$ GeV/c, $15<p_T<35$ GeV/c	pp	7 TeV	CMS	Phys.Lett. B761 (2016) 31-52
Υ(1/2/3S)	- $\mu^+\mu^-$, $\|y\|<1.2$, $p_T >$ 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)	- $\mu^+\mu^-$, $\|y\|<1.93$, $p_T >$ 0 GeV/c	p-Pb	5.02 TeV	CMS	JHEP04(2014)103
Υ(1/2/3S)	- $\mu^+\mu^-$, $\|y\|<1.93$, $p_T >$ 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, $\|y_{max}\|<0.8$, $0.5<p_T<30$ GeV/c	pp	13 TeV	ALICE	Paper in preparation
HF	- e^+e^-, $\|y_e\|<0.8$, $p_{T,e} >$ 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, $\|y_{max}\|<0.8$, $0.5<p_T<26$ GeV/c	P-Pb	8.16 TeV	ALICE	Paper in preparation

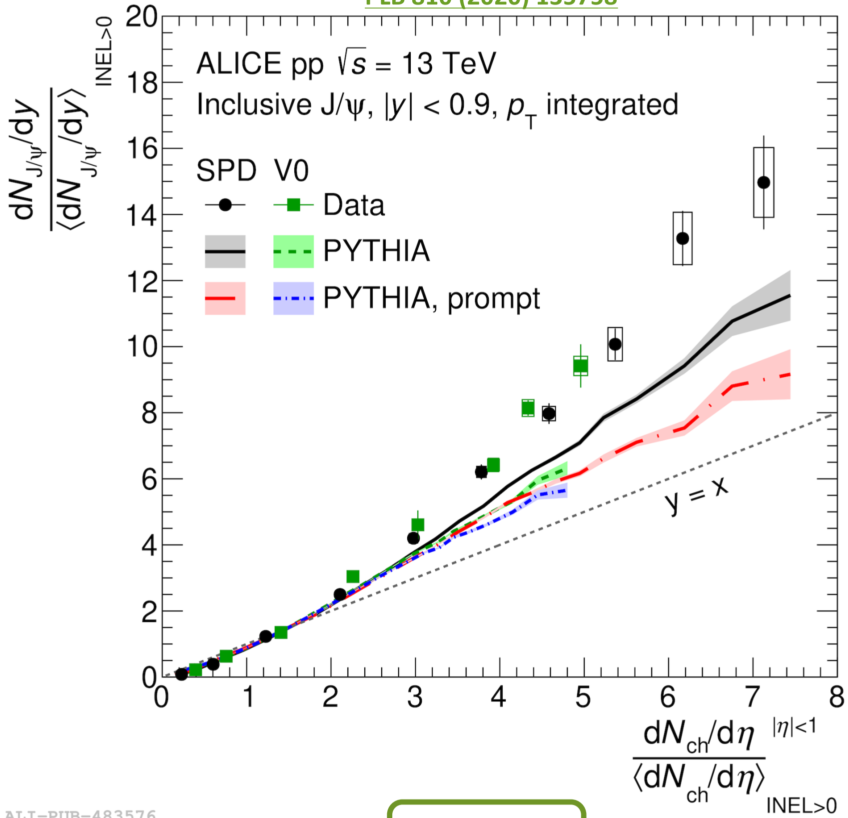
J/Ψ in the central rapidity region

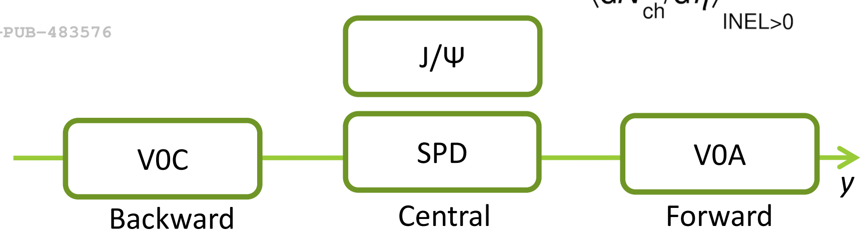
PLB 810 (2020) 135758



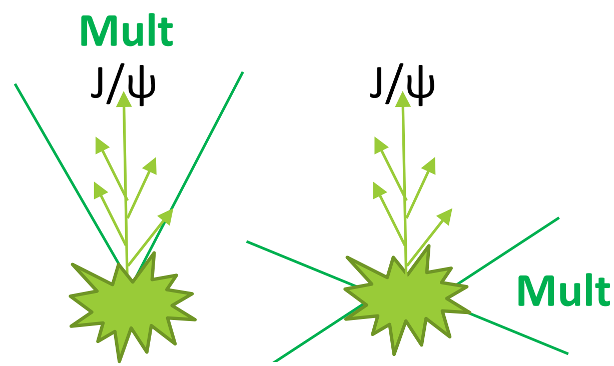
J/Ψ in the central rapidity region

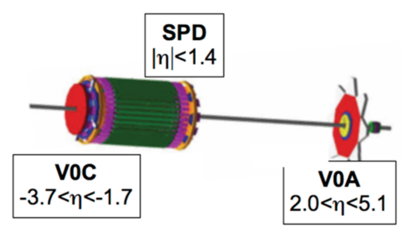
PLB 810 (2020) 135758





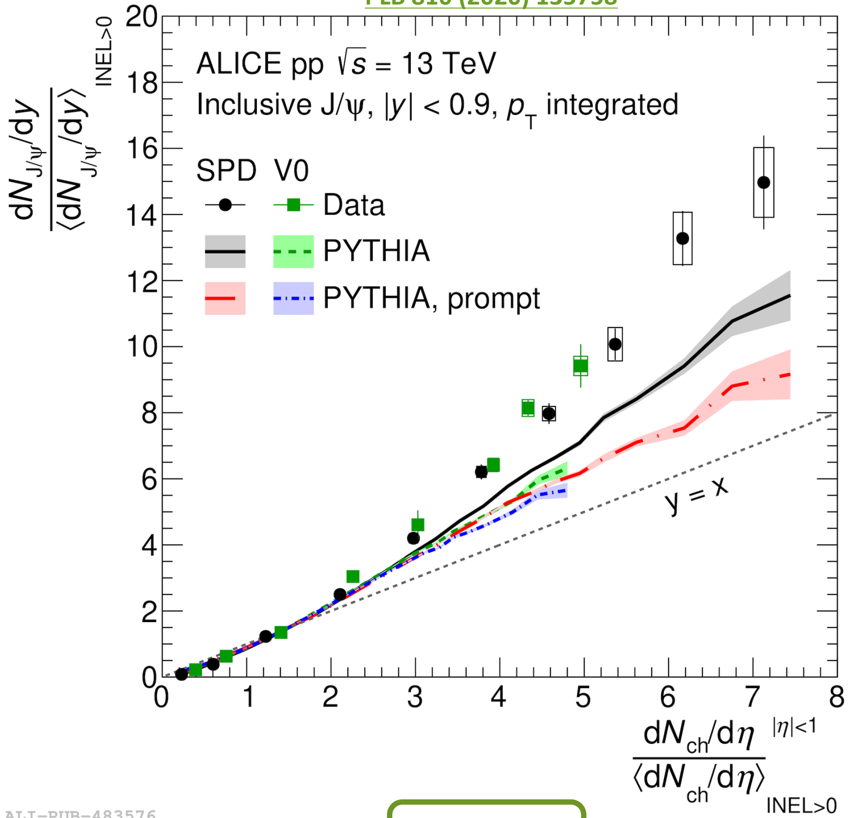
- J/Ψ central
- Multiplicity measurement central or forward
- Observed correlation not linear (~quadratic)
- Similar correlation, independently of the rapidity region of the multiplicity measurement

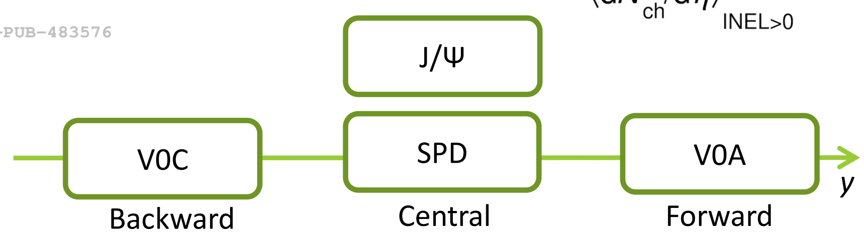




J/Ψ in the central rapidity region

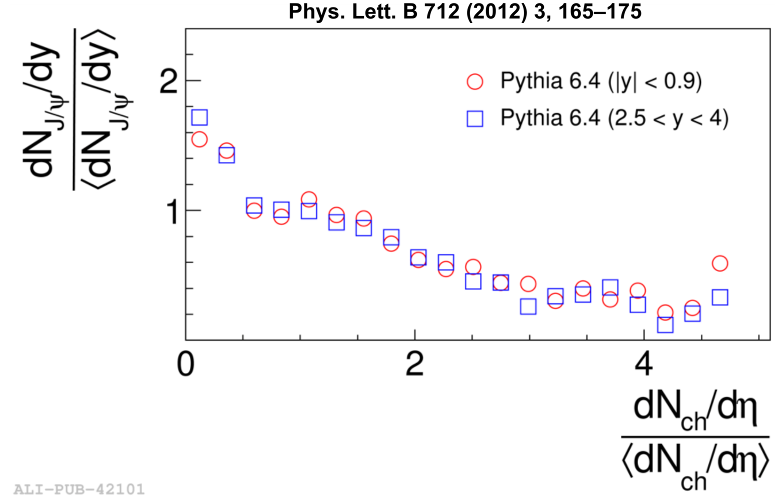
PLB 810 (2020) 135758





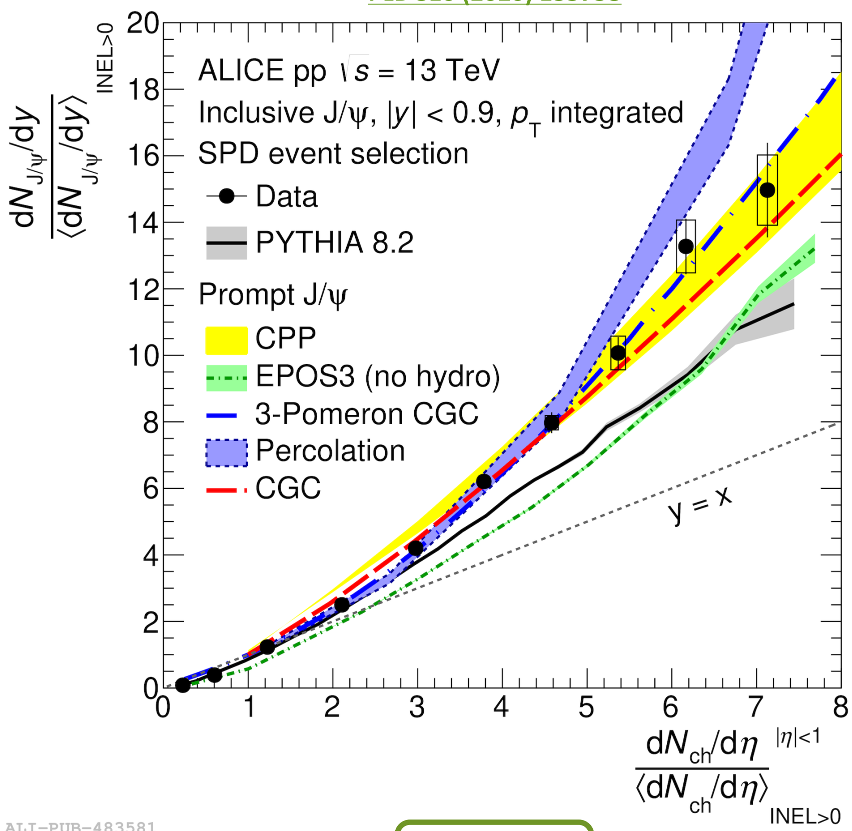
- J/Ψ central
- Multiplicity measurement central or forward
- Observed correlation not linear (~quadratic)
- Similar correlation, independently of the rapidity region of the multiplicity measurement
- Observed correlation not reproduced by PYTHIA*
- Better than PYTHIA 6.4 (MPI)

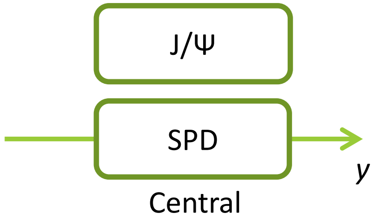
Phys. Lett. B 712 (2012) 3, 165–175



J/Ψ in the central rapidity region

PLB 810 (2020) 135758

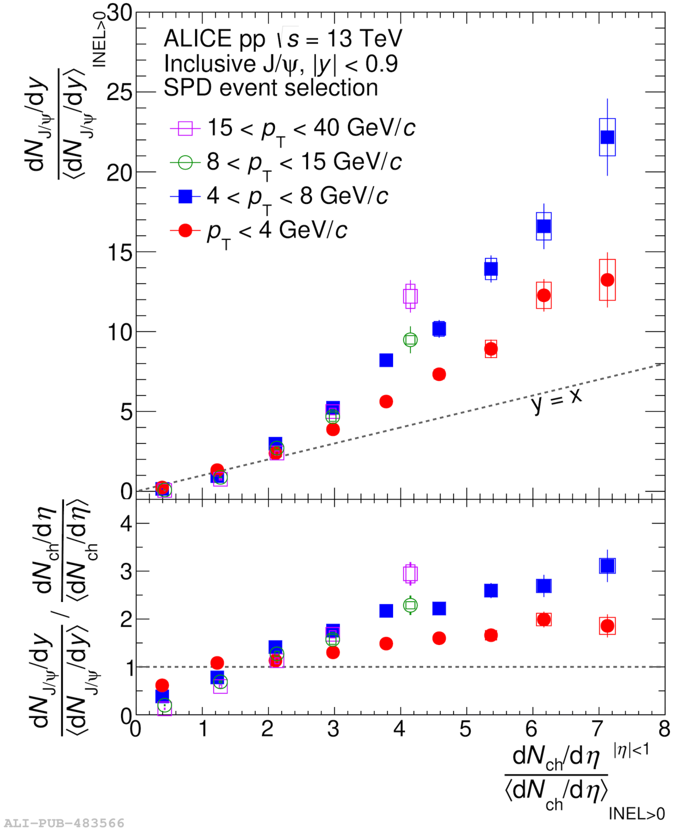


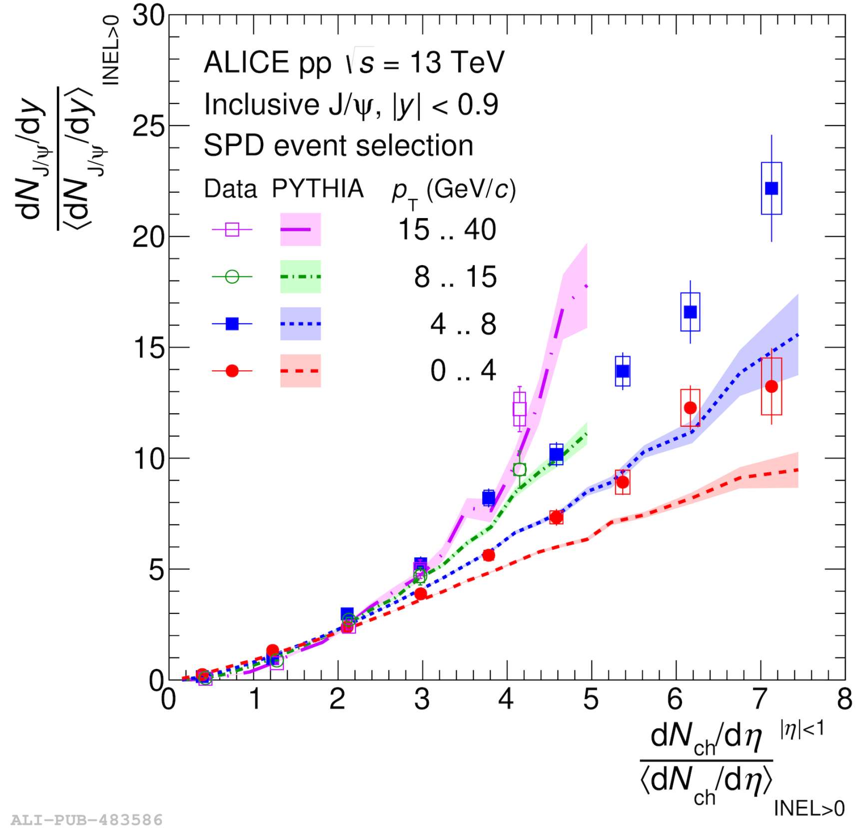


- Features catched by various approaches :
  - Initial state effects with modification of gluon distribution
  - Percolation (reduction of multiplicity)

- 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

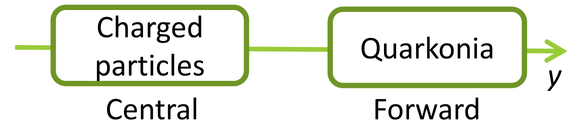


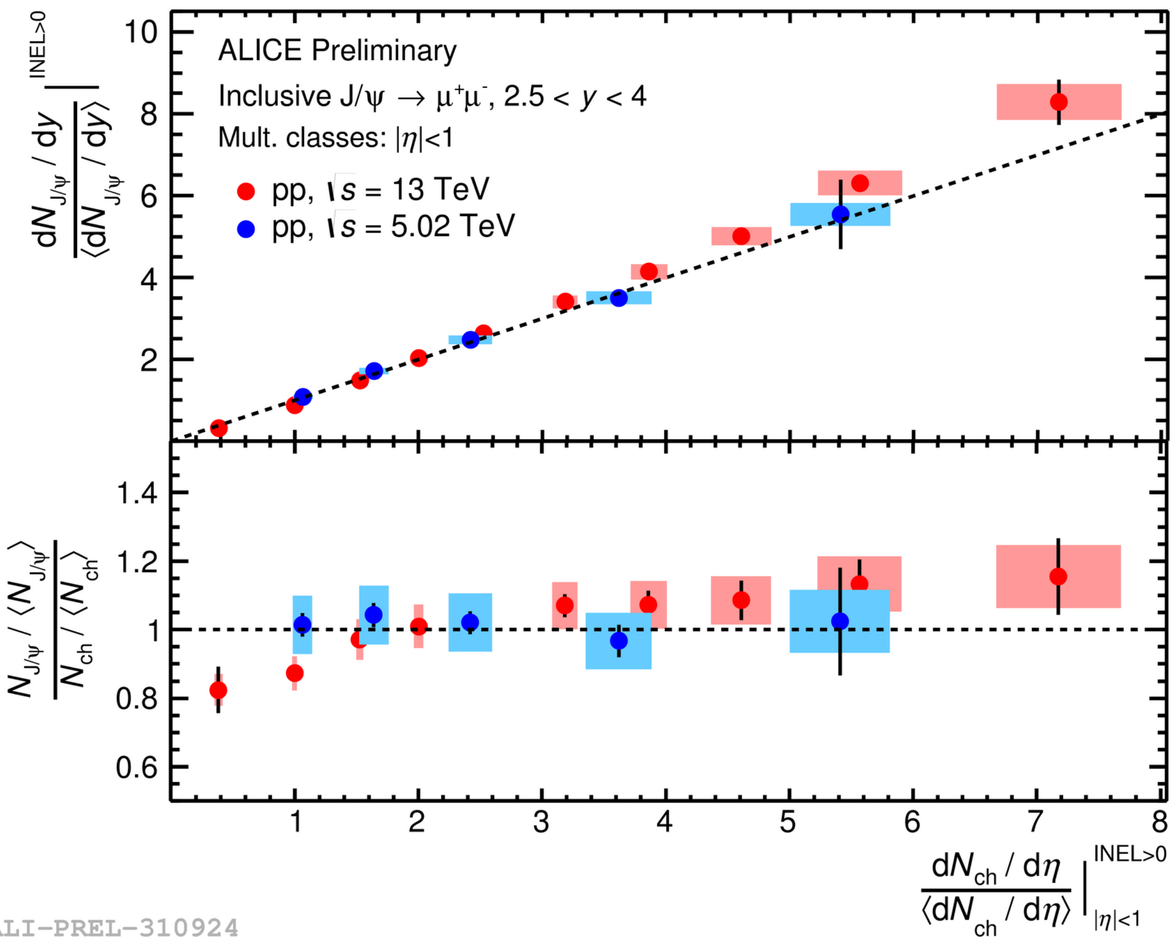


- Correlation varies with p_T ranges of the hard probe
- Number of MPI vs. hardness vs. initial state effects to built the multiplicity
- PYTHIA describes the data for p_T > 8 GeV/c

J/Ψ in the forward rapidity region

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

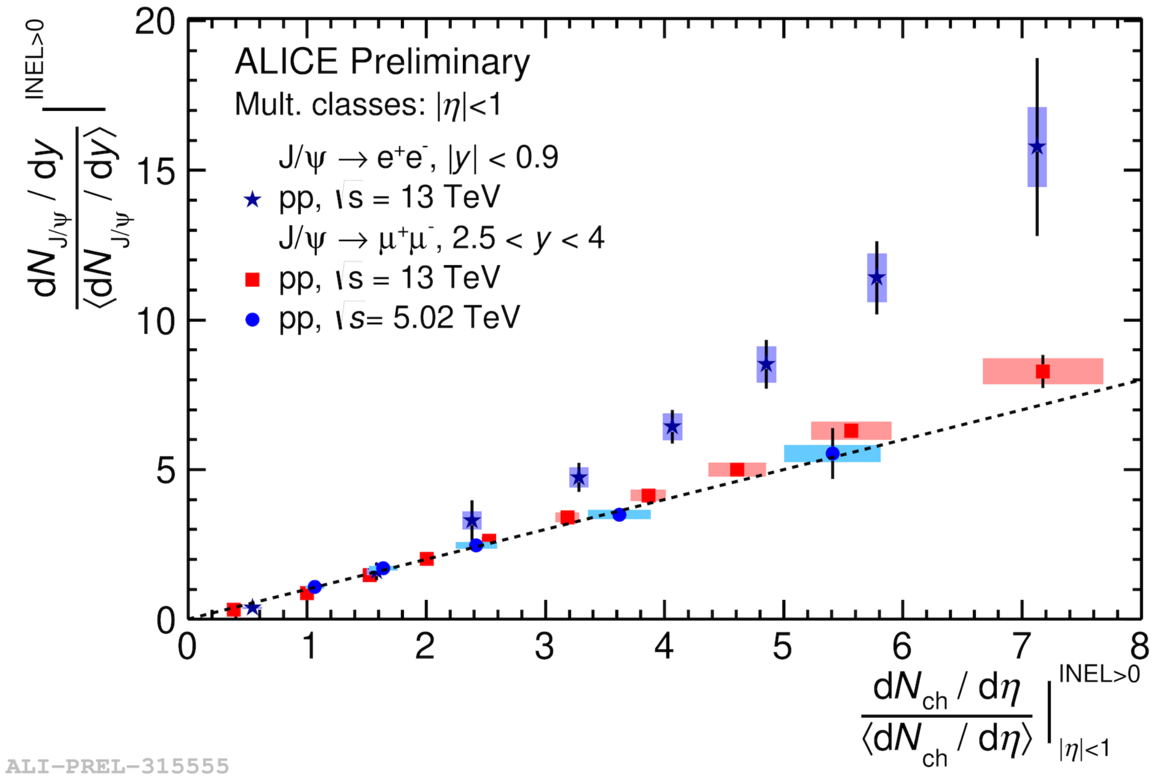


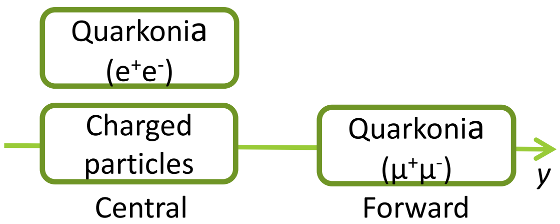


- The multiplicity is always measured in the central rapidity class
- A depletion below mean mult = 1
- Then linear increase, with slope compatible with 1, *x*=*y* correlation
- No energy dependence

J/Ψ in the forward rapidity region

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

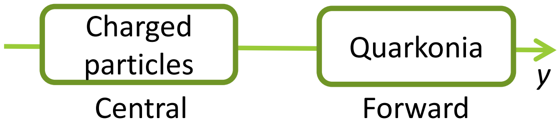


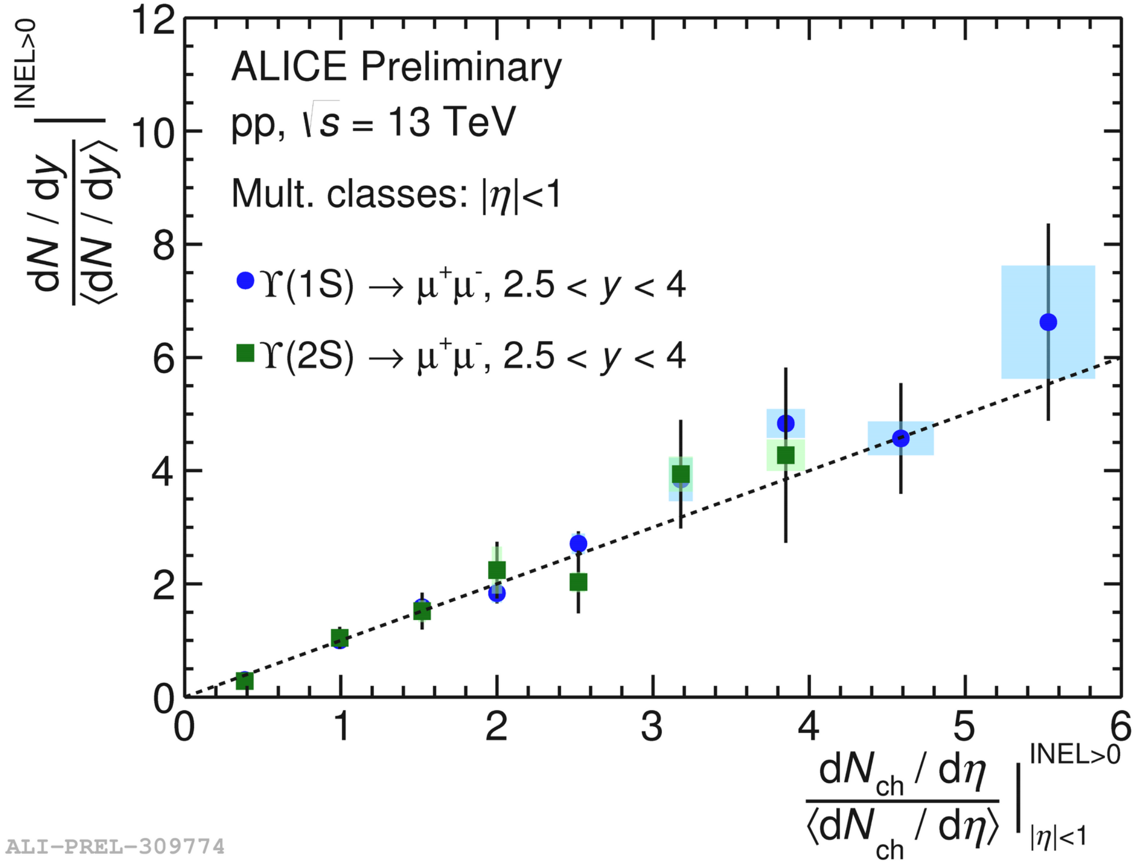


Different behavior when introducing a rapidity gap between the multiplicity estimator and the J/ψ

Υ in the forward rapidity region

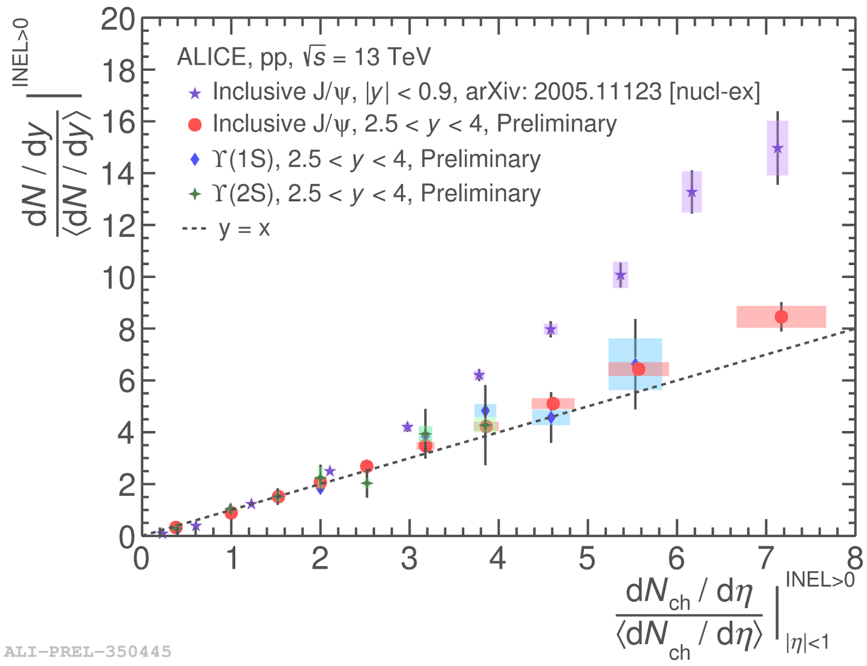
In the forward sectors for pp 13 TeV

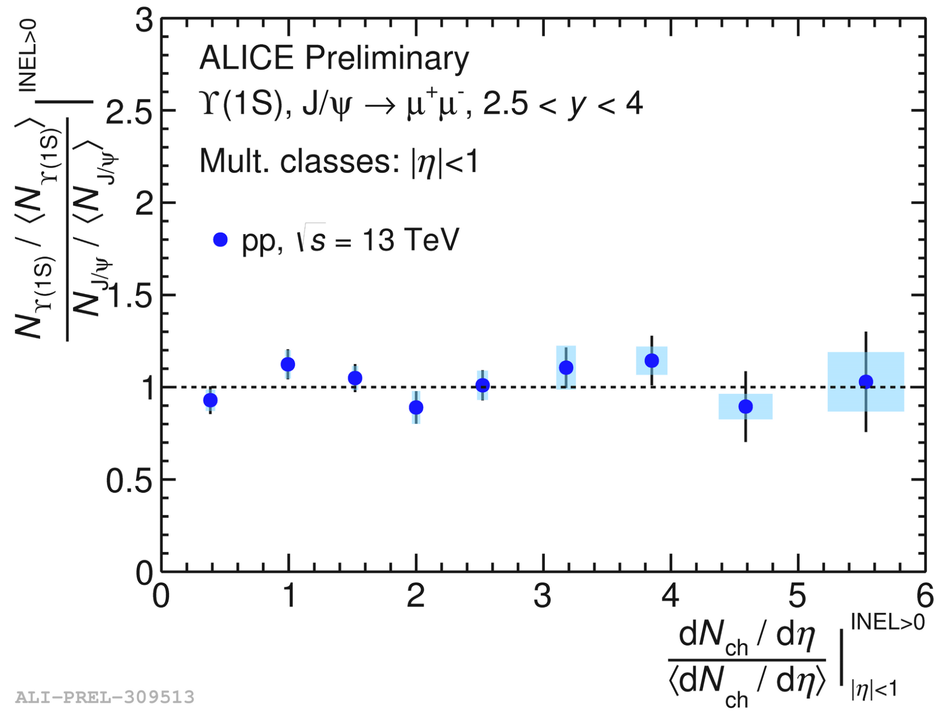




- The multiplicity is always measured in the central rapidity class
- A depletion below mean multiplicity = 1
- Then linear increase, with slope compatible with 1, *x*=*y* correlation

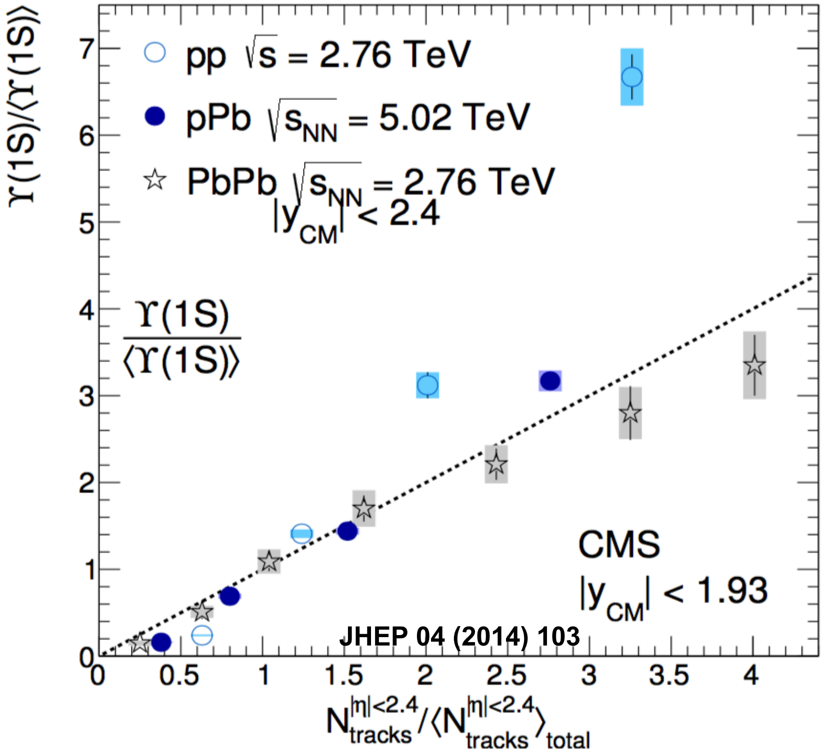
Quarkonia production as a function of multiplicity

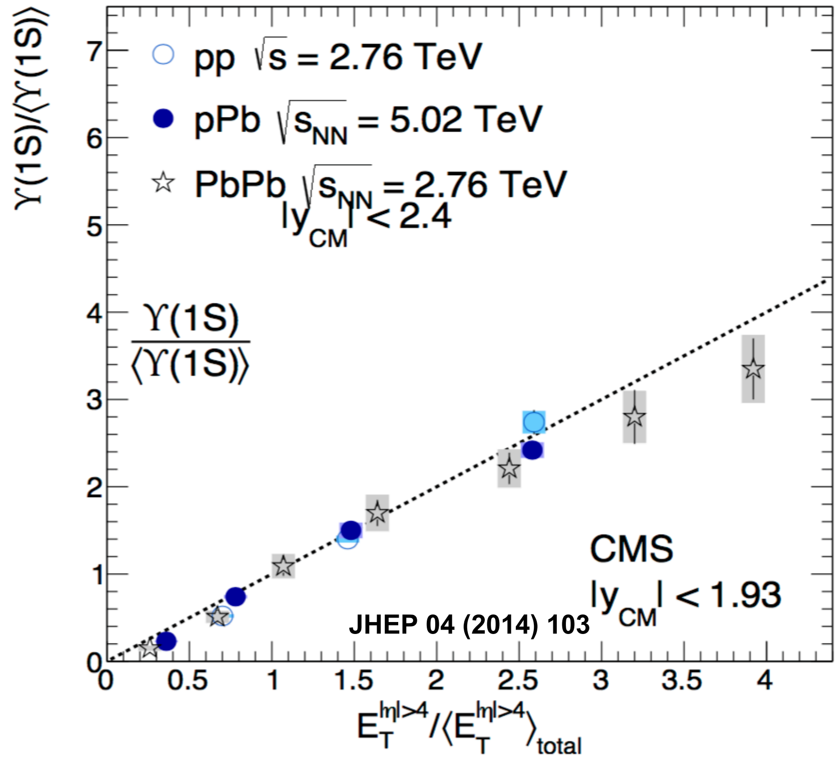




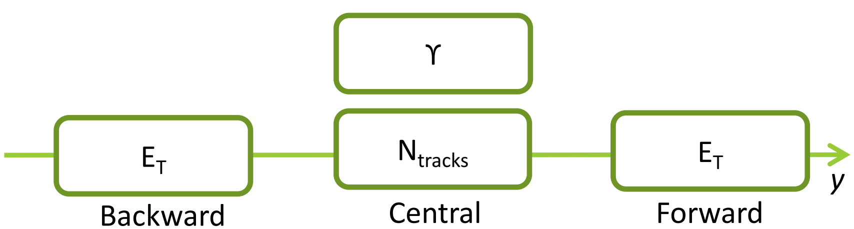
- ϒ have similar behavior as J/ψ in the forward sector within current uncertainties
- No effect seen with respect to quark content or mass

ϒ: What about rapidity gap ?



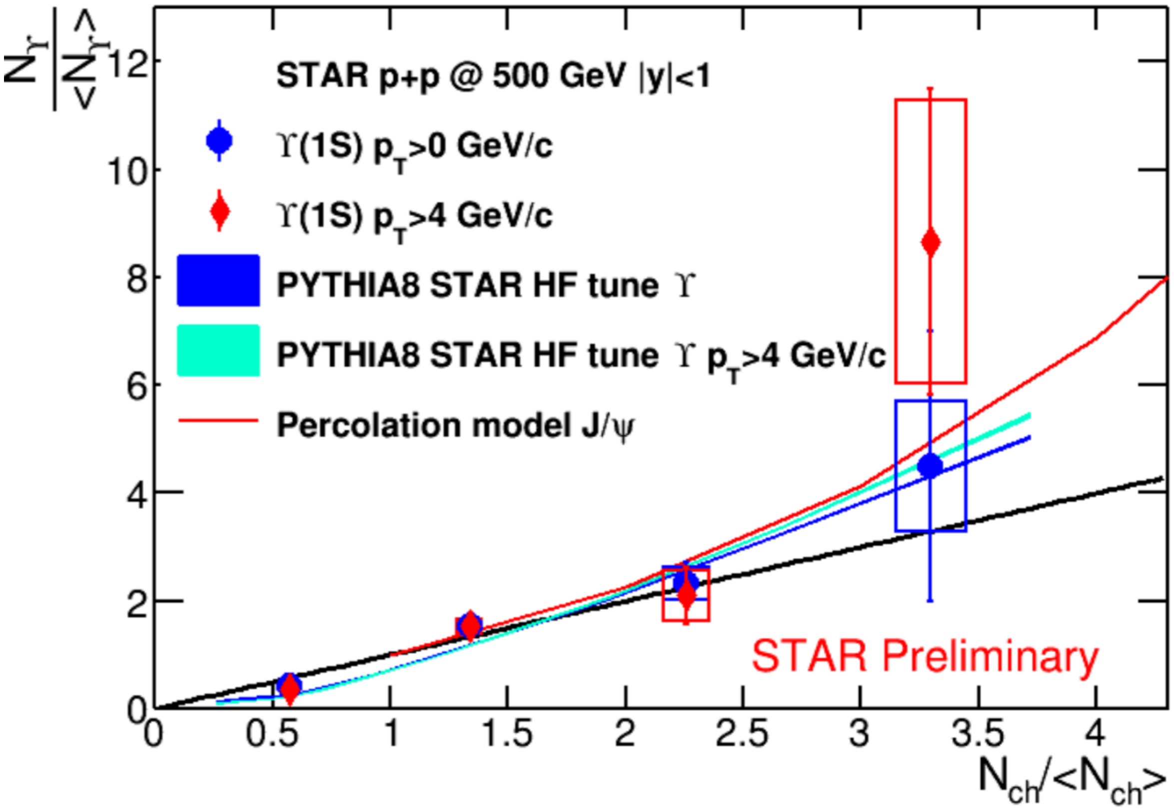


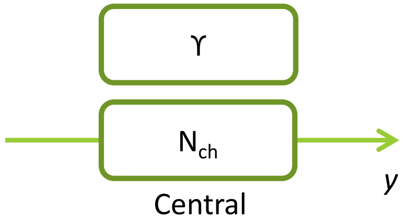
- CMS observes a strong increase of Upsilon states in the central rapidity region (pp 2.76 TeV)
- Linear behavior measured for forward E_T



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

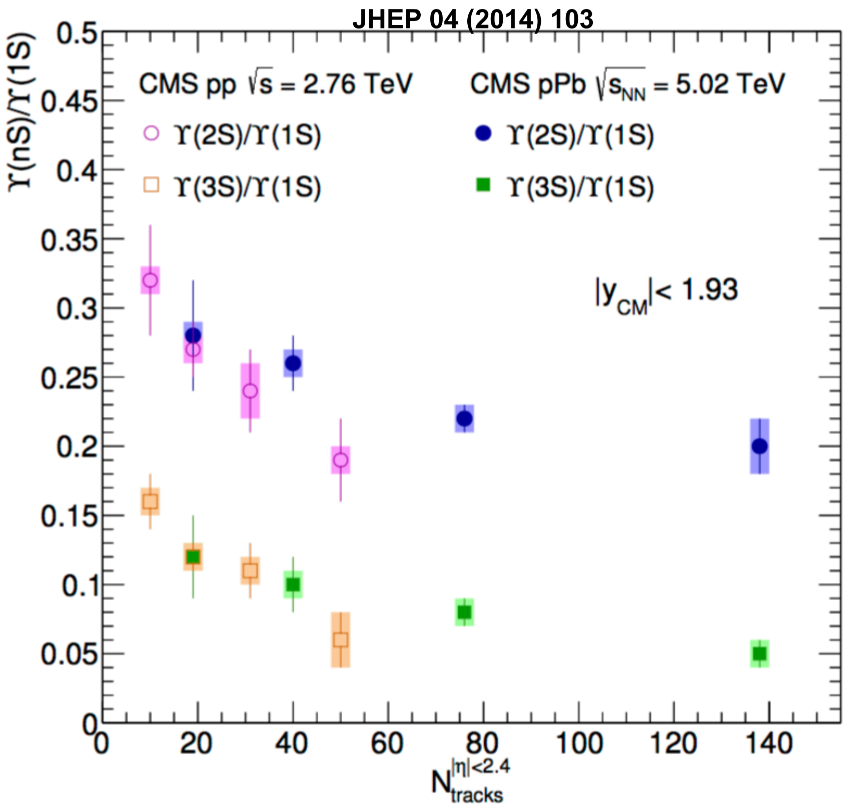
ϒ: What about rapidity gap ?

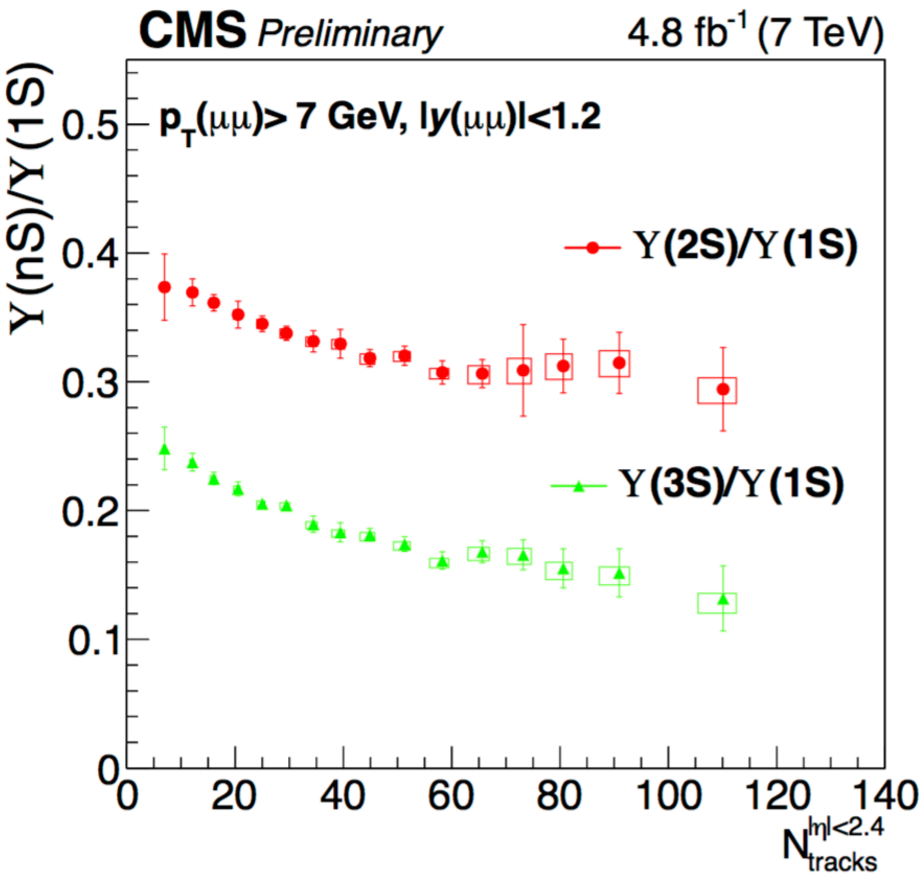




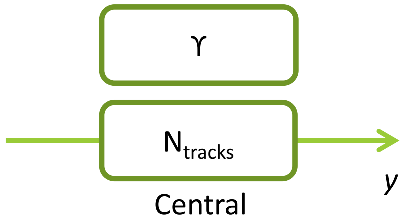
STAR observes in pp at 500 GeV in central rapidity region a deviation from linearity which is not significant with current uncertainties

ϒ: Exited to ground state ratio ?

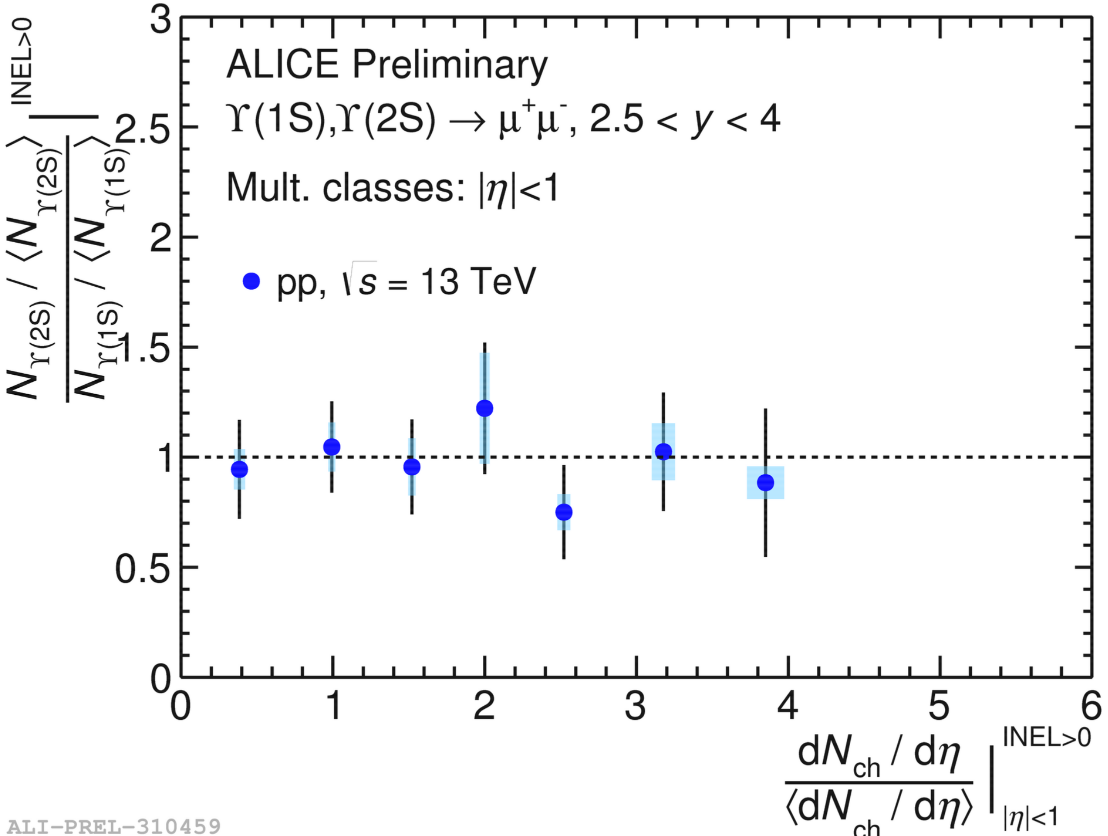


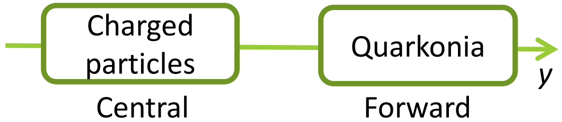


- CMS observes in pp at 2.76 TeV and 7 TeV and p-Pb at 5.02 exited to ground state disappearance in the central rapidity region, confirmed by analysis with sphericity and kinematic region of multiplicity (forward/backward/transverse)



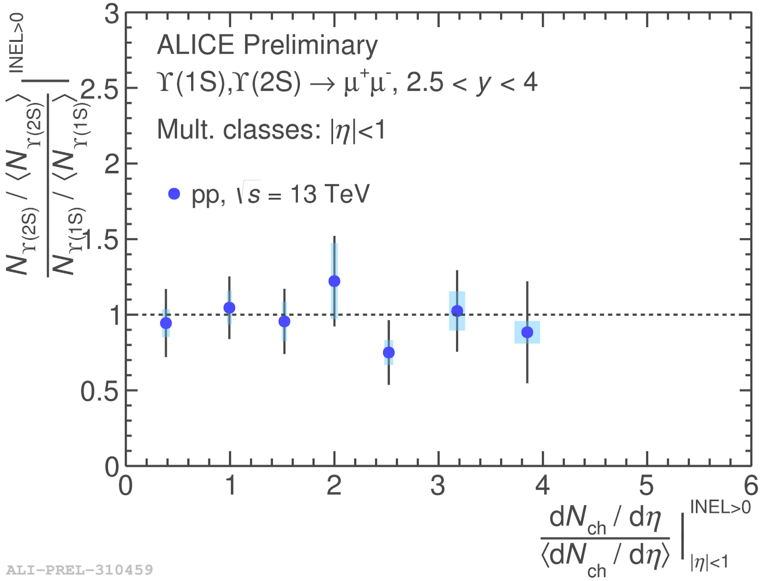
Υ: Exited to ground state ratio ?

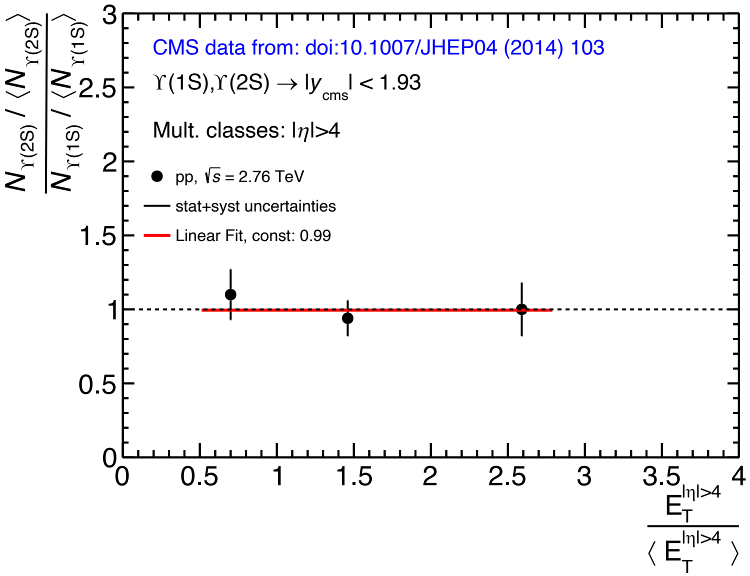


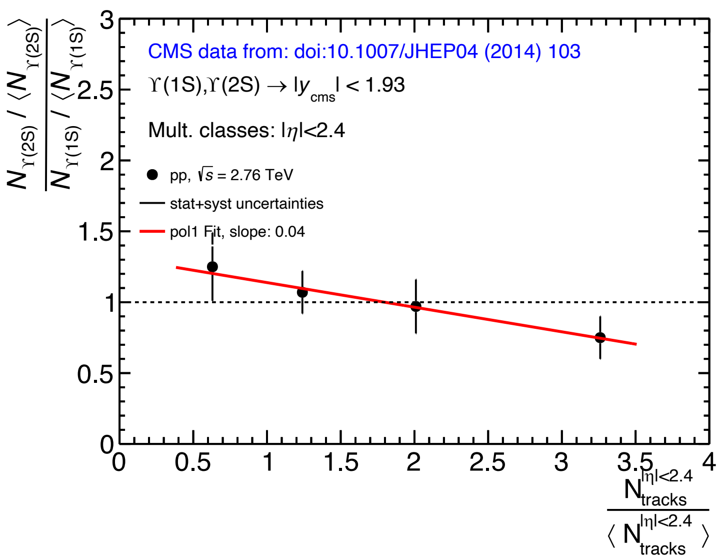


- ALICE observes same behavior as a function of multiplicity for the 1S and 2S states
- Caveats to compare to CMS: not exactly the same observables, definition of multiplicity, INEL>0
- Is the reason du to
  - a physics phenomenon: hadronization of Upsilon, dissociation in final state
  - a definition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

ϒ: Exited to ground state ratio ?

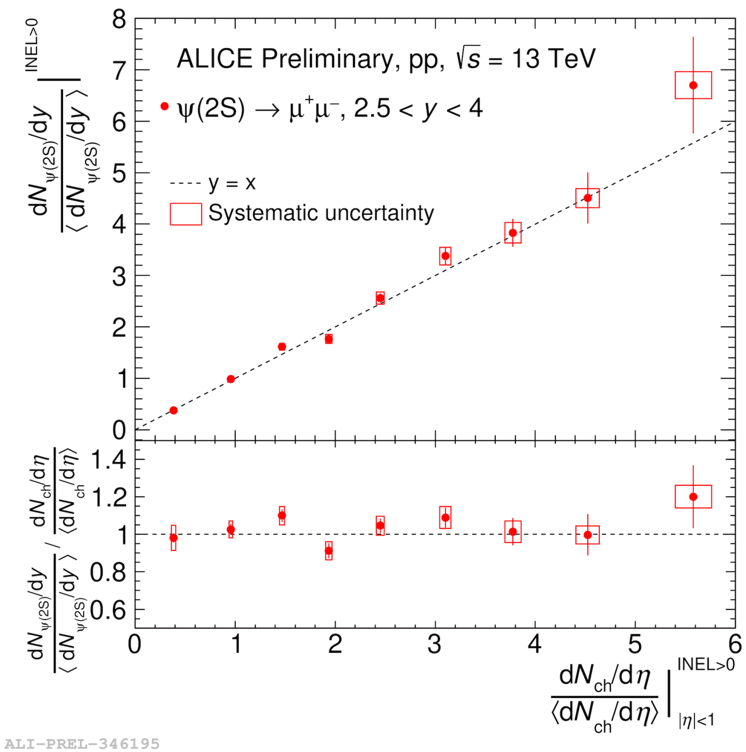


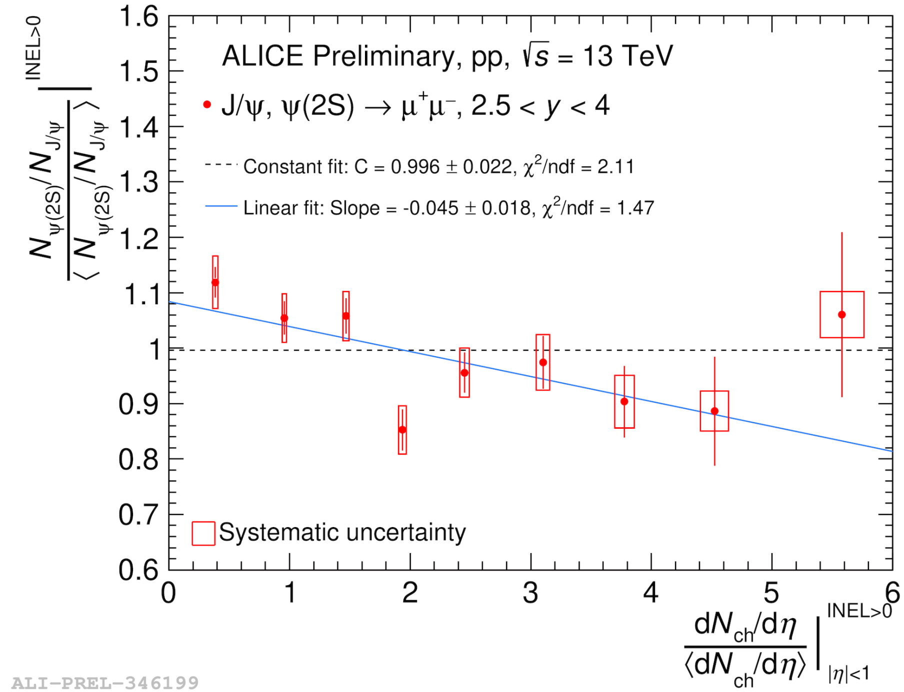




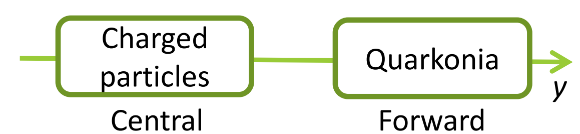
- Replotting CMS results as double ratios
- Decrease not excluded by ALICE results

Ψ(2s) in the forward rapidity region

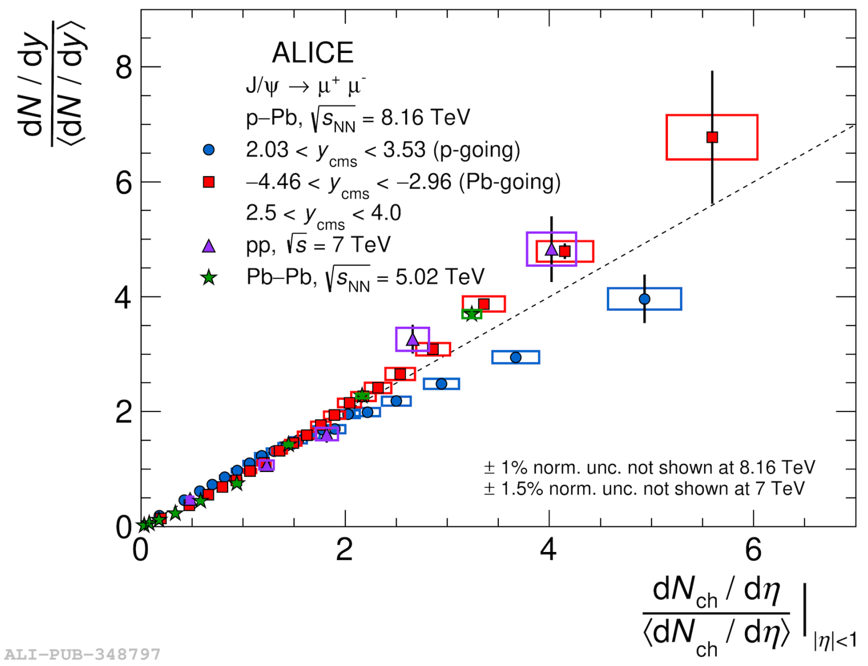


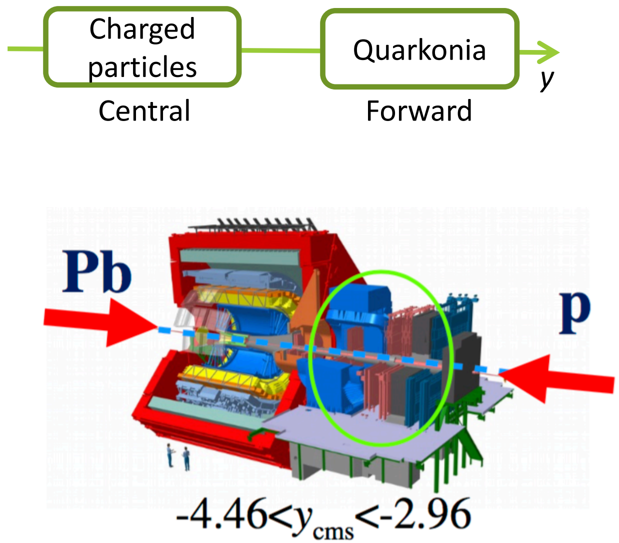


- Ψ(2s) over J/Ψ double ratio to be investigated further at RUN3
- Potential dissociation not excluded



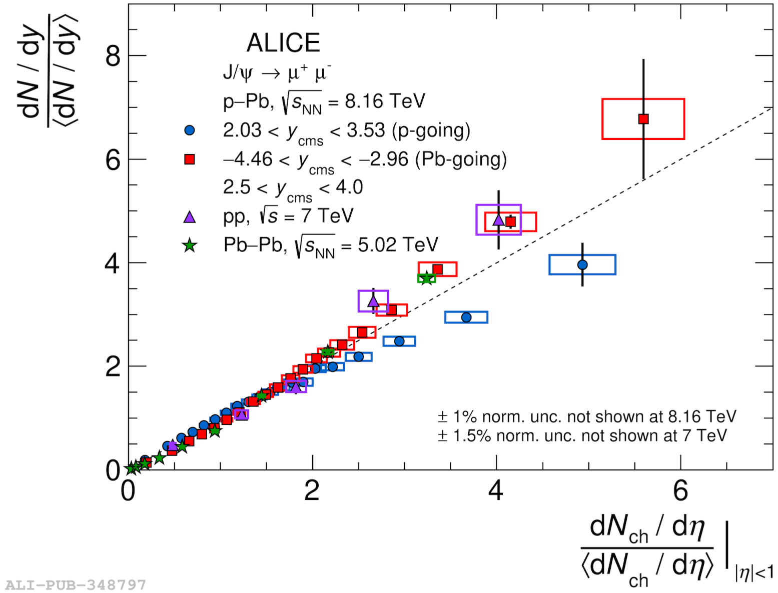
Changing system: p-Pb to Pb-Pb

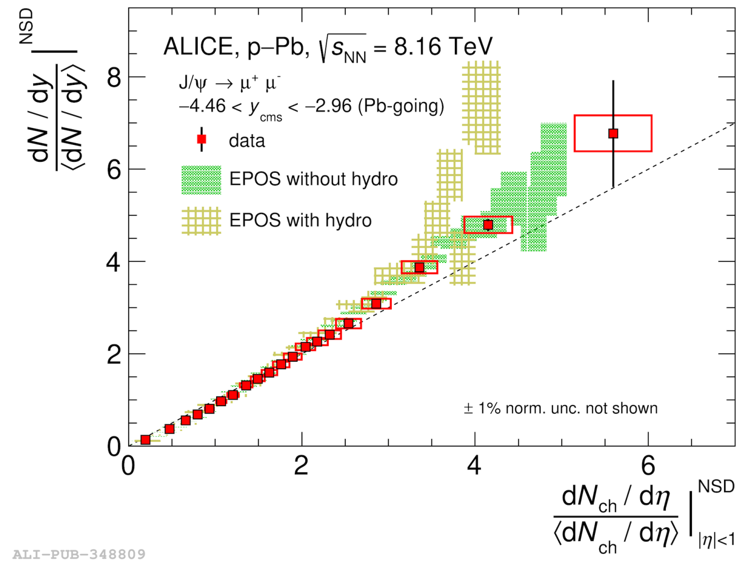


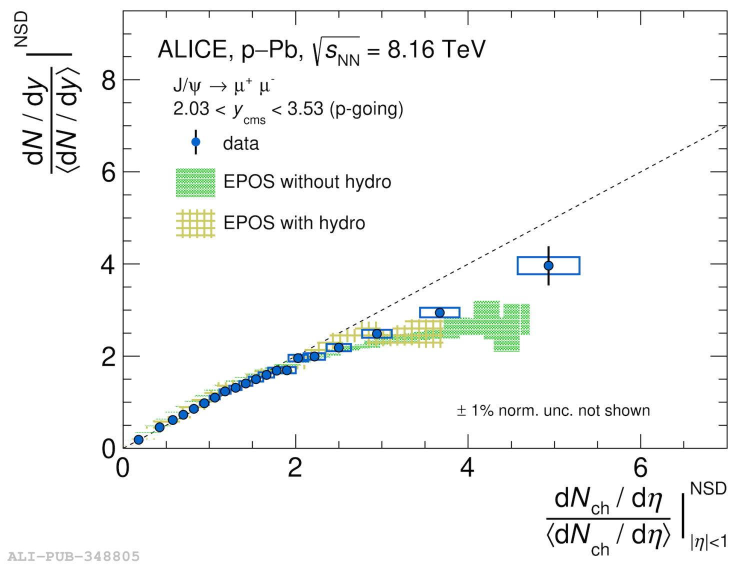


- ➢ Similar behavior from pp, to p-Pb (Pb-going) to Pb-Pb
- ➢ p-Pb (p-going) presents a different trend

Changing system: p-Pb to Pb-Pb







- EPOS3 describes this kinematical feature

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

- Essential to understand the **building of multiplicity in hadronic collisions**, connected to hard processes, especially for quarkonia

- **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)

BACKUP

Dissociation in final state ?

- Not directly MPI studies, but related physics that this kind of observable can help to answer :

  => Creation of a high multiplicity environment: potential dissociation of exited state with a comover like effect

- Related measurements

  - Upsilon exited states suppression with CMS
    - Not clear if it is a final state effect (dissociation in dense environment)
      or initial state effect (production, MPI (hardness bias), hadronization)
    - Compare with J/Ψ in the same rapidity region

      => See recent ALICE measurements for J/Ψ and Υ at forward

  - Psi’ suppression at RHIC in d-Au and LHC p-Pb (JHEP 12 (2014) 073)

    - Measure Ψ’ in pp 13 TeV vs. mult and compare with J/Ψ in the same rapidity region
    - Compare Ψ’ from different systems and energy at same mult and mean mult

Event generators

Goal (dream ?) :

- To reproduce entirely an event : particles in final state with all properties
- Should give access to exclusive observables
- Different from a calculation/computation usually inclusive and for one observable (for example p_T spectrum in pp -> J/Ψ + X)

Strategy :

- Initial state
- Elementary interactions : soft, hard, both?
- Radiation
- Remnants
- Multiple interactions
- Underlying events
- Particle production (string picture)

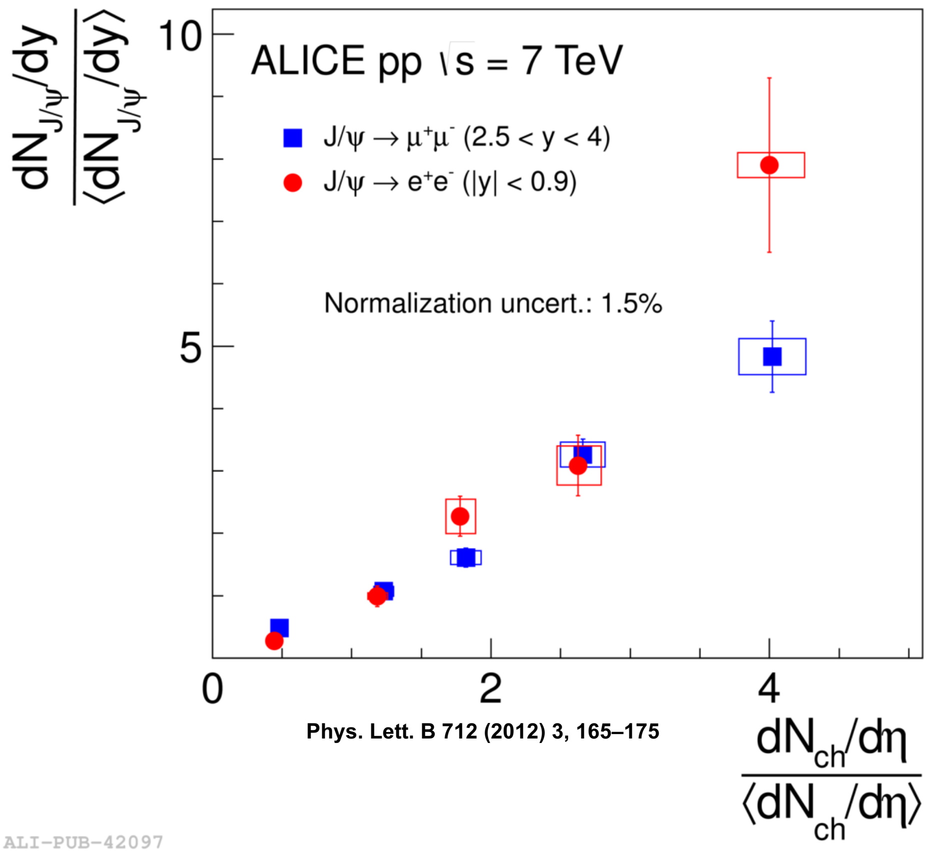
Why to use them ?

- Simulate events for detector/analysis purpose
  - Generate events for corrections
  - Test an analysis process on MC data prior to real data
  - Test your comprehension of your detector
    (MC = Event generation + Geant simulation of detector)

- Model Comparison
  - If you look at inclusive observables,
    maybe there is a model on the market that will be more adapted
  - If you start looking at exclusive staff : particle correlations, soft vs. hard, ...
    Event generators trying to reproduce all aspects of the event could be of interest

→ **New observables in quarkonium production**

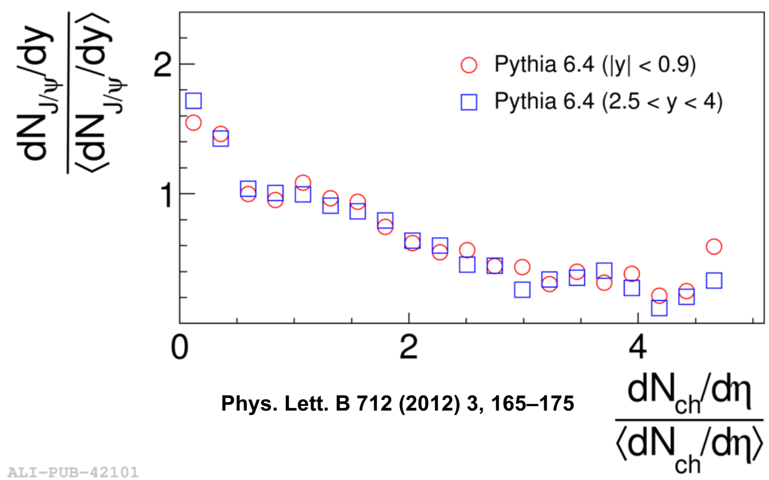
Quarkonia and HF vs. charged particle multiplicity



- **Comparison with PYTHIA 6.4**
  - Tune PERUGIA 2011
  - Direct J/Ψ production only

    J/Ψ produced in initial hard interactions

Trend not reproduced by PYTHIA 6.4
MPI without charm in subsequent interactions
MPI ordered in hardness

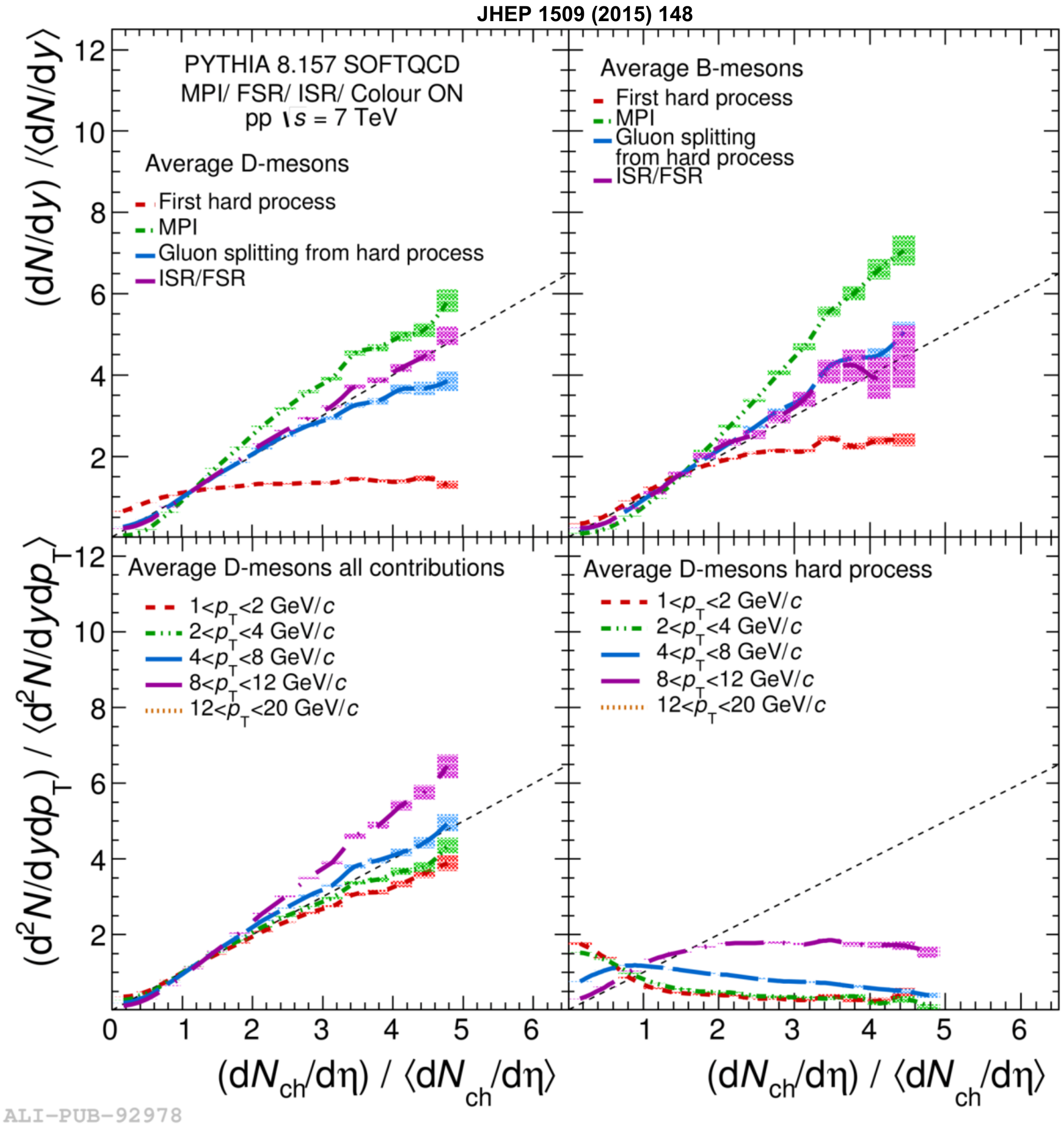


Quarkonia and HF vs. charged particle multiplicity

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



Quarkonia and HF vs. charged particle multiplicity

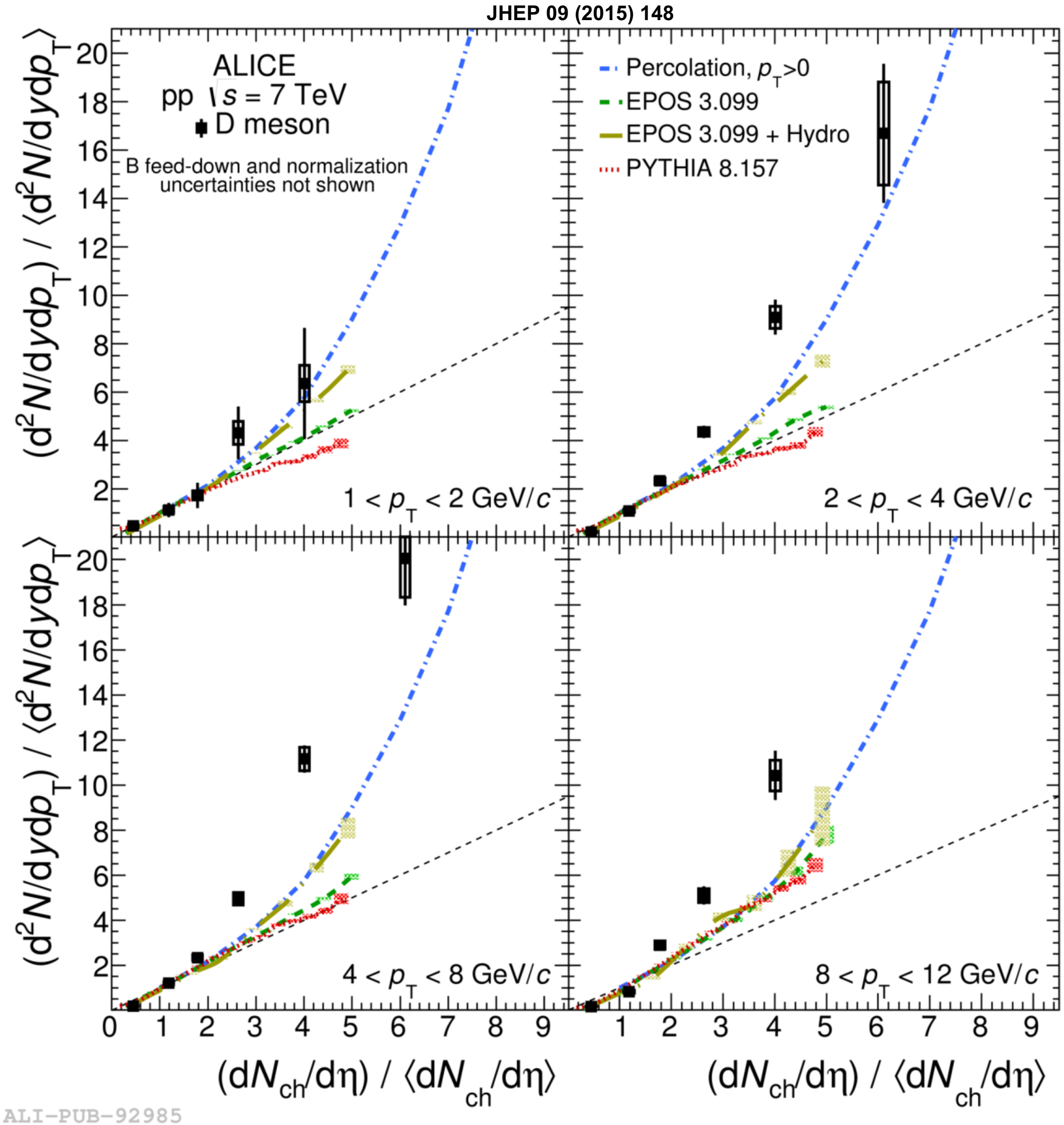
- **PYTHIA and EPOS wo hydro**

  Linear behavior fails to reproduce the data for the highest multiplicities

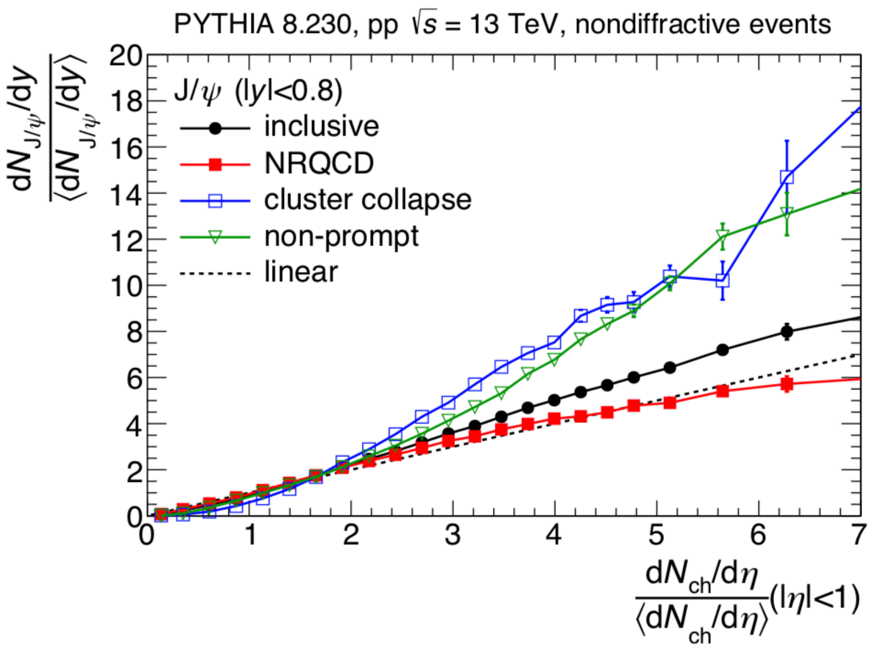
- **EPOS w hydro and percolation**

  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

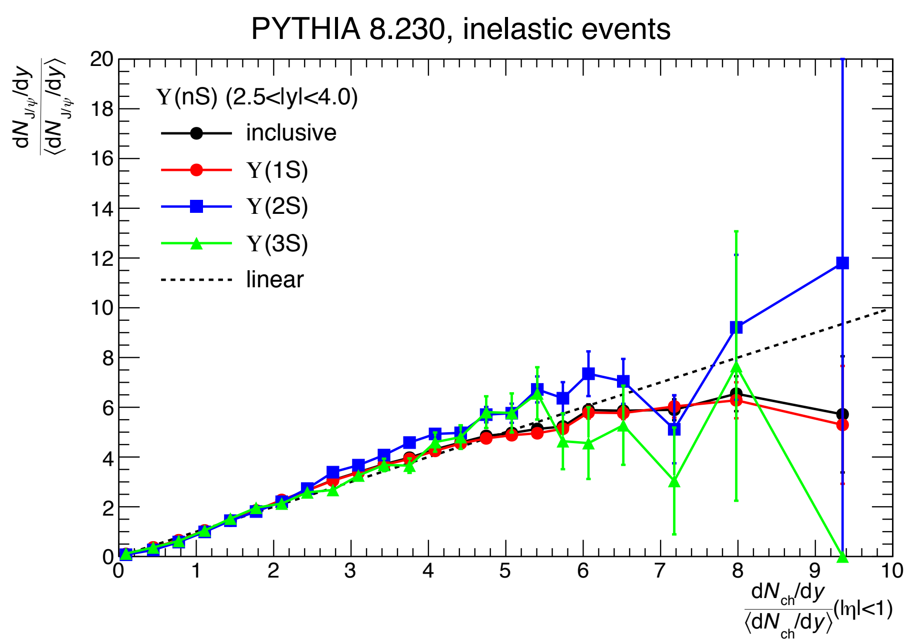


PYTHIA simulations for new quarkonia measurements



- Latest PYTHIA version, continuation of previous woks at 7 and 8 TeV, identifying J/Ψ origin
- Different contributions,
  Inclusive in black is the average

- For Upsilons, the three states
- Similar conclusions for both, difficulties to reproduce dependence up to high mult



Plot: courtesy of Steffen Weber arXiv:1811.07744

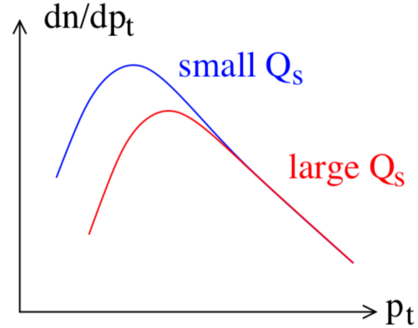
EPOS

Slides stolen from Klaus Werner

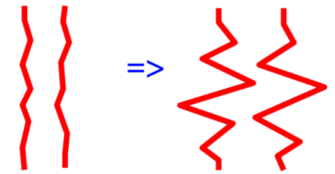
https://indico.in2p3.fr/event/14438/

- Recent development : EPOS 3.2

Parton distributions



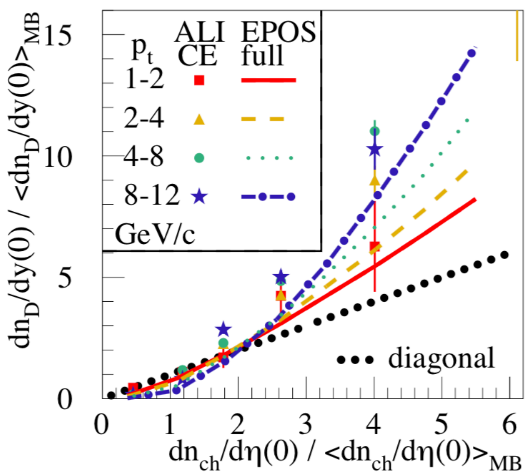
Increasing $\langle dn/d\eta(0)\rangle$ corresponds to increasing N_{Pom}. With $Q_s(N_{\mathrm{Pom}})$
=> Increasing Q_s
=> harder Pomerons
=> harder strings



=> more high pt particles

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

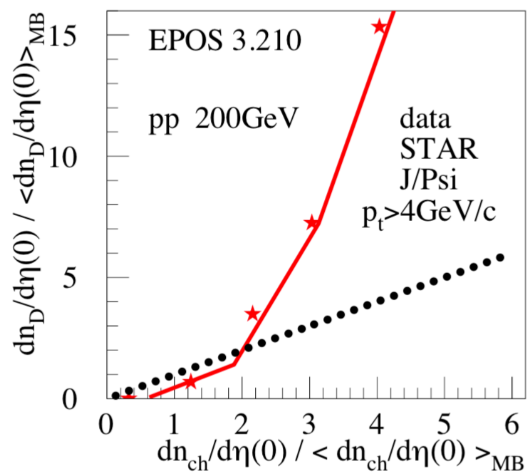
EPOS 3 compared to ALICE data



hadronic cascade on/off has no effect

hydro on/off has small effect

EPOS 3 compared to RHIC data

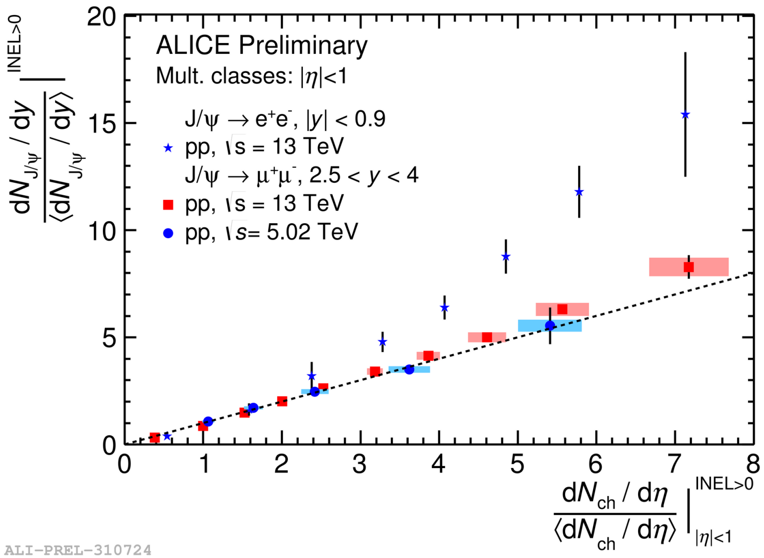


Calculations:
D mesons

Data: J/Ψ

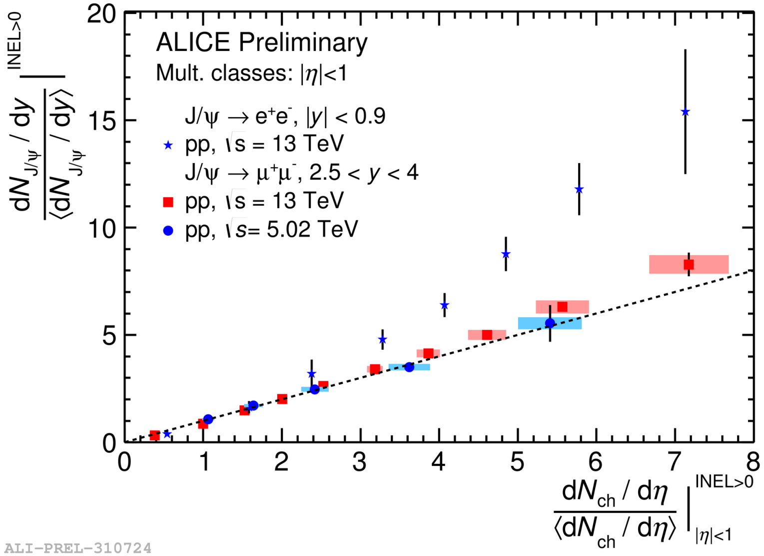
Increase stronger than at LHC

Building multiplicity: Final State Radiation for quarkonia ?



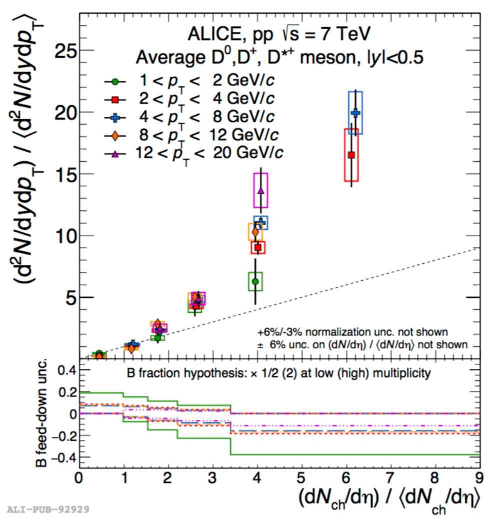
➢ Is the different behavior in different rapidity region of the quarkonium due to the hadronization in final state?

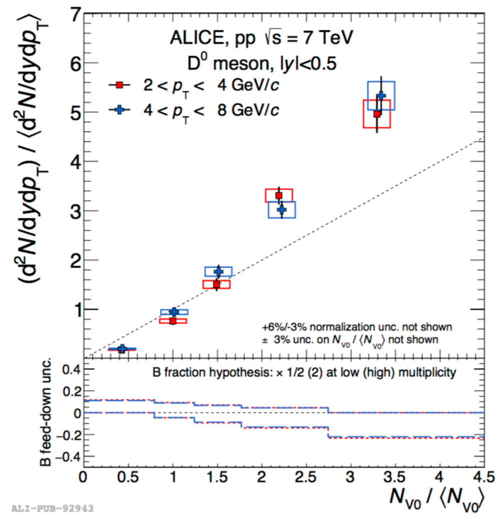
Building multiplicity: Final State Radiation for quarkonia ?

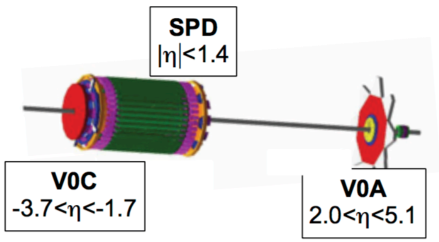


- Is the different behavior in different rapidity region of the quarkonium due to the hadronization in final state?

- This hypothesis was tested for D mesons

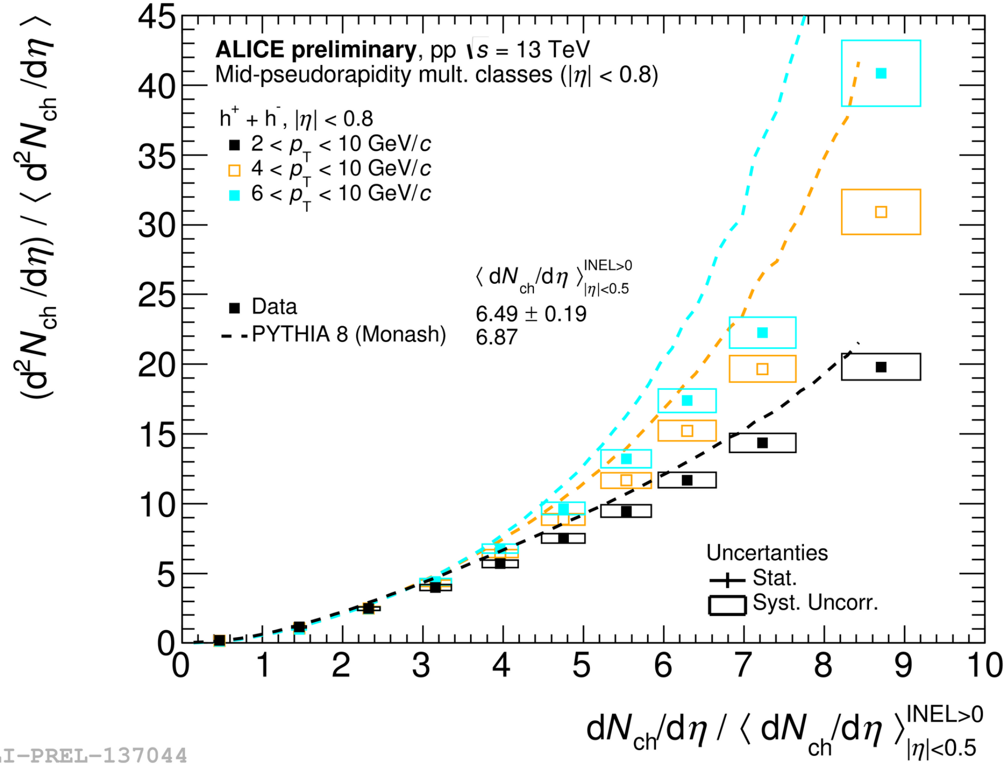


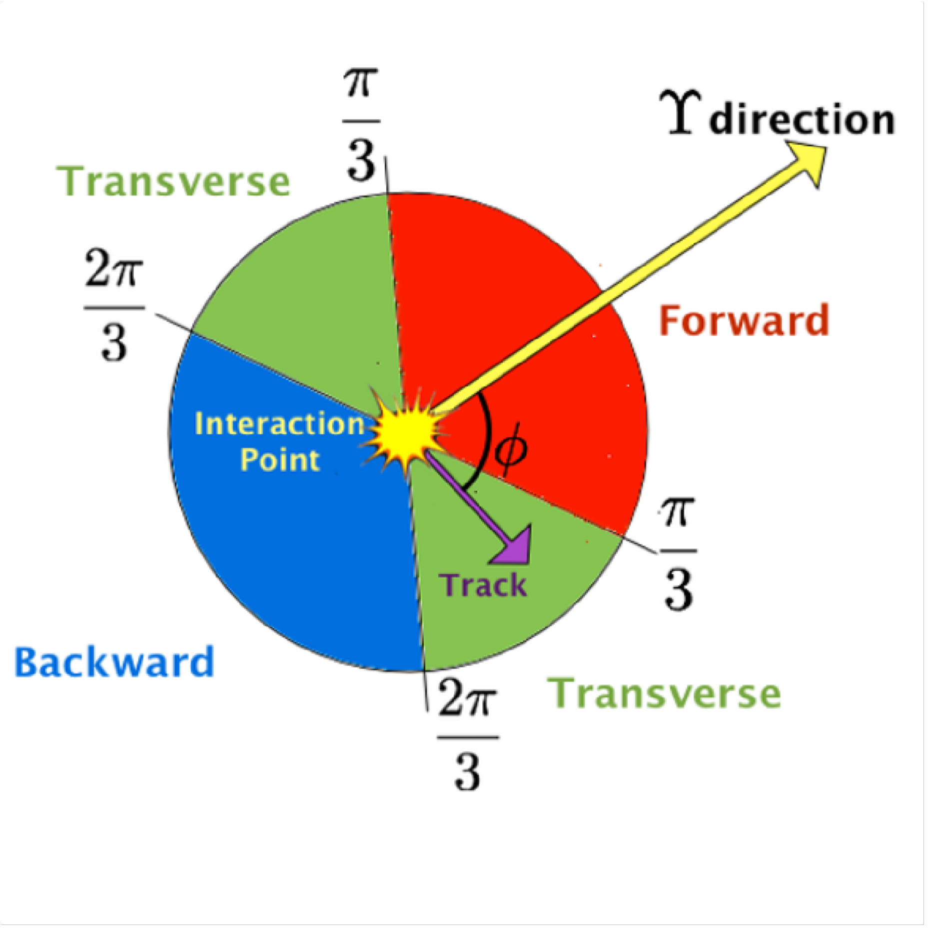




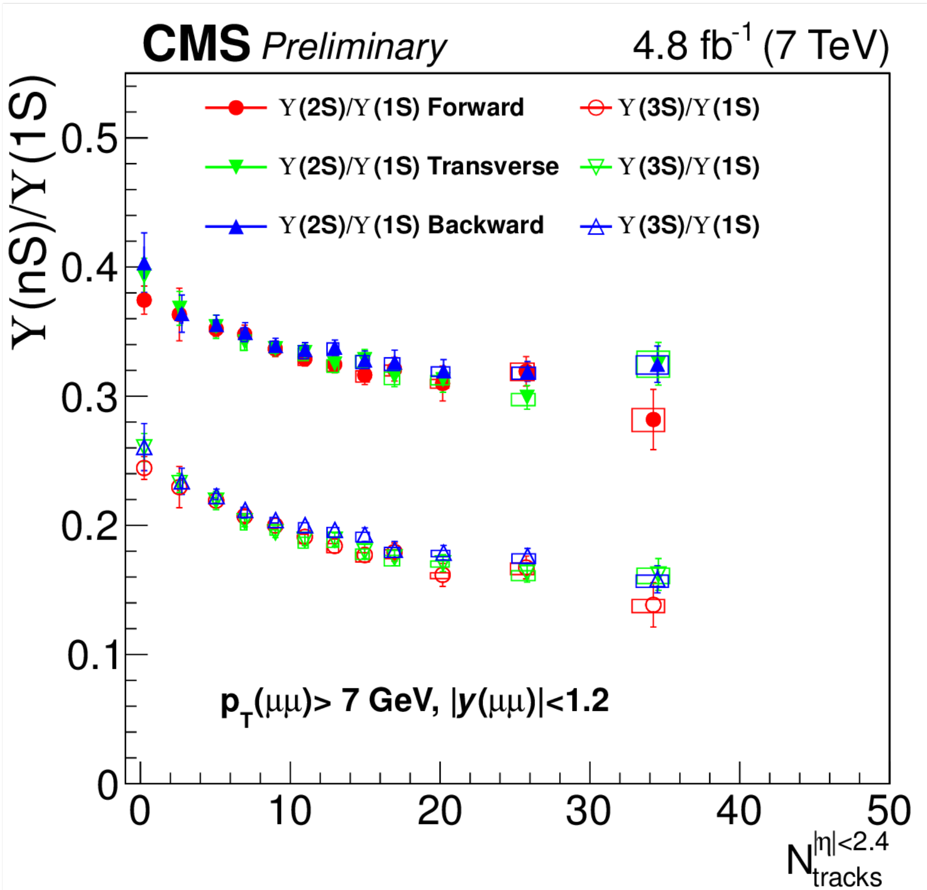
- Not only quarkonia and open heavy flavour

- Some examples :
  - Charged hadrons
  - Strangeness ongoing





(a)

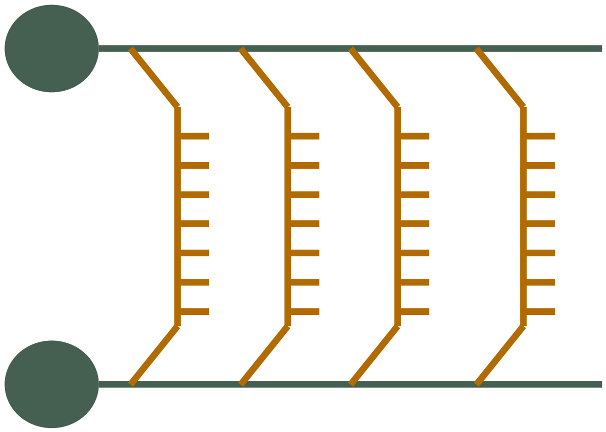


(b)

CMS-PAS-BPH-14-009

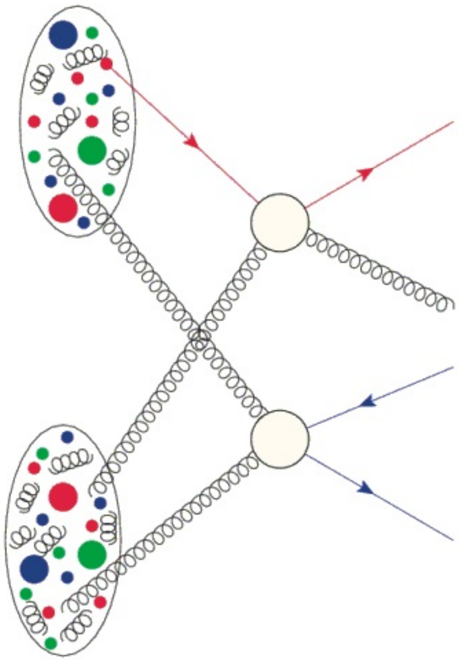
Multiple Parton Interaction (MPI)

✓ A naïve picture



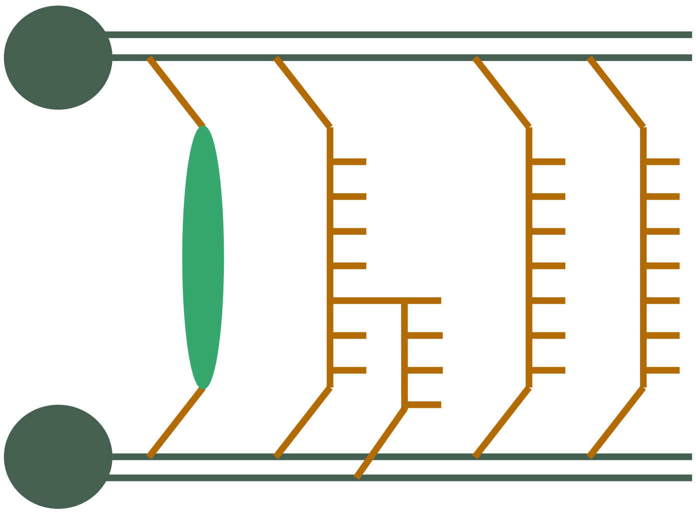
- Several interactions, soft and hard, occur in parallel
- The number of elementary interactions is connected to the multiplicity

- 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.

D-mesons in pp collisions at √s = 7 TeV

ALICE

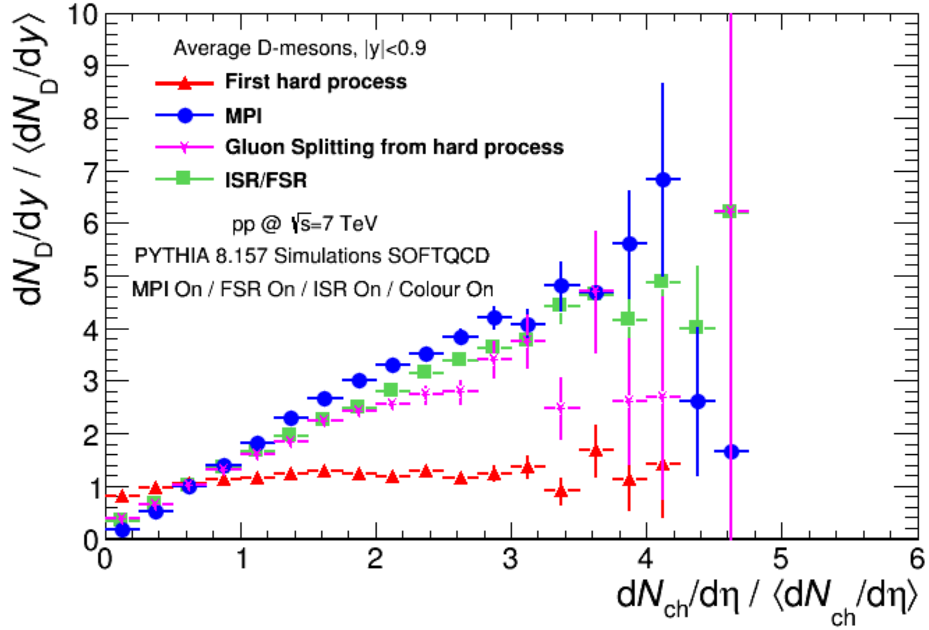
➢ Comparison with PYTHIA 8

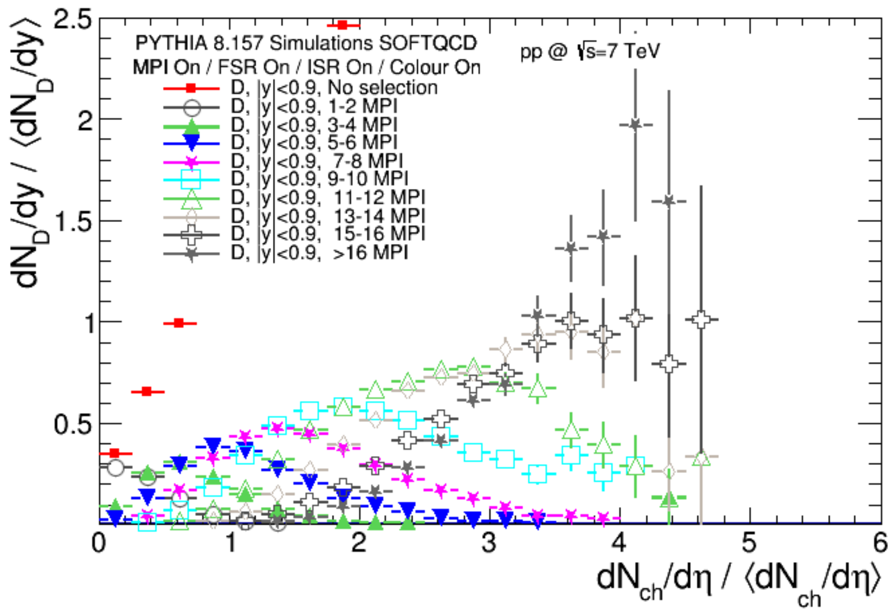
Improvement of MPI scenario
(charm in subsequent MPI)

Various contributions to the total D-meson production

- First hard process: flat
- MPI, ISR/FSR, gluon splitting increase trend with increasing multiplicity

In question: relative amount of each contributions
Major contribution (~60%) from ISR/FSR





Slices with the total number of MPI in the event, grouped by 2

Red (no selection) is the sum of all contribution

Each slices has almost the same weight in the total contribution

Zoom on the different contribution

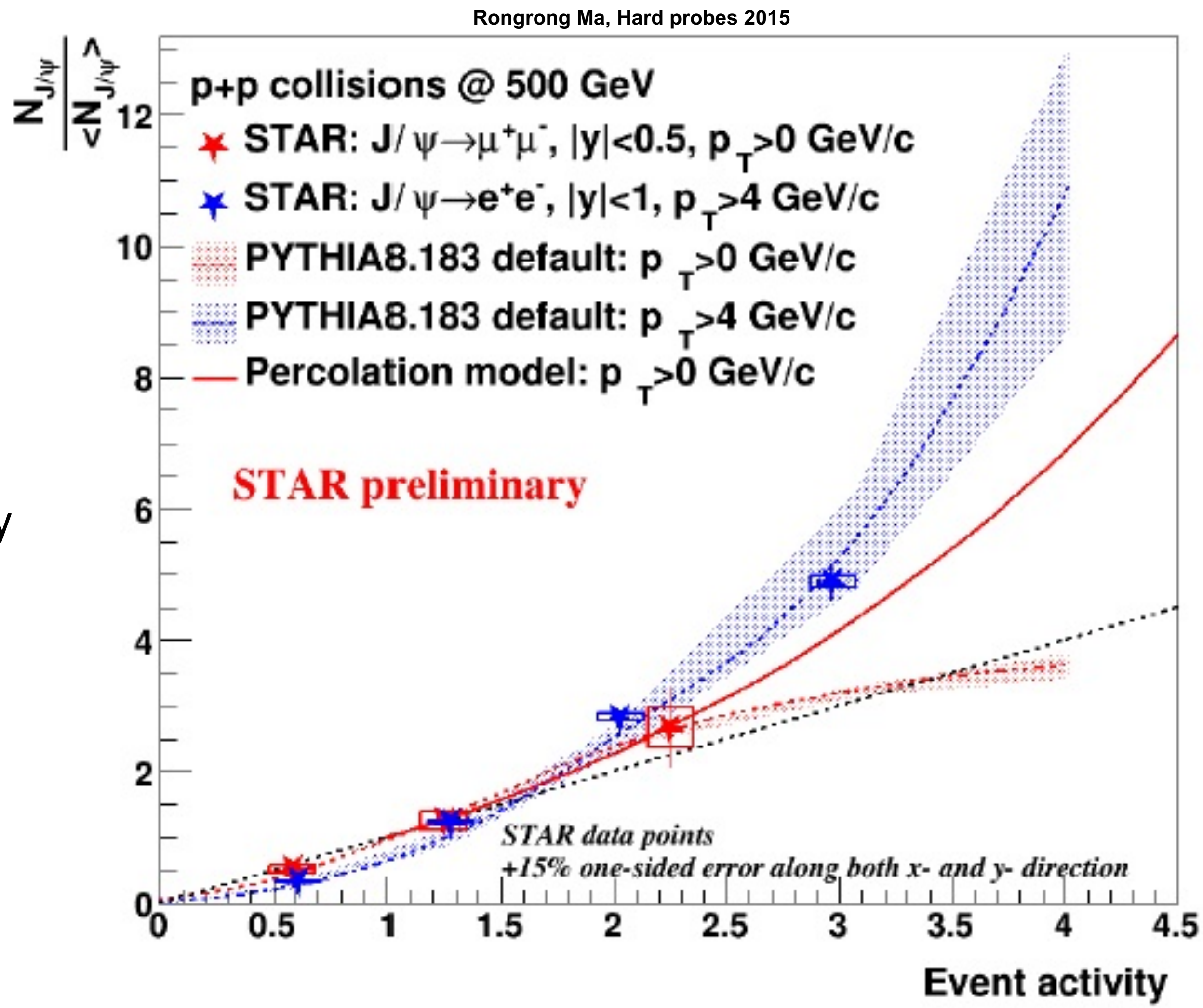
What we expect from MPI: addition of MPI built the multiplicity

Quarkonia and HF
vs. charged particle multiplicity

PYTHIA 8.183

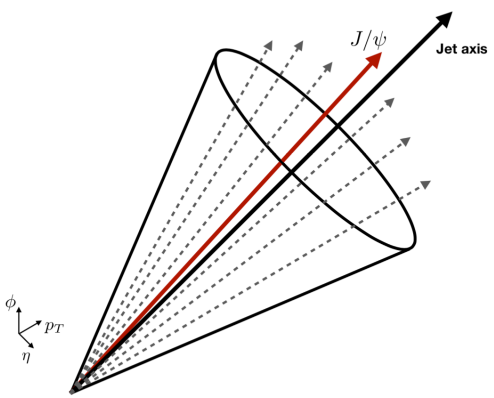
- All contributions for J/Ψ production
  Works pretty well

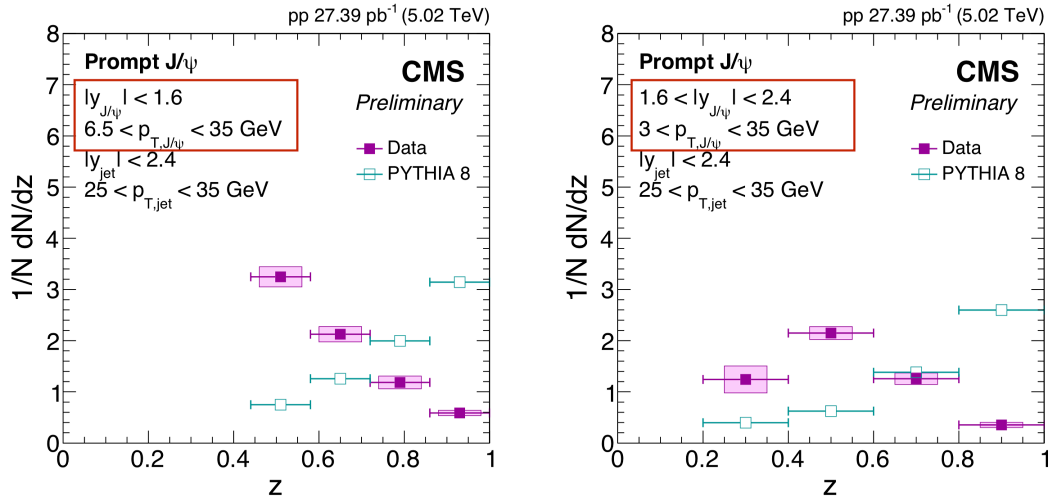
- Up to Event activity = 3 only



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





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

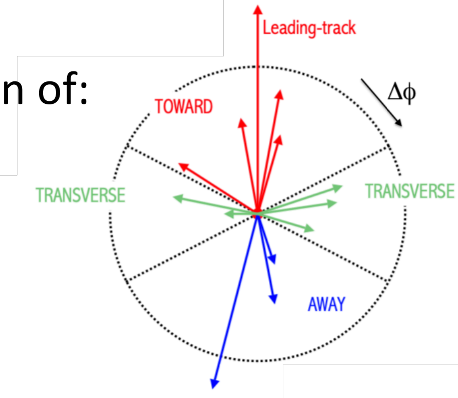
$$\frac{N_{\mathrm{ch}}}{\pi R^3}$$

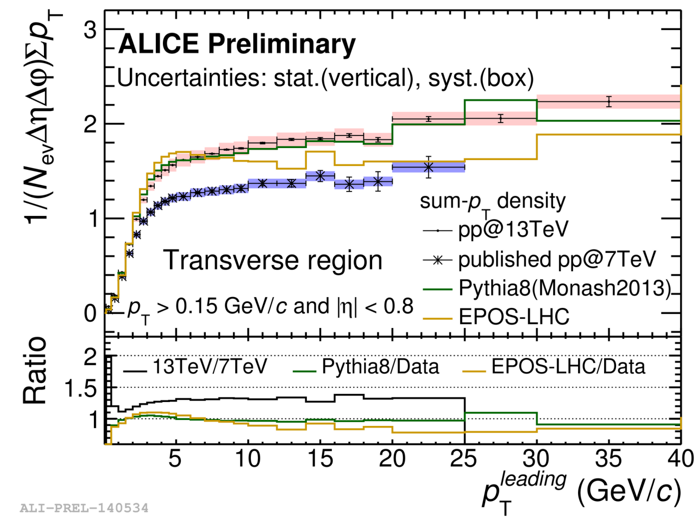
Problem of the definition of the normalization size in pp and p-Pb (*A* or *R* or ?)

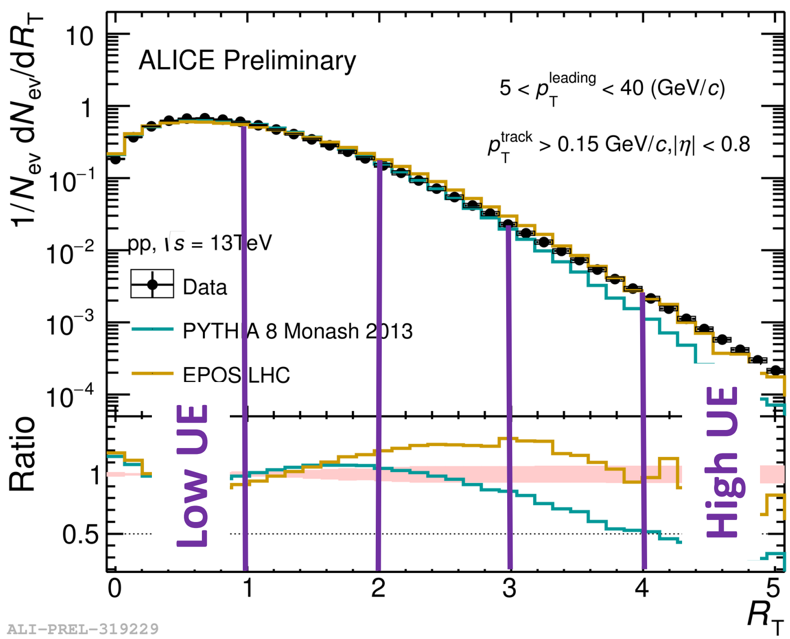
The transverse activity classifier

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

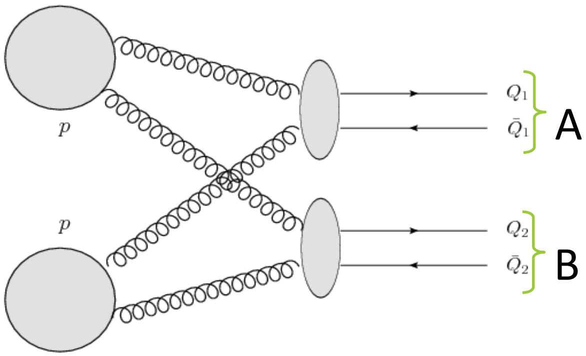
- ➢ R_T classify events in term of high or low UE

Double Parton Scatterings

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

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

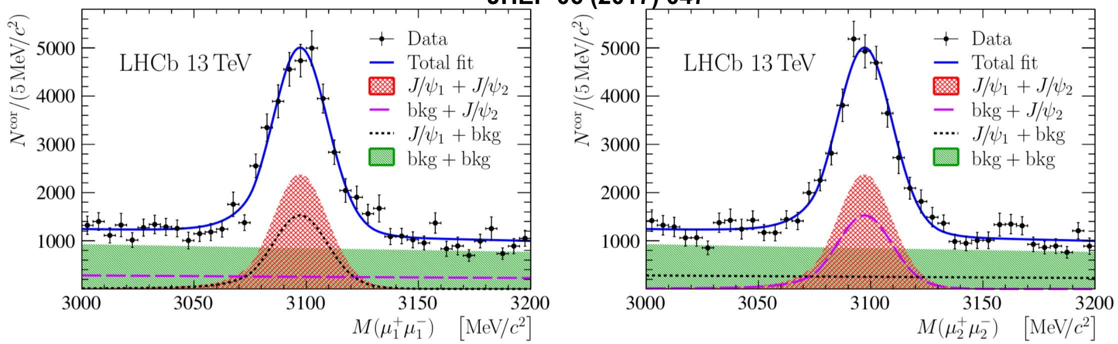
m=2 when A and B are distinguishable
m=1 when indistinguishable



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

- 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

JHEP 06 (2017) 047



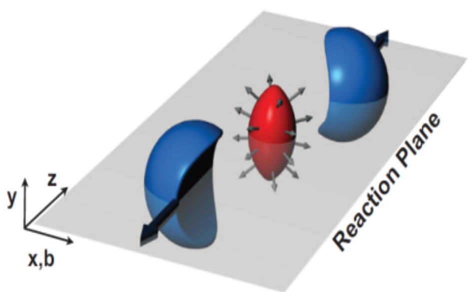
- Require to investigate physics potential and feasibility with ALICE in Run 3 conditions: with muons only, with muons + electrons, with muons + hadronic channels

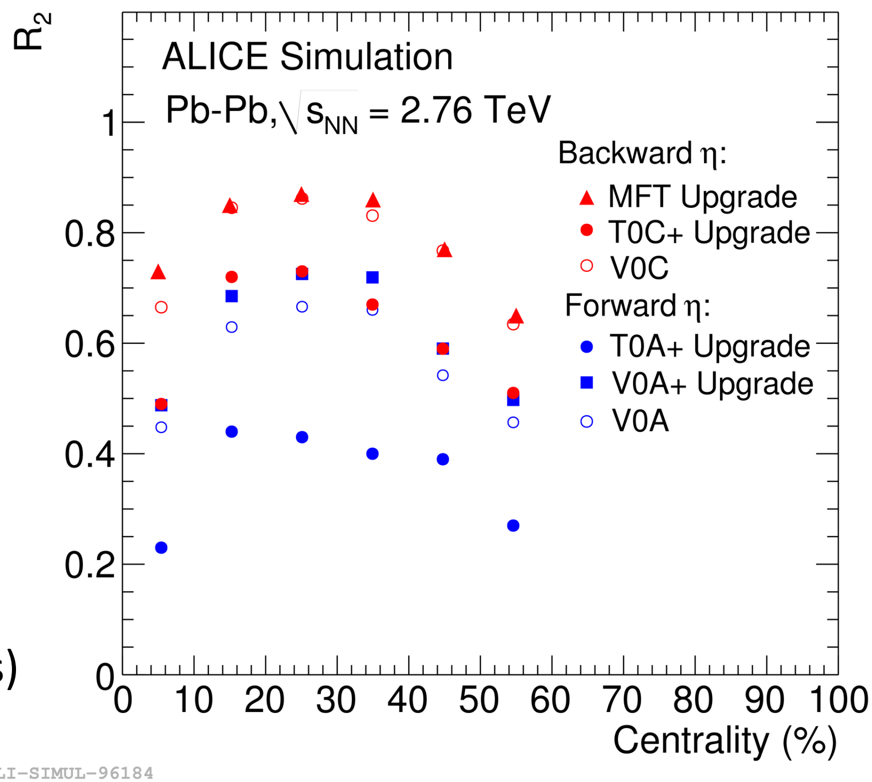
- Possibilities should be enhanced by the continuous readout
  The MFT will specifically improve the signal/background for channels where the signal is composed of prompt muons. First study by D. Stocco and P. Bartalini

[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]

MFT as a multiplicity estimator

- **In addition to muon tracks, MFT will measure unidentified tracks**
- **Clear benefit for study of hard-soft correlations**, like quarkonia vs. multiplicity, with a multiplicity estimator in the acceptance of the hard probes
- Reaction plane measurement

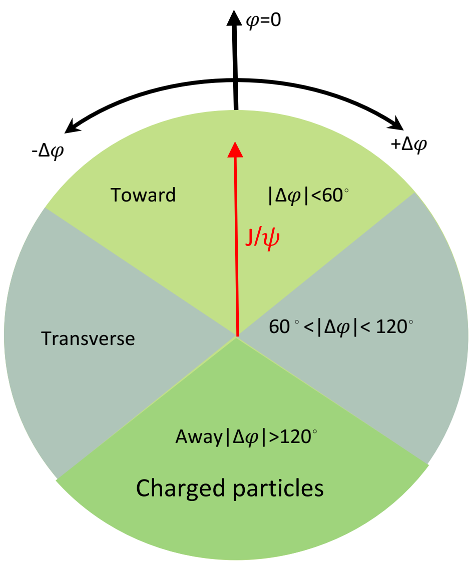


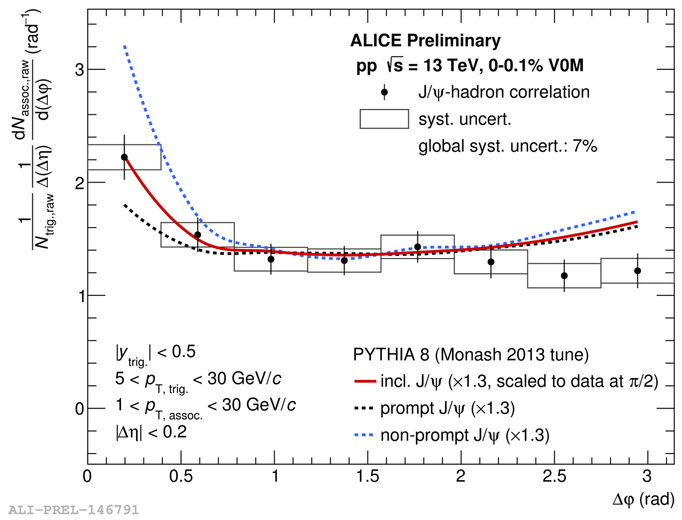


- **Excellent reaction plane resolution with the MFT**, thanks to its high-granularity and the possibility to perform a standalone tracking (excluding contaminations from noisy clusters)

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**

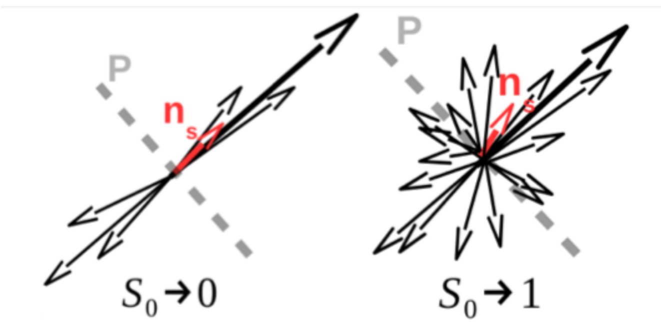




- **Opportunities to be investigated** in the muon channel with the MFT as a vertexer and a multiplicity estimator

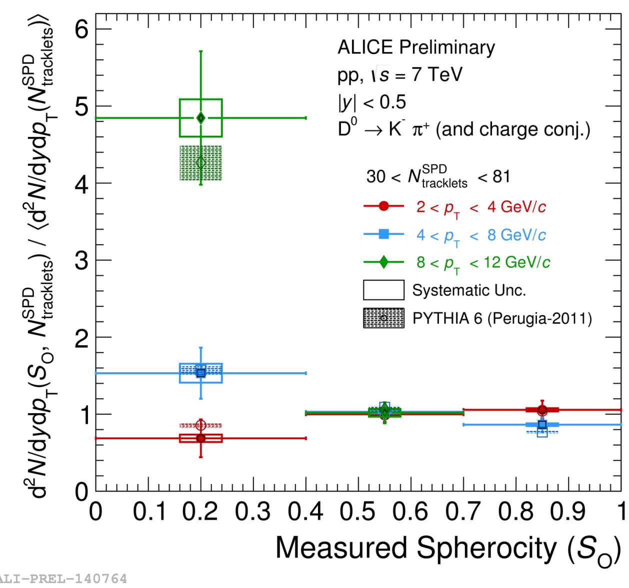
Opening possibilities for correlations in final states

- 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