Flavoured Jets at the LHC
June 11-12, 2024

Brief report: J. Huston

see also talks at LHC EWWG meeting
on July 10-12 by Giovanni Stagnitto and
Federico Sforza

Tuesday, June 11

10:00 AM → 11:00 AM **Theory overview**

- 10:00 AM **Flavour and IRC safety**
  Speaker: Gavin Salam (University of Oxford and All Souls College)
  salam.pdf
- 10:30 AM **Les Houches flavour studies**
  Speaker: Dr Giovanni Stagnitto (University Milano Bicocca)
  stagnitto.pdf

11:00 AM → 11:30 AM **Coffee break**

11:30 AM → 12:30 PM **Jet substructure**

- 11:30 AM **Heavy flavour jet substructure**
  Speaker: Mr Andrea Ghira (Università di Genova and INFN Sezione
  ghira.pdf
- 12:00 PM **ATLAS jet substructure studies**
  Speaker: Mr Alberto Rescia (DESY and Università di Genova)
  rescia.pdf

12:30 PM → 2:00 PM **Lunch break**

2:00 PM → 4:00 PM **Experimental studies on jet flavour labelling**

- 2:00 PM **ATLAS**
  Speaker: Mr Radoslaw Grabarczyk (University of Oxford)
  grabarczyk.pdf
- 2:30 PM **CMS**
  Speaker: Leticia Cunqueiro Mendez (University of Rome Sapienza)
  Cunqueiro Mendez....
- 3:00 PM **LHCb**
  Speaker: Dr Ezra Lesser (CERN)
  lesser.pdf
- 3:30 PM **ALICE**
  Speaker: Dr Nima Zardoshti (CERN)
  zardoshti.pdf

Wednesday, June 12

9:00 AM → 11:00 AM **Parton Distribution Functions and measurements**

- 9:00 AM **CT**
  Speaker: Joey Huston (Michigan State University)
  huston.pdf
- 9:30 AM **NNPDF**
  Speaker: Roy Stegeman (The University of Edinburgh)
  stegeman.pdf
- 10:00 AM **Z + heavy flavour in ATLAS**
  Speaker: Yi Yu (University of Science and Technology of China)
  yu.pdf
- 10:30 AM **Discussion**

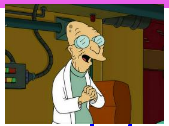
11:00 AM → 11:30 AM **Coffee break**

11:30 AM → 12:30 PM **Precision calculations**

- 11:30 AM **Flavour jet algorithms in fixed-order calculations**
  Speaker: Dr Arnd Behring (CERN)
  behring.pdf
- 12:00 PM **Heavy flavours in parton showers**
  Speaker: Peter Richardson (IPPP)
  richardson.pdf

…so why a workshop now?

Why a workshop?

- Good news 
- 2->2 NNLO revolution has reached final states involving heavy flavor jets, such as Z+b

Why a workshop?

- Good news, everyone!

- 2->2 NNLO revolution has reached final states involving heavy flavor jets, such as Z+b
- Significant reduction in scale uncertainty from NLO to NNLO
- Too good to be true? See later.

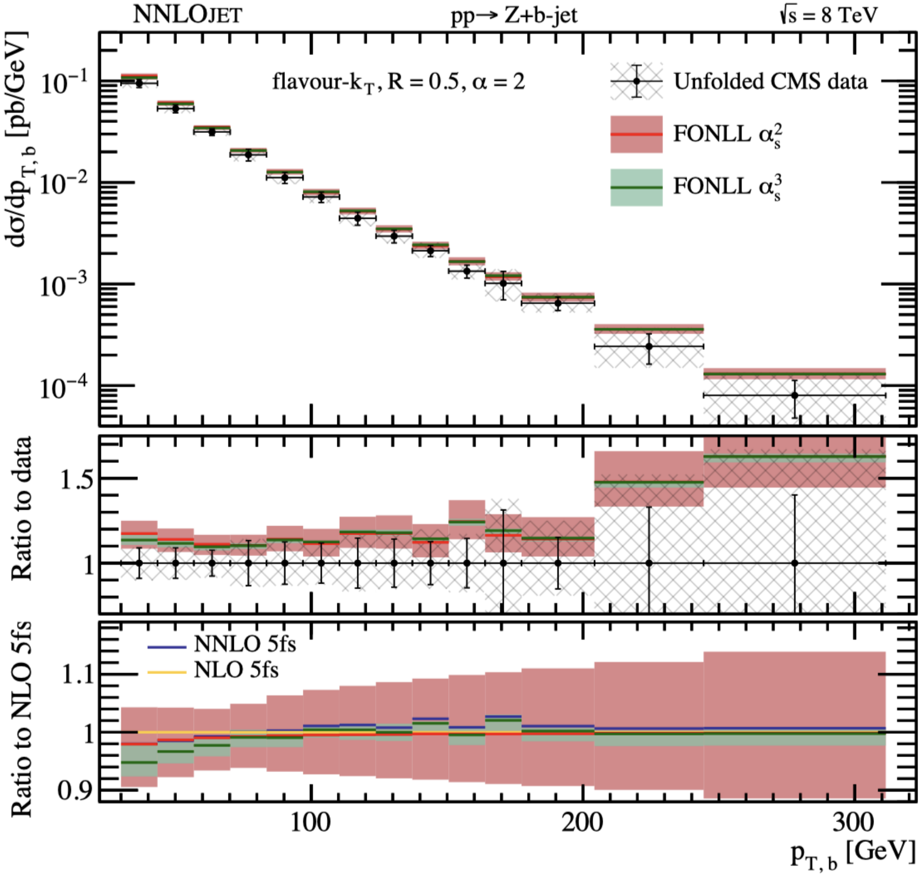
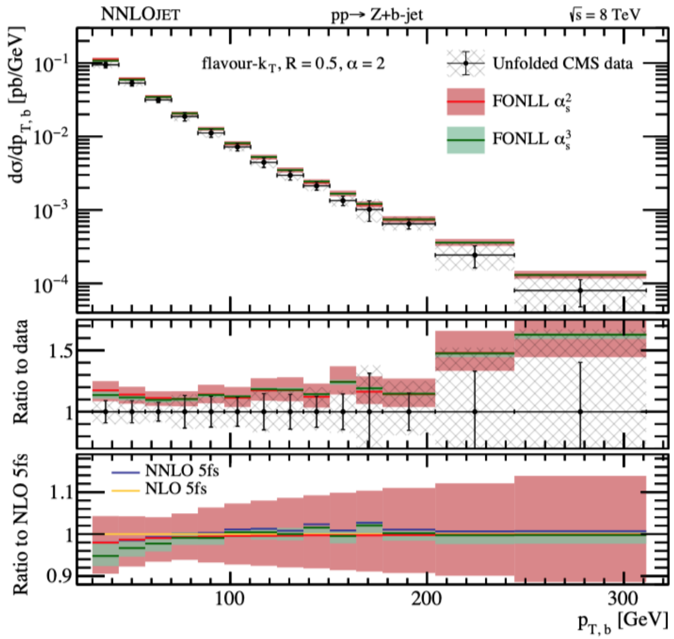


Figure 2: The transverse momentum distribution of the leading flavour-k_T b-jet. The absolute cross-section is shown in the upper panel, the ratio to the unfolded data in the central panel, and the ratio to the NLO 5fs prediction in the lower panel. The shown uncertainty of the FONLL distributions are due to scale variations alone.

Z+b at NNLO prediction

- Carried out by combining a massless NNLO and a massive NLO computation at order (α_s^3) (arXiv:2005.03016)
  - initial state b-quarks from gluon splitting resummed by PDF evolution; finite b-quark mass effects also incorporated (presumably same could be done for Z+c)
  - note: massless calculation means IR-safe definition of jet flavour must be used; not consistent with experimental choice
  - desired to have data unfolded to level of partonic flavour-kT jets or some equivalent



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reasonable agreement with data

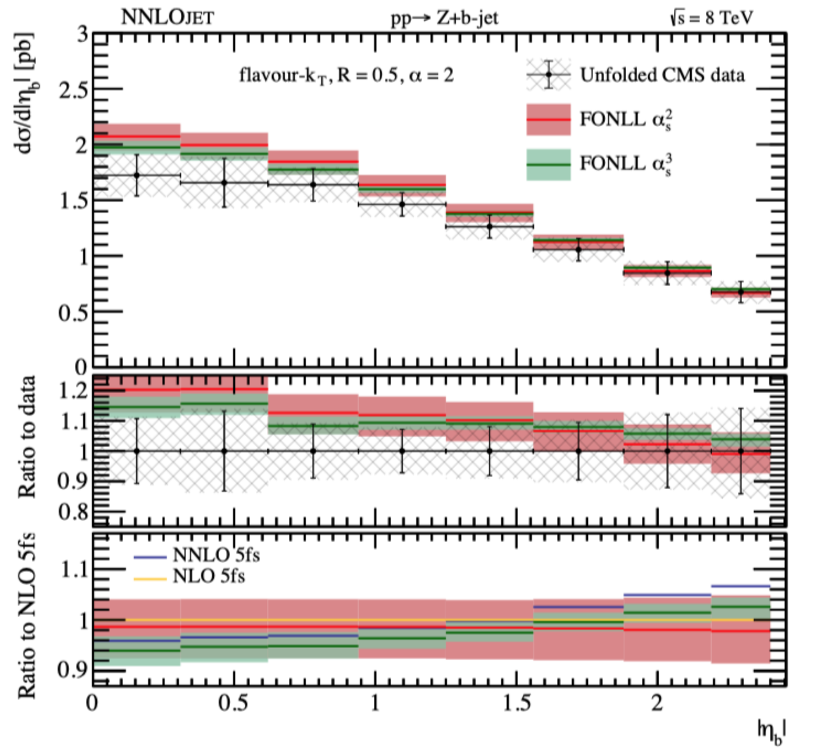
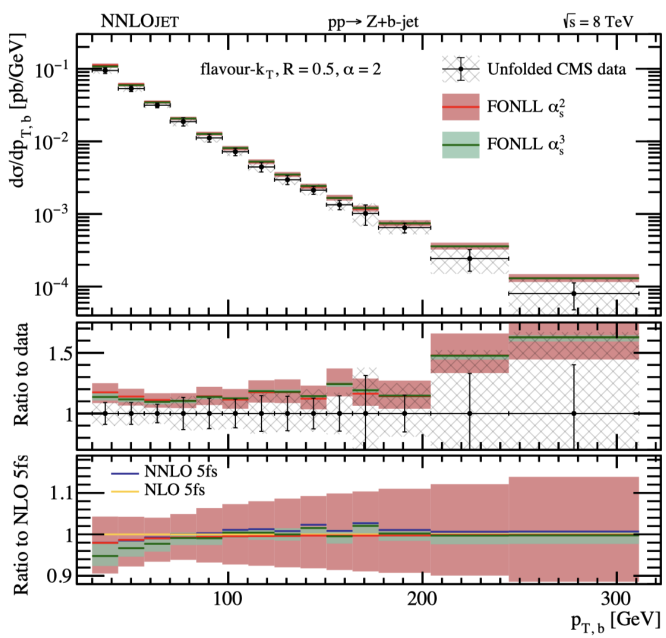


Figure 3: As in Fig. 2, now for the absolute psudorapidity distribution of the leading flavour-k_T b-jet.

Why a workshop?

- Good news

- 2->2 NNLO revolution has reached final states involving heavy flavor jets, such as Z+b
- Significant reduction in scale uncertainty



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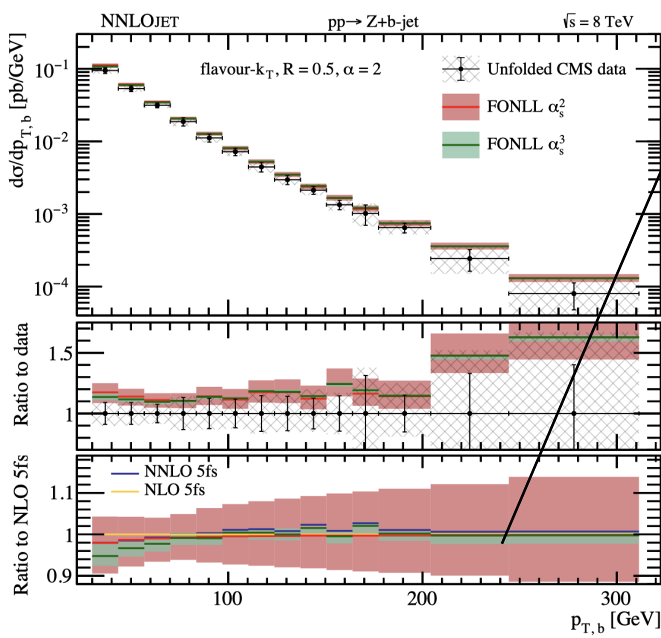
- Bad news
- Hard to include masses in the calculation; with masses, no IRC safe problem
- Without masses, IRC-unsafe jet algorithms more sensitive to log-enhanced effects

$$\alpha_s^n log^m [\frac{p_T}{m_b}]$$

- antikT jet algorithm is IRC unsafe for heavy quark jets
- Use of antikT jets for heavy flavour quark jets introduces an error/uncertainty into the measurement, possibly on the order of 10-20% (my guess)

Why a workshop?

- Good news
- 2->2 NNLO revolution has reached final states involving heavy flavor jets, such as Z+b
- Significant reduction in scale uncertainty



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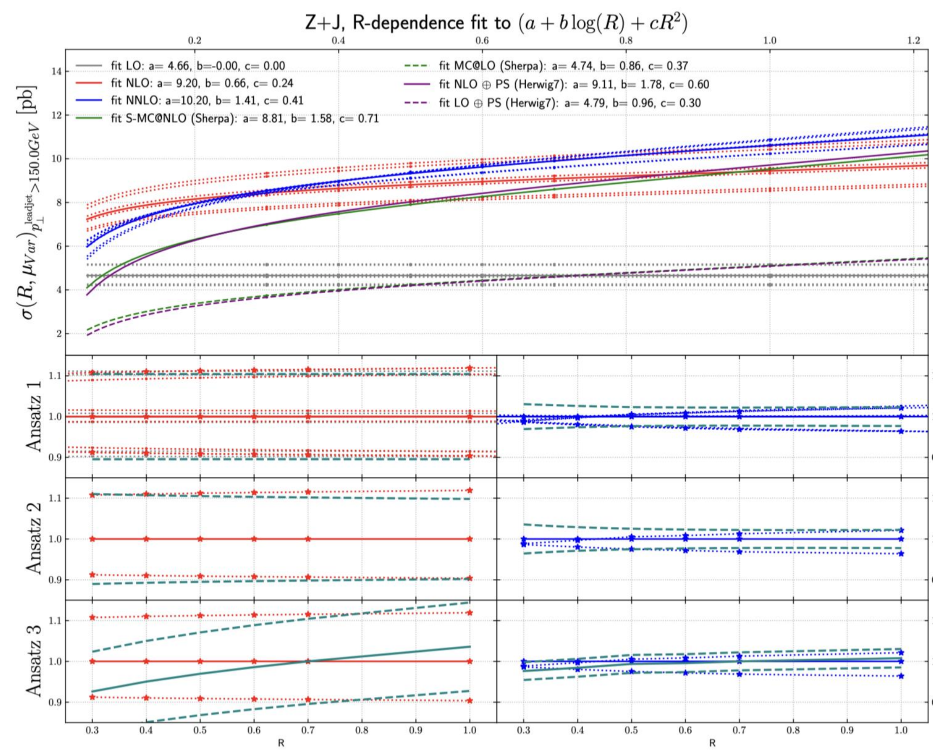
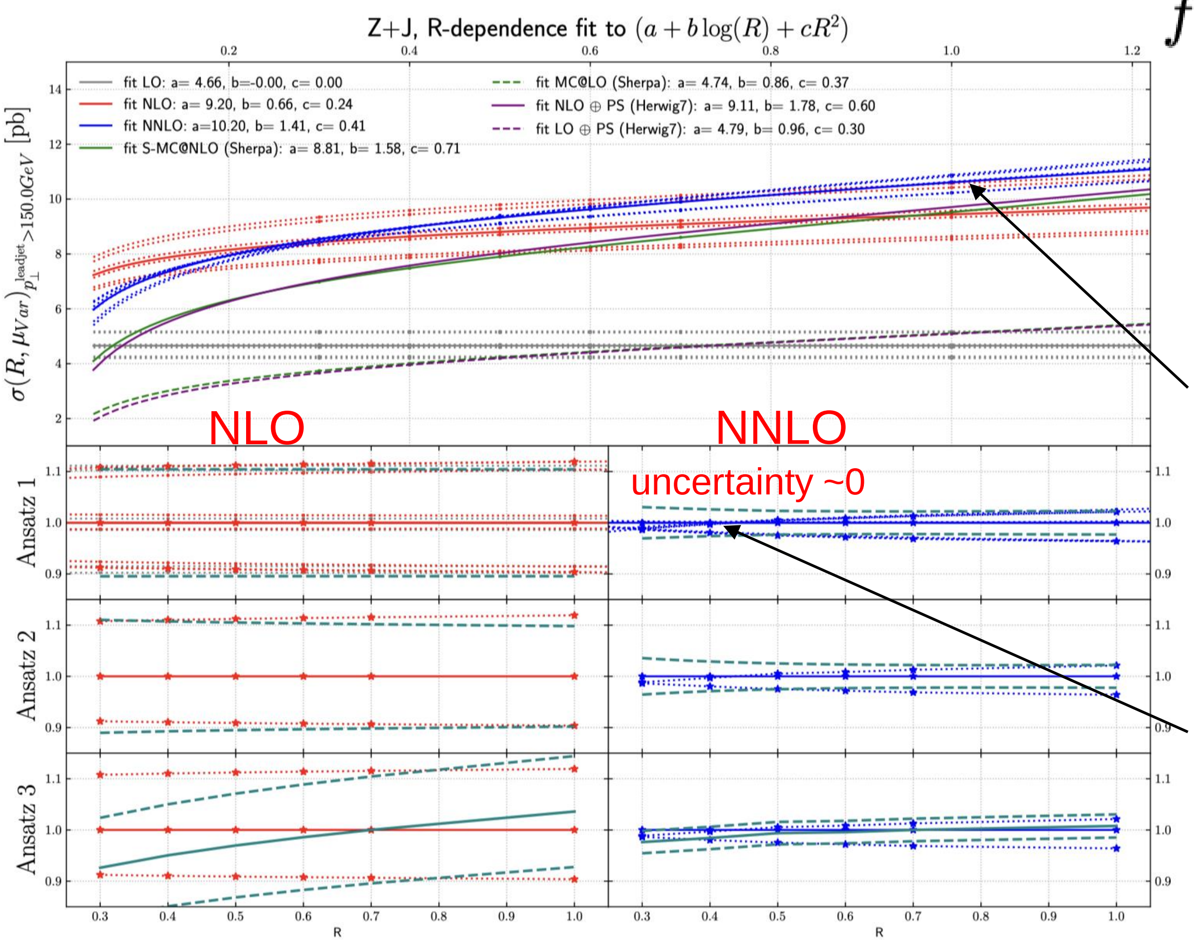
- take this extreme reduction in scale uncertainty with a grain of salt.
- probably sensitive to the same accidental scale cancellations that plague Z+j (or dijet); can be illuminated by calculating R-dependence
- I'm looking into it

arXiv:1903.12563



Now, an aside: Why is the uncertainty so small?



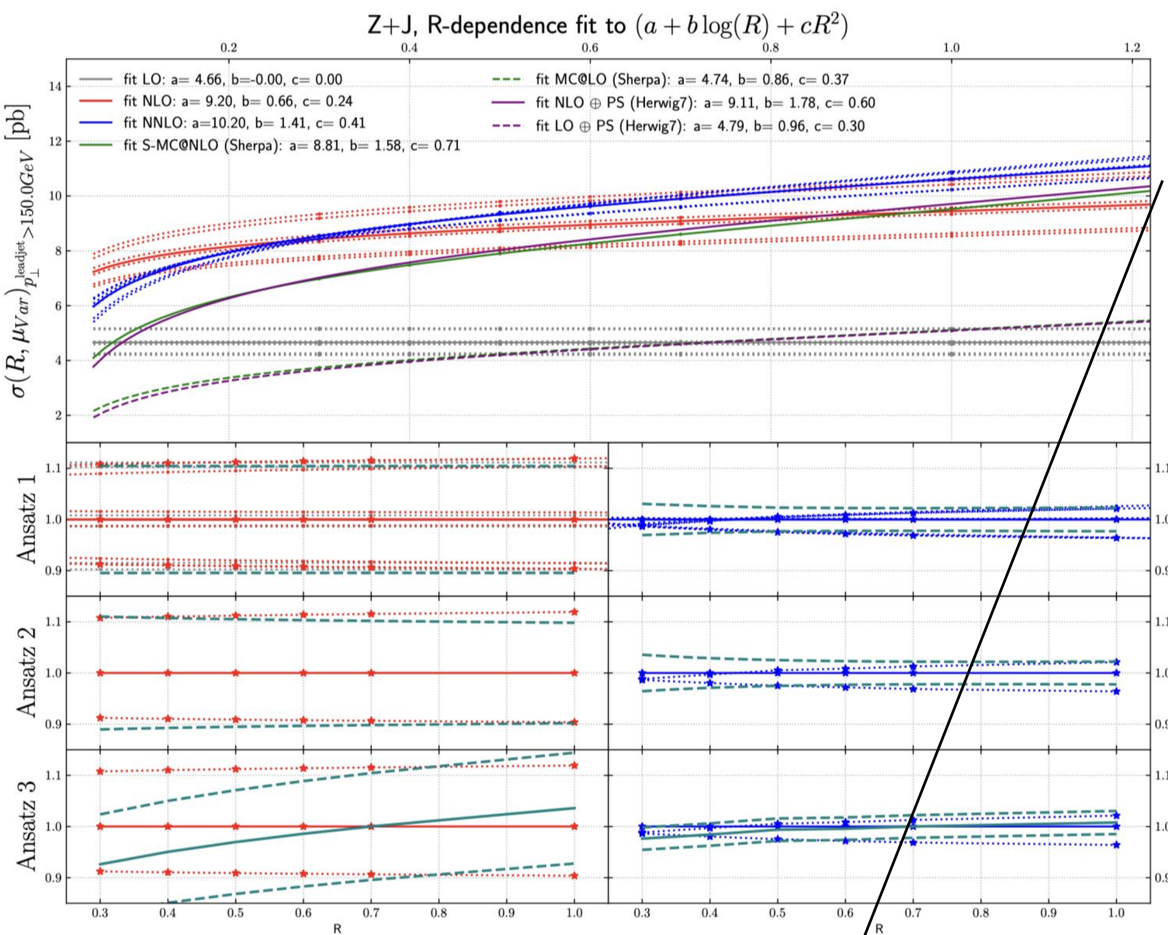
$$f(R) = a + b\log(R) + cR^2$$

Parametrize R dependence according to form shown above; log R term includes effects of radiation inside jet; R^2 term takes into account ISR. Do so for each scale from 7-point scale variation.

There can be accidental cancellations of logarithmically enhanced higher order corrections that appear both as a result of scale variations and as a result of phase space restrictions.

Definition of a jet implies an exclusive measurement and effectively acts as a veto on real-radiative corrections that fall outside the jet area.

What to do?



Expand cross section around reference value R_o (typically 0.7); add in quadrature uncertainty from two first two terms.

Three different ansatze to do this. Ansatz 3 is original from Gavin Salam et al. We proposed Ansatze 1 and 2 as more reasonable (preserves central value).

Result is a larger uncertainty, roughly independent of R, with no accidental zeroes.

$$\sigma(R) = \sigma(R_0)\frac{\sigma(R)}{\sigma(R_0)} \approx \sigma(R_0)\cdot\left(1 + \alpha_S\,\partial_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0} + \alpha_S^2\,\partial^2_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0}\right)\,.$$

also happens for jet production

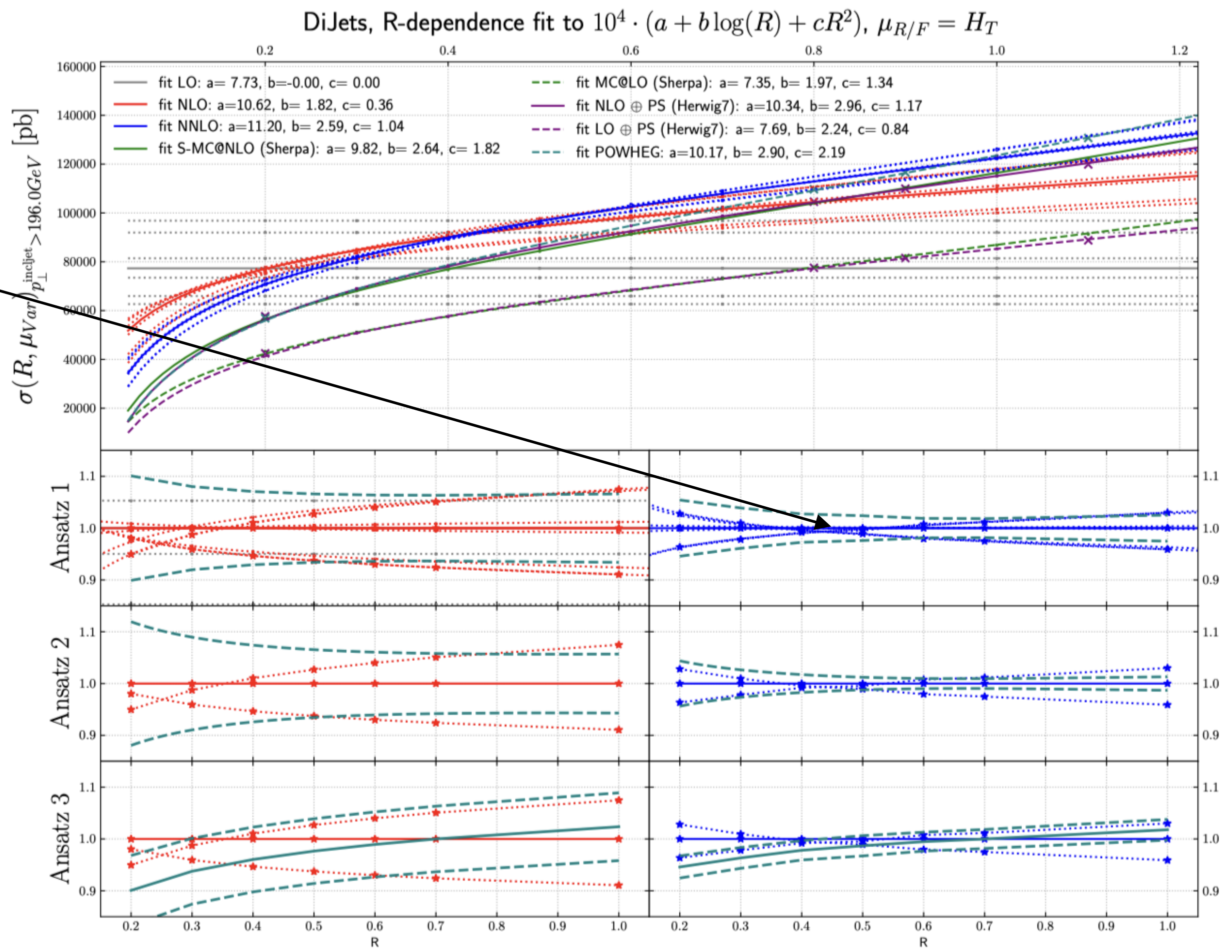


FIG. 9: The R-dependence of the cross sections for inclusive jet production at LO, NLO, NNLO and NLO+PS are shown, for scale variations around a central scale of H_T, as a function of jet radius, for dijet production, for leading jet transverse momenta above 196 GeV.

…but not for H+jet

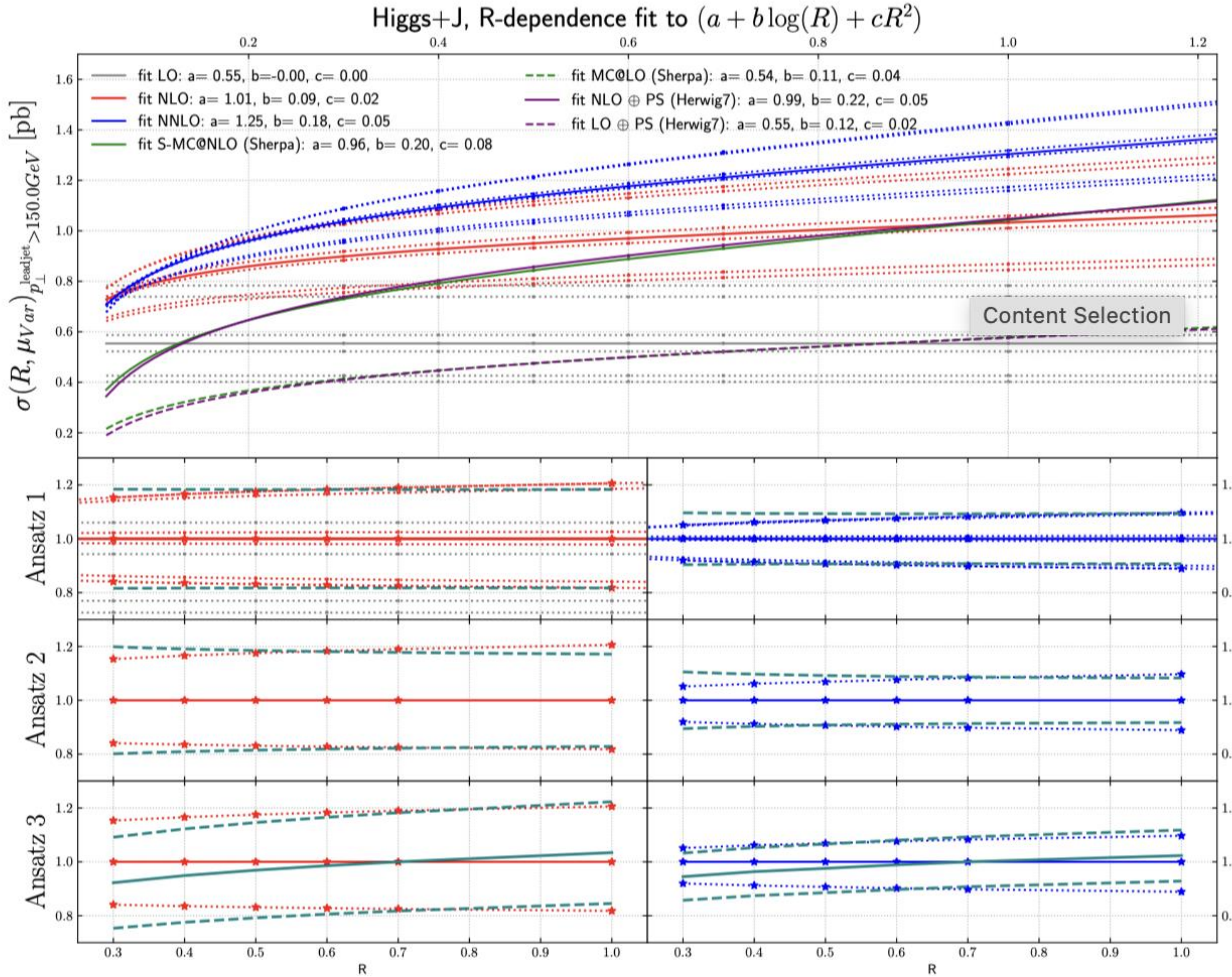


FIG. 7: The R-dependence of the cross sections at NLO, NNLO and NLO+PS are shown, for particular scale values, as a function of the jet radius, for $H+\geq 1$ jet production, for leading jet transverse momenta above 150 GeV.

Ok, back to some history: flavour k_T jet algorithm

- For quark and gluon jets
- Key issue is distance measure

$$d_{ij}^{(k_t)} = 2\min(E_i^2, E_j^2)\,(1-\cos\theta_{ij})$$

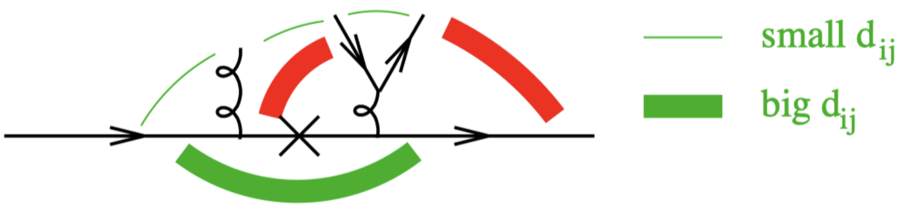
- Quark production only has collinear divergence, but no soft divergence; soft large angle q,qbar from soft gluon deemed similarly close to all particles

How to define a quark jet and a gluon jet?

Solution: modify distance measure for quarks to reflect divergences

[Banfi, GPS & Zanderighi, hep-ph/0601139]

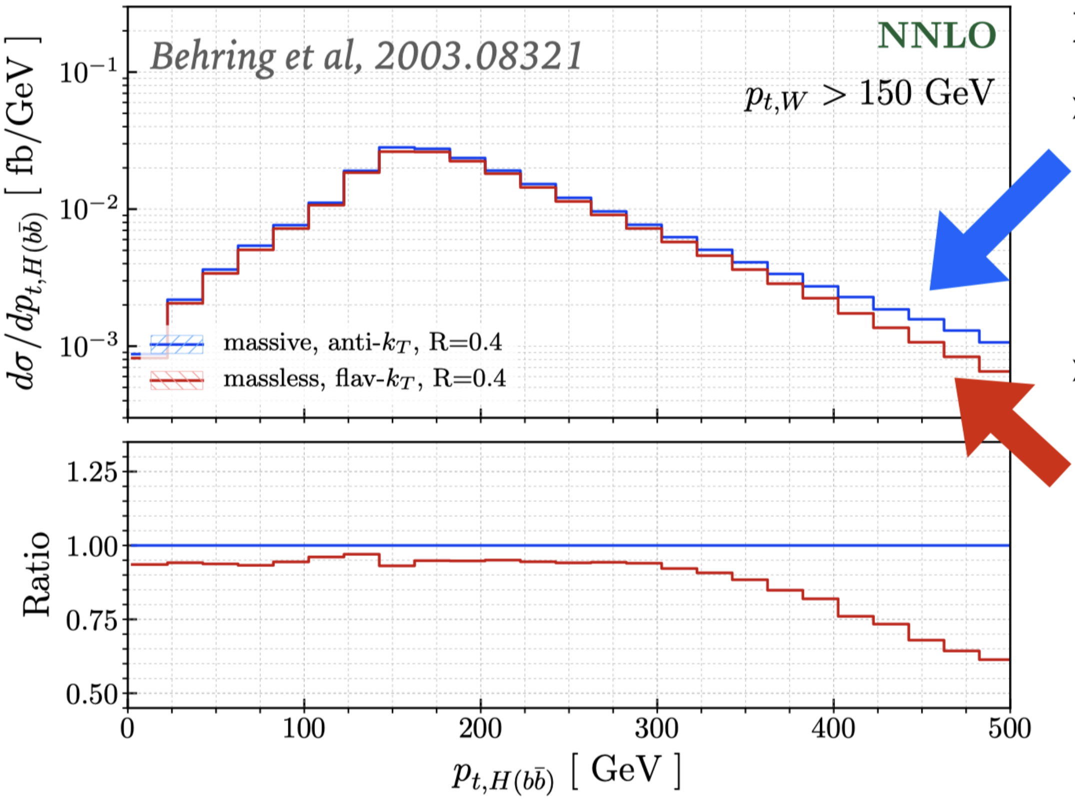
$$d_{ij}^{(F)} = 2(1-\cos\theta_{ij}) \times \begin{cases} \max(E_i^2, E_j^2), & \text{softer of } i,j \text{ is quark-like,} \\ \min(E_i^2, E_j^2), & \text{softer of } i,j \text{ is gluon-like,} \end{cases}$$



…if only it was that easy in the data

GPS

Why a problem? Different algorithms give different jet kinematics



E.g. at NNLO

- Use anti-k_t algorithm (heavy-flavour can only be defined with explicitly massive quarks; unresummed logarithms of p_t/m_b)
- Use flavour-k_t algorithm with massless b-quarks (but kinematics differ wrt anti-k_t and even wrt normal k_t alg.)

What to do?

- Calculate better the flavour that's there
- Make jet algorithms IRC safe up to some order (e.g. NNLO)
- Make jet algorithms IRC safe to all orders


Make Jets IRC
Safe Again


Make Jets IRC
Safe Again
(at least to NNLO)

Recent approaches

Calculate better the flavour that's there (in MCs or resummation)

Caletti, Larkoski, Marzani, Reichelt, 2205.01117
Caletti, Ghira, Marzani, 2312.11623
Larkoski at May 2024 LHCb meeting
Ferrario Ravasio, Hamilton, Karlberg, GPS, Scyboz, Soyez [PanScales "double soft" paper] 2307.11142

Make jet algorithms IRC safe up to some order (e.g. NNLO)

Caletti, Larkoski, Marzani, Reichelt, 2205.01109

Make jet algs. IRC safe to all orders

→ the next few slides

The CMP algorithm

Infrared-safe flavoured anti-kT jets,
Czakon, Mitov, Poncelet 2205.11879

anti-kT: $d_{ij} = \min(k_{T,i}^{-2}, k_{T,j}^{-2}) R_{ij}^2 \qquad d_i = k_{T,i}^{-2}$

Proposed modification:

A soft term designed to modify the distance of flavoured pairs.

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases} \qquad \text{where} \quad \mathcal{S}_{ij} \to 0 \quad \text{if } i, j \text{ are soft}$$

Original proposal:

$$\mathcal{S}_{ij} \equiv 1 - \theta(1 - \kappa_{ij}) \cos\left(\frac{\pi}{2}\kappa_{ij}\right) \quad \text{with} \quad \kappa_{ij} \equiv \frac{1}{a} \frac{k_{T,i}^2 + k_{T,j}^2}{2k_{T,\max}^2} .$$

Issue when $E_i, E_j \gg 1$ but $p_{T,i}, p_{T,j} \ll 1$

Variant IFN paper [2306.07314]

$$\mathcal{S}_{ij} \to \overline{\mathcal{S}}_{ij} = \mathcal{S}_{ij} \frac{\Omega_{ij}^2}{\Delta R_{ij}^2} \qquad \Omega_{ik}^2 \equiv 2\left[\frac{1}{\omega^2}(\cosh(\omega \Delta y_{ik}) - 1) - (\cos \Delta\phi_{ik} - 1)\right]$$

The flavour dressing algorithm: algorithm

The flavour dressing algorithm.—With this information at hand, the flavour dressing algorithm to identify whether a reconstructed jet can be assigned the flavour quantum number $\mathfrak{f}$ proceeds as follows:

1. Initialise empty sets $\text{tag}_k = \varnothing$ for each jet j_k to accumulate all flavoured particles assigned to it.
2. Populate a set $\mathcal{D}$ of distance measures based on all allowed pairings:
   (a) For each unordered pair of particles p_i and p_j, add the distance measure $d_{p_i p_j}$ if either *both particles are flavoured*[1] or *at least one particle is unflavoured and* p_i *and* p_j *are associated with the same jet.*
   (b) If the particle p_i is associated to jet j_k, add the distance measure $d_{p_i j_k}$. In a hadron collider environment, the beam distances $d_{p_i B_\pm}$ should be added if p_i is not associated to any jet.
3. While the set $\mathcal{D}$ is non-empty, select the pairing with the smallest distance measure:
   (a) $d_{p_i p_j}$ is the smallest: the two particles merge into a new particle k_{ij} carrying the sum of the four-momenta and flavour. All entries in $\mathcal{D}$ that involve p_i or p_j are removed and new distances for k_{ij} are added.
   (b) $d_{p_i j_k}$ is the smallest: assign the particle p_i to the jet j_k, $\text{tag}_k \to \text{tag}_k \cup \{p_i\}$, and remove all entries in $\mathcal{D}$ that involve p_i.
   (c) $d_{p_i B_\pm}$ is the smallest: discard particle p_i and remove all entries in $\mathcal{D}$ that involve p_i.
4. The flavour assignment for jet j_k is determined according to the accumulated flavours in tag_k.

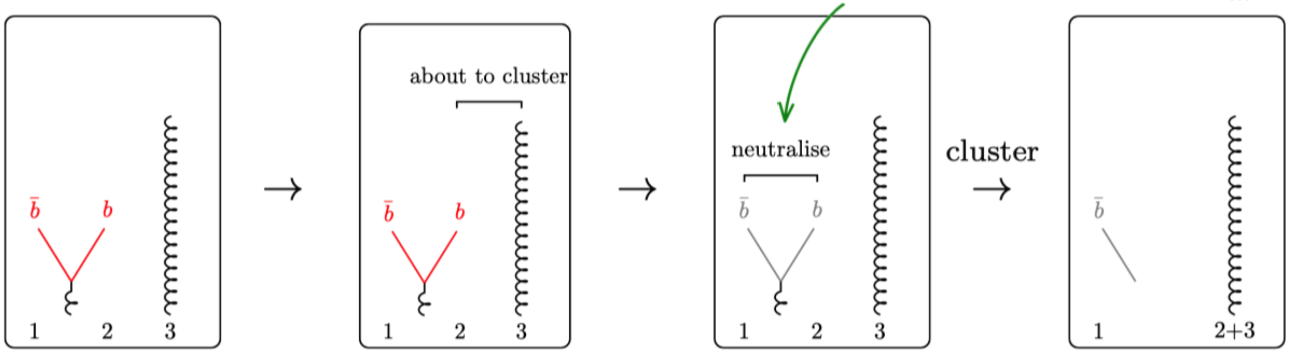
Giovanni Stagnitto, LHCb meeting on jet flavour algorithms

Interleaved Flavour Neutralisation (IFN)

- Cluster particles with a generalised-k_t algorithm (e.g. anti-k_t, C/A),

$$d_{ij} = \min\left(p_{ti}^{2p}, p_{tj}^{2p}\right) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

based on a neutralisation distance u_{ik}



neutralise ≡ remove the (opposite) flavours of both 1 & 2 while maintaining kinematics

need to apply this recursively

Ludovic Scyboz, LHCb meeting on jet flavour algorithms

Distance measures for flavoured clusterings in Flavour-k_t, IFN & Flavour Dressing [GHS]

$$u_{ik} = \underbrace{\max\left(p_{ti}, p_{tk}\right)^{\alpha} \min\left(p_{ti}, p_{tk}\right)^{2-\alpha}}_{\text{flavour}-k_t-\text{like}} \cdot \Omega_{ik}^2$$

$$\Omega_{ik}^2 = 2\left[\frac{1}{\omega^2}\left(\cosh(\omega\Delta y_{ik}) - 1\right) - \left(\cos\Delta\phi_{ik} - 1\right)\right]$$

$\alpha = 1,\ \omega = 2$
$\alpha = 2,\ \omega = 1$

instead of ΔR^2

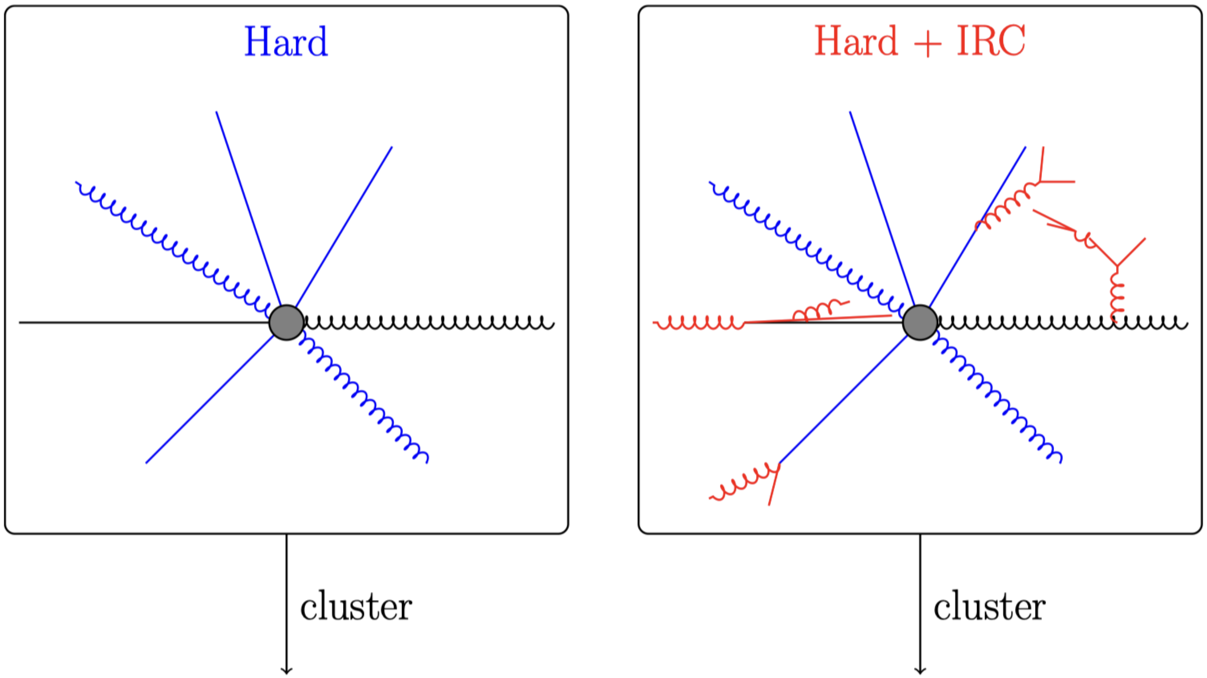
Ω_{ik} needed for IRC safety [initial-state collinear splitting & soft large angle pair]

NB: Flavour-k_t and Flavour Dressing also uses a "beam distance"

$$d_{p_i B_\pm} = \max\left(p_{\mathrm{T},i}^{\alpha}, p_{\mathrm{T},B_\pm}^{\alpha}(y_i)\right)\ \min\left(p_{\mathrm{T},i}^{2-\alpha}, p_{\mathrm{T},B_\pm}^{2-\alpha}(y_i)\right),$$

$$p_{\mathrm{T},B_\pm}(y) = \sum^{m} p_{\mathrm{T},j_k}\left[\Theta(\pm\Delta y_{j_k}) + \Theta(\mp\Delta y_{j_k})\,\mathrm{e}^{\pm\Delta y_{j_k}}\right],$$

Testing IRC safety: analytically & numerically [2306.07314, started in 2020…]



$$\mathcal{J}_{\text{hard}} = \{(p_1, f_1), \ldots, (p_n, f_n)\}$$

$$\mathcal{J}_{\text{hard+IRC}} = \{(\tilde{p}_1, \tilde{f}_1), \ldots, (\tilde{p}_n, \tilde{f}_n)\}$$

Supplement random "hard" event with IRC particles/splittings

Are the hard jets' flavours the same in the original event and the supplemented one?

very considerably expanded relative to SISCone tests [GPS+Soyez, 0704.0292]

First: flavour recombination schemes

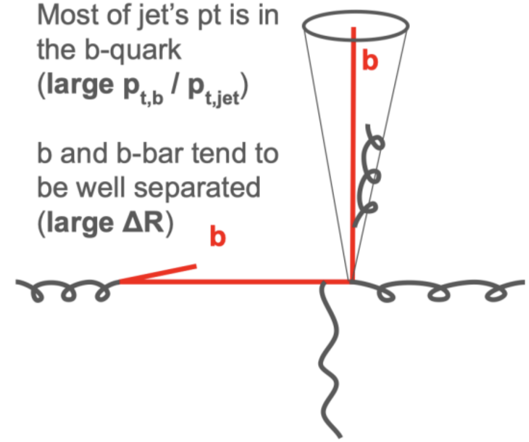
scheme \ jet contents	b	$b+\bar{b}$	$b+b$	
"any flavour"	b	b	b	simplest experimentally (but collinear unsafe for $m_b \to 0$)
net flavour	b	g	$2b$	theoretically "ideal" definition; but not robust wrt B–Bbar oscillations
flavour modulo 2	b	g	g	theoretically OK; robust wrt B–Bbar oscillations

} All algorithms below ~~in the next pages~~ can work with these two

Genuine b-jet

Most of jet's pt is in the b-quark (**large $p_{t,b}$ / $p_{t,jet}$**)

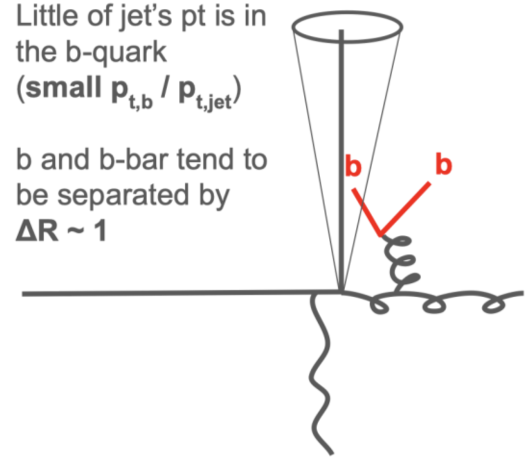
b and b-bar tend to be well separated (**large ΔR**)



Fake b-jet

Little of jet's pt is in the b-quark (**small $p_{t,b}$ / $p_{t,jet}$**)

b and b-bar tend to be separated by **ΔR ~ 1**



Four IRC safe algorithms († including post-IRC safety test adaptations)

Flav-k_t
hep-ph/0601139†

modified k_t-like distance when quark is softer

Flavoured jets have different effective radius & kinematics

replaces k_t alg

Banfi, GPS, Zanderighi

CMP
2205.11879†

modified anti-k_t like distance for low-p_t quark pairs

Jets with flavour ≠ anti-k_t also have ≠ kinematics

replaces anti-k_t alg

Czakon, Mitov, Poncelet

Flav-Dressing
2208.11138†

after-burner on jets above p_t threshold

Identical kinematics to reference alg.

works with anti-k_t, C/A & k_t

Gauld, Huss, Stagnitto

IFN
2306.07314

separates flavour-recomb. from kinematic recomb.

Identical kinematics to reference alg.

works with anti-k_t, C/A (incl. substructure)

Caola, Grabarczyk, Hutt, GPS, Scyboz, Thaler

We've had talks on all of these algorithms within the ATLAS PDF forum

First: flavour recombination schemes

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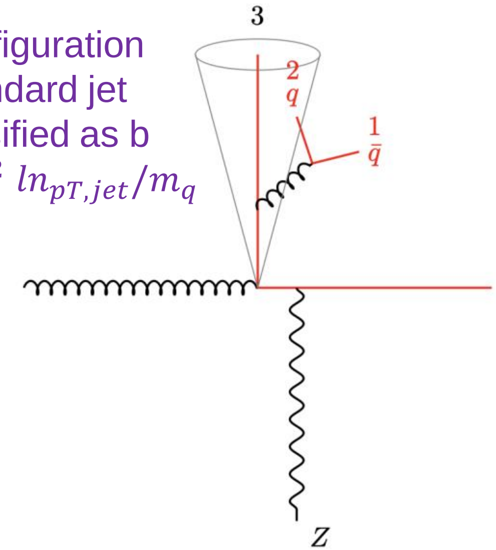
flavour modulo 2	b	g	g	theoretically OK; robust wrt B–Bbar oscillations

} All algorithms below ~~in the next pages~~ can work with these two

problem IRC configuration at NNLO (for standard jet algorithms); classified as b jet; divergence $\alpha_s^2 \, ln_{p_{T,jet}}/m_q$



Four IRC safe algorithms († including post-IRC safety test adaptations)

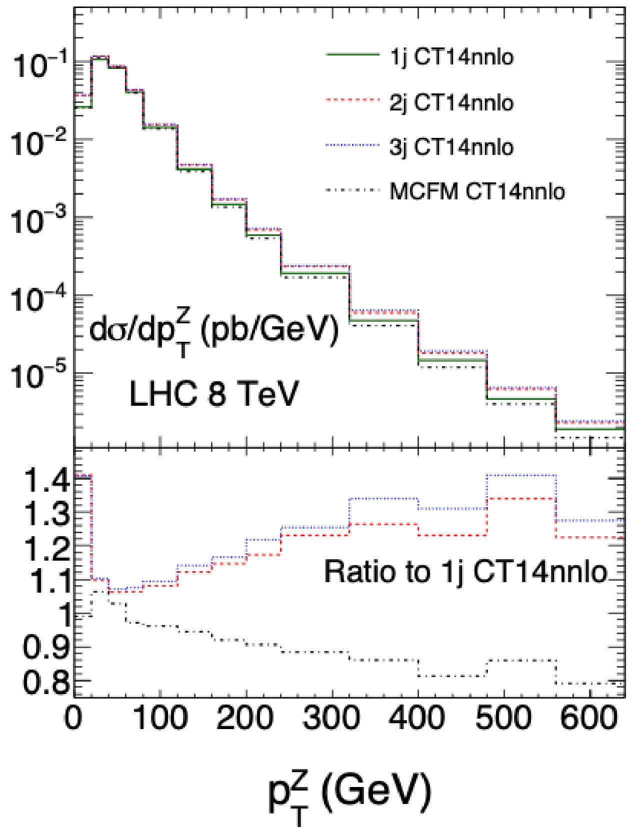
Flav-k_t hep-ph/0601139†	CMP 2205.11879†	Flav-Dressing 2208.11138†	IFN 2306.07314
modified k_t-like distance when quark is softer	modified anti-k_t like distance for low-p_t quark pairs	after-burner on jets above p_t threshold	separates flavour-recomb. from kinematic recomb.
Flavoured jets have different effective radius & kinematics	Jets with flavour ≠ anti-k_t also have ≠ kinematics	Identical kinematics to reference alg.	Identical kinematics to reference alg.
replaces k_t alg	replaces anti-k_t alg	works with anti-k_t, C/A & k_t	works with anti-k_t, C/A (incl. substructure)
Banfi, GPS, Zanderighi	*Czakon, Mitov, Poncelet*	*Gauld, Huss, Stagnitto*	*Caola, Grabarczyk, Hutt, GPS, Scyboz, Thaler*

Algorithms require a knowledge of all heavy flavor quarks in the event.

Ok for theory/MC.
For data?

antikT kinematics may or may not be preserved, depending on algorithm

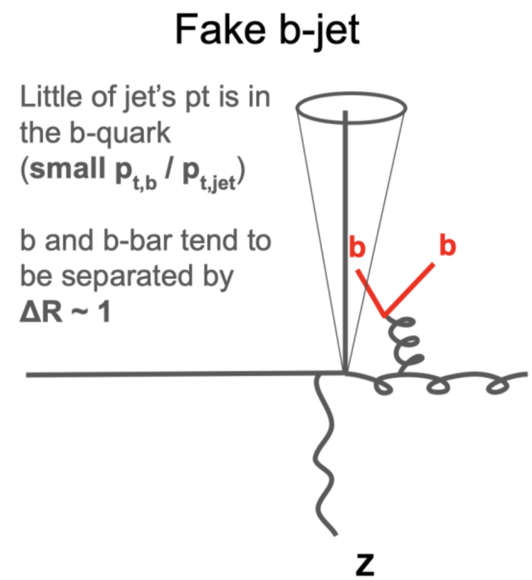
arXiv:1707.00657;JHEP02 (2018) 059



Consider a jet initiated by a gluon. The probability that the gluon splits into a qqbar pair grows logarithmically with jet p_T.

The number of gluons produced in a parton shower (from either a quark or gluon jet) also grows logarithmically. Each gluon can then split into a qqbar pair.

The net enhancement of a heavy flavor tag, where the tag p_T <<jet p_T grows as $\alpha_s^2 L^3$



MPI can also produce heavy flavor pairs that can contaminate jets.

FIG. 19: Transverse momentum distribution of Z bosons produced in association with at least one charm jet at the LHC for $\sqrt{S} = 8$ TeV. Both panels show SHERPA MEPS@LO predictions (obtained by using proper charm tagging) for Z+jets production with a successively increasing number of multileg matrix elements taken into account (i.e. $n_{\rm ME} = 1, 2, 3$ where the $n_{\rm ME} = 1$ curves serve as the reference).

A (very) few highlights

Les Houches flavour studies

G. Stagnitto
Z + b jet

Sherpa

Default parameter choice for the algorithms

[Caletti, Larkoski, Marzani, Reichelt (2205.01109)] **SDF**

$\beta = 1$, $z_{\rm cut} = 0.1$ (soft-drop parameters)

[Czakon, Mitov, Poncelet (2205.11879)] **CMP**

$a = 0.1$ (anti-k_t-like distance)

[Gauld, Huss, Stagnitto (2208.11138)] **GHS**

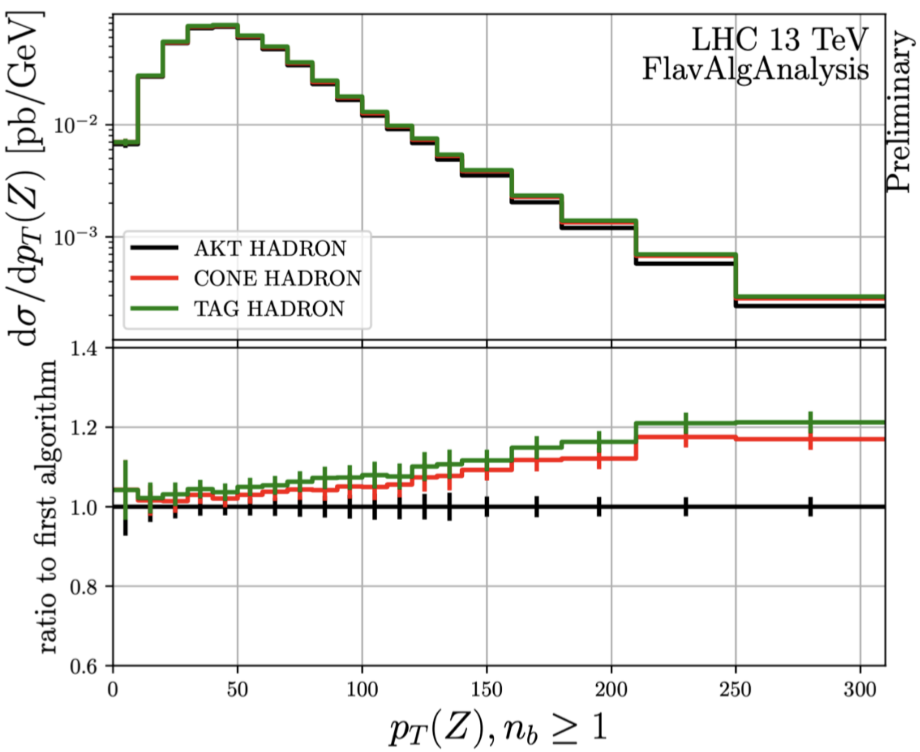
$\alpha = 1$, $\omega = 2$ (flavour-k_t-like and beam distance)

[Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2306.07314)] **IFN**

$\alpha = 1$, $\omega = 2$ (flavour-k_t-like distance)

In plots, **AKT** is the naive IRC-unsafe flavour tagging of anti-k_t jets
(does the jet contain a flavoured parton/hadron?)

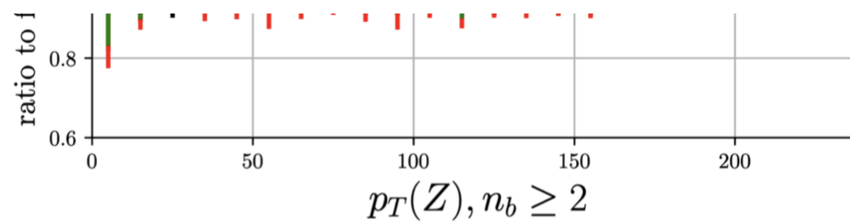
Z+b-jet in the central region: comparison of (unsafe) tagging strategies



AKT:
check if flavoured particle / hadron is inside the anti-k_t jet

CONE:
ATLAS-style tagging
(heavy hadron with $\Delta R(j,h) < 0.3$ and with $p_T > 5$ GeV)

TAG:
CMS-style tagging
(bTagged method with ghost-tagging in Rivet)

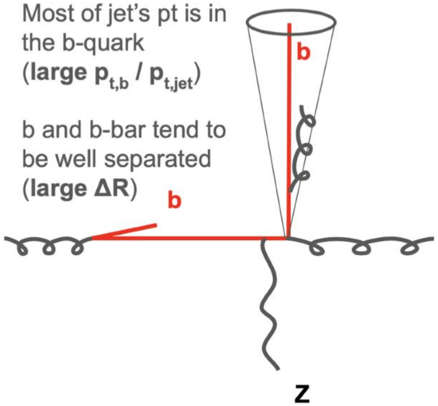


Z+b-jet in the central region: understanding the high-p_T behaviour

Genuine b-jet

Most of jet's pt is in the b-quark (**large $p_{t,b}$ / $p_{t,jet}$**)

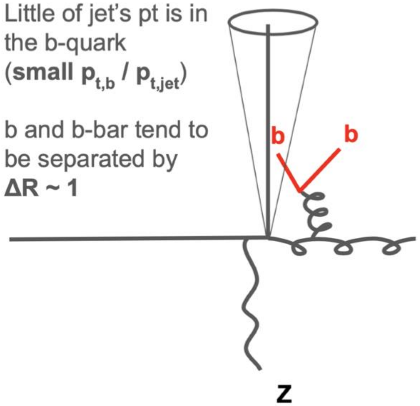
b and b-bar tend to be well separated (**large ΔR**)



Fake b-jet

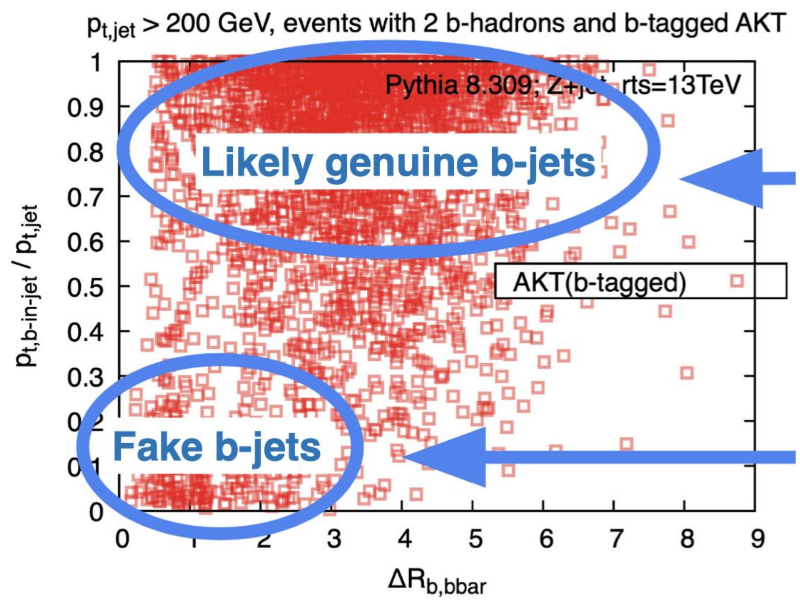
Little of jet's pt is in the b-quark (**small $p_{t,b}$ / $p_{t,jet}$**)

b and b-bar tend to be separated by **ΔR ~ 1**



"Genuine" and "fake" b-jets can be disentangled in a ($p_{T,b}/p_{T,j}$, $\Delta R_{b,\bar{b}}$) plane

Naive AKT will tag both "genuine" and "fake" b-jets



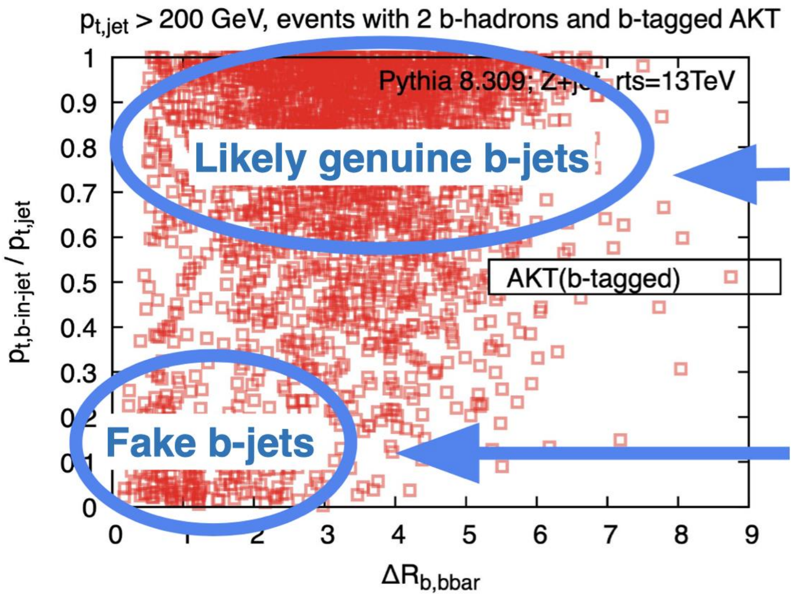
How well do parton showers model g->bb

Z+b-jet in the central region: understanding the high-p_T behaviour

dear Joey, frankly I don't know the answer to your question. On one side, since the tevatron days the modeling of g->QQ splitting in at least some codes has evolved (eg Herwig uses a different algorithm that it used to, certainly in H7, but I believe even since the first C++ version came out). Where the evolution led to a practical improvement vis a vis tevatron I do not know, I wonder whther it's ever even been tested. And for what concerns the LHC I am not aware of recent analysis of this. It's clear that the g->QQ modeling enters in many analysis and to some extent it is being monitored, but I cannot think of recent (or not-so-recent) direct measurements specifically aimed at this process.

You raise a good point, I guess this shold stimulate some dedicated exptl analysis!

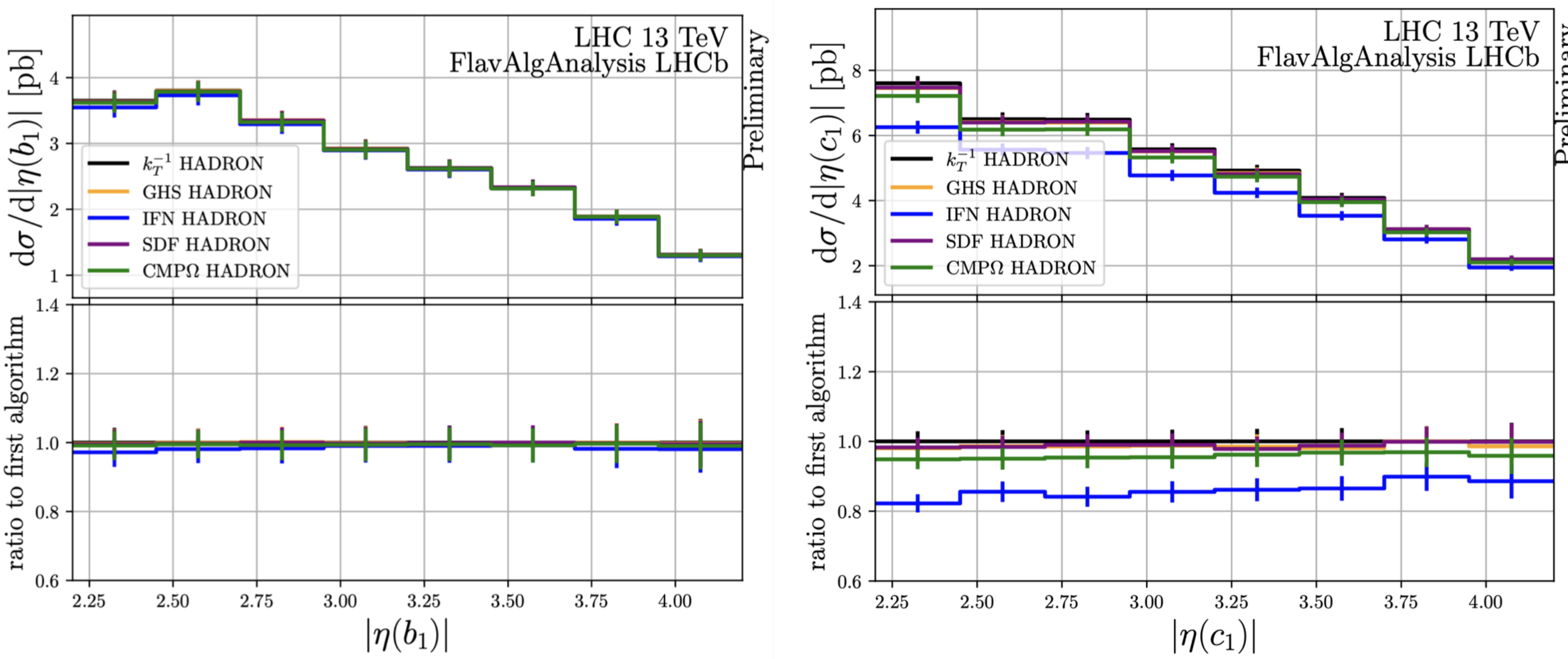
Naive AKT will tag
both “genuine” and “fake” b-jets



best, mlm

Effects more serious for c jets

Z+c-jet in the forward region: comparison of algorithms



We note good agreement between algorithms in case of bottom,
and significant differences in the whole phase space in case of charm

Z+c-jet in the forward region: comparison of algorithms

Z+c-jet in the forward region: comparison of algorithms

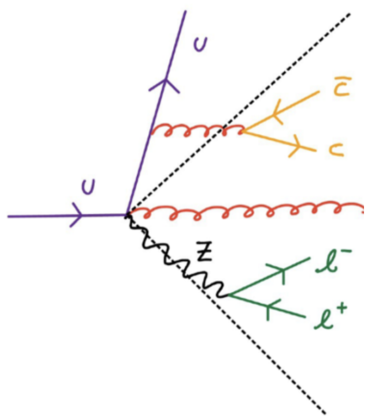
The difference we observe in case of charm needs to be understood, but one can make some considerations:

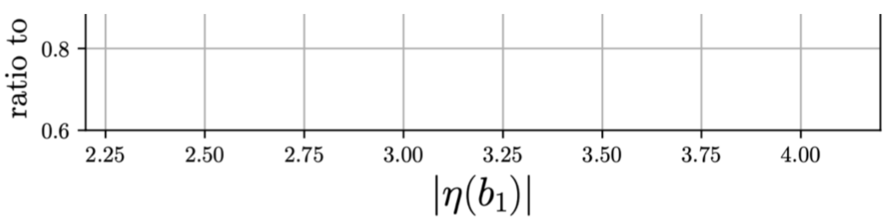
- more $g \to c\bar{c}$ splittings compared to $g \to b\bar{b}$ $\to$ stressing algorithms

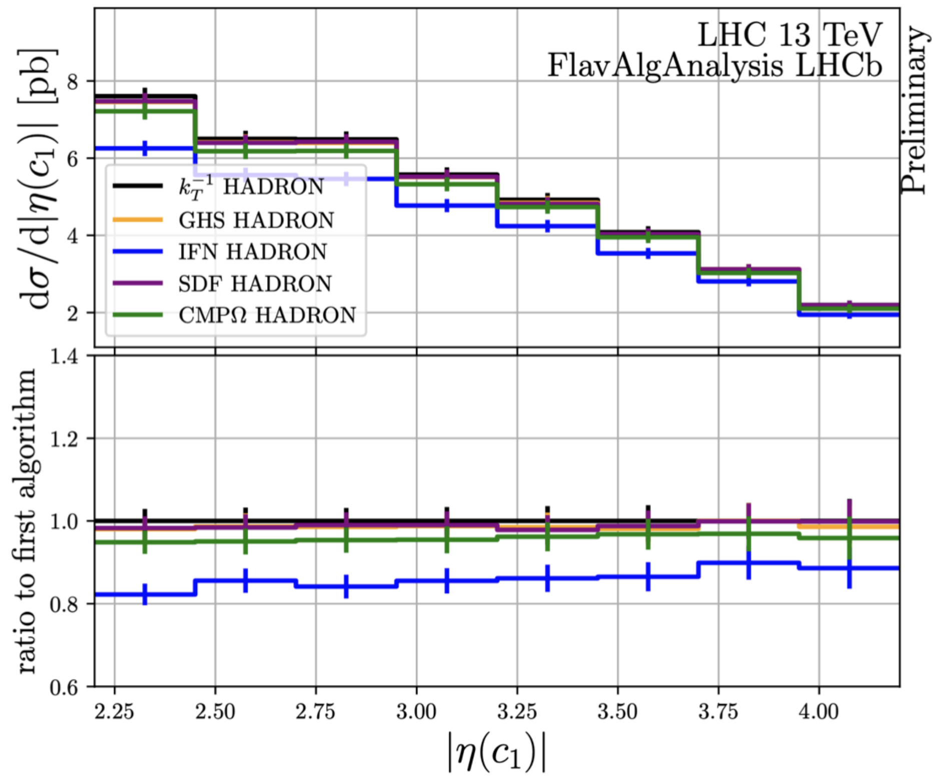
- charm in the LHCb fiducial region likely to come from gluon splitting

- IFN undershooting other algorithms $\to$ it tends to neutralise $c\bar{c}$ pairs more

- interesting to vary parameters and perform a study similar to the Z+b-jet one



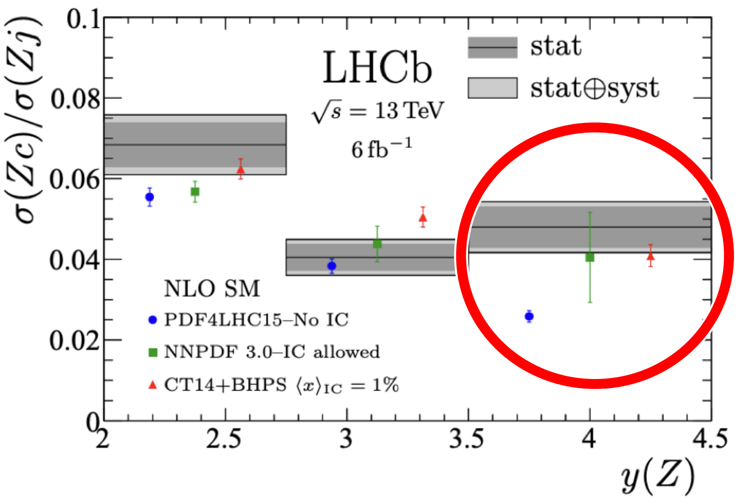




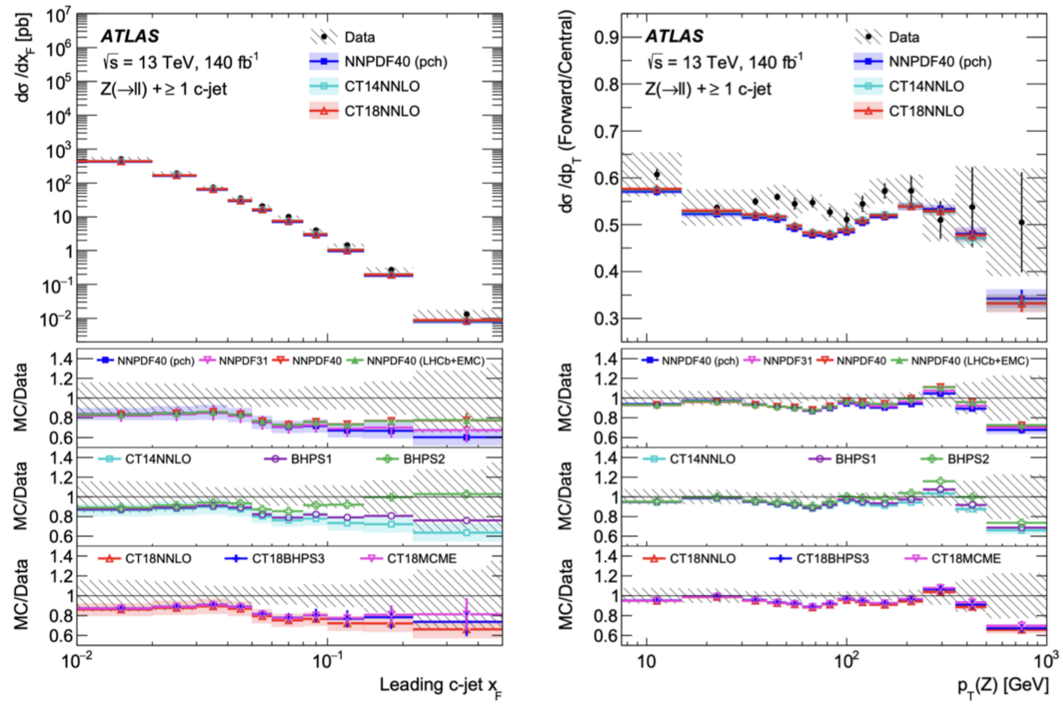
We note good agreement between algorithms in case of bottom, and significant differences in the whole phase space in case of charm

Another reason this is important

Probing HF content of the proton



LHCb 13 TeV, arXiv:2109.08084, PRL128 (2022)



(a) (b)

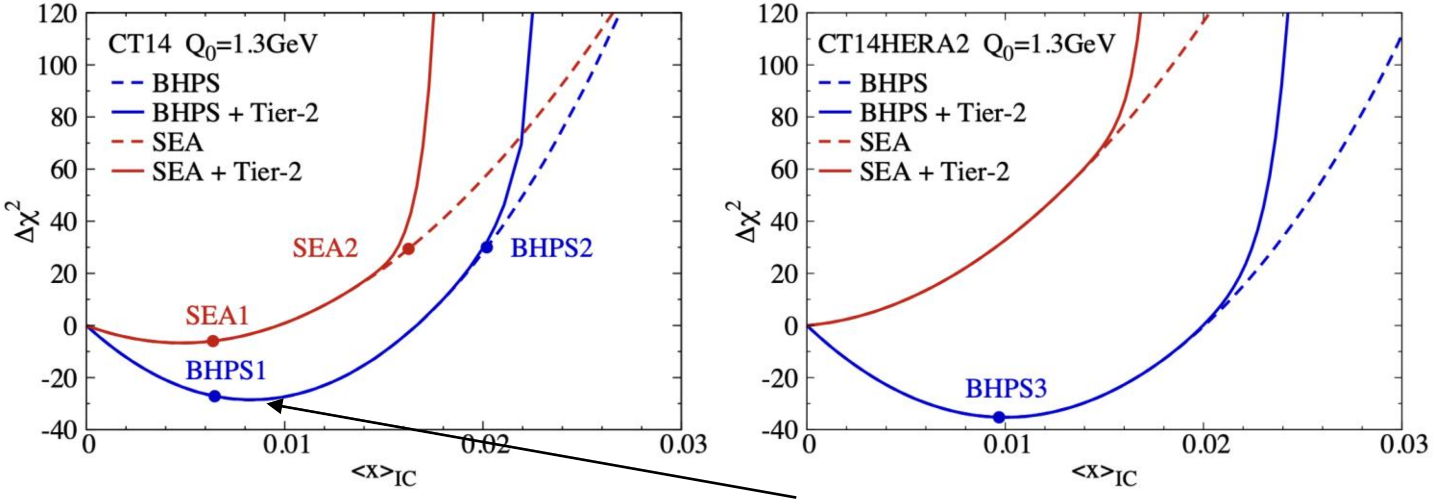
ATLAS13 TeV, Z+c-jet, 140 fb^{-1} arXiv:2403.15093

Is intrinsic charm present in the proton? May need a better understanding of the theory, and in particular the heavy flavor jet algorithm.


One does not simply discover intrinsic charm.

Aside: charm and b quark distributions

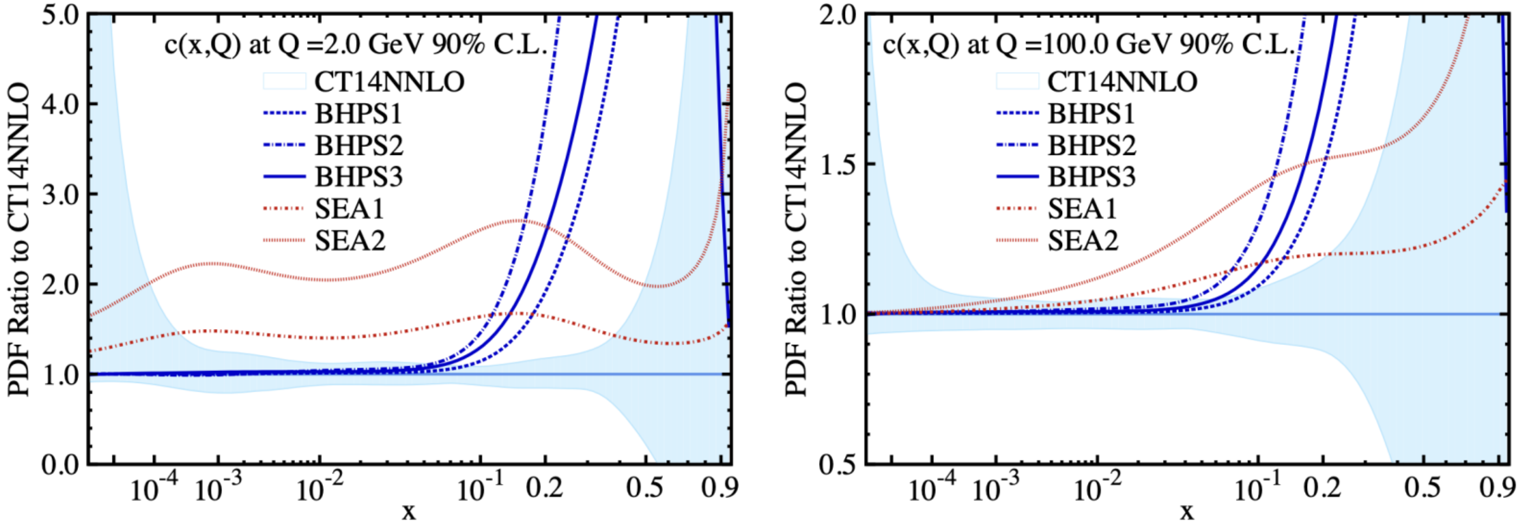
- Perturbative view is that c and b quarks are not present in the proton at scales lower then their masses
- They can be produced in the initial state at scales higher then their masses through gluon splitting into quark-antiquark pairs (thus primarily at lower x)
  - only things that drive production (besides the gluon distribution) are the heavy quark mass and the value of $\alpha_s(m_Z)$
- But the proton can also have an intrinsic charm (and bottom for that matter) component arising from scattering contributions beyond leading twist
  - there are models (BHPS, incorporated by the CTEQ group), and increasingly, predictions from lattice gauge theory, some of which have been incorporated into CT fits
- CT has published PDF sets in which an intrinsic component of charm is modeled. The addition of this intrinsic component leads to a noticeable reduction in global χ^2, but not at the level we would consider to be a discovery



Note: not free fits ->models

We could have claimed a discovery from this, but felt that stronger evidence was needed.

FIG. 5: The change $\Delta\chi^2$ in the goodness of fit to the CT14 (left) and CT14HERA2 (right) data sets as a function of the charm momentum fraction $\langle x \rangle_{\rm IC}$ for the BHPS (blue) and SEA (red) models.

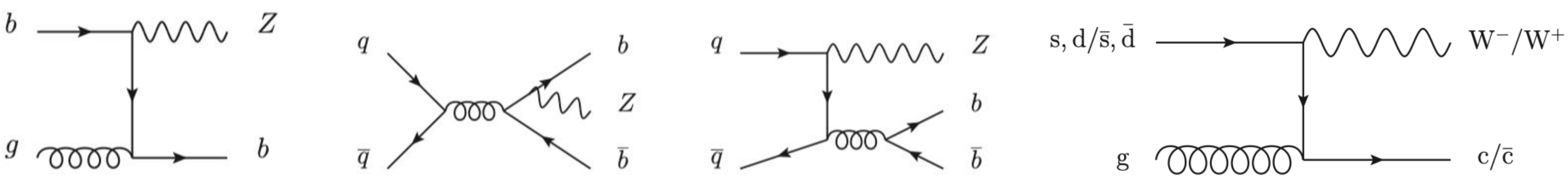


Greatest sensitivity for BHPS models comes from BCDMS and ATLAS 7 TeV W and Z

FIG. 8: Ratio of $c(x,Q)_{\rm IC}/c(x,Q)_{\rm CT14}$ within the CT14 uncertainties at 90% C.L. at the scale $Q = 2$ GeV (left) and $Q = 100$ GeV (right).

V+HF: inputs for (s),b,c PDFs

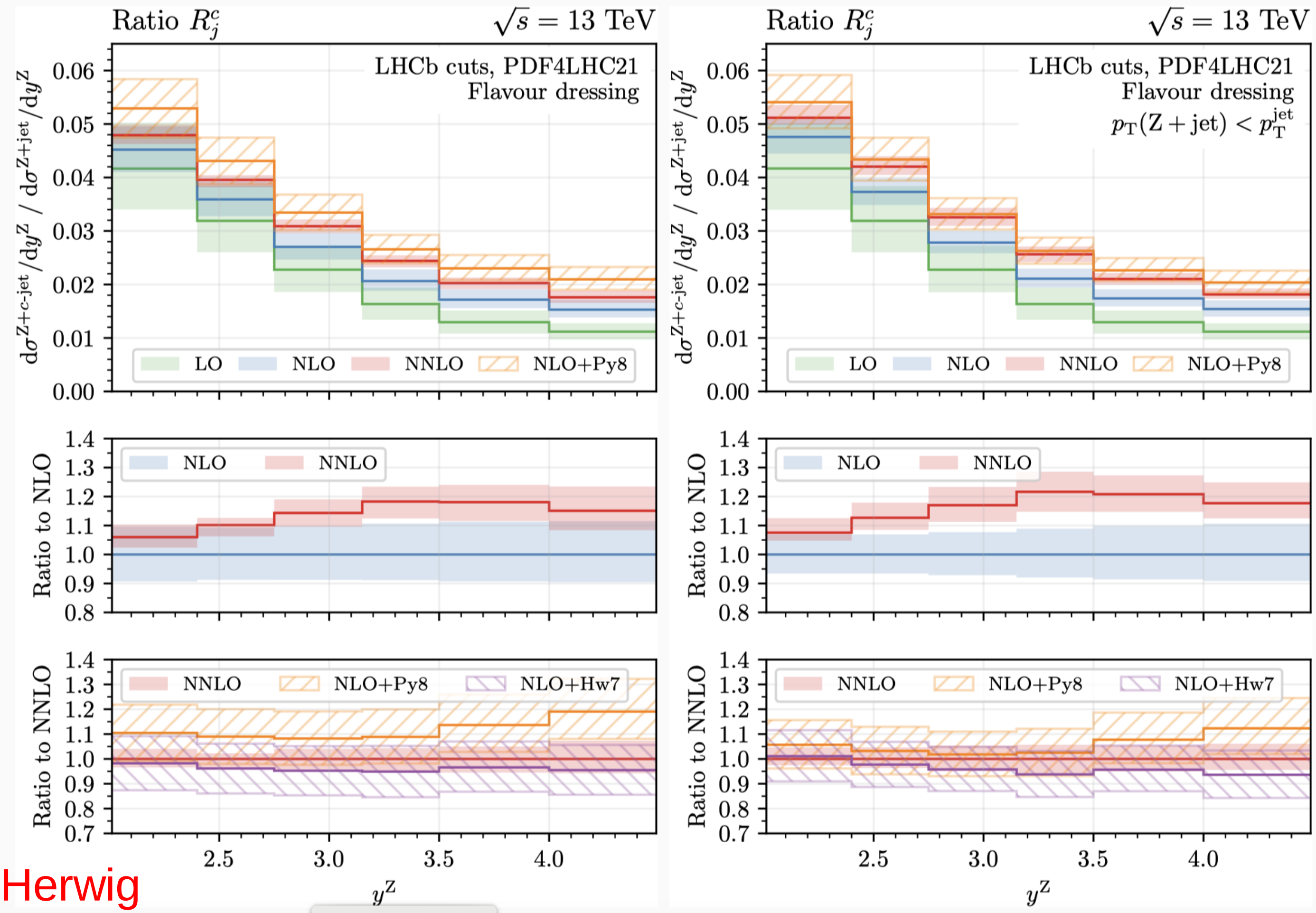
- A heavy flavor quark can be present in the initial state or produced through gluon splitting



- The calculation can be performed in a scheme where there are only 4 parton flavours (4FNS) or in which the b-quark is included (5-FNS)
- The kinematics can drive the subprocess for the production, as for example, whether the final state heavy quark (jet) has to pass only some minimum p_T requirement, or whether it has to roughly balance the boson transverse momentum
- If it’s the former, then the final state c or b quark is likely to arise through gluon splitting, especially given the additional gluon splittings that may occur in a parton shower (*JHEP* 02 (2018) 059)
  - this effect is more pronounced if there is a hierarchy of scales, i.e. $p_T^{jet} >> p_T^{charm}$ (would be useful to measure differentially in p_T^{jet})

Arnd Behring: NNLO (FO)

GHS: $pp \to Z + c$ jet



NNLO has y-dependence

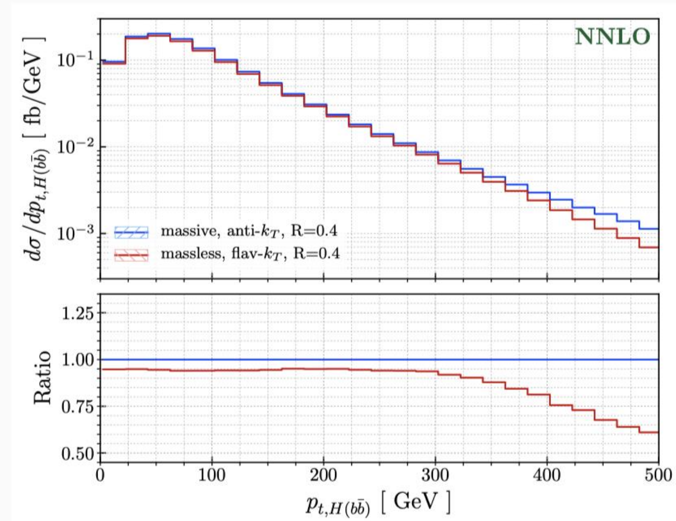
some differences between Pythia and Herwig

Screenshot alias

[Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, Stagnitto '23]

Taking the high road: making the quark massive

- Sometimes it is feasible to keep $m_b \neq 0$
- Enables use of conventional jet algorithms (e.g., anti-k_T)
- We did this for $pp \to WH(\to b\bar{b})$ in [Bizon, AB, Caola, Melnikov, Röntsch '20]
- Comparison to $m_b = 0$ with flavour-k_T: large differences in some distributions



[Bizon, AB, Caola, Melnikov, Rönsch '20]

Also the high road has muddy patches

- Questions about potentially large mass logarithms
- PDFs in $n_f = 4$ vs. $n_f = 5$ flavour scheme
- ...

Alberto Rescia: Z + bB ATLAS

Details & Selections

Madgraph5+Pythia8

- Analysis has 4 signal regions (SRs):
  - Double b-tag and double anti b-tag
  - Boosted and resolved topologies

Analysis selections:

- Require 2 same-flavour opposite sign leptons
- $p_{T,\ell\ell} > 27$ GeV & $m_{\ell\ell} \in [76, 106]$ GeV

Resolved:

- Identify 2 (anti) b-tagged R = 0.4 jets with $p_T > 20$ GeV & $|y| < 2.5$
- Measure JSS observables on these jets

Boosted:

- 1 R = 1.0 jet with $p_T > 200$ GeV & $|y| < 1.5$
- Large-R jet double-b-tagged when 2 b-jets associated to it
- Measure JSS observables on this jet

- Jets selected with high purity b-tagging algorithm (70% efficiency) in boosted and resolved analysis regions
- Double anti-b-tagged selection requires 0 b-tagged jets

Alberto Rescia: Z + bB ATLAS

Details & Selections

- Analysis has 4 signal regions (SRs):
  - Double b-tag and double anti b-tag
  - Boosted and resolved topologies

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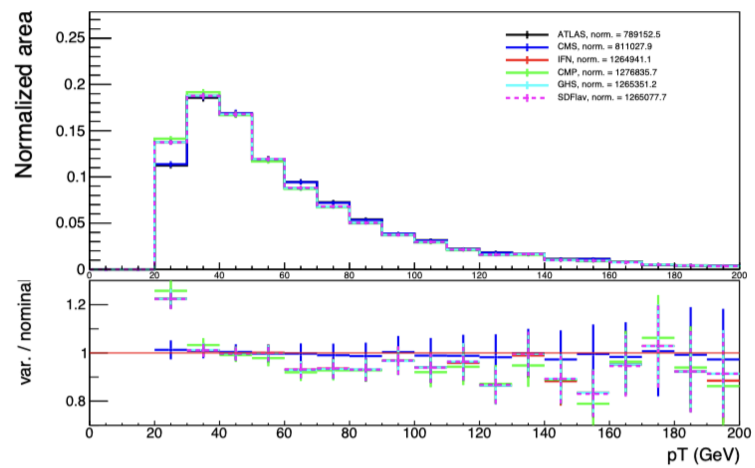
- 1 R = 1.0 jet with $p_T > 200$ GeV & $|y| < 1.5$
- Large-R jet double-*b*-tagged when 2 *b*-jets associated to it
- Measure JSS observables on this jet

For flavour labelling purposes in ATLAS, *only heavy flavour hadrons with $p_T > 5$ GeV are considered*

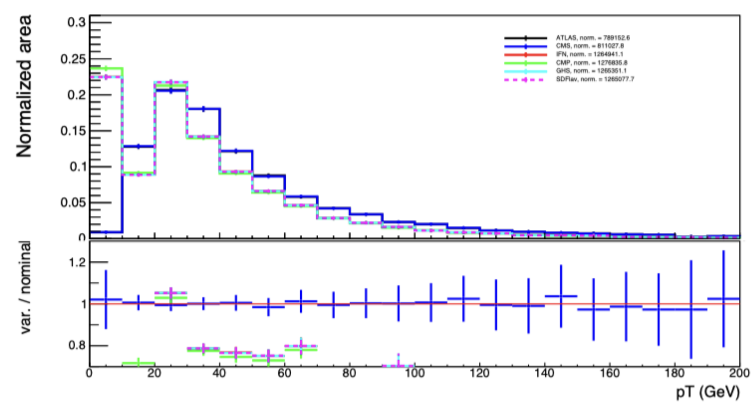
In ATLAS, a jet is labelled as a *b*-jet if a *B* hadron is found within $\Delta R(B, jet) < 0.3$

- No large differences in shape of p_T distribution of leading jet
- At low p_T some differences arise between ATLAS/CMS algorithms and flavour-aware clustering algorithms
- Large differences seen in charged jet p_T distribution
  - Effect due to different constituents
  - ATLAS/CMS include decay products of B-hadrons
  - Flav. algs. include undecayed hadrons

Leading jet



Leading charged jet



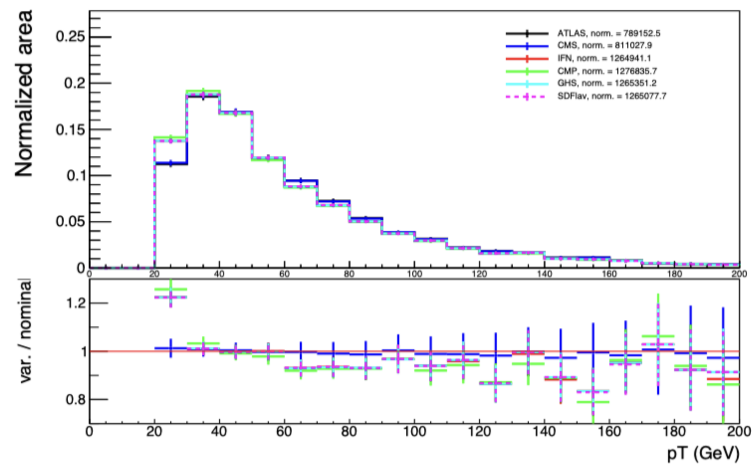
$Z + b\bar{b}$ p_T distribution

Legend

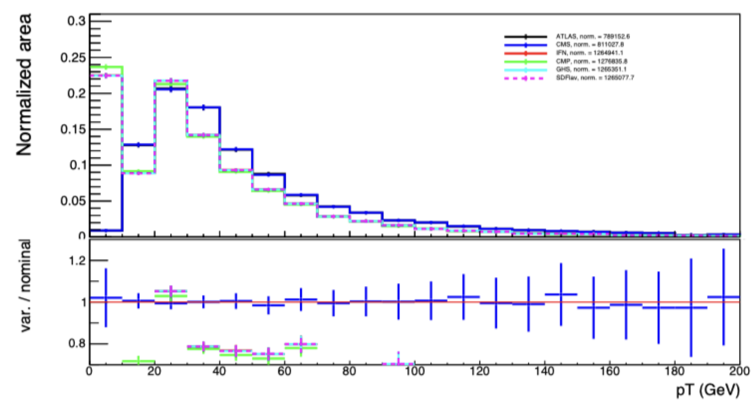
BLACK — ATLAS
BLUE — CMS
RED — IFN
GREEN — CMP
CYAN — GHS
MAGENTA — SDFlav

- Flav. algs. include undecayed hadrons

Leading jet



Leading charged jet



Leticia Cunqueiro (CMS)

- Two recent measurements of inclusive jet substructure at CMS: The primary Lund plane density and the Energy Correlators
  Prospects for heavy flavour jets

- The experimental measurement of heavy flavour jet substructure that is sensitive to the c/b quark mass needs:

  Heavy flavour jet selection
  Treatment of decay products
  Suppression of hadronisation effects

- Flavoured algorithms

  Flavoured algorithms for heavy flavour jets is still unexplored in CMS

> If we consider what is needed for broad usage of a jet flavor algorithm, we can identify at least four criteria that are necessary, or at least highly desirable:
> (i) *IRC safety*. Both the kinematics and the flavors of any hard jets should be IRC safe.
> (ii) *Preserved kinematics*. For a given member of the generalized-k_t algorithm family, the flavor algorithm should not modify the jets' kinematics.
> (iii) *Multiscale flavor resolution*. The flavors of the pseudojets should be well defined at any step of the clustering, so as to leave open the possibility of using flavor information with the full cluster sequence, e.g., for jet substructure studies.

Caola et al, Phys.Rev.D 108,094010 (2023)

Some experimental approaches require the HF hadron to be in the leading prong at each declustering step or in the selected splitting (see ALICE's dead cone measurement)

Other substructure measurements b-tag the jet but not the leading prong of the selected splitting, see *CMS, Phys.Rev.D 98 (2018) 9*

Conclusions (from Alberto)

- Major differences arise due to different definitions of input particles between theory/experiment
  - *Need to harmonise definitions if we wish to apply new algorithms experimentally!*
- CMS and especially ATLAS labelling for large-R jets needs improvement
  - Need to clearly define what it means to double-tag a large-R jet
- All algorithms besides CMP behave similarly for large-R jets

Work in progress! More studies needed

(My)Summary

- Very useful gathering of theorists and experimentalists at workshop
  - unfortunately, not very much participation from CMS; conflict with other meetings
- Work of Les Houches group will continue, with goal of publication
- Key points so far:
  - IRC jet algorithms are necessary to extract full precision of heavy flavor jet cross sections at the LHC
  - such algorithms require full knowledge of heavy quarks in the event, e.g. g>bB; in my opinion difficult to implement on experimental level, but testing how well we can measure g->bB would be useful in (1) understanding the environment and (2) testing how well parton shower Monte Carlos can describe gluon splitting
  - many different IRC-safe jet algorithms have been developed (“let a thousand flowers bloom”); in general, agreement, but there can be differences even at truth level
  - need a way(s) to directly compare/map experimental jet cross sections with theoretical ones using IRC-safe algorithms
    - is one algorithm better than others; does a new algorithm need to be developed?
    - how much of a benefit is having the same antikT jet kinematics?

VBF production at 13 TeV

A comparative study of Higgs boson production from vector-boson fusion

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[9] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*
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[12] *Institute for Mathematics and Physics, University of Vienna, 1090 Wien, Austria*

The data taken in Run II at the Large Hadron Collider have started to probe Higgs boson production at high transverse momentum. Future data will provide a large sample of events with boosted Higgs boson topologies, allowing for a detailed understanding of electroweak Higgs boson plus two-jet production, and in particular the vector-boson fusion mode (VBF). We perform a detailed comparison of precision calculations for Higgs boson production in this channel, with particular emphasis on large Higgs boson transverse momenta, and on the jet radius dependence of the cross section. We study fixed-order predictions at next-to-leading order and next-to-next-to-leading order QCD, and compare the results to NLO plus parton shower (NLOPS) matched calculations. The impact of the NNLO corrections on the central predictions is mild, with inclusive scale uncertainties of the order of a few percent, which can increase with the imposition of kinematic cuts. We find good agreement between the fixed-order and matched calculations in non-Sudakov regions, and the various NLOPS predictions also agree well in the Sudakov regime. We analyze backgrounds to VBF Higgs boson production stemming from associated production, and from gluon-gluon fusion. At high Higgs boson transverse momenta, the Δy_{jj} and/or m_{jj} cuts typically used to enhance the VBF signal over background lead to a reduced efficiency. We examine this effect as a function of the jet radius and using different definitions of the tagging jets. QCD radiative corrections increase for all Higgs production modes with increasing Higgs boson p_T, but the proportionately larger increase in the gluon fusion channel results in a decrease of the gluon-gluon fusion background to electroweak Higgs plus two jet production upon requiring exclusive two-jet topologies. We study this effect in detail and contrast in particular a central jet veto with a global jet multiplicity requirement.

includes NNLOJET, Sherpa, Herwig and Powheg authors

arXiv:2105.11399

comprehensive comparison of the above programs for VBF production (no hadronization/UE); ggF H+2j from Sherpa

original goal was to have ggF predictions from Herwig and Powheg as well, but that fell through; **it will be in the new paper** arXiv:2105.11399

quite a strong R dependence at low p_T due to kinematic cuts

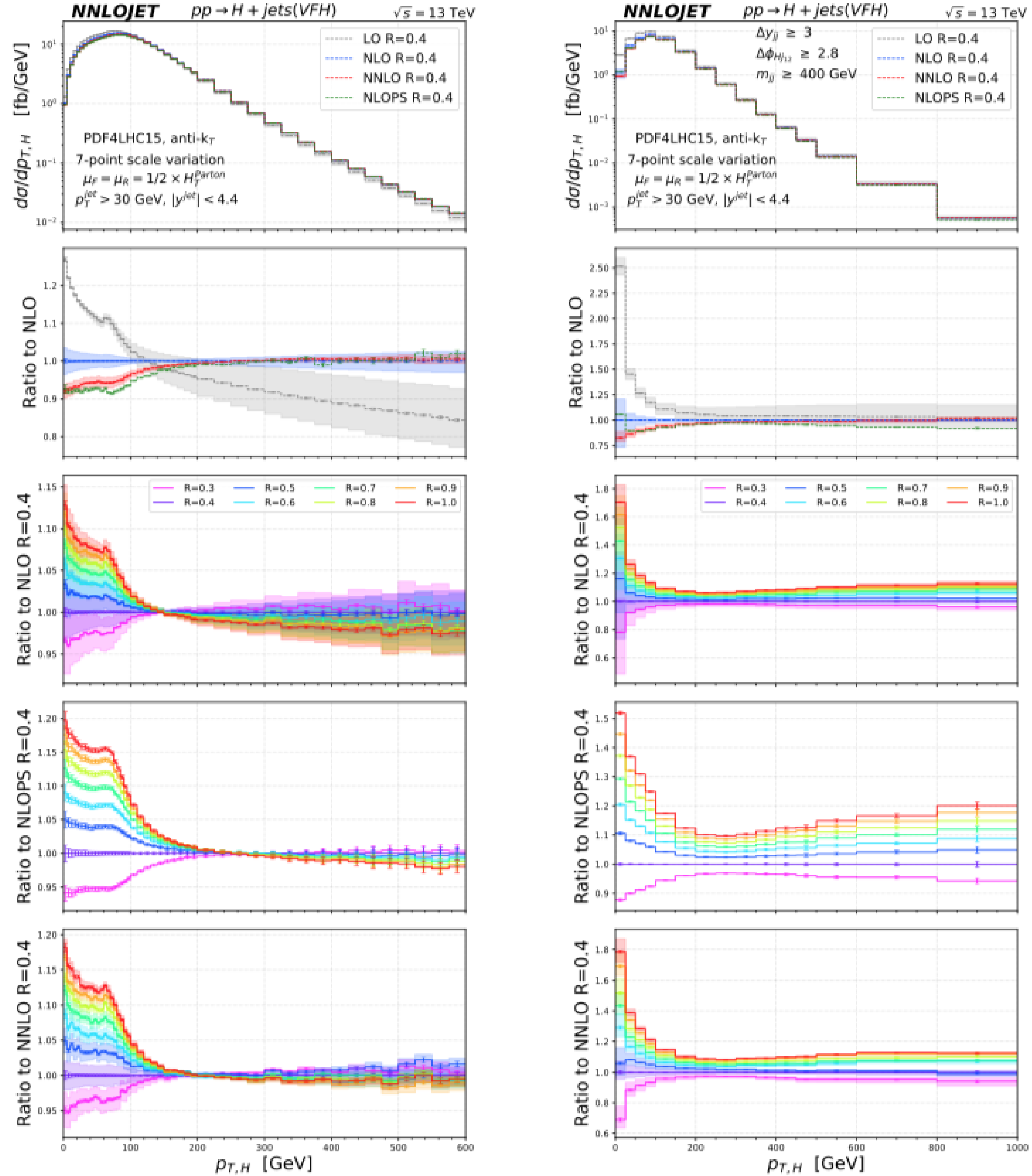
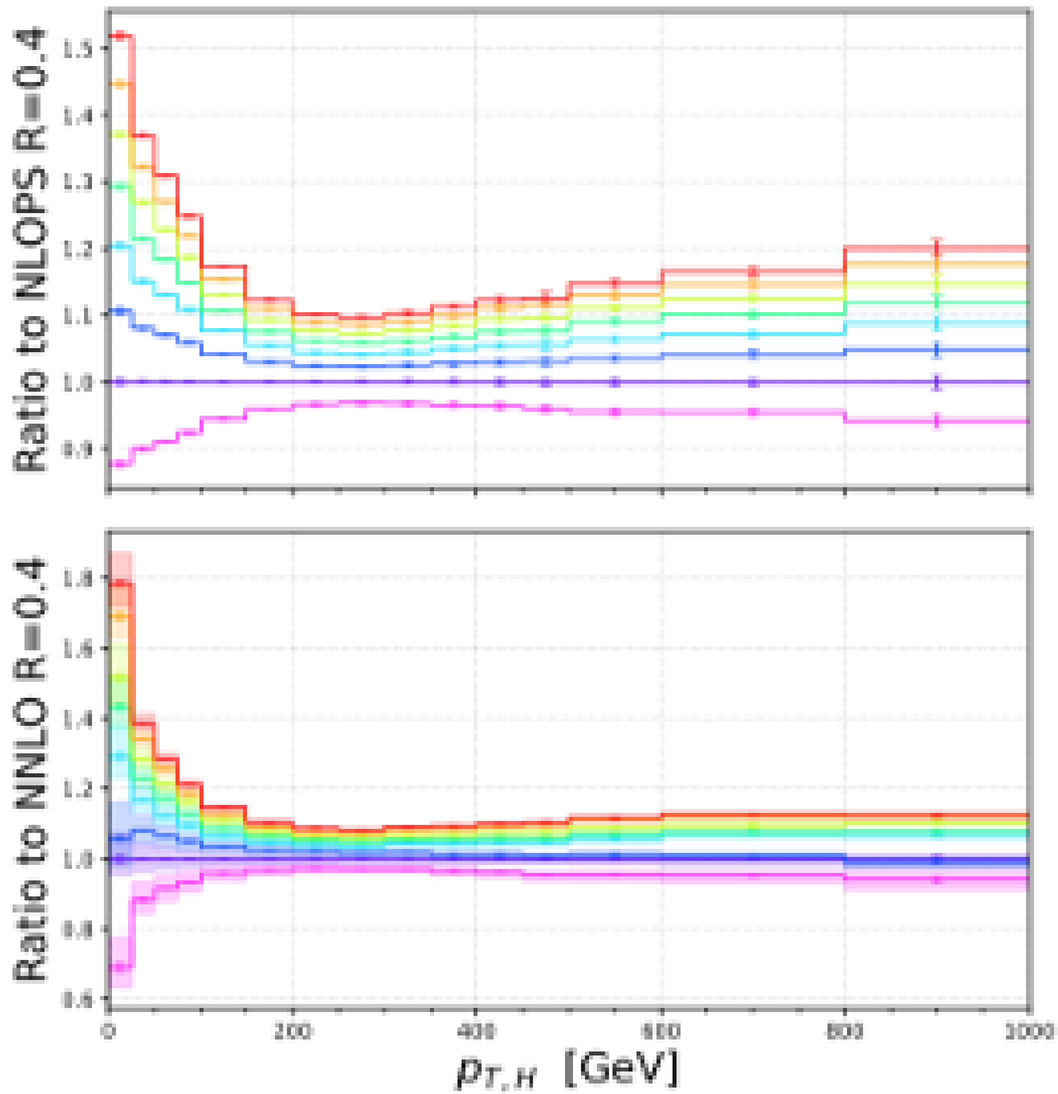


FIG. 18. The Higgs boson transverse momentum distribution from the VBF production channel as a function of jet radius. The left panel is inclusive in Di-jet final state phase space while the right panel is with VBF fiducial cuts used by ATLAS.

How well does the R-dependence for NNLO match onto the R-dependence for NLOPS/data?



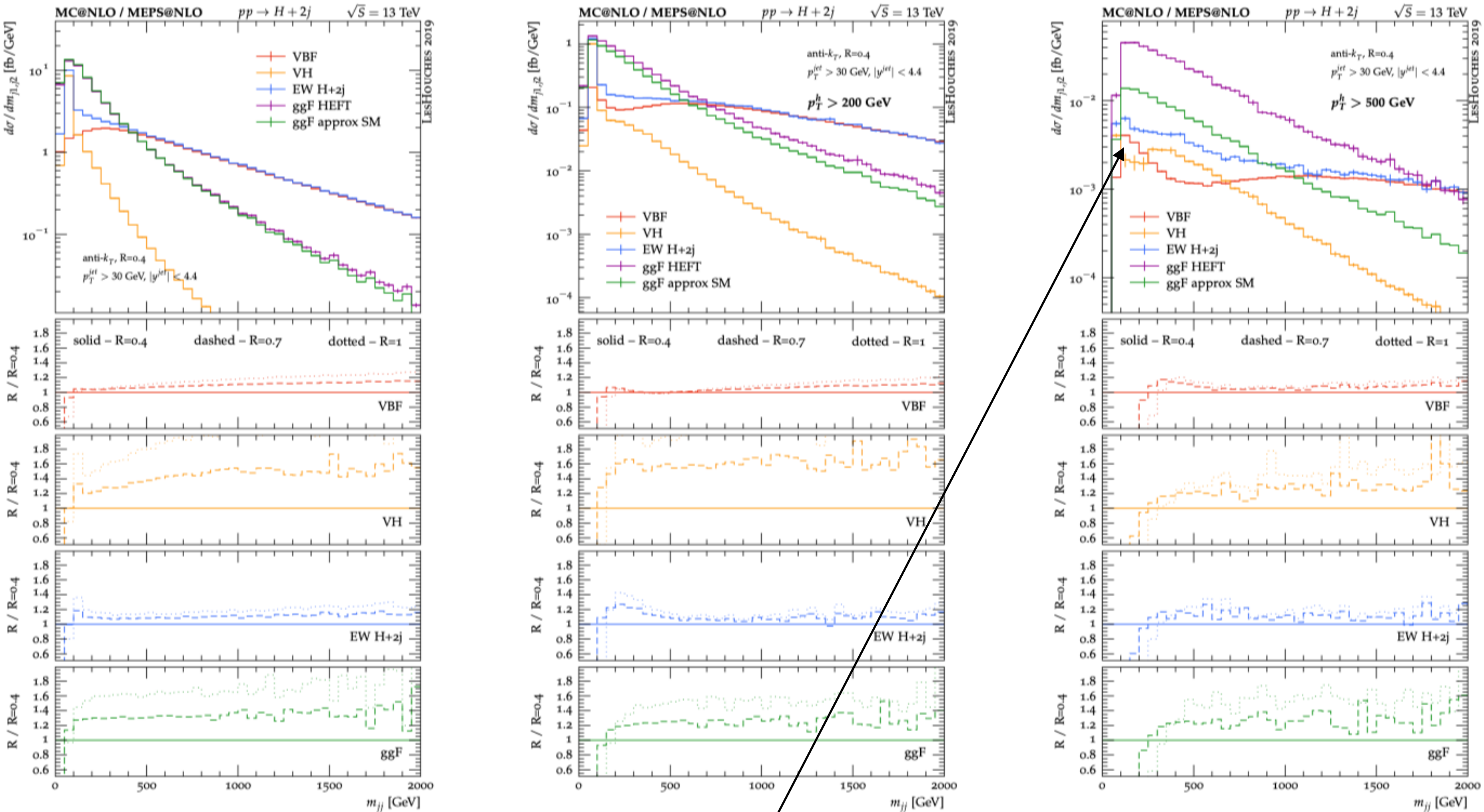


FIG. 7. Dijet invariant mass distribution. The left panels show inclusive predictions, while the middle and right panels show results for a minimum Higgs transverse momentum of 200 and 500 GeV. See Fig. 3 and the main text for details.

Note the growth of the low dijet mass peak for high p_T Higgs. Second jet is not a *tagging* jet, but gluon radiation from lead jet. Loss in efficiency.

New paper

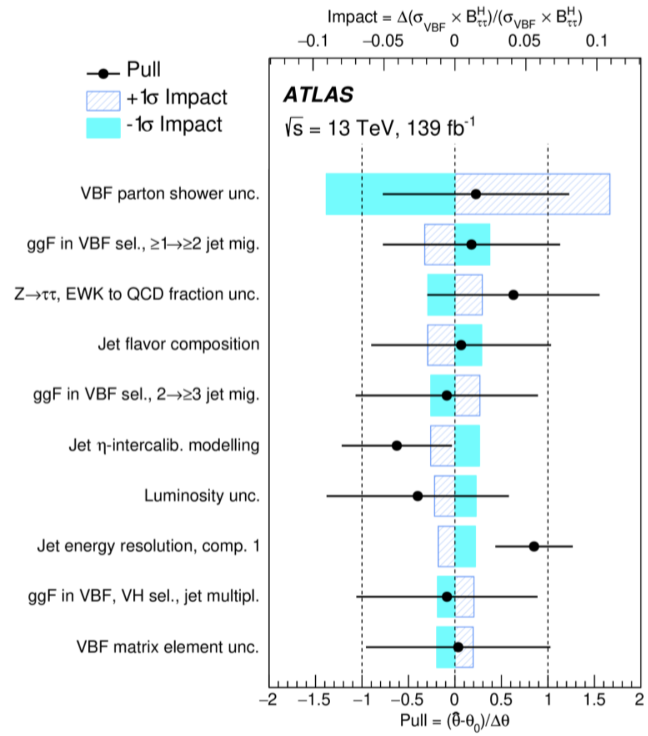
- We are running both ggF and VBF at fixed order at 13.6 TeV, as well as ME+PS predictions for both VBF and ggF from Sherpa, Powheg+Pythia and Powheg+Herwig
- Involving NNLOJET, Powheg, Pythia, Herwig and Sherpa authors
- …as well as Ahmed Tarek and myself from ATLAS, and Yacine Haddad from CMS

Theory uncertainty relative sizes in **typical** VBF measurements

	VBF H	ggH (in VBF-enriched region)
PDF	<1%	<3%
QCD scale	<1%	**2-20%**
UE	<1.5%	<2-3%
Parton shower	**5-15%**	**4-10%**

Stephen Jones

- We would also like to reduce/understand the systematics for VBF and its backgrounds that result from parton shower variations and non-perturbative



Example: ranking plot of theory uncertainty of the μ_{VBF} measurement in HTau

Les Houches 2021: Physics at TeV Colliders: Report on the Standard Model Precision Wishlist

Alexander Huss[1] , Joey Huston[2] , Stephen Jones[3] , Mathieu Pellen[4]

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Abstract

Les Houches activities in 2021 were truncated due to the lack of an in-person component. However, given the rapid progress in the field, and the restart of the LHC, we wanted to continue the bi-yearly tradition of updating the standard model precision wishlist. If nothing else, this will keep us from having even more work to do at Les Houches 2023.

The Les Houches wishlist (arXiv:2207.02122)

A. Huss, J. Huston, S. Jones, M. Pellen

Higgs sector

2023 revision in progress with above plus Raoul Rontsch

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO^{(t)}_{QCD}}$ $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.) $\mathrm{NNLO^{(b,c)}_{QCD}}$
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL} \otimes LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ $\mathrm{NNLO^{(VBF)}_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to VH$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{NLO^{(t,b)}_{gg \to HZ}}$	
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL} \otimes NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to HH + 2j$	$\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (off-diag.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD} + NLO_{EW}}$

Table 1: Precision wish list: Higgs boson final states. $\mathrm{N^xLO^{(VBF^*)}_{QCD}}$ means a calculation using the structure function approximation. $V = W, Z$.

Les Houches 2021: Physics at TeV Colliders: Report on the Standard Model Precision Wishlist

arXiv:2207.02122

Alexander Huss[1], Joey Huston[2], Stephen Jones[3], Mathieu Pellen[4]

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO}^{(t)}_{\mathrm{QCD}}$ $\mathrm{N^{(1,1)}LO}^{(\mathrm{HTL})}_{\mathrm{QCD}\otimes\mathrm{EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.) $\mathrm{NNLO}^{(b,c)}_{\mathrm{QCD}}$
$pp \to H+j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to H+2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ (incl.) $\mathrm{NNLO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ $\mathrm{NLO}^{(\mathrm{VBF})}_{\mathrm{EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ $\mathrm{NNLO}^{(\mathrm{VBF})}_{\mathrm{QCD}}$
$pp \to H+3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO}^{(\mathrm{VBF})}_{\mathrm{QCD}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VH$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NLO}^{(t,b)}_{gg\to HZ}$	
$pp \to VH+j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to HH+2j$	$\mathrm{N^3LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ (incl.) $\mathrm{NNLO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ $\mathrm{NLO}^{(\mathrm{VBF})}_{\mathrm{EW}}$	
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	
$pp \to H+t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (off-diag.)	$\mathrm{NNLO_{QCD}}$
$pp \to H+t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$

1: Precision wish list: Higgs boson final states. $\mathrm{N}^x\mathrm{LO}^{(\mathrm{VBF}^*)}_{\mathrm{QCD}}$ means a calculation using
ucture function approximation. $V = W, Z$.

$H+\geq 2j$: *LH19 status:* VBF production known at $\mathrm{N^3LO_{HTL}}$ accuracy for the total cross section [426] and at $\mathrm{NNLO_{HTL}}$ accuracy differentially [172, 280] in the "DIS" approximation [427]; non-factorizable QCD effects beyond this approximation studied in Refs. [428]. Full $\mathrm{NLO_{QCD}}$ corrections for $H+3j$ in the VBF channel available [429, 430]. $H+\leq 3j$ in the gluon fusion channel was studied in Ref. [431] and an assessment of the mass dependence of the various jet multiplicities was made in Ref. [432]; $\mathrm{NLO_{EW}}$ corrections to stable Higgs boson production in VBF calculated [433] and available in HAWK [434]. Mass effects in $H+2j$ at large energy are known within the "High Energy Jets" framework [435–440].

In Ref. [441] parton-shower and matching uncertainties for VBF Higgs production were studied in detail using PYTHIA and HERWIG. The study found that varying just the renormalisation, factorisation and shower scales underestimates the theoretical uncertainty. Instead, by comparing different parton shower Monte Carlos the authors observe differences at the level of 10% for NLO accurate observables and 20% for LO accurate observables. The work also highlighted the importance of the choice of appropriate recoil schemes in order not to obtain unphysical enhancements for VBF topologies.

$\mathrm{NNLO_{QCD}}$ corrections to VBF Higgs production with $H \to b\bar{b}$ and $H \to WW^*$ decays were computed for fiducial cross sections in Ref. [273], using the nested soft-collinear subtraction scheme. These results have recently been extended to include also anomalous HVV interactions [442].

A comparative study of VBF Higgs production at fixed order and with parton shower Monte Carlos has been carried out over a wide range of Higgs boson transverse momenta [335]. This was an outgrowth of Les Houches 2019. One interesting discovery is that, at very high Higgs boson p_T, current implementations of ME+PS Monte Carlos do not provide a completely accurate description of the VBF production mechanism. Rather than the nominal $2 \to 3$ process, high-p_T VBF Higgs production becomes effectively a $2 \to 2$ process, with the second tagging jet becoming soft with respect to the hard scattering scale. This then requires the use of two factorization scales in the ME+PS VBF calculation to take into account this disparity.

The non-factorisable $\mathrm{NNLO_{QCD}}$ correction to VBF production was studied in Ref. [443] and found to be small.

The impact of the top-quark mass in $H+1,2$ jets was studied in Ref. [444]. For $H+1$ jet, good agreement with the full $\mathrm{NLO_{QCD}}$ result was observed when including the top-quark mass in the real radiation and rescaling the virtual contribution in the HTL by the full Born result. NLO differential predictions for $H+2$ jet were computed using this approximation and the relative correction was found to be very similar to the $\mathrm{NLO_{HTL}}$ prediction, although the absolute predictions differed significantly.

feedback would be appreciated

The current experimental error on the $H+\geq 2j$ cross section is on the order of 25% [424], again dominated by statistical errors, and again for the diphoton final state, by the fit statistical error. With the same assumptions as above, for 3000 fb^{-1}, the statistical error will reduce to the order of 3.5%. If the systematic errors remain the same, at approximately 12% (in this case the largest systematic error is from the jet energy scale uncertainty and the jet energy resolution uncertainty), a total uncertainty of approximately 12.5% would result, less than the current theoretical

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PART 1
Les Houches, there's a place you can go
I said, Les Houches, when you're short on ideas
You can stay there, and I'm sure you will find
Many ways to have a good time!

PART 2
Les Houches, where we all can discuss
I said, Les Houches, in the beautiful Alps
You can stay there, and then try to combine
truth and reco, then go drink wine!

CHORUS A
We want jet's flavour to be I. R. C. Safe
We want jet's flavour to be I. R. C. Safe
Cannot just count the b's, of an anti-kt
because even a soft gluon splits

PART 1
Les Houches, there's a place you can go
I said, Les Houches, when you're short on ideas
You can stay there, and I'm sure you will find
Many ways to have a good time!

PART 2
Les Houches, where we all can discuss
I said, Les Houches, in the beautiful Alps
You can stay there, and then try to combine
truth and reco, then go drink wine!

CHORUS B
We should reduce the ne-ga-tive weights
and compute processes at N3LO
This is our wishlist, to make Joey in peace
and then make the best of stats

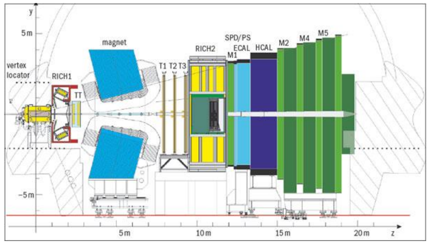
CHORUS A x2
We want jet's flavour to be I. R. C. Safe
We want jet's flavour to be I. R. C. Safe
Cannot just count the b's, of an anti-kt
because even a soft gluon splits
```

…and even the LH2023 song
“I.R.C. safe” (to the tune of YMCA)
was dedicated to flavoured jets

Extra

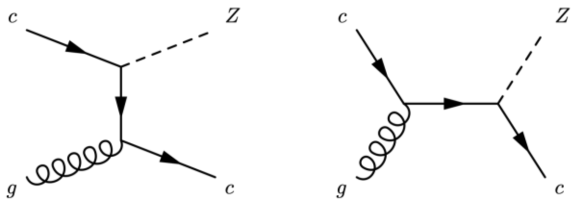
Z+c jets (arXiv:2109.08084)

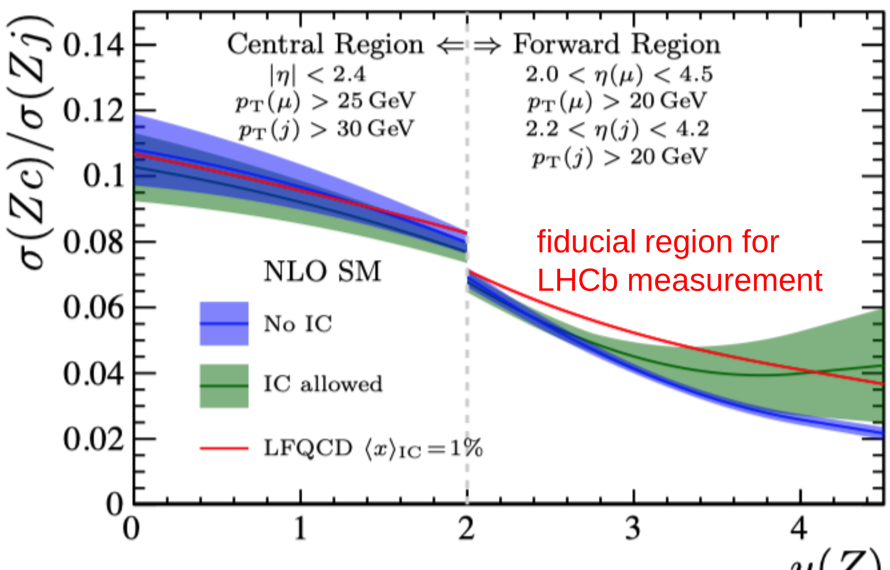
- The forward layout of LHCb makes it particularly sensitive to the presence of any charm component at high x



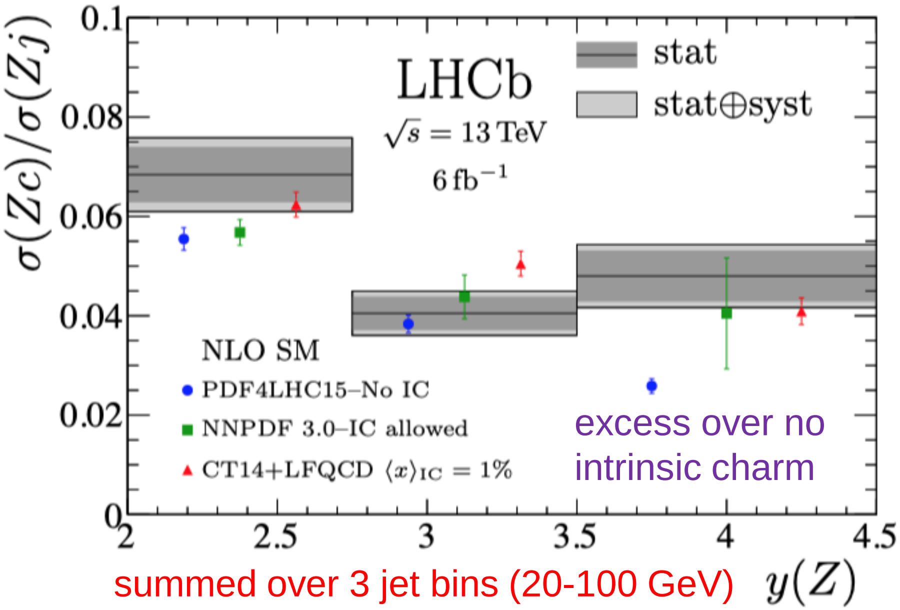
Z bosons	$p_{\mathrm{T}}(\mu) > 20\,\mathrm{GeV}$, $2.0 < \eta(\mu) < 4.5$, $60 < m(\mu^+\mu^-) < 120\,\mathrm{GeV}$
Jets	$20 < p_{\mathrm{T}}(j) < 100\,\mathrm{GeV}$, $2.2 < \eta(j) < 4.2$
Charm jets	$p_{\mathrm{T}}(c\text{ hadron}) > 5\,\mathrm{GeV}$, $\Delta R(j, c\text{ hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

- For greater sensitivity, measure the ratio of Zc to Zj





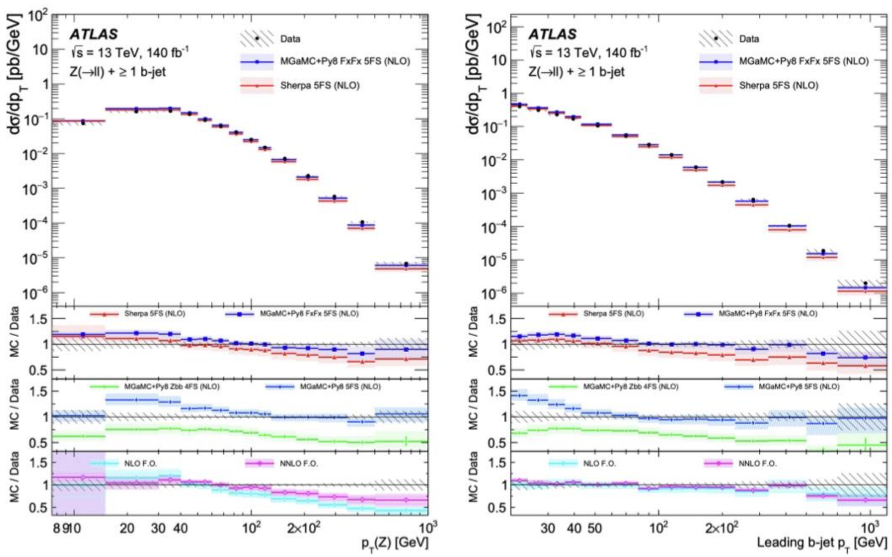
predictions from PRD93 074008



summed over 3 jet bins (20-100 GeV)

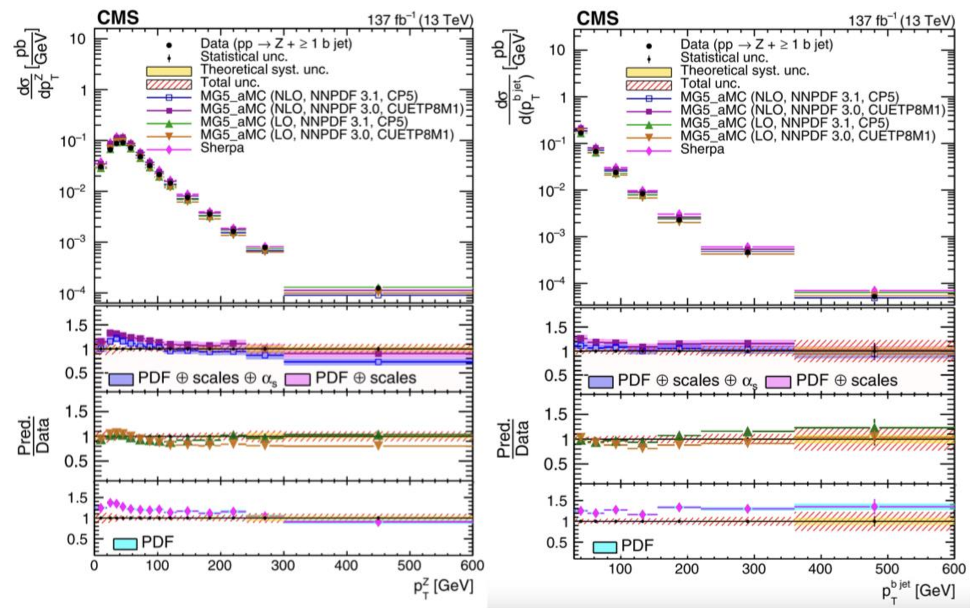
Large inflow of new measurements @LHC

Precise measurements Z + c/b-jets available from the ATLAS, CMS and LHCb collaborations at the LHC



(a) (b)

ATLAS13 TeV, Z+b-jet, 140 fb^{-1} 2403.15093

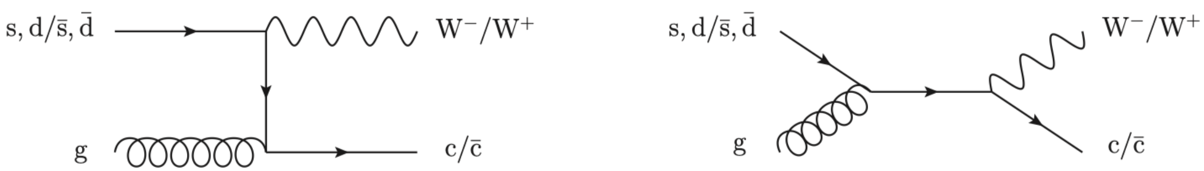


CMS13 TeV, Z+b-jet, 137 fb^{-1} 2112.09659 PRD 105 (2022)

M. Guzzi DIS24

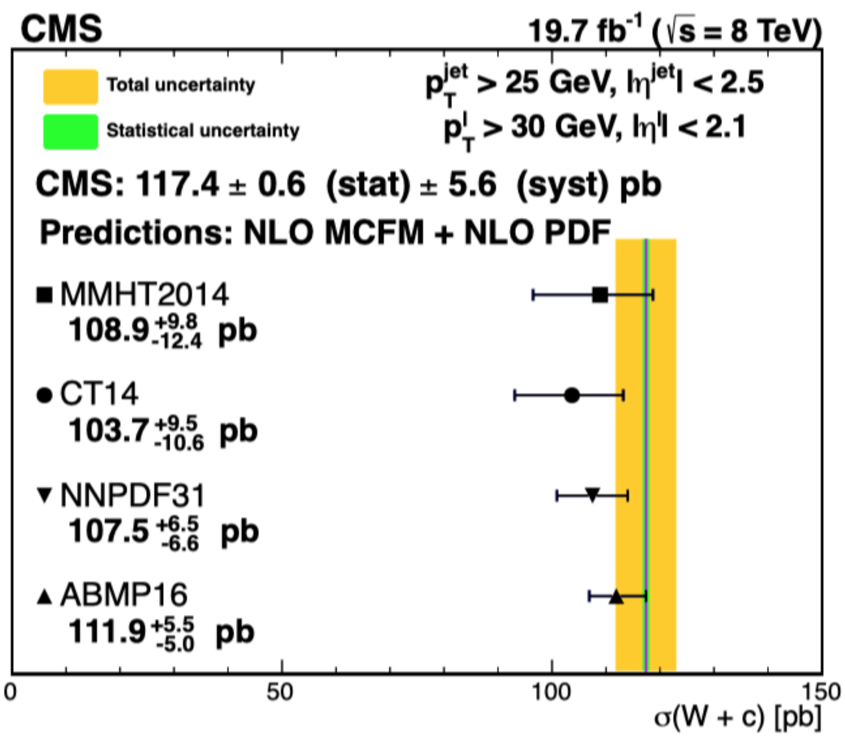
W+c jets

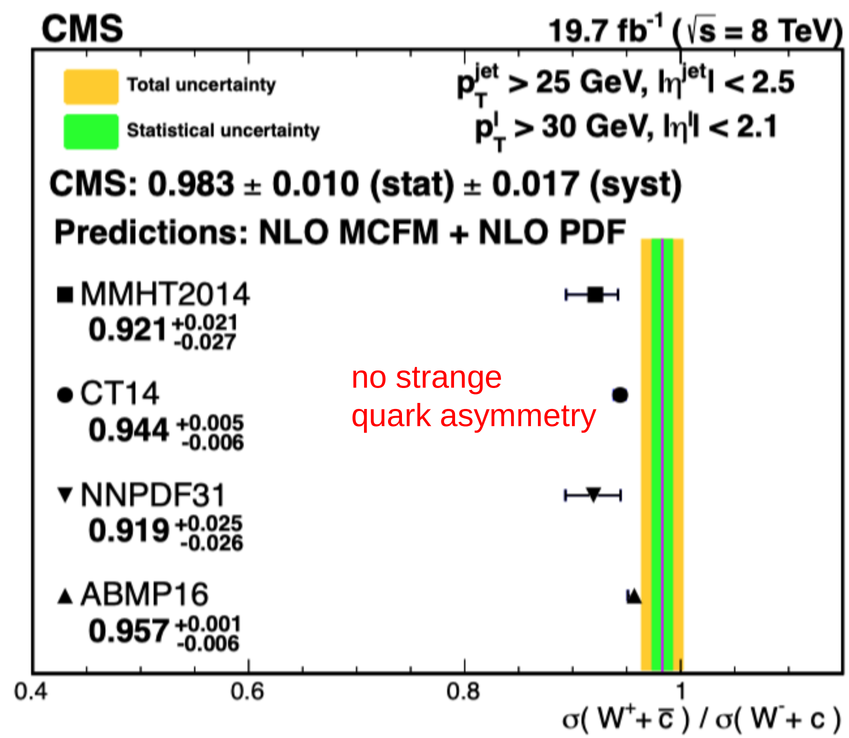
- Measurement carried out inclusively, and differentially as function of p_T and η of lepton



Note: W and c quark should be of opposite sign; SS-OS suppresses contributions from gluon splitting

arXiv:2112.00895 (submitted to EPJC)

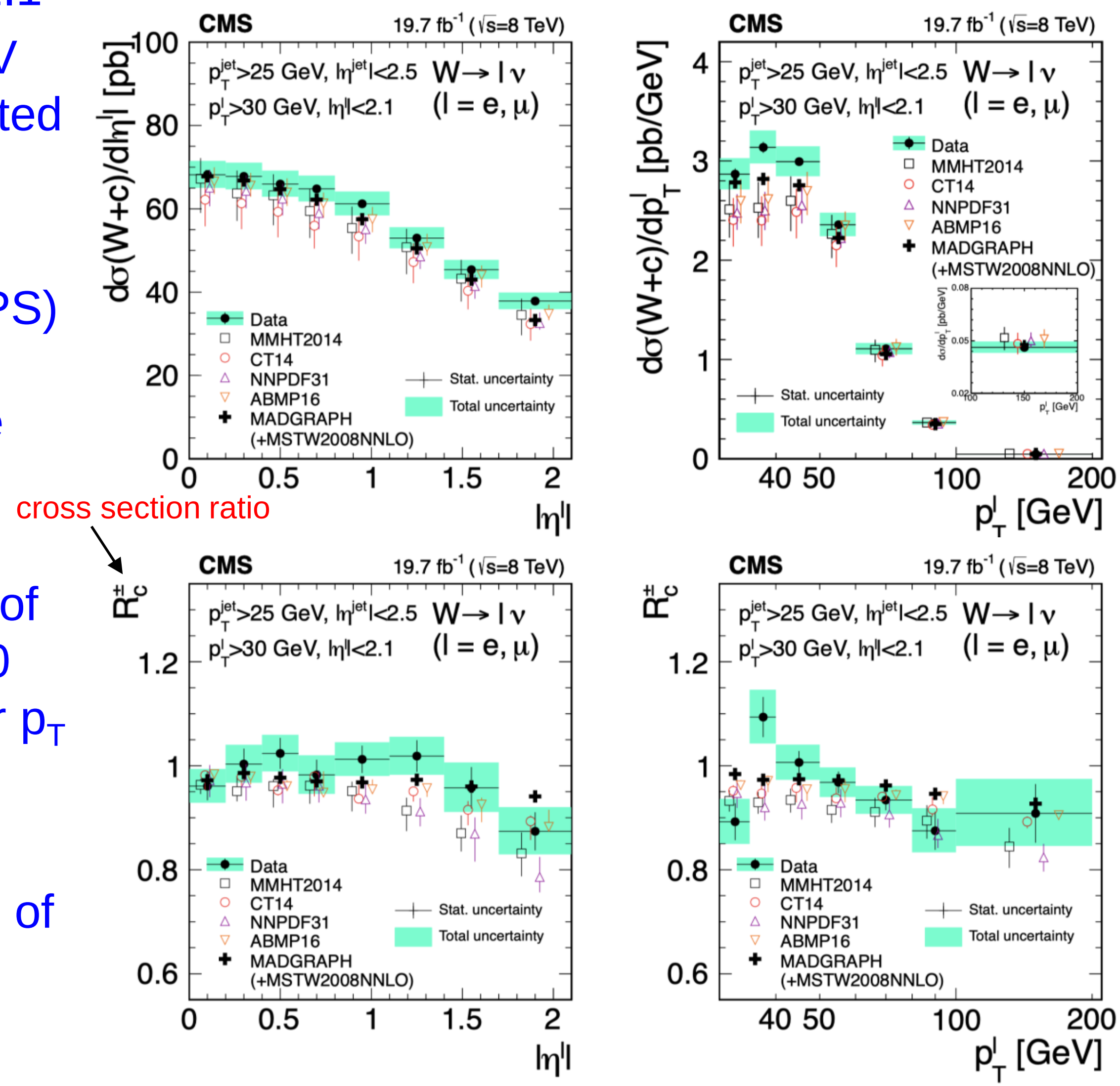




Differential cross sections

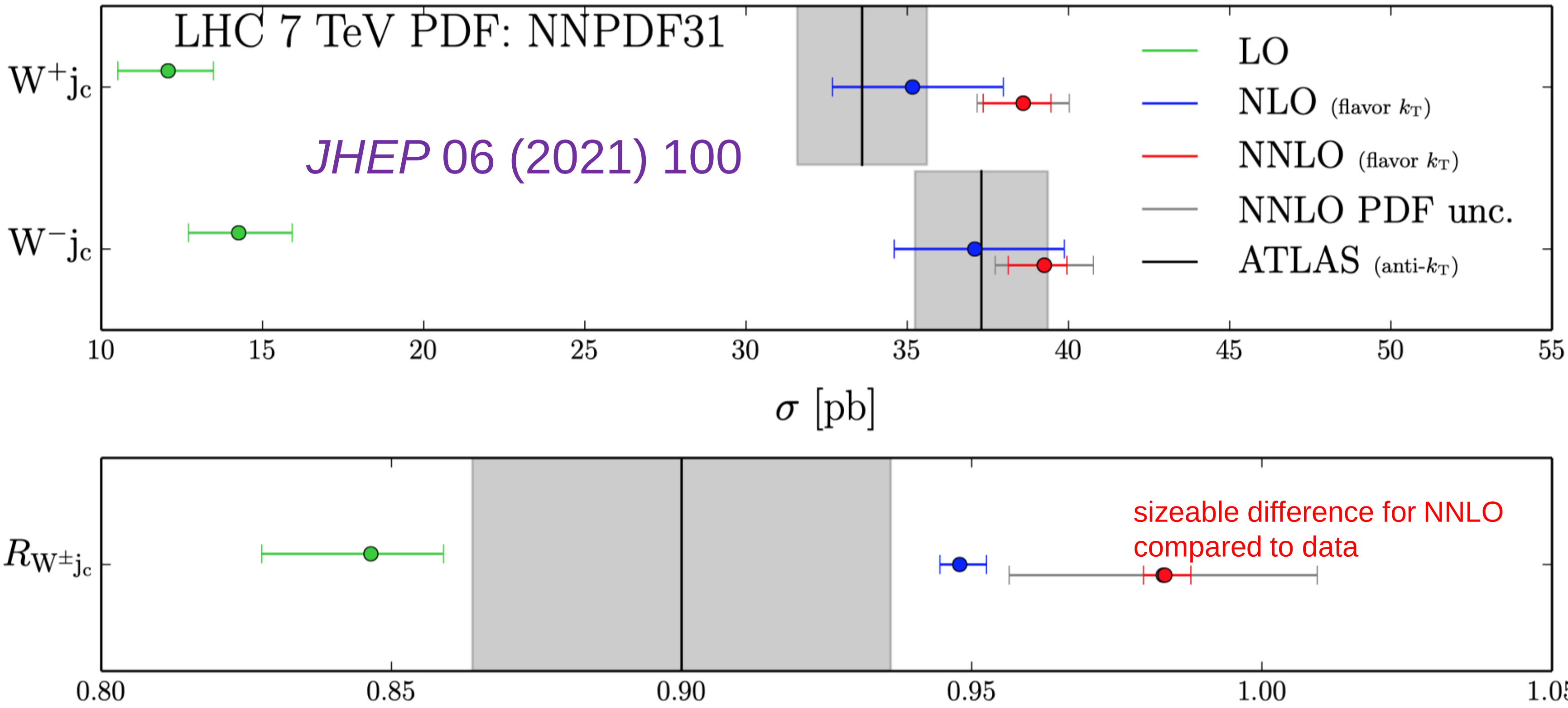
- Require an isolated lepton (e or μ) with p_T>30 GeV and |η|<2.1
- Require a jet with p_T>25 GeV with $|\eta_{jet}|$<2.5. Jets not selected if ΔR(jet,*l*)<0.5
- Data are larger then (NLO+PS) predictions for lepton p_T less then 65 GeV, but compatible within uncertainties
- NNLO corrections for W+c predicted to be on the order of 5% for lepton p_T less then 60 GeV and about 1% for larger p_T values
    - *JHEP* 06 (2021) 100
- This would improve the level of agreement with the data

arXiv:2112.00895 (submitted to EPJC)



NNLO W+c-jet cross section calculation

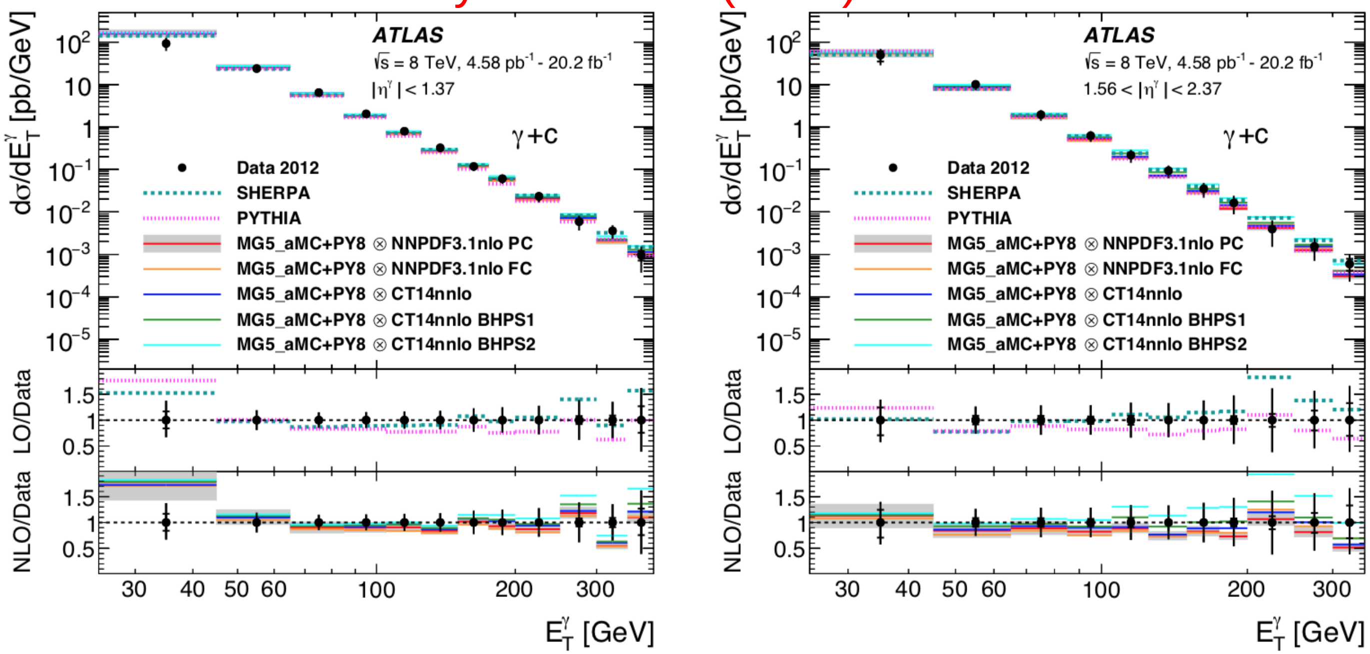
- Large reduction in uncertainties from NLO->NNLO
- NNLO scale uncertainties smaller then PDF uncertainties
- NB: the NNLO calculation used flavor tagging for the charm jet; the experimental measurement used the antikT algorithm with later flavor identification; NNLO corrections to subleading CKM-mediated processes not included in this calculation (but are now available)



Photon+charm jets

- Photons measured in central and forward rapidity
- Jets are defined with antikT algorithm, R=0.4; p_T^{jet}>20 GeV
  - if jet contains a b-hadron with p_T>5 GeV within ΔR=0.3 of jet, then it is assigned as a b-jet; if there is no b-hadron, but there is a charm hadron, it is assigned as a c-jet
- All predictions agree reasonably well with data (relatively large uncertainties)
- There are differences at high E_T when intrinsic charm included in predictions of similar size to uncertainties
- NNLO predictions would be very useful (have to deal with photon isolation)

Phys.Lett.B776(2018) 295

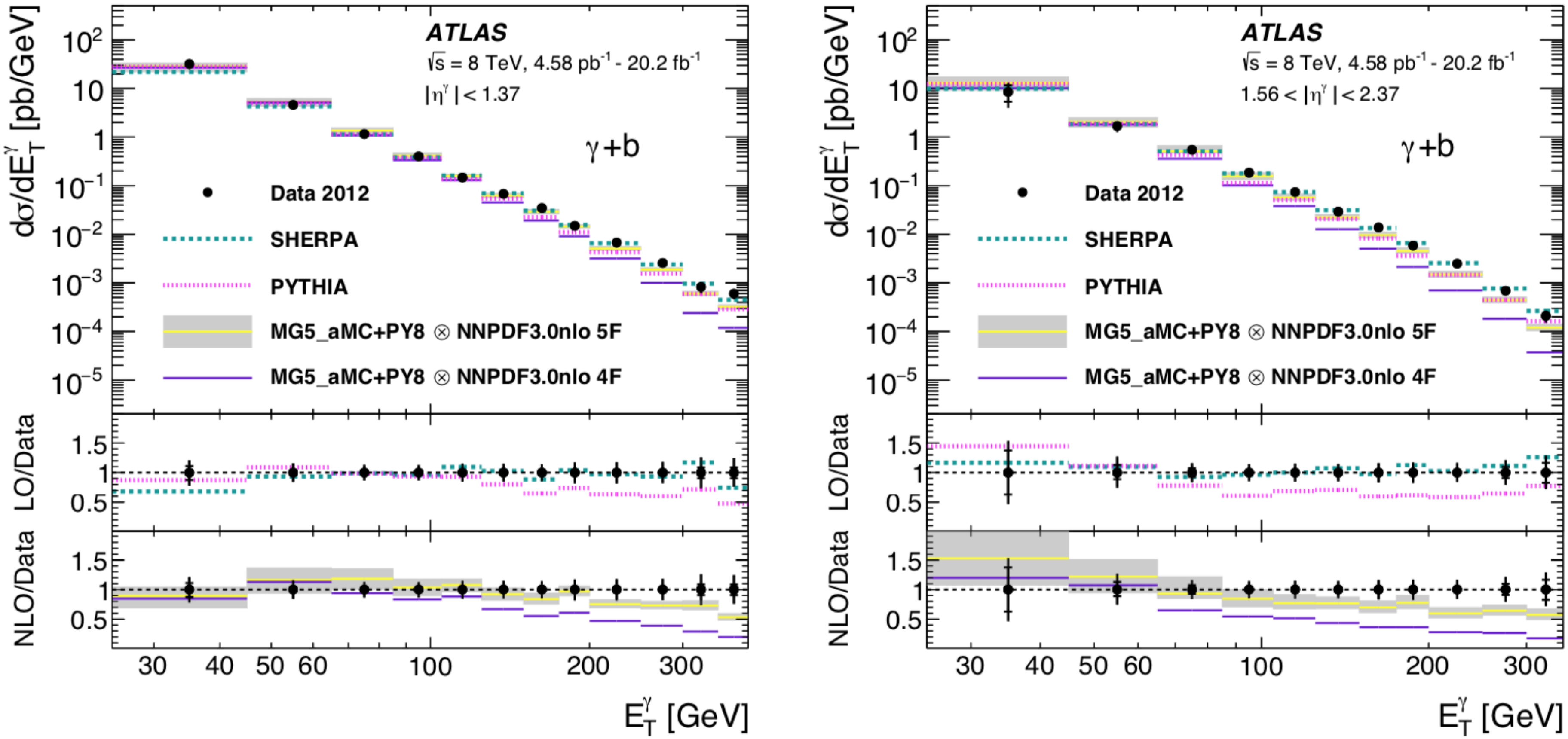


2 intrinsic charm PDFs

Photon+b jets

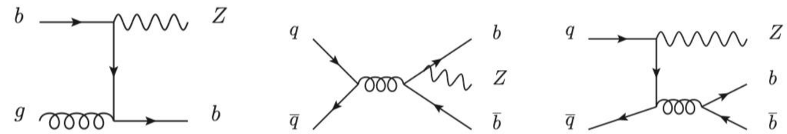
- 5FNS scheme works better then 4FNS scheme
- Best description of the data provided by Sherpa with up to 3 additional partons included in 5FNS scheme
- Again, NNLO would be useful

Phys.Lett.B776(2018) 295



Z+b jets

- The b quark is treated as perturbatively produced by all PDF fitting groups; i.e. inside the proton, at higher Q^2 scales, only things that drive it are the b-quark mass and the value of $\alpha_s(m_Z)$
- Also sensitive to final state gluon splitting



- Calculation can be performed either in 4FNS or 5FNS

ATLAS *JHEP* 07 (2020) 44

- Partial run 2 dataset: 35.6 fb^{-1}
- Z + ≥ 1 or ≥ 2 b jets, b-jet p_T > 20 GeV, |y| < 2.5
- b-jet tagger: ≈ 70% efficiency
- Testing several MC predictions with 4 and 5 FNS: 5FNS includes b quark in PDF

Kinematic variable	Acceptance cut
Lepton p_T	$p_T > 27$ GeV
Lepton η	$\|\eta\| < 2.5$
$m_{\ell\ell}$	$m_{\ell\ell} = 91 \pm 15$ GeV
b-jet p_T	$p_T > 20$ GeV
b-jet rapidity	$\|y\| < 2.5$
b-jet–lepton angular distance	$\Delta R(b\text{-jet}, \ell) > 0.4$

CMS-SMP-20-015 arxiv:2112.09659

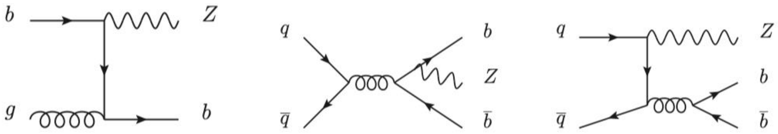
- Full run 2 dataset: 137 fb^{-1}
- Z + ≥ 1 or ≥ 2 b jets, b-jet p_T > 30 GeV $|\eta| < 2.4$
- b-jet tagger: ≈ 50% efficiency (tight WP)

1

Object	Selection
Dressed leptons	p_T (leading) > 35 GeV, p_T (subleading) > 25 GeV, $\|\eta\| < 2.4$
Z boson	$71 < M_{\ell\ell} < 111$
Particle-level bjet	bhadron jet, $p_T > 30$ GeV, $\|\eta\| < 2.4$

Z+b jet

- The b quark is treated as perturbatively produced by all PDF fitting groups; i.e. inside the proton, at higher Q^2 scales only things that drive the PDF are the b-quark mass and the value of $\alpha_s(m_Z)$
- Also sensitive to gluon splitting (and multiplicative factor of parton shower)



- Calculation can be performed either in 4FNS or 5FNS
  - 4FNS underestimates cross section; better agreement with5FNS

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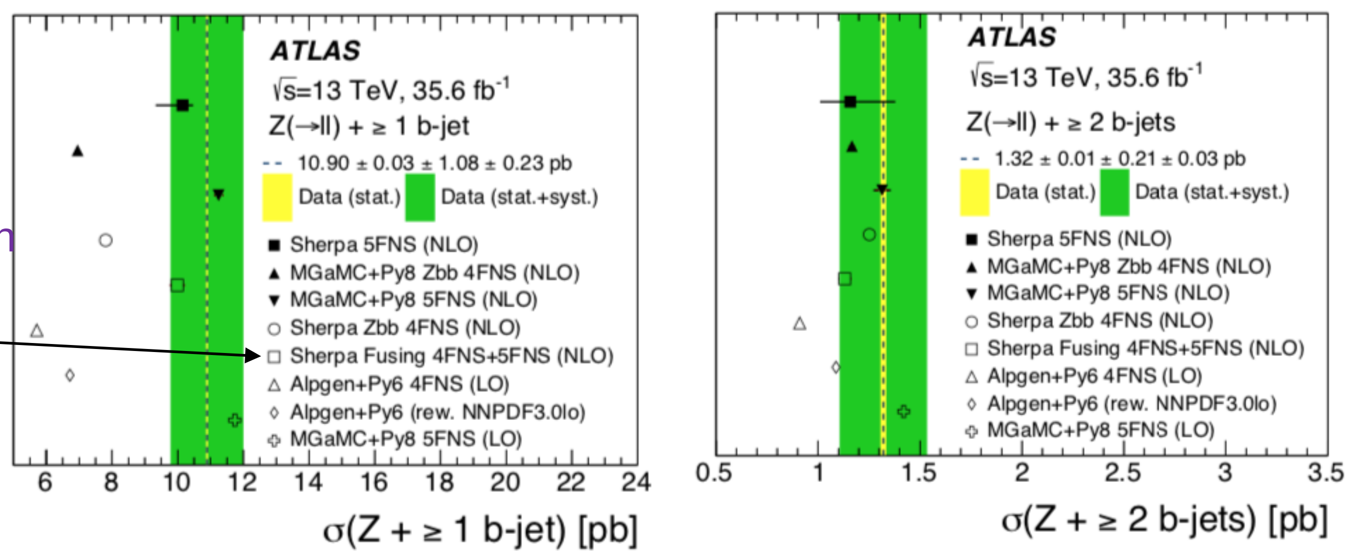

note Fusing prediction of 4FNS+5FNS schemes

Monte Carlo equivalent of FONLL/ ACOT

Most important information comes from differential distributions, though

- NNPDF3.1 PDF is the most up-to-date of the PDFs shown; would be nice to have comparisons of more modern PDFs as well (CT18, MSHT20, NNPDF4.0 (NNPDF3.1'))

arxiv:2112.09659 CMS-SMP-20-015

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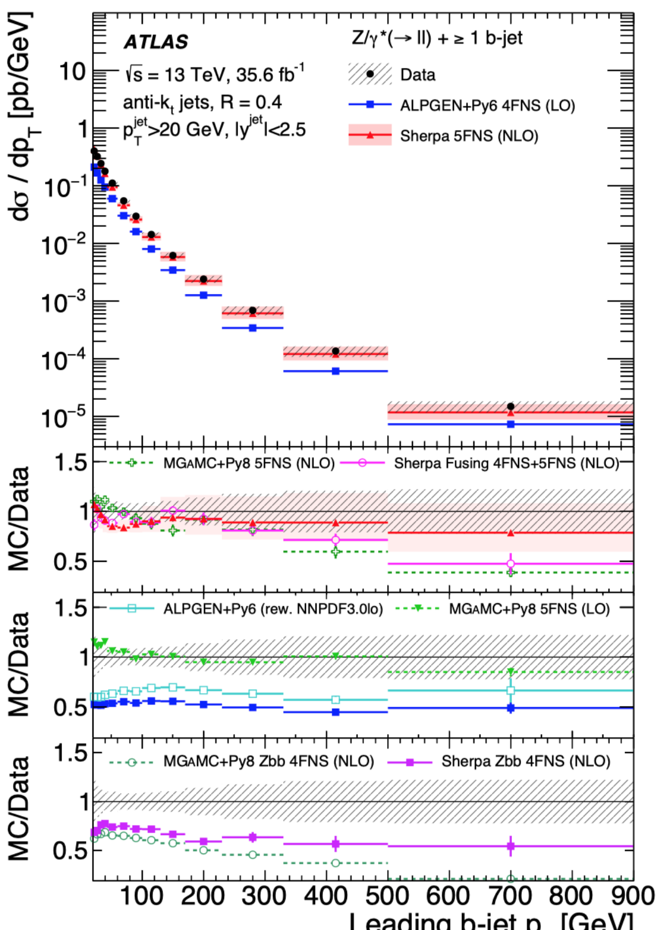
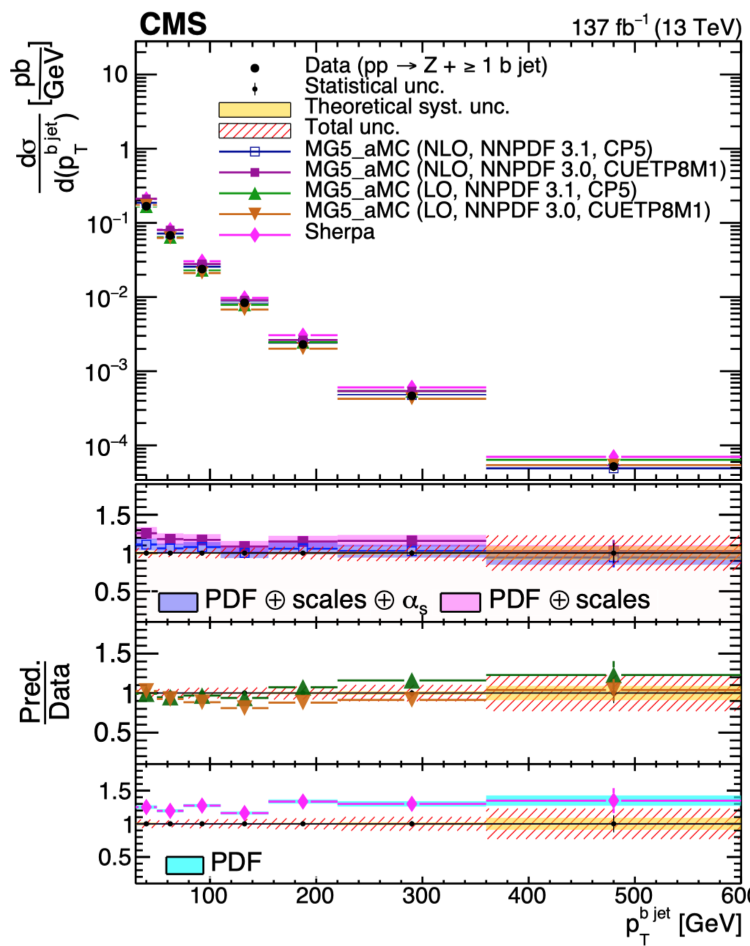


sizeable difference depending on whether massless or massive NLO+PS prediction used



Z+b at NNLO prediction

- Carried out by combining a massless NNLO and a massive NLO computation at order (α_s^3) (arXiv:2005.03016)
  - initial state b-quarks from gluon splitting resummed by PDF evolution; finite b-quark mass effects also incorporated (presumably same could be done for Z+c)
  - note: massless calculation means IR-safe definition of jet flavour must be used; not consistent with experimental choice
  - desired to have data unfolded to level of partonic flavour-kT jets or some equivalent

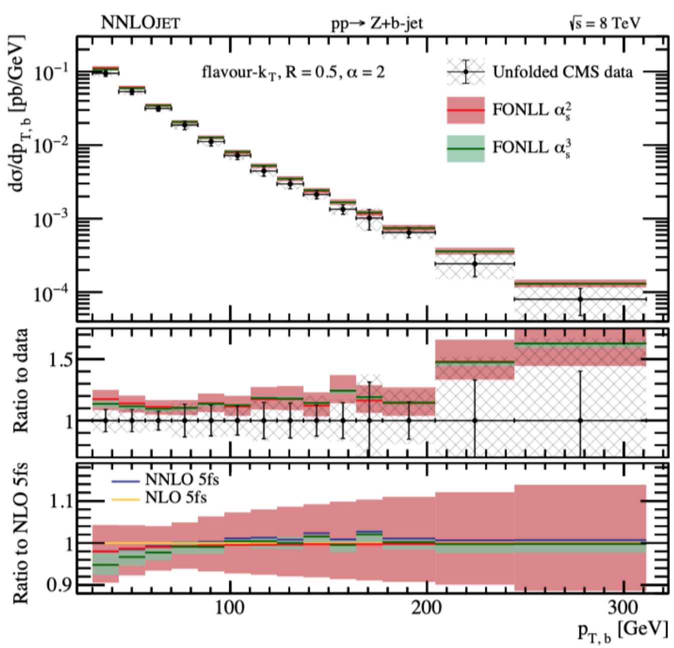


Figure 2: The transverse momentum distribution of the leading flavour-k_T b-jet. The absolute cross-section is shown in the upper panel, the ratio to the unfolded data in the central panel, and the ratio to the NLO 5fs prediction in the lower panel. The shown uncertainty of the FONLL distributions are due to scale variations alone.

large reduction in uncertainty in going from NLO to NNLO

reasonable agreement with data

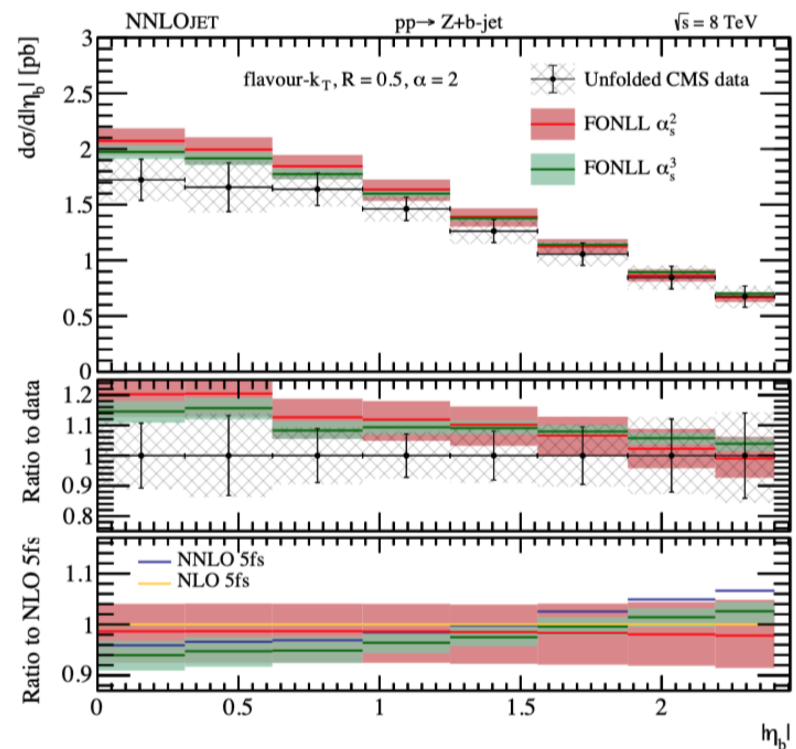
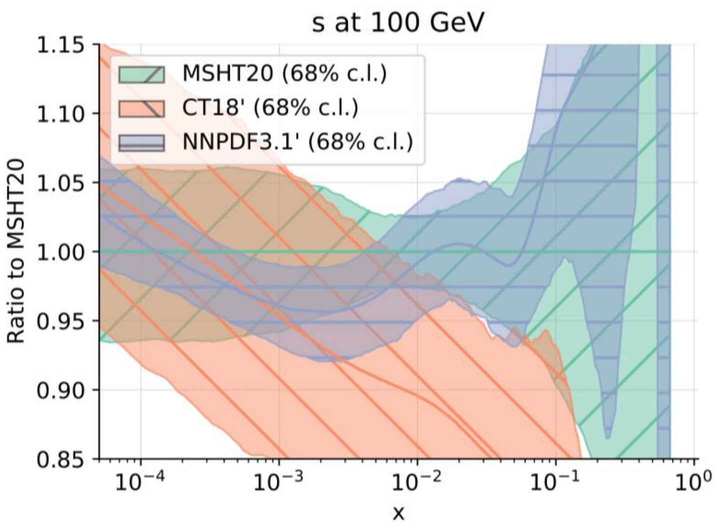


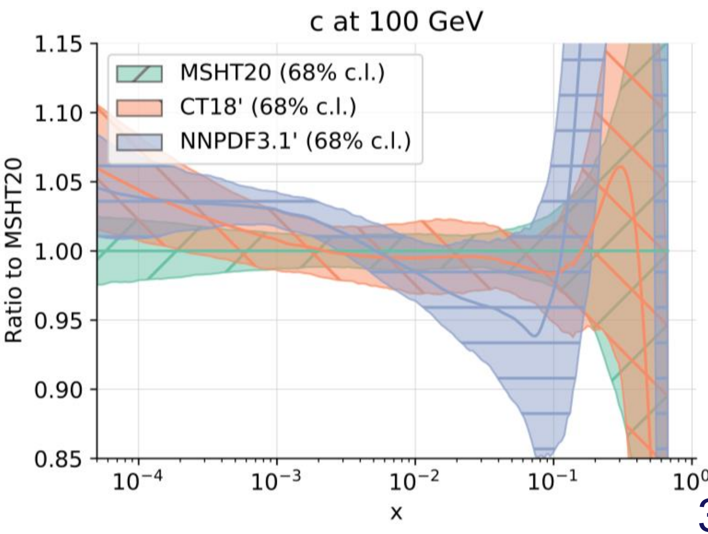
Figure 3: As in Fig. 2, now for the absolute psudorapidity distribution of the leading flavour-k_T b-jet.

Strange/charm PDFs

- Consider the strange quark PDF
- There is a large difference between CT18 and CT18A/MSHT20/NNPDF3.1 due almost entirely to the ATLAS 7 TeV W/Z data (see my talk on Monday)
- The difference between the W and Z cross sections requires a larger strange quark (s-sbar->Z)
- **All 3 groups fit the ATLAS W/Z data equally poorly**
- Because of its fitting criteria, CT18 does not use the 7 TeV W/Z data for its main fit (but it is in CT18A)
- W+c data offer another window on the strange quark distribution
- NNPDF3.1 has a different charm distribution then CT18/MSHT20, due to its fitting the charm distribution as a free parameter, rather then generating perturbatively through gluon splitting; an intrinsic charm component may be present at high x
- CT has published PDF sets in which an intrinsic component of charm is modeled. The addition of this intrinsic component leads to a small, but noticeable, reduction in global χ^2
- Z+c/γ+c offers another window on the charm quark

PDF4LHC21: arXiv:2203.05506

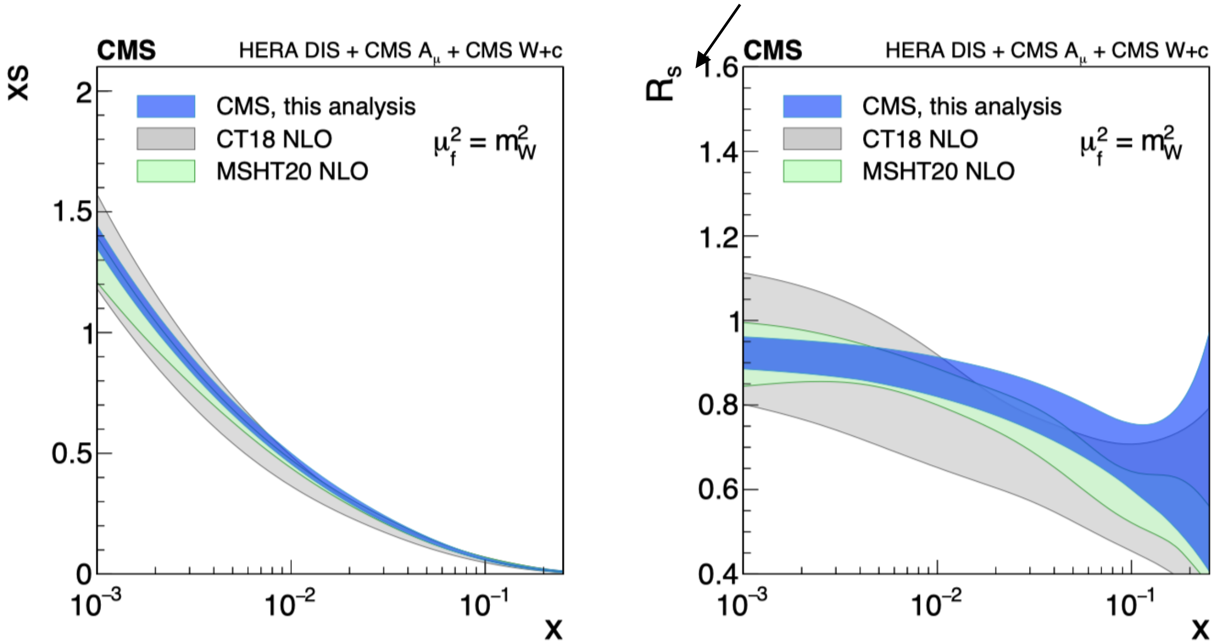




(W+c) strange quark PDF

- Derived CMS strange quark consistent with that obtained by CT18 and MSHT20 for x<0.01; somewhat larger at higher x
  - NB: MSHT20 includes ATLAS 7 TeV W/Z data

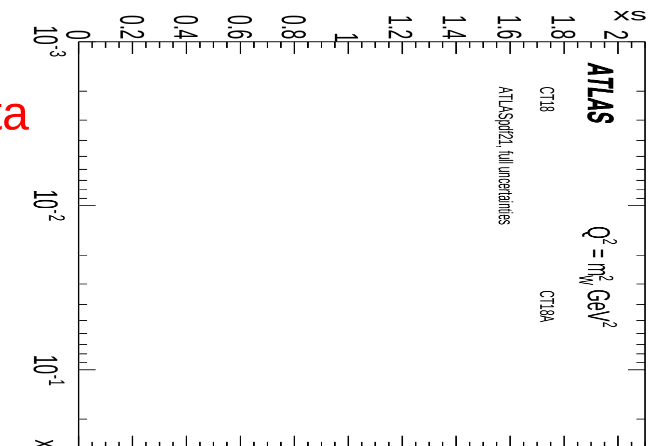
strangeness suppression factor



arXiv:2112.00895 (submitted to EPJC)

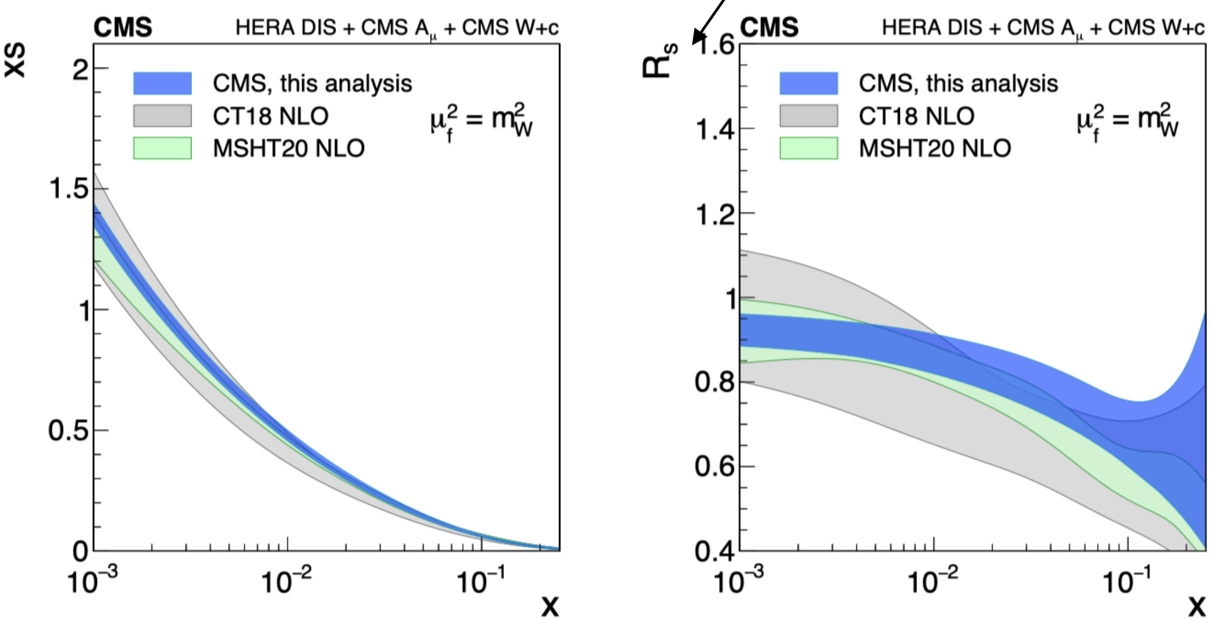
(W+c) strange quark PDF

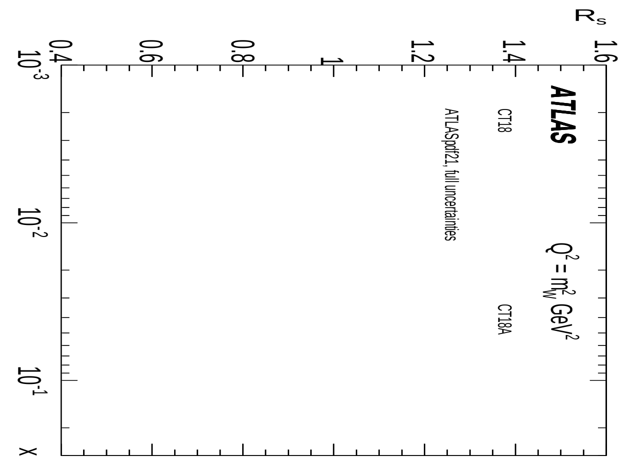
- Derived CMS strange quark consistent with that obtained by CT18 and MSHT20 for x<0.01; somewhat larger at higher x
  - NB: MSHT20 includes ATLAS 7 TeV W/Z data
- Compare to results from ATLAS PDF21 fit
  - CT18 does not include ATLAS 7 TeV W/Z data, CT18A does



perhaps more consistency between ATLAS and CMS determinations of s

strangeness suppression factor





thanks to Francesco Giuli for making the ATLAS plots

arXiv:2112.00895 (submitted to EPJC)

W+c at NNLO-differential

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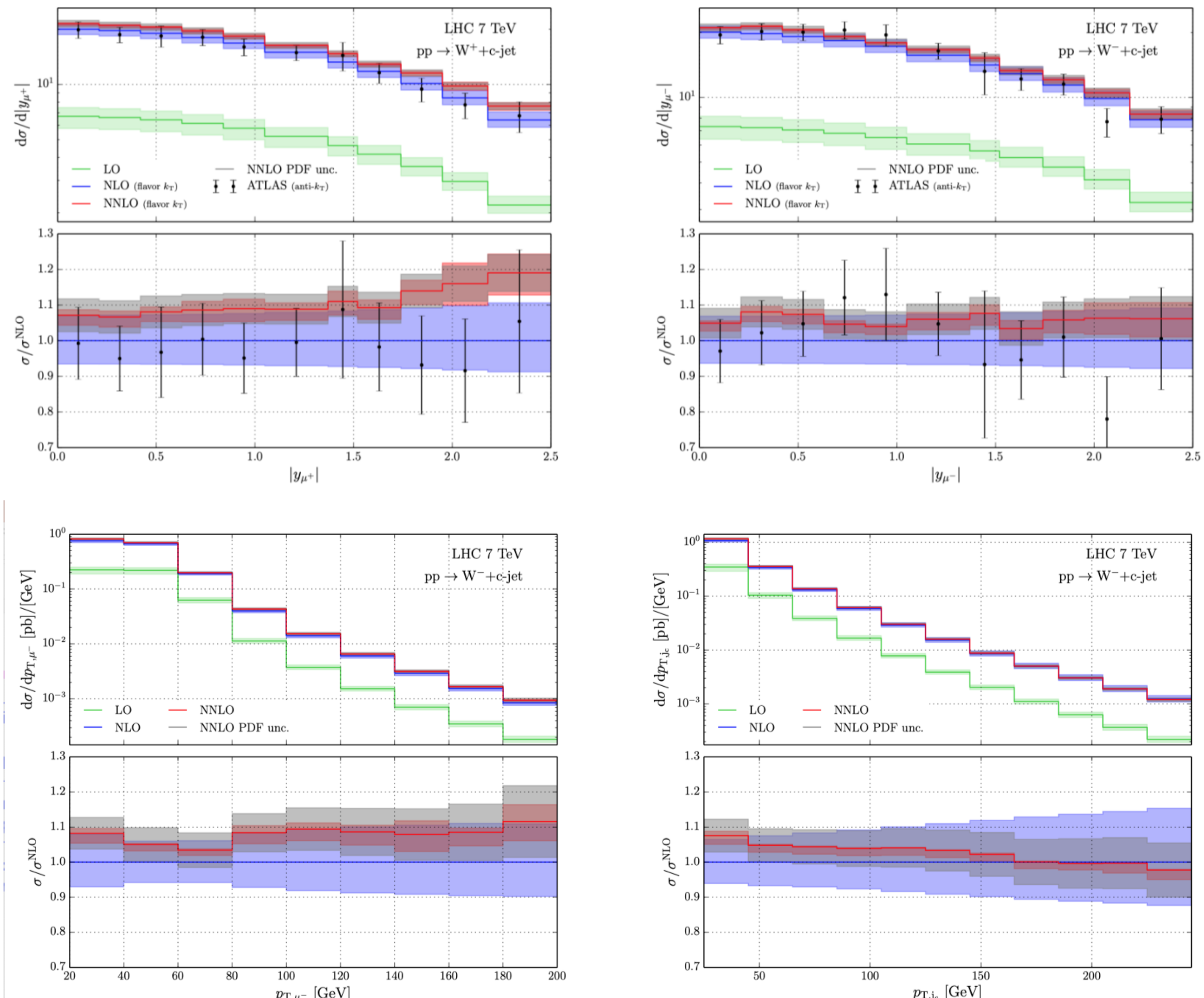

W+c at NNLO

- Ratio plots sensitive to s-$\bar{s}$ asymmetry

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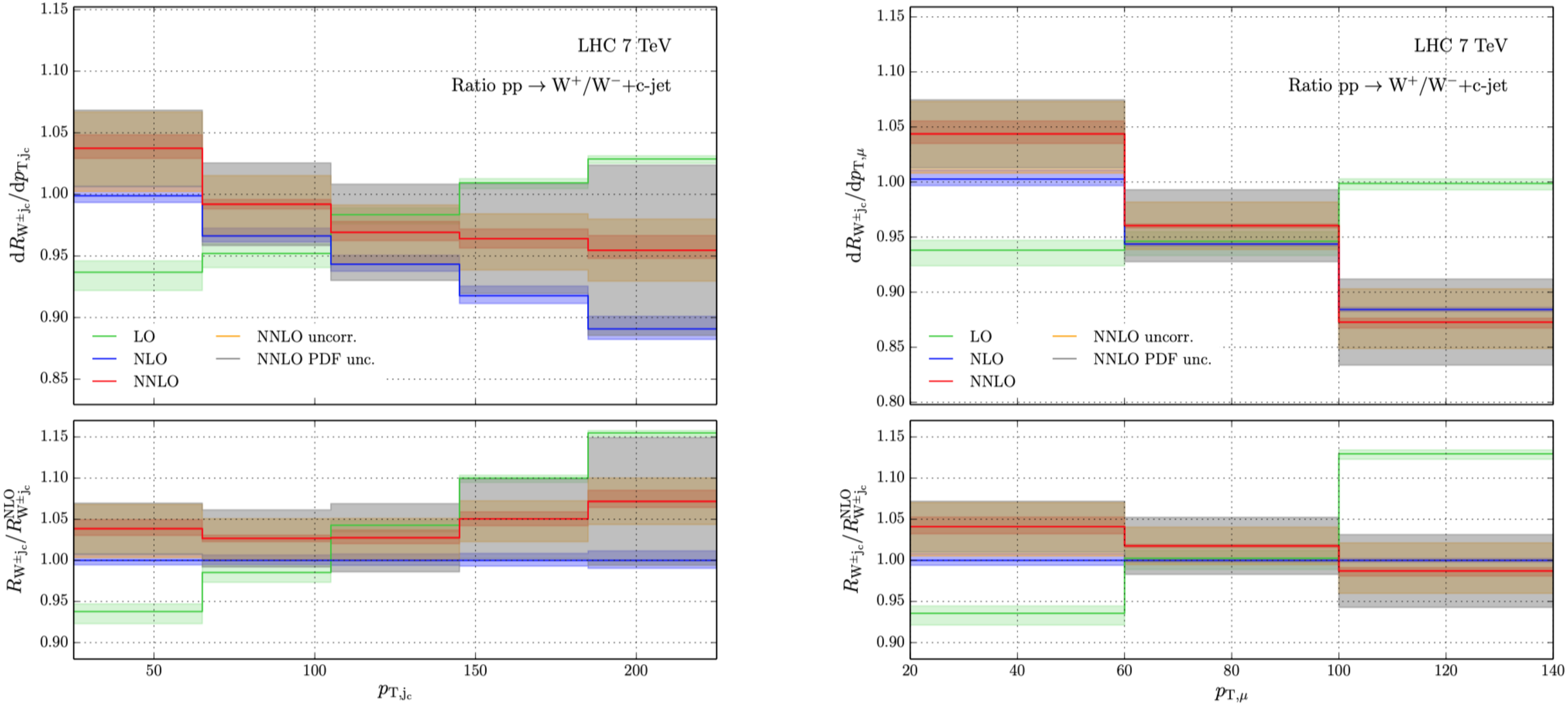

NNLO uncertainties very small; potential for constraining asymmetry