



21-27 September 2014

Las Negras – Cabo de Gata Natural Park,
Andalucia, Spain

From light- to heavy-quark fragmentation in jets: current measurements in pp collisions with the ALICE detector and perspectives

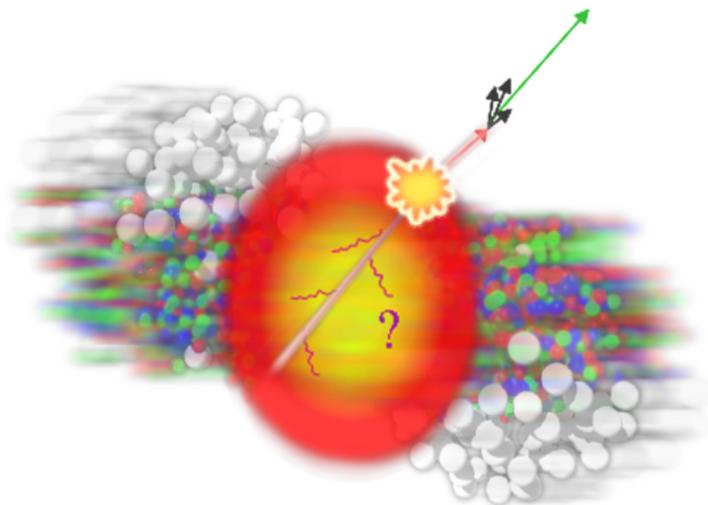
Chiara Bianchin for the ALICE Collaboration



Physics Utrecht

EMMEΦ

Medium effects on quark fragmentation

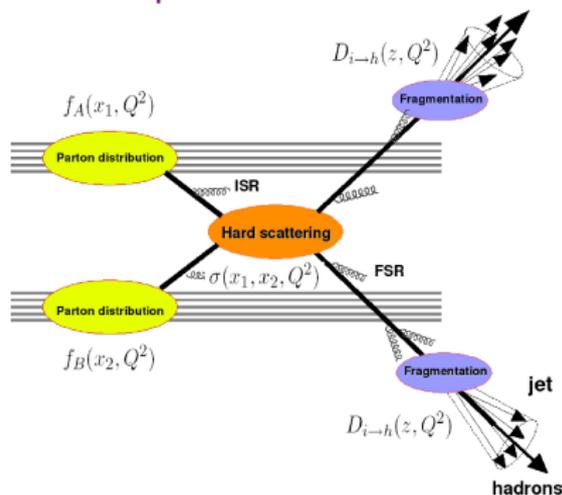


- ▶ The presence of a hot and dense medium influences the propagation and the fragmentation of quarks and gluons
- ▶ The effect depends on the type of parton and on its mass

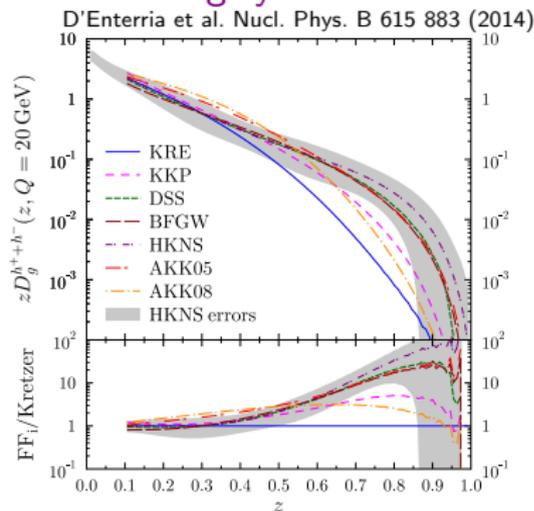
Benchmark: the reference measurements

- ▶ Reference (pp and pA) needed to understand medium effects
- ▶ Gluons dominate hadron production at the LHC, data from $e^+ - e^-$ collisions constrain mostly quark fragmentation functions (FF)

Hadron production factorization



Gluon FF largely unconstrained



Outline

Light flavours:

- ▶ Fragmentation function of charged and identified (p , K , π) particles in pp collisions
- ▶ Comparison with MC

Heavy flavours:

- ▶ Fragmentation function from e^+e^- and ep and comparison to models
- ▶ State-of-the-art in pp collisions at the LHC

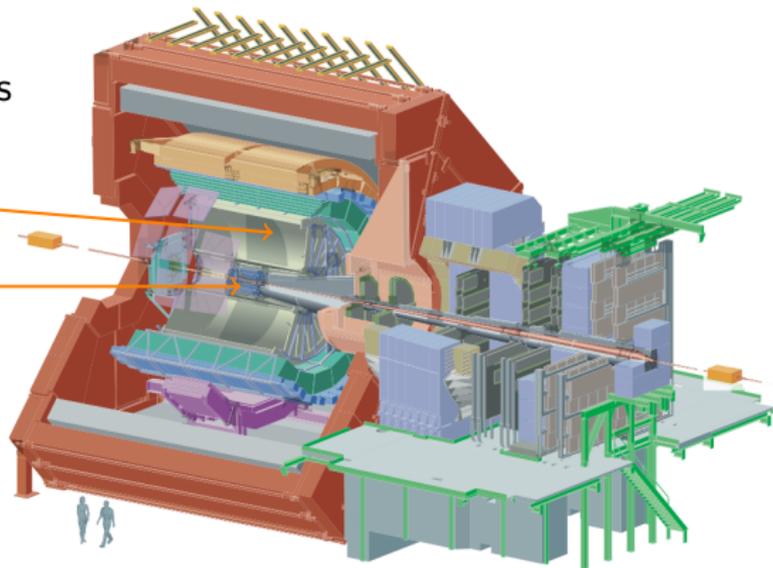
Conclusions & Outlook

Charged particle reconstruction

Tracking detectors

TPC

ITS



Definitions

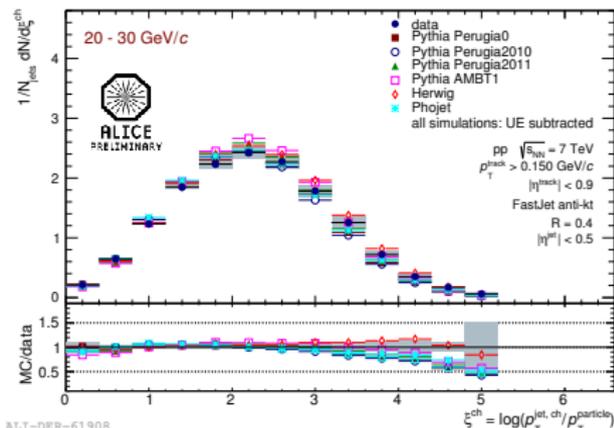
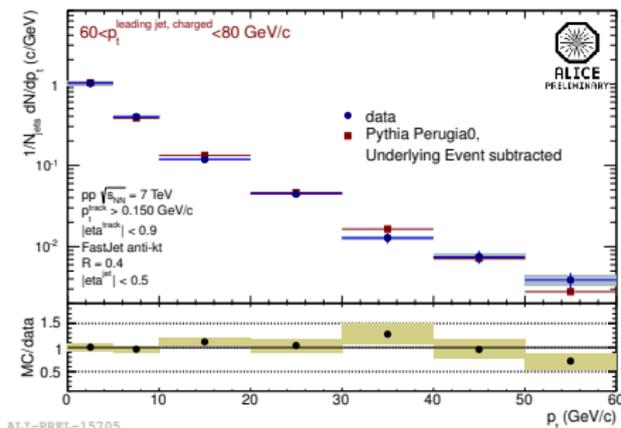
$$z^{\text{ch}} (= z) = p_{\text{T}}^{\text{track}} / p_{\text{T}}^{\text{jet, ch}}$$

$$\xi = \log \frac{1}{z}$$

All ALICE measurements shown are with **charged** jets

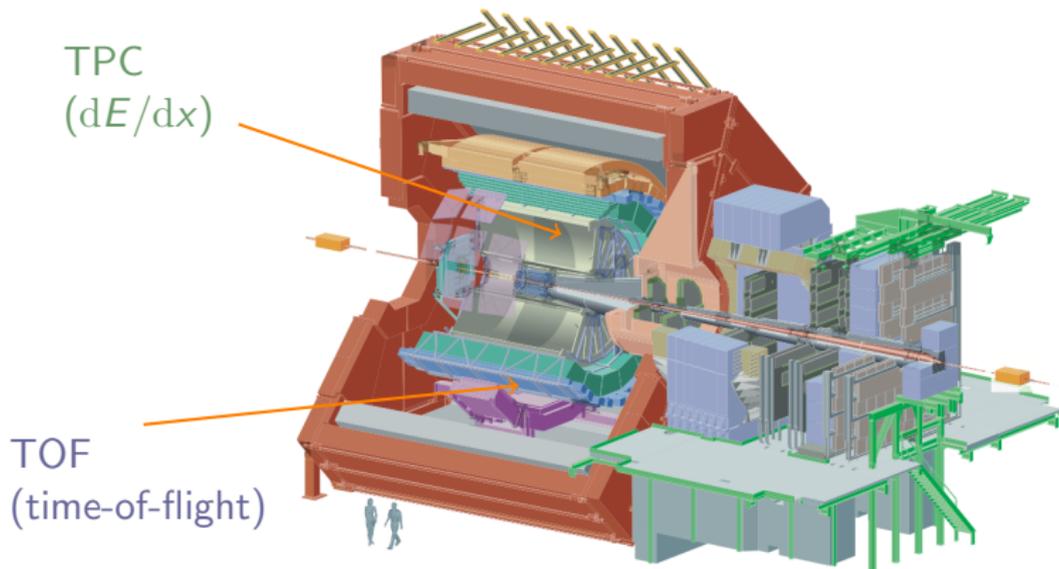
Charged particle distribution in jets

- ▶ Anti- k_T , $R = 0.4$, $p_{T, \text{track}} > 0.150 \text{ GeV}/c$, $|\eta_{\text{jet}}| < 0.5$, $|\eta_{\text{track}}| < 0.9$, $20 < p_T^{\text{jet, ch}} < 100 \text{ GeV}/c$



- ▶ ξ : common scaling for all $p_T^{\text{jet, ch}}$ up to $\xi < 2.3$ (about $z > 0.1$)
- ▶ Several Monte Carlo simulations reproduce the data
 - ▶ The yield in the high ξ region is underestimated by most event generators

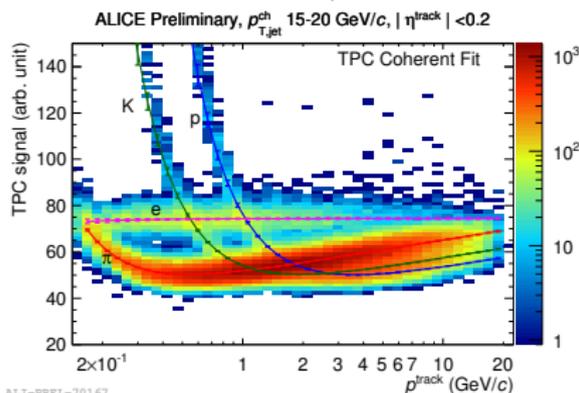
Particle Identification (PID)



Detectors used in this analysis

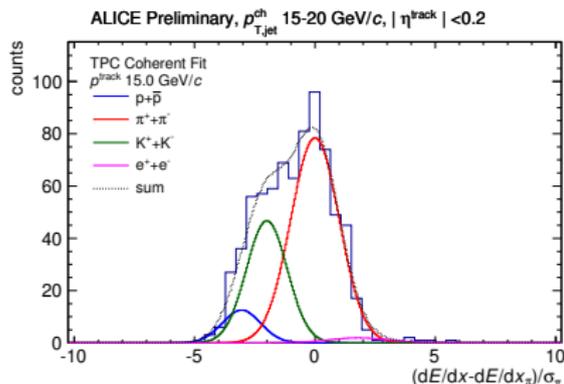
Advanced PID techniques

TPC dE/dx



ALI-PREL-70167

TPC Coherent Fit



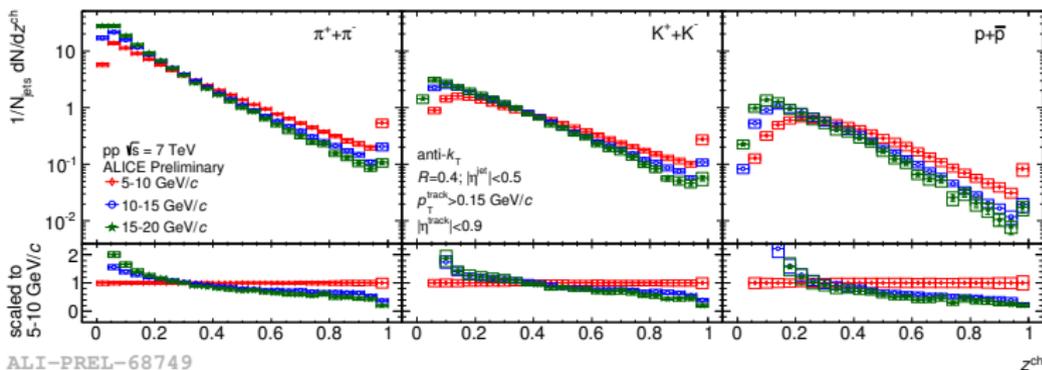
ALI-PREL-70175

- ▶ Particle separation at high p_T requires advanced techniques
- ▶ TPC Coherent Fit
 - ▶ Simultaneous fit of dE/dx model and particle fractions
 - ▶ Regularization imposing a smoothness conditions on the fractions X.G. Lu CERN-THESIS-2013-179
- ▶ TPC Multi-template Fit
 - ▶ Detailed parametrization of TPC signal using pure samples of π , K, p, e using TPC and TOF PID and topological selection of V0 decay
 - ▶ Fit in bins of p_T , z , or ξ with template B. Hees, arXiv:1408.5723 [hep-ex]

Particle yields in jets

- ▶ Final results with the TPC Coherent Fit method, charged jets
- ▶ Yields shown in 3 $p_{T,jet}$ bins 5-10, 10-15, 15-20 GeV/c

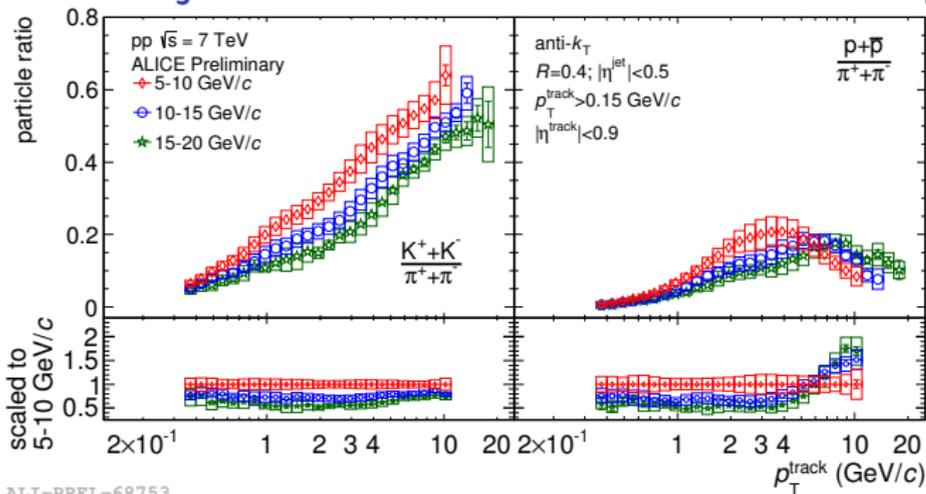
Yield
vs z



- ▶ p_T ordering with crossing at $z^{ch} \sim 0.3$ for all particles
- ▶ Peak at $z \approx 0.1$
- ▶ The yields almost scale for the two highest p_T bins

Particle fractions in jets

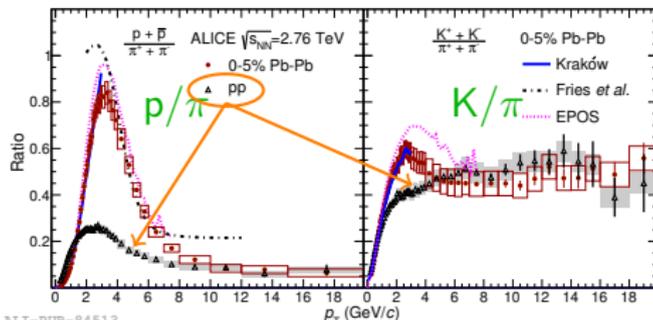
Particle ratio vs p_T



ALI-PREL-68753

ALICE Coll., Phys.Lett.B 736 (2014)

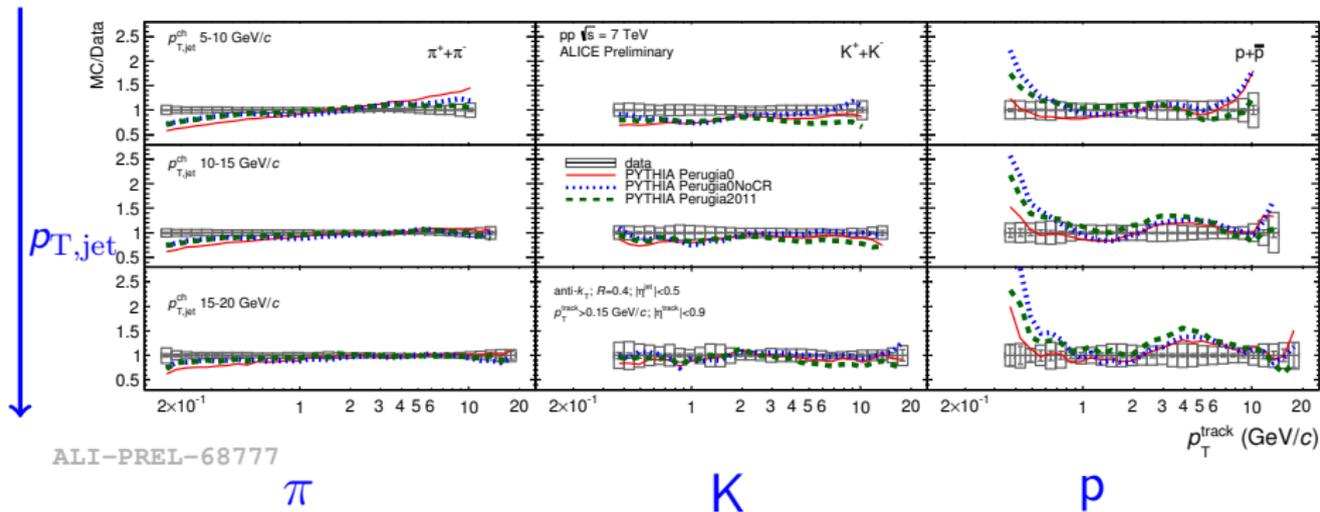
- ▶ Comparison with **inclusive** particle ratios
- ▶ Qualitative agreement with the ratios in jets ($5 < p_T^{\text{jet, ch}} < 10$ GeV/c)



ALI-PUB-84513

MC comparison of particle yields in jets

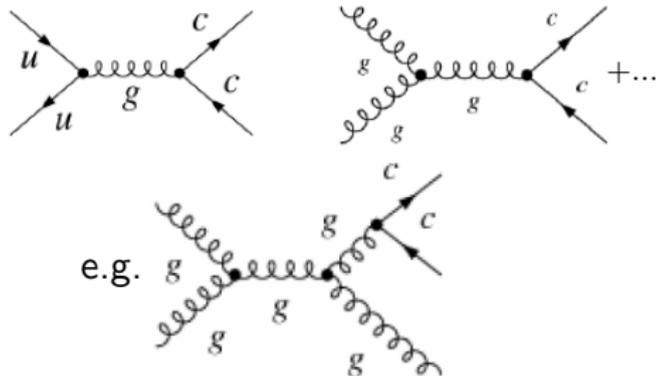
- ▶ PYTHIA different tunes reproduce particle yields reasonably
- ▶ Small deviation for low- p_T π
- ▶ p is reproduced worst, in particular at low- p_T^{track} and high- $p_{T,\text{jet}}$



Heavy flavours (charm and beauty)

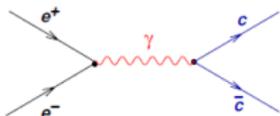
HF production

- ▶ At leading order a $c\bar{c}$ pair is produced via $q\bar{q} \rightarrow c\bar{c}$ or $gg \rightarrow c\bar{c}$
- ▶ At next-to-leading order other processes as gluon splitting contribute

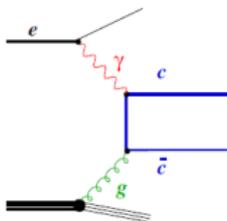


Charm fragmentation in D^{*+} meson

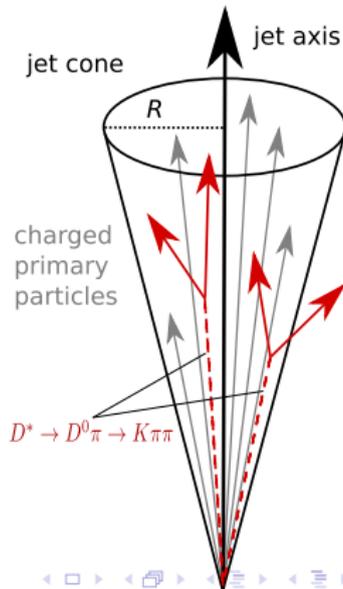
- ▶ Measure D^{*+} momentum fraction distribution with respect to the initial charm momentum



- ▶ In e^+e^- annihilation $E_C = E_{\text{beam}}$



- ▶ In hadronic collisions the quark energy is approximated by the reconstructed jet
- ▶ Charm jets can be identified requiring a D^{*+} (or other D mesons) in the jet cone

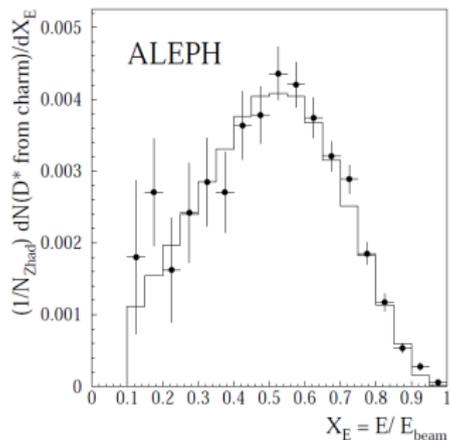
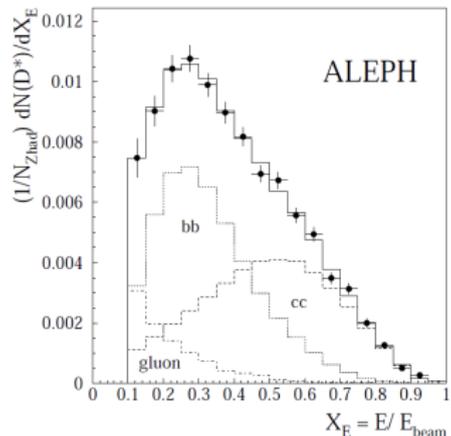


Fragmentation of heavy quarks

- ▶ $e^+ - e^-$ annihilations give a clean environment, estimation of HF-hadron momentum fraction wrt initial energy

$D^{*\pm}$ production from ALEPH EPJC 4 16(2000)

Extracted charm fragmentation function



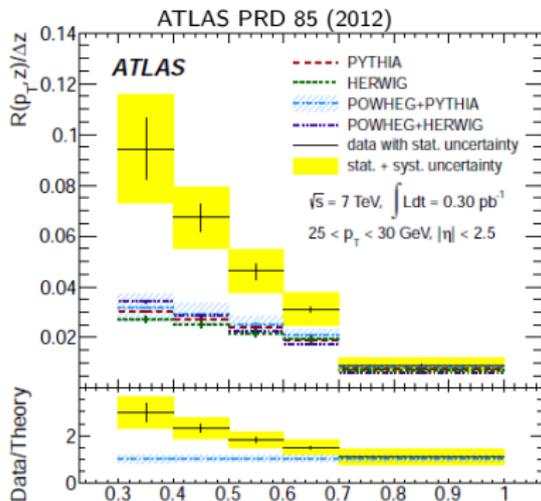
- ▶ $D^{*\pm}$ from $c\bar{c}, b\bar{b} \rightarrow B$, gluon splitting in $c\bar{c}/b\bar{b}$ pair
- ▶ JETSET MC and Peterson fragmentation Phys.Rev.D 105 27 (1983)

- ▶ Harder wrt light flavours
- ▶ Contributions from beauty and gluon splitting subtracted (data)

Charm in pp collisions at the LHC

Are the available models reliable for pp at $\sqrt{s} = 7$ TeV?

- ▶ $25 < p_{T,jet} < 70$ GeV/c,
 $p_T^{D^{*+}} > 7.5$ GeV/c, $|\eta| < 2.5$
- ▶ $0.3 < z < 1$
- ▶ Generators do not reproduce the low p_T and low z regions
 - ▶ Contribution from gluon splitting larger than predicted by pQCD?



$$R(p_T, z) = \frac{N_{D^{*+}}(p_T, z)}{N_{jet}(p_T, z)}$$

$z = p_{||}(D^{*+})/E(jet)$

Generator	process	parton shower	Hadronization	proton str.	UE
PYTHIA 6.421	LO pQCD	p_T -ordered	Lund string model	MSTW LO	multi-part int
HERWIG 6	LO pQCD	angle-ordered	cluster model		multi-part int
POWHEG	NLO pQCD	leading-log	PYTHIA/ HERWIG	CTEQ 6.6	

What do we know on heavy-flavour particle production in pp collisions?

- ▶ Charm fragmentation is harder than that of light quarks/gluons
- ▶ A small fraction of charm quarks is produced by gluon splitting and has softer fragmentation
- ▶ The description of D^{*+} production rate in jets at the LHC by models is not satisfactory

What is missing?

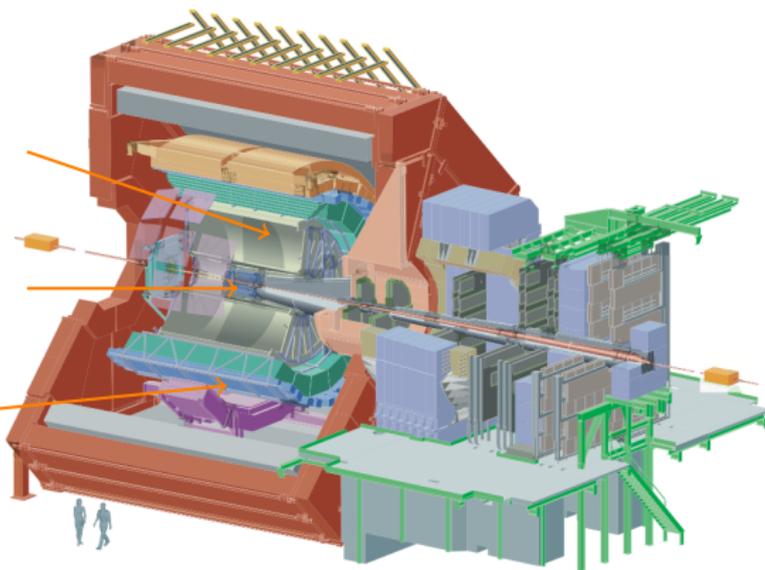
- ▶ Need more precise measurements from hadronic collisions, mostly at low z

D-meson reconstruction in ALICE

TPC (tracking,
PID via dE/dx)

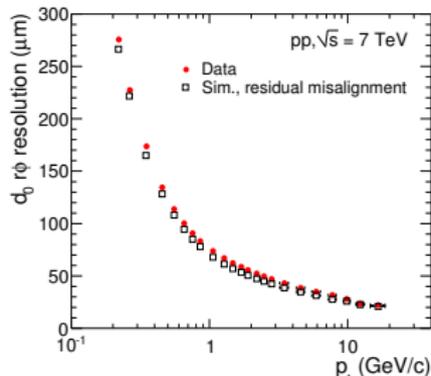
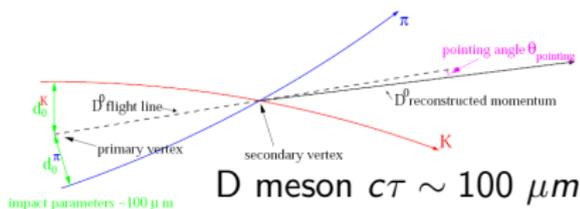
ITS (tracking,
vertex, and im-
pact parameter
resolution)

TOF (PID via
time-of-flight)



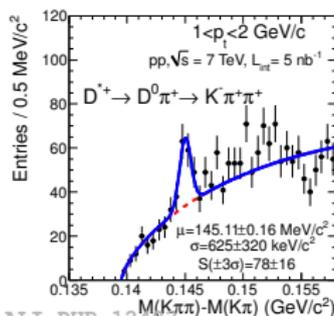
D meson reconstruction in ALICE

1. PID TOF+TPC
2. Topological selections
3. Invariant mass analysis

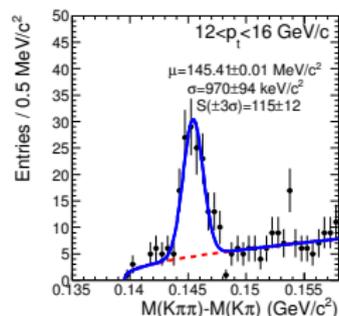
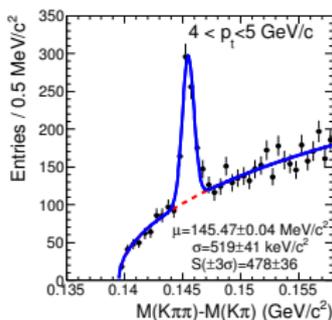


ALICE Coll. JHEP 01 128 (2012)

- $\sqrt{s} = 7 \text{ TeV } D^{*+}$ cross section in the range $1 < p_T < 24 \text{ GeV}/c$



ALI-PUB-12463

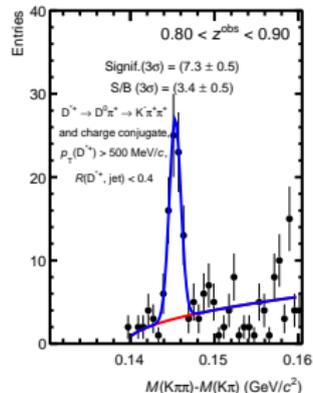
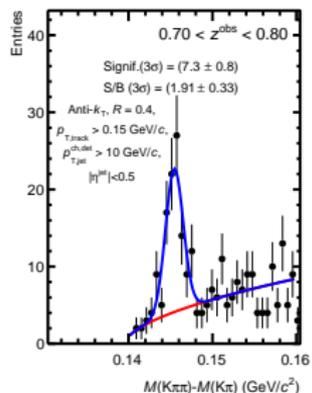
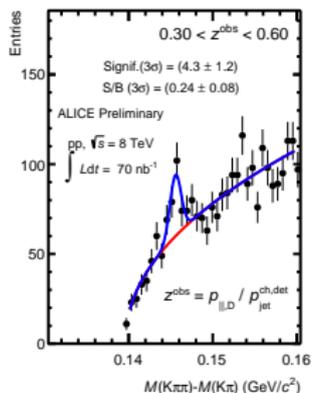


D^{*+} in jets in ALICE

- ▶ $L_{\text{int}} = 200 \text{ nb}^{-1}$ pp collisions at $\sqrt{s} = 8 \text{ TeV}$ (EMCal triggered)
- ▶ Anti- k_T , charged jets, $R = 0.4$, $p_{T,\text{track}} > 0.15 \text{ GeV}/c$
- ▶ D^{*+} in jets $\equiv R(D, \text{jet}) < 0.4$

$$R(D, \text{jet}) \equiv \sqrt{(\varphi_{D^{*+}} - \varphi_{\text{jet}})^2 - (\eta_{D^{*+}} - \eta_{\text{jet}})^2}$$

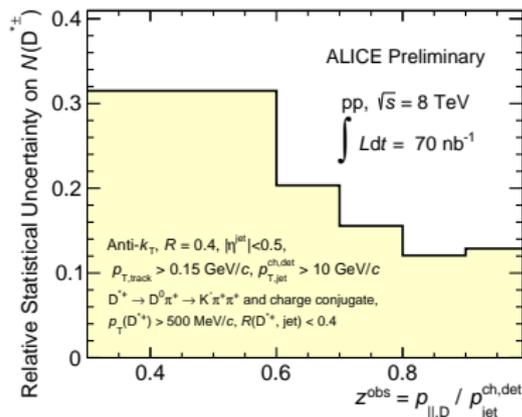
D^{*+} in jets in bins of z^{obs}



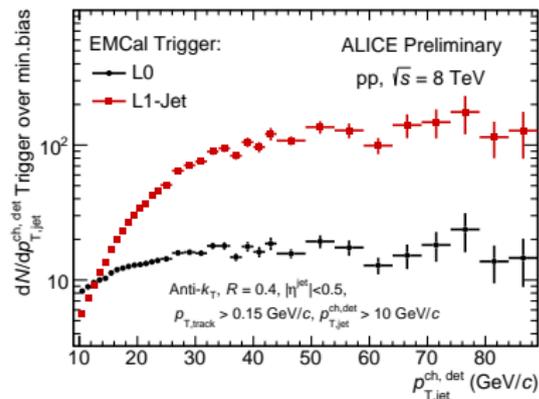
▶ $p_T^{\text{jet,ch}} > 10 \text{ GeV}/c$

▶ D^{*+} in jets signal in $0.3 < z^{\text{obs}} < 1$

Perspectives



- ▶ Statistical uncertainties still large in the low- z^{obs} region
- ▶ With LHC-Run2 (2015-2017) expected up to $L_{\text{int}} = 40 \text{ pb}^{-1}$ (about $\times 100$ more)



- ▶ The triggered sample requires a larger $p_{T,\text{jet}}$ cut
- ▶ In Run2 (2015) 4G MB events foreseen, no trigger bias. Low p_T accessible?

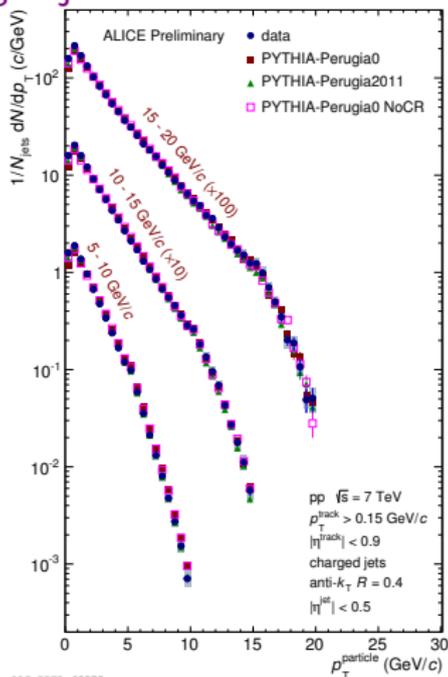
Summary and outlook

- ▶ pp reference is crucial to study medium effect in jets fragmentation
- ▶ ALICE measured jet fragmentation into charged particles
 - ▶ Common scaling for $z > 0.1$
 - ▶ PYTHIA simulations OK, difficulties to reproduce low z
- ▶ ALICE measured jet fragmentation into Identified Particles
 - ▶ Strangeness content increases, leading baryon decreases
 - ▶ PYTHIA simulations OK, difficulties to reproduce low z protons
- ▶ Outlook: Comparison to FF at higher- $p_{T,jet}$, test universality of FF
 - ▶ Run2: PID FF up to $p_{T,jet} = 100$ GeV/ c
- ▶ Heavy flavour measurements with Run 2 data

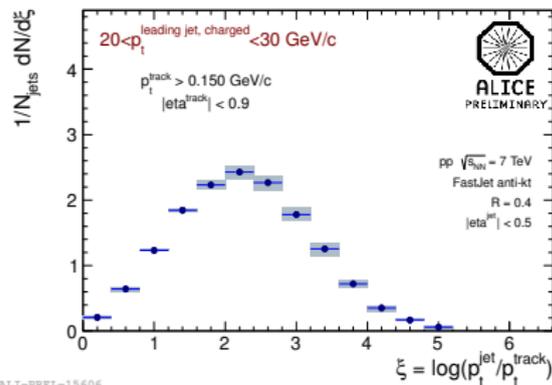
More pp measurements needed for both light and heavy flavours! Looking forward for Run 2 and ALICE upgrade

Charged track distribution in jets in pp collisions

p_T distribution of fragments in charged jets



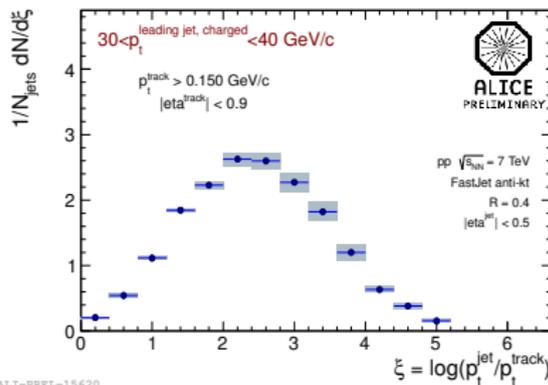
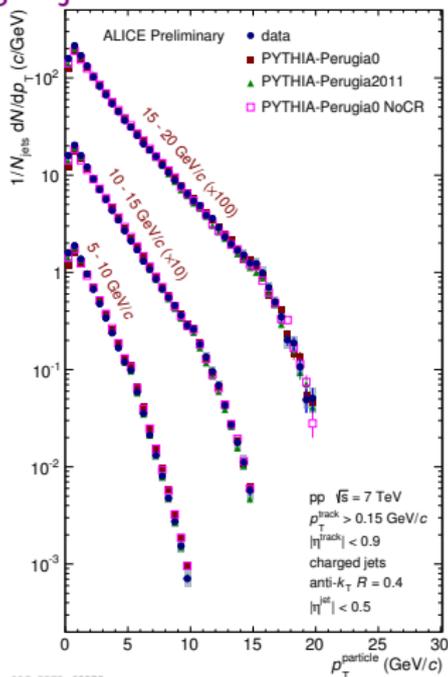
- ▶ Primary particles
- ▶ no underlying event subtraction



- ▶ ξ distribution of charged track within charged jets in pp collisions at $\sqrt{s} = 7$ TeV
- ▶ Underlying event subtracted
- ▶ ξ is following a common scaling for $20 < p_{T,\text{jet}} < 100$ GeV/c up to $\xi < 2.3$ (about $z > 0.1$)

Charged track distribution in jets in pp collisions

p_T distribution of fragments in charged jets



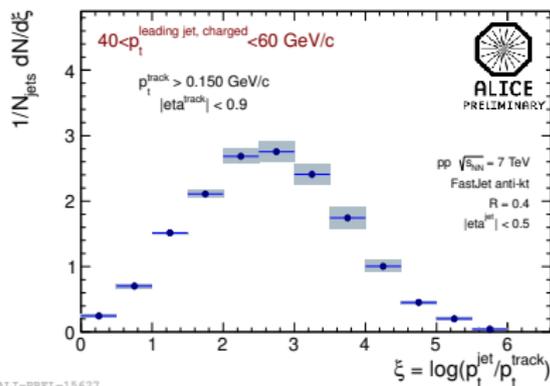
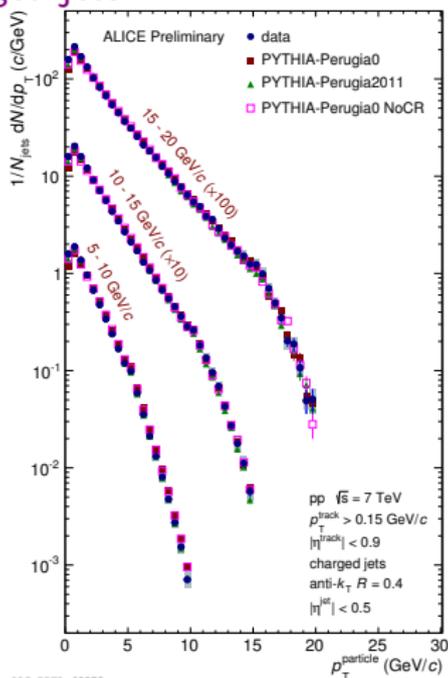
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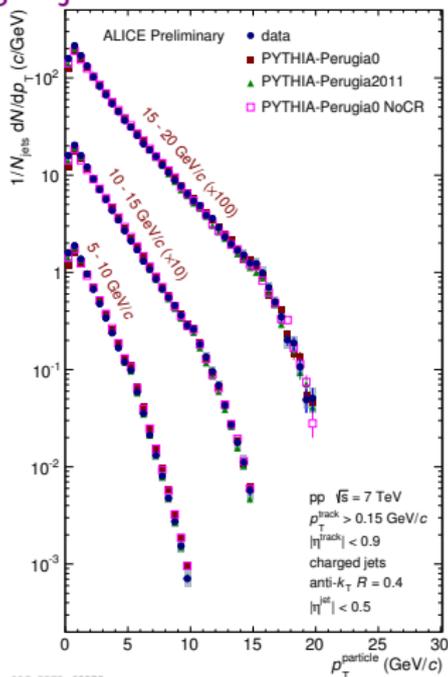
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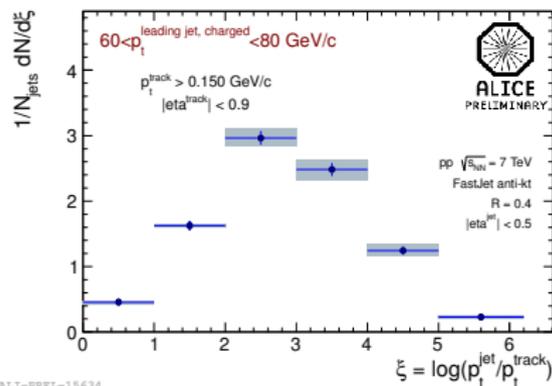
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Charged track distribution in jets in pp collisions

p_T distribution of fragments in charged jets



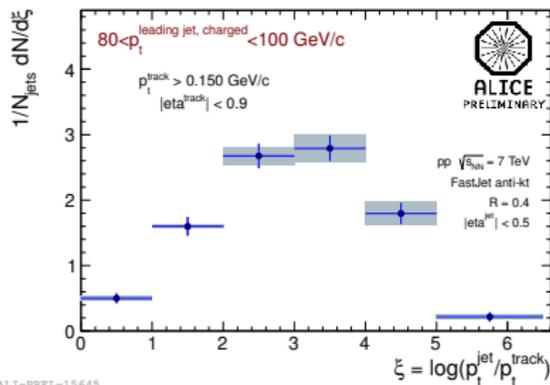
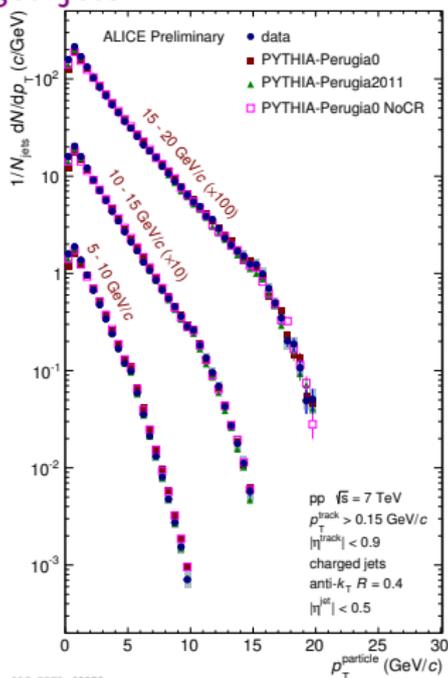
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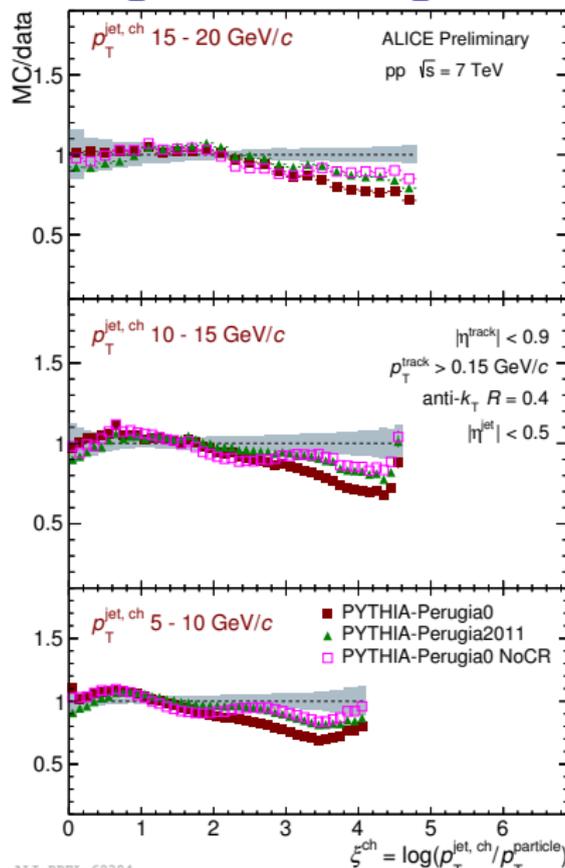


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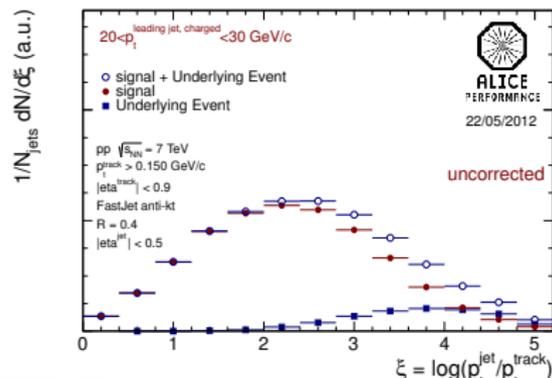
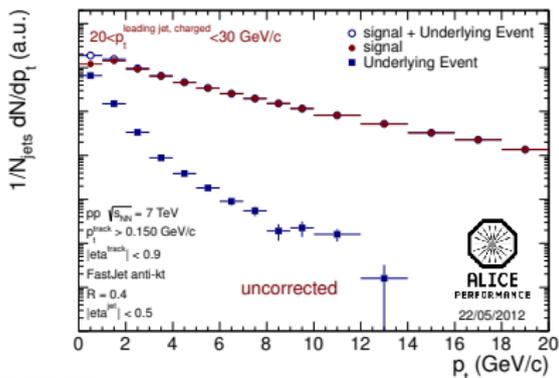
MC comparisons charged track fragmentation



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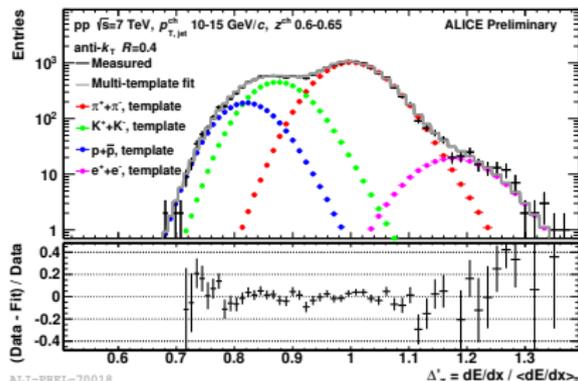
Underlying event subtraction

- ▶ Underline Event = pp event activity not related to hard scattering
 - ▶ In MC: initial state gluon radiation, multiple partonic interactions, and beam remnants. Final-state radiation also contributes
- ▶ Experimentally it can be measured via particles measured in a region distinct from a reconstructed jet, e.g. a transverse region
 - ▶ “Perpendicular cone” method: two cones of $R=0.4$ placed perpendicular to the jet axis at $\varphi = \varphi^{\text{jet}} \pm \pi/2$ and $\eta = \eta^{\text{jet}}$.
 - ▶ the $dN/d\eta$ distributions of the perpendicular cones as well as the η integration range of the tracks follows exactly the jet cones
 - ▶ small φ integration range, minimizes the susceptibility to NLO effects

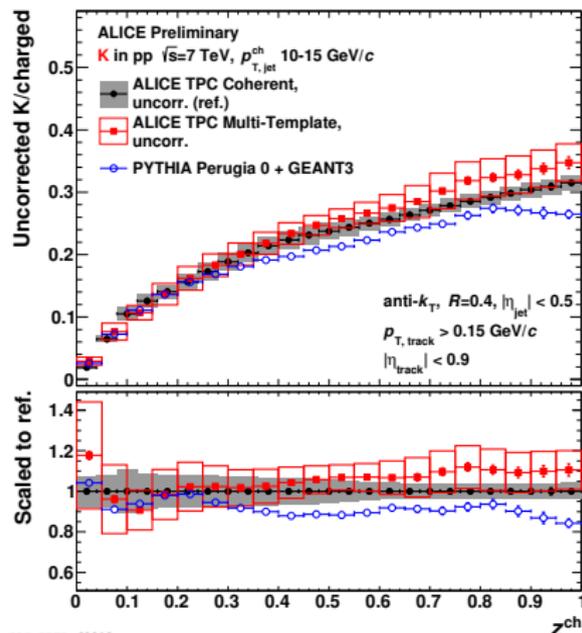


Advanced PID techniques – TPC Multi-template Fit

- ▶ The analysis is cross-checked with the TPC Multi-template Fit
- ▶ Detailed parametrization of TPC signal using pure samples of π , K, p , e using TPC and TOF PID and topological selection of V0 decay
- ▶ Fit the measured distribution in bins of p_T , z , or ξ with templates

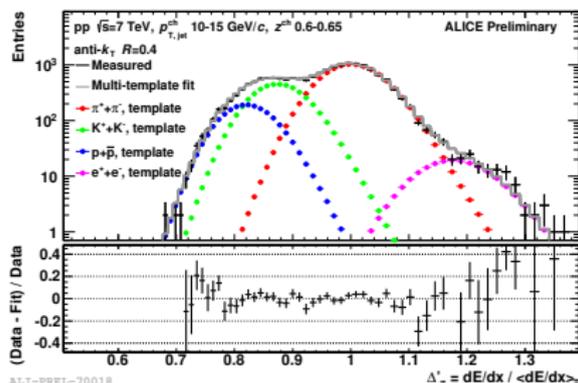


B. Hees, arXiv:1408.5723 [hep-ex]

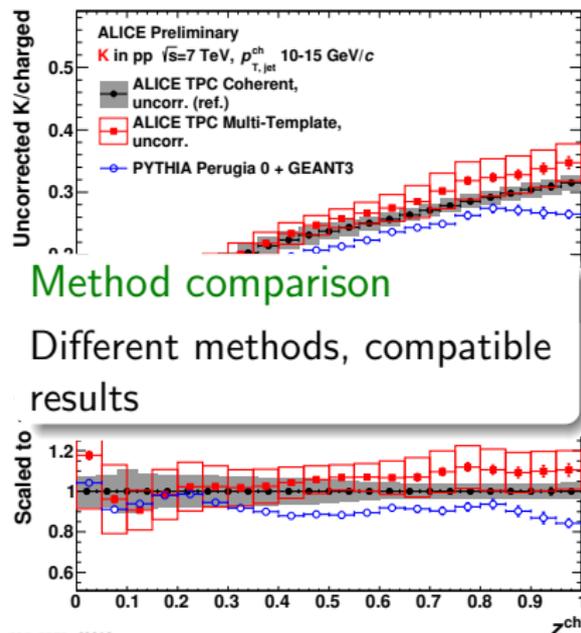


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B. Hees, arXiv:1408.5723 [hep-ex]



More on Coherent Fit

Definitions

Overall signal shape: $\sum_k A_k(p) G(\Delta; \mu, \sigma)$, Δ is the TPC signal, μ and σ the Gaussian (G) mean and width depending on two sets of parameter (**a** and **b**) and on the particle velocity p/m , A_k is the fraction of particle k normalized at $p \sum_k A_k(p) = 1$

Likelihood function

$$l = l_{\text{stat}} + l_{\text{reg}}$$

$$l_{\text{stat}} = \sum_i \sum_j \ln P(w_i f_i(p_i, \Delta_j); w_i \sum_k A_k(p_i) G(\Delta_j; \mu(p_i/m_k, \mathbf{a}), \sigma(\mu, \mathbf{b}))),$$

$$\sum_j f_j(p_i, \Delta_j) = 1, w_i = \min\{C, N_i\} \text{ with } N_i \text{ counts in the bin and } C$$

number, $P(n; \bar{n}) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$ Poisson probability density function

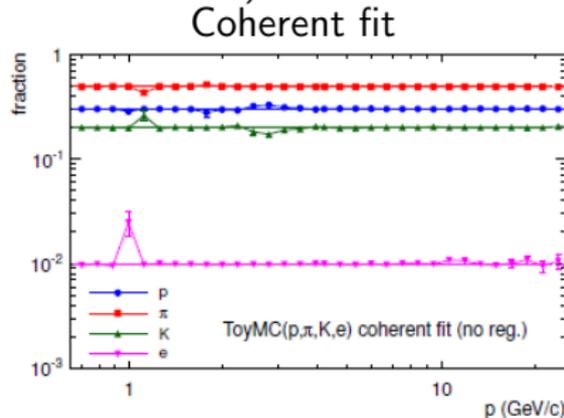
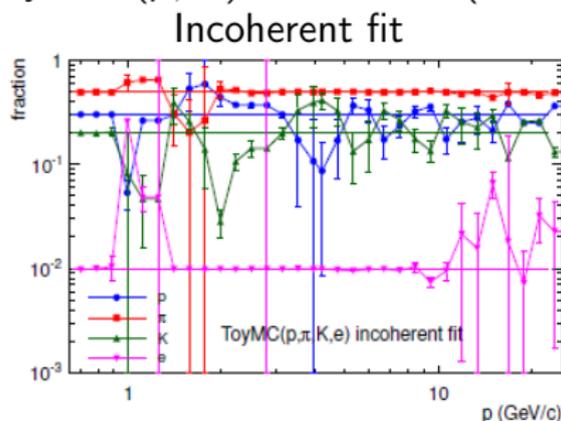
$$l_{\text{reg}} = -\sum_i \sum_k \frac{[A_k(p_i) - \hat{A}_{ki}]^2}{2\delta_{ki}}, \hat{A}_{ki} \text{ } k\text{-particle fraction interpolated from}$$

neighbouring values $A_k(p_{i-1})$ and $A_k(p_{i+1})$, $\delta_{ki} = \sqrt{w_i \frac{A_k(p_i) + \hat{A}_{ki}}{2}} / w_i$ error on $A_k(p_i)$

Advantage of the Coherent fit

- ▶ The maximization of l_{stat} drives the free parameters $A_k(p_i)$, \mathbf{a} , and \mathbf{b}
- ▶ The constructed $\sum_k A_k(p) G(\Delta; \mu, \sigma)$ describes the observed distribution in every p -bin simultaneously (*coherent fit*)
- ▶ l_{stat} can be defined and maximized in each p bin separately (*incoherent fit*)

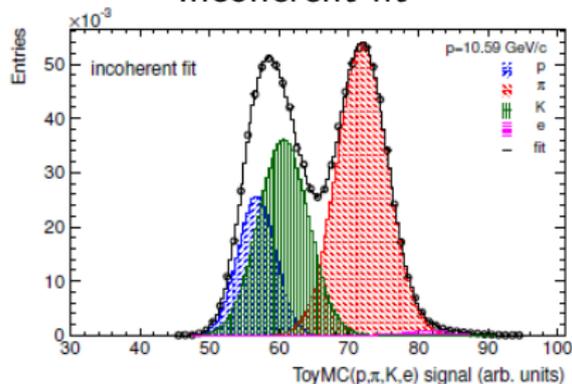
Toy MC (p, Δ)-distribution (from X.G. Lu CERN-THESIS-2013-179)



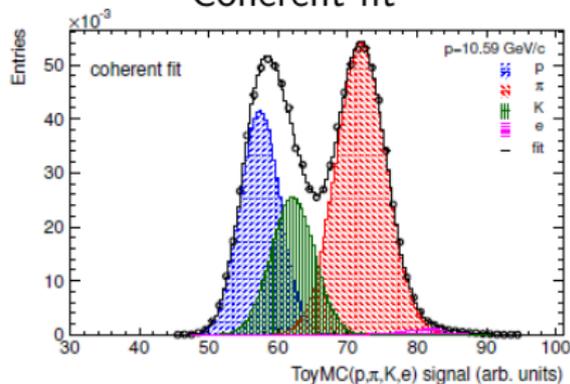
Regularization parameter (l_{reg})

Fit at a given momentum p (from X.G. Lu CERN-THESIS-2013-179)

Incoherent fit



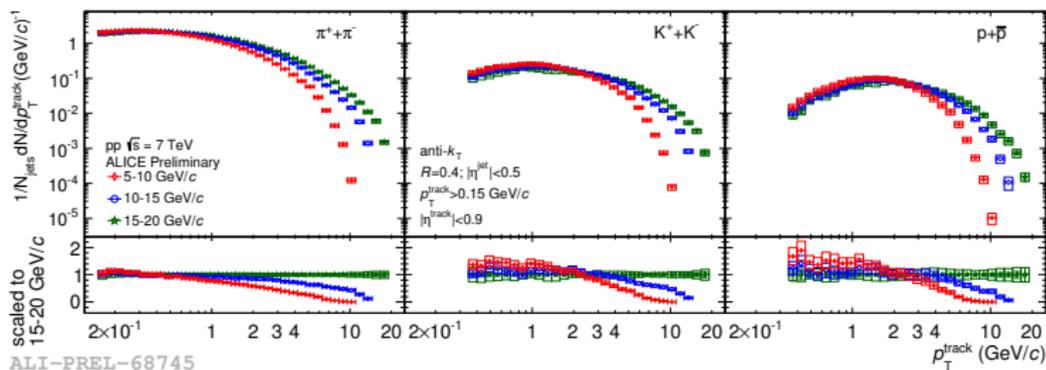
Coherent fit



- ▶ Bias due to the ambiguity of two overlapping distribution
- ▶ The bias happen at the crossing of p-e, π -K, π -p, and p-K
- ▶ Regularization term removes the ambiguity: $A_k(p_i)$ required to be continuous modulo statistical fluctuations (polynomial interpolation of ± 1 neighbouring bins used)

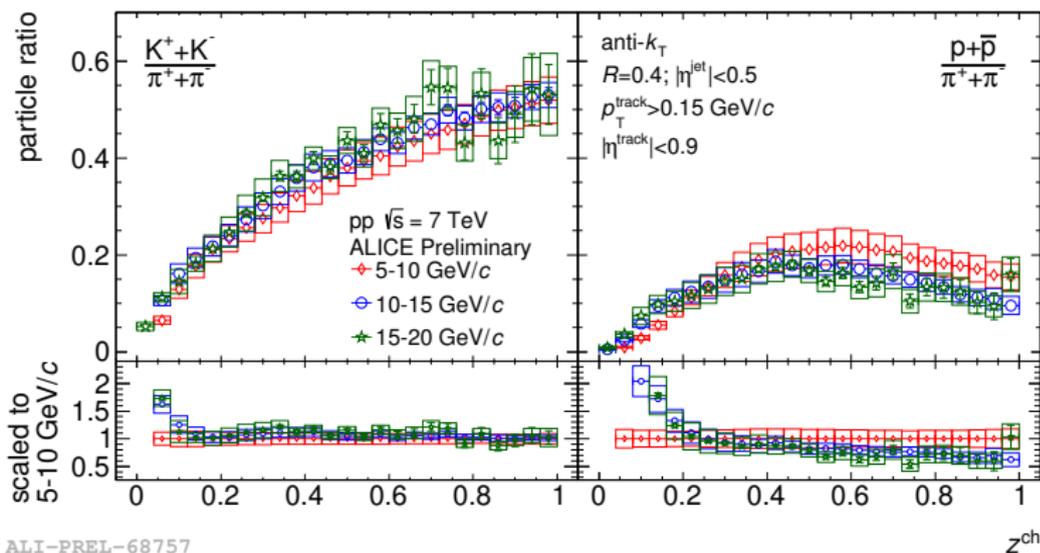
Particle yields in jets

- ▶ Final results with the TPC Coherent Fit method, charged jets
- ▶ Yields shown in 3 $p_{T,jet}$ bins 5-10, 10-15, 15-20 GeV/c

 p_T


- ▶ p_T ordering with crossing at $p_T \sim 2$ GeV/c for K and p

Particle fractions in jets



- ▶ Increasing strangeness fraction
- ▶ Leading baryon suppression

What do we learn on light particle production in pp collisions?

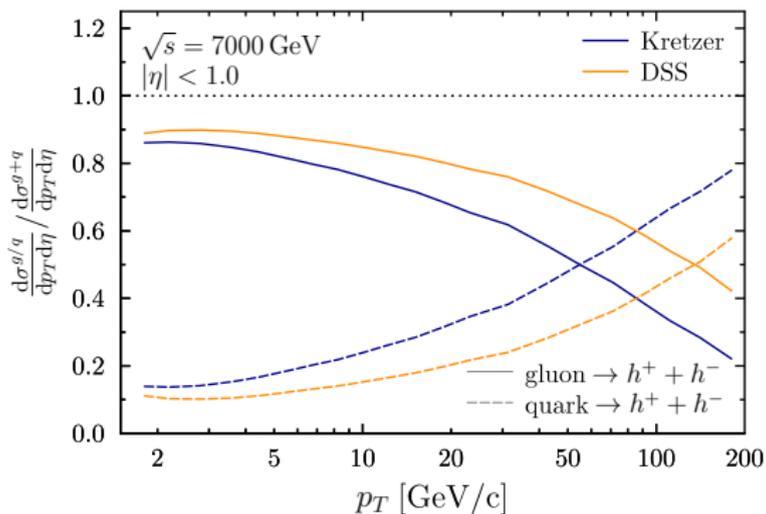
- ▶ The strangeness fraction increases with z^{ch} , while the baryon production is suppressed at high z^{ch}
- ▶ PYTHIA simulations are able to reproduce the data within 30% accuracy, with increasing tension at low p_T

Perspectives for Run2 (pp at $\sqrt{s} = 13$ TeV):

- ▶ From charged jets to full jets to reconstruct all the jet energy (closer to the parton energy)
- ▶ Compare with FF parametrization for gluon, dominant at the LHC

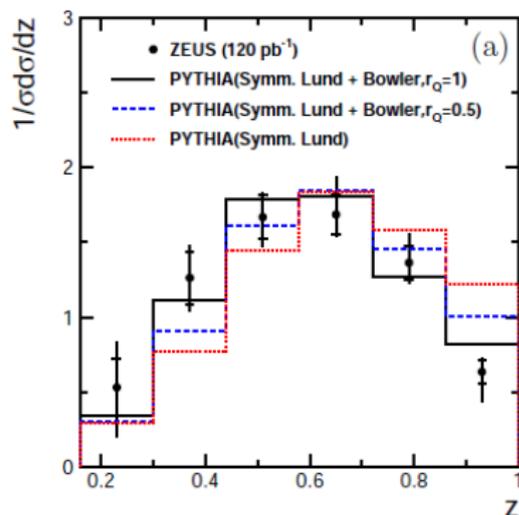
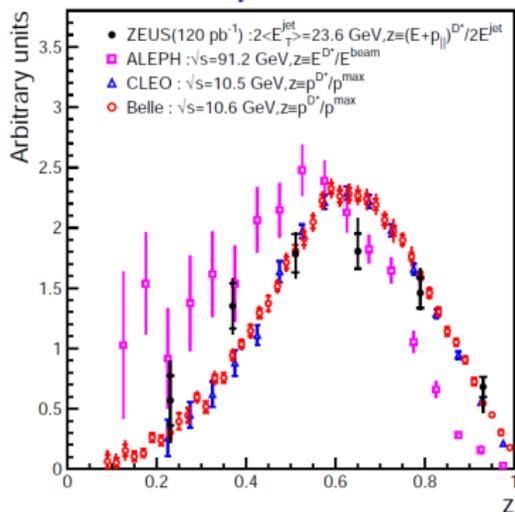
Contribution from gluon and quarks in hadron production

pp 7 TeV



arXiv:1311.1415

e^+e^- and ep collisions



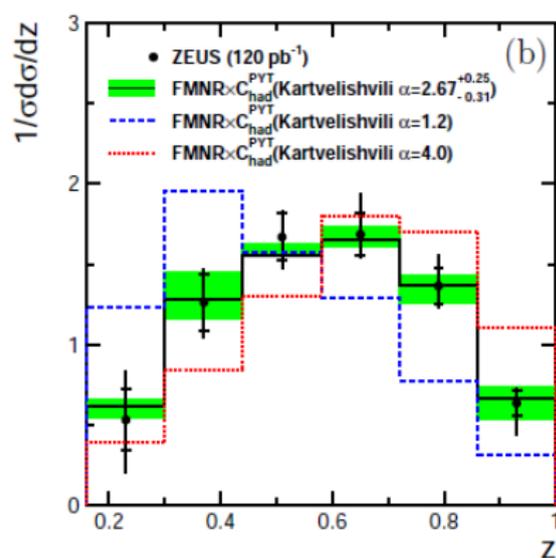
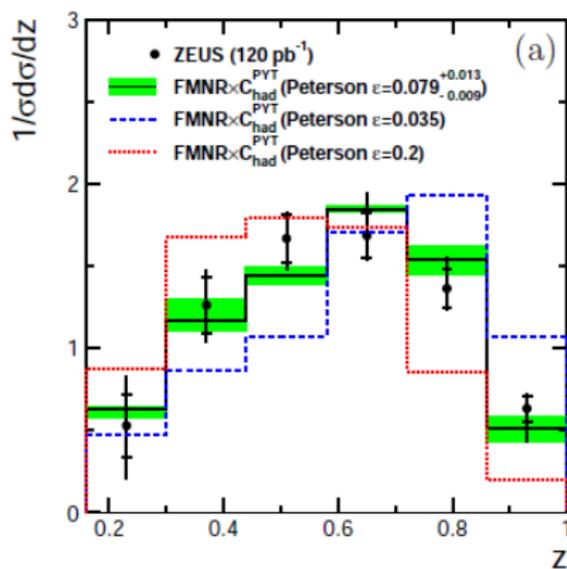
- ▶ Similar results in e^+e^- and ep
- ▶ Not equal definition of z , energy
 - ▶ $\langle z \rangle$ consistent with scaling from QCD

- ✓ PYTHIA + different FF (Peterson or Lund+Bowler for HF)
- ✓ NLO QCD + (Peterson or Kartvelishvili) not shown

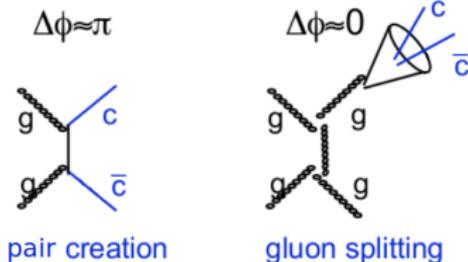
The FF param depends on the scale and colour connection ($e^+e^- \neq ep$)

ZEUS results compared to NLO pQCD calculations

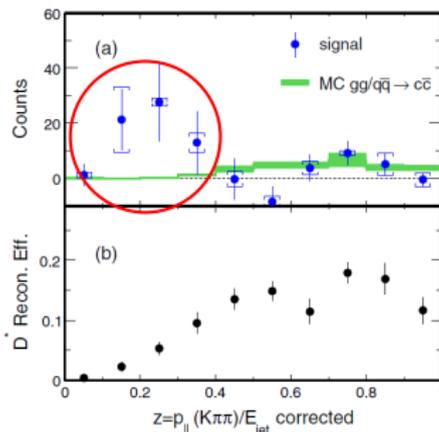
- ▶ Fixed-order calculation from Frixione et al. (FMNR)
- ▶ Hadronization correction factor from PYTHIA



Charm production: contribution from gluon splitting



- ▶ $g \rightarrow c\bar{c}$ is expected (pQCD) to be a small contribution
- ▶ **Simulation** including direct charm creation (from gg or $q\bar{q}$) reproduce high z . Other processes dominate at low z
- ▶ STAR results ($\sqrt{s} = 200$ GeV) confirm gluon splitting is small with respect to the total charm cross section



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