Quarkonia, high multiplicities, isolation, Monte Carlo and all that …

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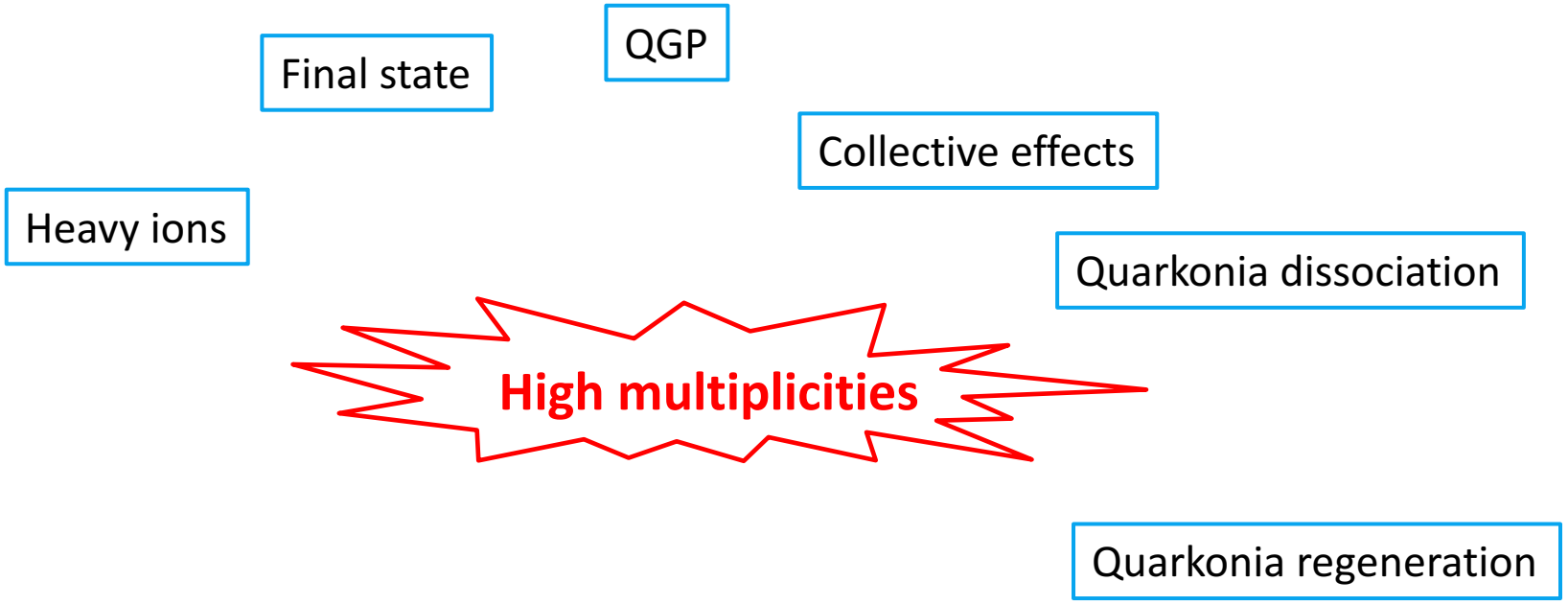
QUARKONIA AS TOOL

13-19 JANUARY 2019 AUSSOIS

Disclaimer: input for round table, not a detailed talk!

Let’s define ”high multiplicities”



Let's define "high multiplicities"

Final state

QGP

Collective effects

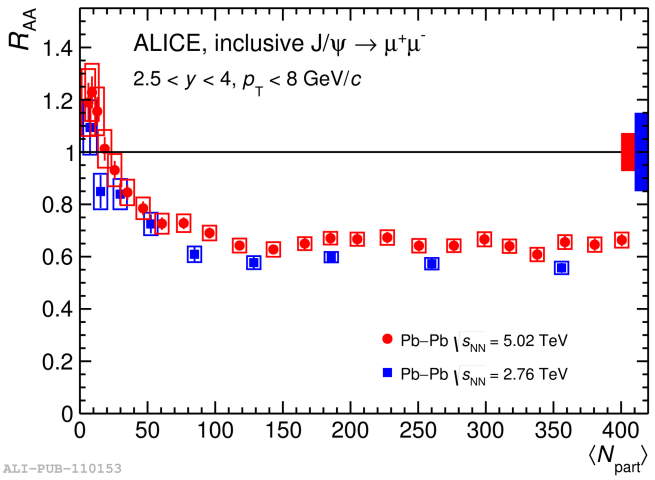
Heavy ions

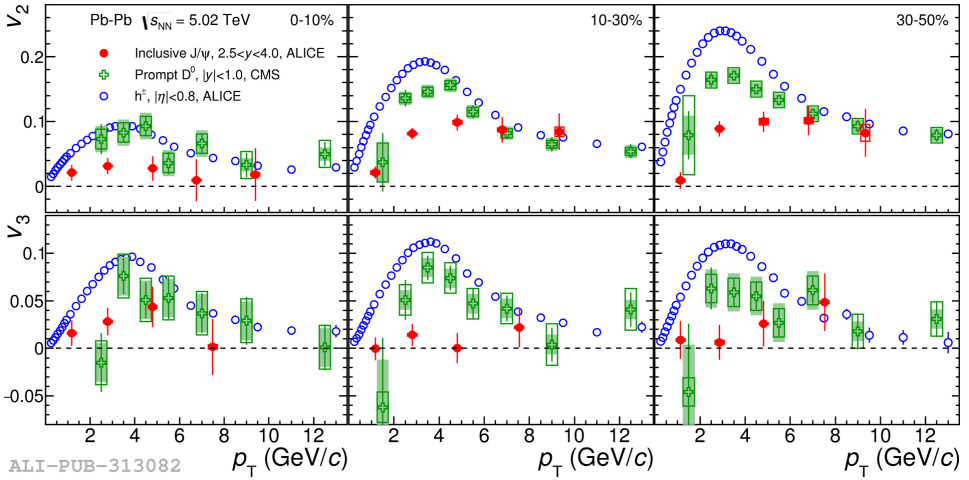
Quarkonia dissociation

High multiplicities

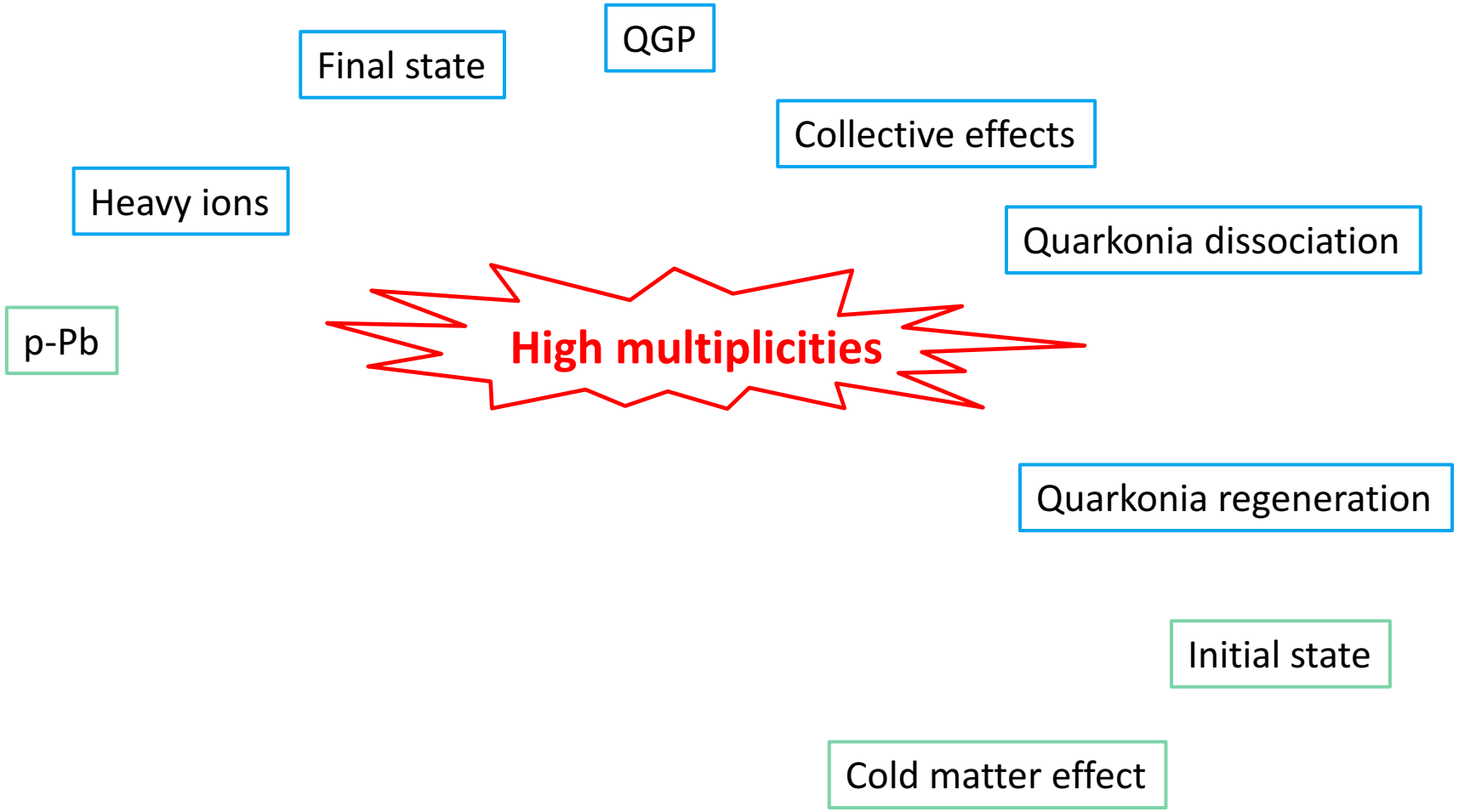
- High multiplicities refers initially to heavy ion physics and the study of QGP via probes such as quarkonia: "Wednesday session"

Quarkonia regeneration





Let's define "high multiplicities"



Let's define "high multiplicities"

Final state

QGP

Collective effects

Heavy ions

Quarkonia dissociation

p-Pb

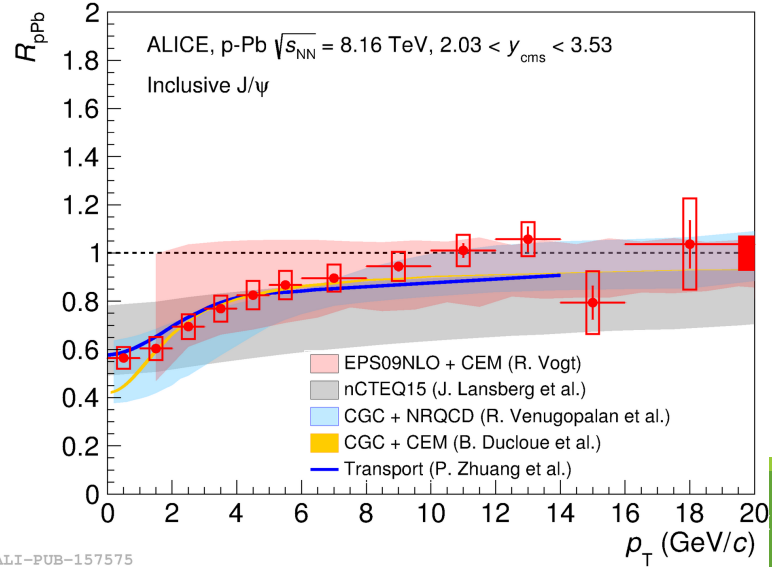
High multiplicities

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

Quarkonia regeneration

Initial state

Cold matter effect



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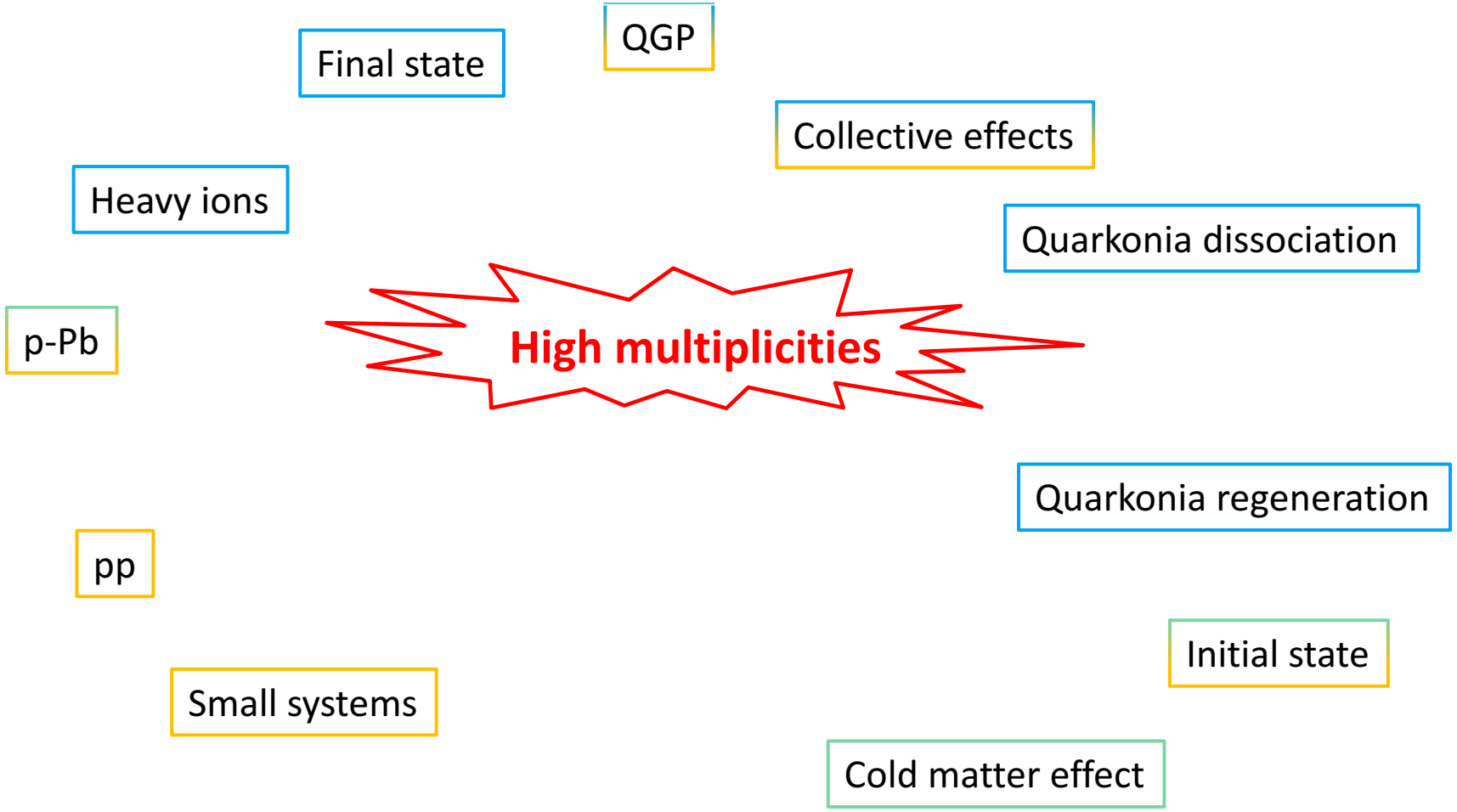
Let's define "high multiplicities"



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

What is a small system for QGP physics?

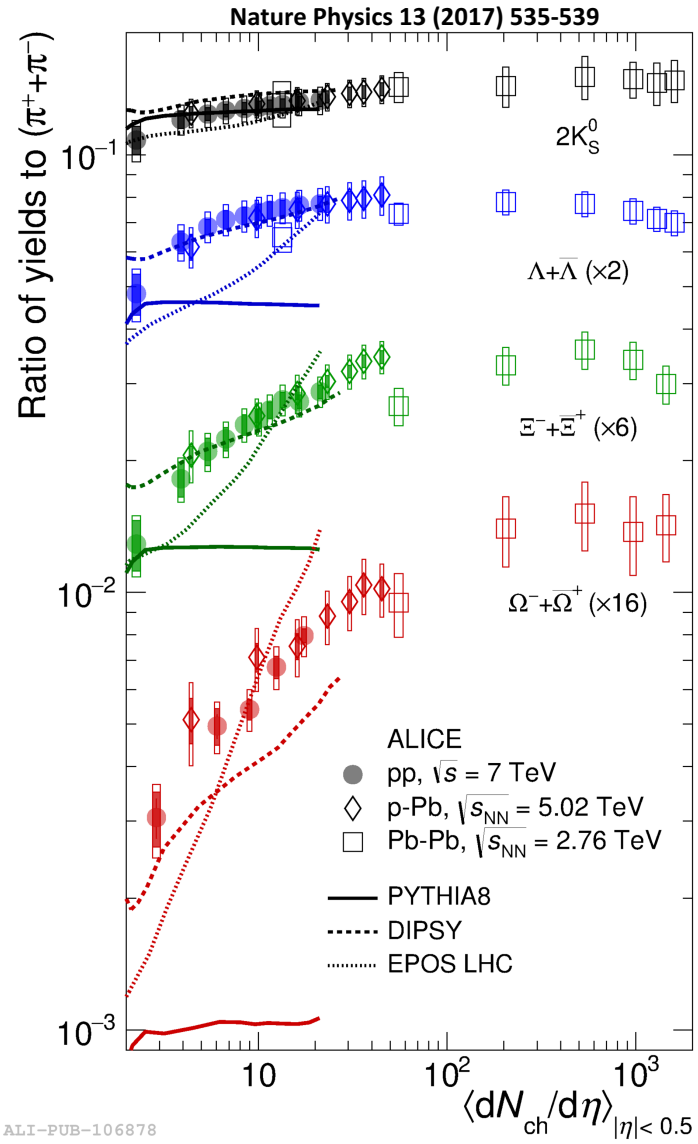
- Small refers to system size: protons in initial stage
- But with sometimes a final state looking like a large system, at least for charged particle multiplicity
- For LHC RUN 1+2 energies, idea of reference system still valid for pp minimum bias. High multiplicity events represent a small contribution 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 ?

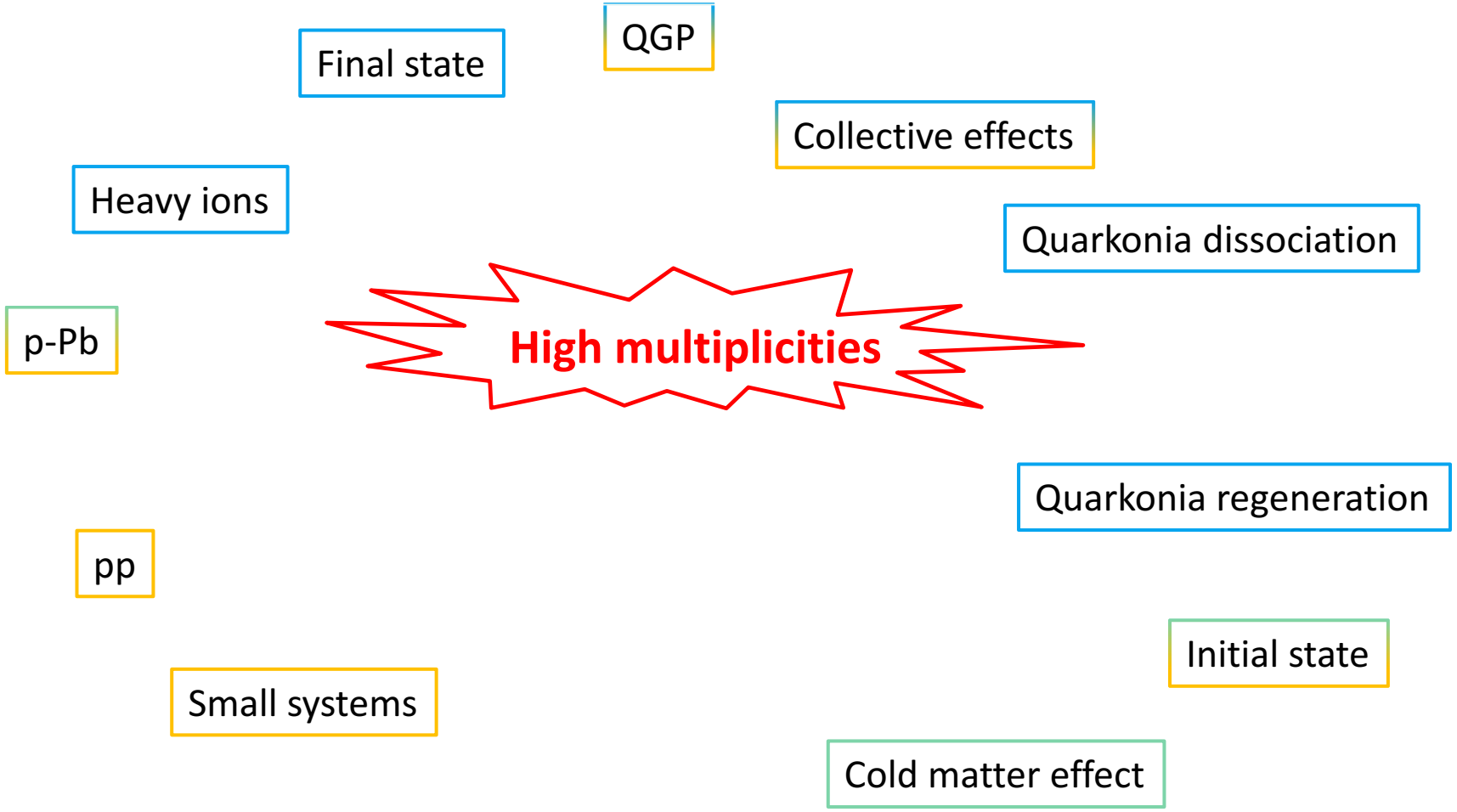


Sign of QGP in small systems at LHC ?

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

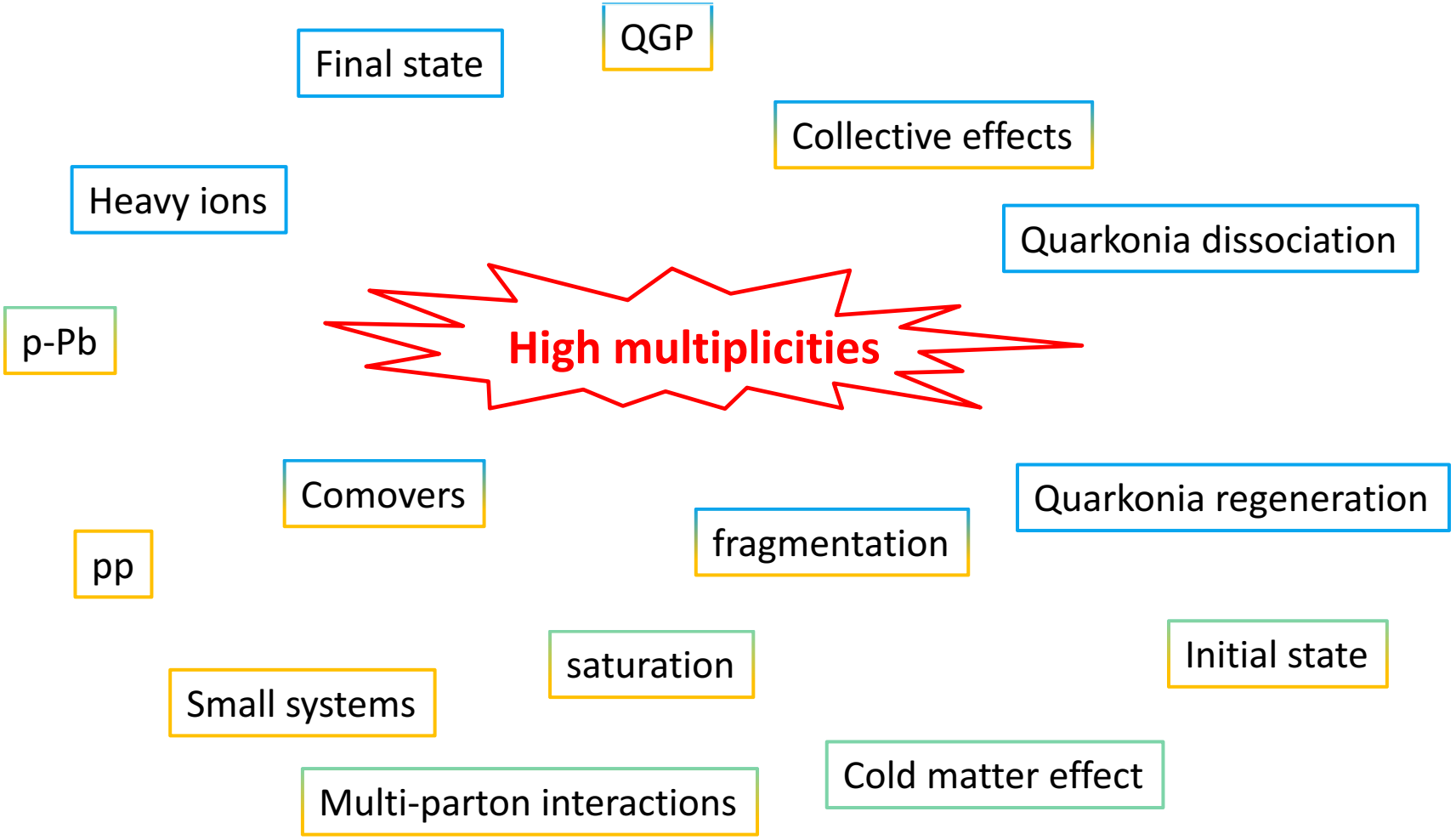
Observable of effect	Pb-Pb	pPb (high mult)	pp (high mult)
SOFT Probes			
low p_T spectra ("radial flow")	yes	yes	yes
Intermediate p_T ("recombination")	yes	yes	yes
HBT radii	R_{out}/R_{side}~1	$R_{out}/R_{side} \leq 1$	$R_{out}/R_{side} \leq 1$
Azimuthal anisotropy (v_n) (2 prt. correlations)	v_1-v_7	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	yes
Jet Quenching	yes	Not observed	Not observed
Quarkonia	J/Ψ regeneration / Y supression	suppressed	Not measured
Heavy-flavor anisotropy	yes	yes	Not measured

Let's define "high multiplicities"



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

Quarkonia as tool for ”high multiplicities”

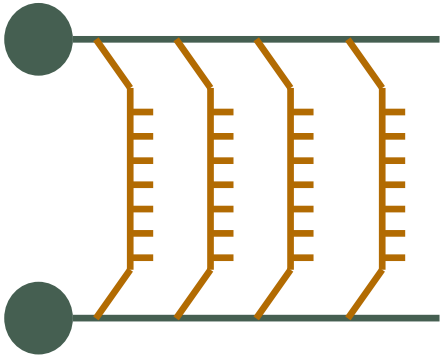


Quarkonia is a rich tool for high multiplicity studies being as well linked to initial and final state

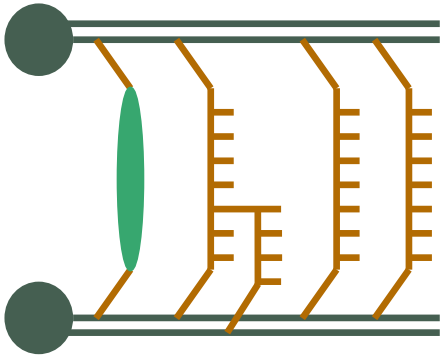
Do we understand initial conditions?
What kind of initial conditions can let pp collisions to reach high density ?

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

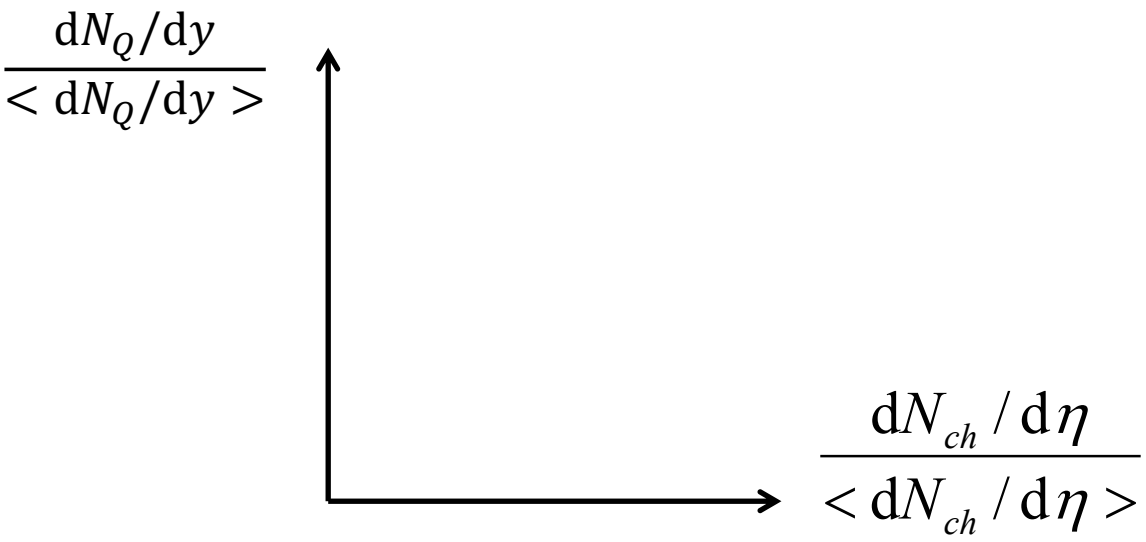
If we want to understand high multiplicity events/small systems/emergence of collectivity, it is mandatory to understand initial state and relation between soft and hard component of events

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)



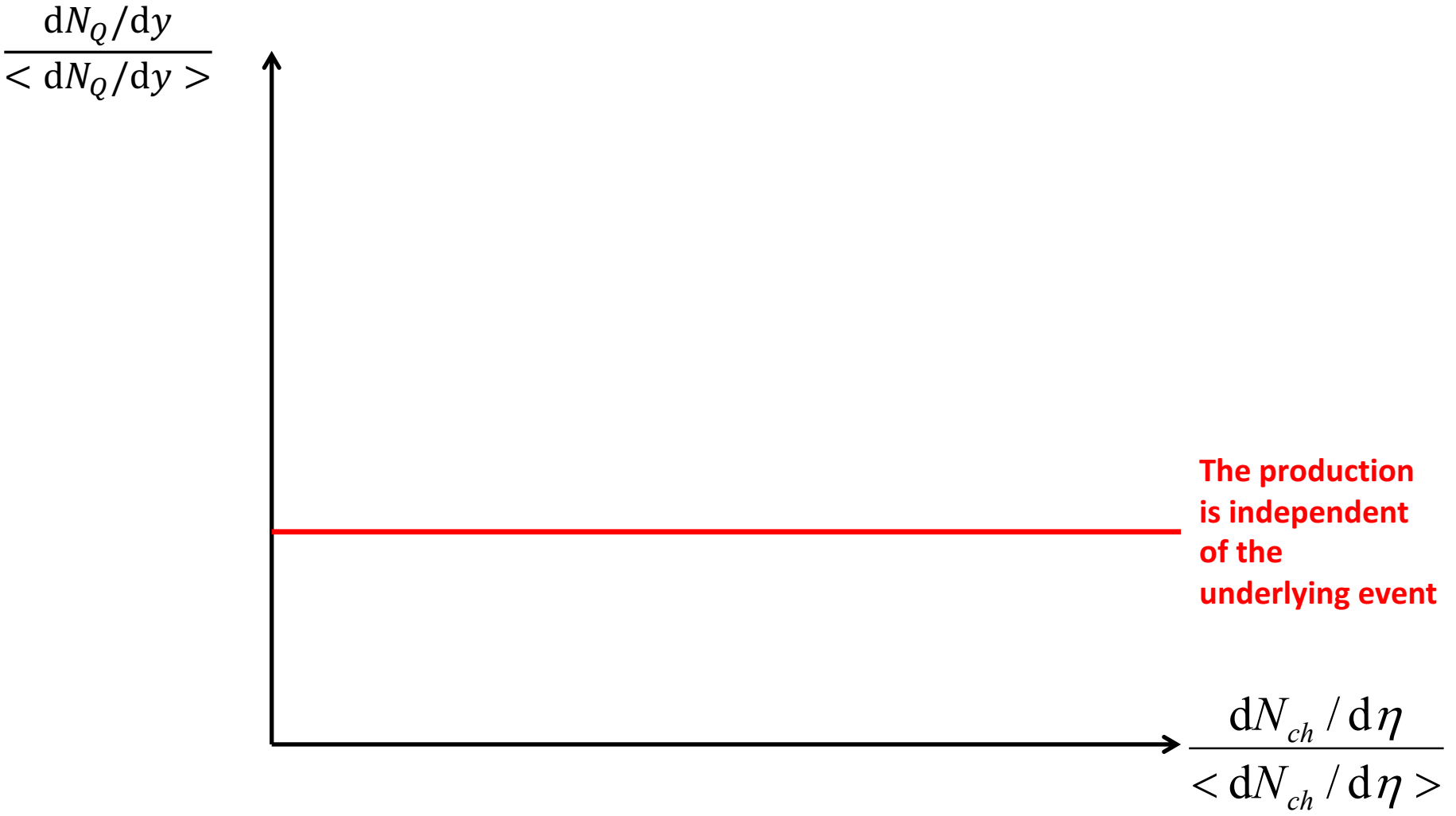
Self-normalized quantities, *x* label: *z* KNO variable

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

(Too) Simple expectations, discussions



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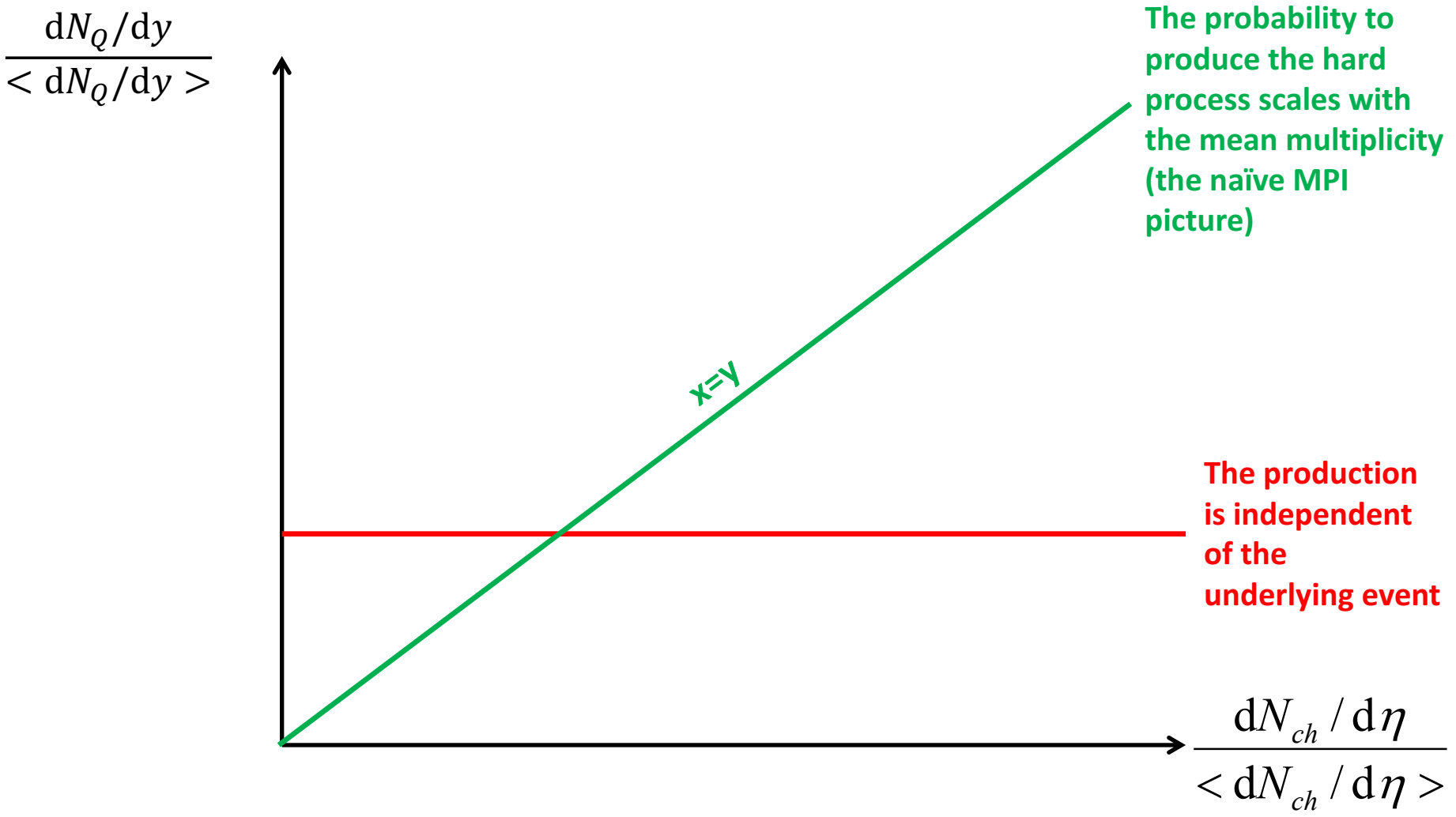

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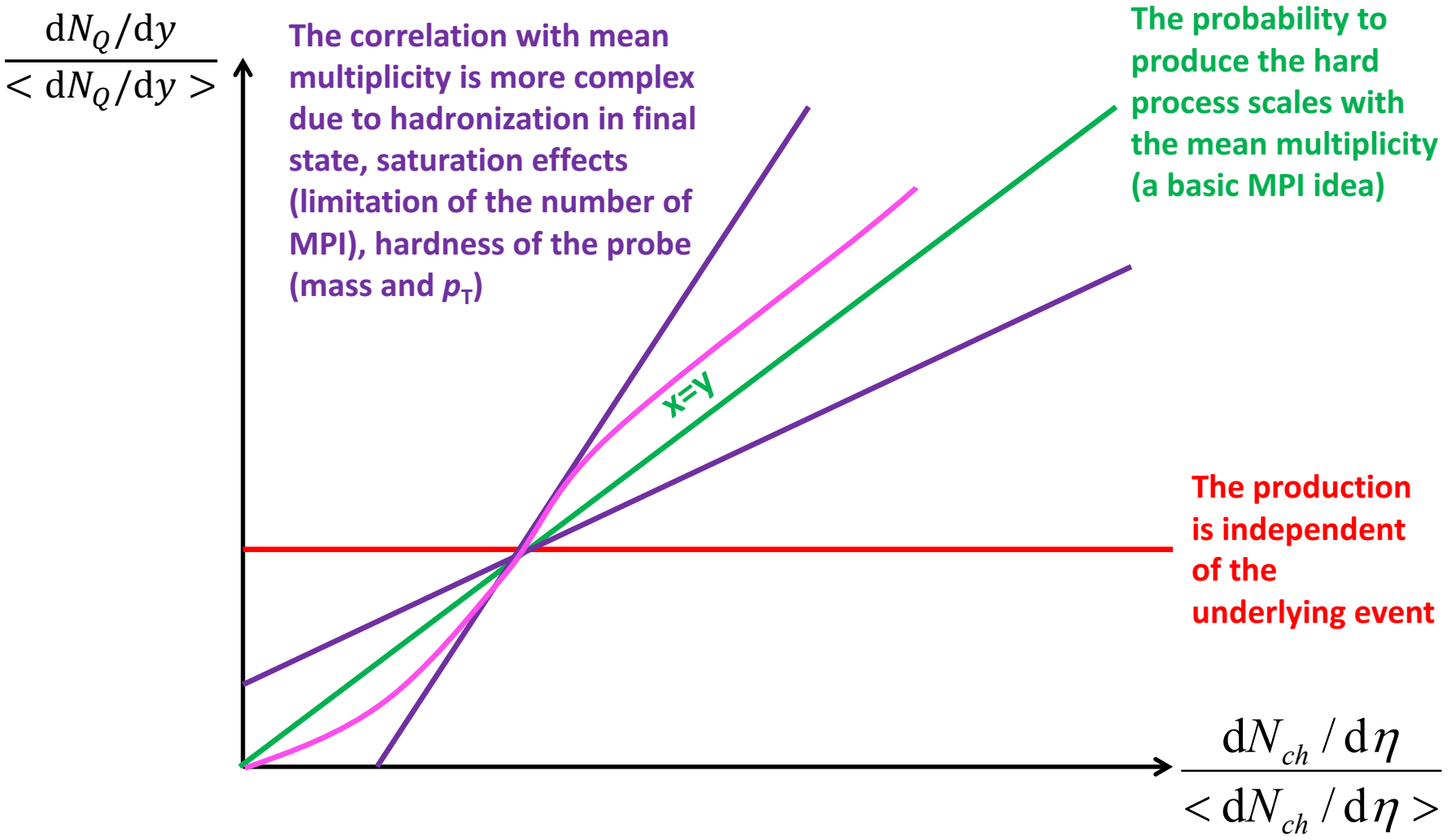

Quarkonia production as a function of multiplicity
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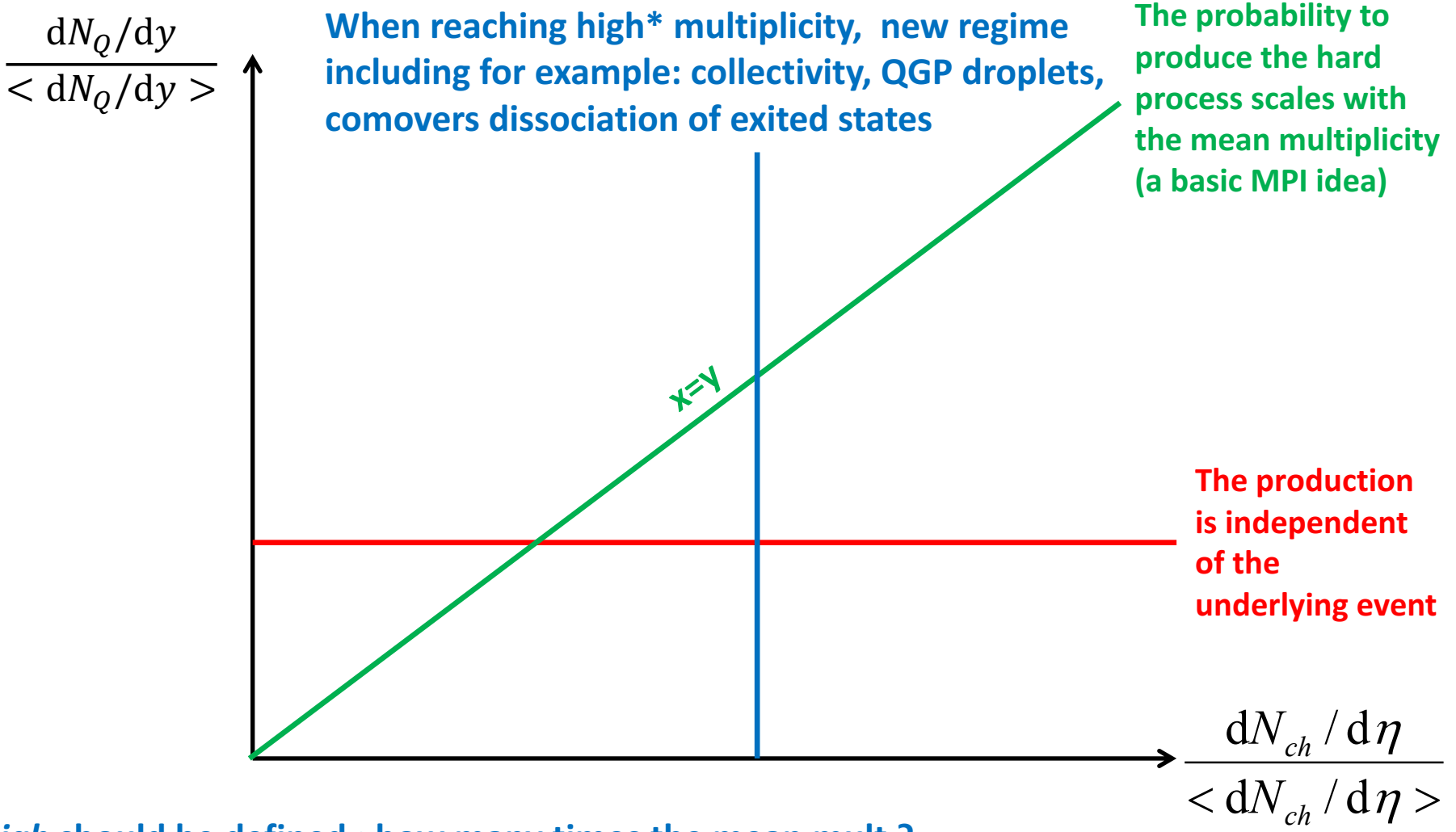

* ***high*** **should be defined : how many times the mean mult ?**

Charm/beauty vs. mult, public results

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 - 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	Preliminaries
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	Preliminary
J/Ψ	- transverse energy deposition in the backward ($3.1<\eta<4.9$) - $-2<y<1.5$, $8 < p_T < 40$ GeV/c	P-Pb	5.02 TeV	ATLAS	Eur. Phys. J. C 78 (2018) 171
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

See Jana's talk on Quarkonia on small systems

Charm/beauty vs. mult, public results

State	Channel	System	Energy	Exp.	ref
Y(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
Y(1/2/3S)	- $\mu^+\mu^-$, $\|y\|<1.93$, $p_T > 0$ GeV/c	pp	2.76 TeV	CMS	JHEP04(2014)103
Y(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
Y(1/2/3S)	- $\mu^+\mu^-$, $\|y\|<1.2$, $p_T > 0$ GeV/c	pp	7 TeV	CMS	Preliminaries CMS PAS BPH-14-009
Y(1/2S)	- $\mu^+\mu^-$, $2.5<y<4$, $p_T > 0$ GeV/c	pp	13 TeV	ALICE	Preliminary
Y(1/2/3S)	- $\mu^+\mu^-$, $\|y\|<1.93$, $p_T > 0$ GeV/c	p-Pb	5.02 TeV	CMS	JHEP04(2014)103
Y(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	- e^-, $1.06<y_{cms}<0.14$, $0.5<p_T< 8$ GeV/c	p-Pb	5.02 TeV	ALICE	

See Jana's talk on Quarkonia on small systems

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)?
- What is the elementary building block of hadronic interaction, is there a continuity from pp to AA and energy?
- 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

Already many answers
See Jana's talk on Quarkonia on small systems

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 Y 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

Related theory in one slide

- 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 wich 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

- PYTHIA:
  - Various production mode (hard process, MPI, ISR/FSR)
  - MPI scenarios, also linked with the repartition : number of MPI vs. hardness
  - Potential bias of hadronization

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

- Kopeliovitch *et al.* https://arxiv.org/pdf/1308.3638.pdf
  - 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

- 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

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By linking production mechanisms, initial state and final sate effects, event generators are very interesting tools.

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)

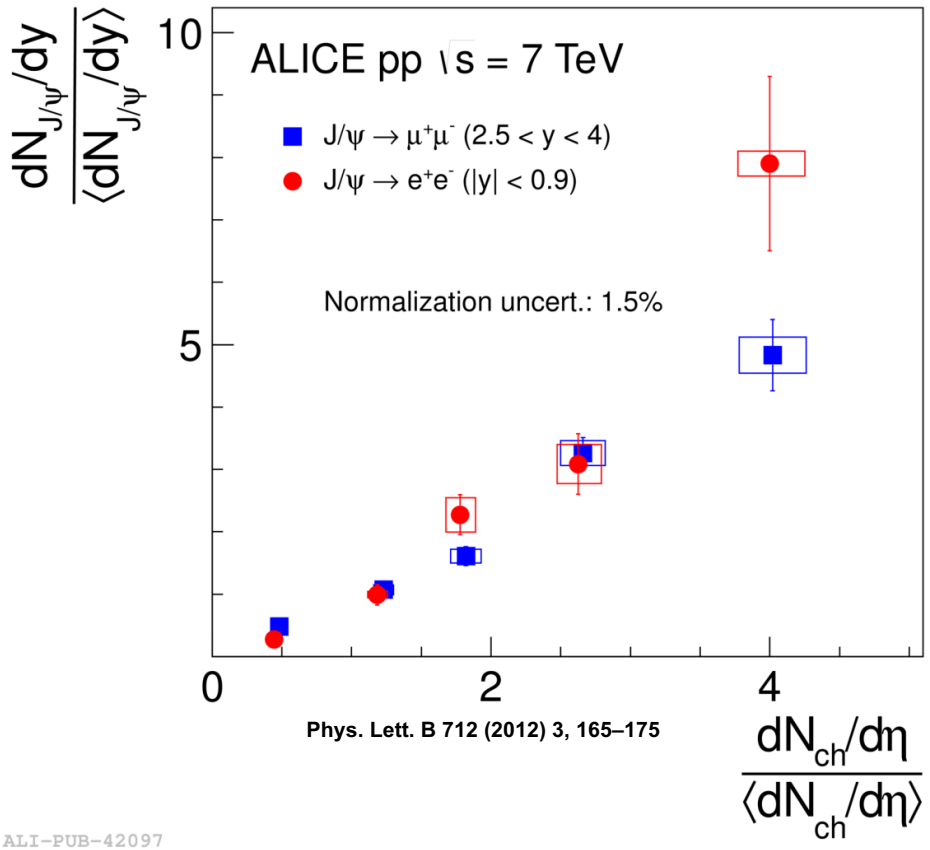
Why to use them ?

- 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



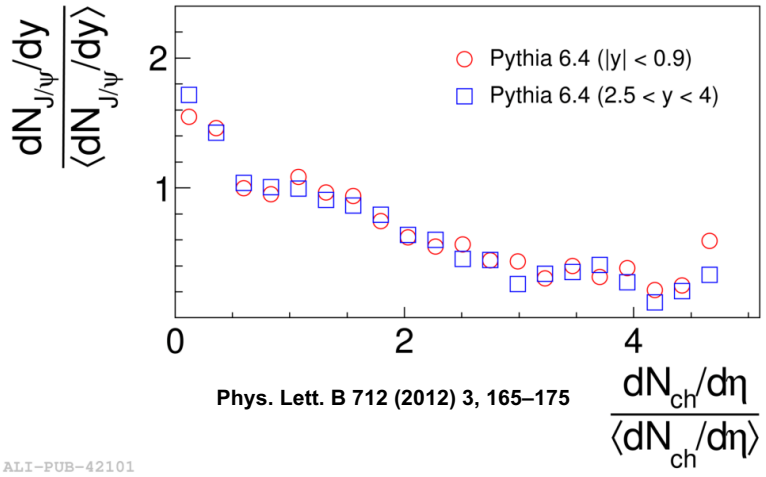
ALI-PUB-42097

➢ 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



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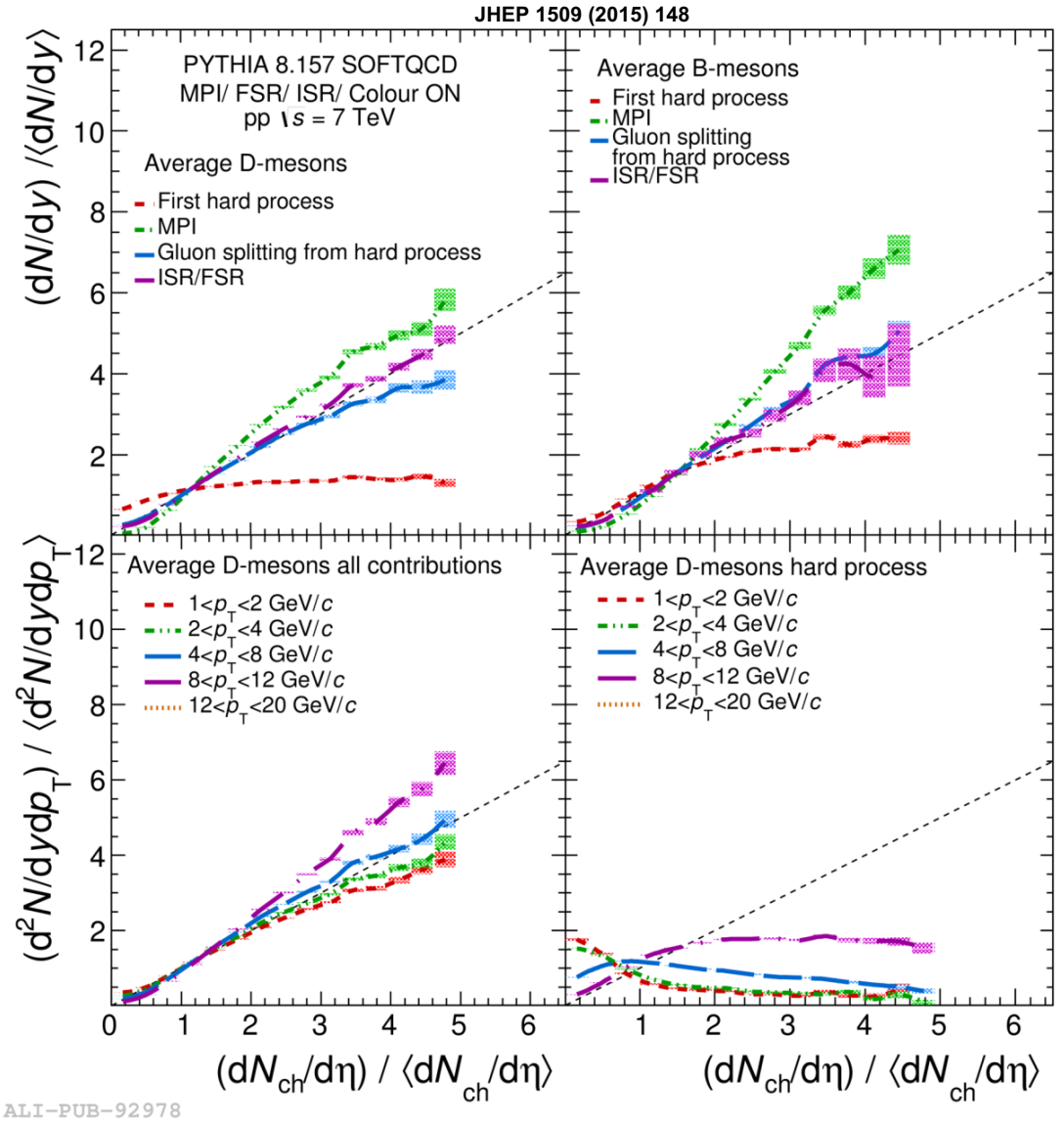
Quarkonia and HF vs. charged particle multiplicity

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

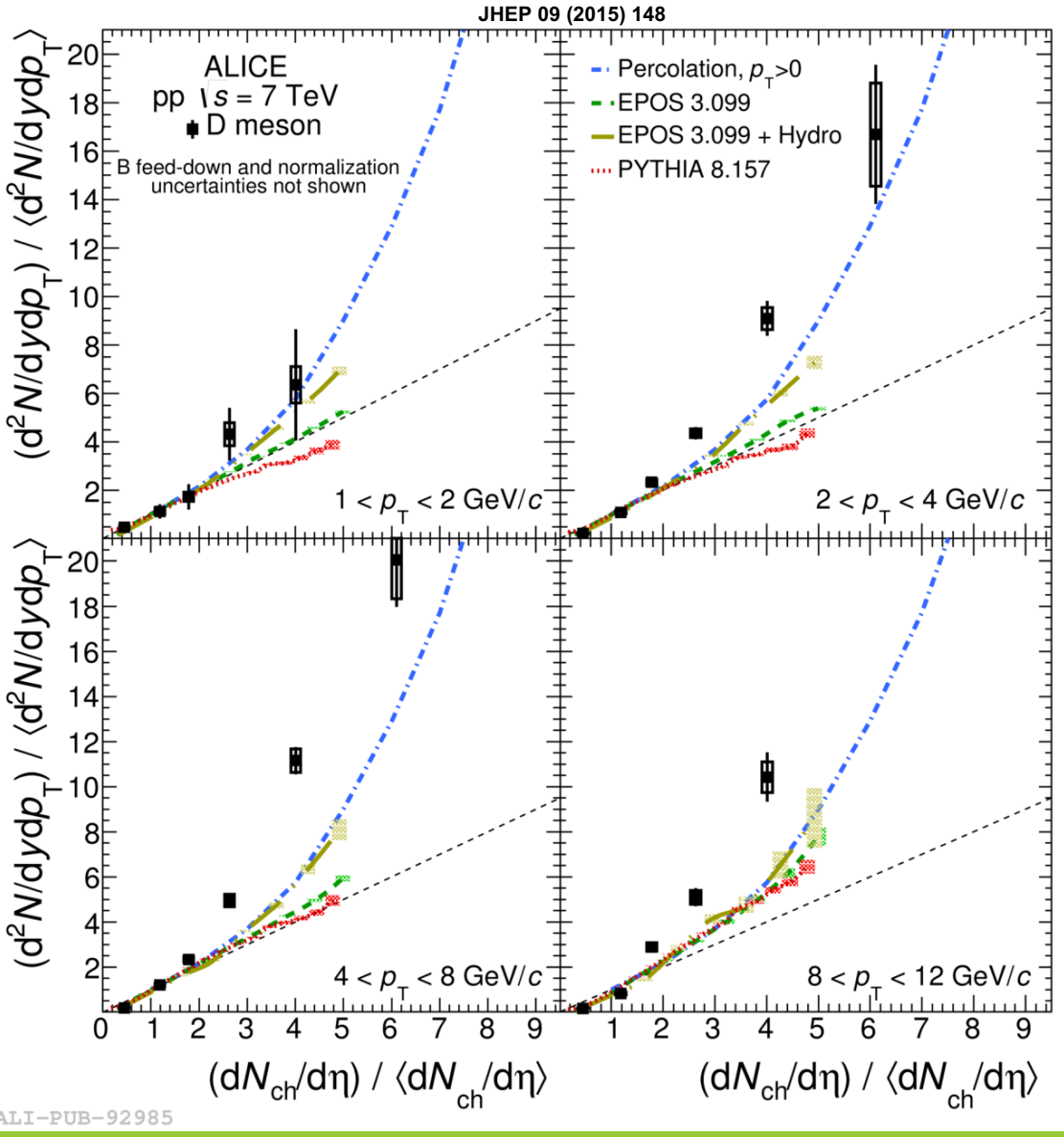
- PYTHIA and EPOS wo hydro

  Linear behavior fails to reproduce the data for the highest multiplicities

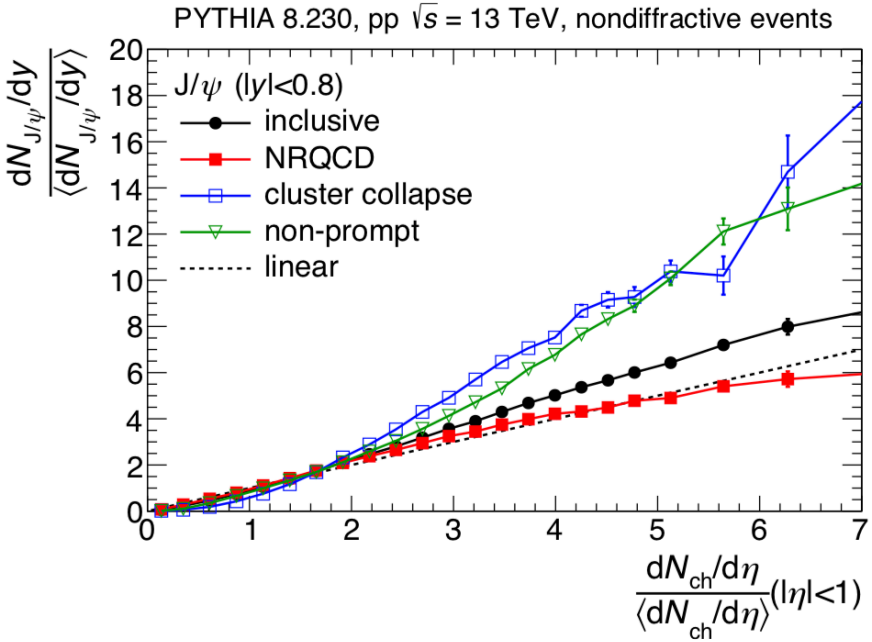
- EPOS w hydro and percolation

  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

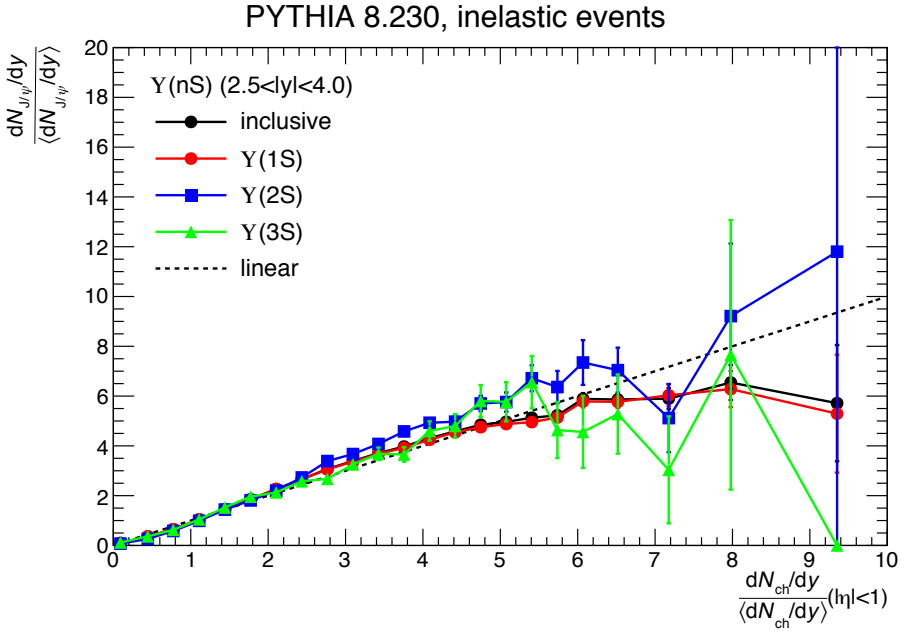


PYTHIA simulations for new quarkonia measurements



- 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

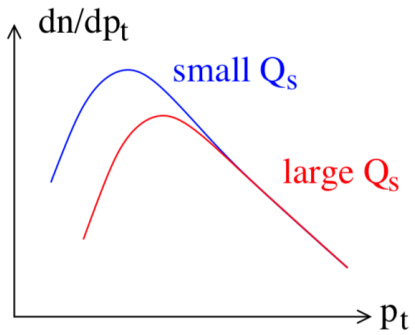
EPOS

Slides stolen from Klaus Werner

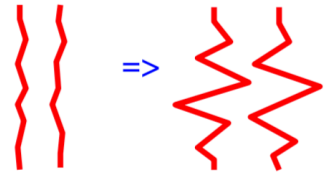
https://indico.in2p3.fr/event/14438/

- Recent development : EPOS 3.2

Parton distributions



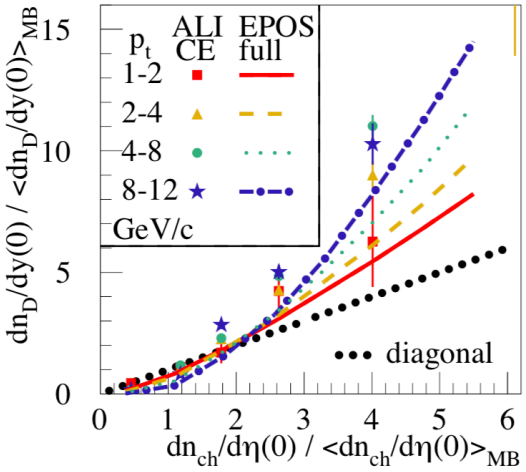
Increasing $\langle dn/d\eta(0)\rangle$ corresponds to increasing $N_{\rm Pom}$. With $Q_s(N_{\rm Pom})$
=> Increasing Q_s
=> harder Pomerons
=> harder strings



=> more high pt particles

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

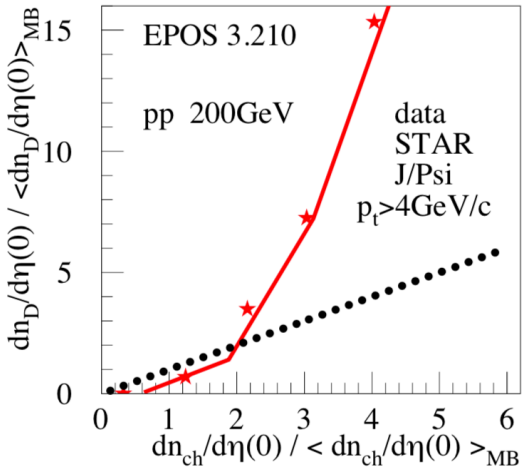
EPOS 3 compared to ALICE data



hadronic cascade on/off has no effect

hydro on/off has small effect

EPOS 3 compared to RHIC data

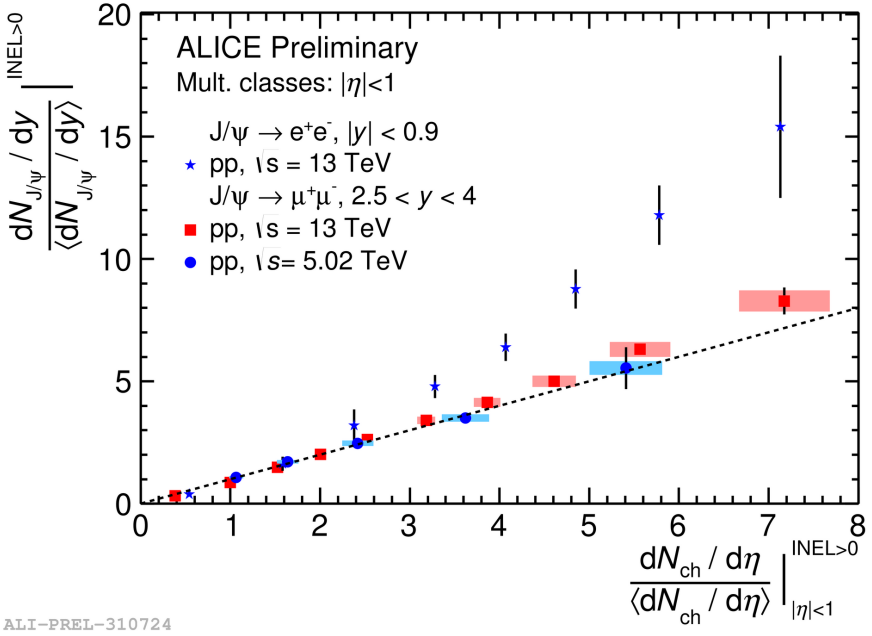


Calculations: D mesons

Data: J/Ψ

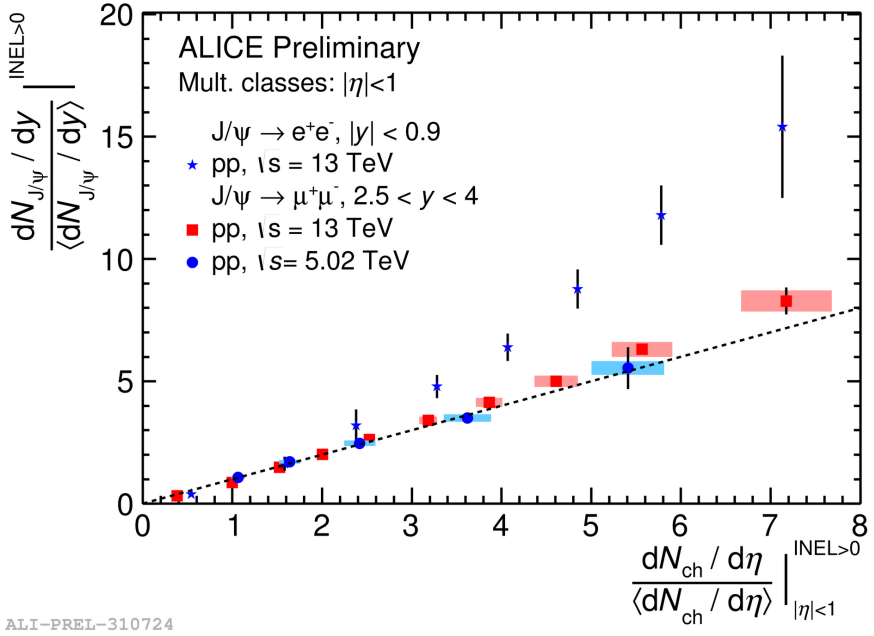
Increase stronger than at LHC

Building multiplicity: Final State Radiation for quarkonia ?



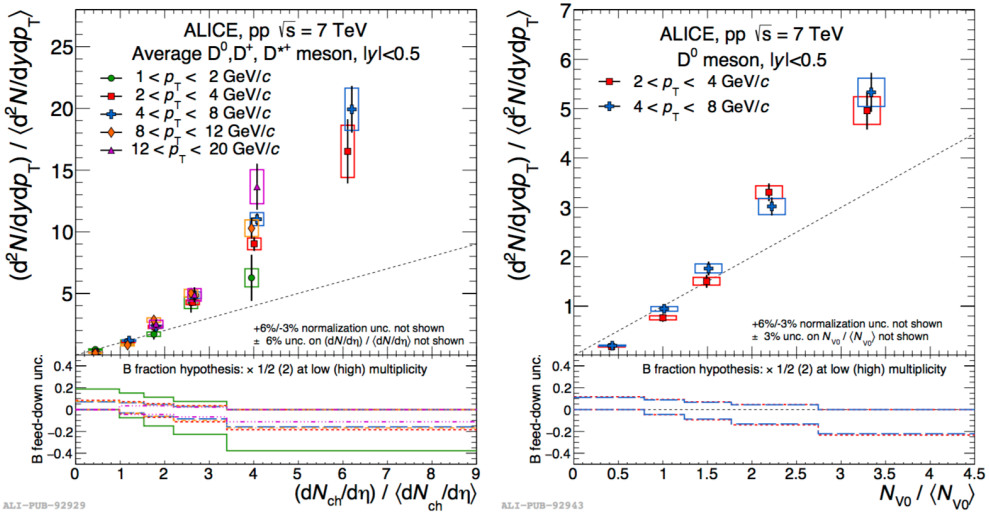
- Is the different behavior in different rapidity region of the quarkonium due to the hadronization in final state?

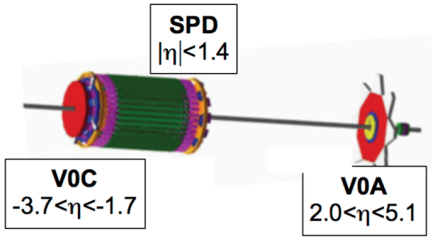
Building multiplicity: Final State Radiation for quarkonia ?



- 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

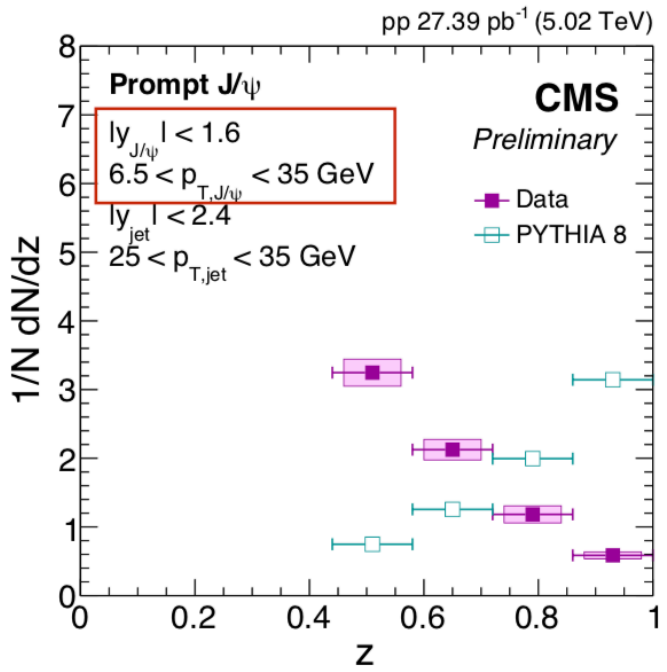


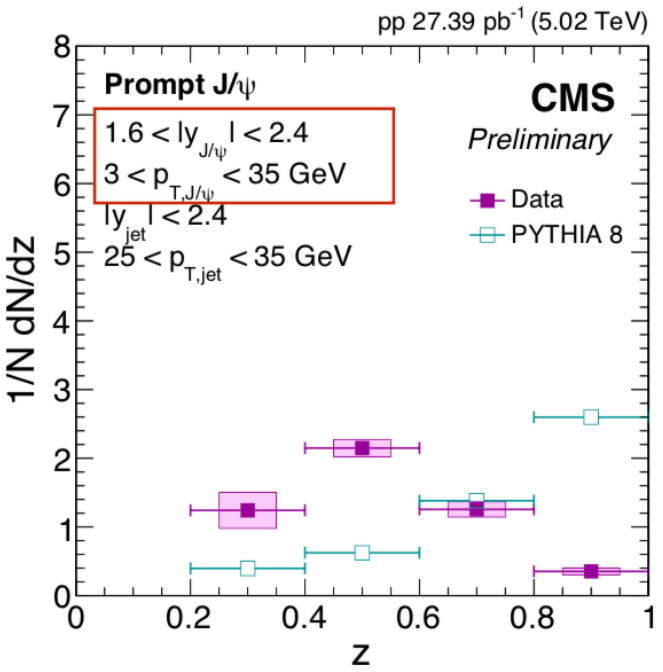


Quarkonia and isolation

stolen from Batoul Diab, QGP-France 2018

Prompt J/ψ results





Different behaviour in data and Pythia

J/ψ are less isolated in data

9

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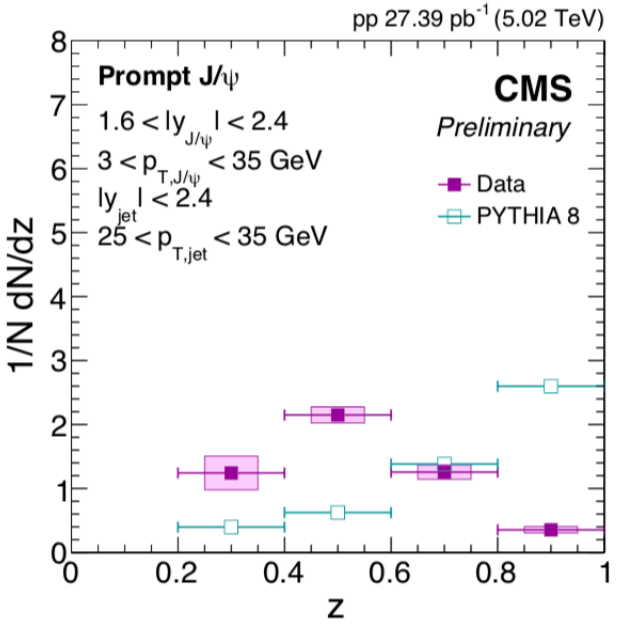
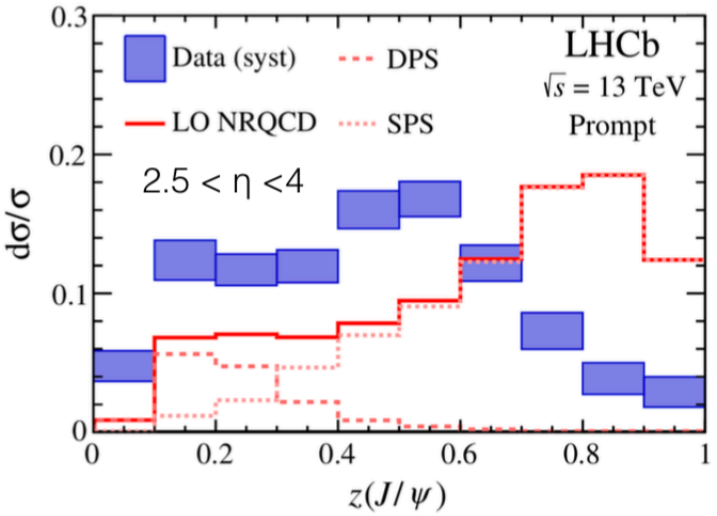
Quarkonia and isolation

stolen from Batoul Diab, QGP-France 2018

CMS Vs LHCb

Similar results in CMS and LHCb in different kinematic regions





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See also talk from Thomas Mehen and Valerio Bertone yesterday

Quarkonia and isolation

- Proper description of quarkonia evolution in final state, fragmentation function, is mandatory to understand how the multiplicity associated with quarkonia production is built.

- Developments, implementations, are also needed on the MC side

- At run 3, can someone do isolated quarkonia in multiplicity bins ?
  Possibly also at low p_T

Conclusions, as inputs for round tables

- High multiplicity / small systems are very interesting regime of hadronic collisions. Leading to fundamental questions on the structure in hadronic collisions.

- Quarkonia are used as tools for high multiplicity

  Quarkonia vs. mult: many recent results! See Jana's talk.

- Event generators are nice playground to look at correlations and exclusive measurements

  Remember to always quote the exact version of PYTHIA/EPOS/Other your are comparing with. Things are evolving fast, pushed by experimental measurements.

Conclusions, as inputs for round tables

- High multiplicity / small systems are very interesting regime of hadronic collisions. Leading to fundamental questions on the structure in hadronic collisions.

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Shopping list

- Rivetization of our analyses to ease comparison with theory/event generators
- Reach higher multiplicities in small systems
- Test other hard probes (Ψ', electromagnetic probes, high p_T hadrons)
- Try to understand geometry of the final state

  Angular correlation and sphericity (uniform or jet-like phase space distribution ?)

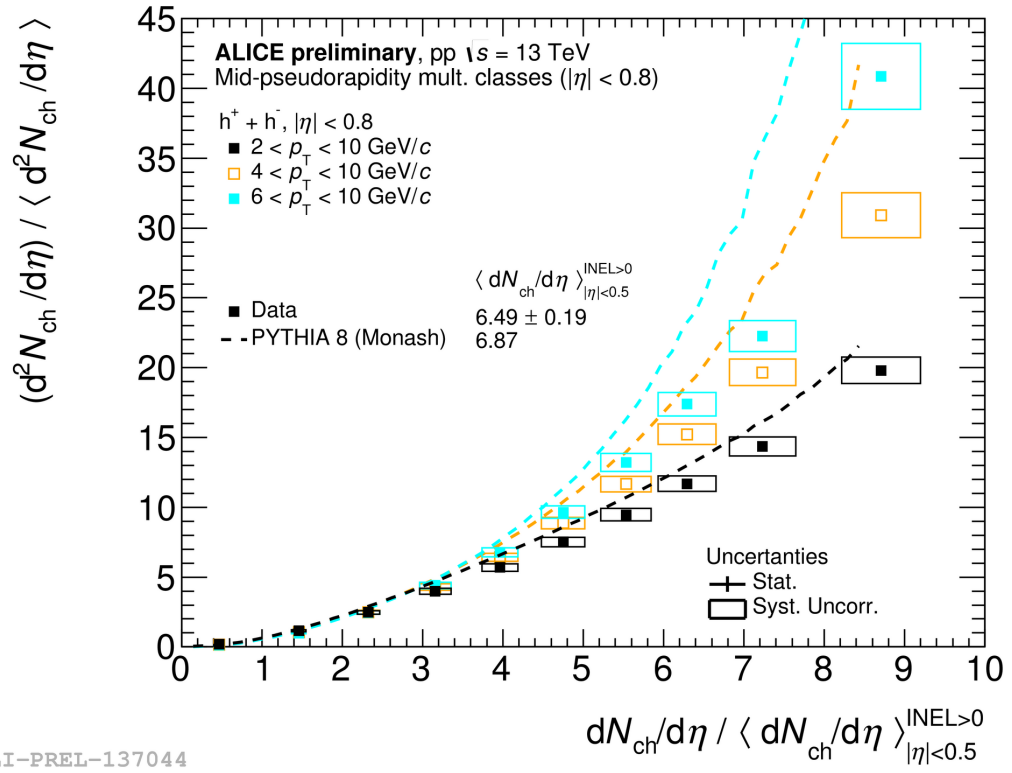
  Applying underlying event study to Quarkonia

  Already started for D-mesons and J/ Ψ in ALICE and Upsilons in CMS

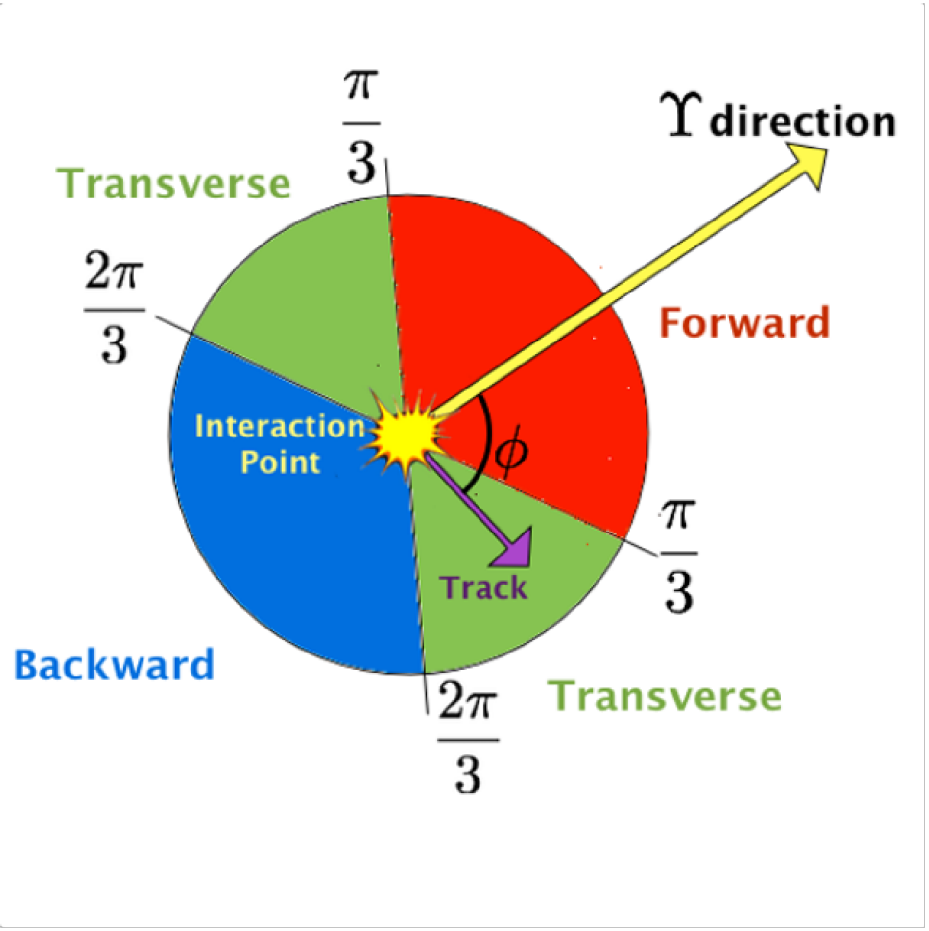
Conclusions, as inputs for round tables

- Not only quarkonia and open heavy flavour

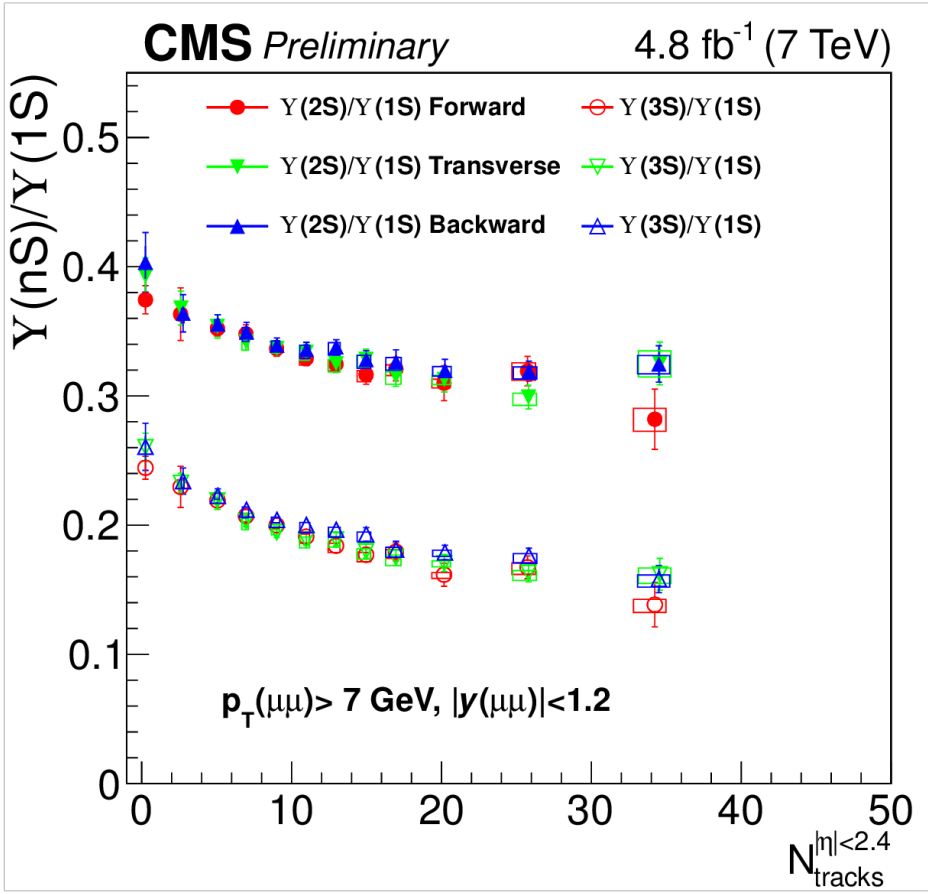
- Some examples :
  - Charged hadrons
  - Strangeness ongoing



Conclusions, as inputs for round tables



(a)



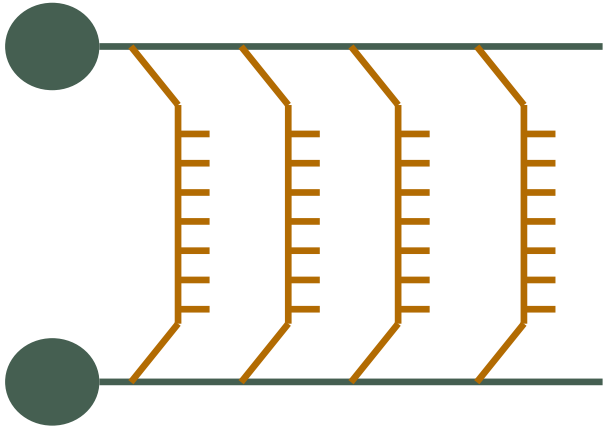
(b)

CMS-PAS-BPH-14-009

BACKUP

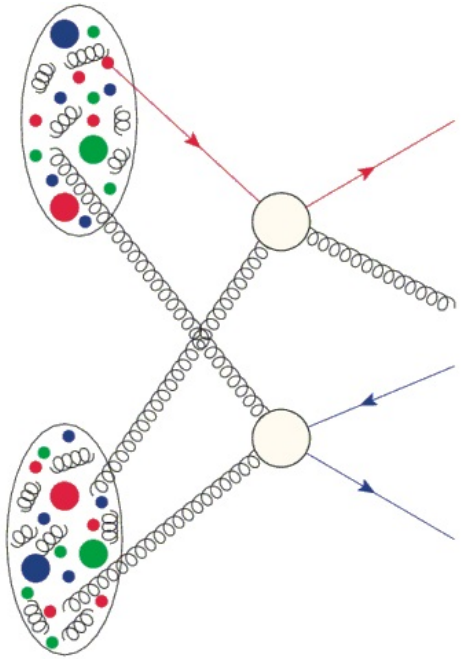
Multiple Parton Interaction (MPI)

✓ A naïve picture



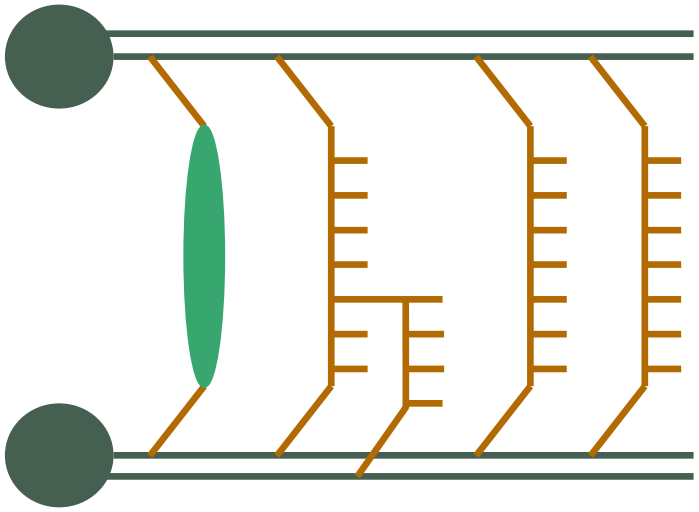
- Several interactions, soft and hard, occur in parallel
- The number of elementary interactions is connected to the multiplicity

- 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)

✓ A less naïve picture



- 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

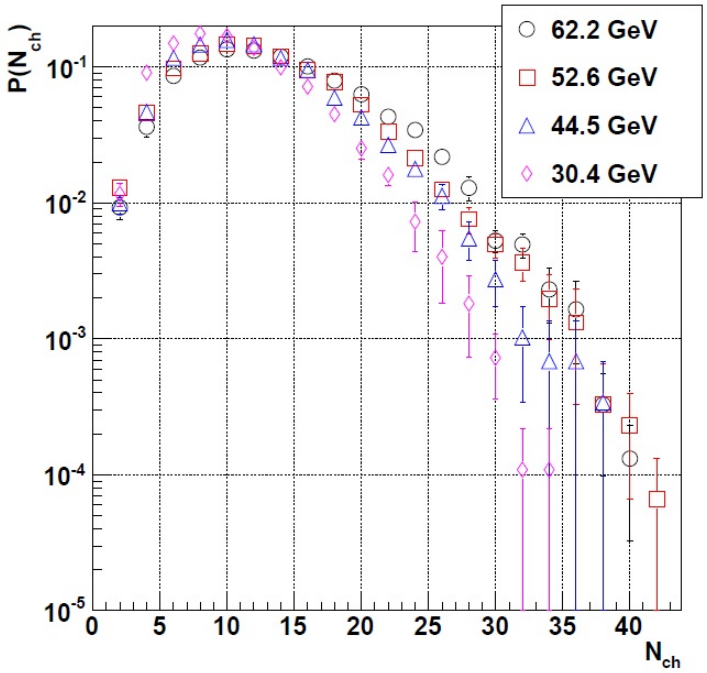
=> Test interaction between hard component and soft component in pp collisions : full collision description, color flow, energy sharing.

Needs for MPI

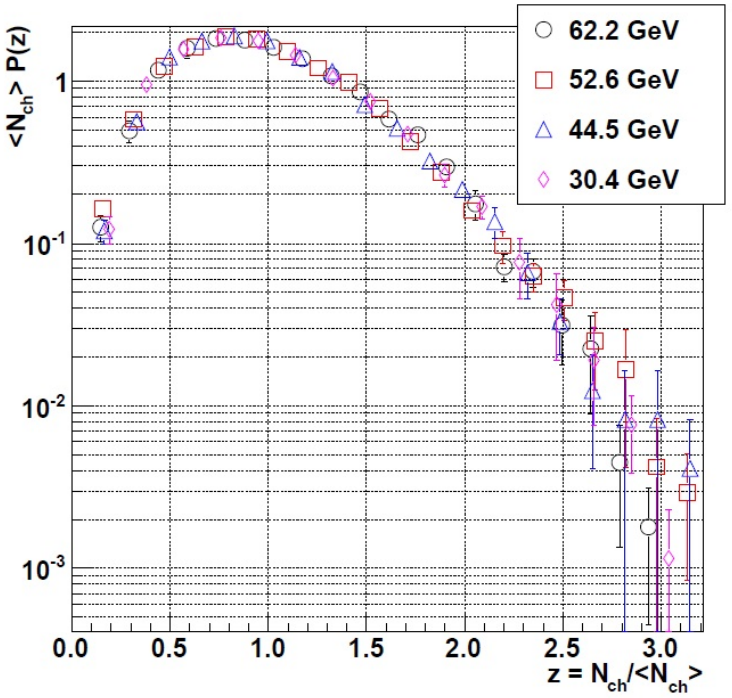
Koba-Nielsen-Oleson (KNO) scaling

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

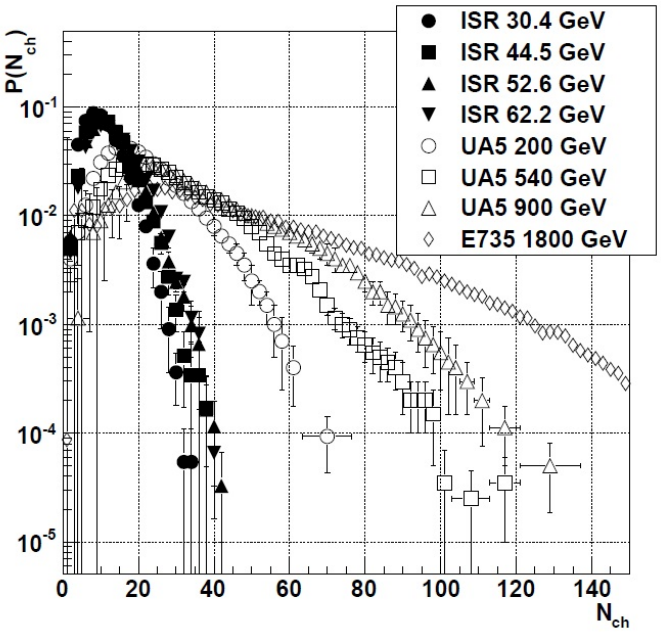
NSD events in full phase space measured by the SFM (Split Field Magnet) at ISR energies
Compilation from **J. Phys. G 37 (2010) 083001**

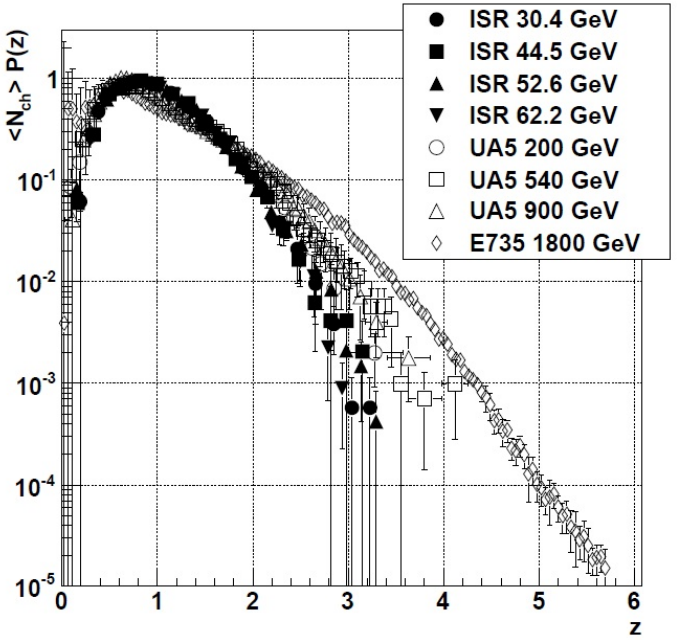
Up to √*s*=200 GeV, it works pretty well!

Needs for MPI

Koba-Nielsen-Oleson (KNO) scaling

At energies greater than $\sqrt{s}$=200 GeV in pp and pp $\bar{c}$ollisions,





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

Violation of KNO-scaling ($\sqrt{s}$ > 200 GeV)
Phys. Lett. B 167 (1986) 476

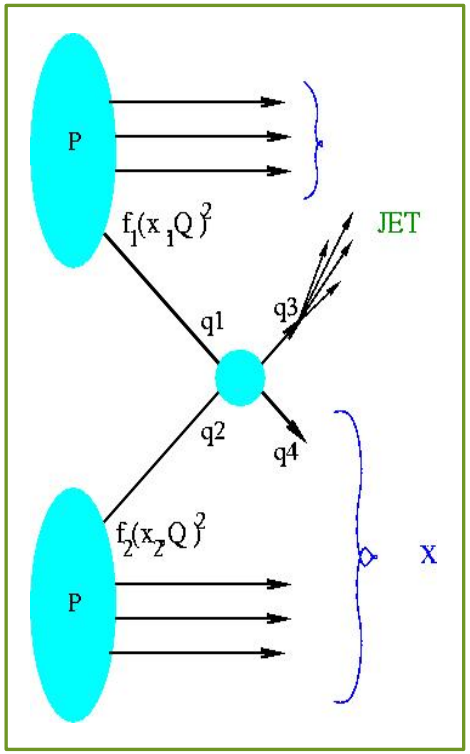
Deviation from KNO-scaling increases with $\sqrt{s}$

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**

Needs for MPI

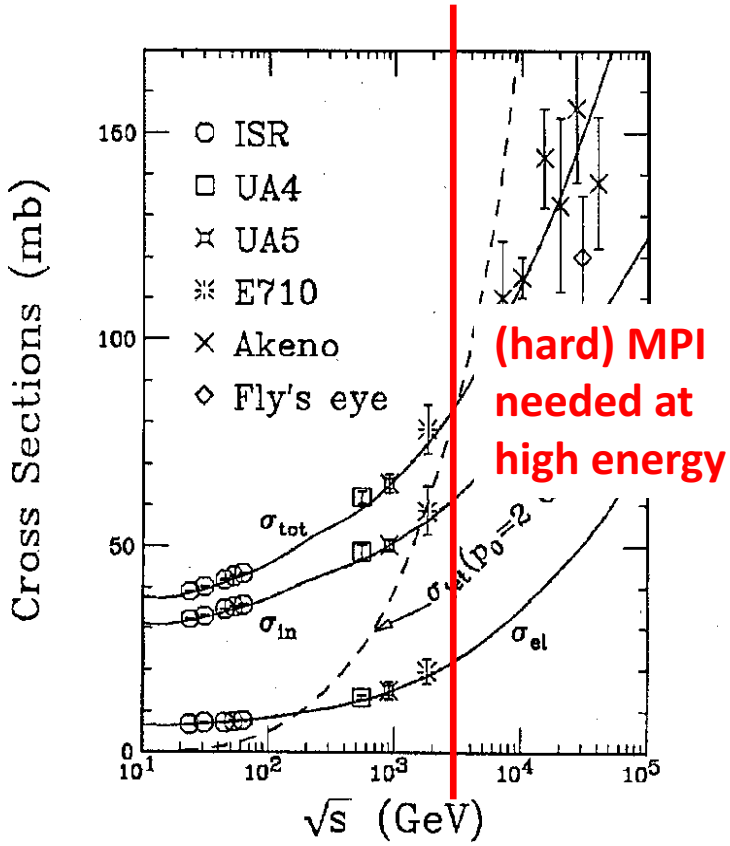
pQCD and inclusive observables



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

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

Limitation at high energy



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

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

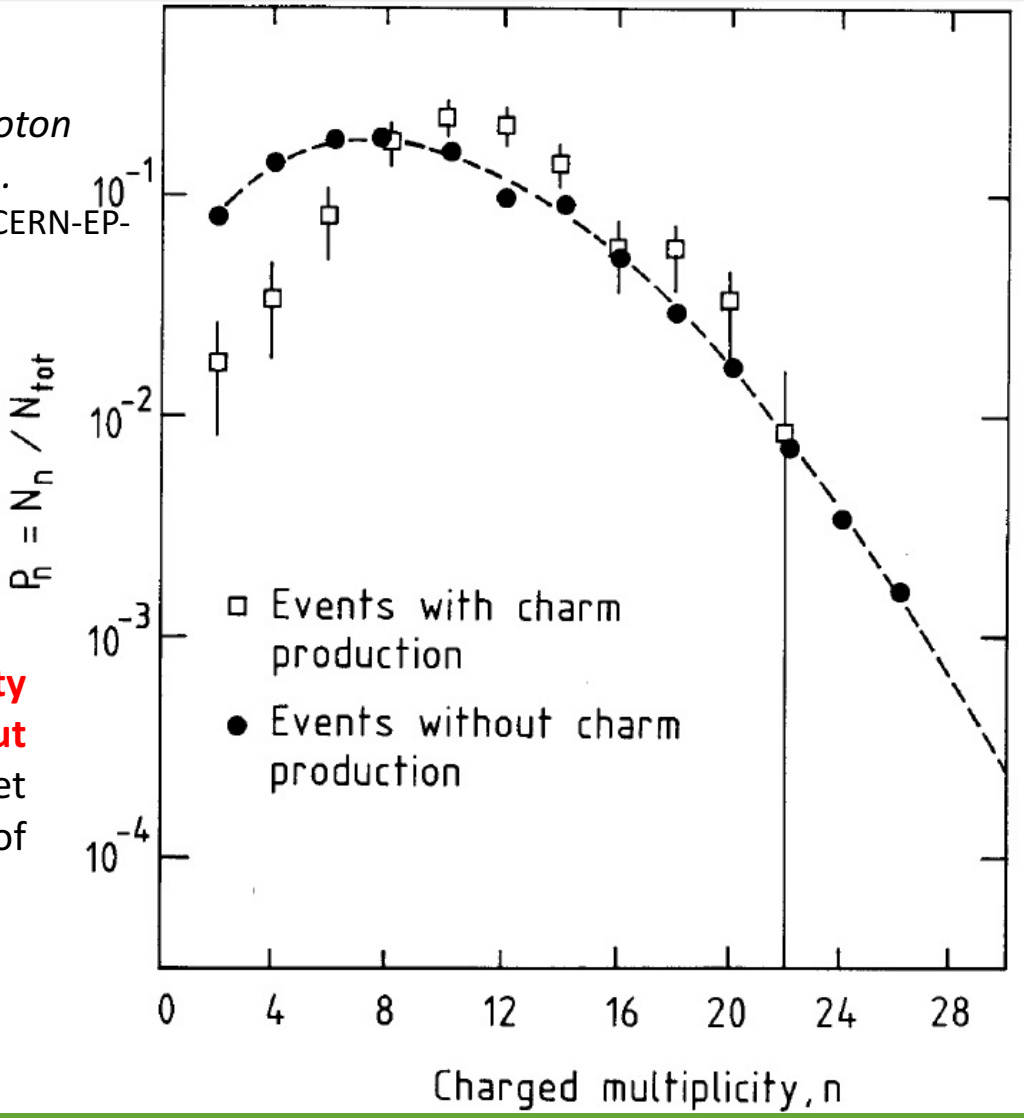
Charm production as a function of multiplicity

NA27 publication

Comparative properties of 400-GeV/c proton-proton interactions with and without charm production.
By LEBC-EHS Collaboration (M. Aguilar-Benitez *et al.*). CERN-EP-88-77, Jun 1988. 16pp.
Z.Phys.C41:191,1988.

Charm production = event with 3,4,5 prongs (signature of charm decay)

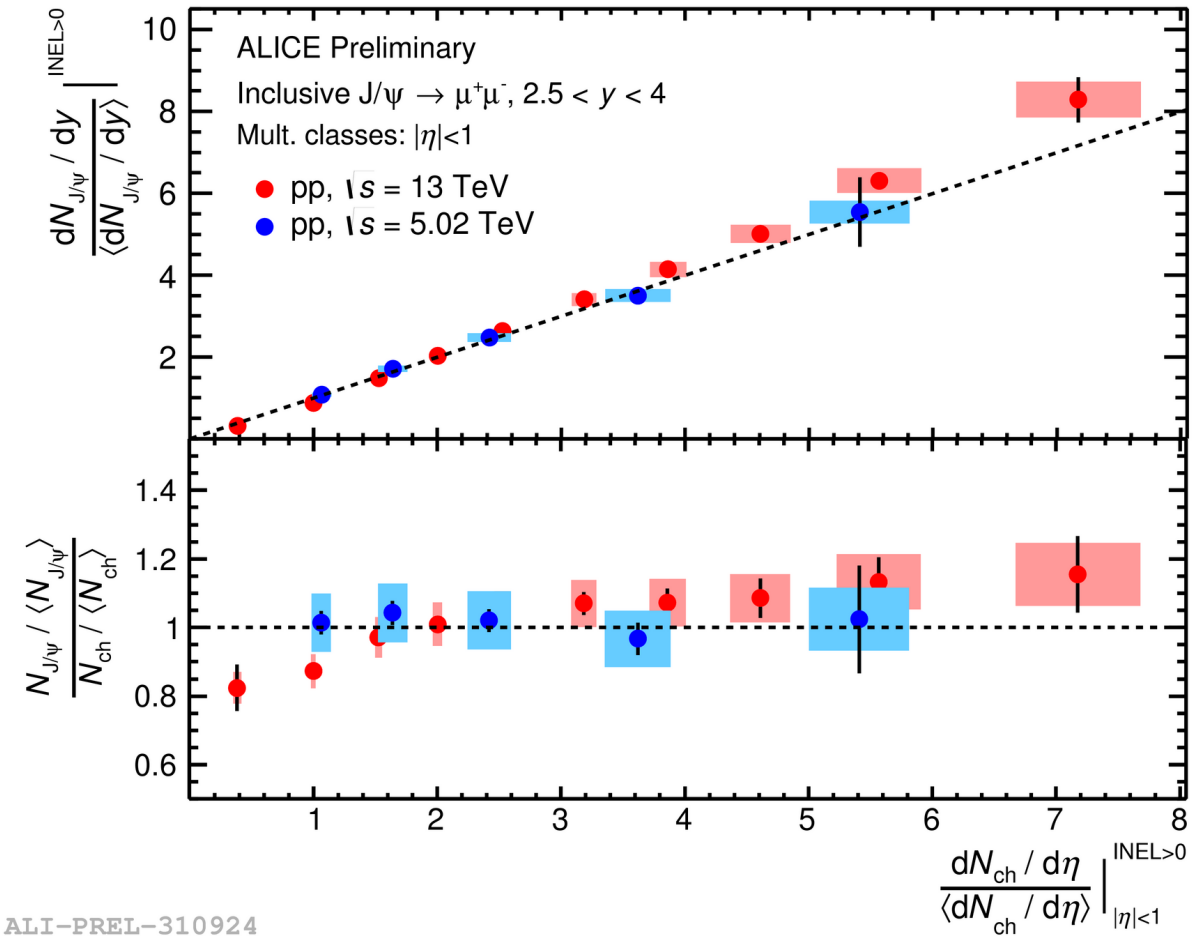
"It is clear from fig.1 that the **multiplicity distributions** for interactions **with and without charm are different**. … It is natural to interpret these differences by the more central nature of collisions leading to charm production."



sarah@clermont.in2p3.fr 45

J/ψ production as a function of multiplicity

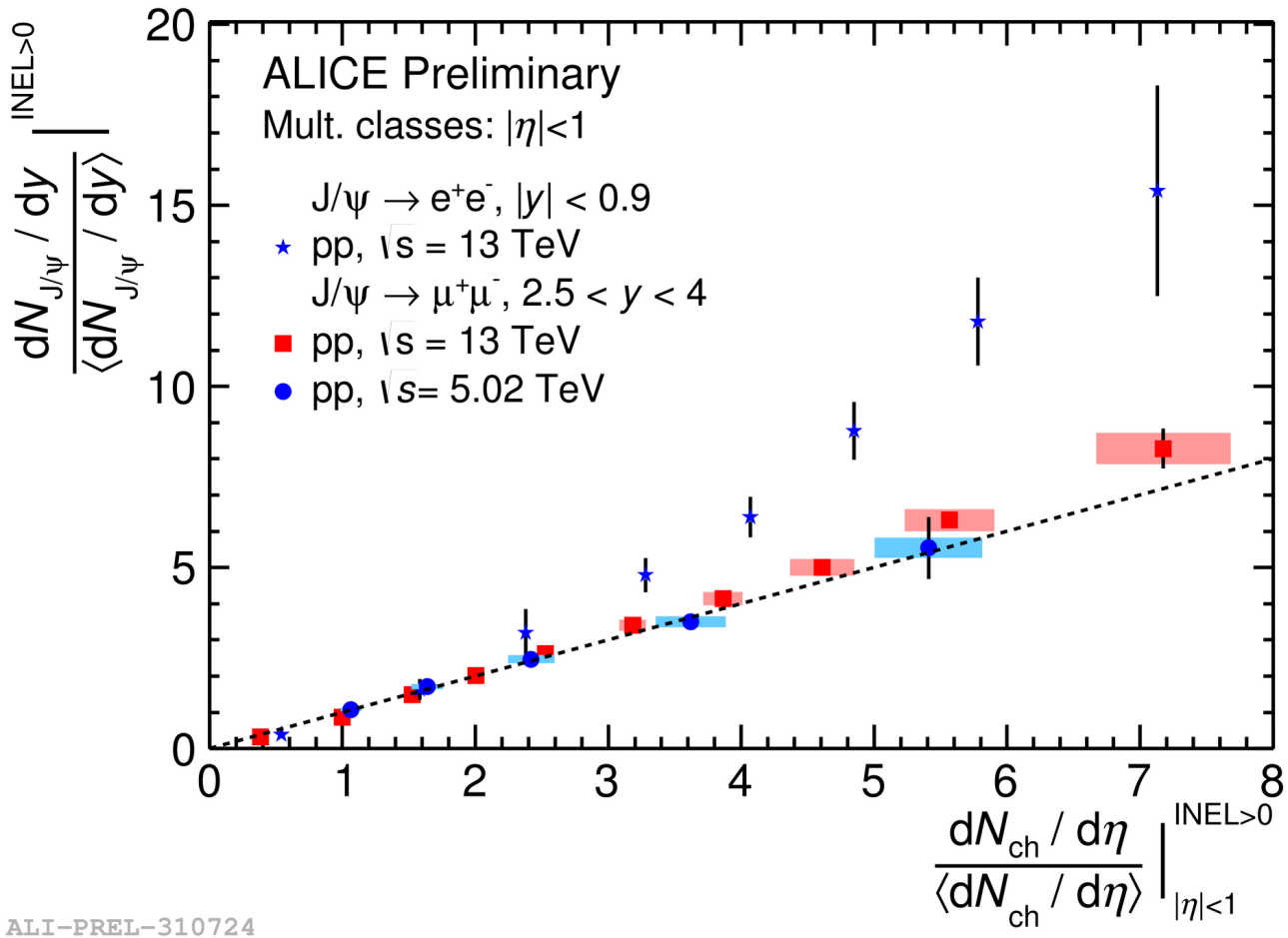
New ALICE results in the forward sectors for pp at 5.02 TeV and 13 TeV



- 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 production as a function of multiplicity

New ALICE results in the forward sectors for pp at 5.02 TeV and 13 TeV



ALI-PREL-310724

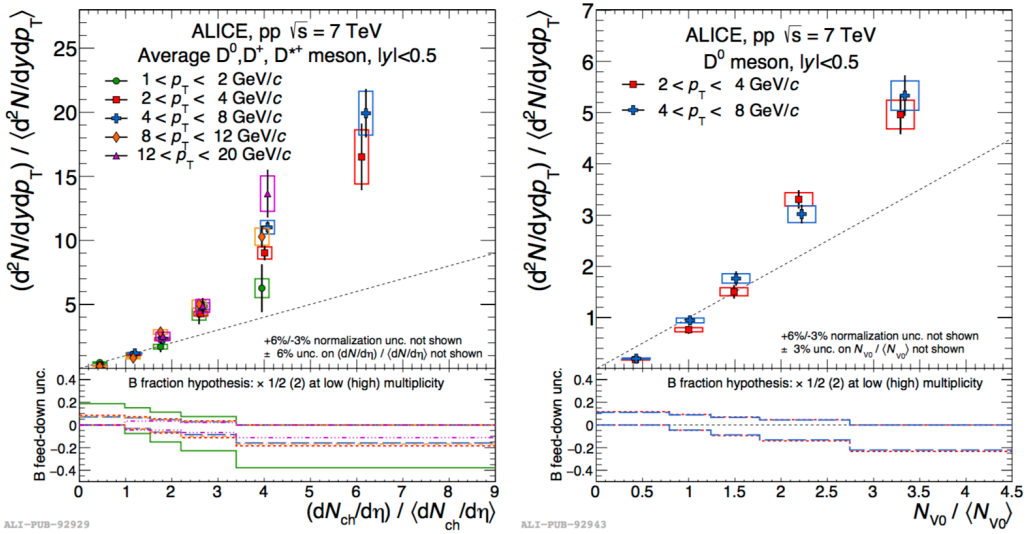
- Different behavior when introducing a rapidity gap between the multiplicity estimator and the J/ψ

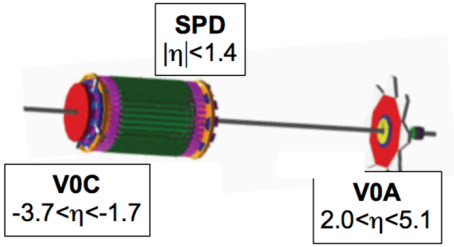
J/ψ production as a function of multiplicity

New ALICE results in the forward sectors for pp at 5.02 TeV and 13 TeV

- Is it due to the hadronization of the Quarkonium?

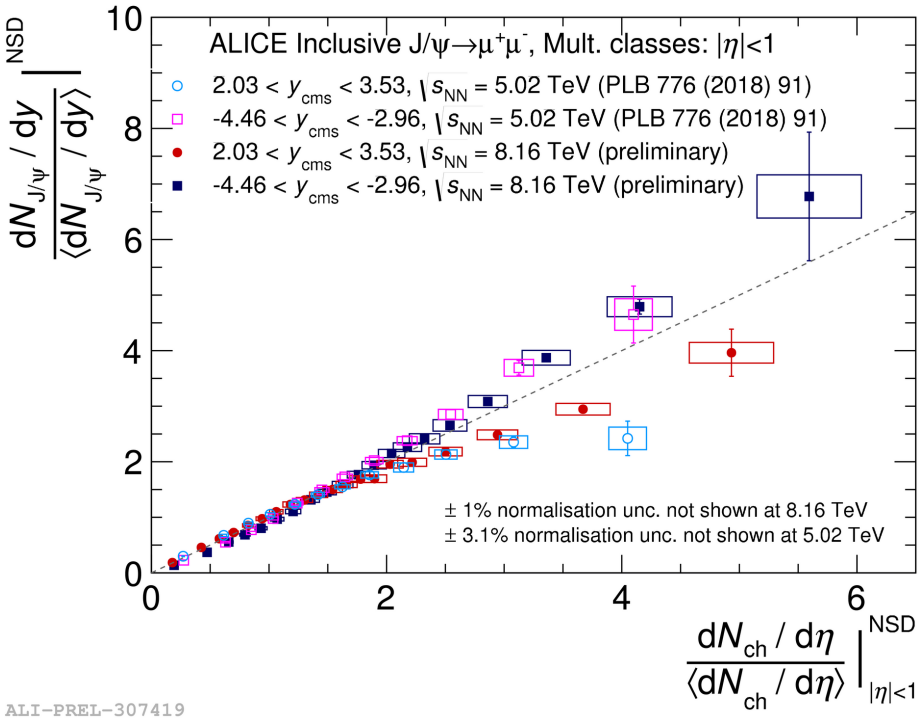
- This hypothesis was tested for D mesons





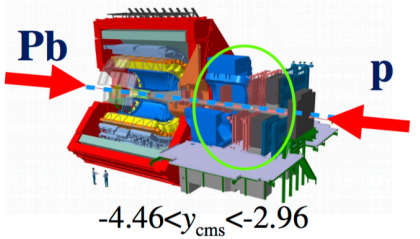
J/ψ production as a function of multiplicity

New ALICE results for p-Pb at 8.16 TeV

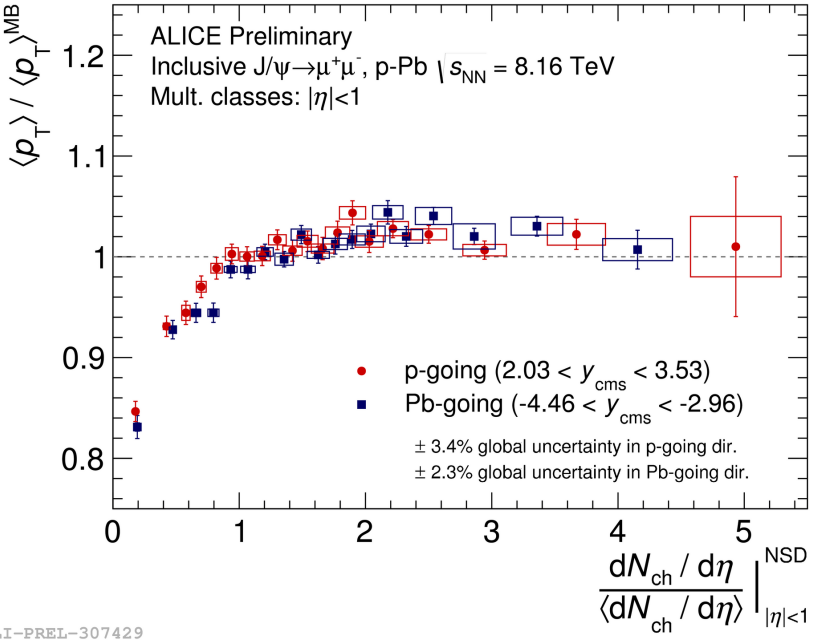


ALI-PREL-307419

- The multiplicity is always measured in the central rapidity class (as for pp)
- Different slope with different rapidity range
- Forward as similar behavior as pp, while it is Pb going



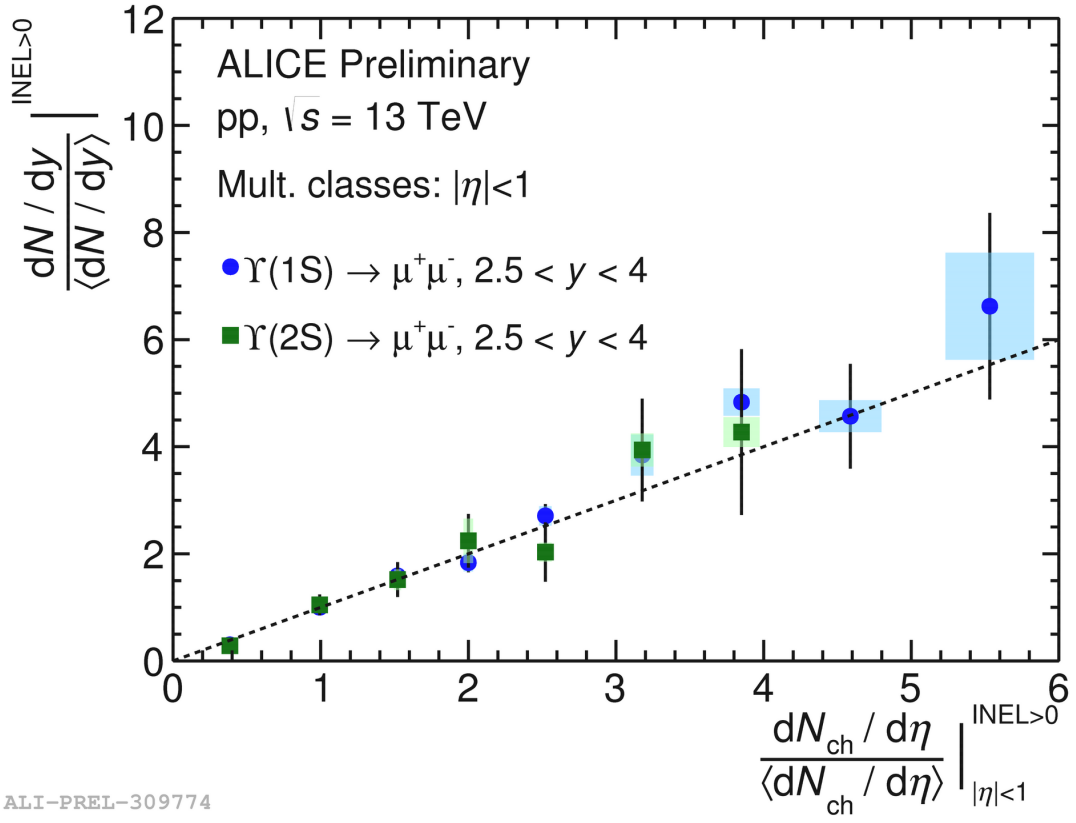
- No energy dependence
- <p_T> saturates at high mult



ALI-PREL-307429

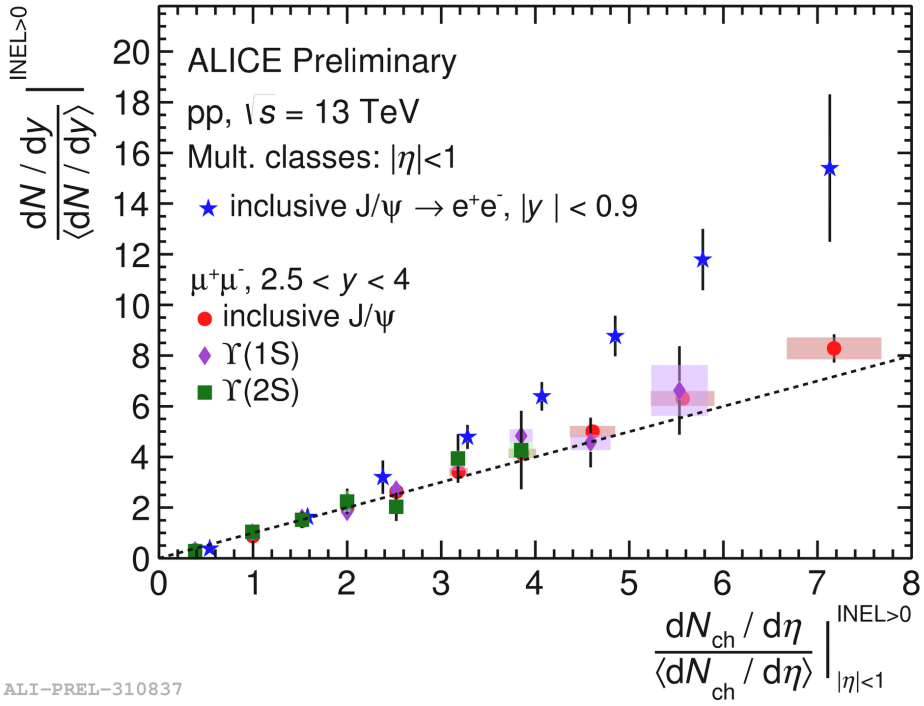
ϒ production as a function of multiplicity

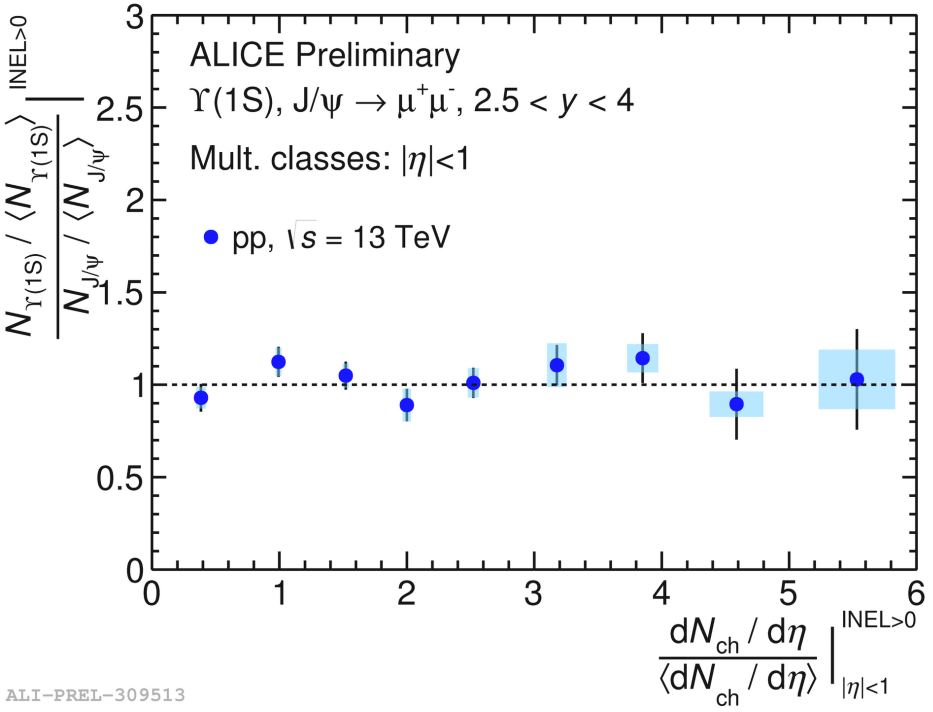
First ALICE results in the forward sectors for pp 13 TeV



- 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

Quarkonia production as a function of multiplicity in the forward sector

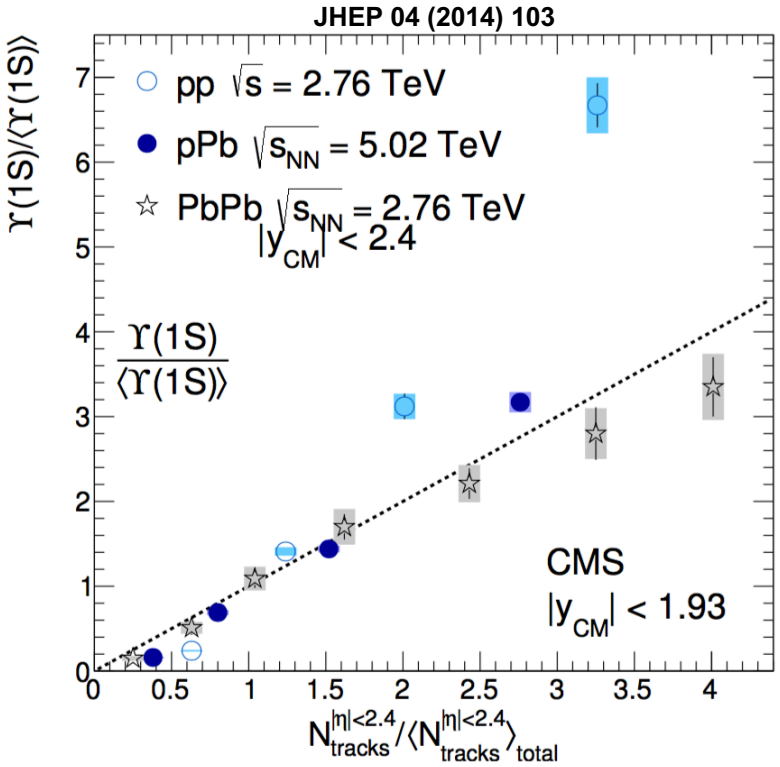




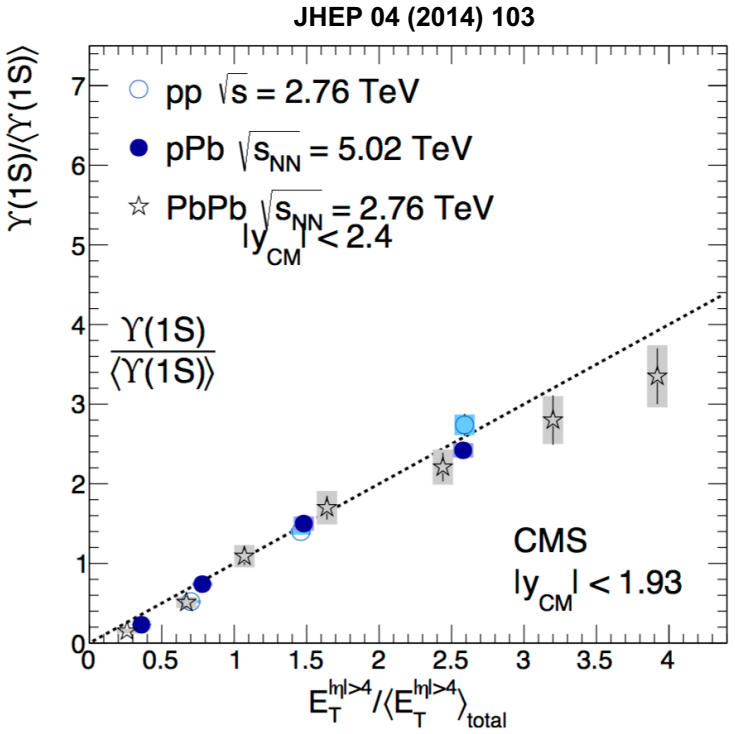
- ϒ have similar behavior as J/ψ in the forward sector within current uncertainties
- No effect seen with respect to quark content or mass

ϒ production as a function of multiplicity

What about the rapidity gap ?



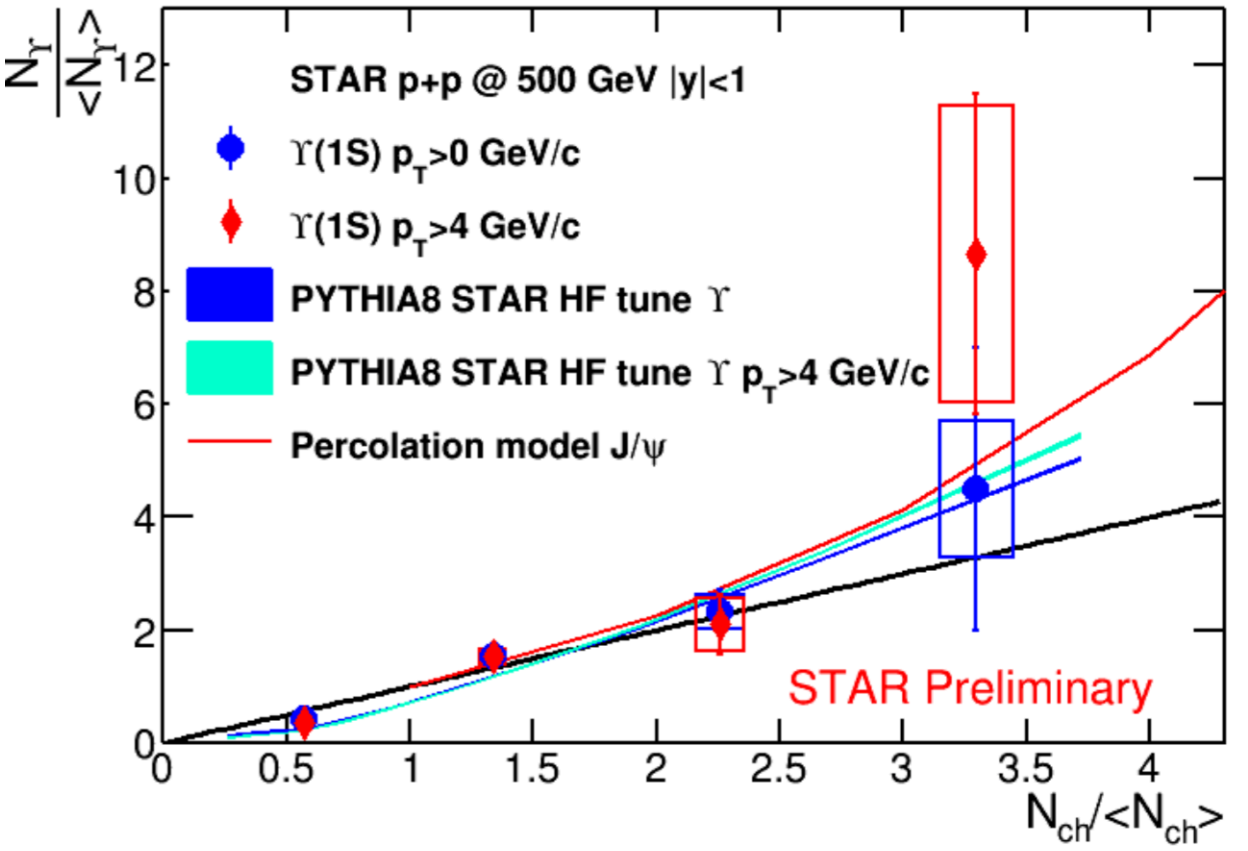
- CMS observes a strong increase of Upsilon states in the central rapidity region (pp 2.76 TeV)
- Different magnitude for the 3 states (see next slides)
- Qualitatively similar to what we observe for J/ψ and D mesons in similar rapidity region



- Linear behavior measured for forward E_T
- Also for Upsilon, different rapidity plays a role in the measurement

ϒ production as a function of multiplicity

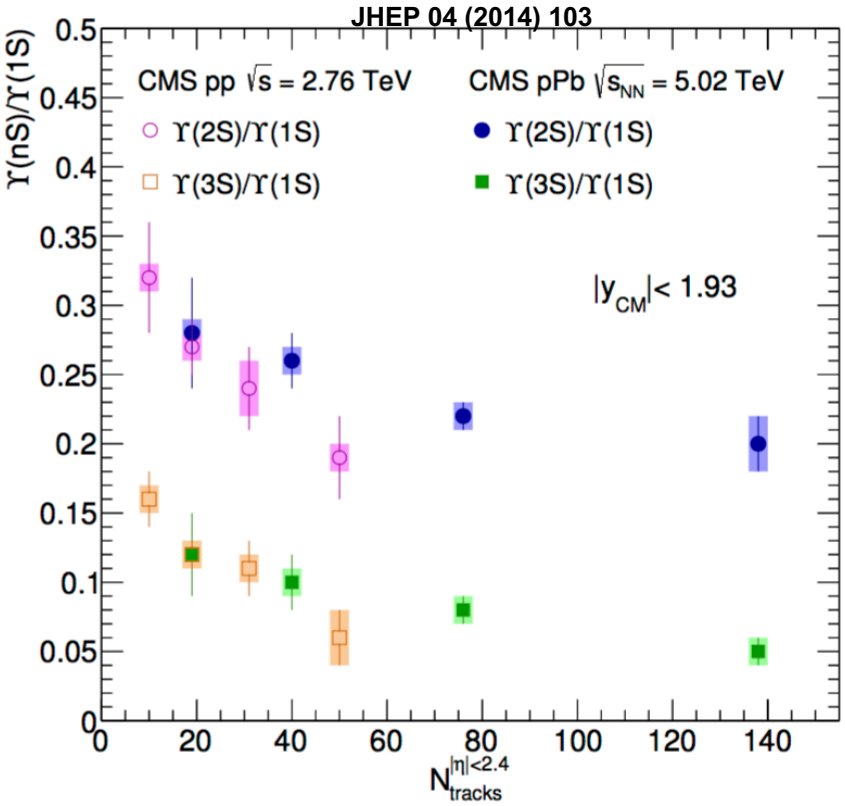
What about the rapidity gap ?

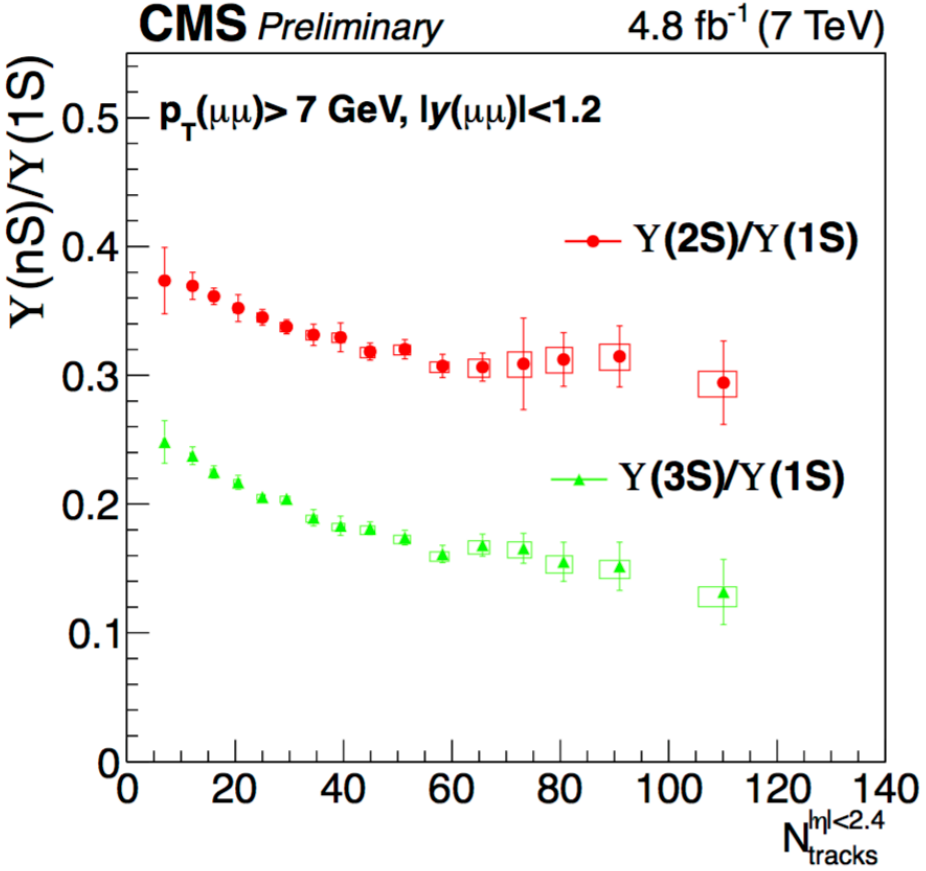


- STAR observes in pp at 500 GeV in central rapidity region a deviation from linearity which is not significant with current uncertainties

ϒ production as a function of multiplicity

What about exited to ground state ratio?

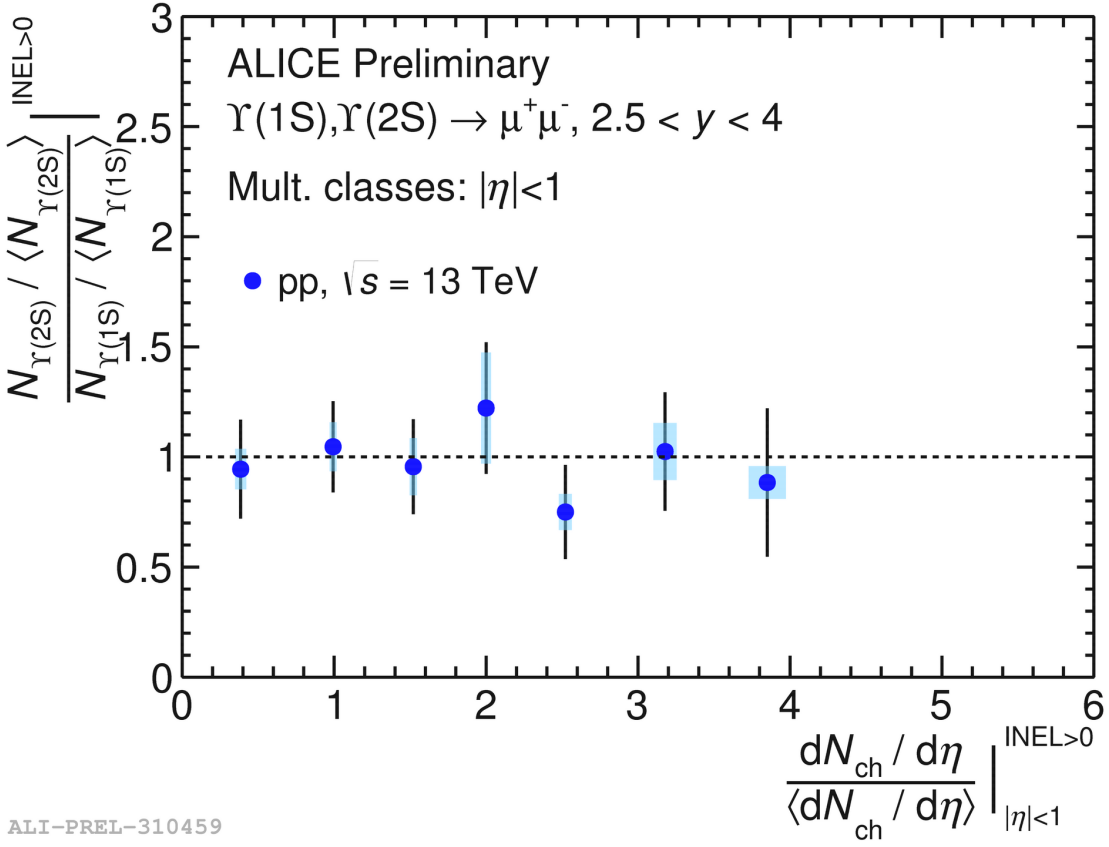




- CMS observes in pp at 2.76 TeV and 7 TeV and p-Pb at 5.02 exited to ground state disappearance in the central rapidity region, confirmed by analysis with sphericity and kinematic region of multiplicity (forward/backward/transverse)

ϒ production as a function of multiplicity

What about exited to ground state ratio?
First measurement at forward



- 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)

- **ALICE** released **new preliminary** results for quarkonium vs.multiplicty

- Those results have to be discussed in coherence with previous measurement at other energies, rapidity ranges, systems, quark contents

- We observe a **strong dependence of the measured correlation with the rapidity range** of the Quarkonia
    - Linear increase close to *x*=*y* over a wide range of multiplicity when the quarkonia is at forward-rapidity
    - Stronger than linear (exponential ?) increase when the Quarkonia is at mid-rapidity
    - The multiplicity is always at mid-rapidity

- In the forward rapidity sector we do not observe any dependence on the energy, quark content, mass, exited vs. ground state for Upsilon

- Development of intensive data/theory comparisons are needed to understand Quarkonium vs. multiplicity in a coherent way

- We should also include in the discussion results from other probes (phi, K0, strangeness, …)

Non-exhaustive overview of event generators

- pp event generators
  - PYTHIA
  - HERWIG

  } Based on pQCD approach : the hard interaction is the basis of the framework

  - EPOS
  - SHERPA

  } Based on Gribov-Regge approach, multiple interactions are the basis of the framework

- Specialization, complement for pp event generators
  - ALPGEN: hard multiparton processes in hadronic collisions, to be coupled to HERWIG or PHYTIA
  - Jimmy: multiparton Interactions in HERWIG
  - Cascade: hard processes with parton evolution (unintegrated PDFs), hadronization by PYTHIA
  - MadGraph5_aMC@NLO
    automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations

Non-exhaustive overview of event generators

➢ Heavier systems : from pp to AA

- Hijing — Based on PYTHIA, with emphasize on minijet, include nuclear shadowing
- AMPT — Hijing for initial condition, add final state scattering to generate elliptic flow
- EPOS — Picture of elementary parton-parton interactions viewed as color flux tube extended to all system, with shadowing and hydro evolution
- Hydjet++ — Hydro evolution (only AA?)

➢ Specialization, complement for heavier systems

- JEWEL in-medium jet energy loss, jet quenching
- Q-PYTHIA in-medium jet energy loss, jet quenching
- MC@sHQ+EPOS2 heavy-quark propagation in a realistic fluid dynamical medium

Model ingredients

model	EPOS	PYTHIA	Hijing	AMPT
systems	pp, pA, AA	pp	pp, pA, AA	pp?, pA, AA
Baseline	Multiple Interaction	Hard process	PYTHIA 5,3? + minijet + nuclear structure	HIJING + transport model (ZPC parton cascade)
MPI	Parton-based Gribov-Regge Theory	Reconstructed after the hard process. Interaction ordered in hardness. In the new model : color reconnection	modeled by excitation of quark-diquark strings with gluon links + multiple low-p_T exchange	
Hard process	Hard and semi-hard ladder with soft pre-evolution u, d, s, g, gamma, c	Based on inclusive cross section Almost everything, if not in the code, can couple with extra code	PYTHIA 5,3	
HF Quarkonia	Open charm and open beauty J/Ψ in progress	Yes		

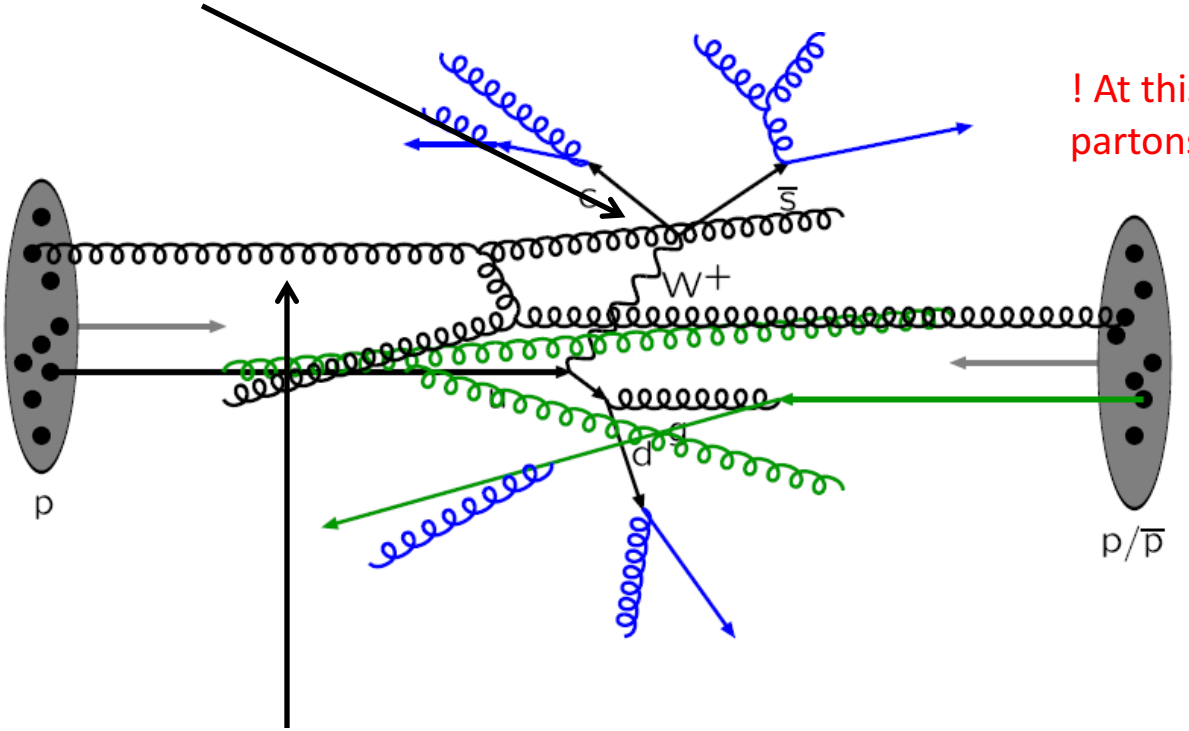
Model ingredients

model	EPOS	PYTHIA	Hijing	AMPT
Initial and Final state radiation	Iterative procedure from partons in hadrons to 2->2 process	A posteriori reconstruction Available for MPI in the new model (6.4)	PYTHIA 5,3	
Collectivity	Yes, string density, eg. for all systems if energy density high enough. Event by event hydro in EPOS2	No	Simple model for jet-quenching (jet-medium interaction in AA)	transport model
Hadronization	String model with area law, diquark for baryon production	String model with fragmentation function, popcorn for baryon production	PYTHIA 5,3	
Remnant	Yes Off-shell treatment	Yes	PYTHIA 5,3	
Connection between hard processes and MPI	Total by construction : several ladders soft or hard, energy conservation and color connection	With color reconnection (6,4), final state effect	modeled by excitation of quark-diquark strings with gluon links + multiple low-p_T exchange	?

Quarkonia and HF in PYTHIA

PYTHIA Physics : ref 6.4 Manual

1) The first hard interaction is the first step of event machinery :
Computed in pQDC framework with factorization, possibility to select hard process : charm, bottom, jets, photon -> can tune this step

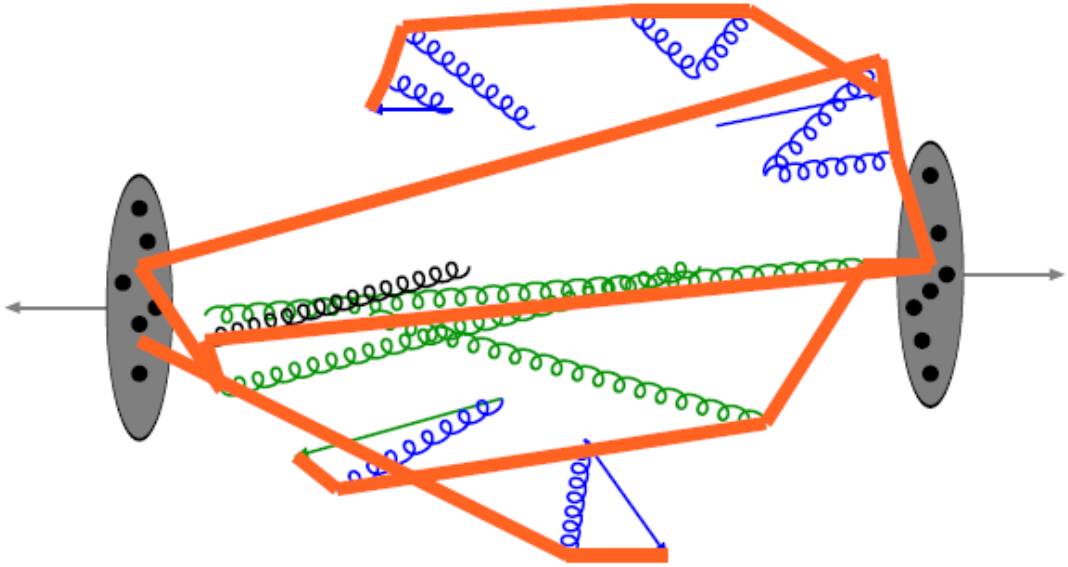


! At this step only partons are produced

2) MPI (Multiple Parton Interaction) : other processes (soft or hard) can happen in parallel:
PYTHIA model : the first hard interaction is particular, other are reconstructed afterward, ordered in hardness, in PYTHIA 6, only g,u,d,s available in other interactions.
In PYTHIA 8 : second hard processes can include charm and bottom

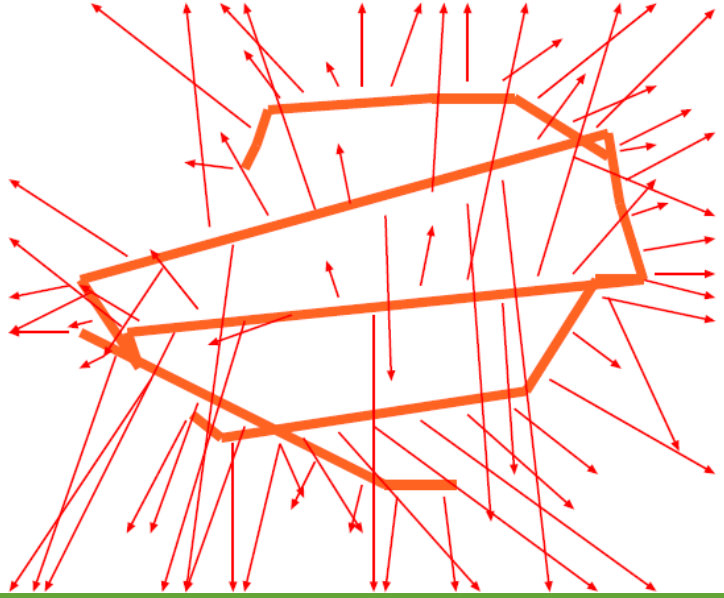
http://arxiv.org/abs/hep-ph/0603175

Quarkonia and HF in PYTHIA



All produced partons:
- hard process,
- ISR/FSR (Initial/Final State Radiation),
- MPI,
- Remnants

are connected via strings: the LUND procedure.
Resonances let out of the machinery

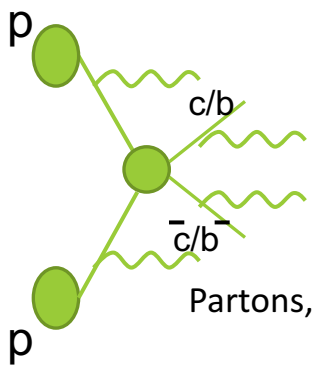


Formed strings decay into hadrons.
Fragmentation via qqbar pairs, pop-corn to produce baryons.
qqbar = u,d,s,c (c is suppressed but available),
heavier not implemented

Quarkonia and HF in PYTHIA

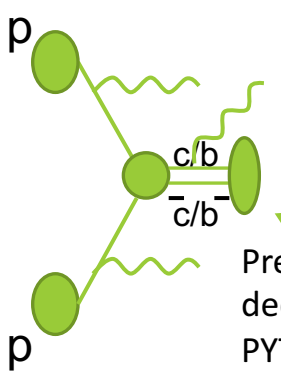
❖ In the 2->2 hard sub-process

1) Open heavy-flavour



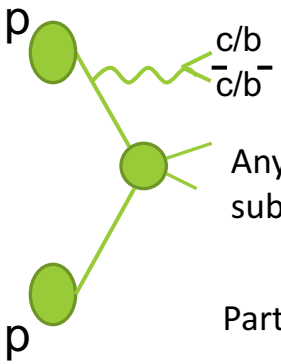
Partons, connected to strings

2) Resonance production



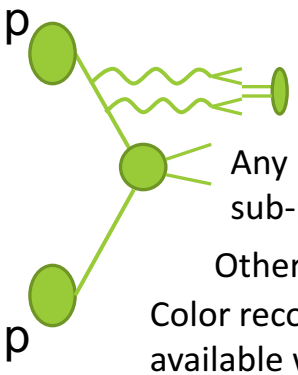
Pre-resonant state (NRQCD):
decay into J/Ψ or Upsilon
PYTHIA 8 : color singlet and octet
Singlet no FSR evolution, octet yes

❖ Gluon splitting (g->QQ, $\bar{g}$luon originated from ISR/FSR)



Any hard 2->2
sub-process (gg->gg for example)

Partons, connected to strings



$c\bar{c}$ cluster decay into J/Ψ

Any hard 2->2
sub-process (gg->gg for example)

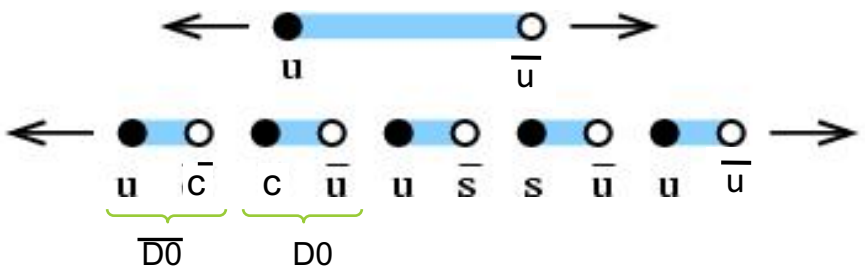
Other c/b connected to strings

Color reconnection make this contribution available with only one g->Qqbar : artificial enhancement of this contribution in PYTHIA6.4

(N.B : Cluster : small peace of string : decay directly into hadrons)

Quarkonia and HF in PYTHIA

❖ String fragmentation



An event can still produce J/Ψ and D mesons via string fragmentation

$c\bar{c}$ pair production suppressed as compared to u, d, s.

Higher states not available

Origin of heavy flavours in PYTHIA 8.157

Origin of c and b quark content	D mesons	B mesons
First hard process	11%	36%
gluon fusion	2%	15%
c/b sea	9%	21%
Hard process in MPI	21%	24%
Gluon splitting from hard process	6%	included in ISR/FSR
ISR/FSR	62%	40%
Remnant	< 0.2%	< 0.4%

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

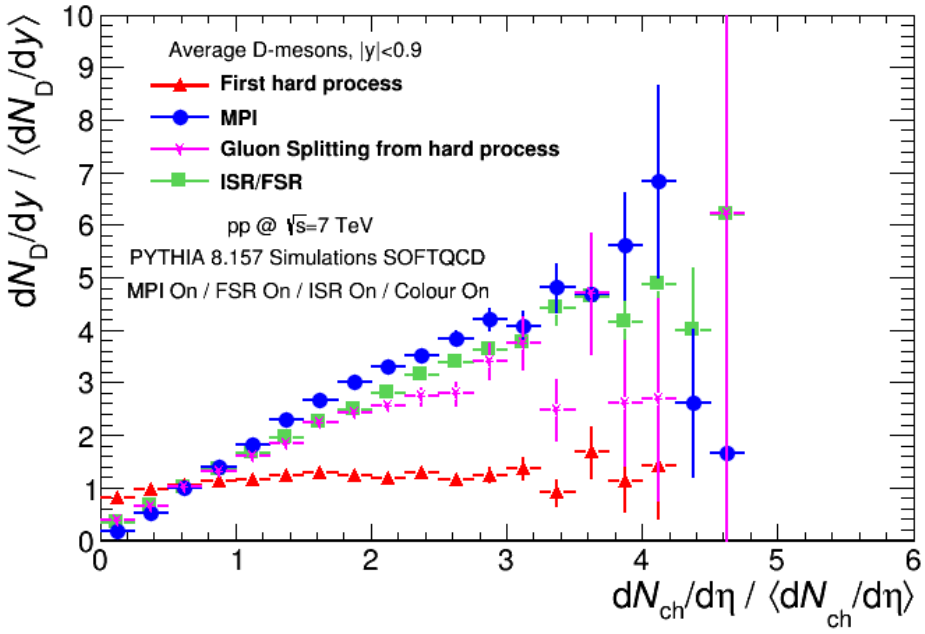
➢ Comparison with PYTHIA 8

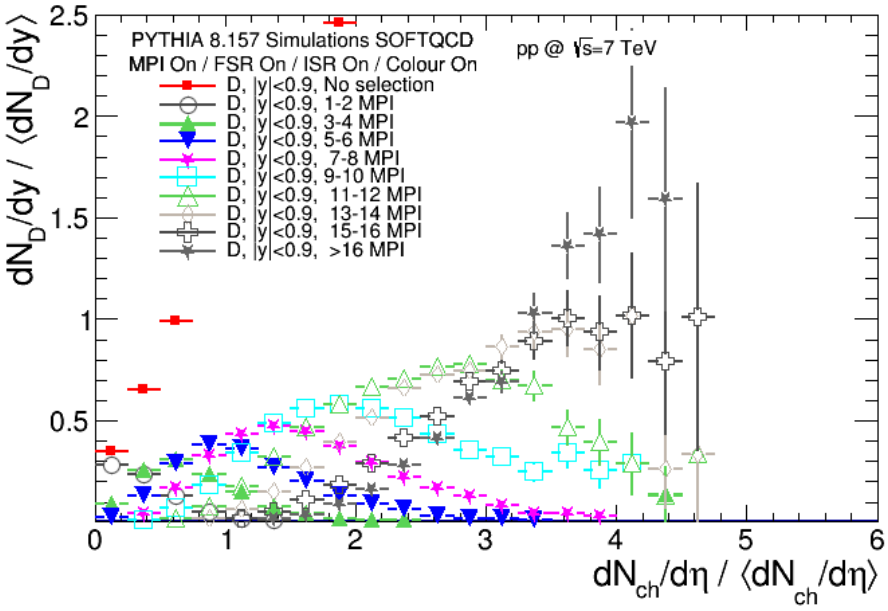
Improvement of MPI scenario
(charm in subsequent MPI)

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

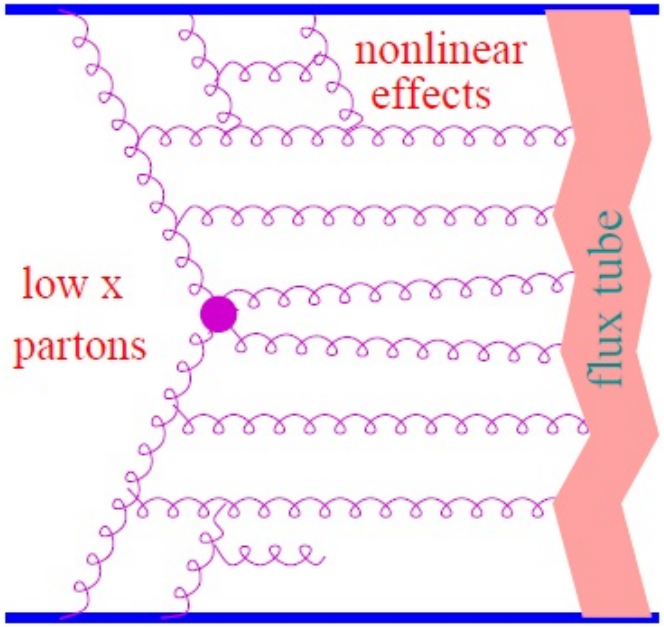
Each slices has almost the same weight in the total contribution

Zoom on the different contribution

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

Quarkonia and HF in EPOS

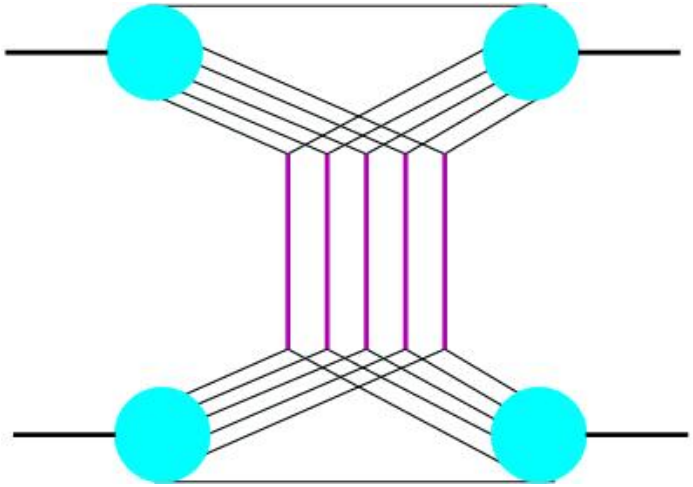
Elementary scattering - flux tube

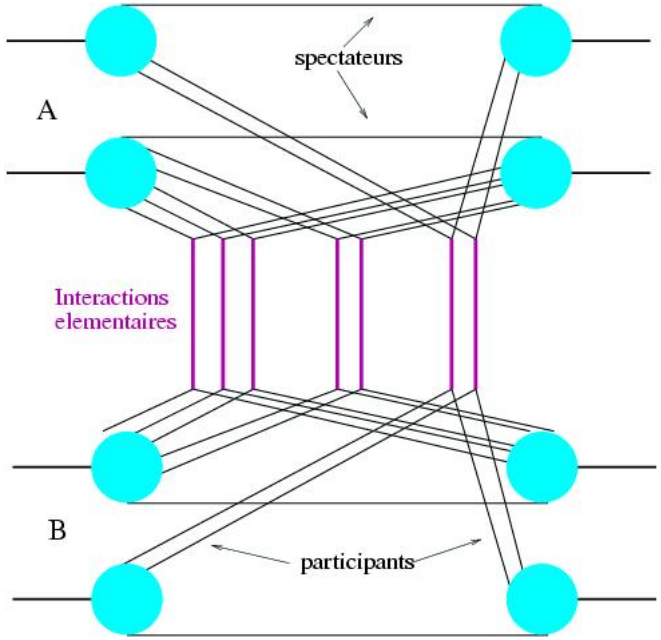


- Parton evolutions from the projectile and the target side towards the center (small x)
- Evolution is governed by an evolution equation, in the simplest case according to DGLAP.
- **Parton ladder may be considered as a quasi-longitudinal color field, a so-called flux tube, conveniently treated as a relativistic string.**
- **Intermediate gluons are treated as kink singularities in the language of relativistic strings, providing a transversely moving portion of the object.**
- flux tubes decay via the production of quark-antiquark pairs, creating in this way fragments – which are identified with hadrons

Quarkonia and HF in EPOS

Same framework extended

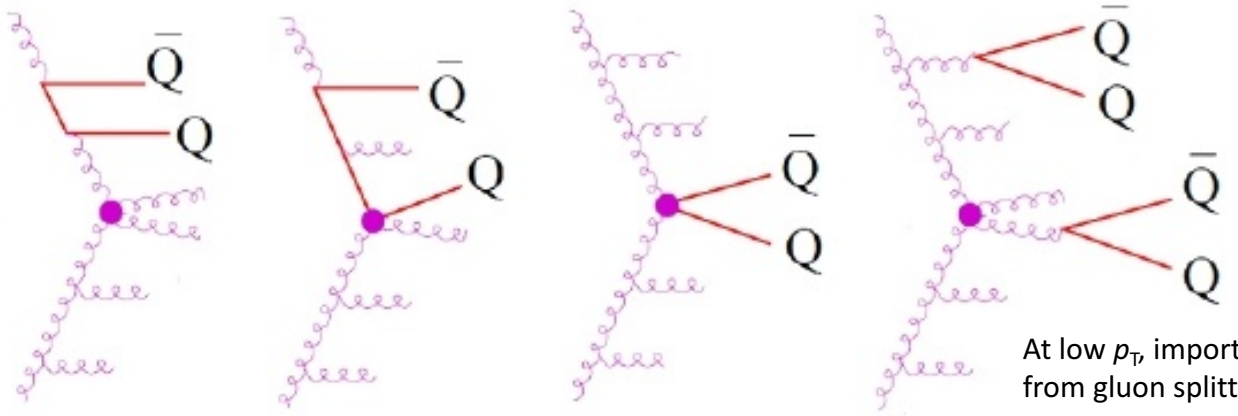




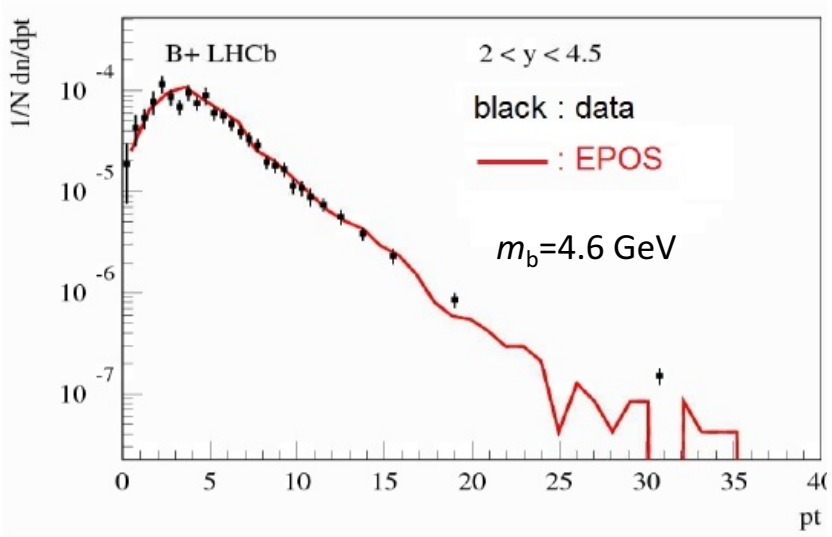
pp → AB

Quarkonia and HF in EPOS

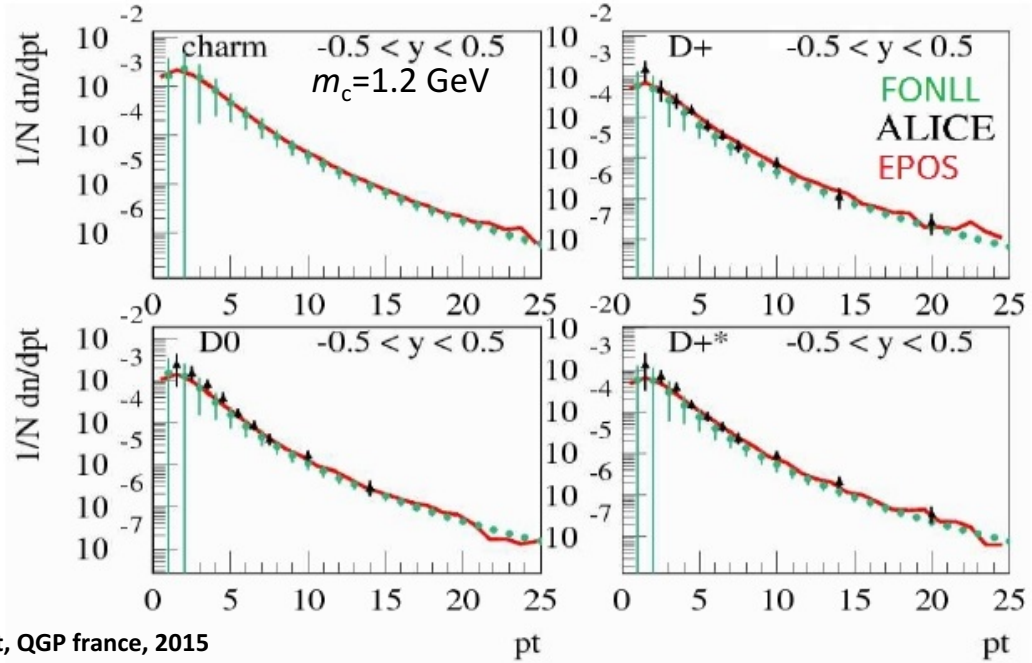
$Q\bar{Q}$ production



At low p_T, important contribution from gluon splitting



Data : arXiv 1306.3663

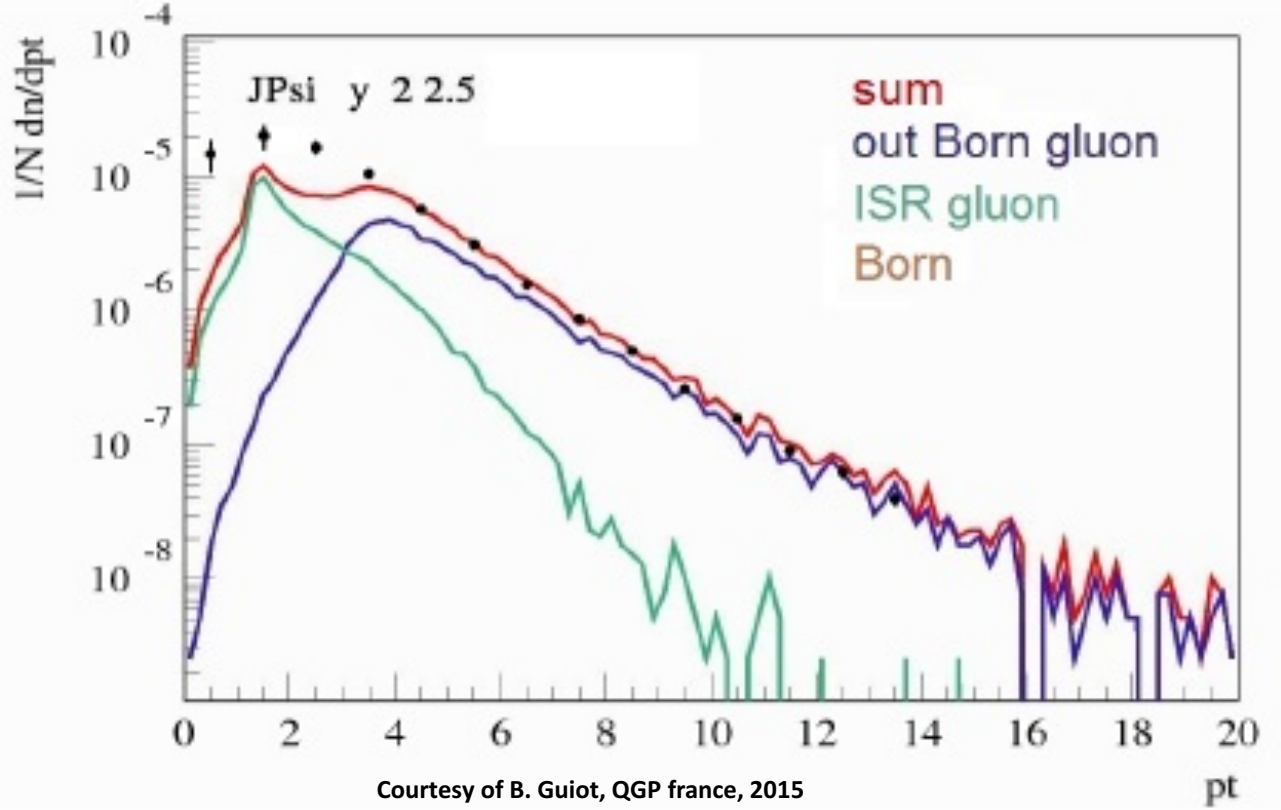


Courtesy of B. Guiot, QGP france, 2015

Quarkonia and HF in EPOS

J/Ψ production within the CEM model

A parameter for the fraction of cc t̄hat hadronize into J/Ψ

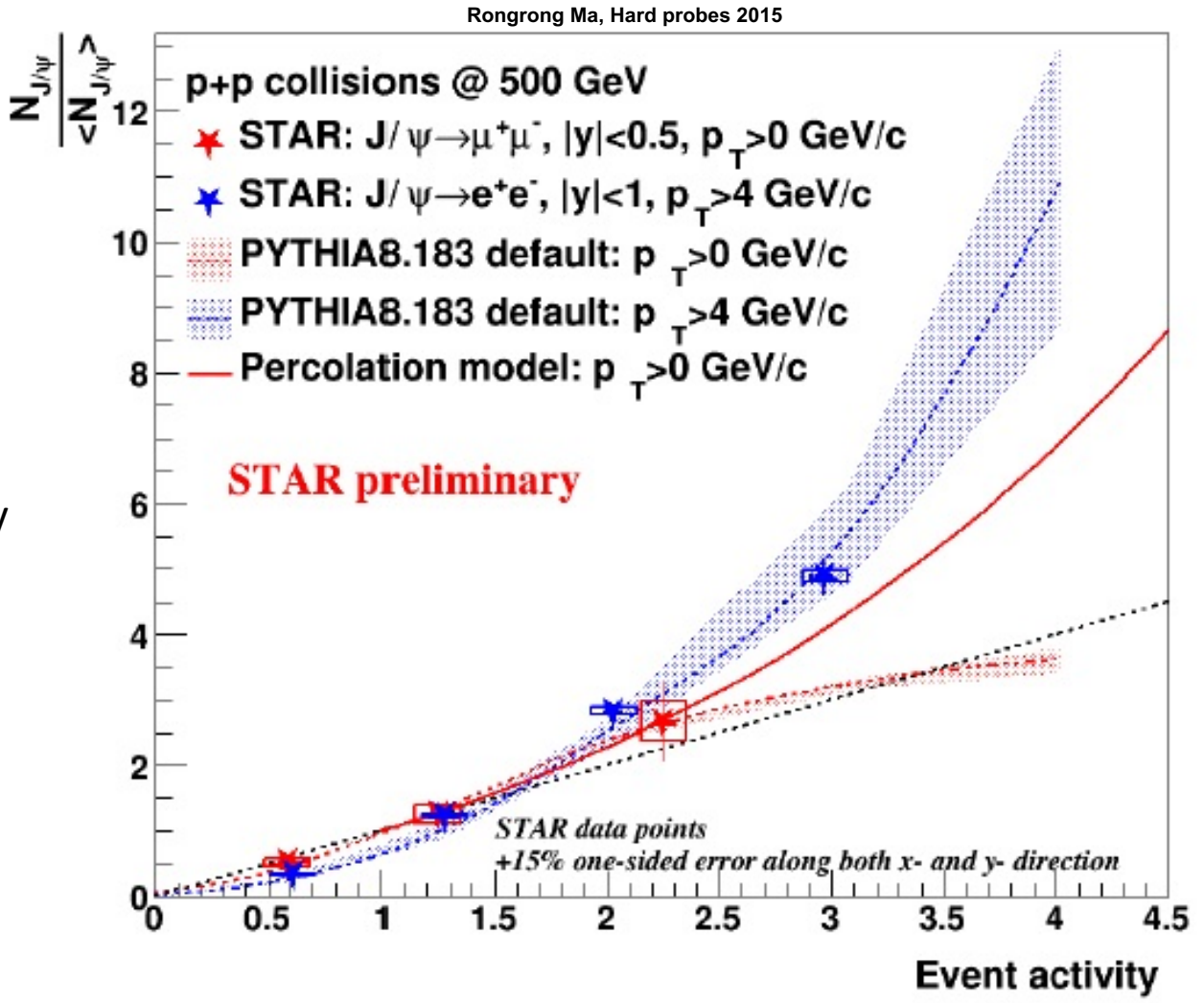


Courtesy of B. Guiot, QGP france, 2015

Work in progress

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