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LPC Seminar

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First presented at 2nd International spring

Correlations between partons in nucleons

ALICE :

ALICE

the LHC dedicated experiment for heavy ion collision studies



A question asked by LHC Run I



Looks like signs, hints (something) of collectivity in small systems (pp and p-Pb) Do we understand initial conditions?

Importance of multi-parton interactions in hadronic collisions (this talk)

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OUTLINE



Multi-Parton interaction study: physics motivations

- The ALICE experiment
- Charm production as a function of multiplicity
 - J/Ψ production as a function of multiplicity in pp and p-Pb collisions
 - D-meson production as a function of multiplicity in pp and p-Pb
 - Non-prompt J/Ψ as a function of multiplicity in pp collisions

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Multiple Parton Interaction (MPI)



✓ <u>A naïve picture</u>



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

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



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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.



O 62.2 GeV

52.6 GeV

Koba-Nielsen-Oleson (KNO) scaling

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

Scaling variable $z = \frac{N_{ch}}{\langle N_{ch} \rangle}$ and $P(N_{ch}) < N_{ch} >= \Psi(z)$ Energy independent function 0 62.2 GeV (N 10 52.6 GeV △ 44.5 GeV 0 30.4 GeV 10-2 10-3



<N_{ch}> P(z) △ 44.5 GeV 30.4 GeV 10-1 10-2 10-3 2.5 3.0z = N_{ch}/<N_{ch}> 0.0 1.0 1.5 2.0

When self normalized : KNO scaling

Different multiplicity distributions

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 \sqrt{s} =200 GeV, it works pretty well!



Koba-Nielsen-Oleson (KNO) scaling

At energies greater than \sqrt{s} =200 GeV in pp and pp collisions,



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

Violation of KNO-scaling ($\sqrt{s} > 200 \text{ GeV}$) 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



MPI

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Limitation at high energy



✓ <u>A naïve picture</u>

<u>A less naïve picture</u>





✓ <u>A more complex picture</u>

High multiplicity 7 TeV pp events comparable to RHIC Cu-Cu collisions рновоз, рнуз. Rev. С 83, 024913 (2011)

 $dN_{ch}^{pp}/d\eta$ up to 70, $dN_{ch}^{Cu-CU}/d\eta$ = 75 in 25-30% at \sqrt{s} =200 GeV, $dN_{ch}^{Au-AU}/d\eta$ = 73 in 50-55% at \sqrt{s} =200 GeV ~100 charged particles expected in pp 13 TeV $|\eta|$ <1 to be compared with RHIC Cu-Cu 15-20%

- Collectivity in pp к. Werner at al. Phys.Rev.C83:044915,2011 / k. Werner at al. J.Phys.Conf.Ser.316:012012,2011
- Final state effects on quarkonium production in pp collisions s. Vogel et al. J.Phys.Conf.Ser. 420 (2013) 012034/T. Lang Phys.Rev. C87 (2013) 024907
- Quarkonium production mechanism still to be understood, while open charm and beauty production is well described by pQCD

Understanding of elementary interactions in pp collisions is crucial: Interplay soft-hard, MPI structure, Underlying event (UE)

Where to look for MPI?



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

Multiplicity differential studies and exclusive measurements

Seen by others @ LHC

> CMS

Jet and underlying event properties as a function of charged-particle multiplicity in proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ Eur. Phys. J. C 73 (2013) 2674 hep-ex/1310.4554

Need MPI to describe data, even if actual description not satisfactory (PYTHIA, HERWIG) *Υ* production as a function of multiplicity

≻ LHCb

Observation of double charm production involving open charm in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ JHEP 06 (2012) 141 Observation of J/ ψ -pair production in pp collisions at $\sqrt{s}=7 \text{ TeV}$ Phys. Lett. B 707 (2012) 52

Double charm and J/Ψ production agree better with models including double parton scattering (DPS), 2 explicit hard interactions

Where to look for MPI with ALICE?



Underlying event measurements

- Underlying Event measurements in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV with the ALICE experiment at the LHC, JHEP 07 (2012) 116
- \blacktriangleright Toward and Away region dominated by jet fragmentation (number density and summed $p_{\rm T}$)
- > Transverse region dominated by UE activity, low-pT increase due to MPI, saturation independent of hard scale

Multiplicity dependence of two-particle azimuthal correlations

- Multiplicity dependence of two-particle azimuthal correlations in pp collisions at the LHC JHEP 09 (2013) 049 ٠
- Multiplicity dependence of jet-like two-particle correlations in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV arXiv:1406.5463, submitted to PLB
- <*N*_{uncorrelated seeds}> can probe number of MPI
 PYTHIA Perugia 2011 gives the best description of ALICE results
- At high multiplicities deviation from linear scaling
- Similar behavior of $\langle N_{uncorrelated seeds} \rangle$ in p-Pb collisions (no deviation from linear)

Charm production as a function of multiplicity

- *I*/Ψ production as a function of multiplicity in pp and p-Pb collisions J/ψ production as a function of charged particle multiplicity in pp collisions at $\sqrt{s} = 7$ TeV Phys. Lett. B 712 (2012) 3, 165-175
- D-meson production as a function of multiplicity in pp and p-Pb, Paper in preparation ٠
- Non-prompt J/ Ψ as a function of multiplicity in pp collisions, Paper in preparation •

No inclusion of $\langle p_T \rangle$ vs. N_{ch} ; $\lambda/k0$; long range angular correlations (ridge)

The Large Hadron Collider (LHC)



CERN Accelerator Complex



▶ p [proton] ▶ ion ▶ neutrons ▶ p [antiproton] → +→ proton/antiproton conversion ▶ neutrinos ▶ electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine Device LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

LHC 27 km circumference 50 to 175 m underground





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ALICE



ACORDE

EMCal

PMD TOF TRD

Trigger, Centrality determination VZERO

D mesons $D^{0}-> K^{\pi^{+}}$ $D^{+}->K^{\pi^{+}\pi^{+}}$ $D^{*+}-> D^{0}\pi^{+}$ $D_{s}^{+}->\phi\pi^{+}->K^{K^{+}\pi^{+}}$ $|\eta| < 0.9$ ITS: tracking, vertexing TPC: tracking PID TOF: PID

L3 Magnet

PHOS

ITS parah appendin 2p3

HMPID

Absorber Tracking HF decay electrons, J/Ψ Chambers Dipole and non-prompt J/Ψ Magnet D, B, Λ_c , ... -> e + X $J/\Psi \rightarrow e^+e^ B \rightarrow J/\Psi \rightarrow e^+e^-$ |η| < 0.9 **ITS: tracking, vertexing TPC: tracking PID TOF, EMCAL, TRD : e-ID** HF decay muons and J/Ψ D, B, Λ_c , ... -> μ + X **J/Ψ -> μ⁺μ**⁻ -4 < η < -2.5 Muon Spectrometer : trigger and µ -ID

ALICE Particle identification







✓ extremely low-mass tracker e.g. low material budget ✓ particle identification down to $p_{\rm T} \sim 100 \, {\rm MeV}/c$

Where to look for MPI with ALICE?



Charm production as a function of multiplicity

- J/Ψ production as a function of multiplicity in pp and p-Pb collisions
 J/ψ production as a function of charged particle multiplicity in pp collisions at √s = 7 TeV
 Phys. Lett. B 712 (2012) 3, 165–175
- D-meson production as a function of multiplicity in pp and p-Pb
- Non-prompt J/Ψ as a function of multiplicity in pp collisions

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H.



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."



ALICE

The observable

Relative charm production yield as a function of relative charged multiplicity

Charm will be a generic term to refer to quarkonia (J/ Ψ) and open charm (D and non-prompt J/ Ψ) production

$$\frac{dN_{c}/dy}{\langle dN_{c}/dy \rangle}$$

$$\frac{dN_{c}/d\eta}{\langle dN_{ch}/d\eta \rangle}$$

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



➤ <u>x label</u>

Multiplicity estimator: N_{tracklets}





≻ <u>y label</u>

Self-normalized yield in multiplicity intervals relative to multiplicity integrated value



J/Ψ production as a function of multiplicity in pp @ 7 TeV



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J/Ψ production as a function of multiplicity in pp @ 7 TeV





J/Ψ production as a function of multiplicity in pp @ 7 TeV

AT.T-PUB-4210





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



Comparison with the string percolation model

Total multiplicity and number of J/Ψ proportional to elementary initial parton-parton interactions (elementary strings)

Close to a MPI scenario

Reproduce the trend observed in data Caveats : post-diction

J/Ψ production as a function of multiplicity in p-Pb @ 5,02 TeV



Definition of forward and backward rapidity in p-Pb collisions

Muon: forward rapidity p-going direction 2.03 < y < 3.53

Muon: backward rapidity Pb-going direction -4.46 < y < -2.96



J/ Ψ production as a function of multiplicity in p-Pb @ 5,02 TeV







Non-prompt J/Ψ







Approximately linear increase with charged particle multiplicity within uncertainties Deviation from linearity in the highest multiplicity bins

Vertical size of boxes : systematic uncertainties wo feed-down Horizontal size of boxes : systematic uncertainty on $dN/d\eta/\langle dN/d\eta \rangle$ Bottom panels line: relative feed-down systematic uncertainties

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D-mesons in pp collisions at $\sqrt{s} = 7$ TeV



Comparison with PYTHIA 8



D-mesons in pp collisions at $\sqrt{s} = 7$ TeV



Comparison with EPOS

- ✓ Initial conditions:
 marriage of pQCD+ Gribov-Regge Theory + Energy sharing
- ✓ Same framework for pp p-A and A-A collisions
- ✓ Saturation scale
- ✓ Hydro evolution of a dense core

In EPOS Gribov-Regge multiple scattering gives naturally

 $N_{hard} \alpha N_{charged} \alpha N_{elementary interactions}$ N_{hard} = multiplicity of particles produced in hard processes

Comparison with the percolation scenario

- \checkmark High-energy hadronic collisions driven by colour sources exchange btw projectile and target
- ✓ Colour sources with finite spatial extension => interact
- ✓ High-density environment : coherence effect reduces their effective number
- ✓ Transverse size $\alpha 1/m_{\rm T}$, separation of soft and hard with $m_{\rm T}$
- ✓ High densities => soft sources (charged particle mult) reduced
 => hard sources (J/Ψ) less affected due to the smaller transverse mass

Faster-than-linear increase of hard processes production vs. multiplicity



D-mesons in pp collisions at $\sqrt{s} = 7$ TeV





D-mesons (D⁰, D⁺, D^{*+}) in p-Pb collisions at $\sqrt{s} = 5,02$ TeV in central rapidity region ($|y_{lab}| < 0,5$)



- Average D-meson yields show an increase with charged-particle multiplicity
- \blacktriangleright Results in different $p_{\rm T}$ bin are in agreement within uncertainties

Comparing D-mesons in pp and p-Pb collisions





- > pp and p-Pb collisions present similar trends
- Highest multiplicity events in pp collisions mainly due to MPI's
- Highest multiplicity events in p-Pb collisions also originates from higher number of binary collisions

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Comparing D-mesons and J/Ψ in p-Pb collisions



- In p-Pb collisions D and J/Ψ show an increasing trend with multiplicity
- Deviation at highest multiplicity

But:

D-mesons and J/Ψ are measured in different $p_{\rm T}$ and rapidity regions

Leading to different cold nuclear matter (CNM) effects and different Bjorken-x probed values



Comparing D-mesons in pp, p-Pb and Pb-Pb collisions





- At low multiplicity, similar trend in the three systems
- > In Pb-Pb collisions, reflects evolution of N_{coll} with centrality
Comparing with Y in pp, p-Pb and Pb-Pb collisions





- Y measurement from CMS (JHEP 04 (2014) 103) shows increasing trend in pp, p-Pb and Pb-Pb collisions
- Increase up to 8 for average D-mesons and J/Ψ in central rapidity region, comparable to the magnitude of $\Upsilon(1s)$ measured by CMS

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Looking at the future



How to improve our understanding of proton-proton collisions and multi-parton interactions?

More exclusive measurements and higher multiplicities

D More particles vs. mult $(\Psi', \Upsilon, \text{ isolated } \gamma \text{ and jets})$

 \square $p_{\rm T}$ differential study (started with D-mesons)

□ Higher multiplicities and energies in pp (RUN 2 @ 13 TeV)

 Higher multiplicities and energies in heavier systems (p-Pb and Pb-Pb)
 (RUN 2 ~ 8 and 5 TeV)

More on correlations and hadronic activity around heavy-flavor

Underlying Event (UE) event study with charm as trigger particle, "à la Rick Field"

Already discussed by F. Hautmann @MPI2011

III. J/ψ PRODUCTION AND ASSOCIATED JET MULTIPLICITIES

 \triangleright underlying event analysis using gluonic probe [cfr. Z+ jets] \triangleright perturbative calculation down to p_ of order m_ψ





 \triangleright See also: J/ψ vs. charged particle multiplicity $\triangleright J/\psi$ pairs as a probe of DPI [Kom, a

Itiplicity [Portebeuf & Granier, arXiv:1012.0719] [Kom, Kulesza & Stirling, arXiv:1105.4186] [LHCb Coll., LHCb-Conf-2011-009]

All ideas are welcome!

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Conclusions



- ✓ LHC made us enter a new era for the understanding of proton-proton collisions and multi-parton interactions, vital for a full comprehension of pp, pA and AA.
- ✓ The ALICE experiment allows us to study MPI (4 related published papers and several analysis ongoing)
- ✓ <u>Charm production as a function of multiplicity</u>
 - J/Ψ, D-mesons and non-prompt J/Ψ self-normalized yield show an increasing trend with increasing charged-particle multiplicity
 - Suggest presence of MPIs at high multiplicities
 - Trends compatible in pp and p-Pb collisions



A bright future for the understanding of MPI with ALICE during RUN 2



Back-Up

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Where to look for MPI with ALICE?



Underlying event measurements

Underlying Event measurements in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV with the ALICE experiment at the LHC, JHEP 07 (2012) 116

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Underlying event measurement



pp collision description "à la" PYTHIA



Energy scale given by the leading particle (approximation to the original outgoing parton momentum)

Toward: $|\Delta \phi| < \pi/3$

Transverse: $\pi/3 < |\Delta \phi| < 2\pi/3$

Away: $|\Delta \phi| > 2\pi/3$

1 hard scattering on top of underlying event (UE) activity

UE = fragmentation of beam remnants
+ MPI
+ initial and final state radiation (ISR/FSR)



 \sqrt{s} =0.9 and 7 TeV, $p_{\rm T}$ threshold: 0.15, 0.5 and 1 GeV/c

Study of charged particle in the three regions gives insight into the UE behavior

Underlying event measurement $-\Delta \phi$ -correlation





Underlying event measurement – Number density





Average charged particle density vs. leading track transverse momentum $p_{\rm T,LT}$

 $\frac{1}{\Delta\eta\Delta\varphi}\frac{1}{N_{ev}(p_{T},LT)}N_{ch}(p_{T},LT)$

Toward and Away

Monotonic increase with leading p_T regions dominated by jet fragmentation, \uparrow leading p_T : \uparrow hadronic activity

Transverse

Increase interpreted in term of MPI

In PYTHIA: higher p_T biases towards more central collisions (higher MPI probabilities)

Plateau at \sim 4 GeV/*c* : production independent of hard scale

Underlying event measurement – Number density



Comparison of number density in the plateau of the Transverse region (underlying event) And $dN_{ch}/d\eta$ in minimum bias event



UE number density grows logarithmically and faster than MB $dN_{ch}/d\eta$



Where to look for MPI with ALICE?



Multiplicity dependence of two-particle azimuthal correlations

- Multiplicity dependence of two-particle azimuthal correlations in pp collisions at the LHC JHEP 09 (2013) 049
- Multiplicity dependence of jet-like two-particle correlations in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV arXiv:1406.5463, submitted to PLB

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Observables definition

- ✓ Per-trigger pair yield in the combinatorial background $\langle N_{isotrop} \rangle = \frac{1}{N_{trigger}} C$
- ✓ Per-trigger pair yield in the near-side peak

$$\langle N_{\text{assoc, near-side}} \rangle = \frac{\sqrt{2\pi}}{N_{\text{trigger}}} (A_1 \sigma_1 + A_2 \sigma_2)$$

- ✓ Per-trigger pair yield in the away-side peak $\langle N_{\text{assoc, away-side}} \rangle = \frac{\sqrt{2\pi}}{N_{\text{trigger}}} (A_3 \sigma_3)$
- ✓ Average number of trigger particles $\langle N_{\text{trigger}} \rangle = \frac{N_{\text{trigger}}}{N_{\text{events}}}$
- ✓ Average number of uncorrelated seeds $\langle N_{\text{uncorrelated seeds}} \rangle = \frac{\langle N_{\text{trigger}} \rangle}{\langle 1 + N_{\text{assoc near + away } p_{\text{m}} > p_{\text{m}}} \rangle}$



 $N_{\rm trigger}$ sensitive to MPI and parton fragmentation The ratio reduces fragmentation contribution

Number of uncorrelated sources of particles \Rightarrow linked with the number of MPI in the event





- Near-side pair yield grows as a function of multiplicity
- General trend (increase with multiplicity) present in MC
- Away-side pair yield grows as a function of multiplicity
- None of the MC is able to describe nearside and away-side simultaneously





Average number of trigger particles Per-trigger pair yield in the combinatorial background

ALICE

PHOJET

- ALI-PUB-62473
 - Linear increase as a function of multiplicity
 - Well described by the MC

- Deviation from linear increase at high multiplicity
- Both MPI and hadronic activity increase with multiplicity, leading to an increase of particle above a $p_{\rm T}$ threshold, not reproduced by PHOJET

- > $N_{\rm MPI}$ = number of hard or semi-hard scatterings in a single pp collision
- Perugia-0 and Pro-Q20: 2 different tunes with a good description of Tevatron data and LHC predictions Phys. Rev. D 82 (2010) 074018
- > Lead to different probability distributions of $N_{\rm MPI}$
- \succ N_{uncorrelated seeds} directly proportional to N_{MPI}

Average number of uncorrelated seeds

High multiplicity: increase less than linear

 \triangleright

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- Near side yield at same multiplicity bin grows with increasing center of mass energy
- > Splitting between slopes for different \sqrt{s} is larger for PHOJET

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▶ Only a small \sqrt{s} dependence

> At high multiplicities, the number of uncorrelated seeds saturates.

Multiplicity dependence of jet-like two-particle correlations in p-Pb collisions

 Long-range angular correlation subtracted (ridge)

Linear increase (fit in dash-dotted)

No evidence of a saturation in the number of MPI

Similar behavior as in pp collisions

 $\left< \pmb{N}_{cb} \right>^{V0A}$ ($|\eta| < 0.9, \ p_{_{T}} > 0.2 \ {\rm GeV}/c$)

arXiv:1406.5463, submitted to PLB

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Conclusions

- LHC made us enter a new era for the understanding of proton-proton collisions and multi-parton interactions
- The ALICE experiment allows us to study MPI (3 related published papers and several analysis ongoing)

Multiplicity dependence of two-particle azimuthal correlations

- $< N_{uncorrelated seeds} >$ can probe number of MPI PYTHIA Perugia 2011 gives the best description of ALICE results
- At high multiplicities deviation from linear scaling
- Similar behavior of <*N*_{uncorrelated seeds}> in p-Pb collisions (no deviation from linear)
- Charm production as a function of multiplicity
 - \blacktriangleright [/ Ψ , D-mesons and non-prompt]/ Ψ self-normalized yield show an increasing trend with increasing charged-particle multiplicity
 - Suggest presence of MPIs at high multiplicities
 - Trends compatible in pp and p-Pb collisions

Why to compare to PYTHIA?

- > Several possible physics interpretation:
 - MPI,
 - hadronic activity
 - gluon fluctuation in the proton and proton size effect

The model used need to provide the soft part and the hard part of the event in the same computation, an inclusive computation is not enough.
MC well suited

> The hard part should contain heavy quarks: PYTHIA, Cascade.

> Even if we know PYTHIA is not intended for J/Ψ study: a good start and a reference in MC world!

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How to produce heavy states in Pythia8?

In the 2->2 first hard sub-process: hard production

✤ In the 2->2 hard sub-processes of MPI: hard production

Same production mechanisms

Complement the contribution from first hard sub-process

Beam remnant treatment

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How to produce heavy states in Pythia8?

Gluon splitting (g->QQbar, gluons originated from ISR/FSR)

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C/b C/b Any hard 2->2 sub-process (gg->gg for example) Partons, connected to strings

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

String fragmentation

cc 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 in PYTHIA6.4

In PYTHIA8 : cc->J/ Ψ , with c and c originating from various sources, no explicit cluster state

A MB event can still produce J/Ψ and D mesons via gluon splitting and string fragmentation

cc pair production suppressed as compared to u, d ,s, but available

D-mesons in pp collisions at $\sqrt{s} = 7$ 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

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D-mesons (D⁰, D⁺, D^{*+}) in p-Pb collisions at $\sqrt{s} = 5,02$ TeV in central rapidity region ($|y_{lab}| < 0,5$)

D⁺-meson yields show an increase with charged-particle multiplicity compatible within p_T bins
 D⁰, D⁺ and D^{*+}-meson yields show an increase with charged-particle multiplicity

D⁰, D⁺ and D^{*+}-meson yields are consistent with each other within uncertainties

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LHC schedule after LS1

approved by CERN management, LHC experiments spokespersons and technical coordinators Monday 2nd December 2013

LHC Run I

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Nuclear collisions at the LHC!

two successful Pb-Pb runs already

- 2010 → ~10/μb
- 2011 → ~150/μb
- - 2013 → ~ 30/nb

some numbers (2011 Pb-Pb run):

- ~ 1.2 10⁸ ions/bunch
- 358 bunches
 - 200 ns basic spacing
- β* = 1 m
- L ~ 5 10²⁶ cm⁻²s⁻¹
- \rightarrow ~ 4000 Hz interaction rate

Slide from F. Antinori – EMMI Workshop – LBNL – 20 November 2013

Recent results from pp collisions @ \sqrt{s} = 7 TeV HF cross sections

D mesons

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pp: the baseline for heavy ion study, reference measurement, test of pQCD

Heavy-flavour decay electrons Heavy-flavour decay muon

pQCD-based calculations compatible with data

FONLL: JHEP 1210 (2012) 137; GM-VFNS: Eur. Phys. J. C 72 (2012) 2082

Recent results from pp collisions @ \sqrt{s} = 2.76 TeV HF cross sections

pp: the baseline for heavy ion study, reference measurement, test of pQCD

Heavy-flavour decay electronsHeavy-flavour decay muons **D** mesons JHEP 1207 (2012) 191 Phys. Rev. Lett. 109 (2012) 112301 10 $\frac{1}{2} \left(2\pi p_{T} \right) d^{2}\sigma/dp_{T} dy (mb/(GeV/c)^{2}) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} - 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left(2\pi p_{T} - 2\pi p_{T} + 2\pi p_{T} \right) = \frac{1}{2} \left($ (hb/GeV/c) (pb/0.5 GeV/c) ALICE ALICE pp √s=2.76 TeV, µ±←HF in 2.5<y<4 10⁸ D^{0} , pp \s = 2.76 TeV, L_{int} = 1.1 nb⁻¹ FONLL data 10² ALICE, $(b+c) \rightarrow e$ $\mu^{\pm} \leftarrow HF$, FONLL 10 u[±]←charm, FONLL $d\sigma / dp_t |_{y|<0.5}$ (10⁶ 10) 10[°] dp/_{∃H→}10⁵ 10⁴ μ[±]←beauty, FONLL ALIC PRELIMINARY 10⁻¹ svst. und 10^{3} FONLL pp $s = 2.76 \text{ TeV}, |\eta| < 0.7, L_{int} = 11.9 \text{ nb}^{-1}$ 1.9% lumi, ± 1.3% BB norm, unc. (not show) $L_{int}=19 \text{ nb}^{-1}$ 10 10² Additional 1.9% normalization uncertainty 1.9% normalization uncertainty not included Theory Data/FONLL 0 T N S 2.5 2 1.5 data/FONLL Data / GM-VFNS Data 0.5 2 6 8 10 12 10 12 p_{_} (GeV/c) 8 p, (GeV/c) p (GeV/c) ALI-PREL-33002 ALI-PUB-16725

pQCD-based calculations compatible with data FONLL: JHEP 1210 (2012) 137; GM-VFNS: Eur. Phys. J. C 72 (2012) 2082

HF muon data used as reference for Pb-Pb at the same energy

For other channels, a scaling based on pQCD calculations is used arXiv:1107.3243

Recent results from p-Pb collisions @ $\sqrt{s_{\rm NN}}$ = 5.02 TeV Nuclear modification factor ($R_{\rm pPb}$)

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D mesons

(Shadowing)

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Nucl. Phys. B 373 (1992) 295 + JHEP 0904 (2009) 065

Phys. Rev. Lett. 109 (2012) 24301

$$R_{\rm pPb} = \frac{dN_{\rm pPb}/dp_{\rm T}}{\times dN_{\rm pp}/dp_{\rm T}} = \frac{dN_{\rm pPb}/dp_{\rm T}}{\times d\sigma_{\rm pp}/dp_{\rm T}}$$

Recent results from Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV HF decay electrons & muons nuclear modification factor (R_{AA}) =

LI-DER-36791

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- Clear suppression observed for $3(4) < p_T < 18(10)$ GeV/*c* for the most central collisions Final state effects: HF decay e R_{pPb} compatible with unity (cf. S.9)
- Similar suppression at central (electrons) and forward (muons) rapidity

$$R_{\rm AA} = \frac{\mathrm{d}N_{\rm AA}/\mathrm{d}p_{\rm T}}{< N_{\rm coll} > \times \mathrm{d}N_{\rm pp}/\mathrm{d}p_{\rm T}} = \frac{\mathrm{d}N_{\rm AA}/\mathrm{d}p_{\rm T}}{< T_{\rm AA} > \times \mathrm{d}\sigma_{\rm pp}/\mathrm{d}p_{\rm T}}$$

Muons results: Phys. Rev. Lett. 109 (2012) 112301

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Recent results from Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV D meson nuclear modification factor (R_{AA})

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as a function of $p_{\rm T}$

$$R_{\rm AA} = \frac{dN_{\rm AA}/dp_{\rm T}}{\langle N_{\rm coll} \rangle \times dN_{\rm pp}/dp_{\rm T}} = \frac{dN_{\rm AA}/dp_{\rm T}}{\langle T_{\rm AA} \rangle \times d\sigma_{\rm pp}/dp_{\rm T}}$$

- Suppression up to a factor of 5 at $p_{\rm T} \sim 10$ GeV/*c* for 0-7.5% central collisions. Hot medium effect: D $R_{\rm pPb}$ measurement compatible with unity (cf. S.9)
- R_{AA} (D) ~ R_{AA} (charged π) 0.6 within large uncertainties 0.4 Not trivially linked to $\Delta E(g)$ and $\Delta E(c)$: different fragmentation, spectral shape, bulk 2 properties arXiv:1307.4702

Recent results from Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV D meson nuclear modification factor (R_{AA})

as a function of N_{part}

 $R_{\rm AA} = \frac{\mathrm{d}N_{\rm AA}/\mathrm{d}p_{\rm T}}{\langle N_{\rm coll} \rangle \times \mathrm{d}N_{\rm pp}/\mathrm{d}p_{\rm T}} = \frac{\mathrm{d}N_{\rm AA}/\mathrm{d}p_{\rm T}}{\langle T_{\rm AA} \rangle \times \mathrm{d}\sigma_{\rm pp}/\mathrm{d}p_{\rm T}}$

• Smaller suppression in peripheral than in central collisions at high- $p_{\rm T}$ for D mesons

 Indication of a larger suppression for charm than for beauty Supported by predictions from energy-loss models for R_{AA} D and non-prompt J/Ψ
 => Hint of the quark-mass dependence of energy loss: ΔE(c) > ΔE (b)

> J. Phys. G 38 (2011) 124152; J. Phys. G 38 (2011) 124114; Phys. Rev. C 80 (2009) 054902

Recent results from Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV Azimuthal anisotropy (v_2)

D mesons

HF decay electrons and muons

Recent results from Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV D R_{AA} and v_2 : comparison with models



A global picture of QGP from the D mesons



Low $p_{\rm T}$ D mesons thermalized in the formed medium and acquire properties of the expanding bulk

Simultaneous description of R_{AA} and v_2 gives insight on quark transport coefficients of the medium

Still a challenge for models

Only models with predictions for both RAA and v2 are shown

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J. Phys.G38 (2011) 124064, Eur. Phys J. C 71 (2011) 1666; arXiv:1308.0617; Phys. Rev. C 79 (2009) 044906; arXiv:1112.1559; arXiv:1204.4442; arXiv:1204.4442