CMS Experiment at LHC, CERN
Data recorded: Thu Sep 13 05:21:23 2012 CEST
Run/Event: 202792 / 1737666483
Lumi section: 918
Orbit/Crossing: 240400935 / 1986

Jet effects in high multiplicity pp events: CR vs hydro

Guy Paić, Eleazar Cuautle, Gyula Bencedi and A. Ortiz

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WIGNER

January 19, 2016

Outline

- Introduction
- Tools
- Particle production as a function of the event multiplicity and hardness
- Energy dependence
- Summary

INTRODUCTION

Introduction

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- Small systems (like those produced in pp and p-Pb collisions) have attracted the attention of the heavy-ion community because:
  - In high multiplicity events, sQGP-like signatures have been found (flow & long range azimuthal correlations)
  - The origin of such effects is still unknown
  - More differential studies are needed

Introduction

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A hydro-inspired model (Blast-Wave):

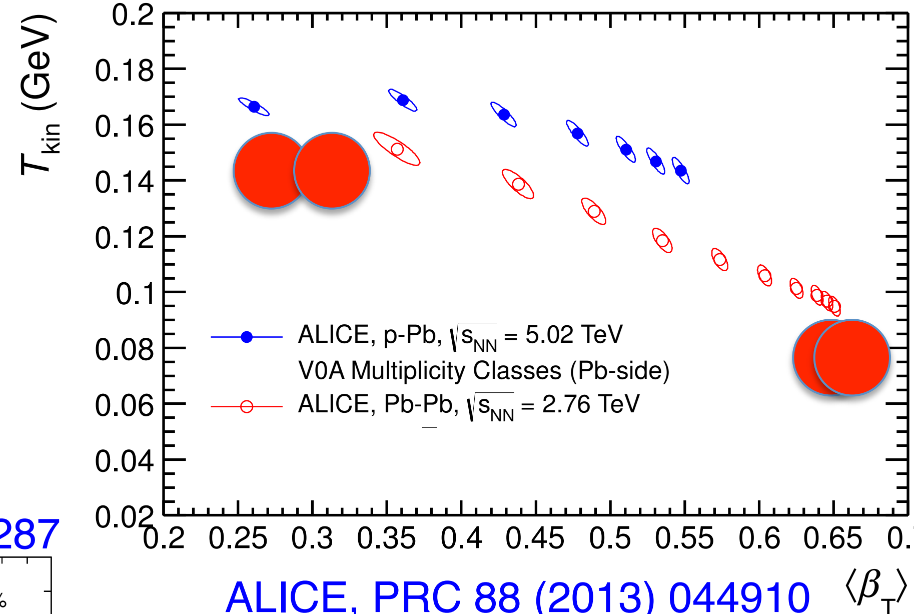
$$\frac{1}{p_{\rm T}}\frac{{\rm d}N}{{\rm d}p_{\rm T}} \propto \int_0^R r\,{\rm d}r\,m_{\rm T} I_0\left(\frac{p_{\rm T}\sinh\rho}{T_{\rm kin}}\right) K_1\left(\frac{m_{\rm T}\cosh\rho}{T_{\rm kin}}\right)$$

$$\rho = \tanh^{-1}\beta_{\rm T} = \tanh^{-1}\left(\left(\frac{r}{R}\right)^n \beta_{\rm S}\right)$$

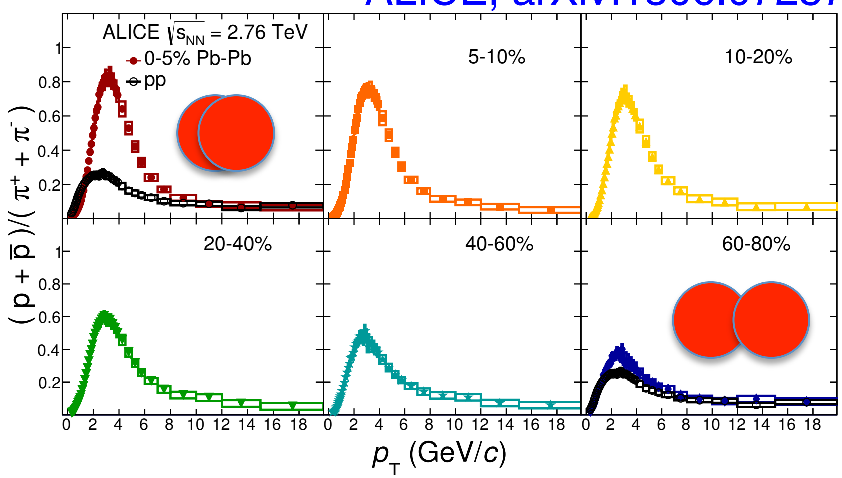
Describes the $p_{\rm T}$ spectra of identified hadrons in:

- p-Pb and Pb-Pb data

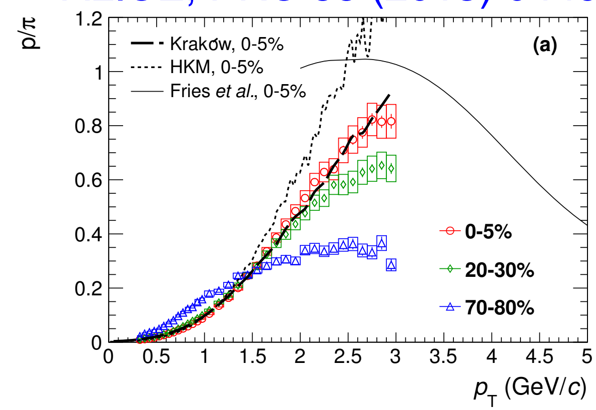
ALICE, PLB 728 (2014) 25-38



ALICE, arXiv:1506.07287



ALICE, PRC 88 (2013) 044910



Introduction

A hydro-inspired model (Blast-Wave):

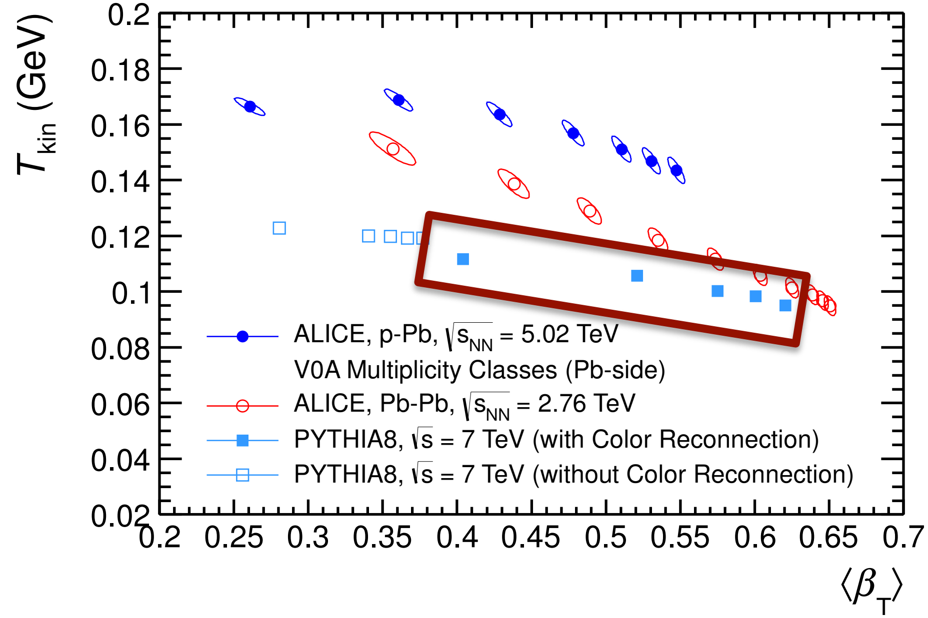
$$\frac{1}{p_{\mathrm{T}}}\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}} \propto \int_0^R r\,\mathrm{d}r\, m_{\mathrm{T}} I_0\left(\frac{p_{\mathrm{T}}\sinh\rho}{T_{\mathrm{kin}}}\right) K_1\left(\frac{m_{\mathrm{T}}\cosh\rho}{T_{\mathrm{kin}}}\right)$$

$$\rho = \tanh^{-1}\beta_{\mathrm{T}} = \tanh^{-1}\left(\left(\frac{r}{R}\right)^n \beta_{\mathrm{S}}\right)$$

Describes the p_{T} spectra of identified hadrons in:

- p-Pb and Pb-Pb data
- Also the p_{T} distributions generated with Pythia (where no hydrodynamical evolution is assumed)

ALICE, PLB 728 (2014) 25-38



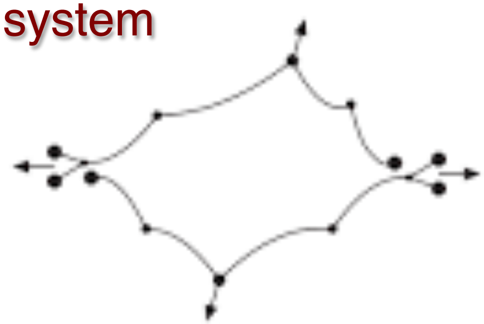
- It has been discussed that color reconnection (CR) produces radial flow-like patters due to boosted strings

G. Paić, E. Cuautle, P. Christiansen, I. Maldonado and A. O., PRL 111 (2013) 042001

Introduction

- Figure taken from: G. Gustafson, Acta Phys. Polon. B40, 1981 (2009)

1st partonic system



Introduction

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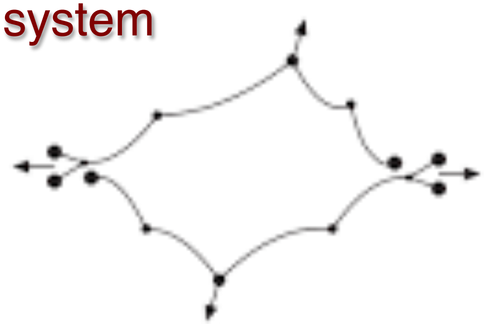
1st partonic system



+2nd partonic system

Introduction

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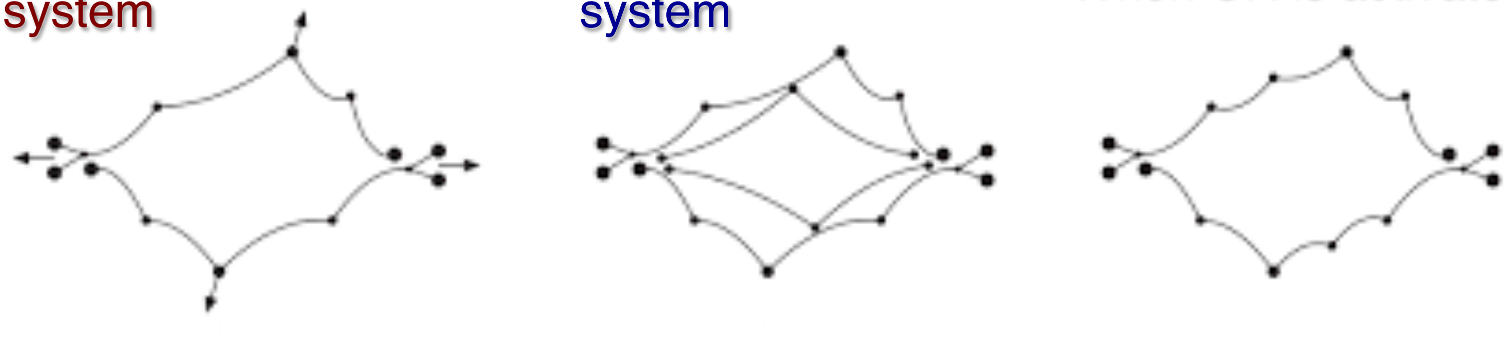
- Figure taken from: G. Gustafson, Acta Phys. Polon. B40, 1981 (2009)

1st partonic system

+2nd partonic system

When CR is activated



Introduction

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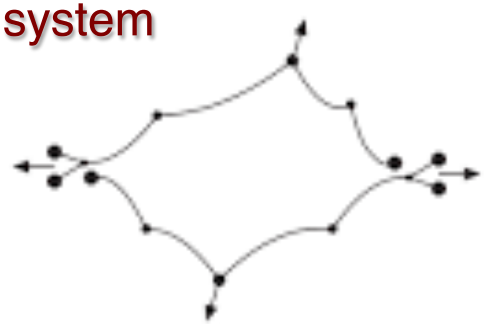
- Figure taken from: G. Gustafson, Acta Phys. Polon. B40, 1981 (2009)

1st partonic system



+2nd partonic system

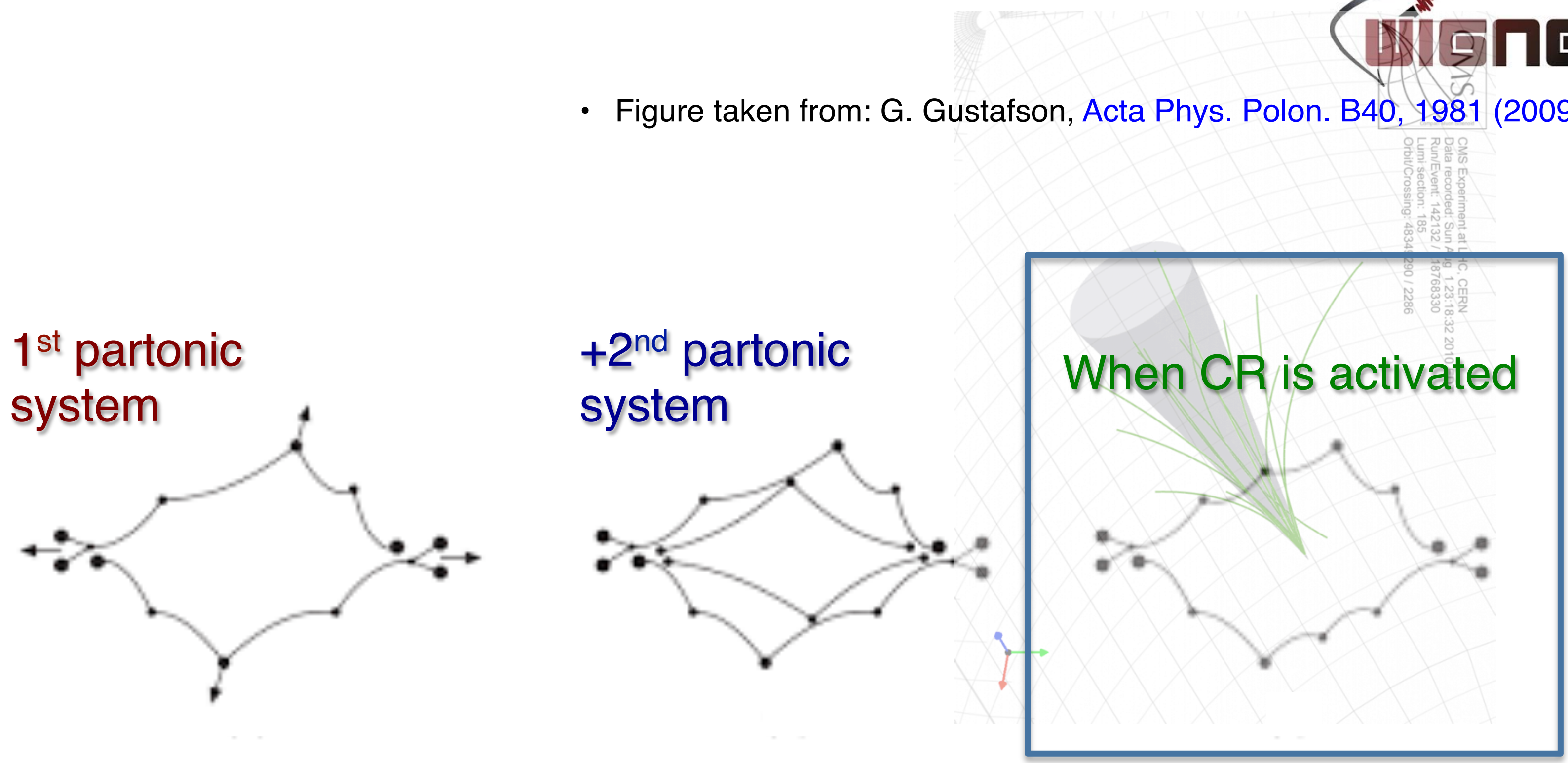
When CR is activated

This was the focus of this work: PRL 111 (2013) 042001

- ❑ The more N_{MPI} the higher the flow-like effect

Introduction

- Figure taken from: G. Gustafson, Acta Phys. Polon. B40, 1981 (2009)



Due to the large N_{MPI} a high p_T jet in the event is expected (high probability):

- ❑ Can we quantify the effects of the high p_T jets?
- ❑ I would expect a higher boost with increasing the parton p_T

Introduction

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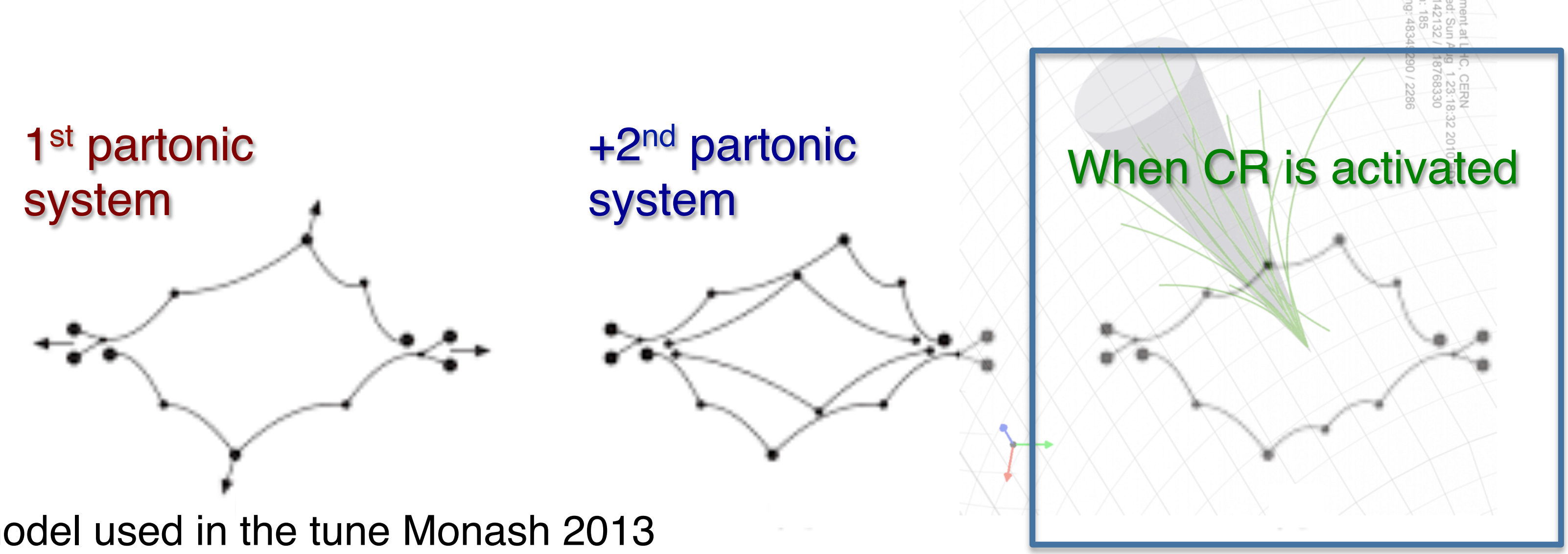
- Figure taken from: G. Gustafson, Acta Phys. Polon. B40, 1981 (2009)
- Effects of CR on hadron flavor observables, C. Bierlich and J. R. Christiansen, PRD 92 (2015) 9, 094010



In the CR model used in the tune Monash 2013 (Mo2013), an MPI system with a scale p_T of the hard interaction (normally $2 \to 2$) can be merged with one of a harder scale with a probability that is:

$$P(p_{\mathrm{T}}) = \frac{(RR \times p_{\mathrm{T0}})^2}{(RR \times p_{\mathrm{T0}})^2 + p_{\mathrm{T}}^2}$$

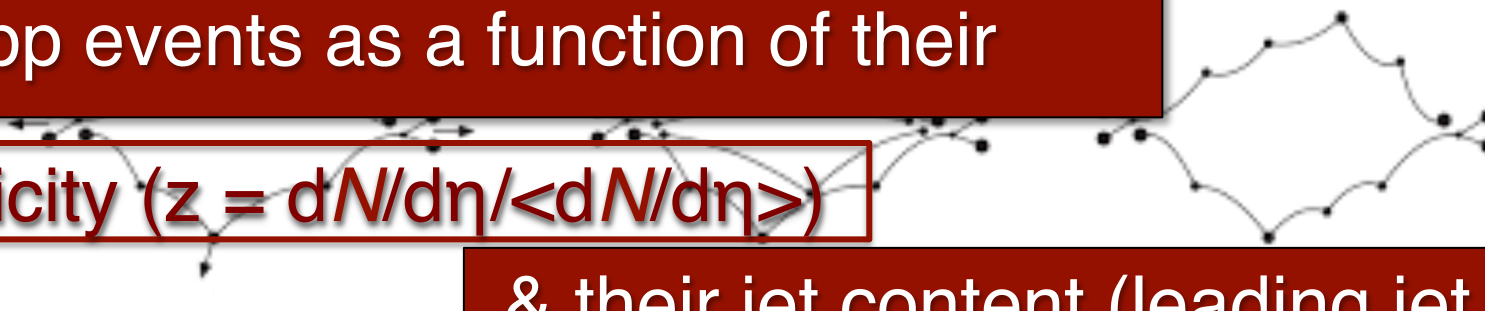
Reconnection Range (*RR*): 0-10
Tune Monash 2013: $RR \mathrm{x} p_{T0} \approx 3$

http://home.thep.lu.se/~torbjorn/pythia82html/Welcome.html

Introduction

- Figure taken from: G. Gustafson, Acta Phys. Polon. B40, 1981 (2009)
- Effects of CR on hadron flavor observables, C. Bierlich and J. R. Christiansen, PRD 92 (2015) 9, 094010

n CR is activated



This work: study the properties of the pp events as a function of their

multiplicity ($z = dN/d\eta/\langle dN/d\eta \rangle$)

& their jet content (leading jet p_T)

Tools

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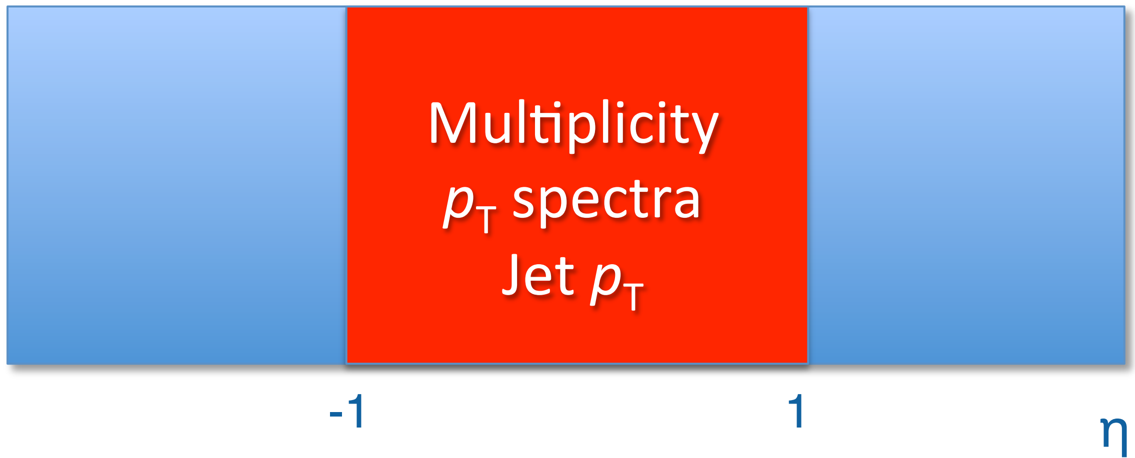
- Generator: **Pythia 8.212**, T. Sjöstrand et. al, CPC191 (2005) 159
  - Tune Monash 2013, P. Skands, EPJC74 (2014) 8, 3024
  - 900M events
- Generator **EPOS 3.117**, K. Werner et al., PRC89 (2014) 6, 064903; K. Werner et al., PRC 82 (2010) 044904; H.J. Drescher et al., PR 350 (2001) 93-289
  - 1000M events
- Jet Finder: **FastJet 3.1.3**, M. Cacciari et al., EPJC72(2012)1896
  - Anti-k_T algorithm
  - R=0.4
  - p_T^{min} = 5 GeV
  - Visible particles (Pythia definition) are considered for the jet reconstruction

We thank Klaus for providing the code and for the useful discussion

INCLUSIVE PARTICLE PRODUCTION AS A FUNCTION OF THE EVENT MULTIPLICITY AND HARDNESS



* The underlying event contribution to the jet p_T was not studied, because we are only interested in the event classification

INCLUSIVE PARTICLE PRODUCTION AS A FUNCTION OF THE EVENT MULTIPLICITY AND HARDNESS

p_T^{jet} vs. multiplicity

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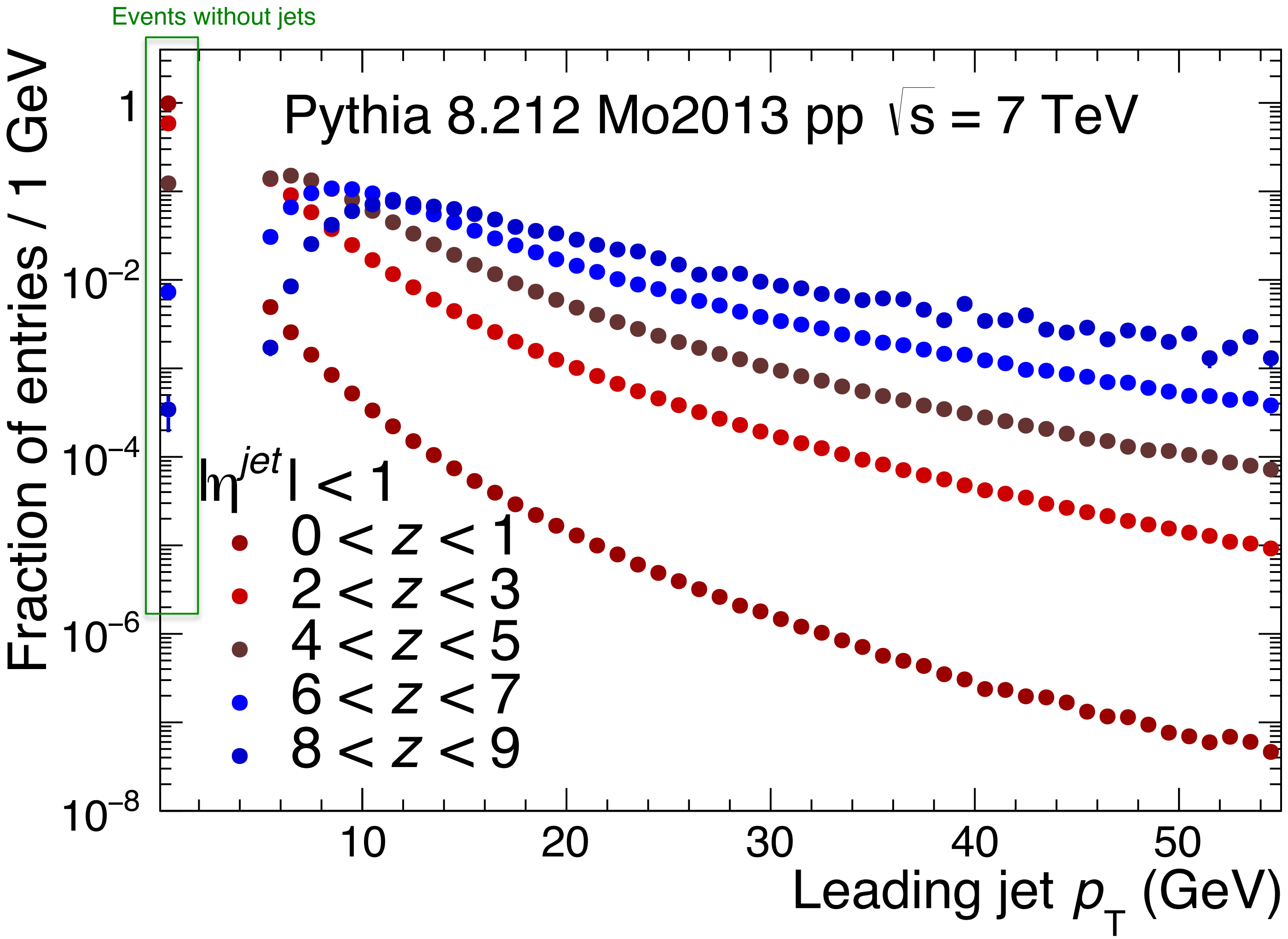

$\langle z \rangle$	$\langle p_T^{jet} \rangle$ (GeV/c)
0.5	7.09
1.5	7.49
2.5	7.83
3.5	8.48
4.5	9.55
5.5	11.1
6.5	13.2
7.5	15.85

The higher the event multiplicity the higher the average p_T^{jet}

p/π vs. p_T (low multiplicity)

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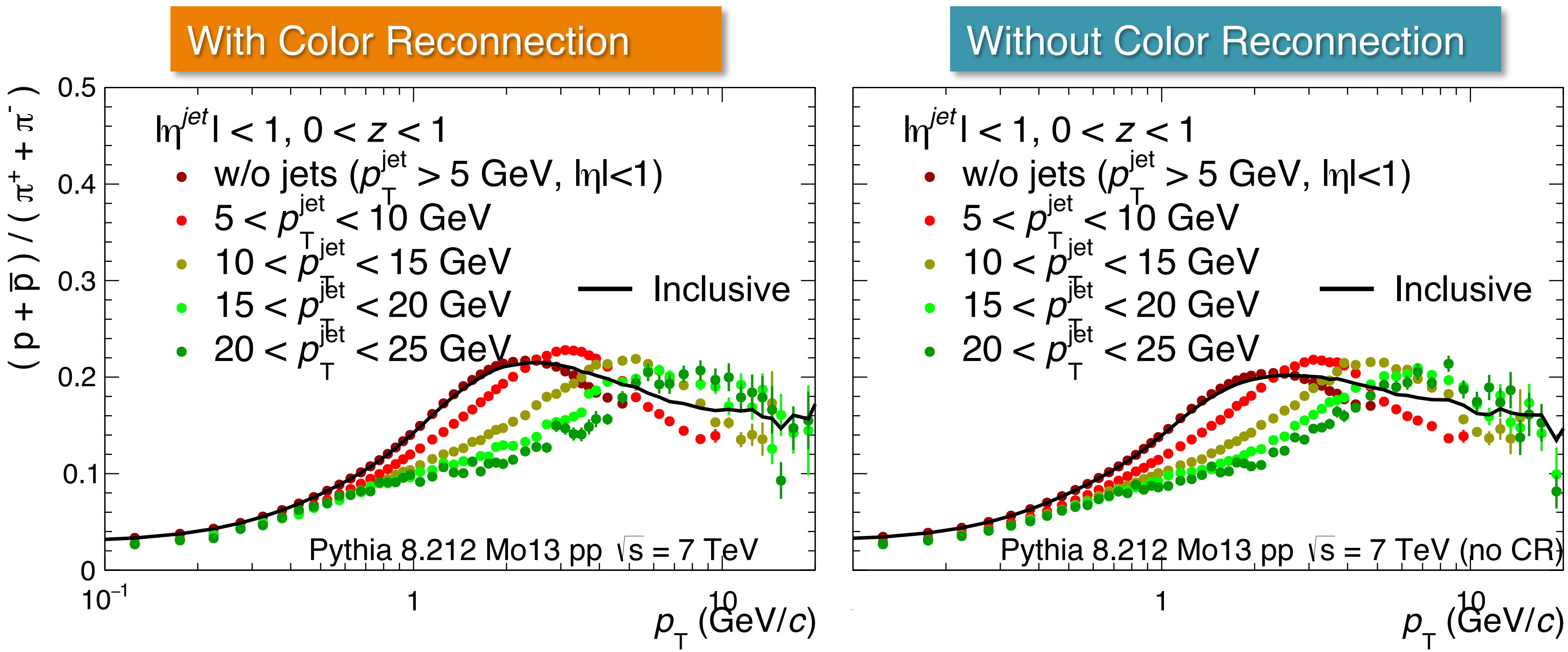
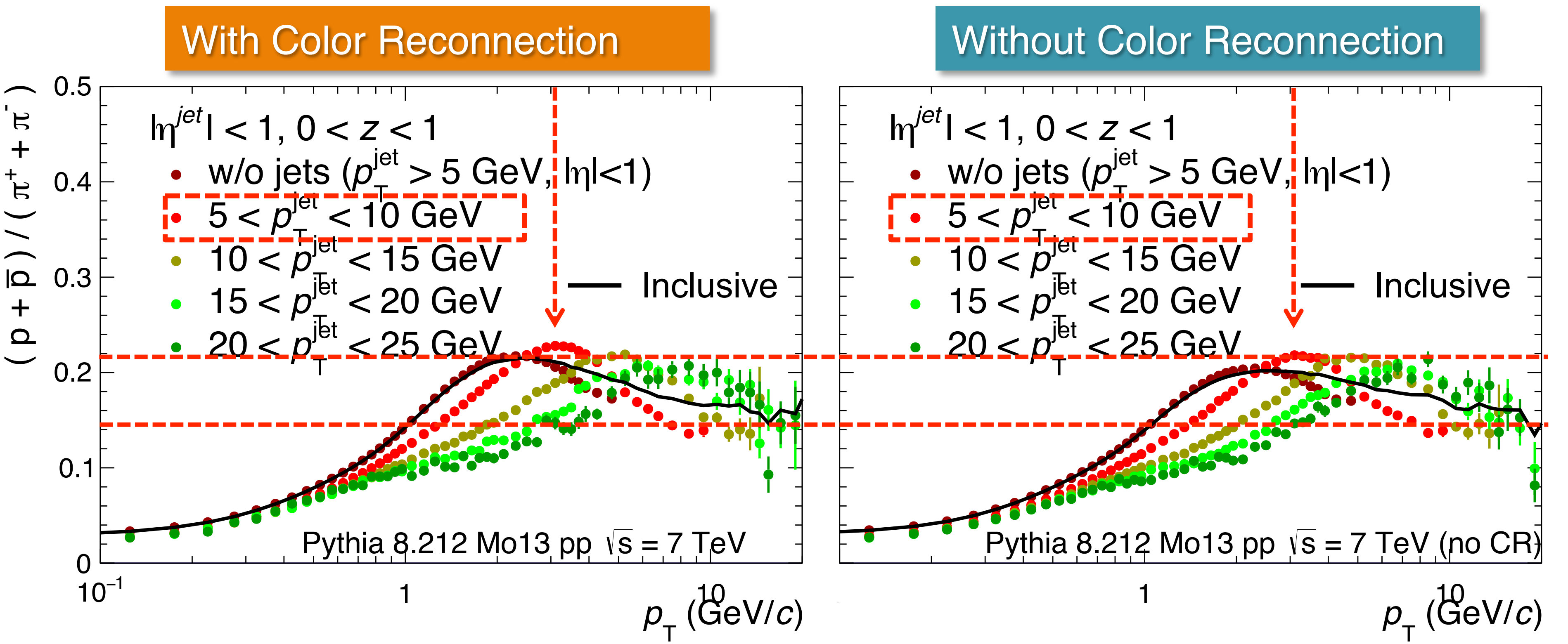


p/π vs. p_T (low multiplicity)



- CR effects are observer for $p_T^{jet} < 10$ GeV

p/π vs. p_T (low multiplicity)

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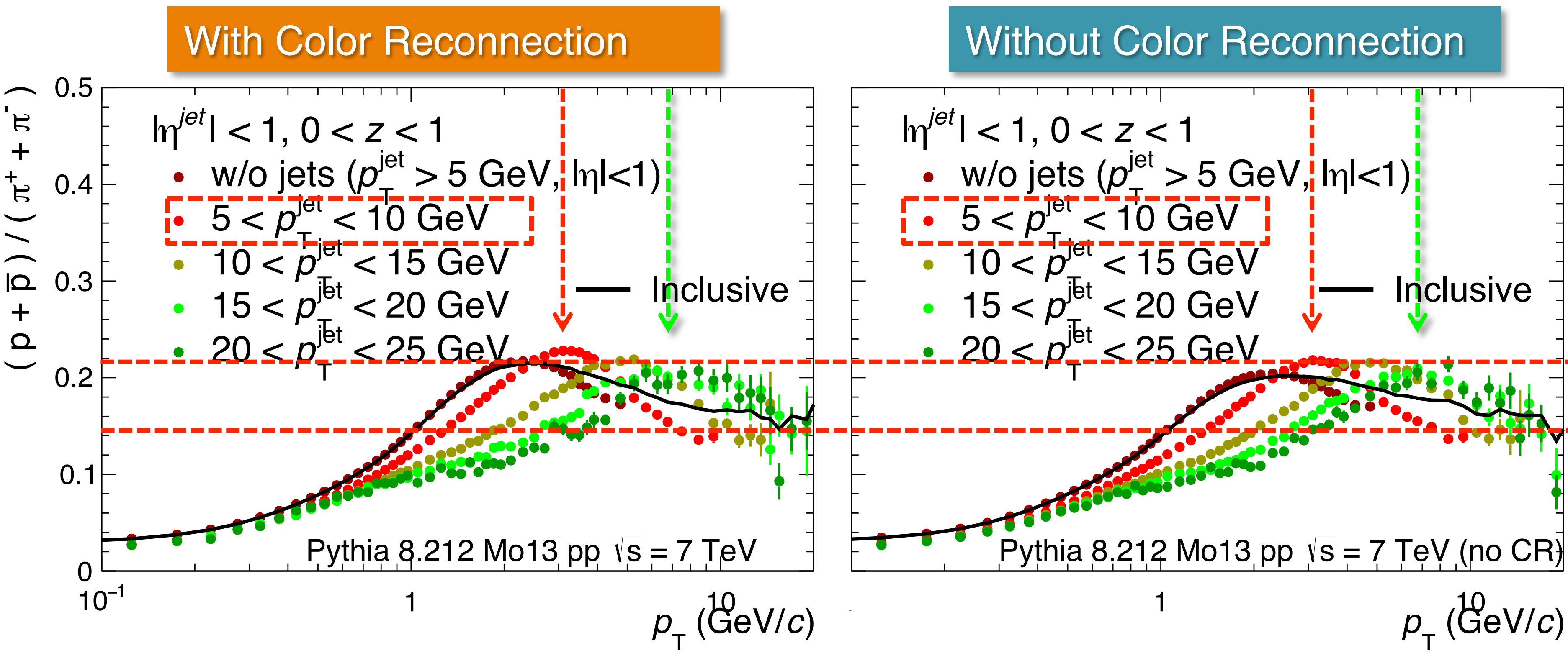

- CR effects are observer for p_T^{jet} < 10 GeV
- The position of the peak is shifted to higher p_T when p_T^{jet} increases. The shift is accompanied by an increase of $<\beta_T>$

p/π vs. p_T (low multiplicity)

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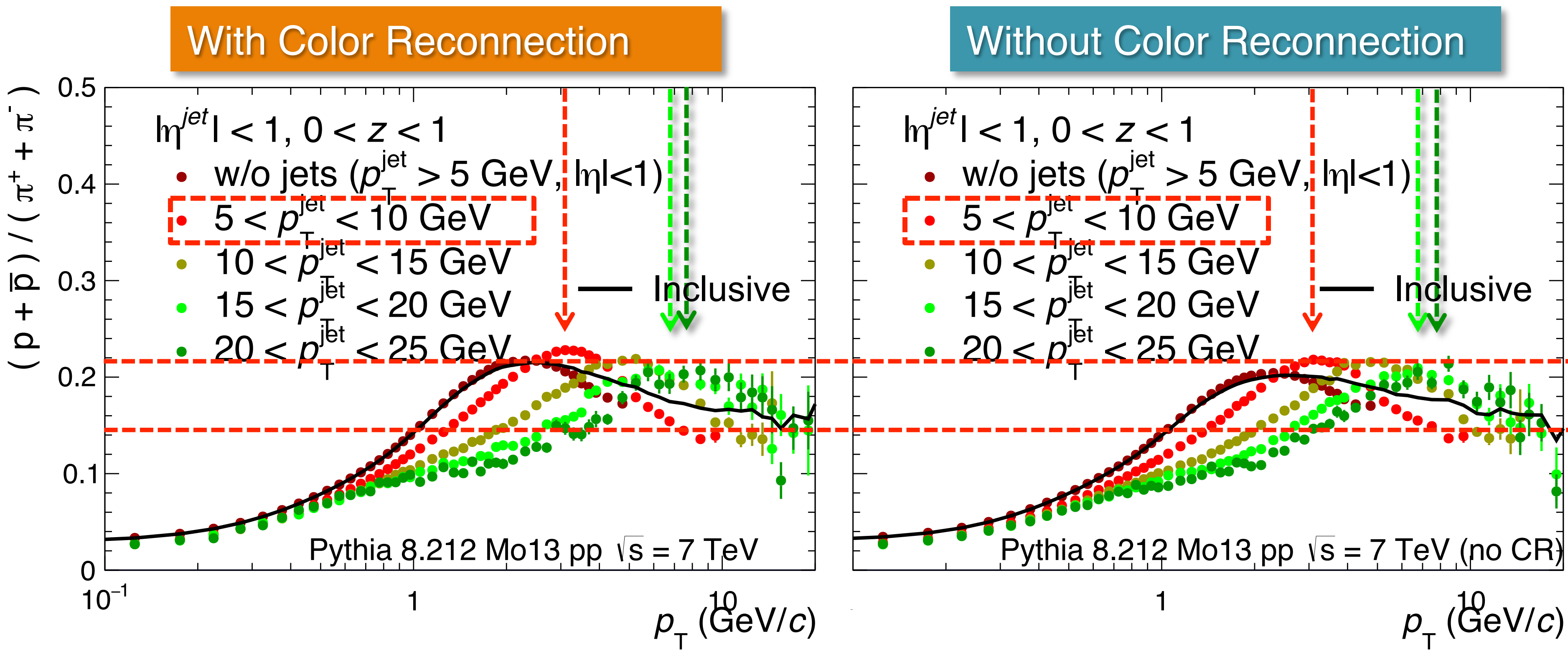
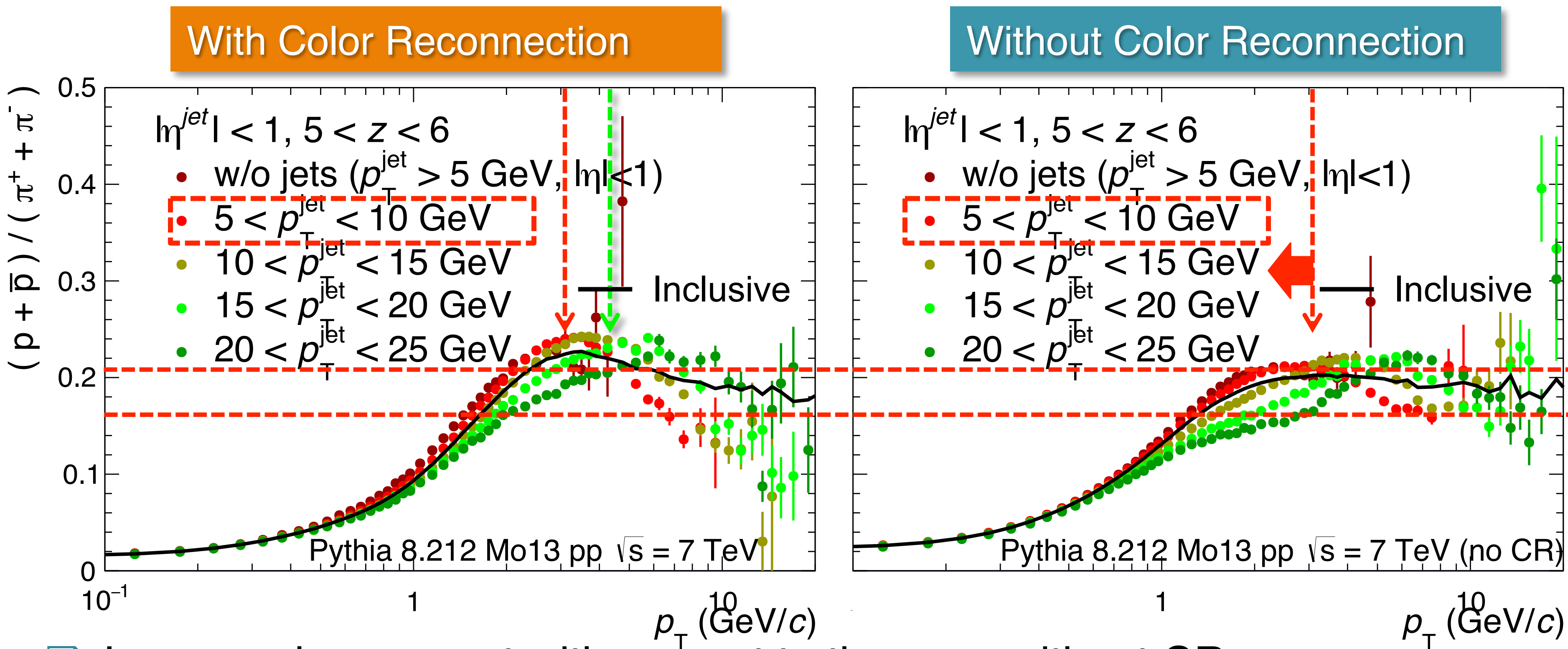


- CR effects are observer for $p_T^{jet} < 10$ GeV
- The position of the peak is shifted to higher p_T when p_T^{jet} increases. The shift is accompanied by an increase of $<\beta_T>$ (from Blast-Wave analysis)
  - The effect is very small for $p_T^{jet} > 15$ GeV

p/π vs. p_T (high multiplicity)



- Larger enhancement with respect to the case without CR
- With CR, jet effects (peak position) are smaller than in the low N_{ch} case
  - Dominated by underlying event

Study of the inclusive light flavored hadron production

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Results from the Blast-Wave analysis are presented, for this a simultaneous fit of the BW function to the the p_T spectra is performed in order to extract $<\beta_T>$. The fitting ranges are the following:

π	K	K^0_S	p	φ	Λ	Ξ	Ω
0.5-1.0	0.3-1.5	0.3-1.5	0.8-2.0	0.8-2.0	1.0-2.1	1.2-2.6	1.3-2.8

p_T ranges (GeV/c)

(Same p_T ranges as in: G. Paić, E. Cuautle and A. O. NPA 941 (2015) 78-86, where the p_T spectra in high multiplicity events were described by BW model within 10%)

Analysis vs. N_{ch}

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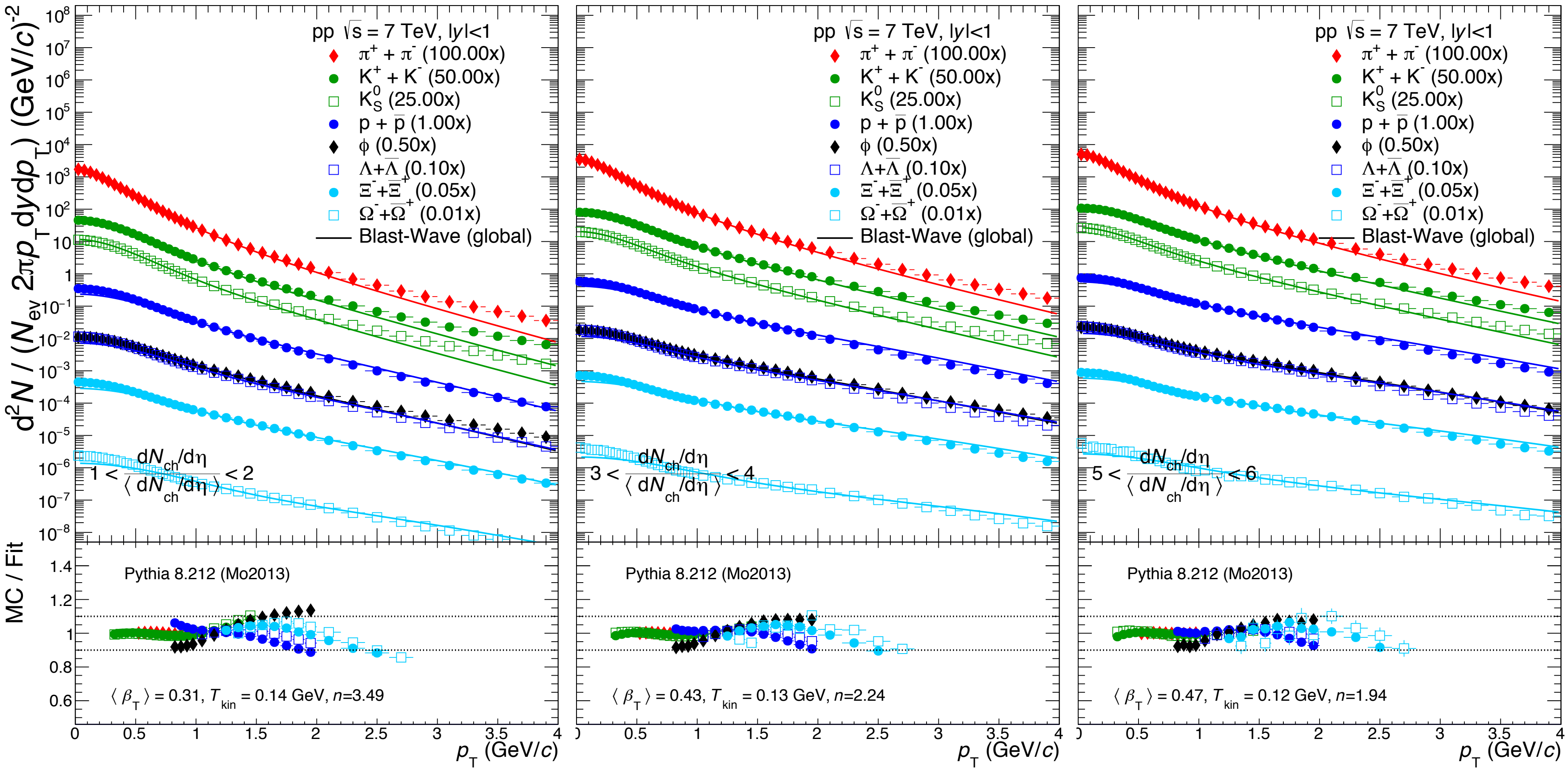

Analysis vs. N_{ch}

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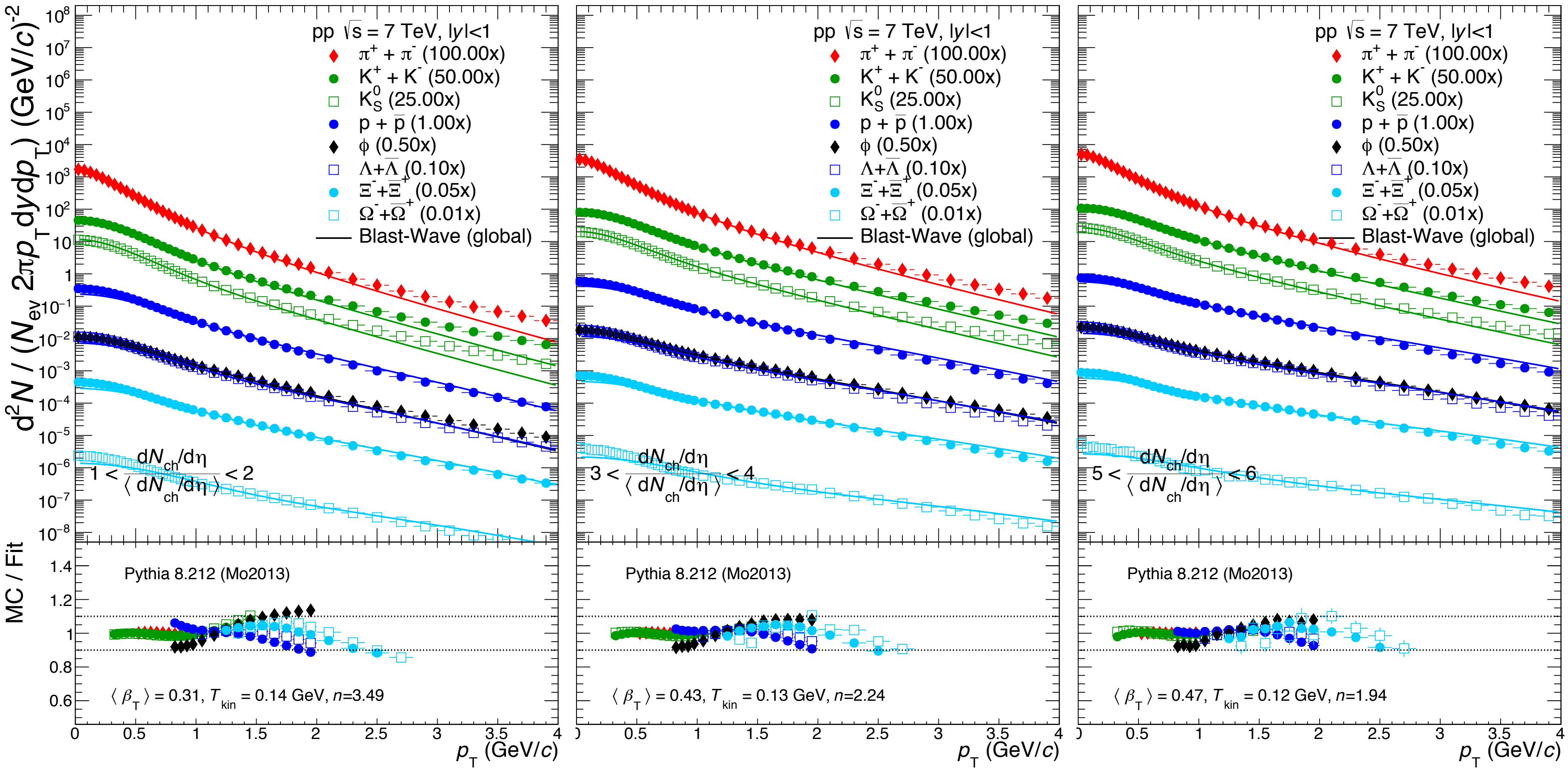
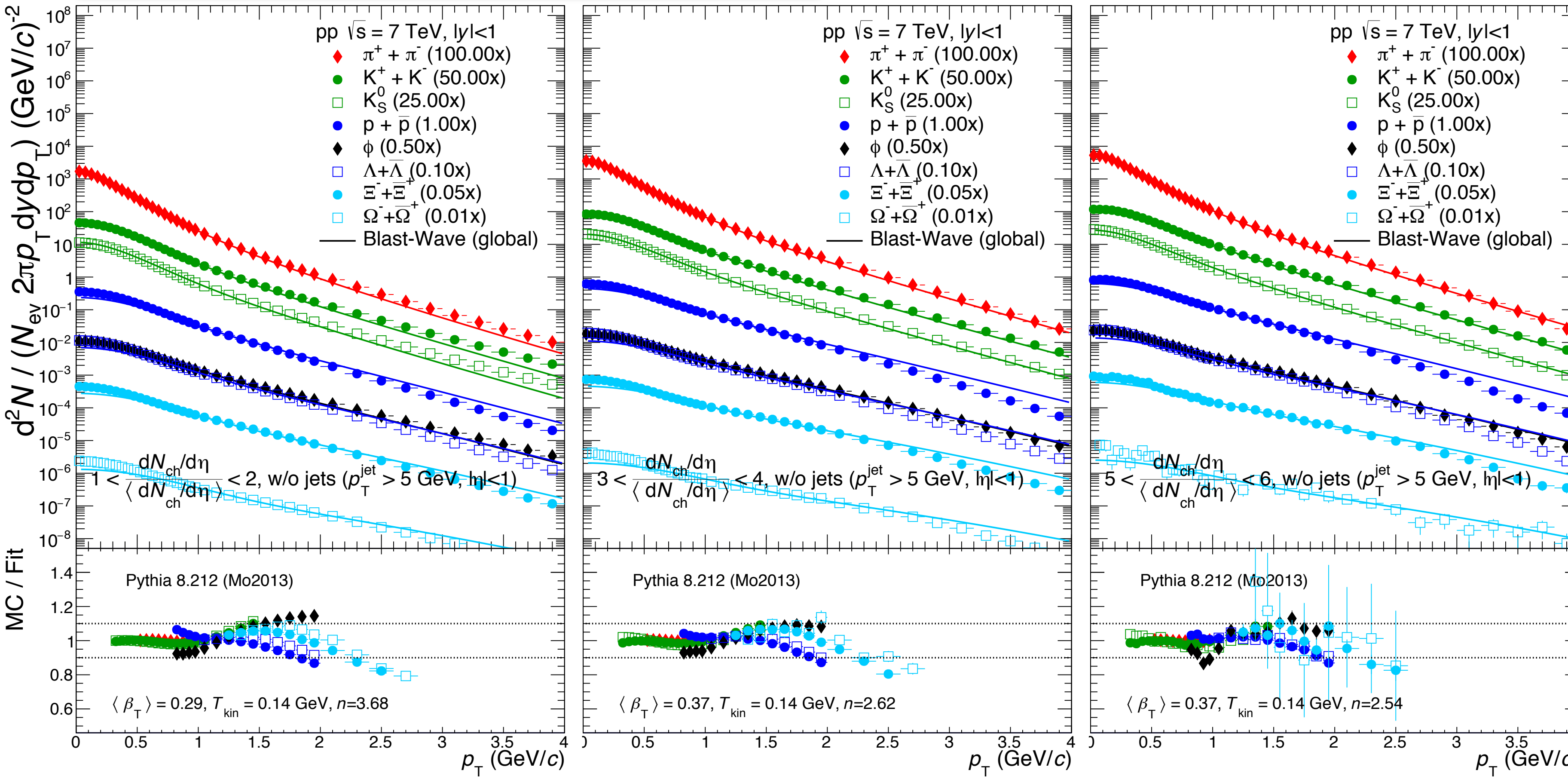


$\langle N_{ch} \rangle_{|\eta|<1} \approx 16.73$ $\langle N_{ch} \rangle_{|\eta|<1} \approx 38.52$ $\langle N_{ch} \rangle_{|\eta|<1} \approx 60.08$

Without Jets

$<\beta_T>\approx 0.34$, $<T_{kin}>\approx 0.14$, $<n> \approx 2.94$



$<N_{ch}>_{|\eta|<1} \approx 16.23$ $<N_{ch}>_{|\eta|<1} \approx 38.02$ $<N_{ch}>_{|\eta|<1} \approx 59.58$

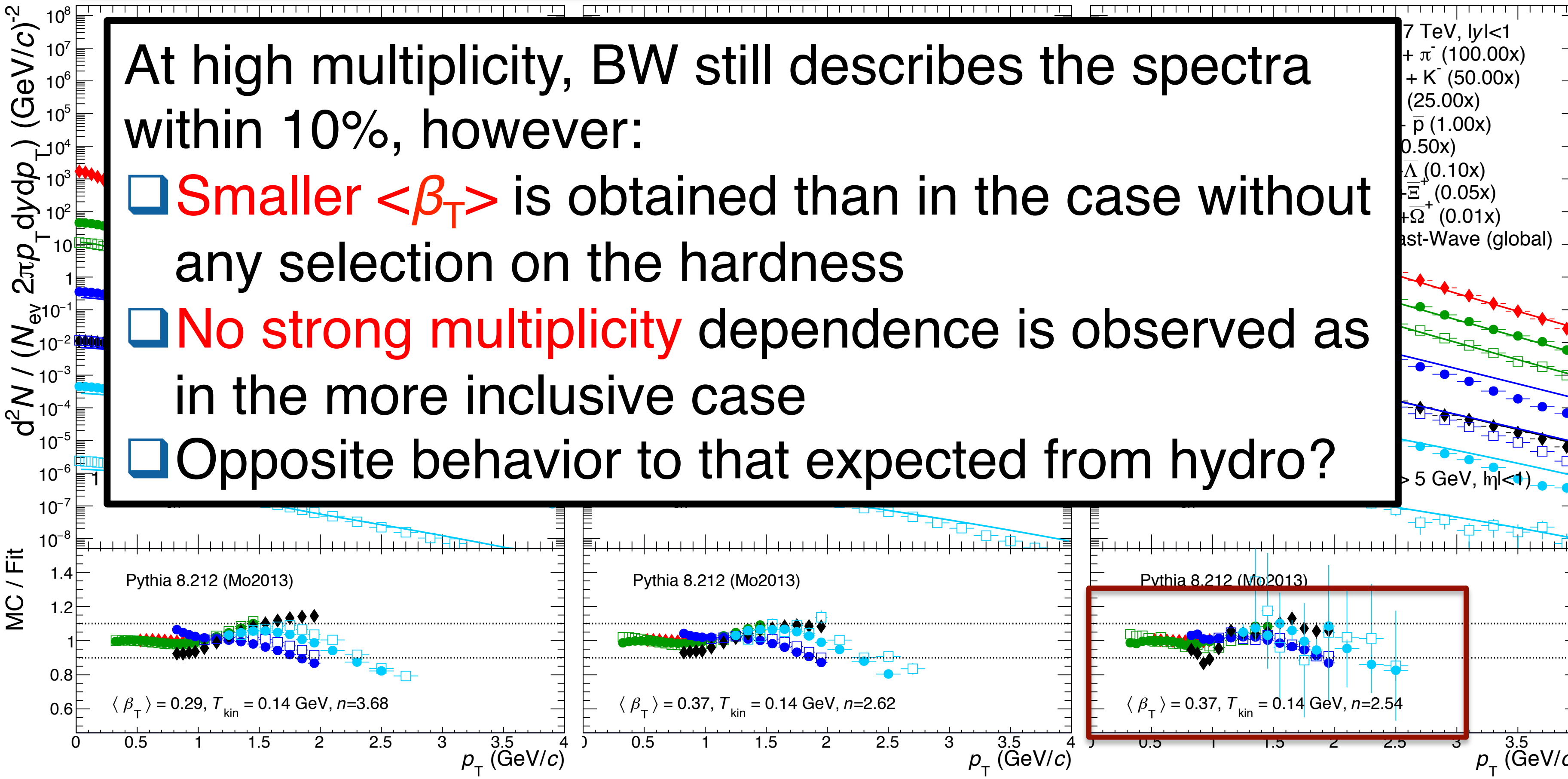
Quality of the fit is slightly worst & smaller $<\beta_T>$ reach

Without Jets

$\langle\beta_T\rangle \approx 0.34$, $\langle T_{kin}\rangle \approx 0.14$, $\langle n\rangle \approx 2.94$

At high multiplicity, BW still describes the spectra within 10%, however:

- Smaller $\langle\beta_T\rangle$ is obtained than in the case without any selection on the hardness
- No strong multiplicity dependence is observed as in the more inclusive case
- Opposite behavior to that expected from hydro?



$\langle N_{ch}\rangle_{|\eta|<1} \approx 16.23$ $\quad$ $\langle N_{ch}\rangle_{|\eta|<1} \approx 38.02$ $\quad$ $\langle N_{ch}\rangle_{|\eta|<1} \approx 59.58$

$15 < p_T^{Jet} < 20$ GeV

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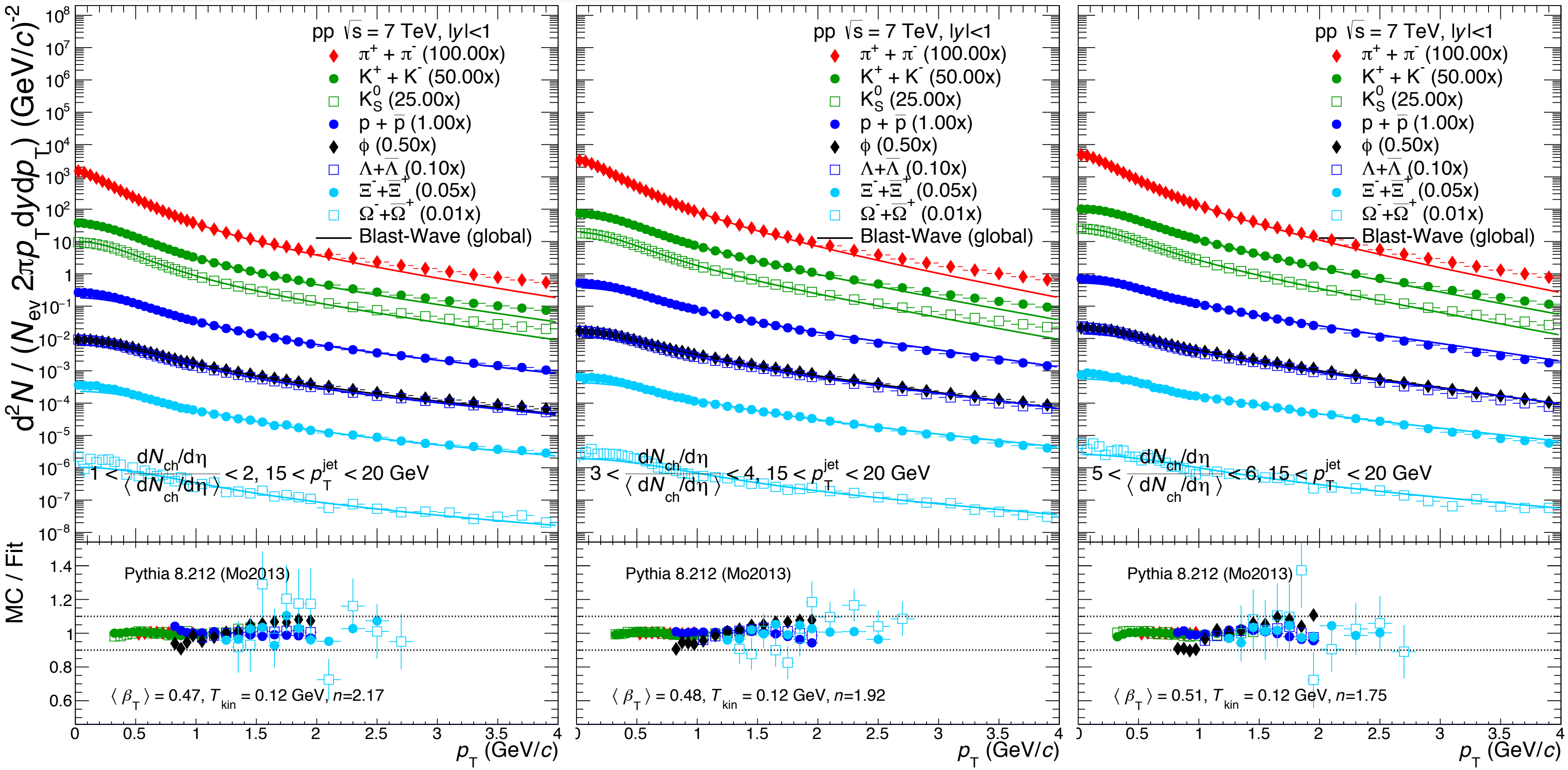
$<\beta_T>\approx 0.48$, $<T_{kin}>\approx 0.12$, $<n>\approx 1.94$



$<N_{ch}>_{|\eta|<1} \approx 18.22$ $<N_{ch}>_{|\eta|<1} \approx 39.18$ $<N_{ch}>_{|\eta|<1} \approx 60.47$

Quality of the fit is **better** & **higher** $<\beta_T>$ reach

$15 < p_T^{Jet} < 20$ GeV

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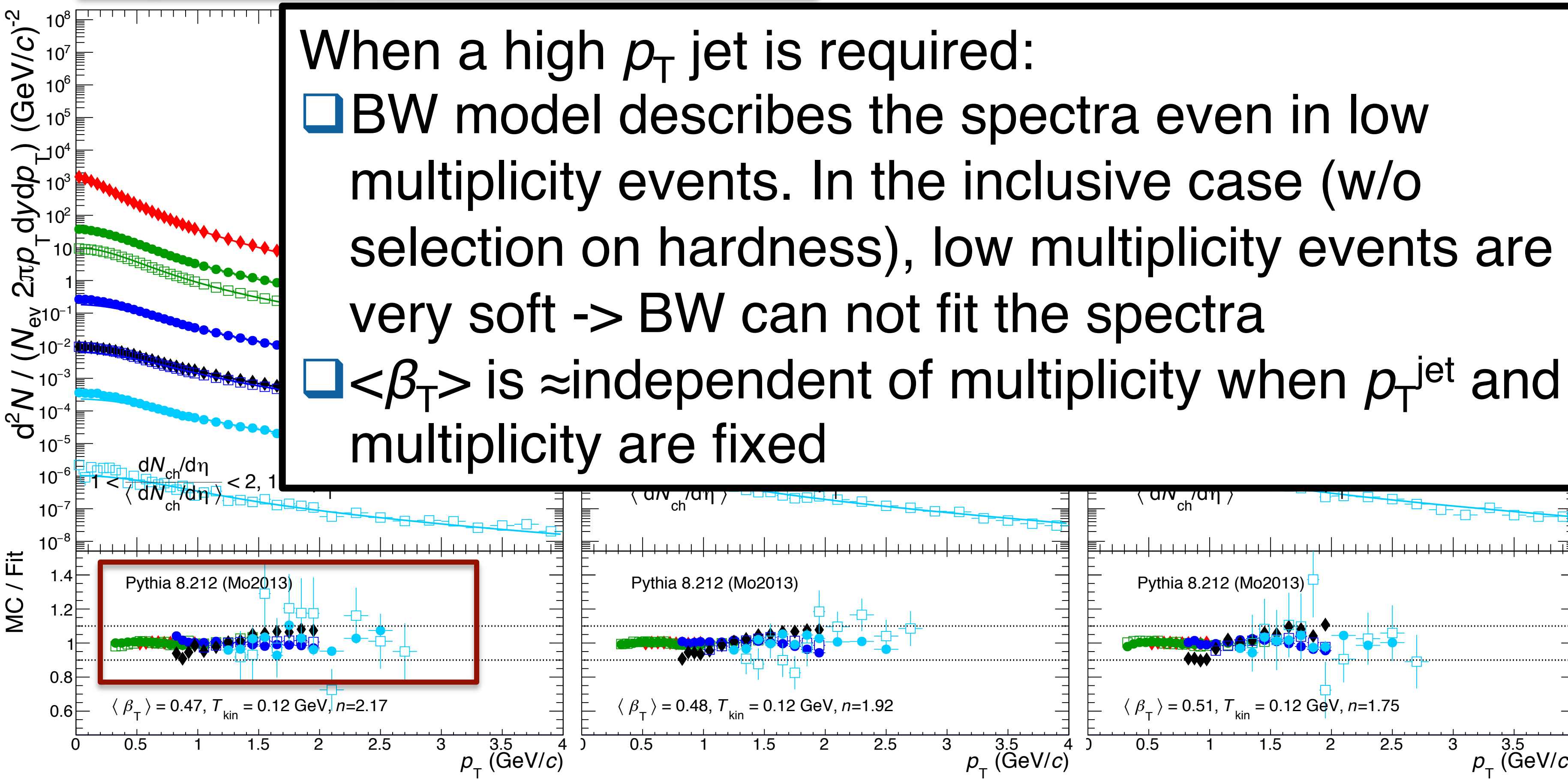
$\langle\beta_T\rangle \approx 0.48$, $\langle T_{kin}\rangle \approx 0.12$, $\langle n\rangle \approx 1.94$

When a high p_T jet is required:

- BW model describes the spectra even in low multiplicity events. In the inclusive case (w/o selection on hardness), low multiplicity events are very soft -> BW can not fit the spectra
- $\langle\beta_T\rangle$ is ≈independent of multiplicity when p_T^{jet} and multiplicity are fixed



$\langle N_{ch}\rangle_{|\eta|<1} \approx 18.22$ $\langle N_{ch}\rangle_{|\eta|<1} \approx 39.18$ $\langle N_{ch}\rangle_{|\eta|<1} \approx 60.47$

T_{kin} vs $<\beta_T>$

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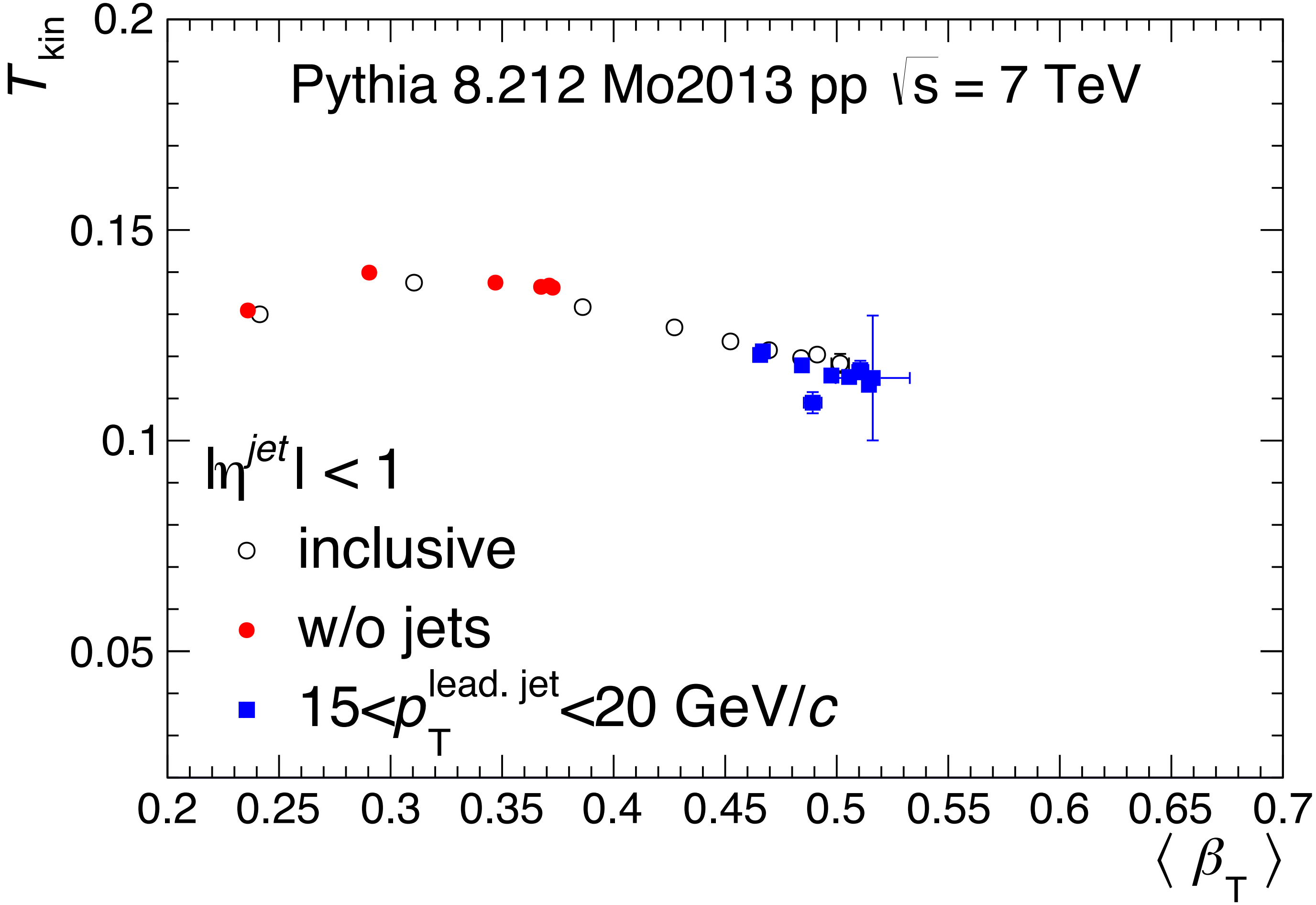
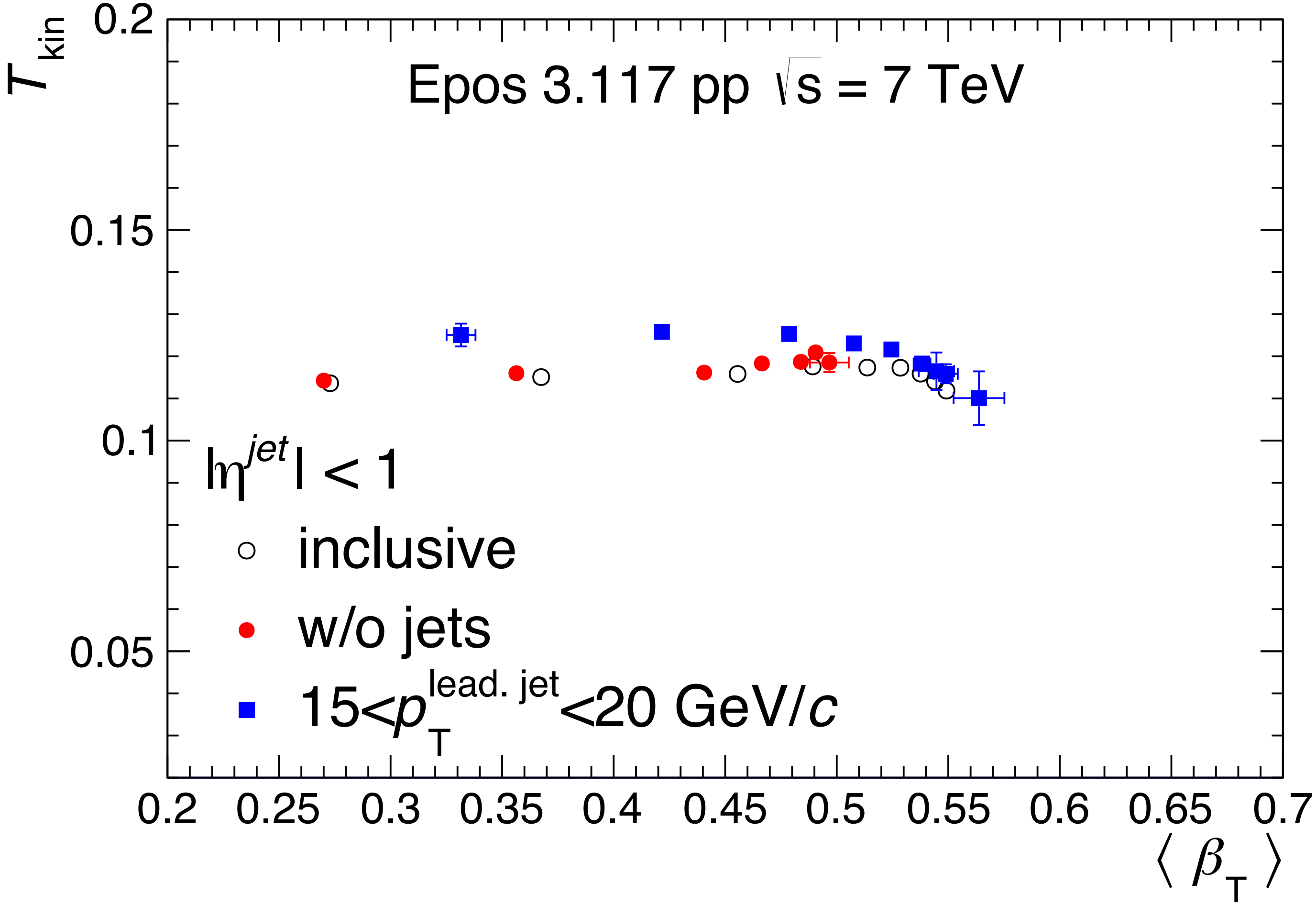
PYTHIA



Qualitatively similar result obtained using the event shape: **spherocity** E. Cuautle, G. Paić and A. O., NPA 941 (2015) 78-86

T_{kin} vs $<\beta_T>$

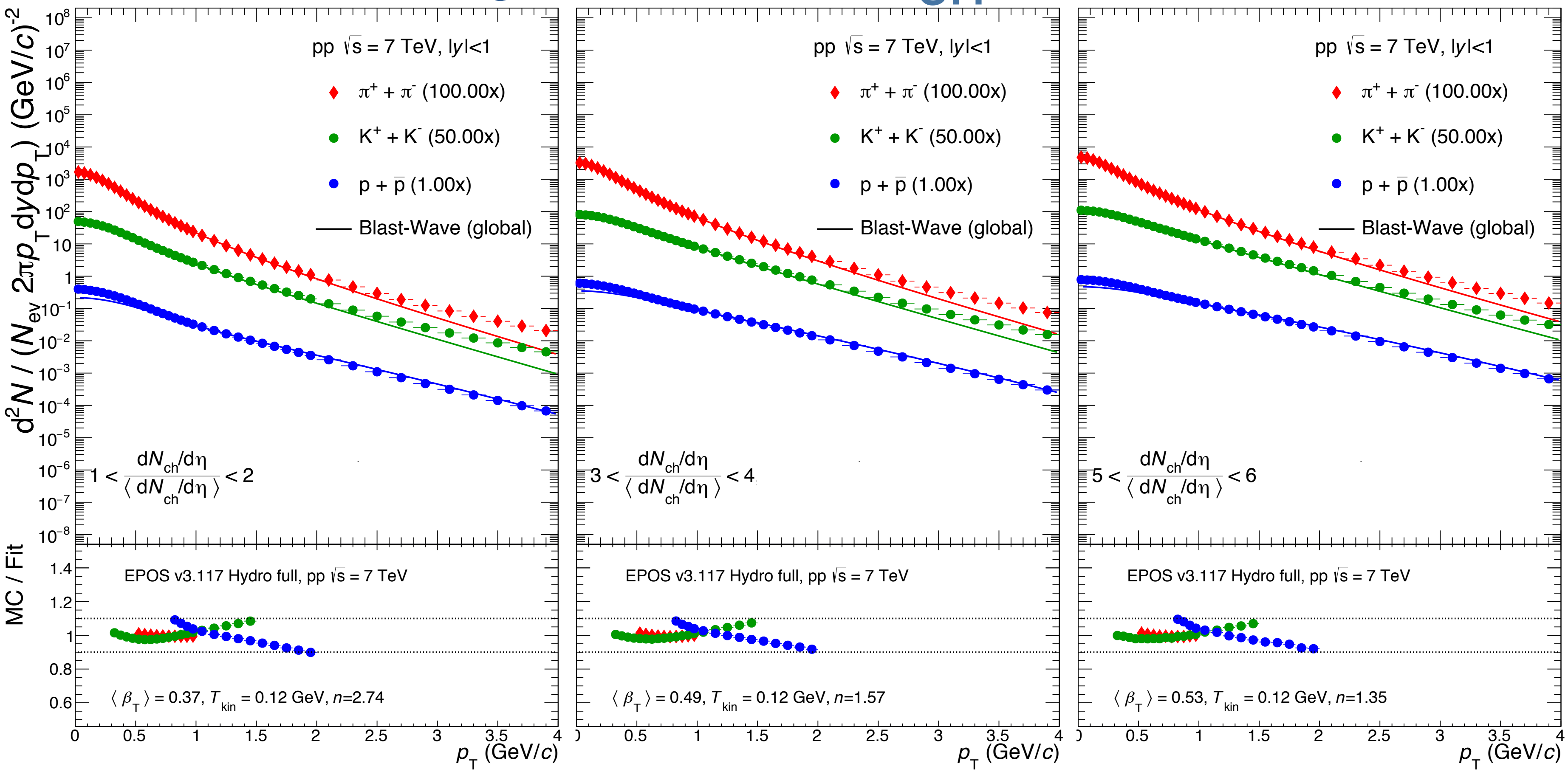
EPOS



- Jet effects seem to be smaller than in Pythia
- We always observe a strong multiplicity dependence

EPOS

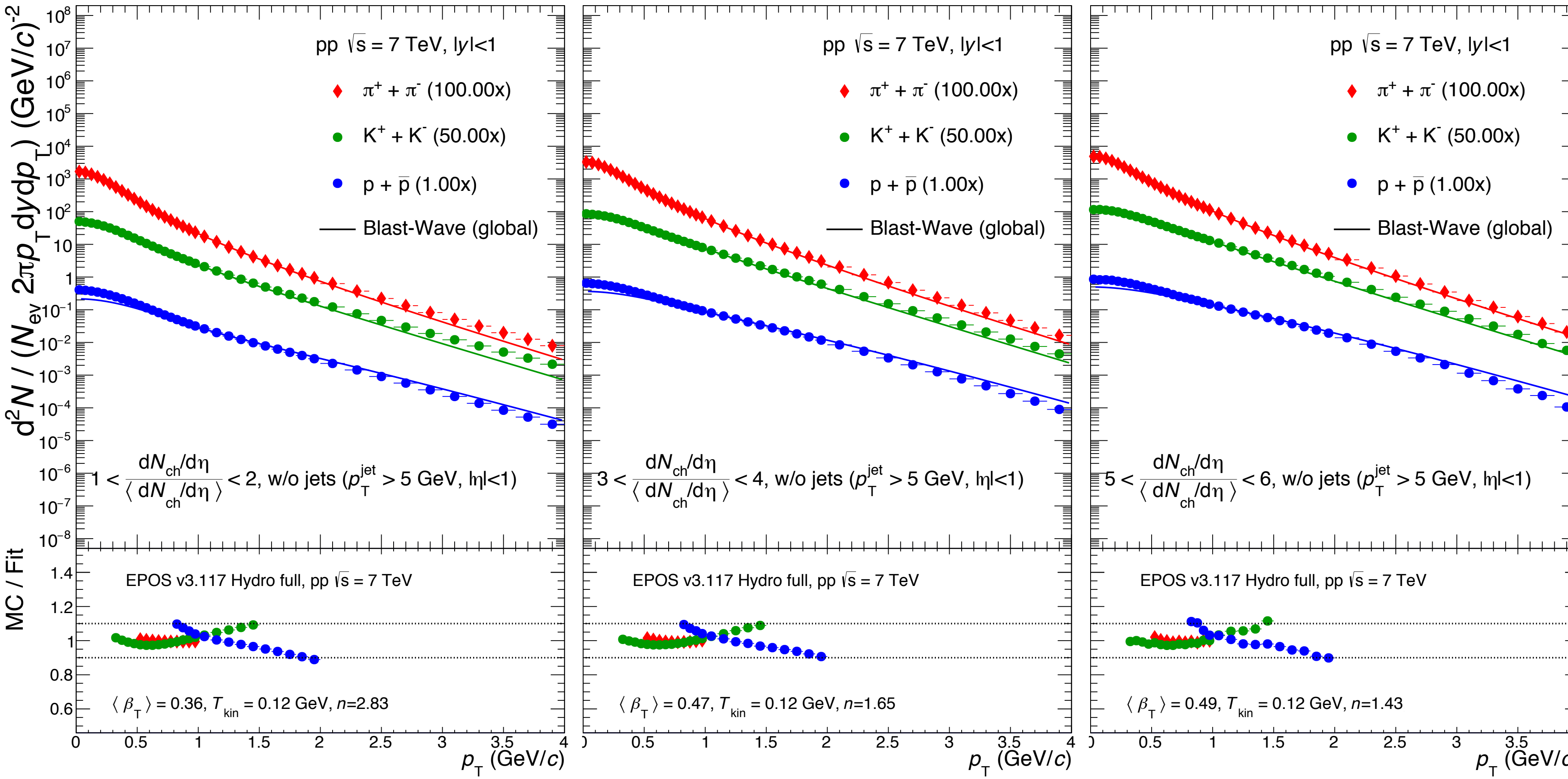
Analysis vs. N_{ch}



$\langle N_{ch} \rangle_{|\eta|<1} \approx 15.27$ $\langle N_{ch} \rangle_{|\eta|<1} \approx 35.12$ $\langle N_{ch} \rangle_{|\eta|<1} \approx 56.06$

EPOS

Without Jets



$<N_{ch}>_{|\eta|<1} \approx 15.15$ $<N_{ch}>_{|\eta|<1} \approx 34.71$ $<N_{ch}>_{|\eta|<1} \approx 55.18$

EPOS

$15 < p_T^{Jet} < 20$ GeV

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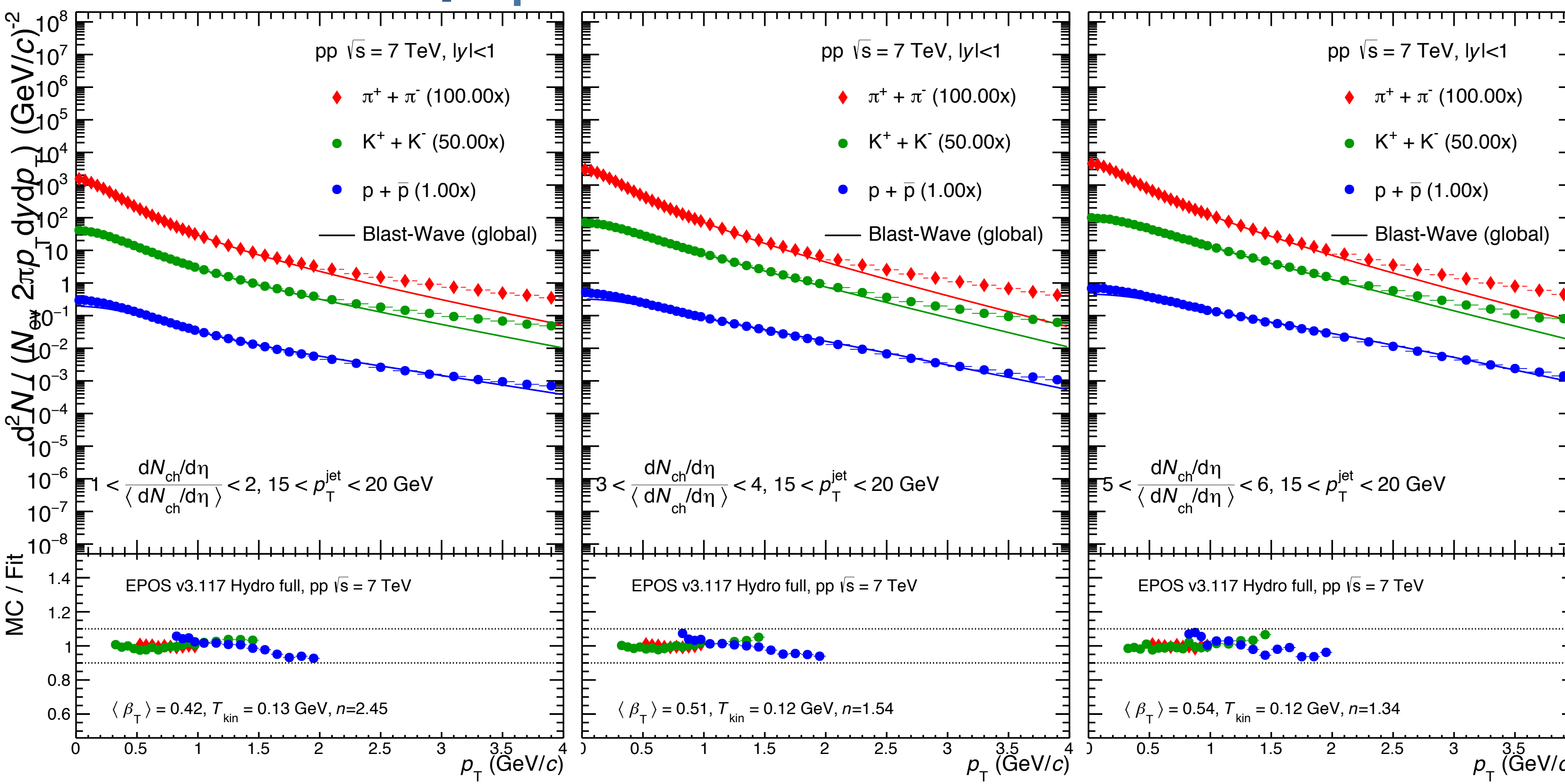

$<N_{ch}>_{|\eta|<1} \approx 16.39$ $<N_{ch}>_{|\eta|<1} \approx 35.56$ $<N_{ch}>_{|\eta|<1} \approx 56.27$

Quality of the fit is slightly **better** & **higher** $<\beta_T>$ reach (but a stronger multiplicity dependence than in Pythia)

ENERGY DEPENDENCE

$15 < p_T^{Jet} < 20$ GeV

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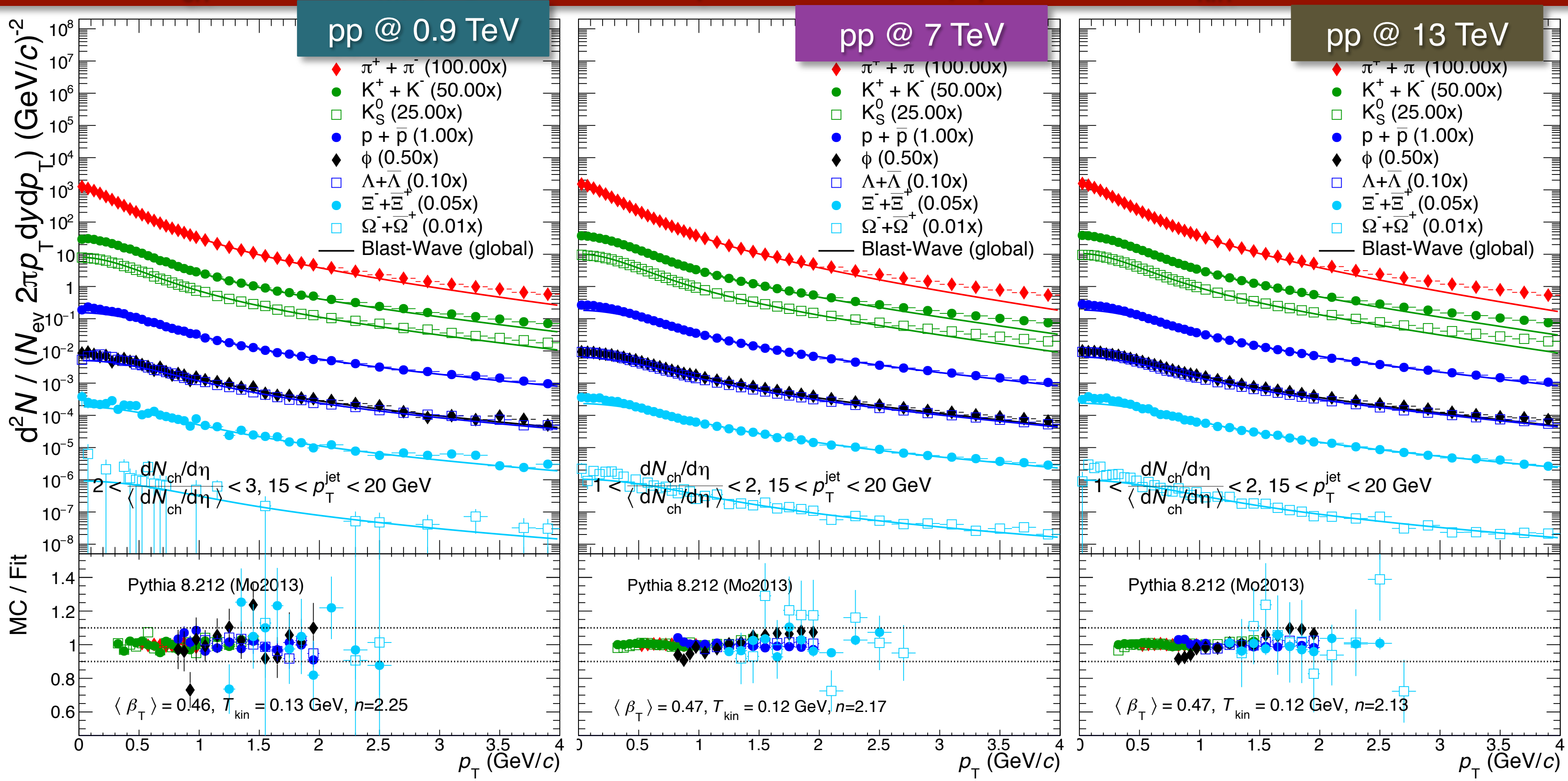
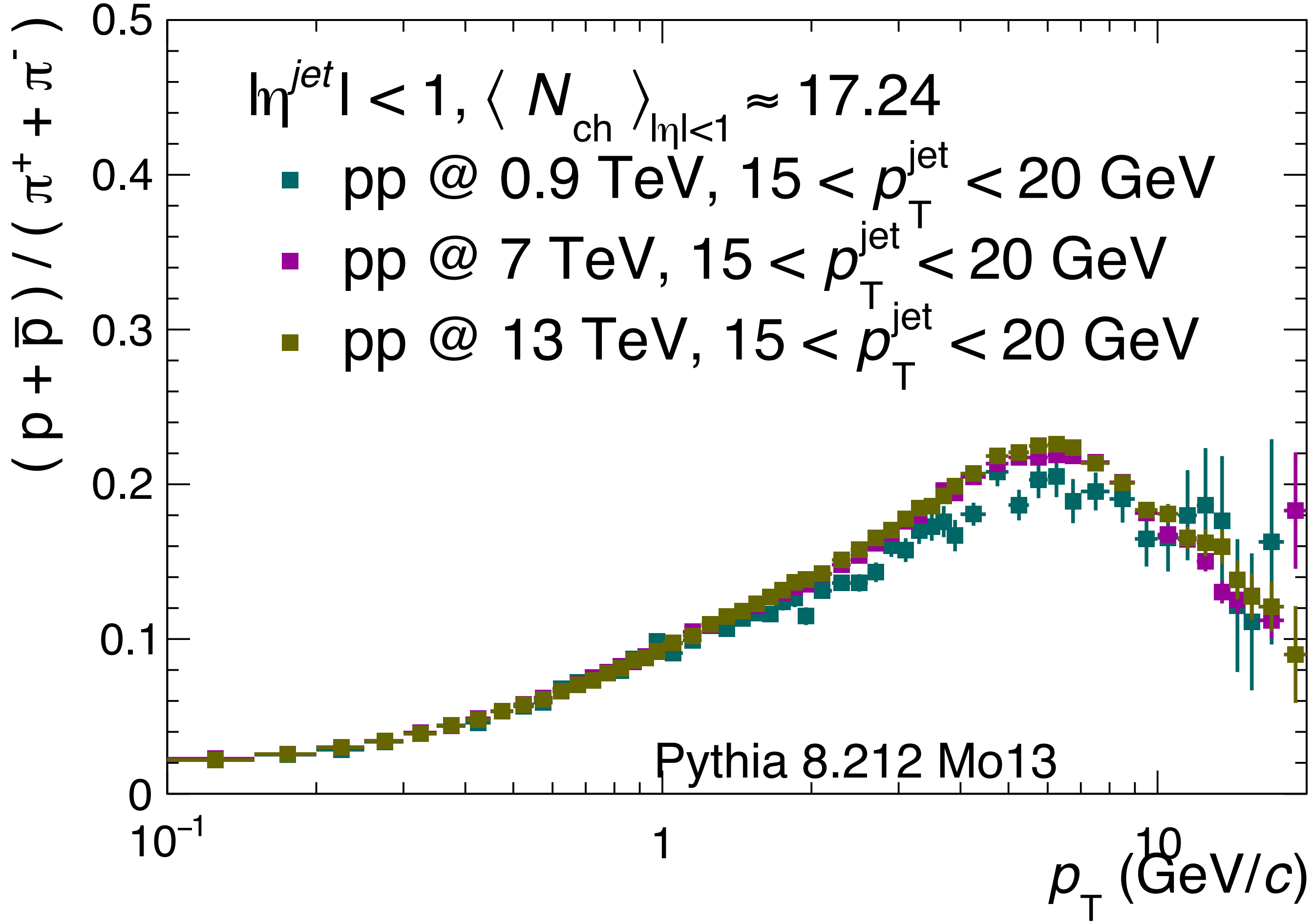
Similar $<N_{ch}>$ and $<N_{MPI}>$ gives similar parameters: $<\beta_T>\approx0.47$, $<T_{kin}>\approx0.12$, $<n>\approx 2.18$



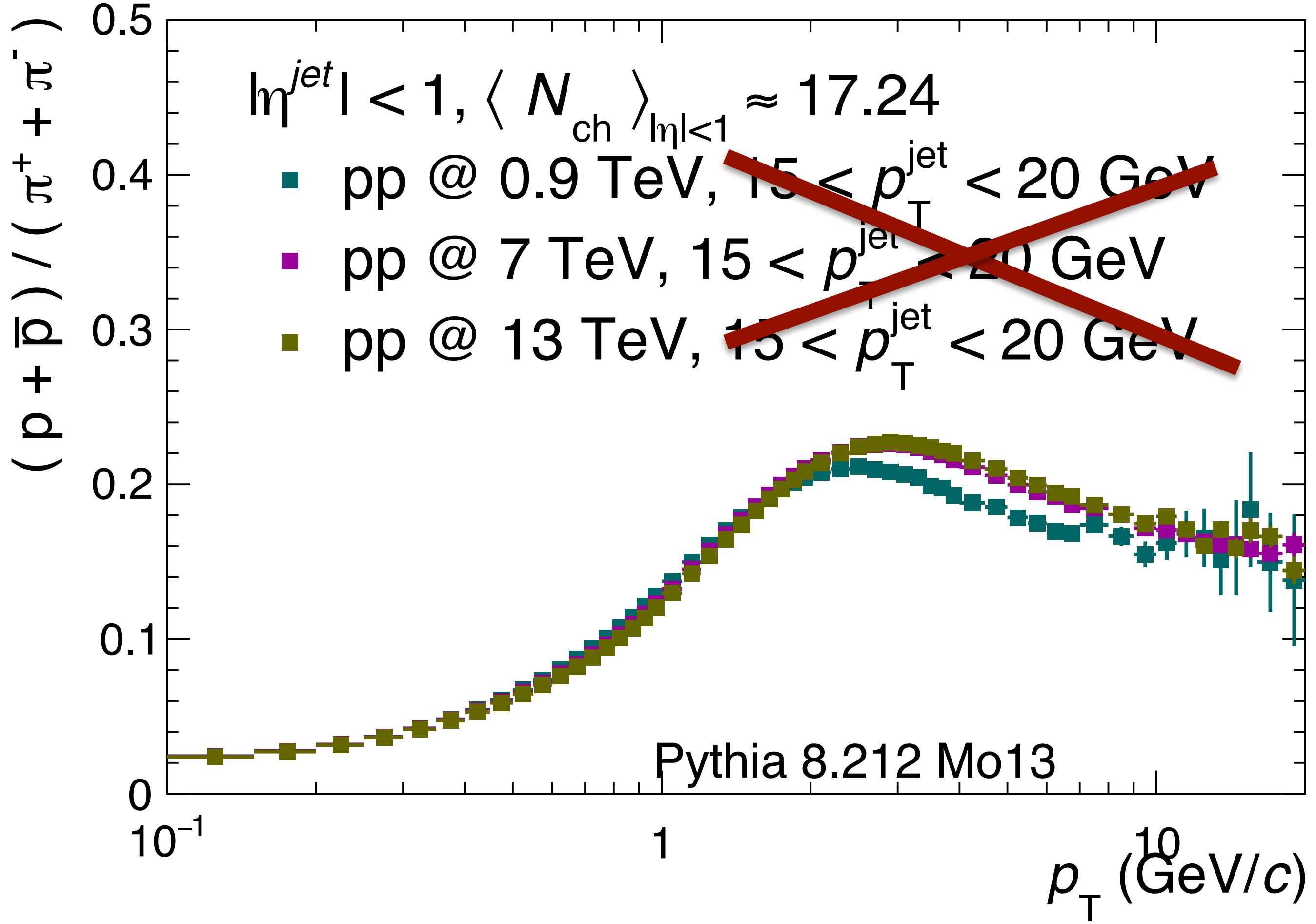
$<N_{ch}>_{\|\eta\|<1} \approx 15.65$	$<N_{ch}>_{\|\eta\|<1} \approx 17.72$	$<N_{ch}>_{\|\eta\|<1} \approx 18.35$
$<N_{MPI}>\approx 3.53$	$<N_{MPI}>\approx 4.14$	$<N_{MPI}>\approx 4.26$

Spectral shapes



Proton-to-pion ratio show little or no dependence with √s
(p_T position of the peak is the same for the three colliding systems)

Spectral shapes

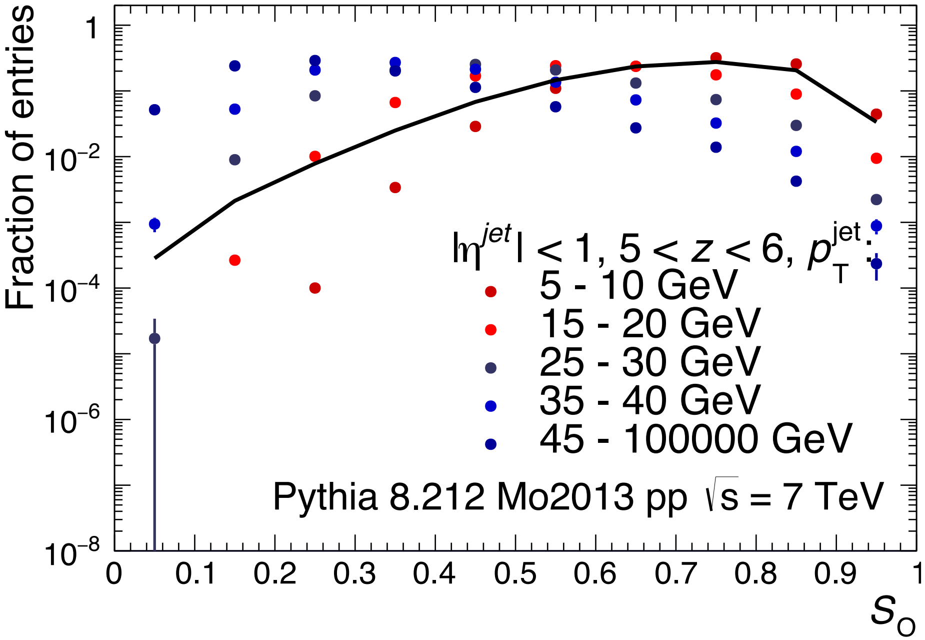


Without the jet requirement, the ratios look more different due to the different jet biases

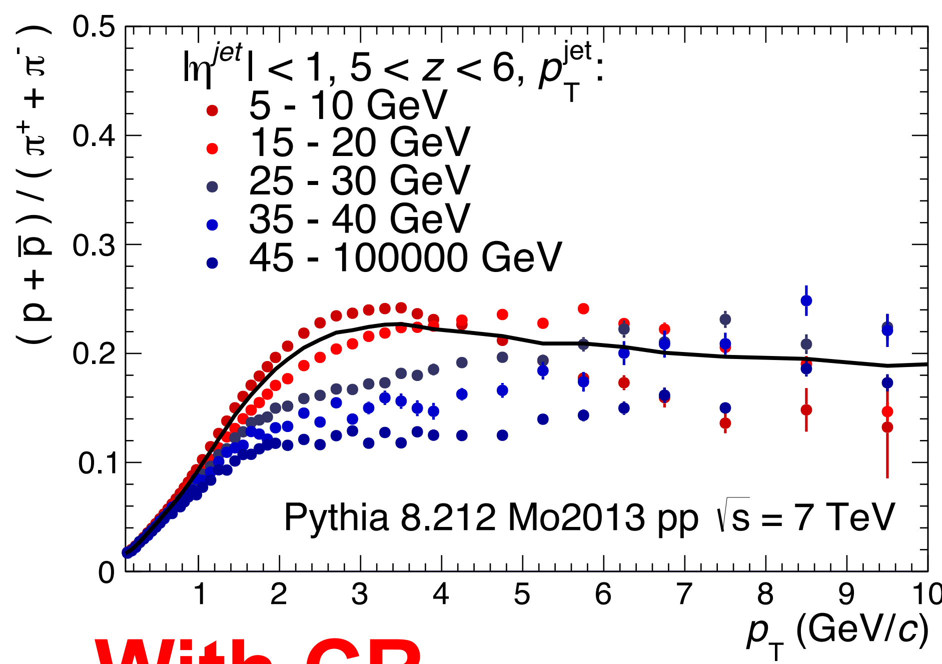
Summary

- In Pythia, MPI (semi-hard and hard partonic scatterings) and CR produce flow-like effects
- In Pythia, jets play an important role in the generation of the flow-like behavior
- With a selection based on the hardness, EPOS always gives a strong N_{ch} dependence of $\langle\beta_T\rangle$, whereas for Pythia, it stays more or less constant with N_{ch}

BACKUP

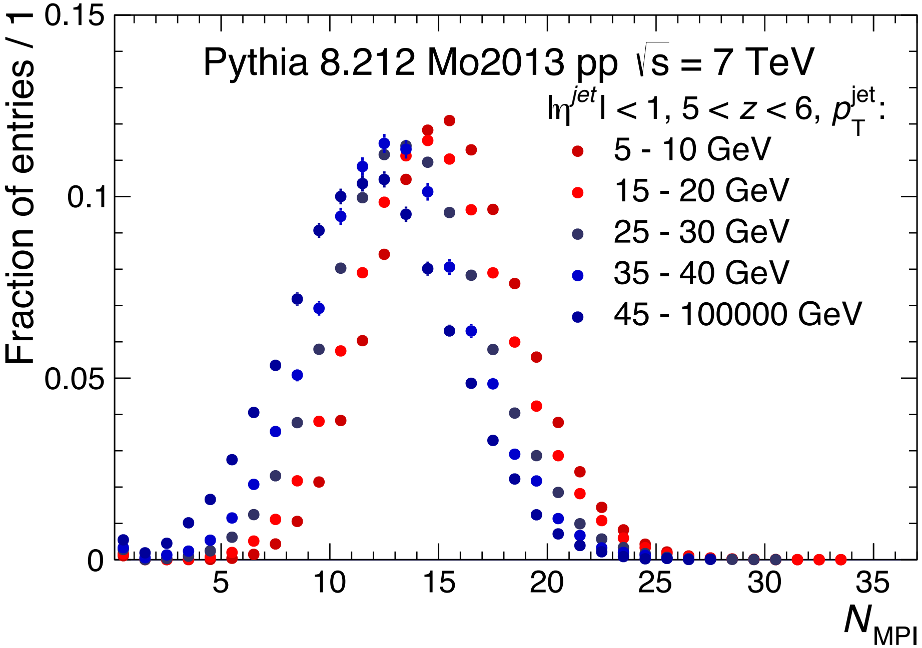


Fraction of entries
|η^jet| < 1, 5 < z < 6, p_T^jet:
5 - 10 GeV
15 - 20 GeV
25 - 30 GeV
35 - 40 GeV
45 - 100000 GeV
Pythia 8.212 Mo2013 pp √s = 7 TeV
S_O

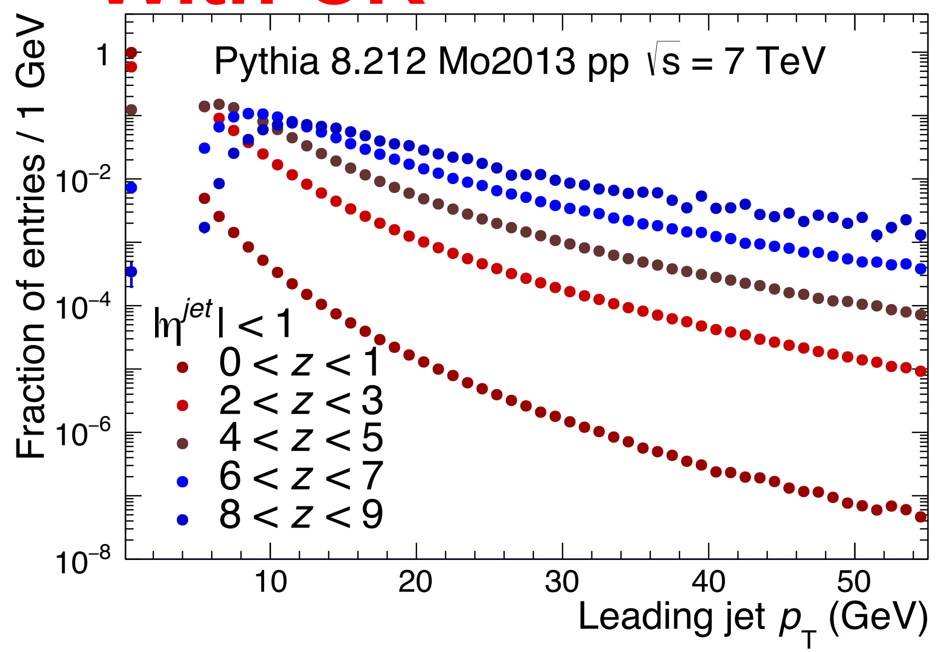


(p + p̄) / (π⁺ + π⁻)
|η^jet| < 1, 5 < z < 6, p_T^jet:
5 - 10 GeV
15 - 20 GeV
25 - 30 GeV
35 - 40 GeV
45 - 100000 GeV
Pythia 8.212 Mo2013 pp √s = 7 TeV
p_T (GeV/c)

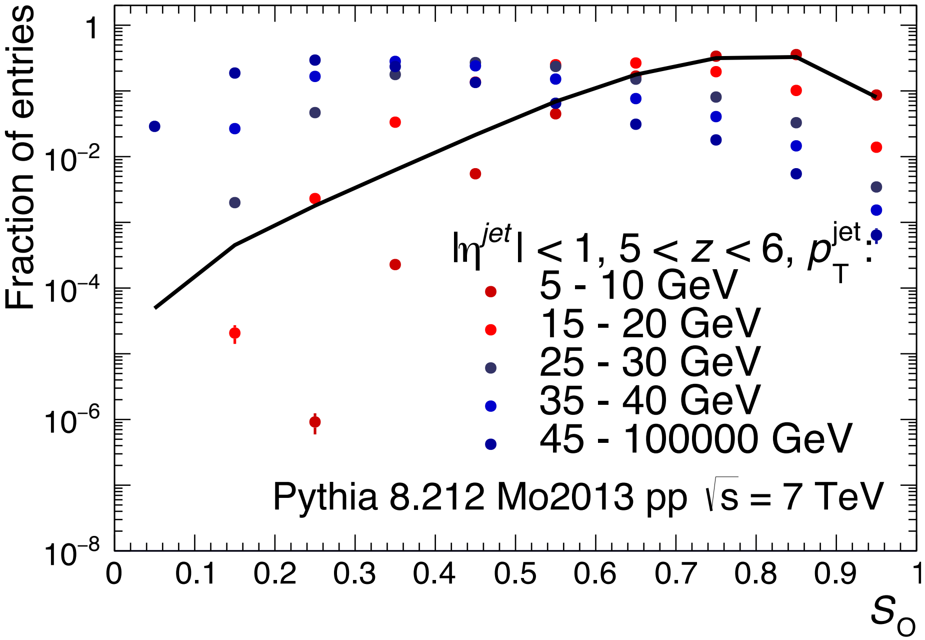
With CR

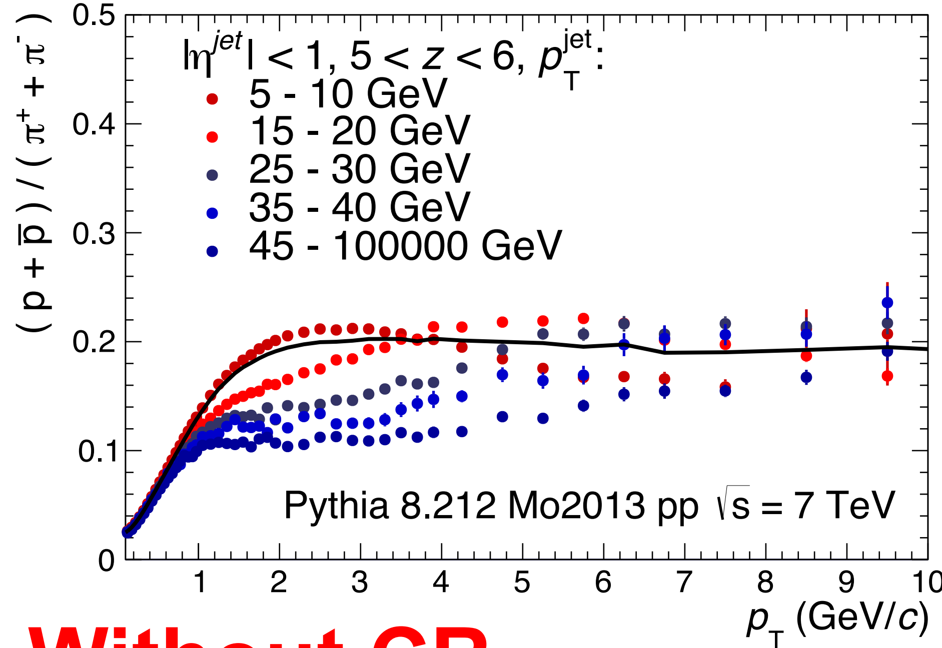


Fraction of entries / 1
Pythia 8.212 Mo2013 pp √s = 7 TeV
|η^jet| < 1, 5 < z < 6, p_T^jet:
5 - 10 GeV
15 - 20 GeV
25 - 30 GeV
35 - 40 GeV
45 - 100000 GeV
N_MPI

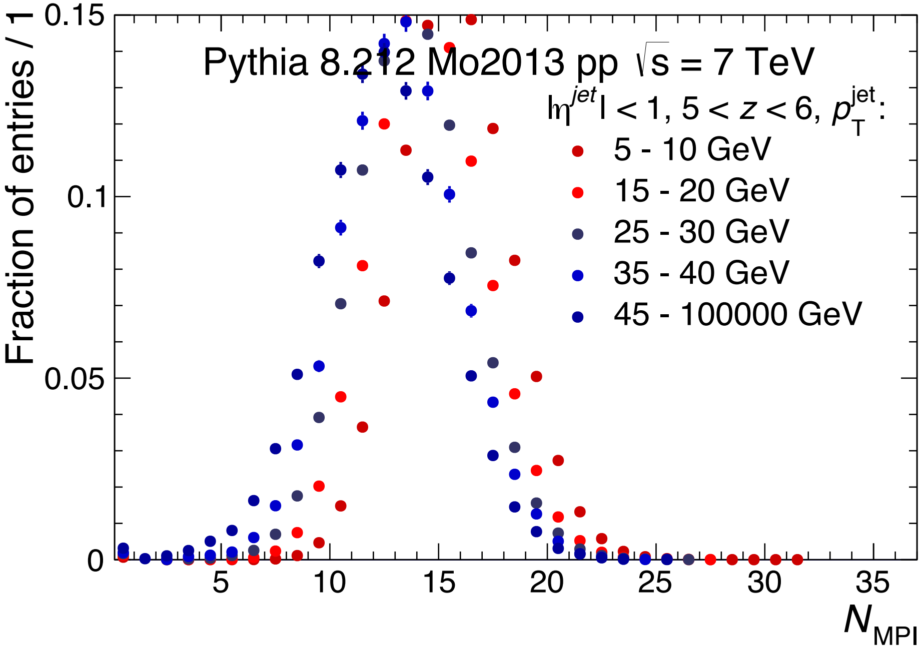


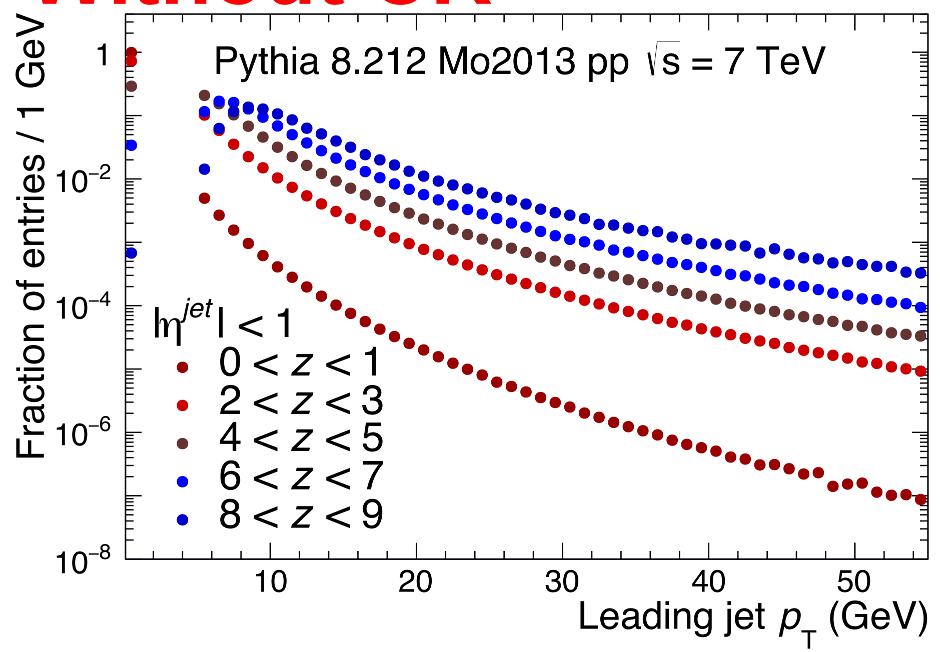
Fraction of entries / 1 GeV
Pythia 8.212 Mo2013 pp √s = 7 TeV
|η^jet| < 1
0 < z < 1
2 < z < 3
4 < z < 5
6 < z < 7
8 < z < 9
Leading jet p_T (GeV)


Fraction of entries
$|\eta^{jet}| < 1$, $5 < z < 6$, p_T^{jet}:
5 - 10 GeV
15 - 20 GeV
25 - 30 GeV
35 - 40 GeV
45 - 100000 GeV
Pythia 8.212 Mo2013 pp $\sqrt{s}$ = 7 TeV
S_O

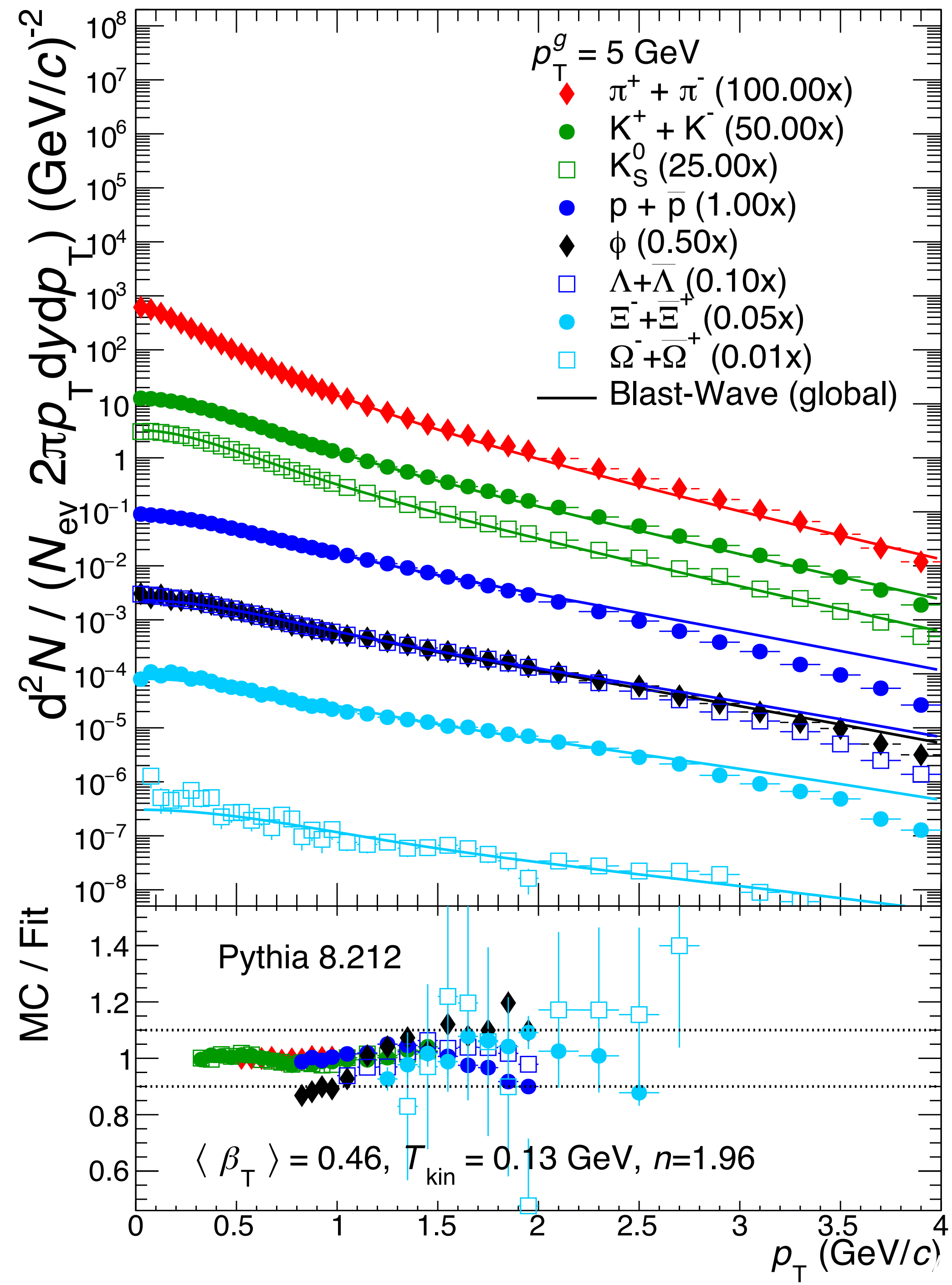

$(p + \bar{p}) / (\pi^+ + \pi^-)$
$|\eta^{jet}| < 1$, $5 < z < 6$, p_T^{jet}:
5 - 10 GeV
15 - 20 GeV
25 - 30 GeV
35 - 40 GeV
45 - 100000 GeV
Pythia 8.212 Mo2013 pp $\sqrt{s}$ = 7 TeV
p_T (GeV/c)

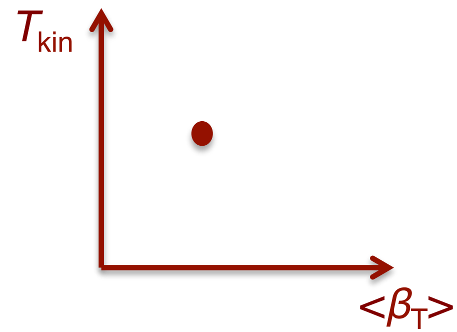
Without CR

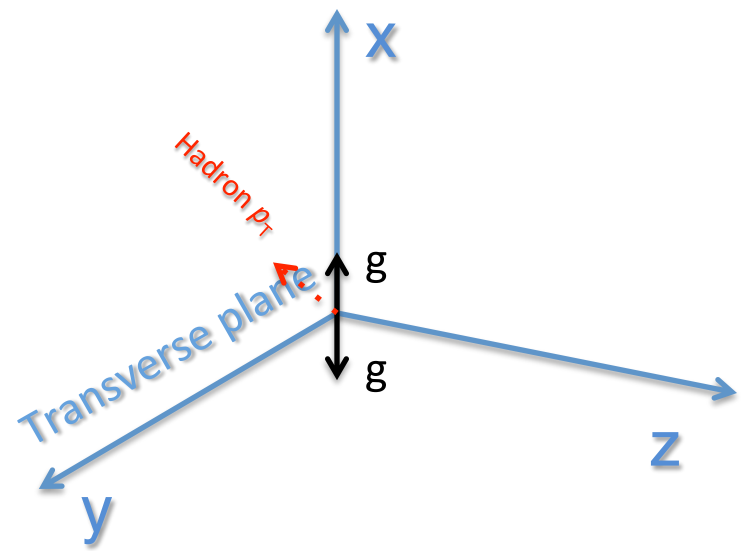

Fraction of entries / 1
Pythia 8.212 Mo2013 pp $\sqrt{s}$ = 7 TeV
$|\eta^{jet}| < 1$, $5 < z < 6$, p_T^{jet}:
5 - 10 GeV
15 - 20 GeV
25 - 30 GeV
35 - 40 GeV
45 - 100000 GeV
N_{MPI}


Fraction of entries / 1 GeV
Pythia 8.212 Mo2013 pp $\sqrt{s}$ = 7 TeV
$|\eta^{jet}| < 1$
$0 < z < 1$
$2 < z < 3$
$4 < z < 5$
$6 < z < 7$
$8 < z < 9$
Leading jet p_T (GeV)

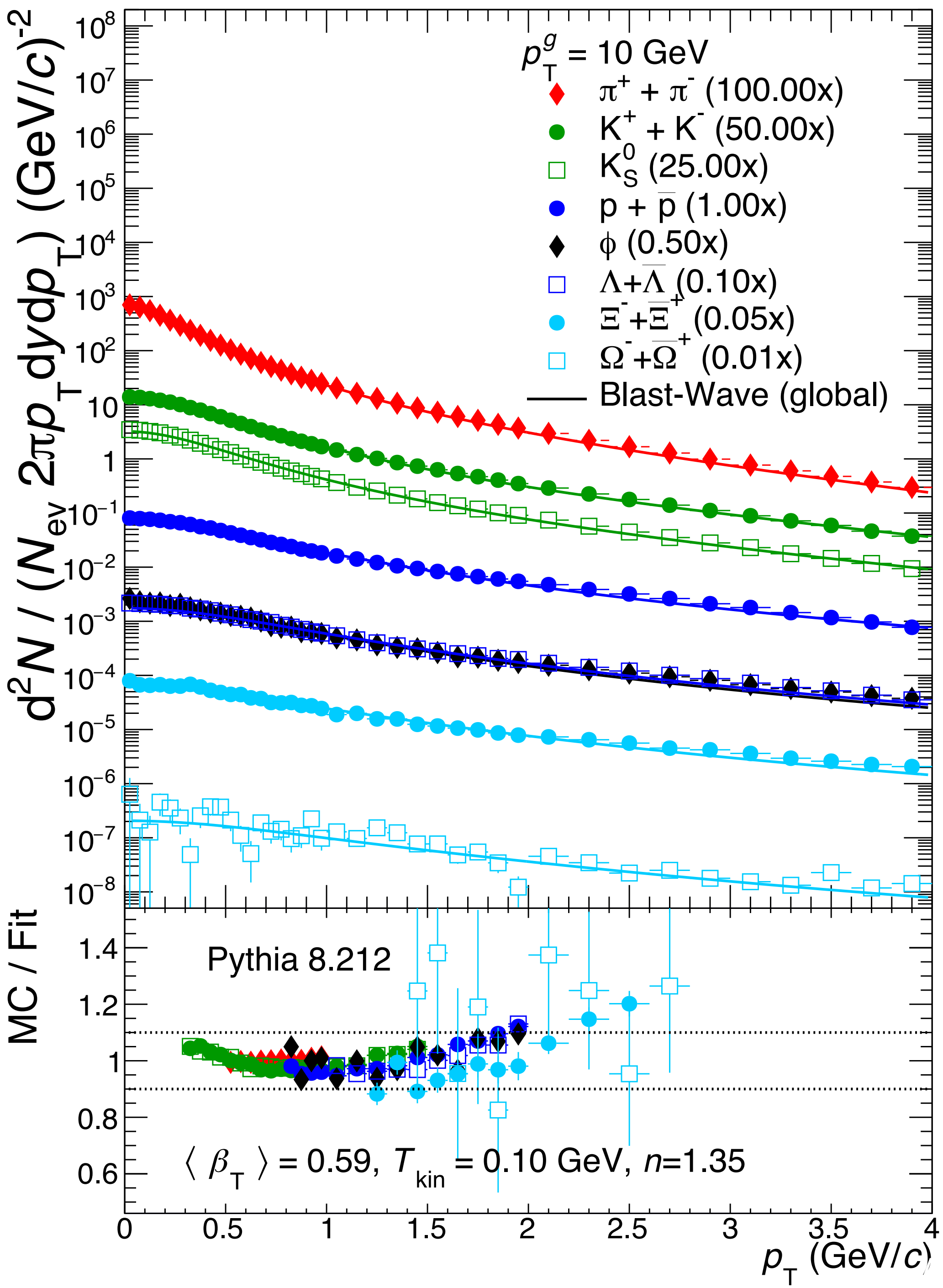
HADRONIZATION IN A CLEAN PARTONIC CONFIGURATION

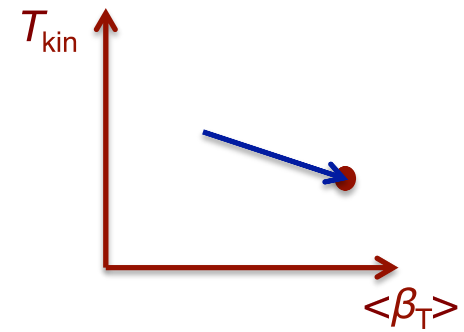


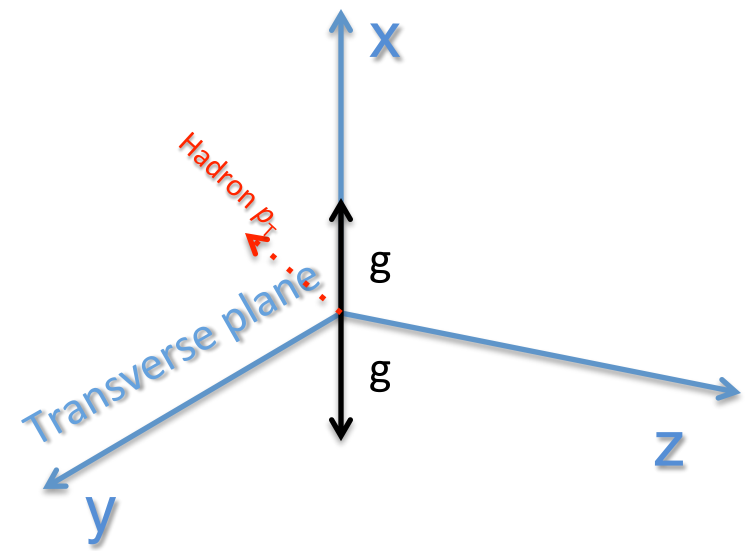




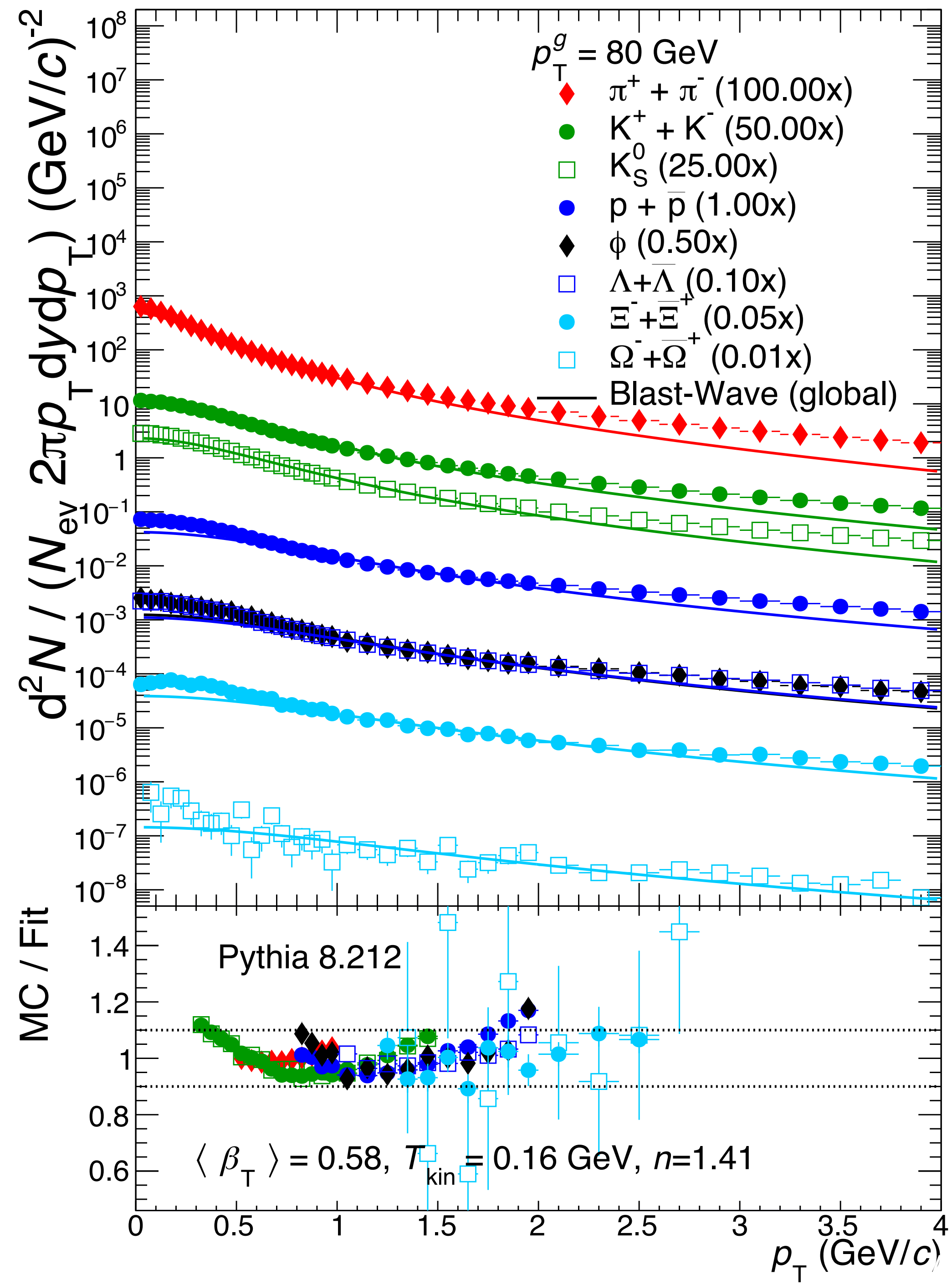
Parton-level configurations as direct input for hadronization

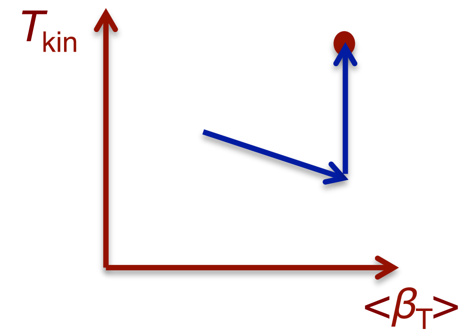


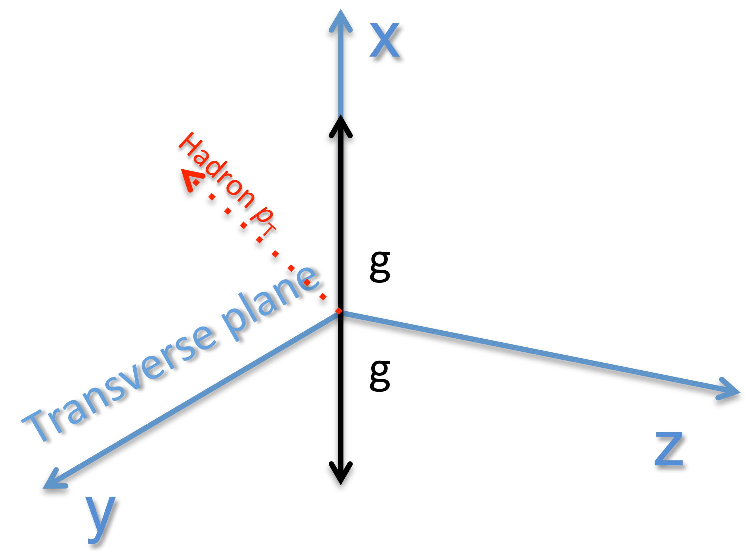




Parton-level configurations as direct input for hadronization







Parton-level configurations as direct input for hadronization

OTHER APPROACHES

Jet effects can be also seen in a more inclusive analysis

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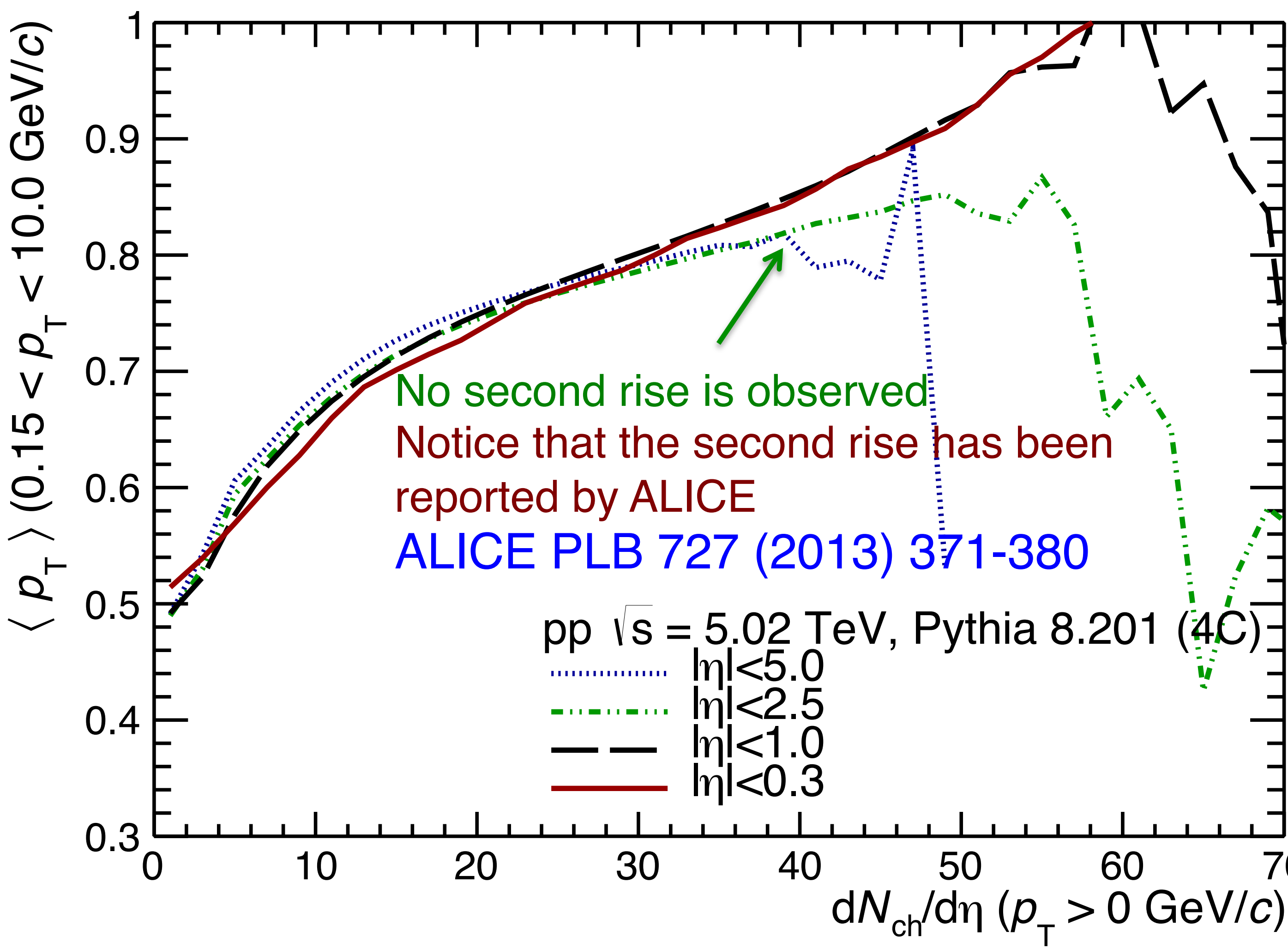

- $<p_T>$ was computed with charged particles within $|\eta|<0.3$
- $dN_{ch}/d\eta$ was computed using different η windows

Jet effects can be also seen in a more inclusive analysis

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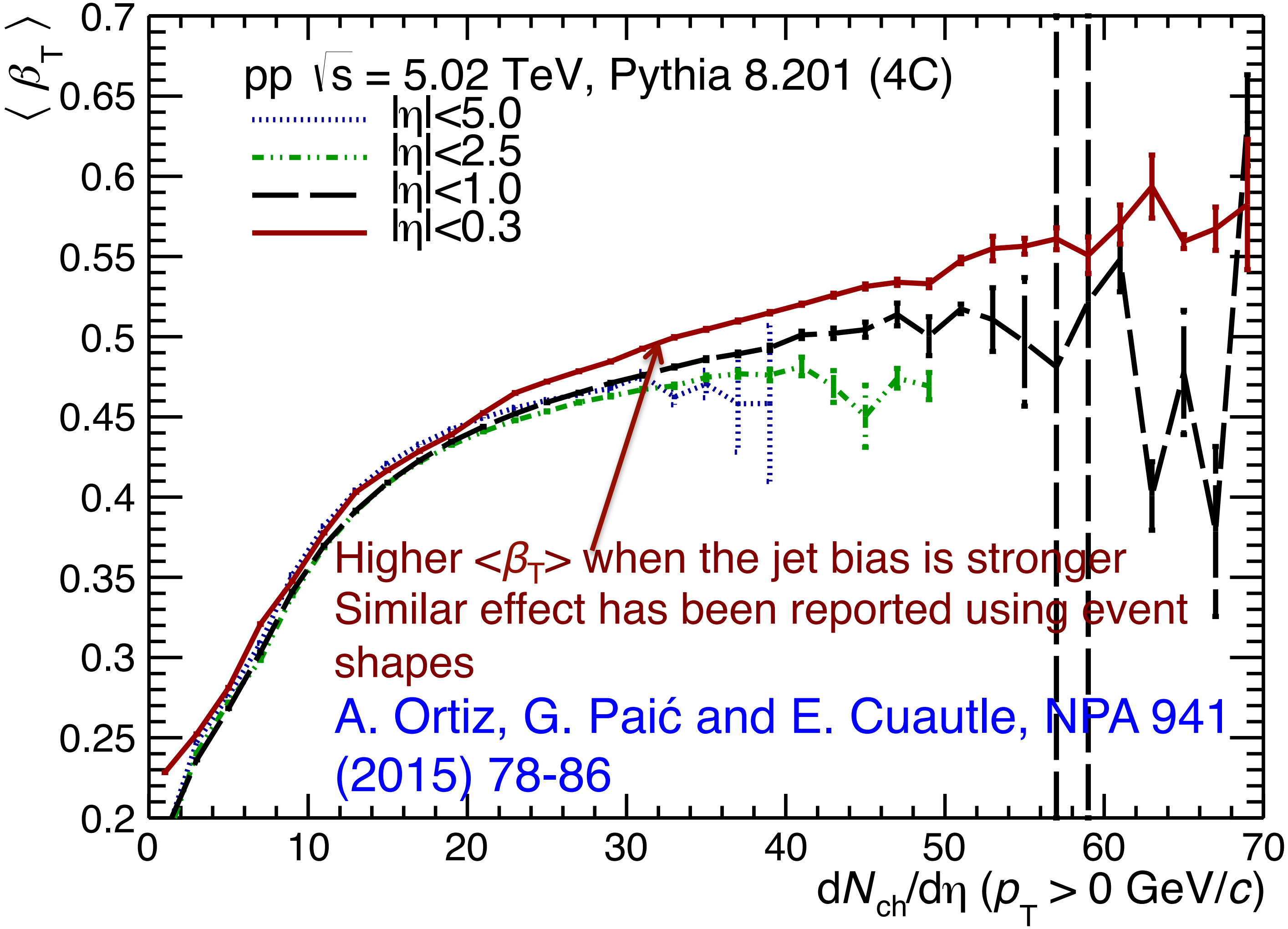

- $\langle\beta_T\rangle$ was computed with charged particles within |η|<0.3
- $dN_{ch}/d\eta$ was computed using different η windows

PID in charged jets

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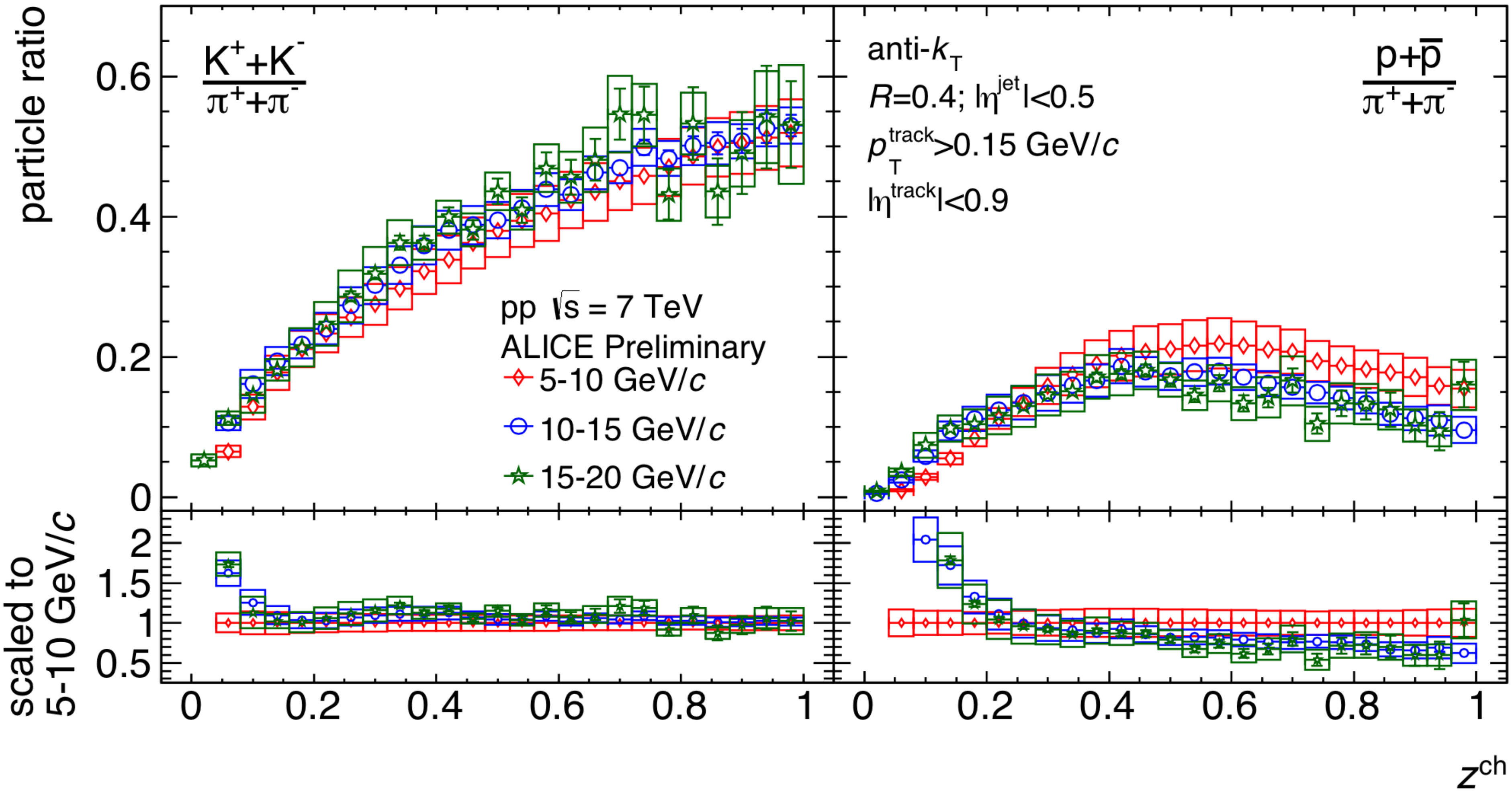
Xianguo Lu, for the ALICE Collaboration, NPA 00 (2014), 1-4



$15 < p_T^{Jet} < 20$ GeV

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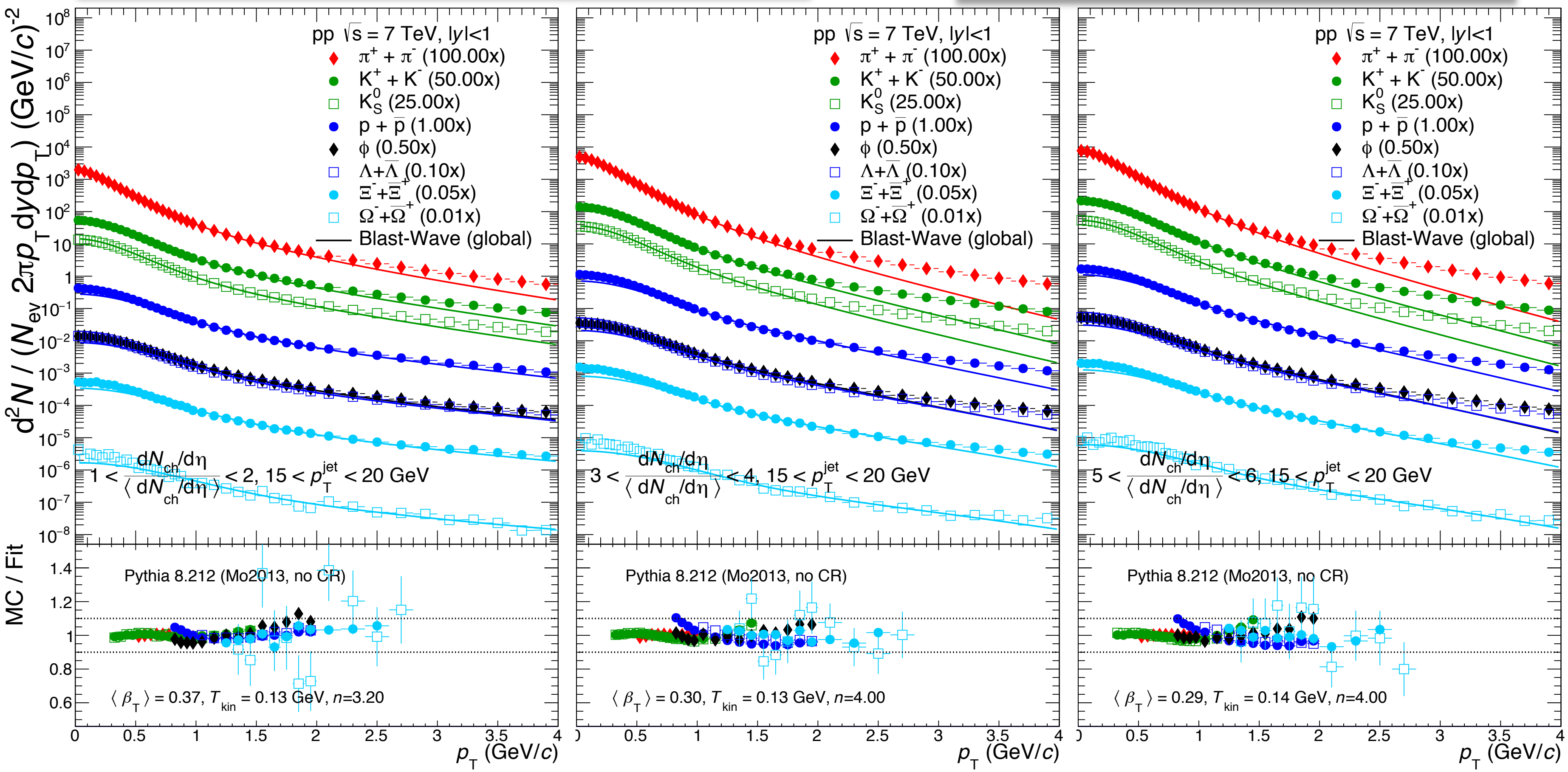
Smaller $\langle\beta_T\rangle \approx 0.32$ & larger $\langle n\rangle \approx 3.7$

Without Color Reconnection



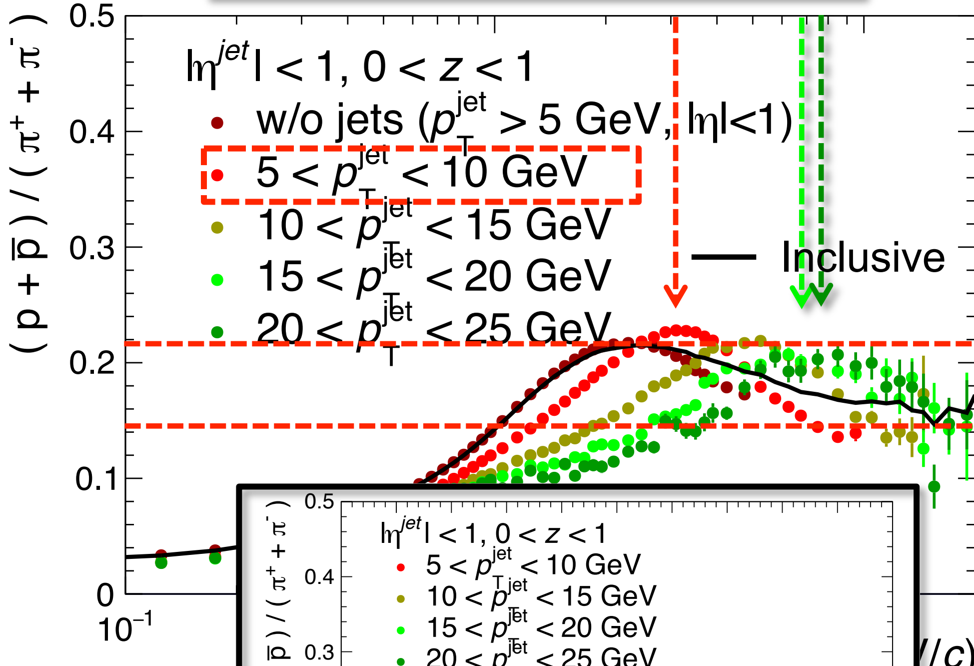
Slight increase of $\langle\beta_T\rangle$

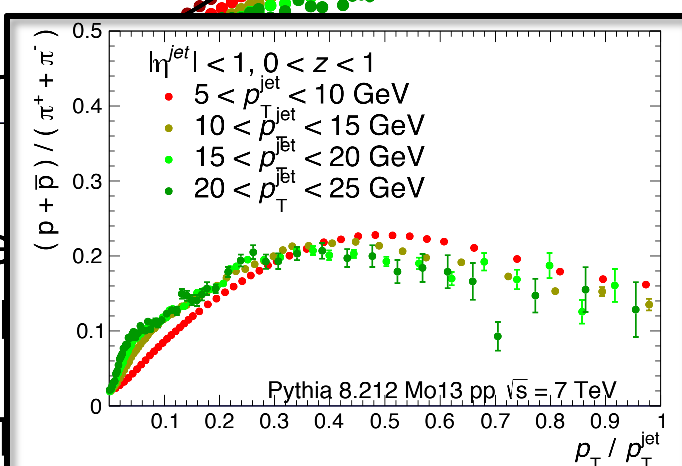
p/π vs. p_T (low multiplicity)

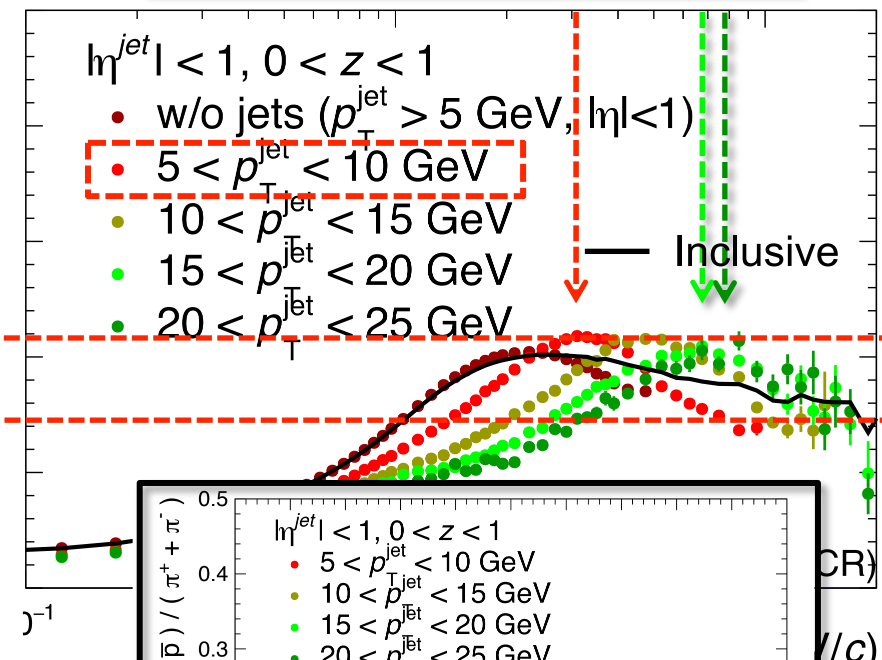
This is a FF effect (p/π vs. p_T/p_T^{jet} is ≈p_T^{jet} independent)

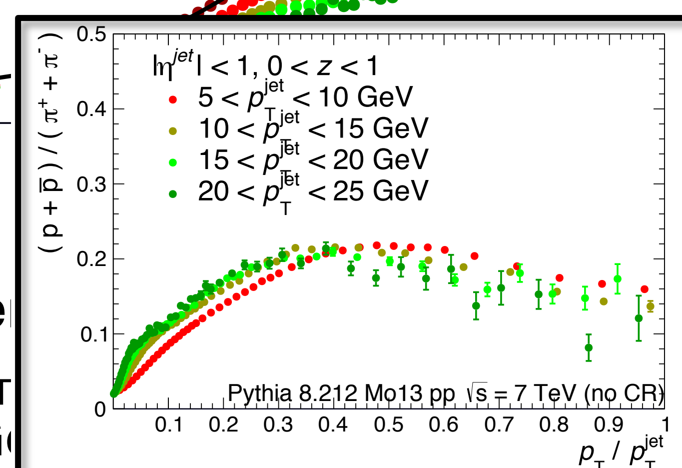
With Color Reconnection

Without Color Reconnection









- CR e … 10 GeV
- The … to highe… shift … se of <β_T
  - T … et > 15 G…

p/π vs. p_T (high multiplicity)

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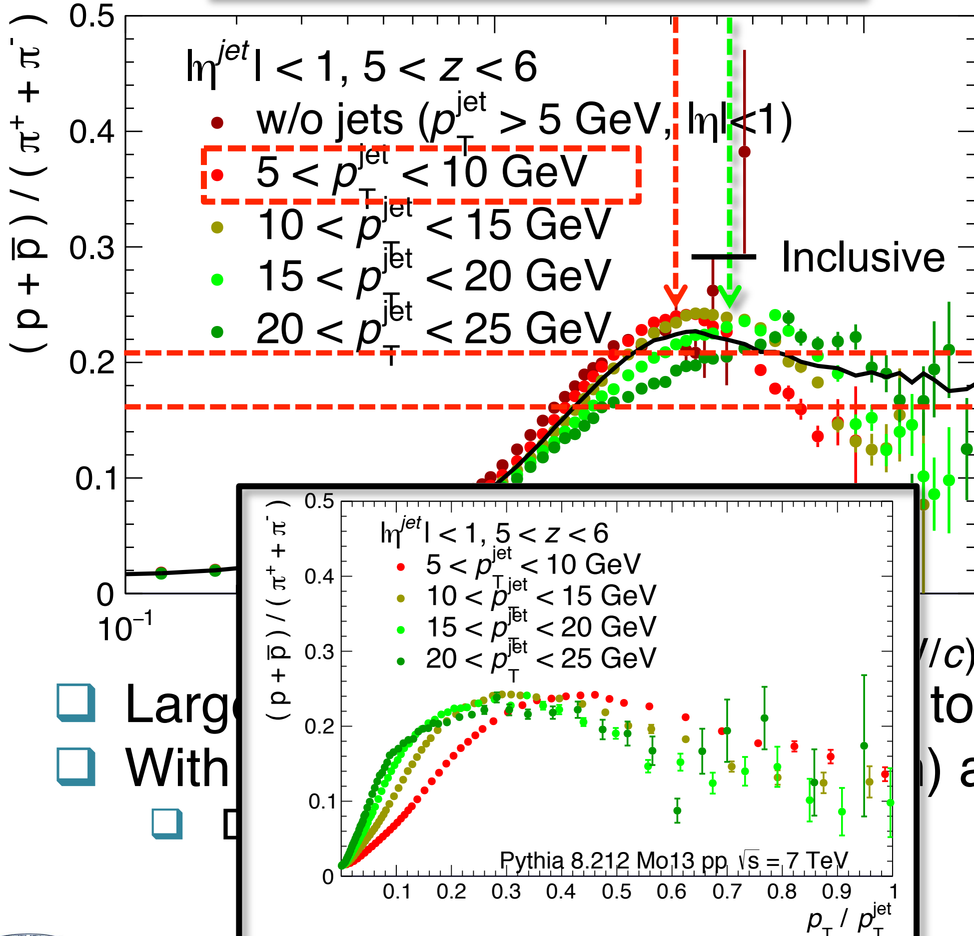
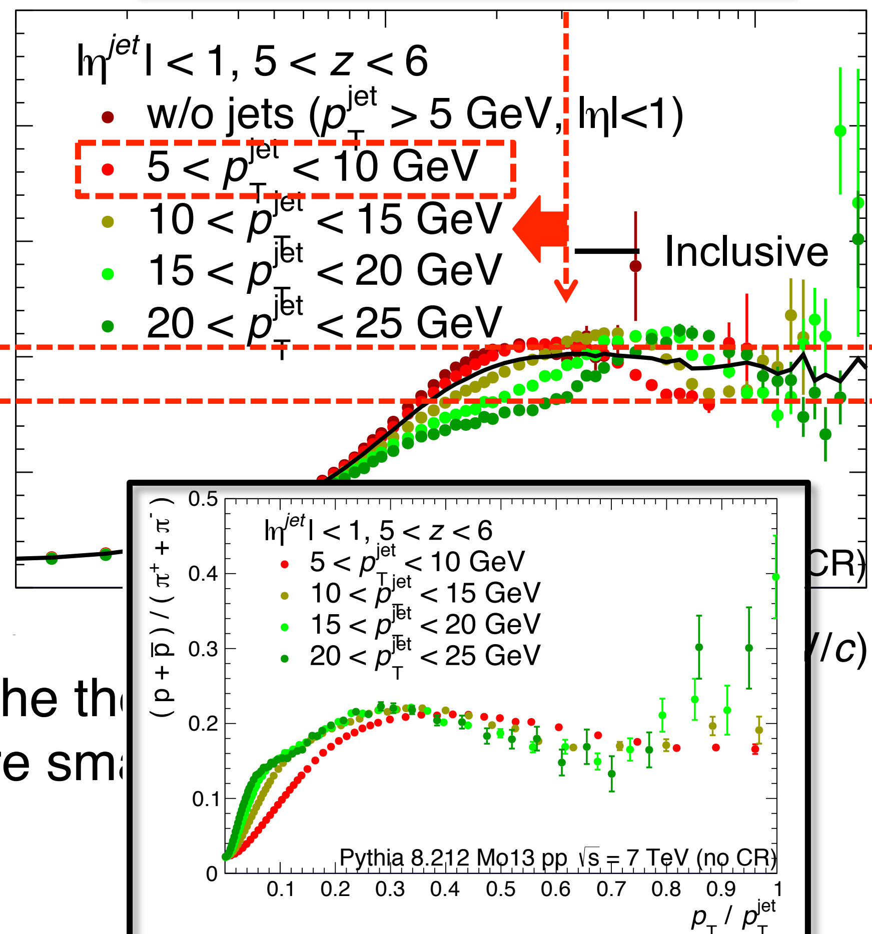
Without CR: p/π vs. p_T/p_T^{jet} is ≈p_T^{jet} independent (FF)

With Color Reconnection



Without Color Reconnection



- Larg … to the th
- With …) are sma
  - D