$Z + c$ at the LHC

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on behalf of the ATLAS, CMS, and LHCb collaborations

SM@LHC
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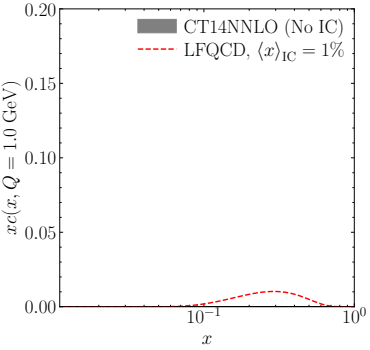
Intrinsic charm (IC)

Most PDF fits assume heavy quarks in the proton are generated perturbatively above $Q^2 \sim m_c^2$, but "intrinsic" heavy quarks are also possible.



JHEP 02 (2018) 059

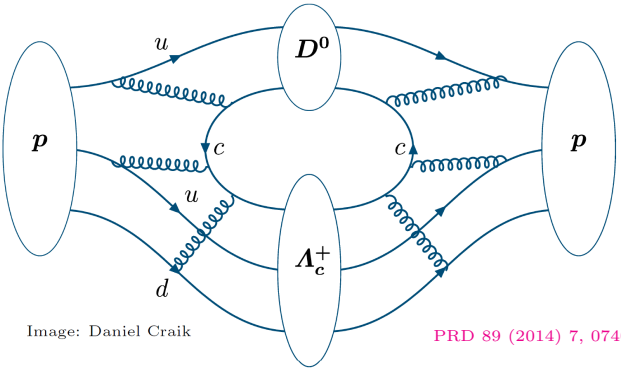


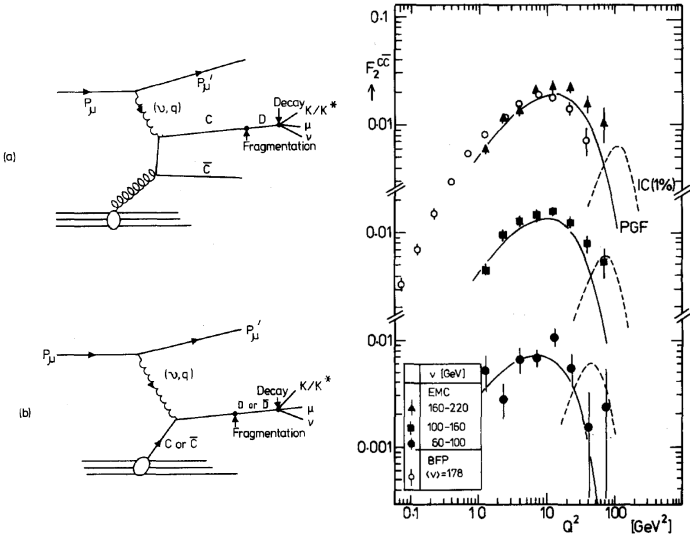
Image: Daniel Craik

PRD 89 (2014) 7, 074008

Intrinsic charm predicted by Light-Front QCD (BHPS model): PLB 93 (1980) 451-455

Heavy charm quarks carry most of the proton momentum → valence-like bump.

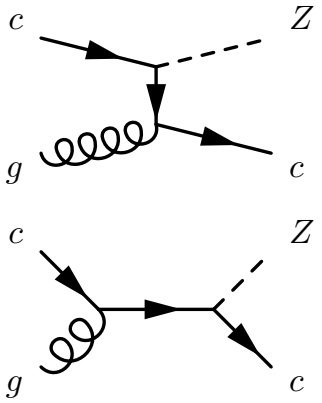
European Muon Collaboration (EMC) $F_2^{c\bar{c}}$ (Nucl. Phys. B 213 (1983), 31-64)

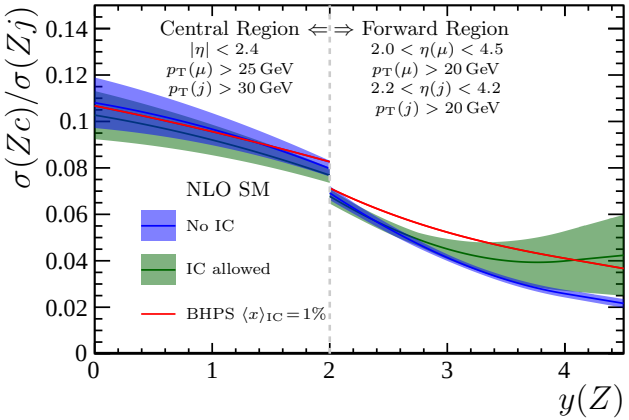


- First claimed evidence for IC
- Fixed target DIS: $Q \lesssim 10\,\text{GeV}$
- Interpretation has been controversial (Adv. High Energy Phys. 2015, 231547)
- Typically omitted from global PDF fits

Looking for intrinsic charm with $Z + c$ (PRD 93, 074008 (2016))

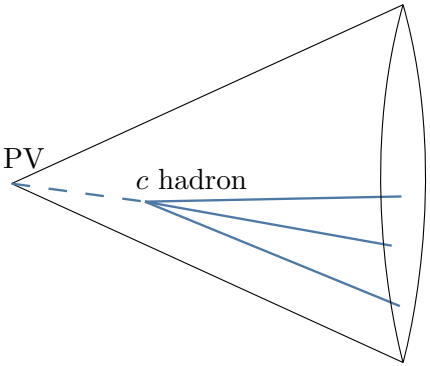
At leading order, $Z + c$ occurs via $gc \to Zc$. In the forward region (high $y(Z)$), this probes the valence region where IC is expected.





Identifying c-jets

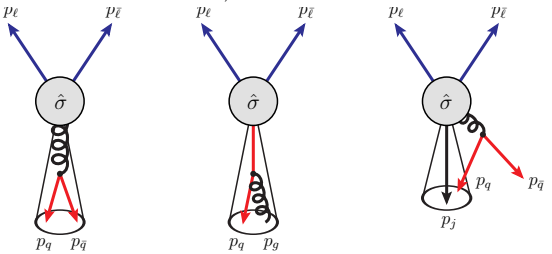
What exactly is a charm jet?



A charm jet...

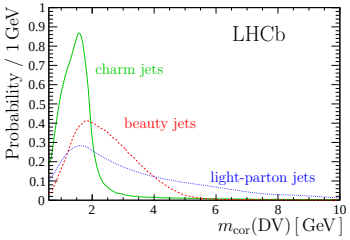
- contains a c hadron
- does NOT contain a b hadron
- can be identified using a displaced decay vertex or a fully reconstructed c-hadron decay

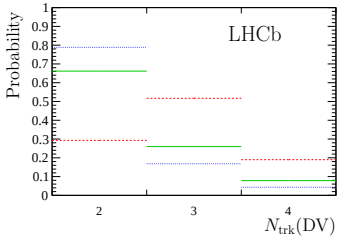
A convenient definition, but not IRC safe...

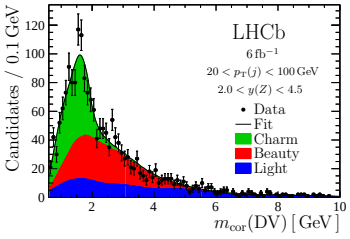


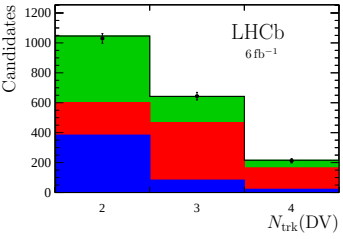
EPJC 83 (2023) 4, 336

Identifying c jets at LHCb (JINST 17 P02028 (2022))







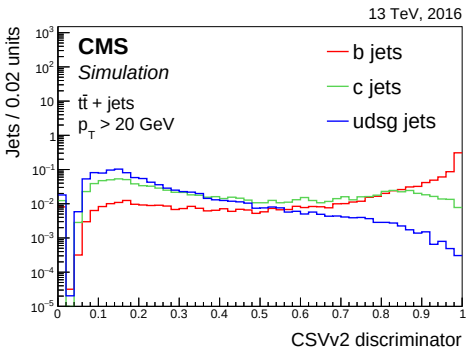


$$m_{\rm cor} = \sqrt{m({\rm DV})^2 + p_\perp({\rm DV})^2} + p_\perp({\rm DV})$$

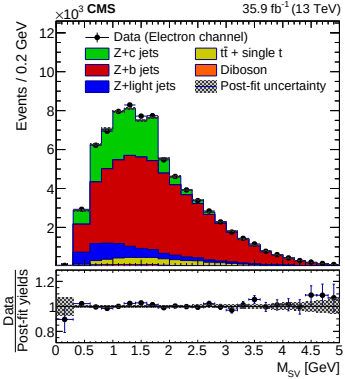
- Define charm jets as jets containing a weakly decaying c hadron with $p_{\rm T}(\text{c hadron}) > 5\,\text{GeV}$
- "Tag" jets with a displaced vertex (DV)
- Determine composition of the tagged sample with a 2D fit to $m_{\rm cor}$ and $N_{\rm trk}$
- Charm jets tagged with an efficiency of $\epsilon = (24.0 \pm 0.6 \pm 1.4)\%$

Identifying c jets at CMS

Tag jets using a NN that uses the properties of displaced tracks and vertices in the jet.
Fit the SV mass distribution to determine the composition of the tagged sample.



JINST 13 (2018) P05011

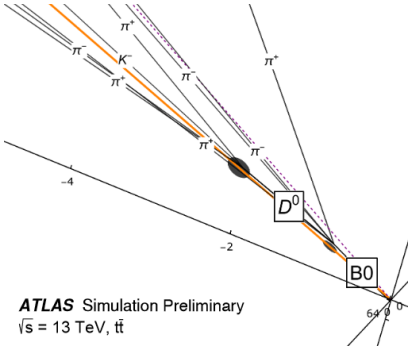


PRD 102, 032007 (2020)

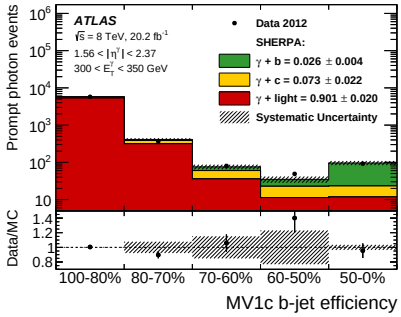
Heavy flavor jet tagging at CMS is evolving: JINST 17 (2022) P03014

Identifying c jets at ATLAS

Combine track IP-based and SV-based classifier outputs using a neural network (JINST 11 P04008 (2016))



ATL-PHYS-PUB-2018-025

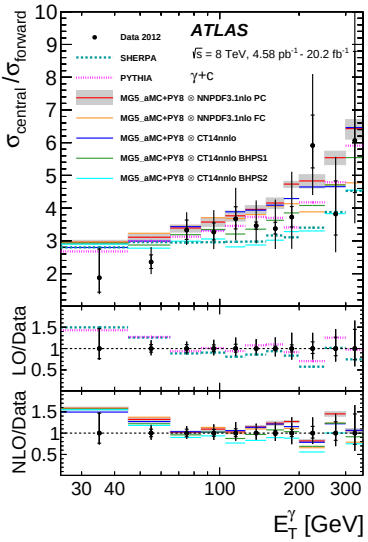


PLB 776 (2018) 295

Charm tagging at ATLAS is also evolving: arXiv:2211.16345.

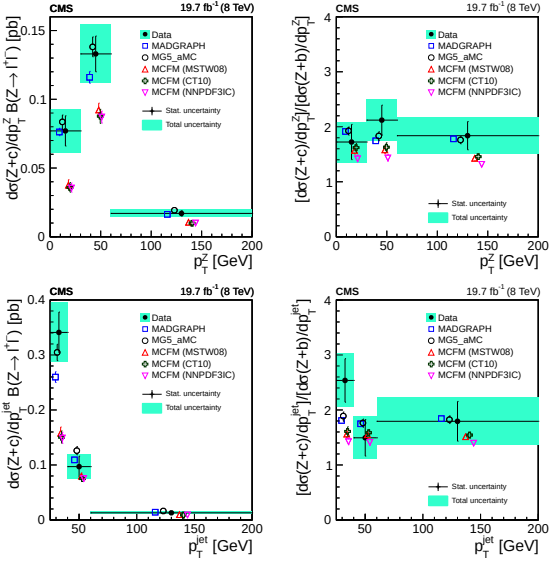
Results

ATLAS $\gamma + c$ at 8 TeV (PLB 776 (2018) 295)



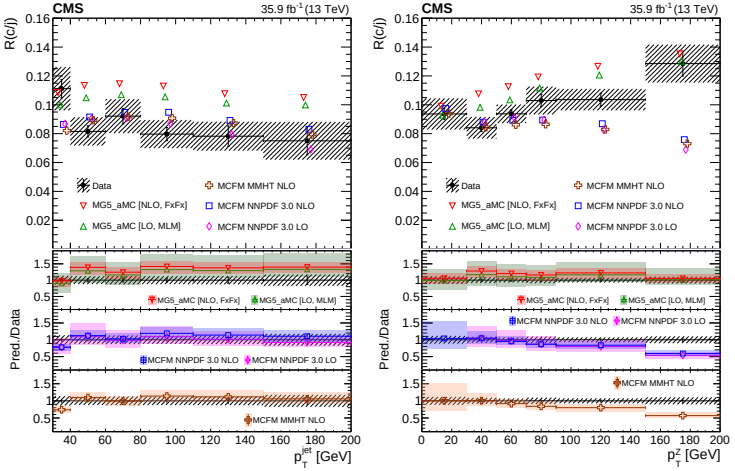
- Similar process to $Z + c$
- Central-forward ratio provides some sensitivity to the high-x charm PDF with cancellation of some uncertainties
  - Central: $|\eta(\gamma)| < 1.37$
  - Forward: $1.56 < |\eta(\gamma)| < 2.37$
- Uncertainties are too large to observe/constrain valence-like IC at the level of $\sim 1\%$

CMS $Z + c$ at 8 TeV (EPJC 78 (2018) 287)



- First measurement of the $Z + c$ differential cross section at the LHC
- Identify c-jets using semileptonic decays or fully reconstructed $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ or $D^{*+} \to D^0\pi^+$ decays
- Measure $(Z + c)/(Z + b)$ to cancel some systematic uncertainties
- Consistent with no IC, although not sensitive to valence-like IC at the $\sim 1\%$ level

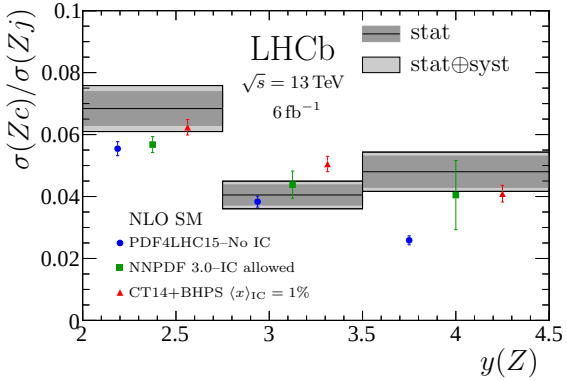
CMS $Z + c$ at 13 TeV (PRD 102, 032007 (2020))



- First measurement of $(Z + c)/(Z + j)$ at 13 TeV
- The parton shower has a much larger effect than 1%-level IC, especially at high p_{T}.

LHCb $(Z+c)/(Z+j)$ at 13 TeV (PRL 128 (2022) 082001)

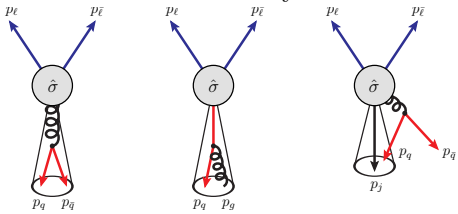
Results disagree with no-IC predictions at forward $y(Z)$ and are consistent with valence-like IC.



NNPDF analysis finds LHCb $Z+c$ and EMC $F_2^{c\bar{c}}$ data both favor IC at about 3σ

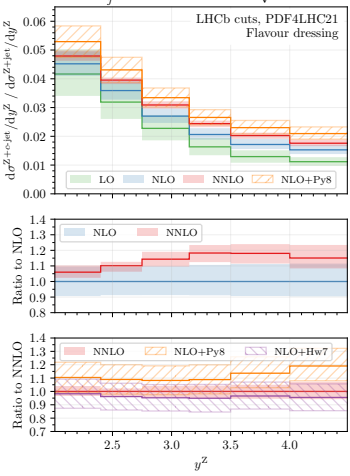
Some complications (EPJC 83 (2023) 4, 336)

IRC safety

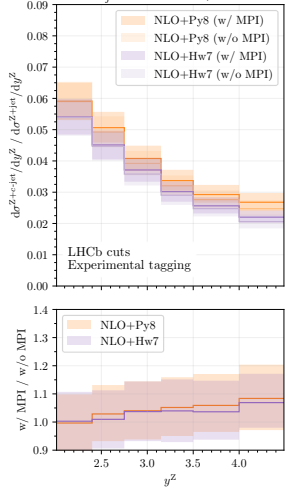


- Old predictions use NLO + parton shower
- c jet definition isn't IRC safe, so data can't be compared directly to NNLO predictions
- Need to account for MPI contributions

NNLO predictions



Multi-parton interactions



Final thoughts

- LHC $Z/\gamma + c$ data is starting to challenge our assumptions about the heavy quark content of the proton.
- These measurements are possible because of major advances in heavy-flavor jet tagging in the past 5-10 years.
- Definitive proof of IC in $Z/\gamma + c$ measurements will require another major paradigm shift to IRC-safe jet tagging to confront NNLO predictions.

Thank you!