Quarkonia and open heavy flavours in event generators

OUTLINE

- Why event generators are needed for new observables ?
- Event generators on the market (pp to AA)
- Quarkonia and HF production in PYTHIA
- Quarkonia and HF production in EPOS
- Quarkonia and HF production vs. multiplicity
- Conclusions

New observables in quarkonium production workshop

ECT*, Trento, 29/02 - 04/03

Event generators

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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 ?

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- 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**

Non-exhaustive overview of event generators

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➢ <u>pp event generators</u>

- 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

➢ <u>Specialization, complement for pp event generators</u>

- 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

https://karman.physics.purdue.edu/OSCAR-old/models/list.html http://en.wikipedia.org/wiki/Event_generator

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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

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In the following, focus on two :

generalist event generators
that include heavy flavour and quarkonia
and extension for heavy-ion physics

- PYTHIA
- EPOS

Model ingredients

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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

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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

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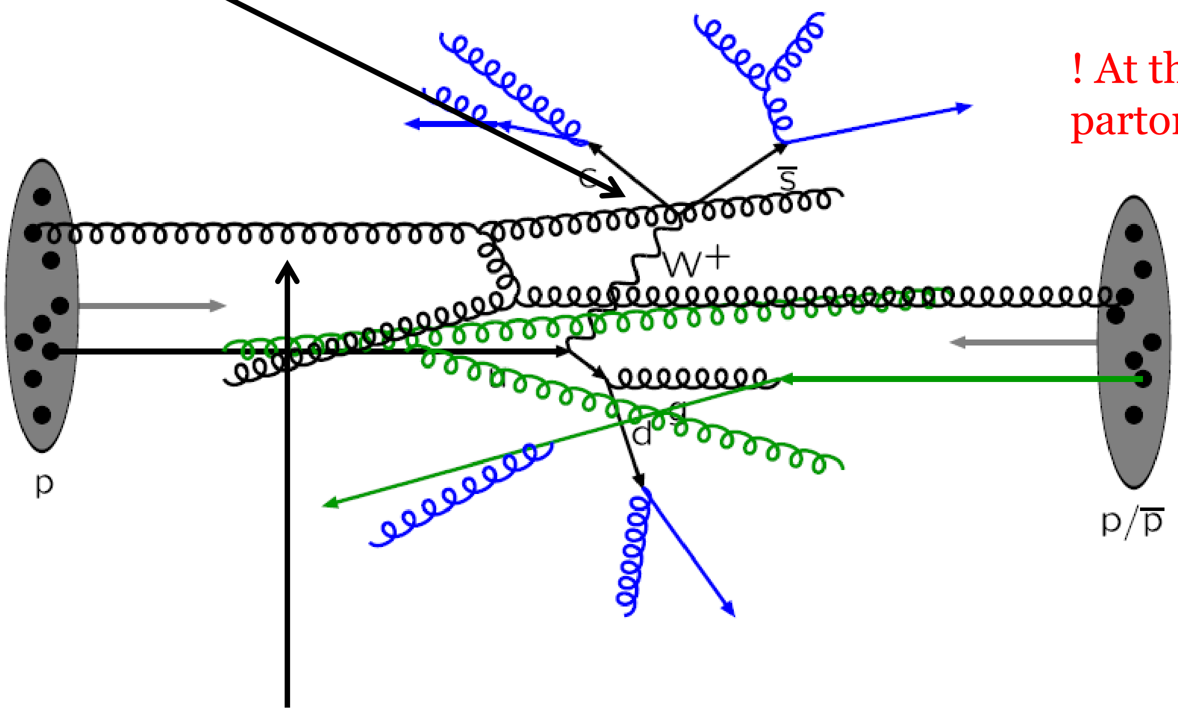
PYTHIA Physics : ref 6.4 Manual

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

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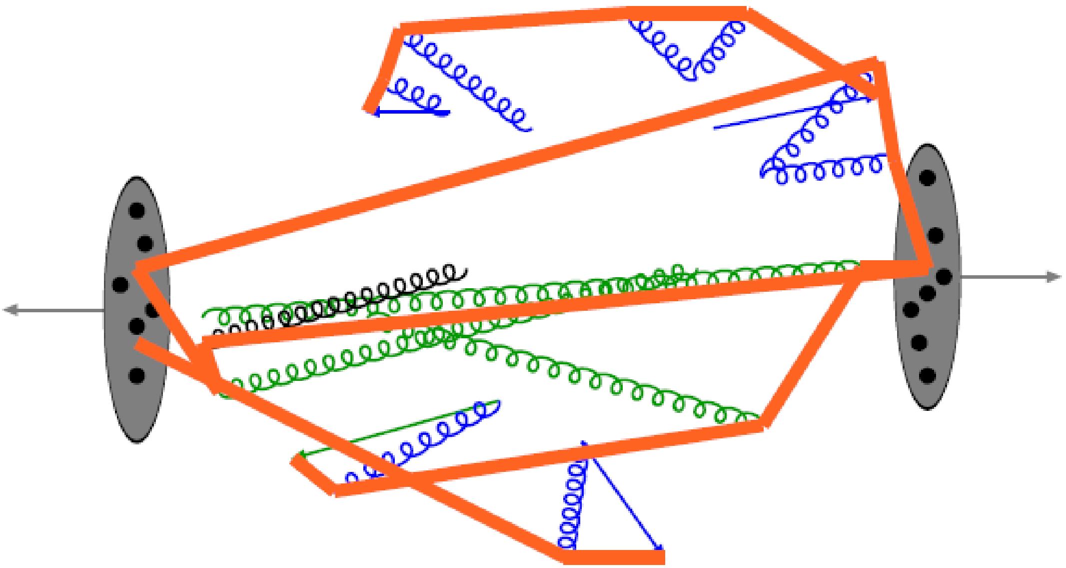
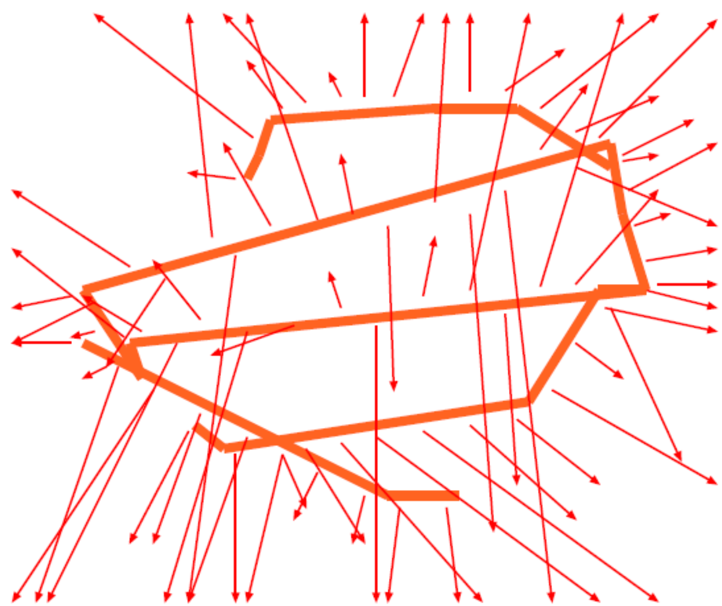


All produced partons:
- hard process,
- ISR/FSR (Initial/Final State Radiation),
- MPI,
- Remnants

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

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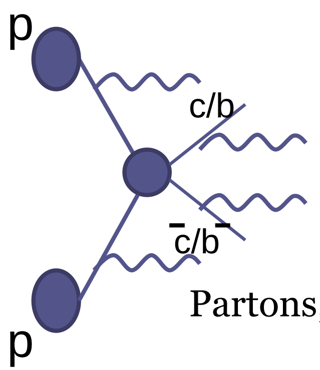
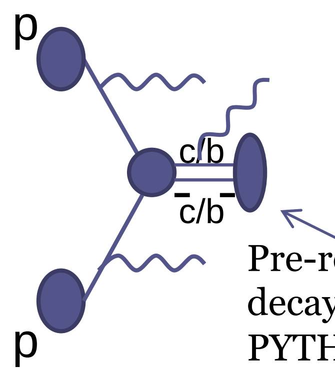
- In the 2->2 hard sub-process

1) Open heavy-flavour



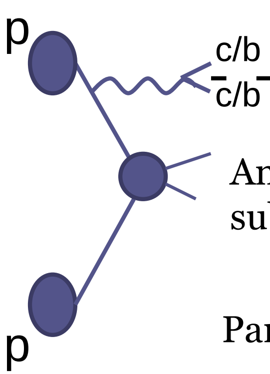
Partons, connected to strings

2) Resonance production



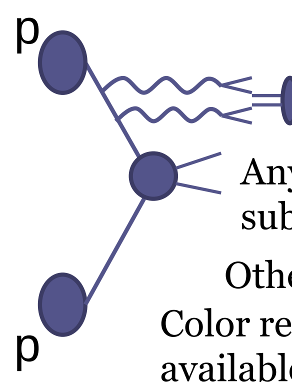
Pre-resonant state (NRQCD):
decay into J/Ψ or Upsilon
PYTHIA 8 : color singlet and octet
Singlet no FSR evolution, octet yes

- Gluon splitting (g->QQ̄, gluon originated from ISR/FSR)



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

Partons, connected to strings



cc̄ 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

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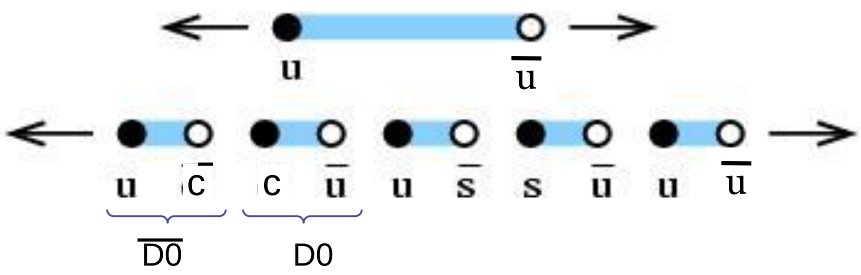
❖ String fragmentation



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

<u>Origin of heavy flavours in PYTHIA 8.157</u>

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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Quarkonia and HF in EPOS

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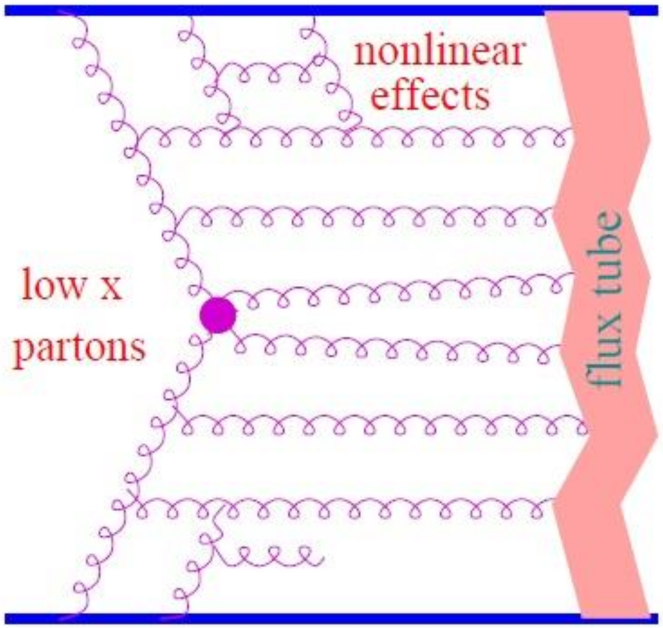
Elementary scattering - flux tube



- 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

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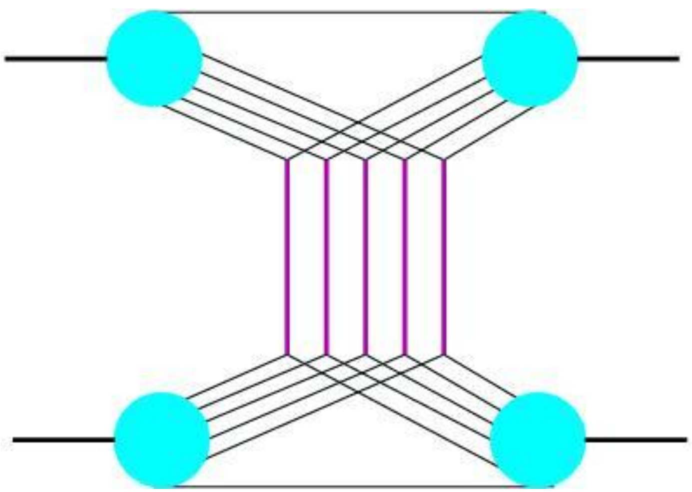
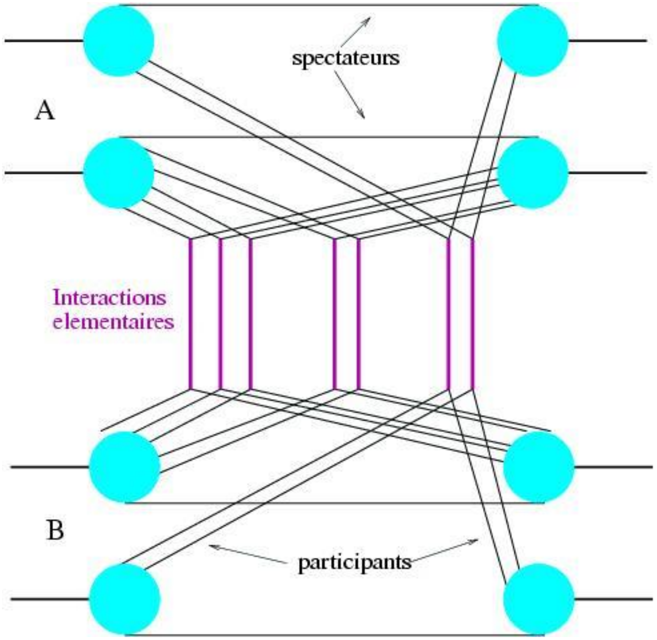
Same framework extended





pp → AB

Quarkonia and HF in EPOS

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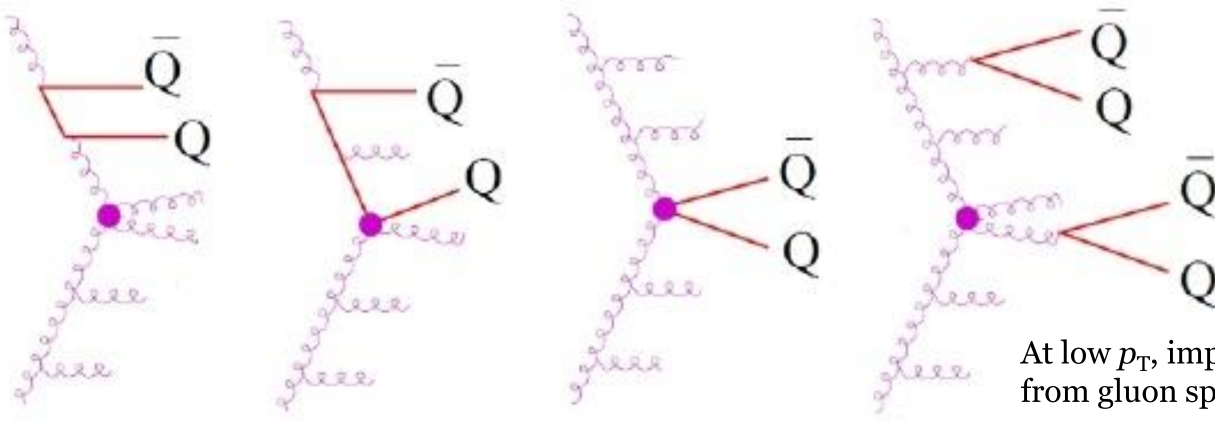
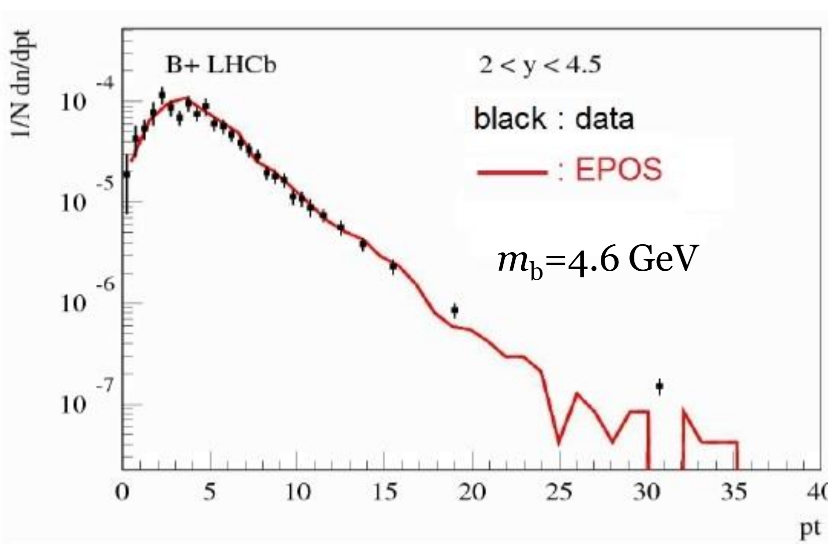
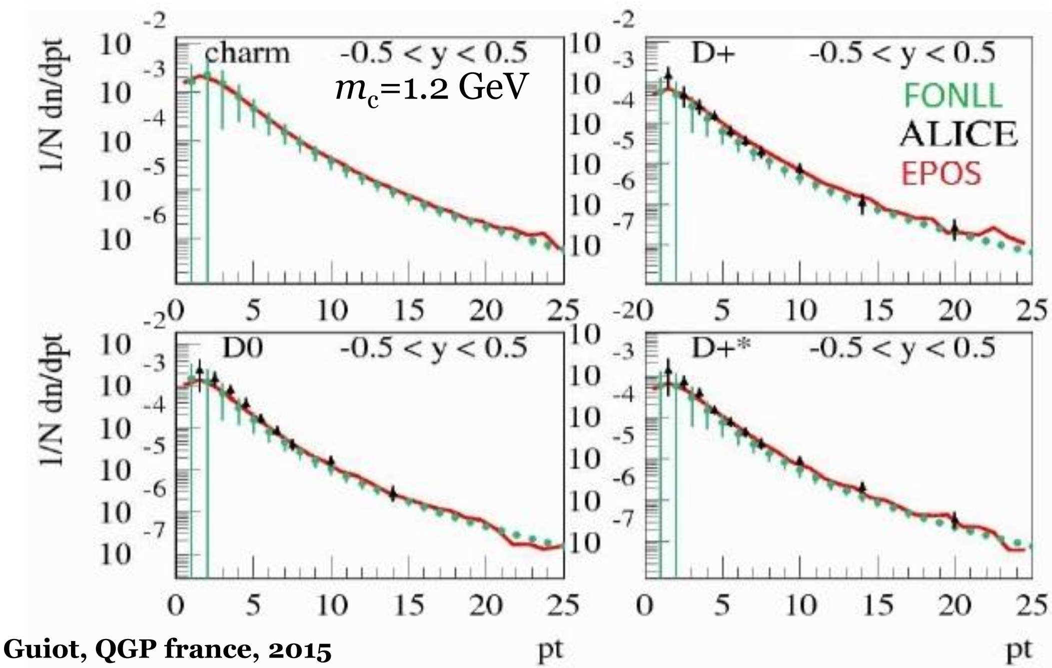
$Q\bar{Q}$ production



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

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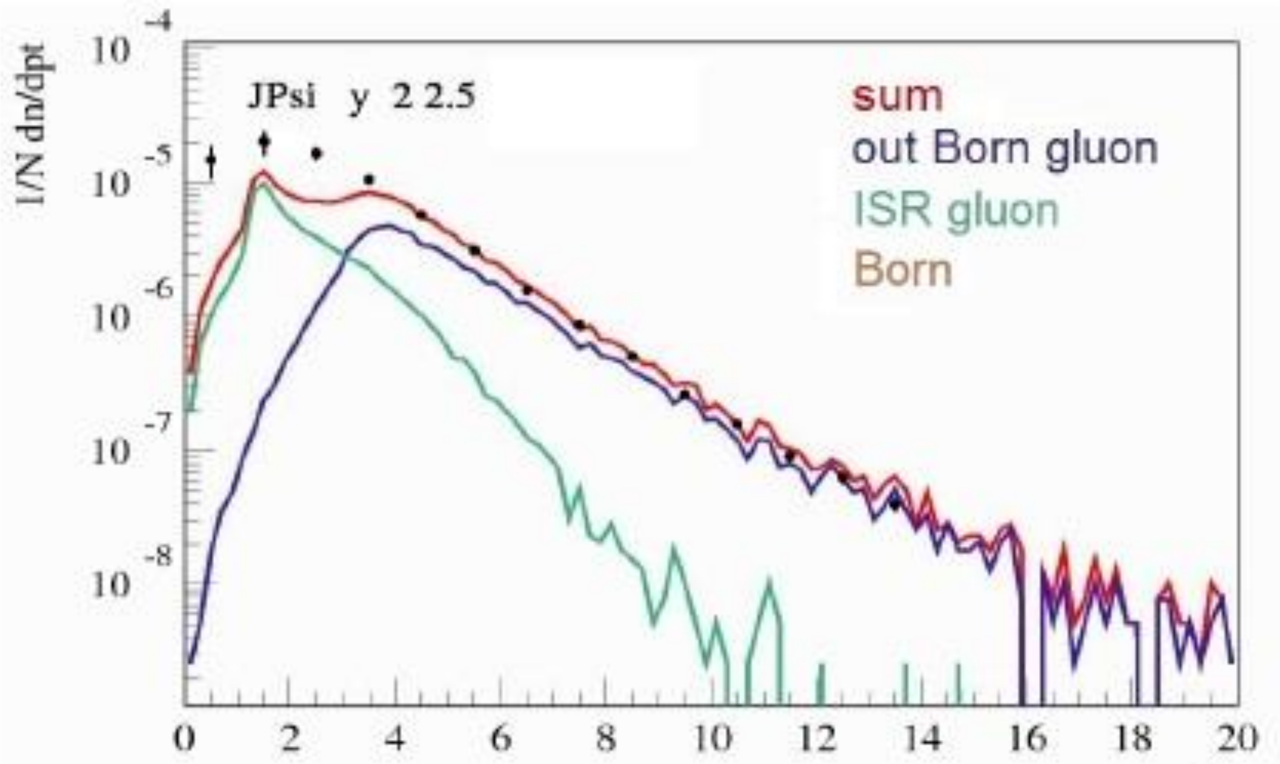
J/Ψ production within the CEM model

A parameter for the fraction of $c\bar{c}$ that hadronize into J/Ψ



Courtesy of B. Guiot, QGP france, 2015

Work in progress

Quarkonia and HF vs. charged particle multiplicity

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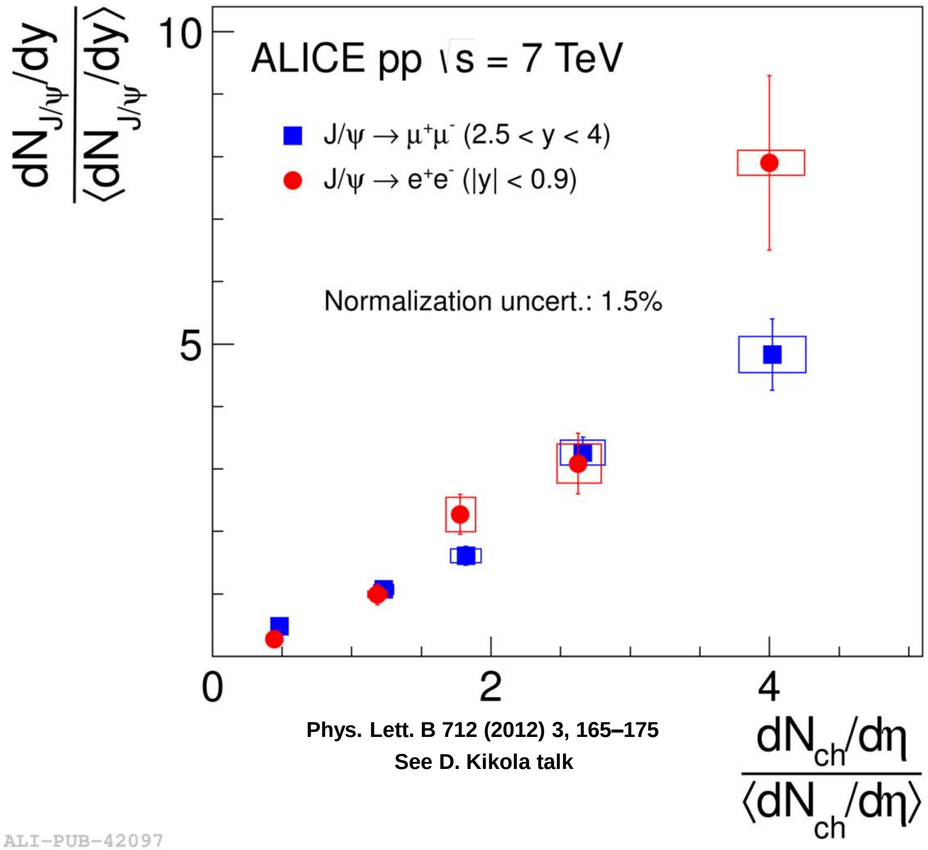


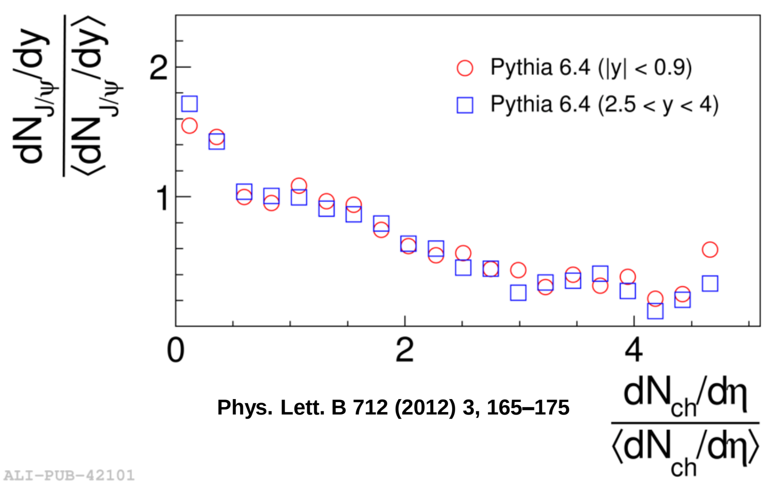
Phys. Lett. B 712 (2012) 3, 165–175

See D. Kikola talk

- <u>Comparison with PYTHIA 6.4</u>
  - 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



Phys. Lett. B 712 (2012) 3, 165–175

Quarkonia and HF vs. charged particle multiplicity

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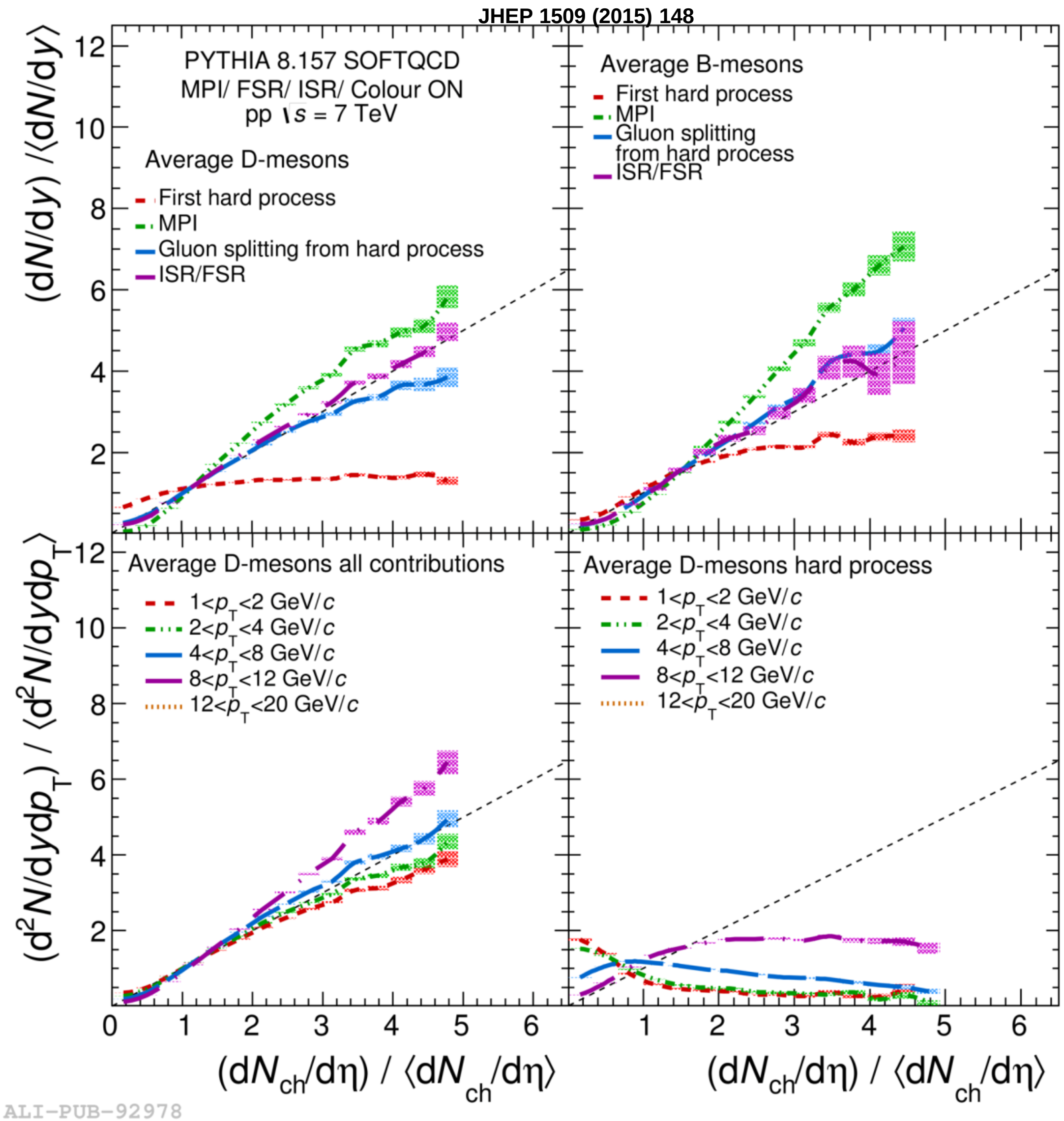
PYTHIA 8.157

- 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



Quarkonia and HF vs. charged particle multiplicity

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➢ 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

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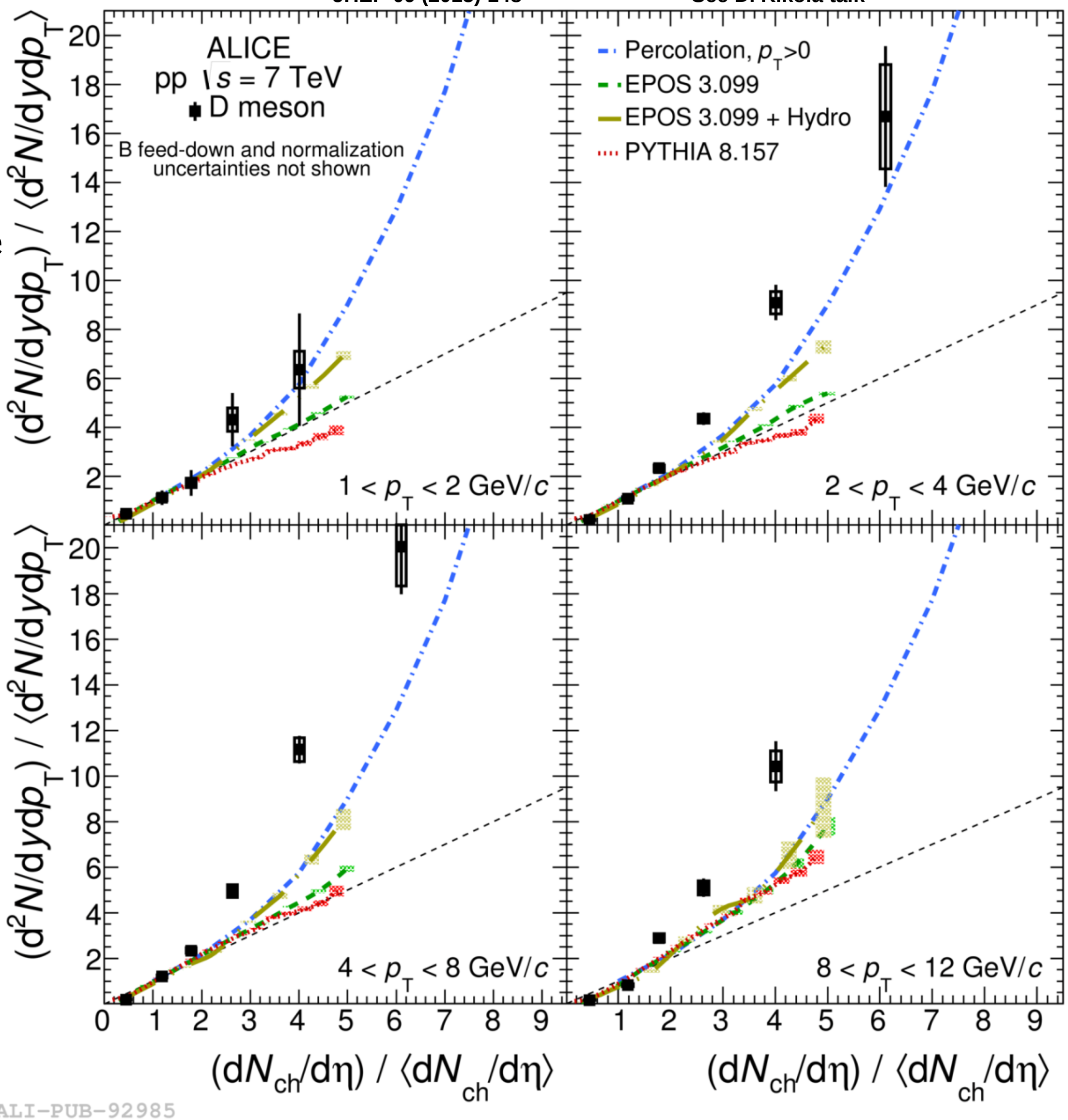
See D. Kikola talk



Quarkonia and HF vs. charged particle multiplicity

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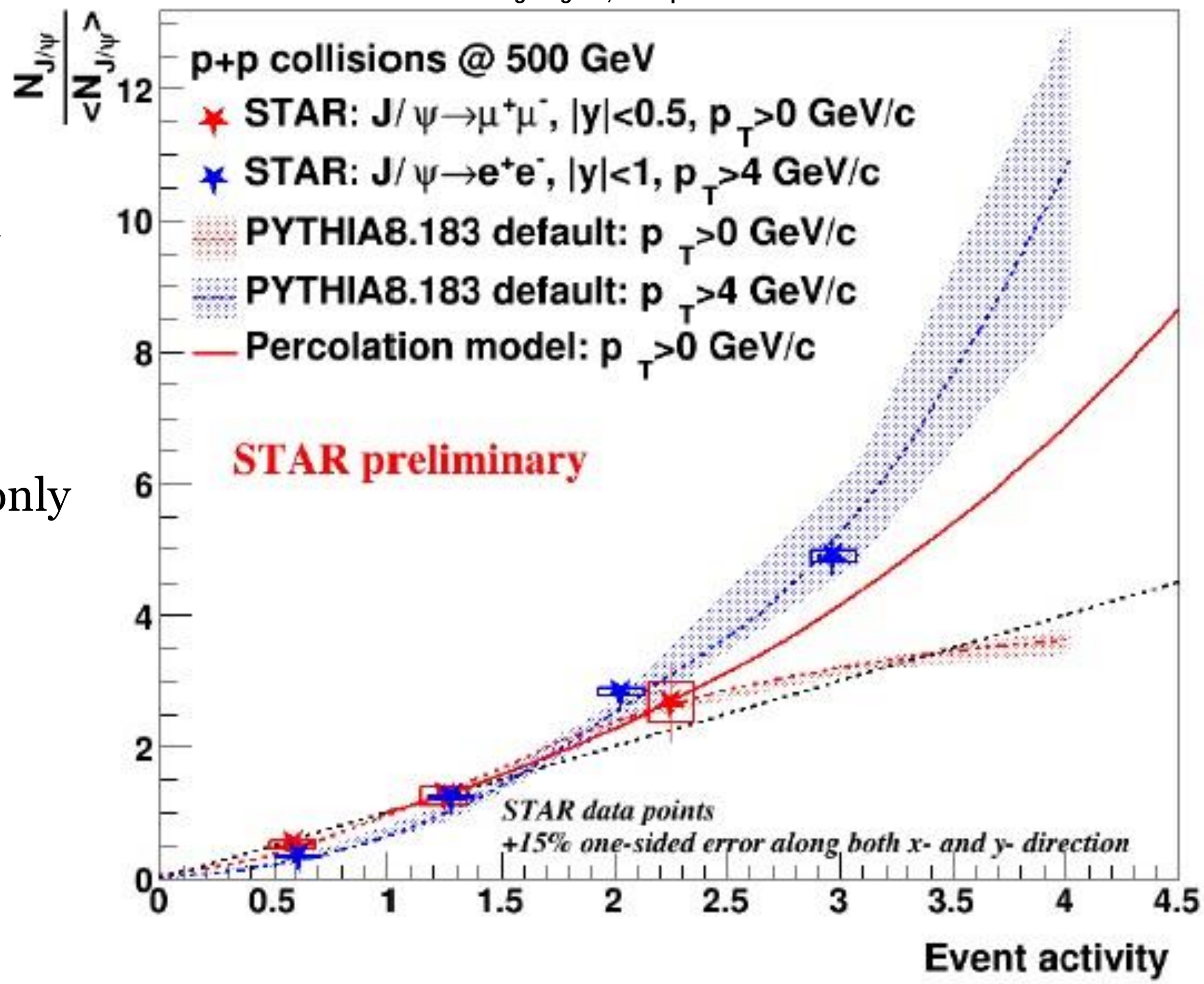
PYTHIA 8.183

- All contributions for J/Ψ production
  Works pretty well

- Up to Event activity = 3 only

Rongrong Ma, Hard probes 2015



Conclusions

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- Event generators are of interest for new observables in quarkonium production : prospective and model comparison

- Many event generators available, few with quarkonia and underlying events, for light and heavy systems

- Heavy-flavours and quarkonia production in PYTHIA
  - Contribution from hard process, first and MPI, (D 38%, B 60%) and ISR/FSR radiation (D 62%, B 40%)
  - HF : ISR/FSR contribution scales with multiplicity
  - HF : MPI with hard processes scale with multiplicity
  - J/Ψ : total production reproduce STAR Data

- Heavy-flavours in EPOS, quarkonia in progress
  - Only event generator with hydro evolution for all systems
  - Contribution from ladder evolution, gluon fusion in hard process, gluon splitting
  - HF : MPI scale with multiplicity
  - HF : hydro evolution helps to describe the data by reducing the number of charged particles

Monte Carlo event generators can play a role in understanding HF and onia production in (dense) hadronic environment