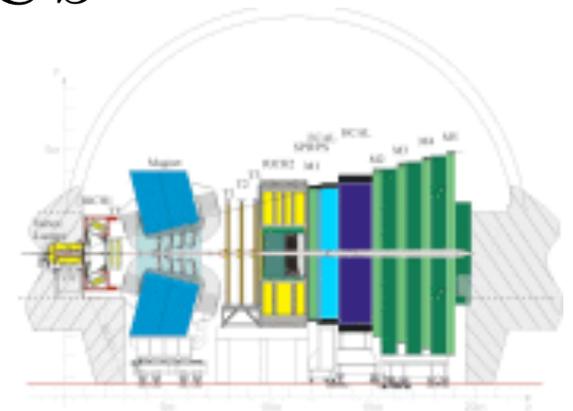




Studies of Jet Fragmentation and Hadronisation at LHCb

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on behalf of the LHCb collaboration

EPS-HEP

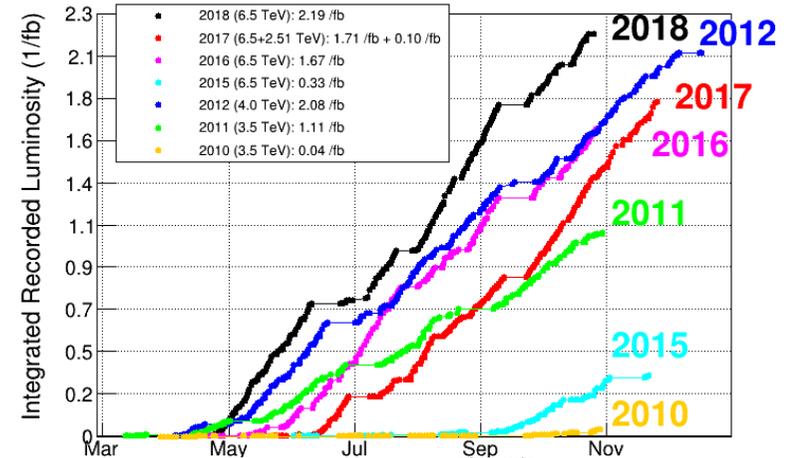
Ghent, Belgium, July 10th – 17th 2019

Jet studies at LHCb

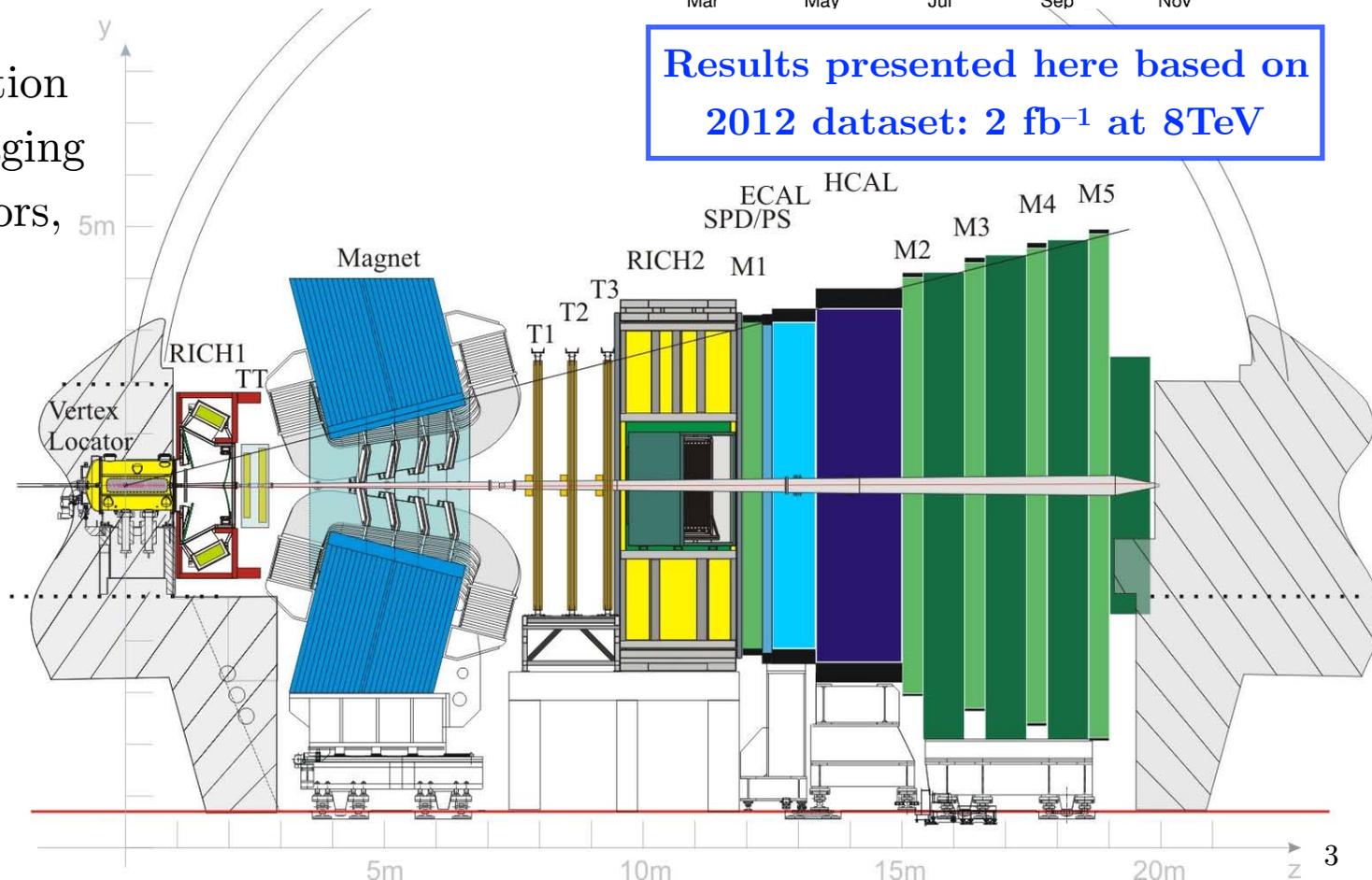
- Many jet-physics results at large rapidity from the LHCb experiment, e.g.:
 - “Study of forward Z +jet production in pp collisions at $\sqrt{s}=7\text{TeV}$ ”, JHEP 01 (2014) 33
→ $\sigma_{Z+\text{jet}} = 6.3 \pm 0.1 \pm 0.5 \pm 0.2 \text{ pb}$ ($p_{\text{T}} > 20 \text{ GeV}/c$ and $2 < \eta < 4.5$)
 - “Measurement of the Z + b -jet cross-section in pp collisions at $\sqrt{s}=7\text{TeV}$ in the forward region”, JHEP 01 (2015) 064
→ $\sigma_{Z+b\text{-jet}} = 128 \pm 36 \pm 22 \pm 5 \text{ fb}$ ($p_{\text{T}} > 20 \text{ GeV}/c$ and $2 < \eta < 4.5$)
 - “Measurement of forward W and Z boson production in association with jets in proton-proton collisions at $\sqrt{s}=8\text{TeV}$ ”, JHEP 05 (2016) 131
→ $\sigma_{Z+\text{jet}} = 5.71 \pm 0.06 \pm 0.27 \pm 0.07 \text{ pb}$ ($p_{\text{T}} > 20 \text{ GeV}/c$ and $2.2 < \eta < 4.2$)
→ high Z +jet purity of 97.8%
 - “Study of J/ψ production in jets”, Phys. Rev. Lett. 118 (2017) 192001
→ measured fraction of jet p_{T} carried by the J/ψ
- Today, present recent results on the study of Z -tagged jet structure and hadronisation in pp collisions at 8TeV:
 - Measurement of charged hadron production in Z -tagged jets in proton-proton collisions at $\sqrt{s}=8\text{TeV}$, arXiv:1904.08878 (submitted to Phys. Rev. Lett.)

The LHCb detector

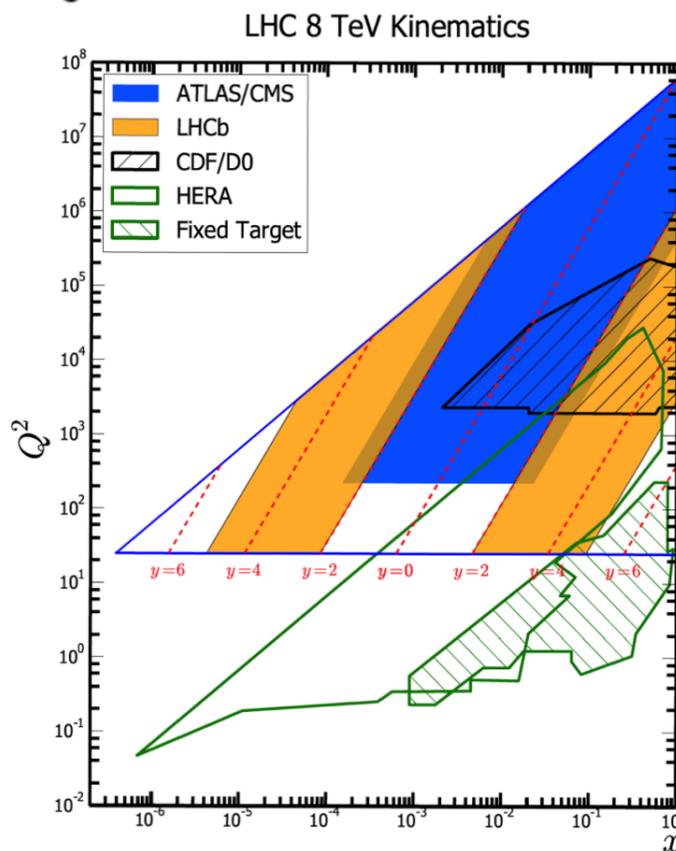
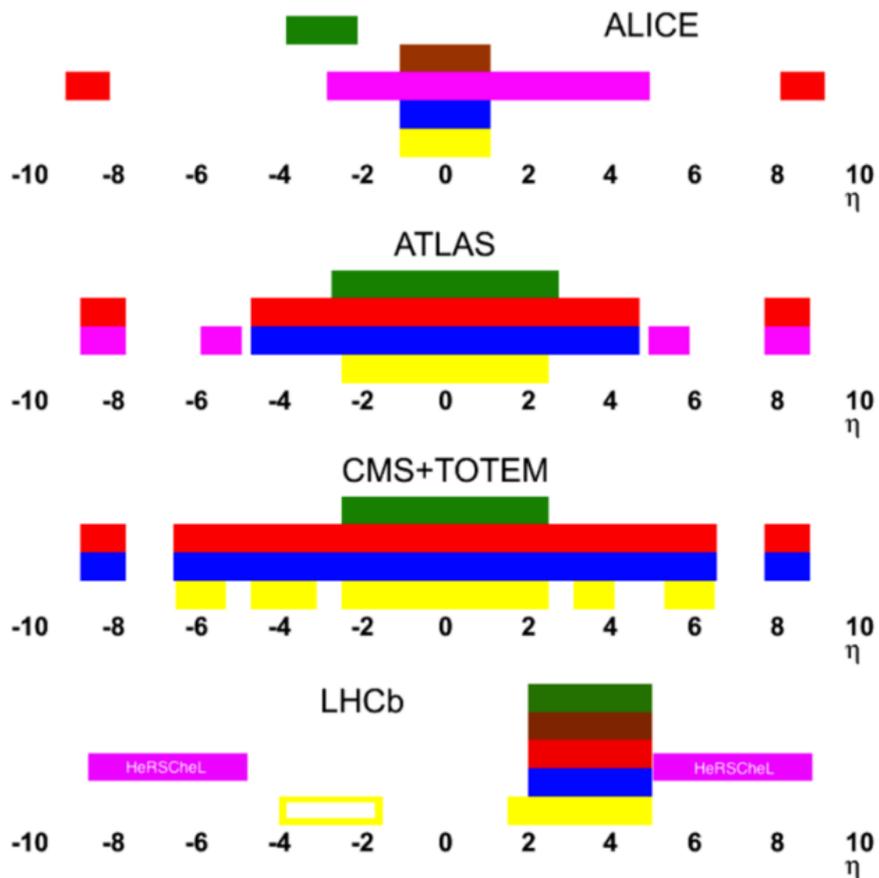
- LHCb is a single-arm forward spectrometer at the LHC ($2 < \eta < 5$)
- Fully instrumented in the forward region
 - excellent vertex resolution
 - tracking stations before and after 4Tm dipole magnet
 - particle identification with two ring-imaging Cherenkov detectors, calorimeters and muon detectors



Results presented here based on 2012 dataset: 2 fb⁻¹ at 8TeV



LHCb vs other LHC experiments



Unique (pseudo)rapidity coverage at LHCb ($2 < \eta < 5$), with uniform tracking, PID, and calorimetry on this range
 \Rightarrow identification of all particles within jets

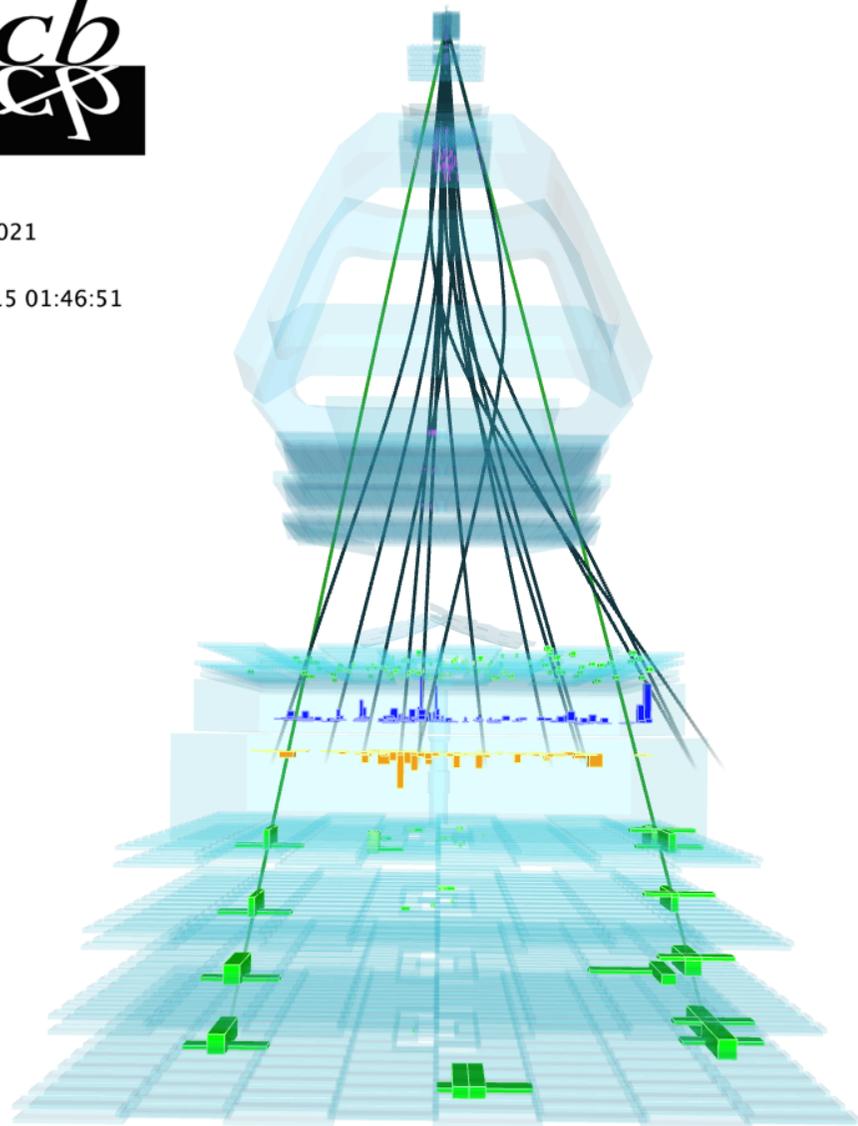
LHCb occupies a unique region in (Q^2, x) space

Z+jet events in pp collisions

- Z+jet cross section in the forward direction ≈ 6 pb at LHC energies
- The Z+jet topology selects preferentially light quark jets, while inclusive jets are gluon dominated
- Studies of the jet structure in Z+jet events will provide an improved understanding of the fragmentation functions
→ input to simulation (e.g. PYTHIA)
- Experimentally, the clean $Z \rightarrow \mu^+ \mu^-$ signature allows to achieve a high signal-to-noise ratio in Z+jet event selection



Event 537023021
Run 157596
Sat, 11 Jul 2015 01:46:51



Observables

- The following variables are used to characterise the jet structure:

- longitudinal momentum fraction:

$$z = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{hadron}}}{|\vec{p}_{\text{jet}}|^2}$$

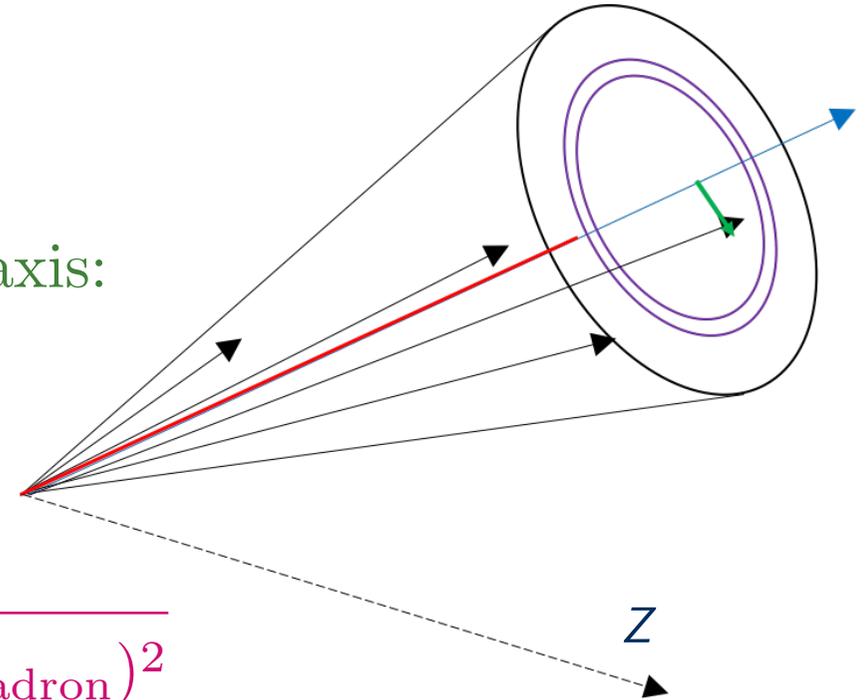
- momentum transverse to the jet axis:

$$j_{\text{T}} = \frac{|\vec{p}_{\text{jet}} \times \vec{p}_{\text{hadron}}|}{|\vec{p}_{\text{jet}}|}$$

- radial distribution:

$$r = \sqrt{(\phi_{\text{jet}} - \phi_{\text{hadron}})^2 + (y_{\text{jet}} - y_{\text{hadron}})^2}$$

- These variables are measured for each hadron in the jet, and normalised distributions are obtained



Analysis strategy

- Similar analysis strategy as previously used by ATLAS [[EPJC 71 \(2011\) 1795](#)] and LHCb [[Phys. Rev. Lett. 118 \(2017\) 192001](#)]

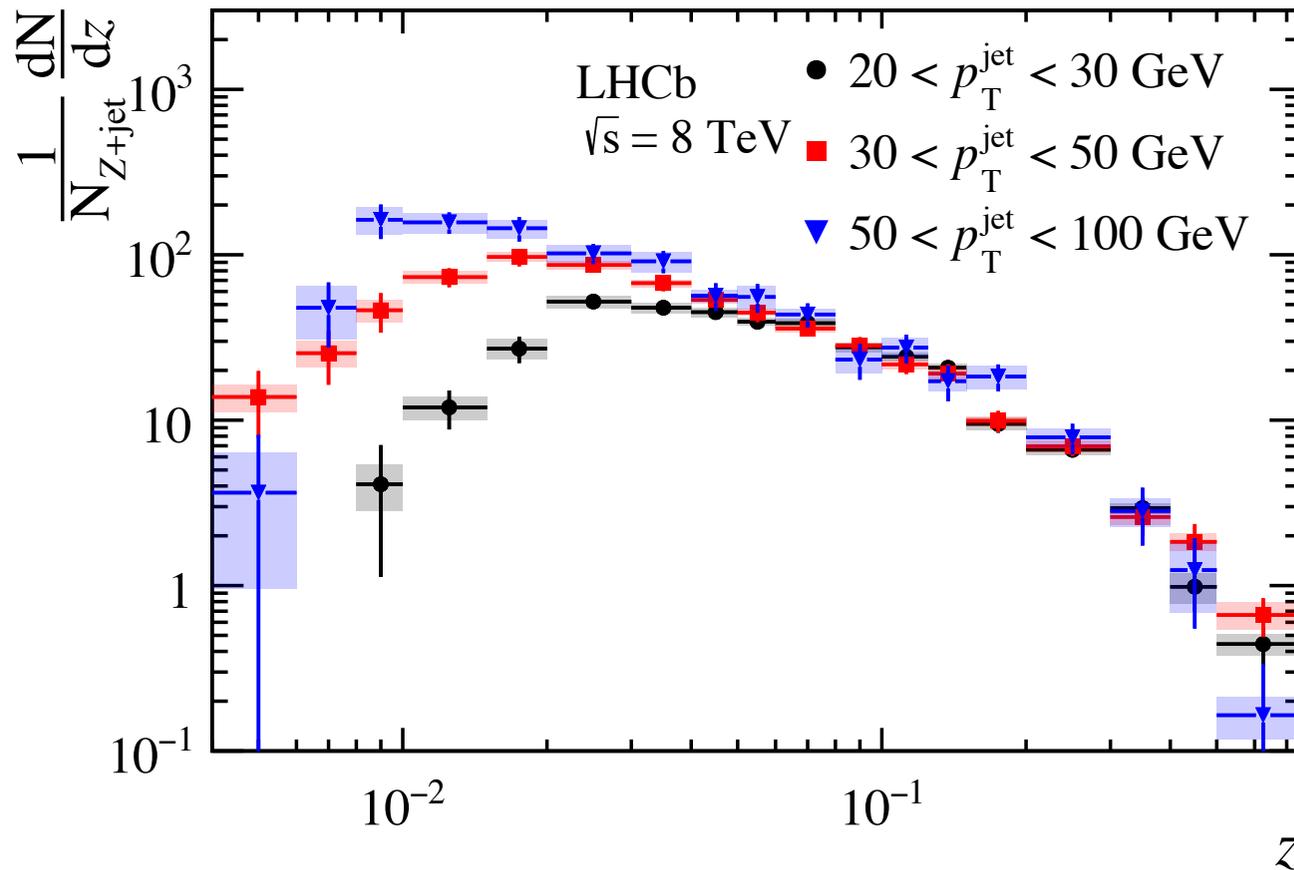
- Event selection

- select clean events with only one pp interaction vertex (no pile-up)
- $Z \rightarrow \mu^+ \mu^-$ selected with $60 < M_{\mu\mu} < 120 \text{ GeV}/c^2$, and muons with $p_T > 10 \text{ GeV}/c$ and $2 < \eta < 4.5$
- jet reconstruction with anti- k_T algorithm ($R=0.5$), $p_T(\text{jet}) > 20 \text{ GeV}/c$, and $2.5 < \eta(\text{jet}) < 4$
- $|\Delta\varphi(Z+\text{jet})| > 7\pi/8$
- charged hadrons selected with $p_T > 0.25 \text{ GeV}/c$, $p > 4 \text{ GeV}/c$, $\Delta R < 0.5$

$$\Delta R \equiv \sqrt{(\phi_{\text{jet}} - \phi_{\text{hadron}})^2 + (\eta_{\text{jet}} - \eta_{\text{hadron}})^2}$$

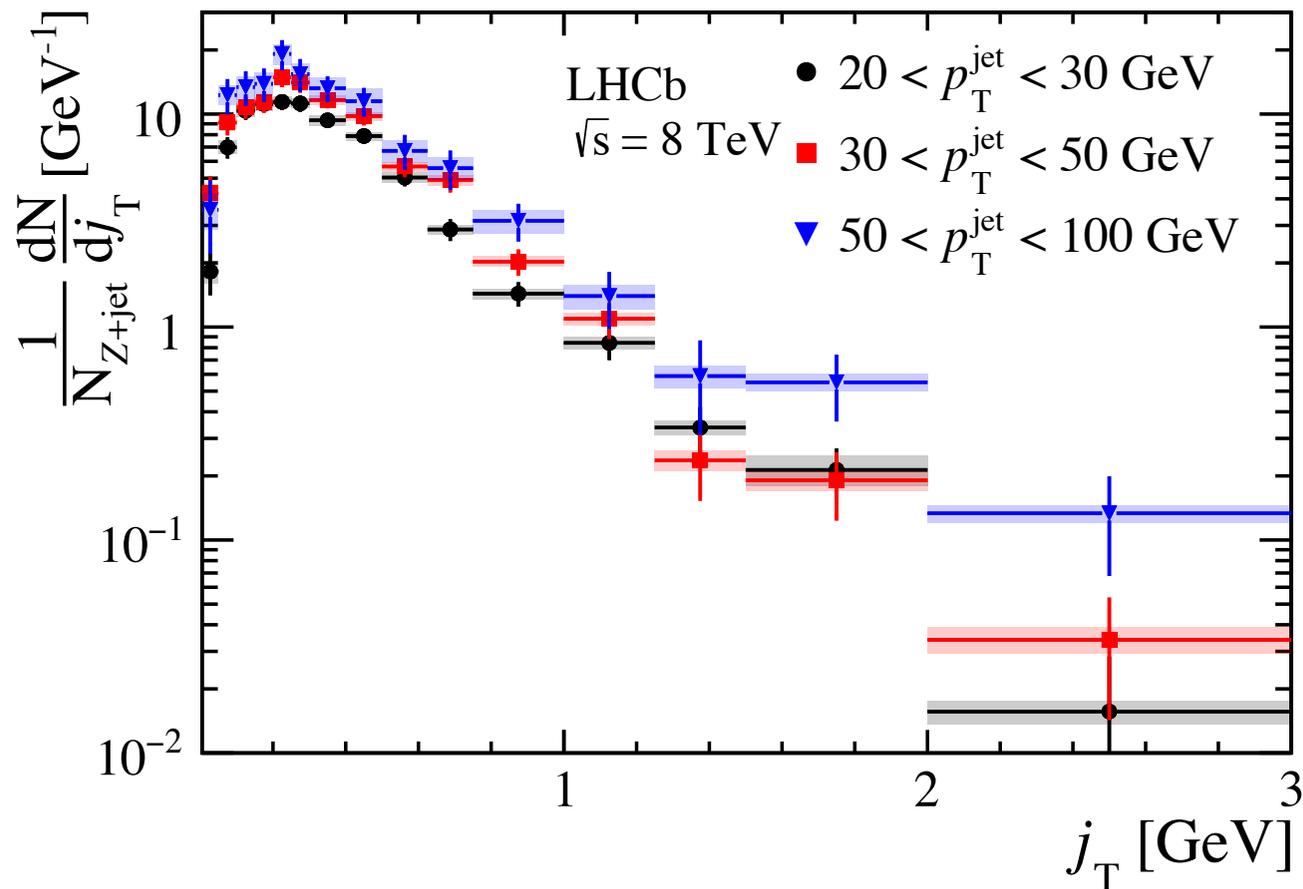
- Normalised distributions are constructed for the z , j_T and r observables of the selected hadrons in the jet
 - present results in 3 jet p_T bins: ($20 < p_T < 30$, $30 < p_T < 50$, $50 < p_T < 100 \text{ GeV}/c$)
 - the distributions are efficiency and resolution corrected

Results: longitudinal momentum fraction



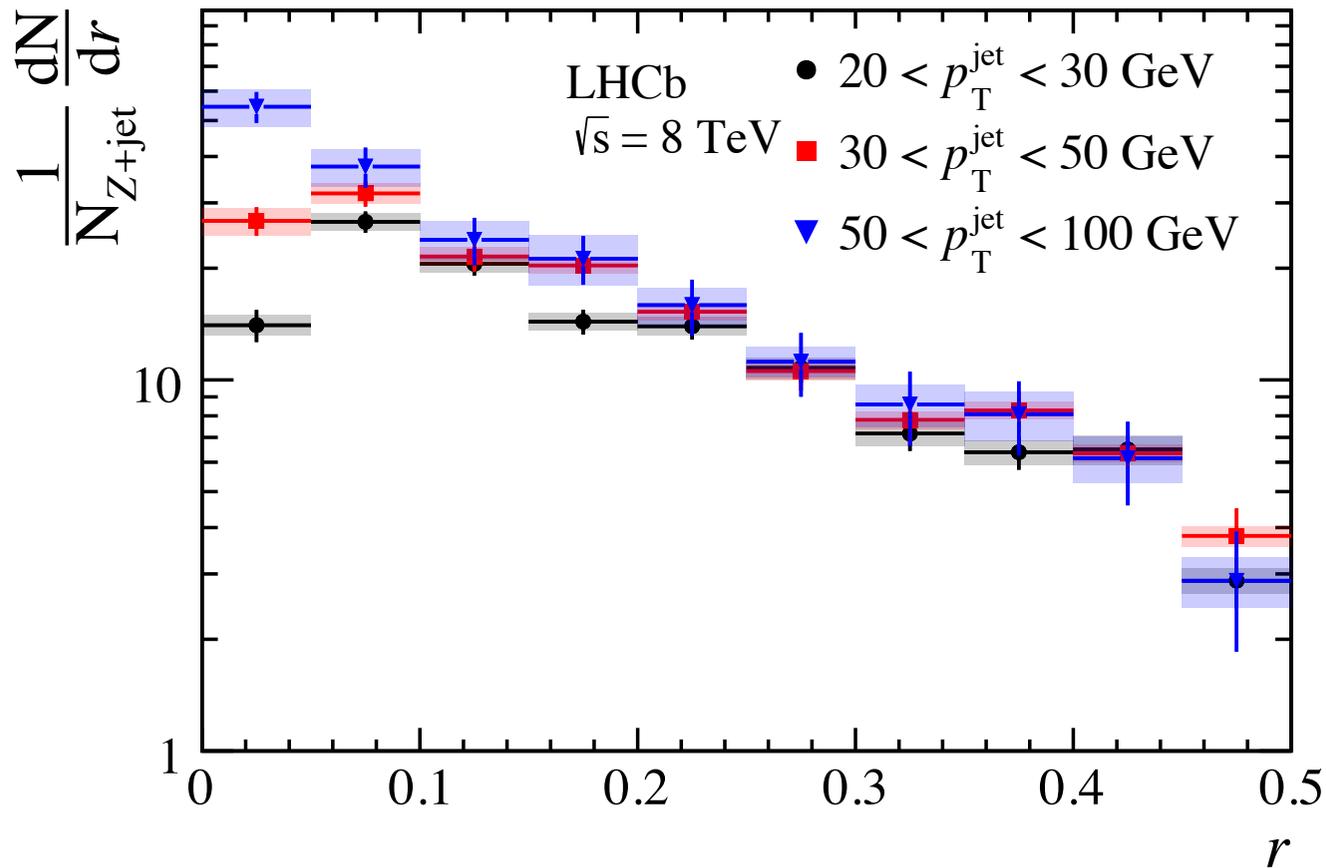
- At high z , the longitudinal momentum fraction of hadrons in the jet are mostly independent of the jet p_T
- At low z , the distributions diverge because of the available kinematic phase space within the selection constraints

Results: transverse momentum



- Transition from nonperturbative shape (low j_T) to perturbative tail (high j_T) is visible
- The distributions are similar for all jet p_T bins

Results: radial distribution



arXiv:1904.08878

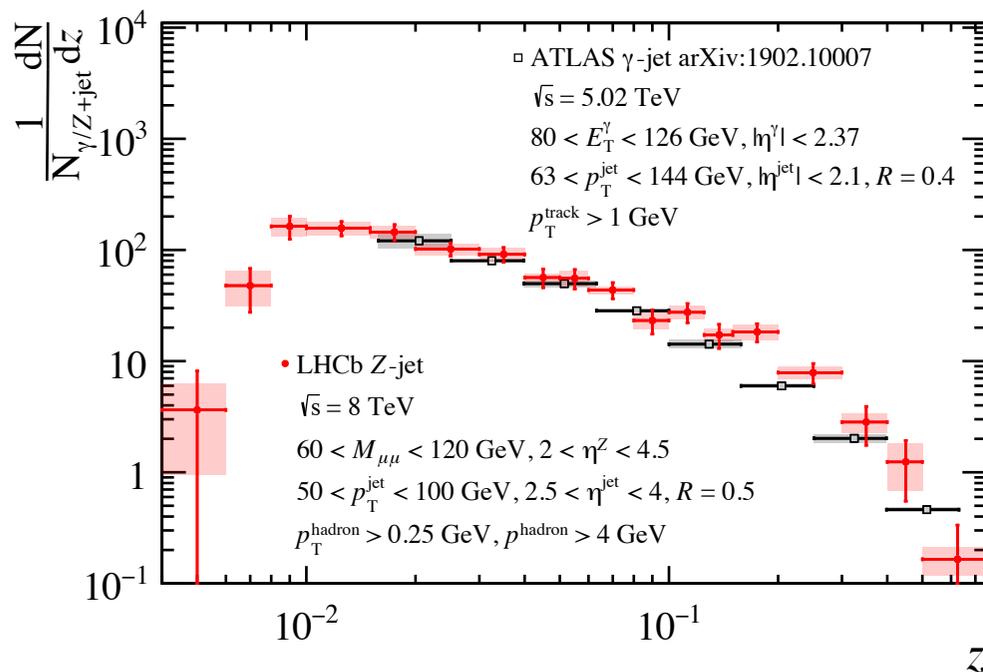
- At small r , the distributions are very dependent on the jet p_T
⇒ multiplicity of hadrons along the jet axis rises sharply with jet p_T
- At large r , the radial distribution is mostly independent of the jet p_T
- indication that nonperturbative contributions are independent of the jet p_T ?

Comparison with ATLAS results

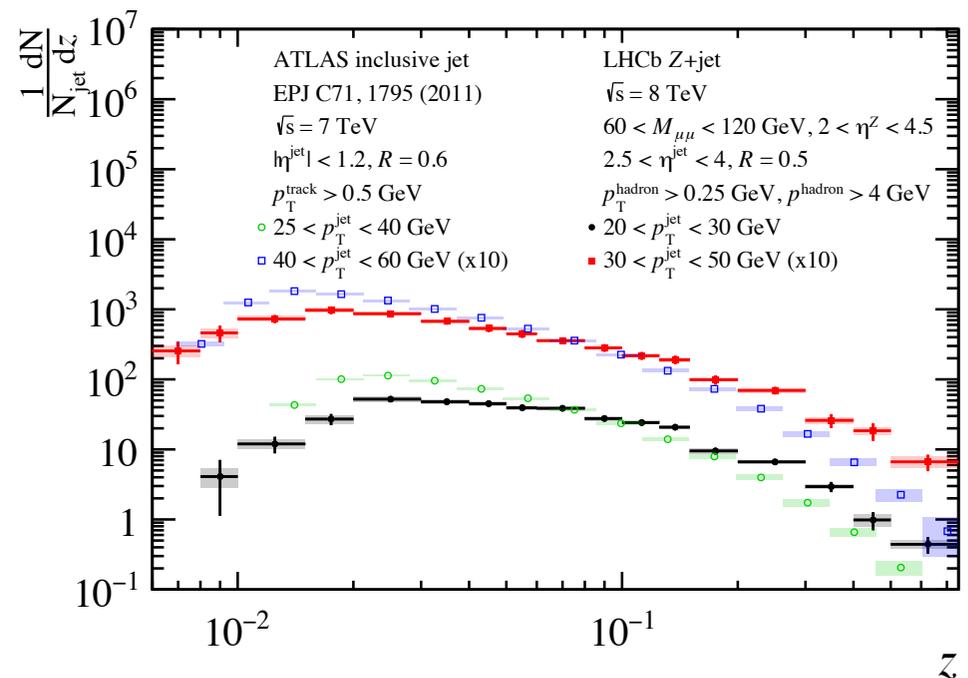
- Comparison with ATLAS γ +jet [[arXiv:1902.10007](#)] and inclusive jet [[EPJC 71 \(2011\) 1795](#)] measurements
- Only qualitative comparison because of the different kinematics

Longitudinal fractions

[arXiv:1904.08878](#)



ATLAS γ +jet (black)
versus LHCb Z+jet (red)

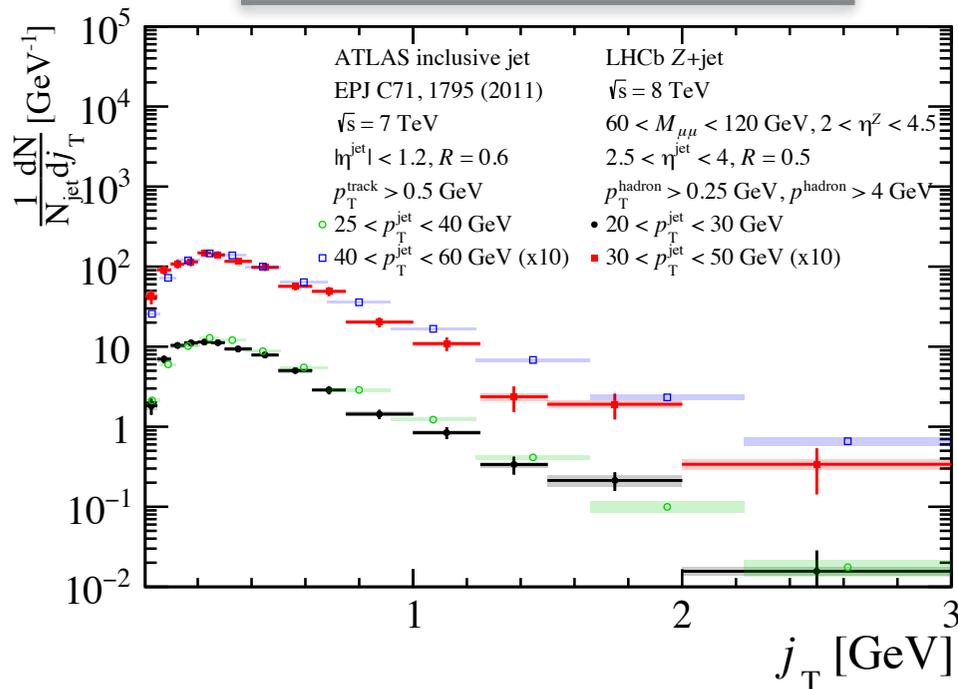


ATLAS inclusive jet (green and blue)
versus LHCb Z+jet (black and red)

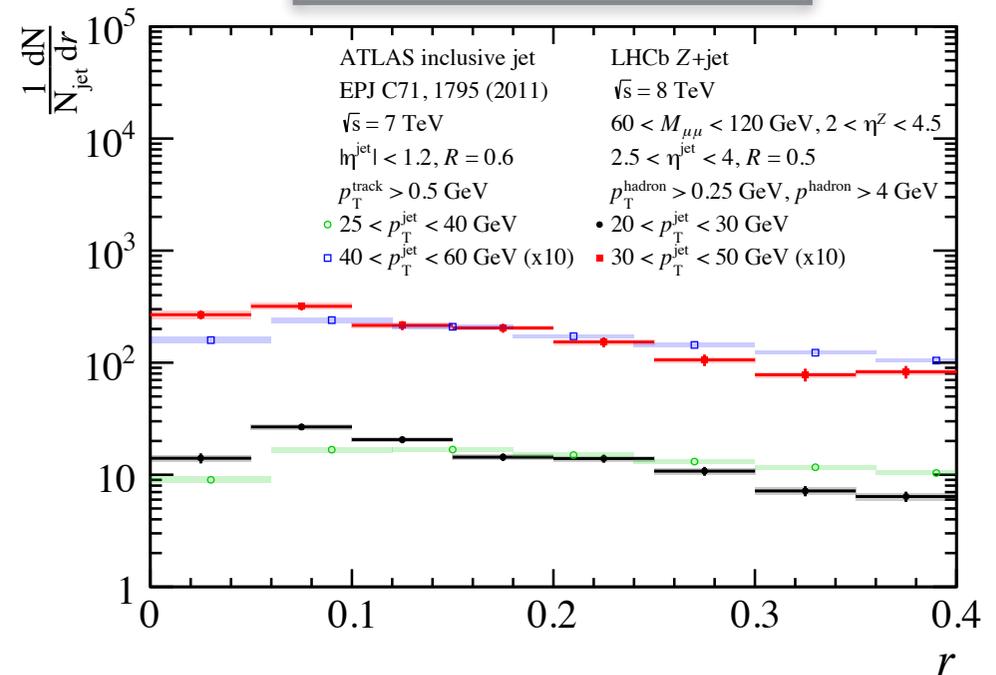
Comparison with ATLAS results

- Transverse momentum distributions show smaller average j_T in forward Z +jet than in inclusive jets at small j_T
- Radial and longitudinal fraction (previous page) distributions show that the Z -tagged jets are more collimated than in inclusive jets

Transverse momentum



Radial distribution

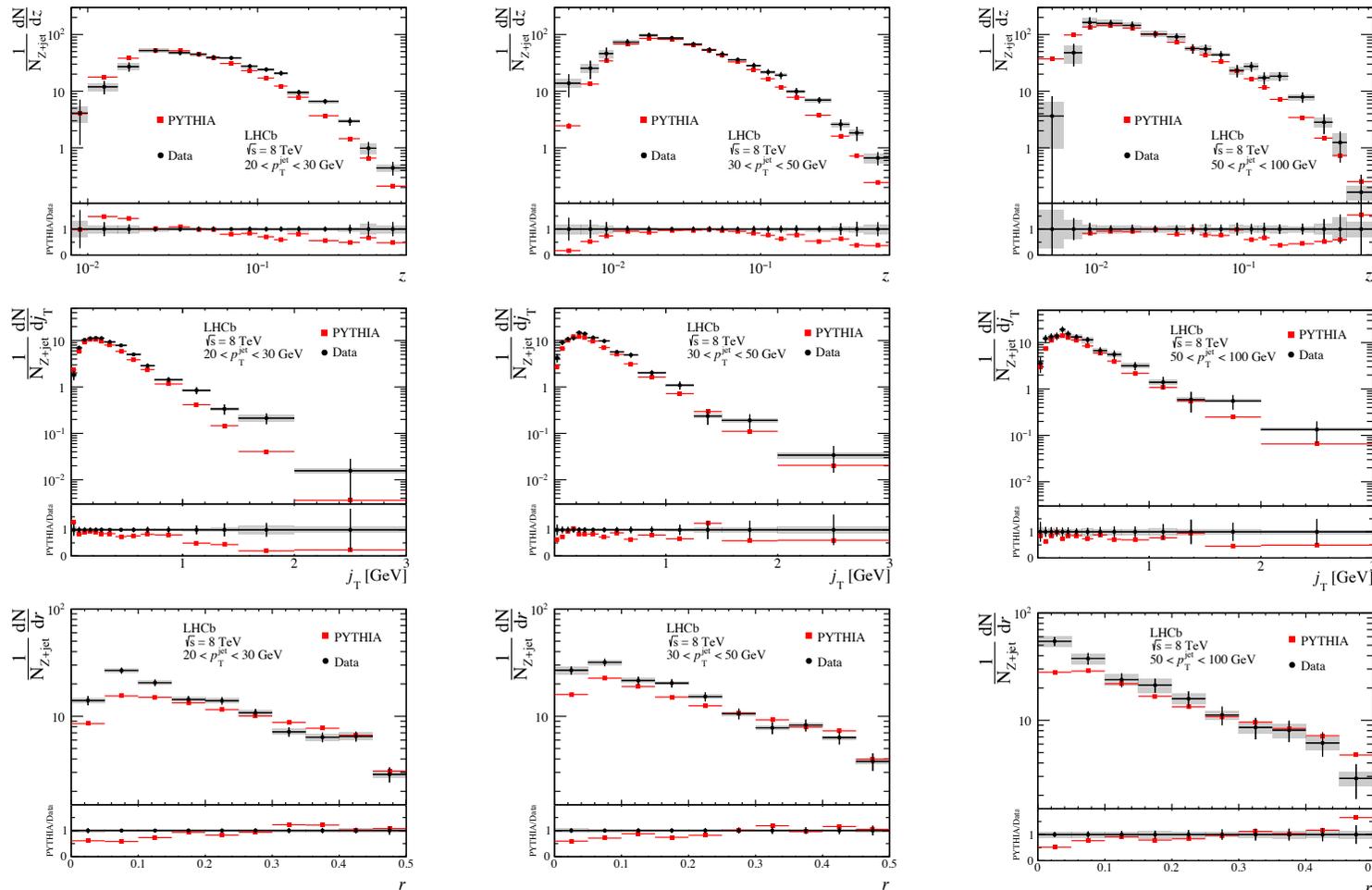


ATLAS inclusive jet (green and blue)
versus LHCb Z+jet (black and red)

arXiv:1904.08878

Comparison with PYTHIA

- Version: PYTHIA 8.175 + CTEQ6L.1 parton distribution function set



arXiv:1904.08878

- PYTHIA underestimates charged hadron production by $\sim 20\%$, mostly at large z and small r

Conclusion

- LHCb studied hadronisation in Z -tagged jets at large rapidities, produced in pp collisions at $\sqrt{s}=8\text{TeV}$
- Observables related to the longitudinal and transverse hadron distributions within the jets are measured
- Results show mostly similar distributions as predicted by PYTHIA, and as obtained by ATLAS at central rapidities
 - the remaining differences will allow to study the differences in gluon and quark fragmentation
- Using the unique LHCb capabilities, future studies will allow to study hadronisation using particle ID, jet tagging, resonance production, or correlations within jets

Backup

PYTHIA settings

Table 1: Settings used in comparisons between PYTHIA and these measurements.

General	Multiparton Interactions	String Flavor
SpaceShower:rapidityOrder = off	MultipartonInteractions:bProfile = 1	StringFlav:mesonUDvector = 0.6
WeakBosonAndParton:qg2gmZq = on	MultipartonInteractions:ecmRef = 7000	StringFlav:mesonSvector = 0.6
WeakBosonAndParton:qqbar2gmZg = on	MultipartonInteractions:pT0Ref = 2.88	StringFlav:mesonCvector = 3.0
WeakZ0:gmZmode = 2	MultipartonInteractions:ecmPow = 0.238	StringFlav:mesonBvector = 3.0
23:onMode = off		StringFlav:probStoUD = 0.30
23:onIfAny = 13		StringFlav:probQQtoQ = 0.10
SigmaProcess:alphaSorder = 2		StringFlav:probSQtoQQ = 0.4
		StringFlav:probQQ1toQQ0 = 0.05
		StringFlav:mesonUDL1S0J1 = 0.0989
		StringFlav:mesonUDL1S1J0 = 0.0132
		StringFlav:mesonUDL1S1J1 = 0.0597
		StringFlav:mesonUDL1S1J2 = 0.0597
		StringFlav:mesonSL1S0J1 = 0.0989
		StringFlav:mesonSL1S1J0 = 0.0132
		StringFlav:mesonSL1S1J1 = 0.0597
		StringFlav:mesonSL1S1J2 = 0.0597
		StringFlav:mesonCL1S0J1 = 0.0990
		StringFlav:mesonCL1S1J0 = 0.0657
		StringFlav:mesonCL1S1J1 = 0.2986
		StringFlav:mesonCL1S1J2 = 0.2986
		StringFlav:mesonBL1S0J1 = 0.0990
		StringFlav:mesonBL1S1J0 = 0.0657
		StringFlav:mesonBL1S1J1 = 0.2986
		StringFlav:mesonBL1S1J2 = 0.2986
		StringFlav:etaSup = 1.
		StringFlav:etaPrimeSup = 0.4