b-fragmentation studies in $t\bar{t}$ events in ATLAS and CMS

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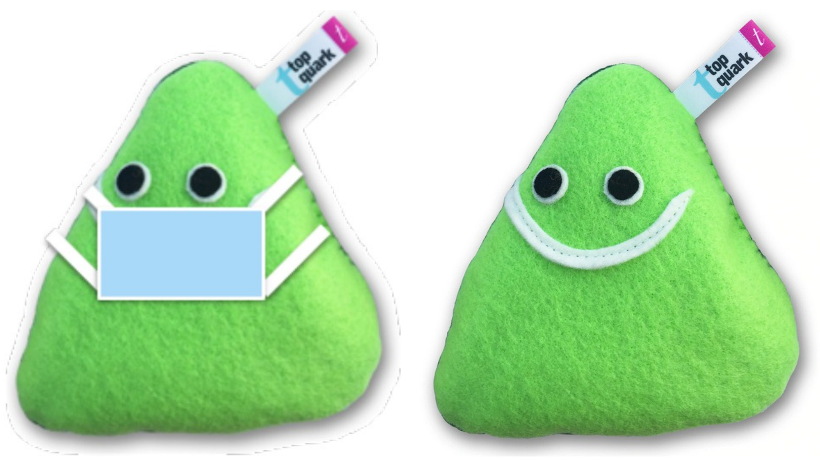


Top LHC France 2022
9th May 2022, IP2I Lyon, France

- ○ motivations
- ○ r_b measurements
- ○ using $t\bar{t}$ pairs for tuning
- ○ analytic calculations

Modelling of $t\bar{t}$ events

ATLAS and CMS use same generators but different settings and procedures to assess uncertainties associated

Hadronisation
Pythia 8 vs Herwig 7
Pythia 6 vs Herwig++
impact on jet energy response

Hard interaction
Powheg vs MC@NLO as uncertainty
Powheg vs MC@NLO as cross check

Detector uncertainties

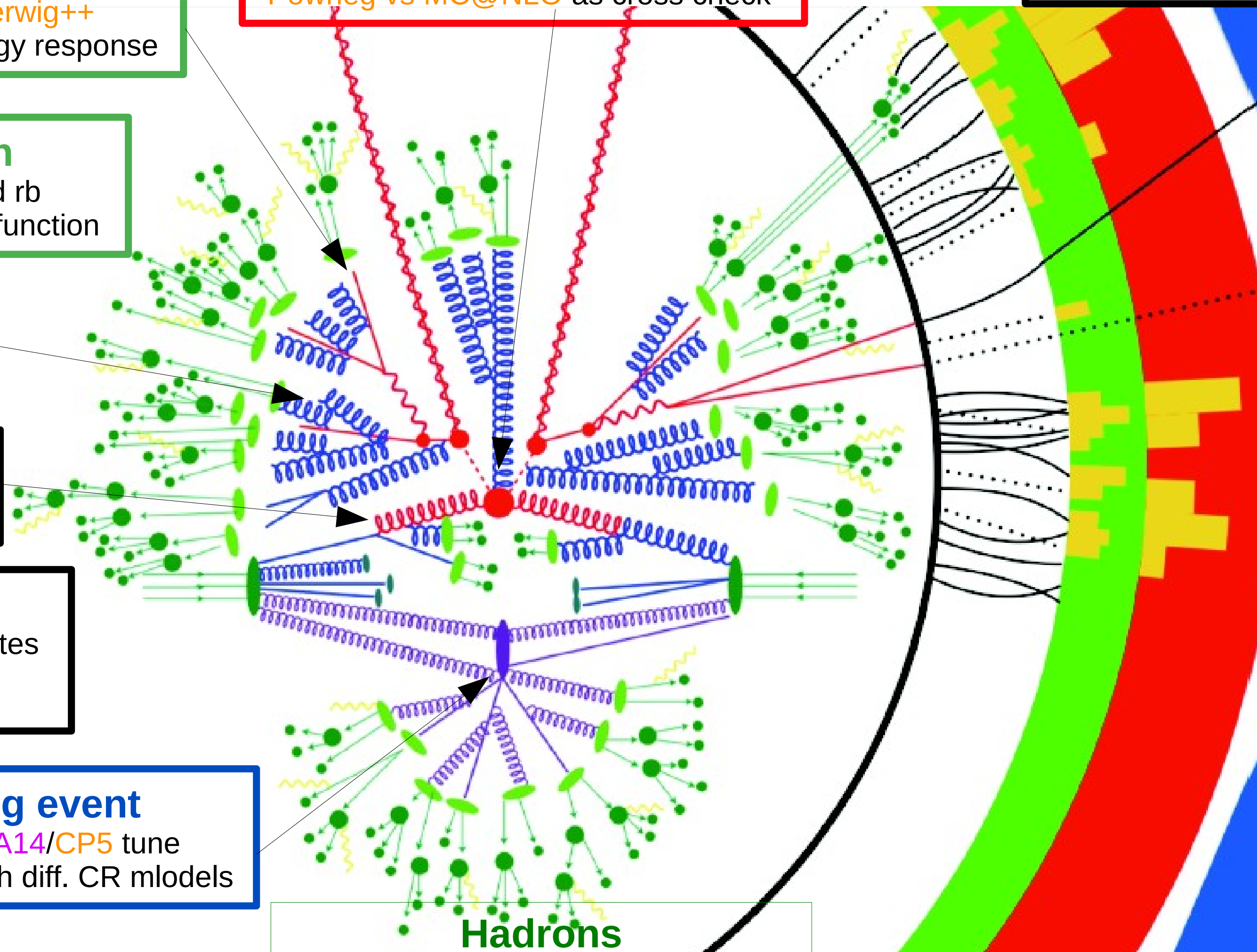
b-fragmentation
variation of Bowler-Lund rb parameter of fragmentation function

FSR
μ_F (from 0.5 to 2)

ISR
α_s, μ_R, μ_F (from 0.5 to 2)

ME-PS matching
variation of $\mathbf{h}_{damp}$ that regulates first high-p_T emission

Underlying event
UE : variation of A14/CP5 tune
CR : retuning UE with diff. CR mlodels

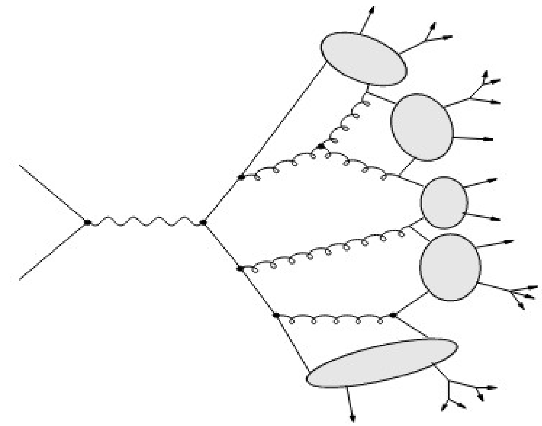


Hadrons
Varying B production and decays BF within PDG value uncertainties

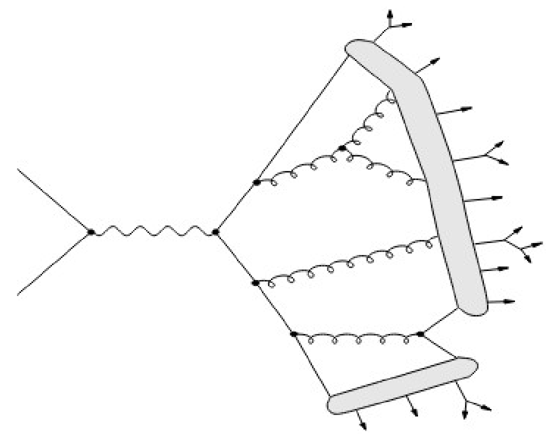
Hadronization models

After the parton shower, due to confinment, the partons start to create stable hadrons

- **Cluster model (used by HERWIG)**
  - ○ perturbative evolution ends at $Q^2 = Q^2_0$
  - ○ partons clustered in colourless groups
    ⇒ colour preconfinement
  - ○ forced gluon splitting ($q\bar{q}$) at the end of the parton shower
  - ○ colour-singlet clusters decay into the observed hadrons



- **String model (used by PYTHIA)**
  - ○ for q and $\bar{q}$ moving in opposite direction
  - ○ the colour field collapses into a string, with uniform energy density
  - ○ virtual gluons produced ⇒ colour confinement
  - ○ new $q\bar{q}$ pairs are produced
  - ○ the string breaks into the observed hadrons

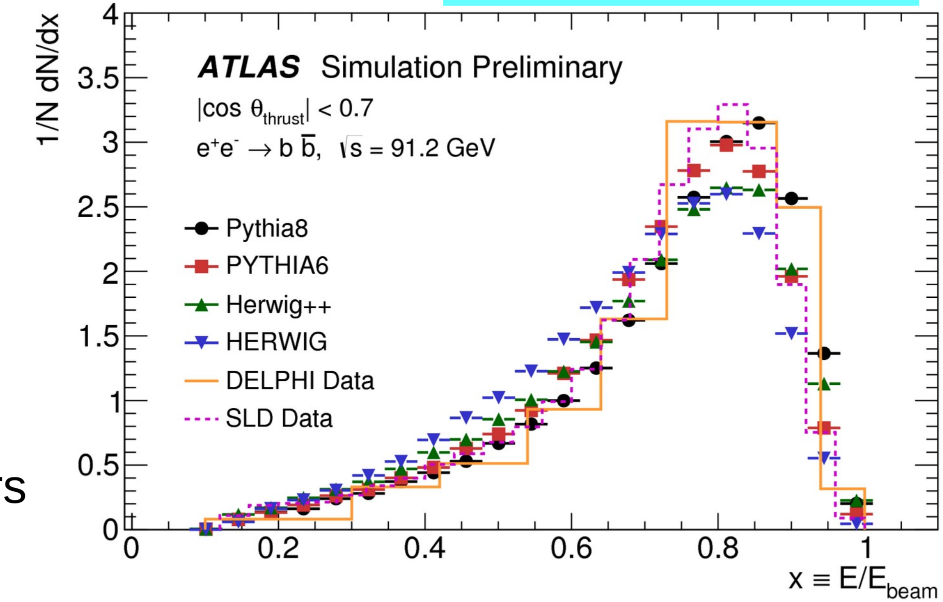


Cluster and string models also used in conjunction with other Monte Carlo programs (MadGraph, ALPGEN, POWHEG, SHERPA, aMC@NLO)

b-quark fragmentation studies

- **Motivations**
  - the fragmentation of b-quarks into hadrons is of interest for many reasons
  - b-hadrons leave a striking experimental signature and …
  - a unique correspondence to the originating b-quarks
    - ergo a precise probe of QCD

ATLAS-PHYS-PUB-2014-008



- **Lund-Bowler model**
  - feasibility of PYTHIA to use Peterson, Kartvelishvili, Lund-Bowler models
  - standard analyses use tuning to $e^+e^- \to Z \to b\bar{b}$ data and best-fit parameters to predict b-fragmentation in hadron collisions, such as top events
    - events in a clean environment with back-to-back events : production of $b\bar{b}$ colour singlets, no colour reconnection to the beam or underlying events
  - then extrapolated to the LHC environment
    - to what degree is this correct ?
    - tuning Monte Carlo models directly to LHC data, e.g. $t\bar{t}$, $b\bar{b}$ or γ/Z+b not yet carried out, but can be useful to validate Monte Carlo programs and test hadronization models and factorization

some tension between $e^+e^- \to Z \to b\bar{b}$ measurements of b-fragmentation

parton-shower generators, using same tunes as at LHC, are also not in good agreement

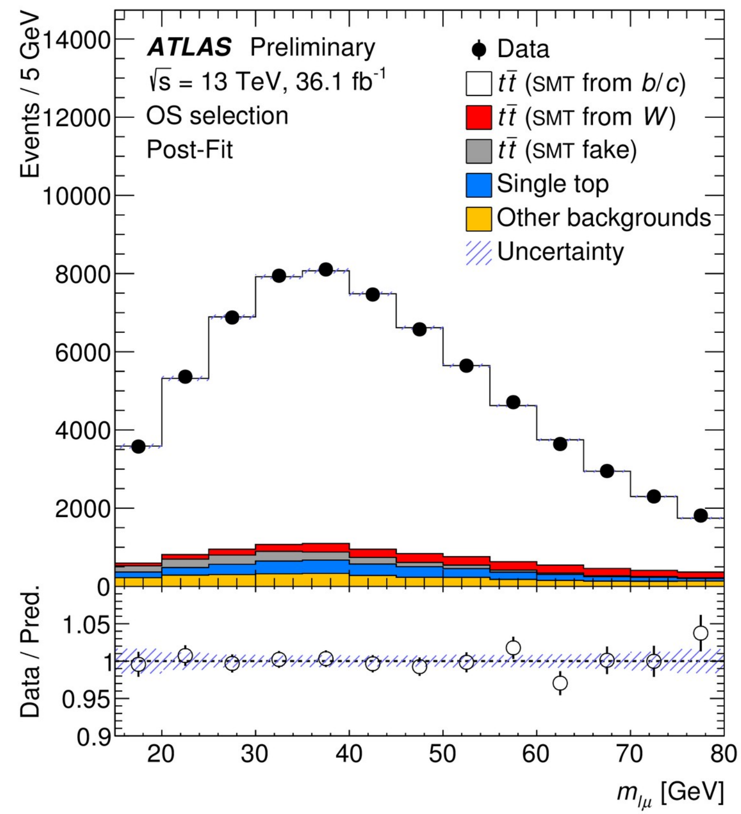
ATLAS r_b parameter tuning

ATLAS-CONF-2019-046

- **Lund-Bowler parametrization**
  - cannot be calculated by theory, can only be modelled
  - analytic description in PYTHIA

$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-bm_T^2/z)$$

  - standard r_b value used in ATLAS with A14 tune* : r_b = 0.855, α_S(FSR)=0.127
- **r_b tuning**
  - refit of the b-fragmentation function to improve the modelling in POWHEG+PYTHIA with the A14 tune, using data from LEP and SLD, and lead to an optimal value r_b = 1.05±0.02
    - new A14-r_b tuning used to estimated systematic uncertainites from « PS and hadronization » and « b-fragmentation »
- **used for m_t with b→μX**
  - m_t = 174.48 ± 0.40 (stat) ± 0.67 (syst) GeV
  - σ(PS and hadronization) = 0.07 ± 0.07 GeV σ(b-fragmentation) = 0.19 ± 0.02 GeV



b→μ momentum transfer key for new top mass measurements, which rely on precise b→B prediction

* for comparison of ATLAS and CMS MC tunes, see ATL-PHYS-PUB-2021-016, CMS NOTE-2021/005

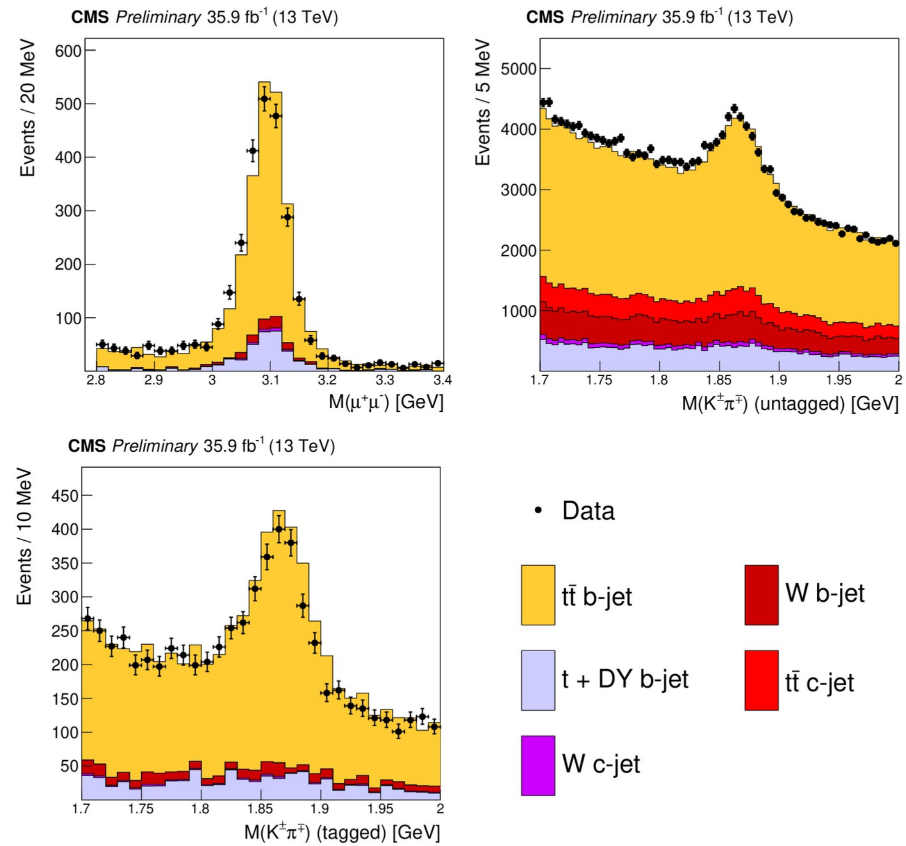
CMS r_b parameter fitting

- **Lund-Bowler parametrization**
  - cannot be calculated by theory, can only be modelled
  - Lund-Bowler fragmentation analytic description in PYTHIA

$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-bm_T^2/z)$$

  - standard r_b value used in CMS with CP5 tune* : r_b = 0.855, α_S(FSR)=0.118

CMS-PAS-TOP-18-012, June 2021



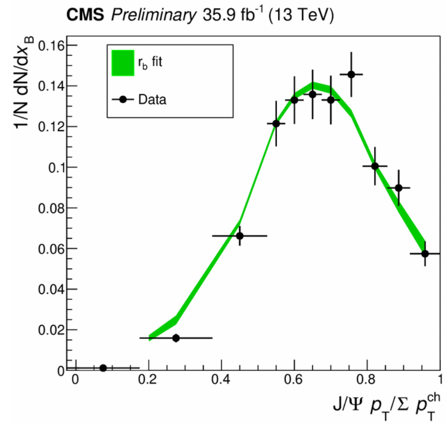
- **using J/ψ and D^0 mesons**
  - explicit reconstruction of the two mesons
    - two muons p_T>3 GeV, 2.8<$m_{\mu\mu}$<3.4 GeV
    - for D^0, with and without a muon-tagged decay, requiring the presence of a nonisolated muon with p_T > 3 GeV in the same jet as the $K^{\pm}\pi^{\mp}$ pair

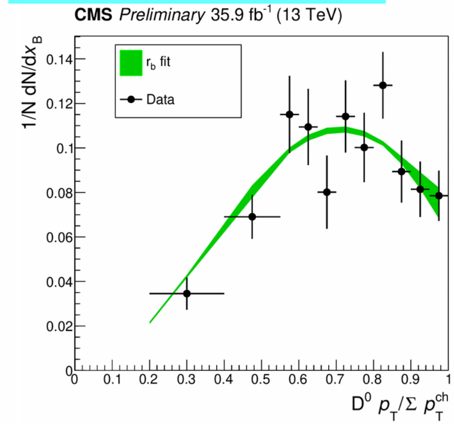
* for comparison of ATLAS and CMS MC tunes, see ATL-PHYS-PUB-2021-016, CMS NOTE-2021/005

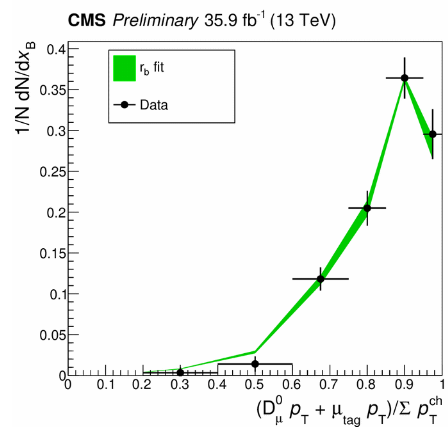
CMS r_b parameter fitting

CMS-PAS-TOP-18-012, June 2021

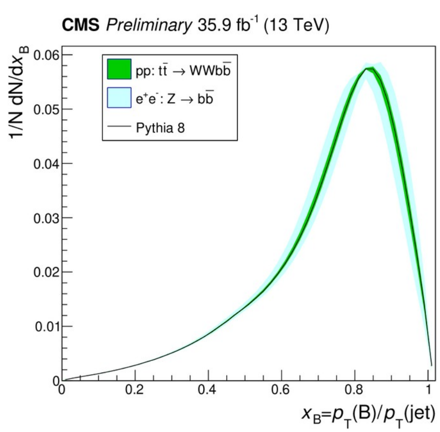
- **Observables**
  - use mesons as final-state proxies for the decayed b-hadron
  - distributions of momentum fractions used to fit r_b
    - the input to the fit is a set of thirteen simulated x_B templates with values of r_b between 0.655 and 1.055
    - PYTHIA 8 generator-level calculations, which were used to reweight fully reconstructed simulated event

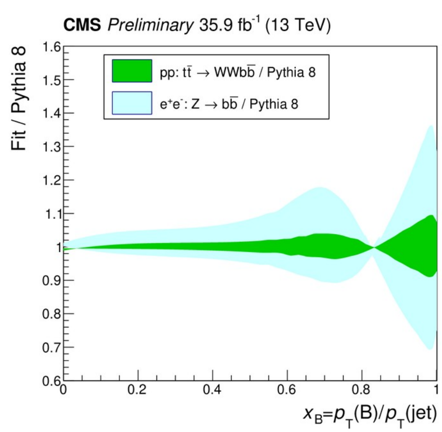






- **Result**
  - $r_b = 0.858 \pm 0.037$ (stat) ± 0.031 (syst)





- agreement with the e^+e^- data
- significant precision improvements wrt LEP/SLD Z-pole tunes
- no evidence for an environmental dependence of the fragmentation function

ATLAS b-fragmentation using mesons

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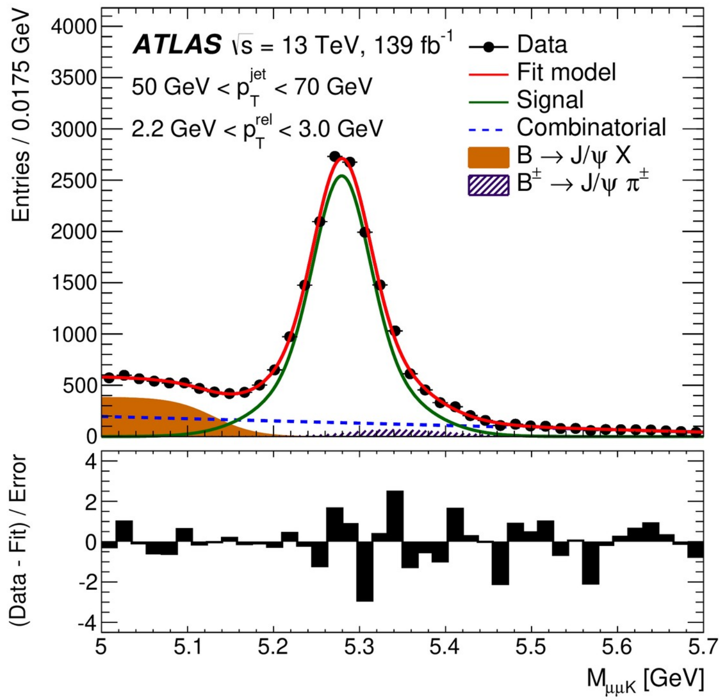
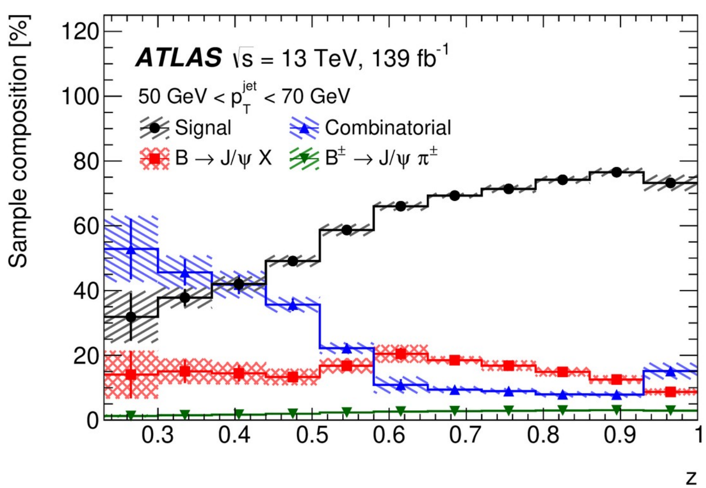
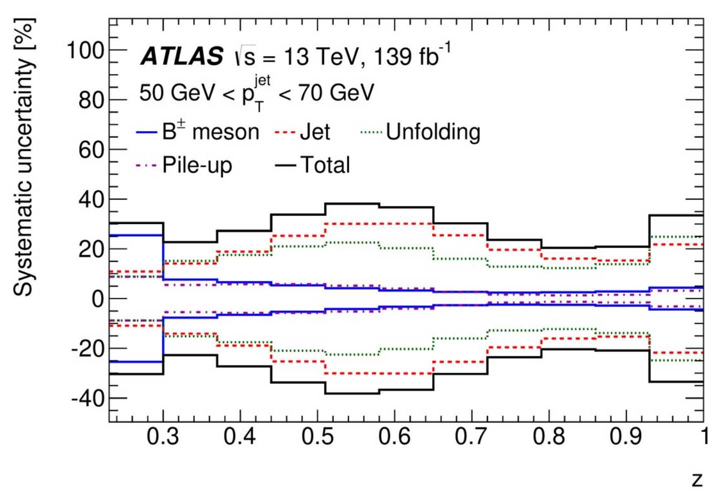
- **Analysis**
  - explicit reconstruction of $B^{\pm} \rightarrow J/\psi K$
    - two muons p_T>6 GeV, 2<$m_{\mu\mu}$<9 GeV
    - third track, cut on vertex $\chi2$ & pair/triplet
- **Unfolding**
  - unfold to particle level with kinematic cuts on μ and K p_T
  - observables $z = \frac{\vec{p}_B \cdot \vec{p}_j}{|\vec{p}_j|^2}; \quad p_T^{rel} = \frac{|\vec{p}_B \times \vec{p}_j|}{|\vec{p}_j|},$
- **Systematic uncertainties**
  - unfolding more limited by transfer resolution for $p_T(rel)$ than z
    - limiting systematics a balance between B reco, jet reco and unfolding uncertainties







ATLAS b-fragmentation using mesons

- **Results**
  - longitudinal and tranverse fragmentation functions in jet-p_T bins
    - Herwig 7 showers and Sherpa cluster hadronisation show deviations wrt data
  - average values of fragmentation functions vs jet p_T
    - flags around 10% mismodelling

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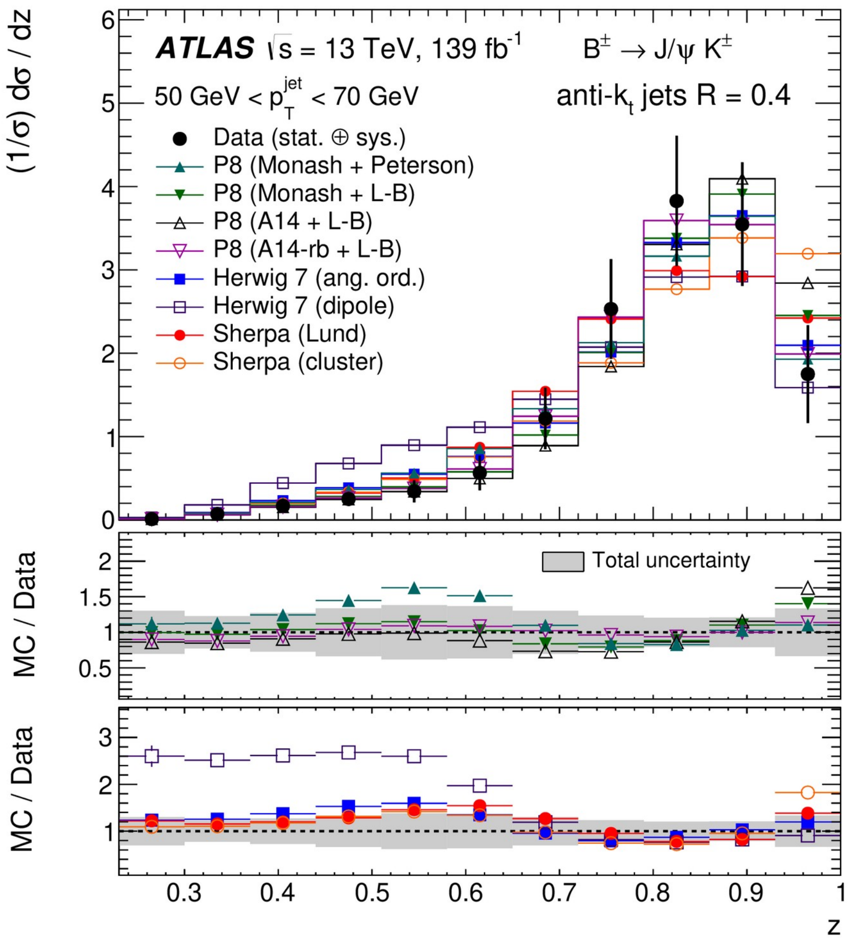
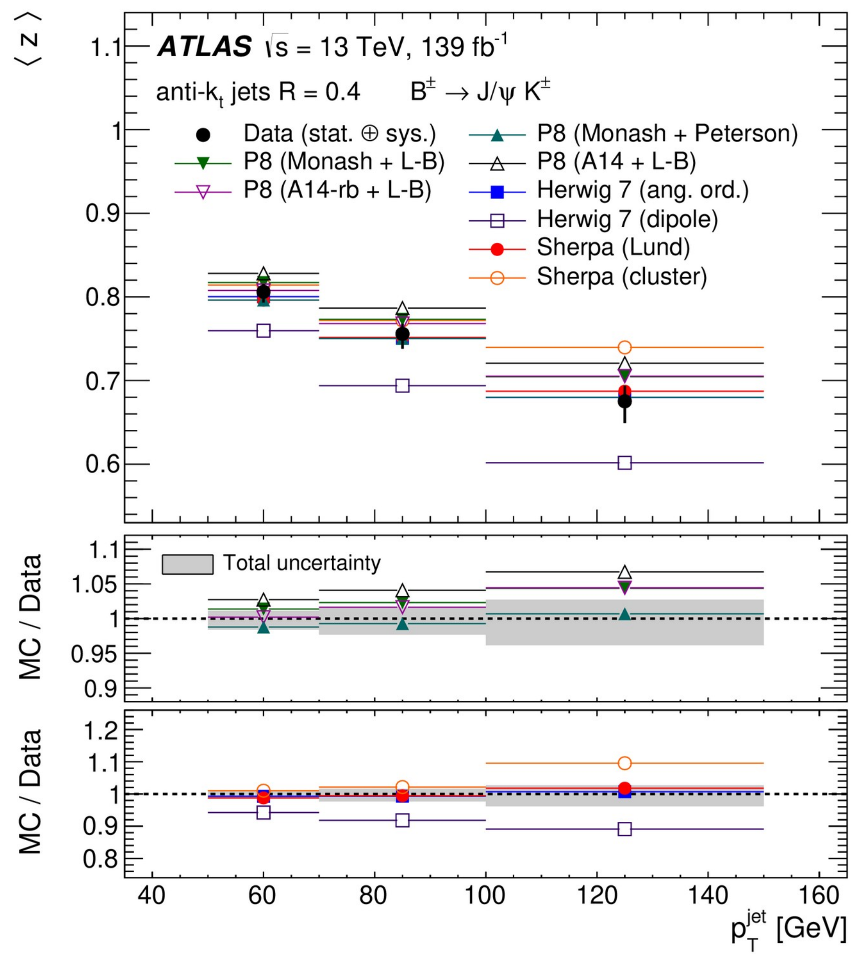




ATLAS b-quark fragmentation in $t\bar{t}$ events

arXiv:2202.13901

- **Analysis**
  - measurements of b-jet moments sensitive to b-quark fragmentation in $t\bar{t}$ events (eμ channel, 2015-2016 data)

- **Unfolding**
  - observables are relative to the jet and use information from associated charged tracks
    - sensitive to momentum of b-hadron relative to the local hadronic activity and parameters r_b, α_S(FSR)

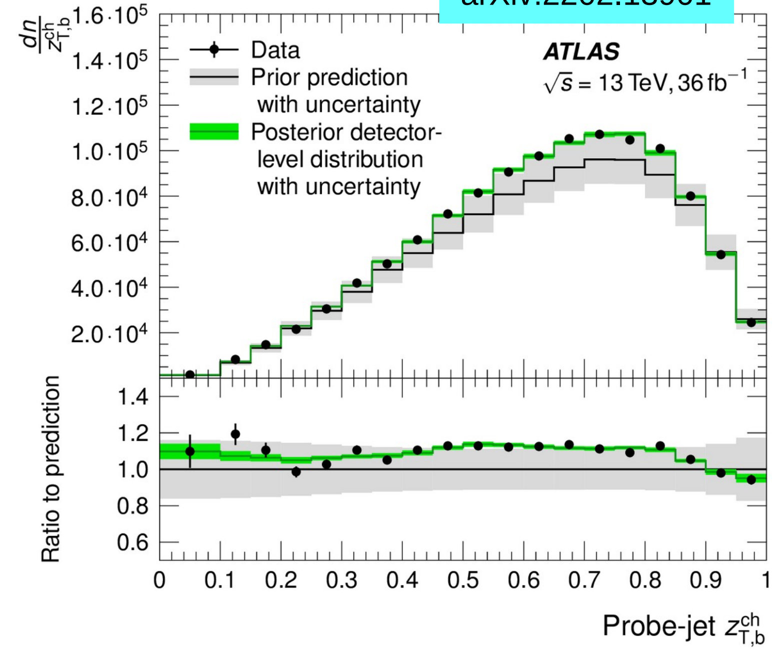
$$z^{\mathrm{ch}}_{\mathrm{T},b} = \frac{p^{\mathrm{ch}}_{\mathrm{T},b}}{p^{\mathrm{ch}}_{\mathrm{T,jet}}} \qquad z^{\mathrm{ch}}_{\mathrm{L},b} = \frac{\vec{p}_b^{\,\mathrm{ch}} \cdot \vec{p}_{\mathrm{jet}}^{\,\mathrm{ch}}}{|p^{\mathrm{ch}}_{\mathrm{jet}}|^2}$$

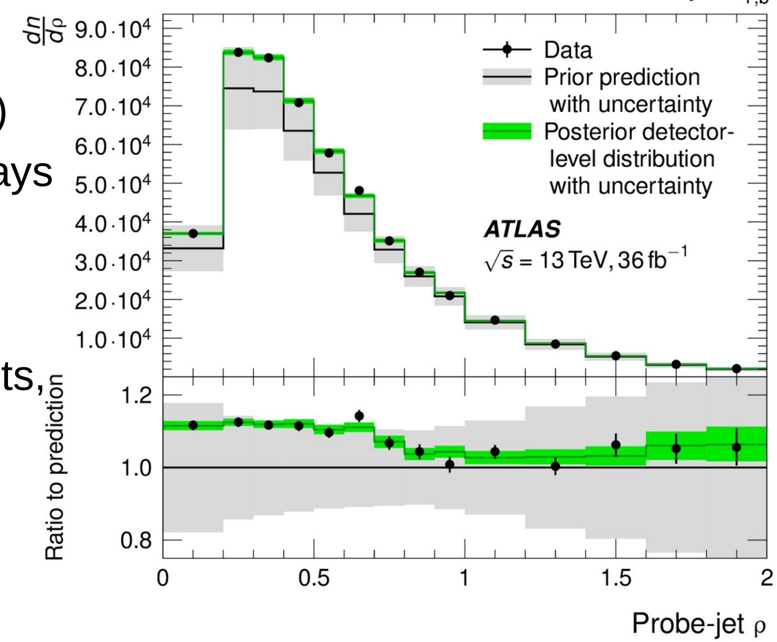
    - transverse momentum of b-hadron relative to the average p_T of the leptons, to the choice of α_S(FSR) but not α_S(ISR), to wide-angle radiation in top decays

$$\rho = \frac{2p^{\mathrm{ch}}_{\mathrm{T},b}}{p^{e}_{\mathrm{T}} + p^{\mu}_{\mathrm{T}}}$$

    - number of charged, stable b-hadron decay products, sensitive to the b-hadron species production rates

$$n^{\mathrm{ch}}_b = \text{number of fiducial } b\text{-hadron children.}$$





ATLAS b-quark fragmentation in $t\bar{t}$ events

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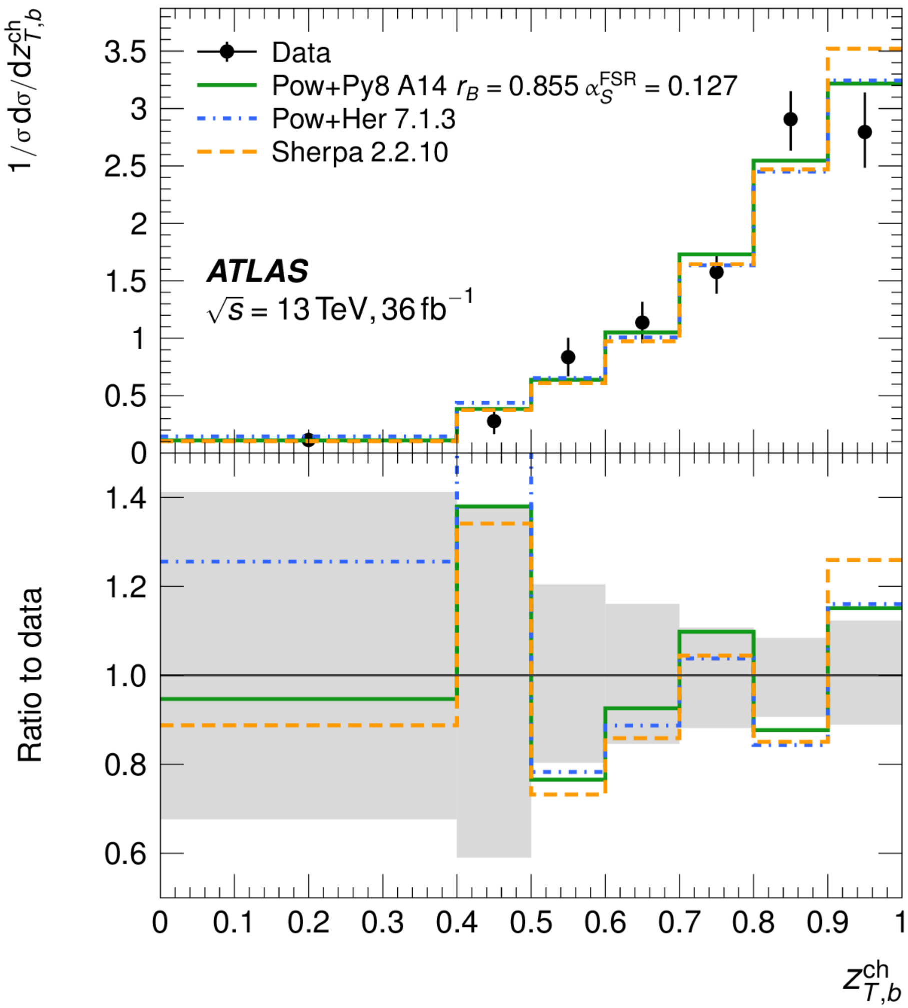
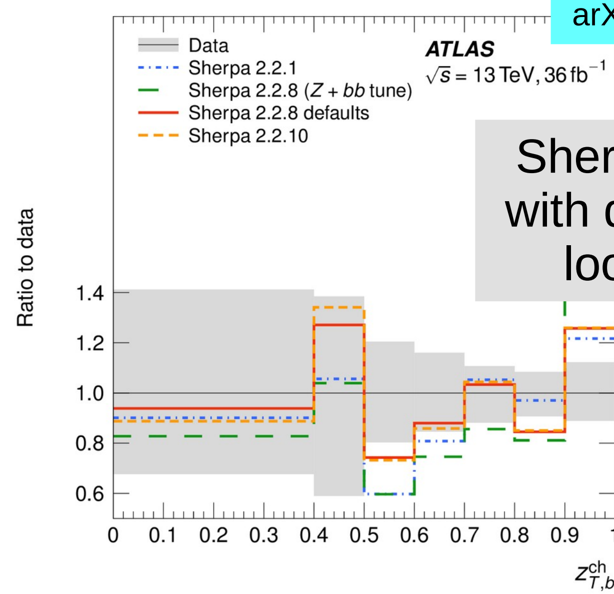
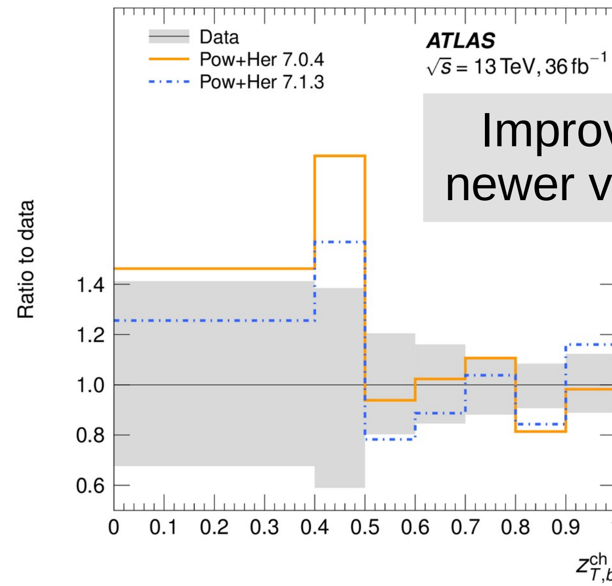




Sherpa : 2.2.10 with default tune looks good

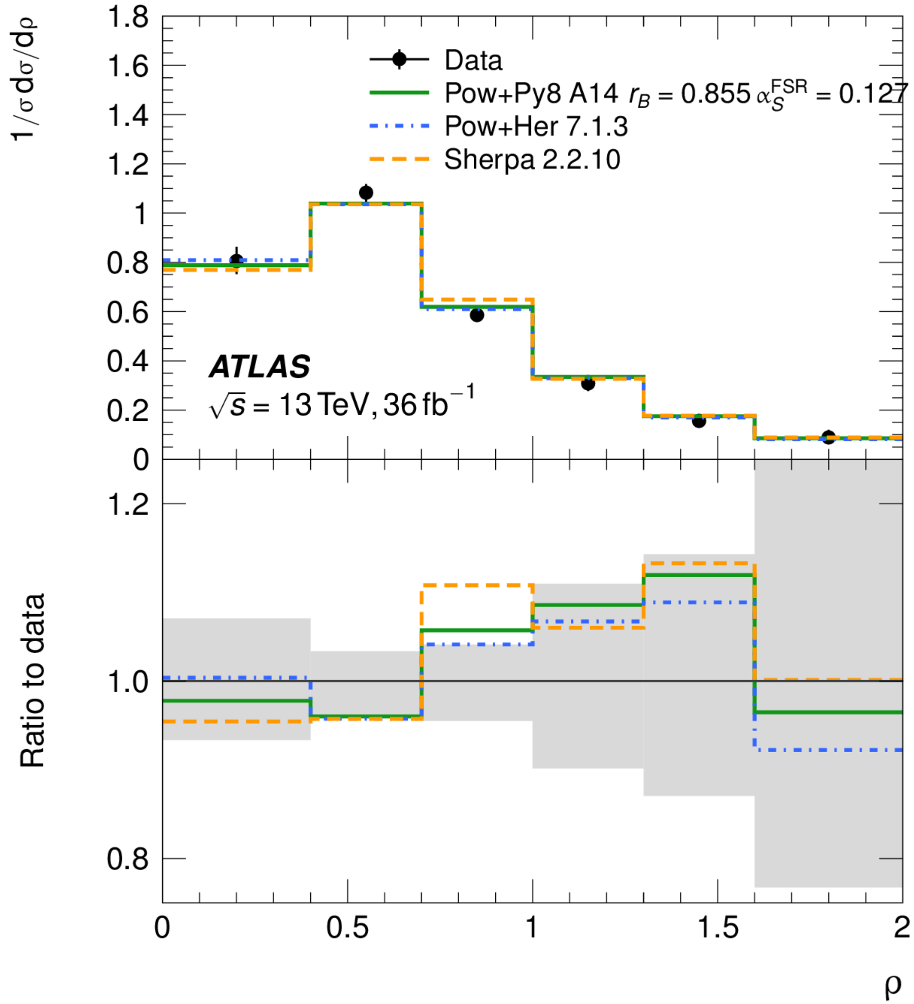


Improvements in newer version of H7

Recent generator tunes to $e^+e^- \rightarrow Z \rightarrow$ bb do a reasonable job

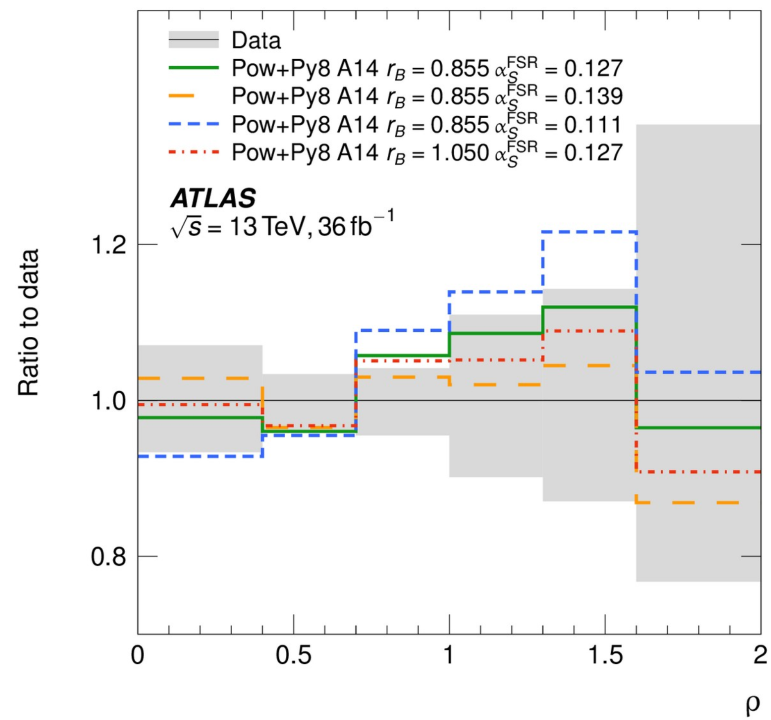
ATLAS b-quark fragmentation in $t\bar{t}$ events

arXiv:2202.13901



~1 tensions with recent generators
⇒ further investigation

Large impact from A14 α_s(FSR) variations
no senstivity to α_s(ISR)



ATLAS b-quark fragmentation in $t\bar{t}$ events

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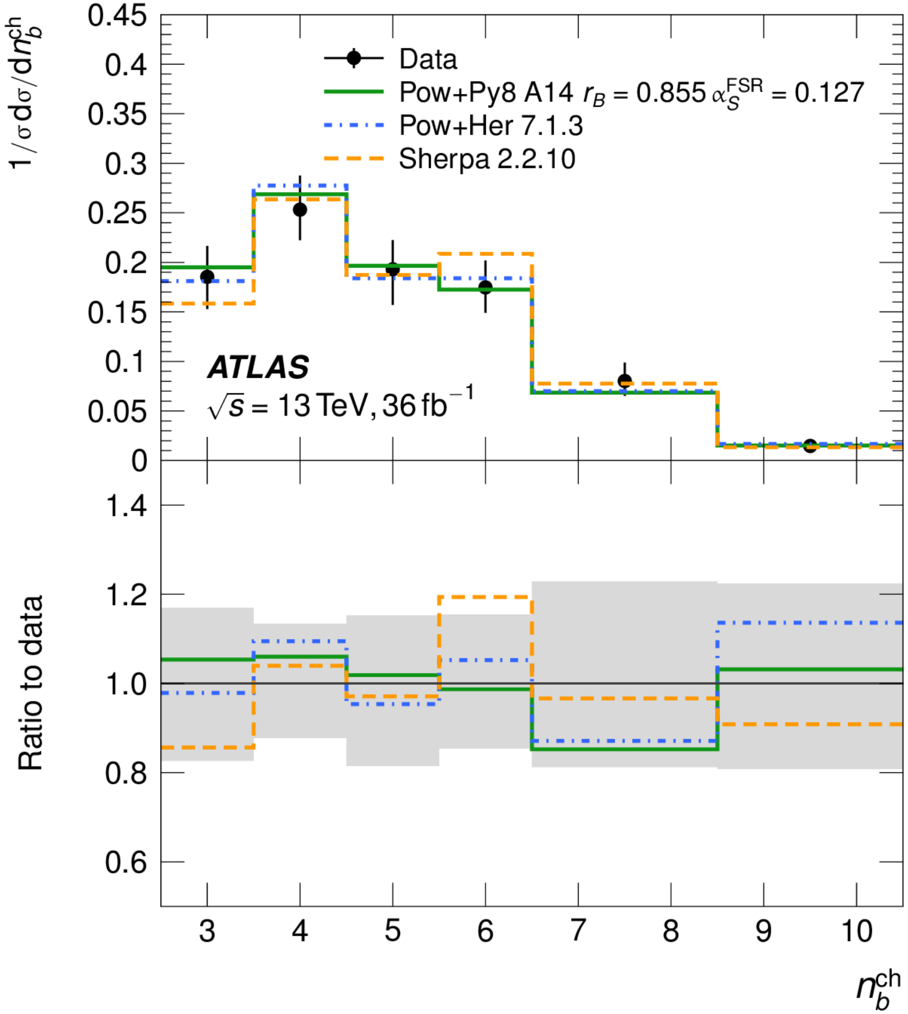
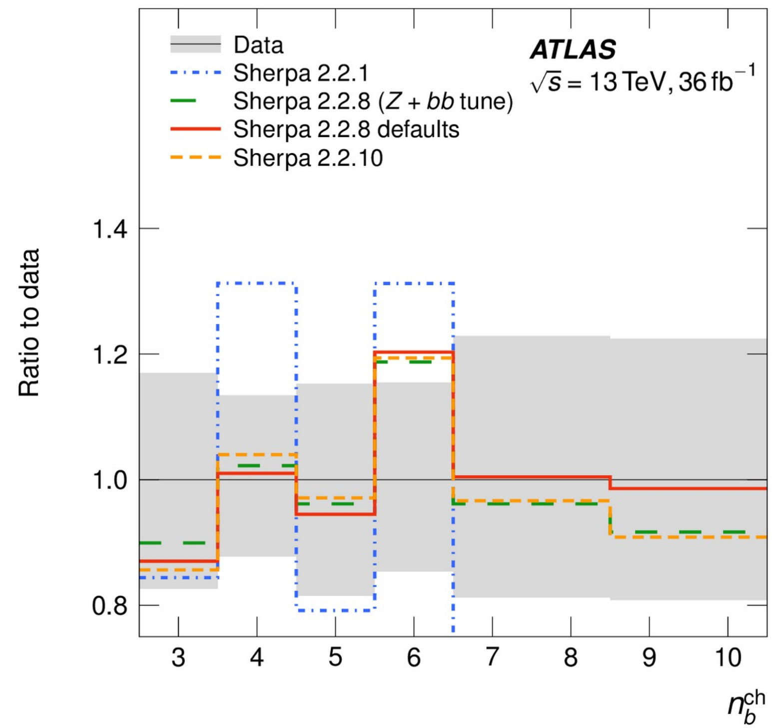


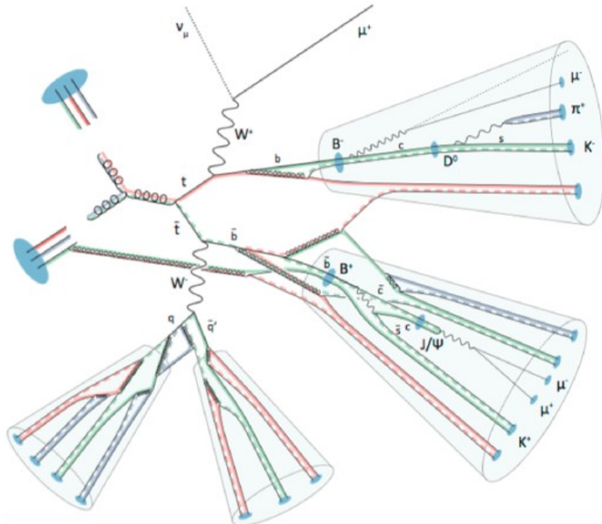
Py8/H7 + EvtGen and Sherpa 2.2.10 all perform admirably

Poor choice of heavy baryon enhancement in ATLAS's Sherpa 2.2.1 setup has now been fixed



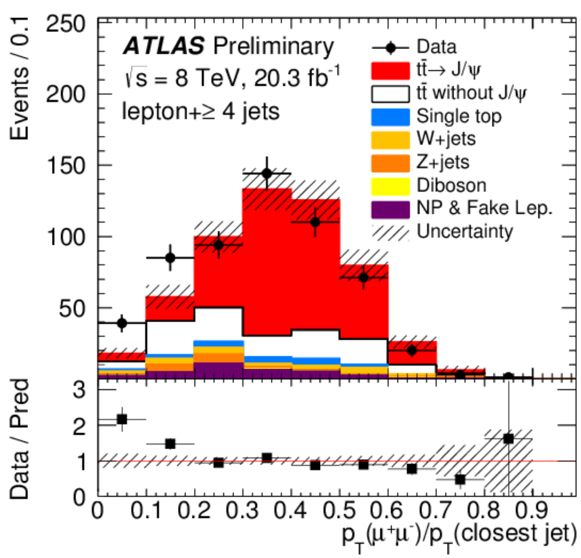
ATLAS b-fragmentation in $t\bar{t}$ events with mesons

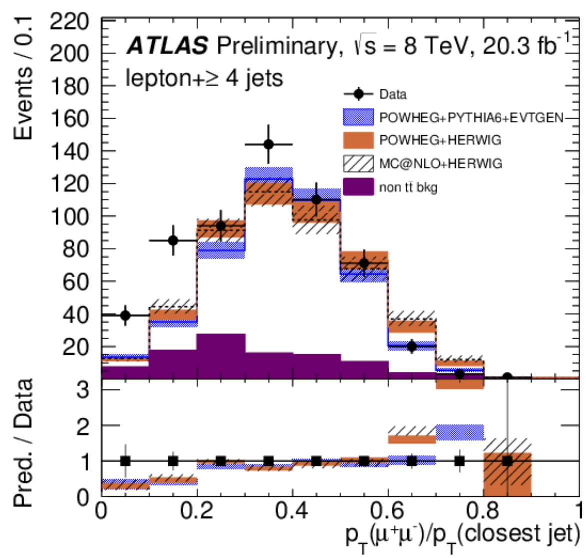
Study of $t\bar{t}$ pairs with in final state a B-hadron decaying in J/ψ ($b \to J/\psi \to \mu\mu$) offers alternative channel to measure m_t using the sensitivity of $m_{l\mu\mu}$ to m_t



- **Motivations**
  - purely leptonic/tracking observables less sensitive to JES than the ones from jet reconstruction
  - sensitive to parton shower, hadronization, b-fragmentation effects…
  - help to reduce the uncertainties in combination of all measurements
- **Low BR final states**
  - $BR(b \to J/\psi \to \mu\mu)$ ~6.8×10^{-4}

ATLAS-CONF-2015-040





Old work done at LPNHE, currently ongoing with Run 2 data using J/ψ and D mesons to measure m_t and b-fragmentation studies

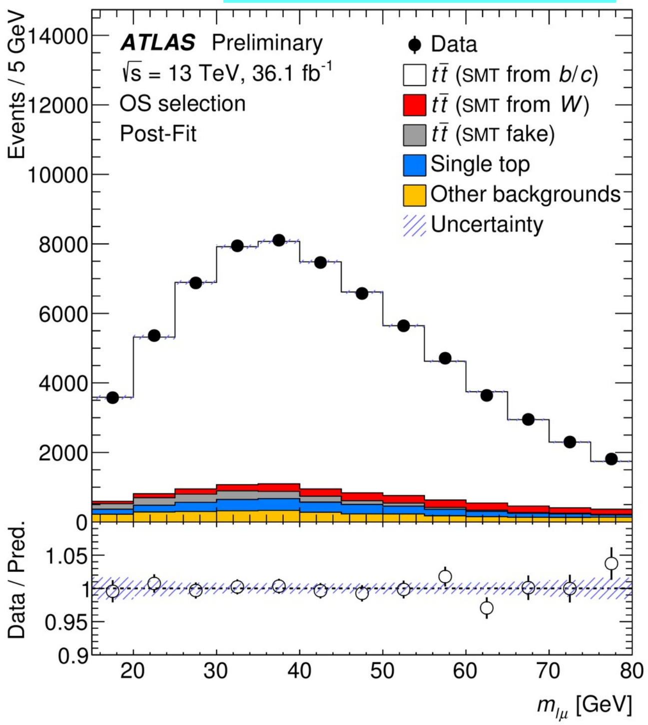
Impact for m_t measurements

at our current precision, generators well-tuned to e^+e^-
predictions in $t\bar{t}$ events and top-quark decays

- ○ we now have unfolded data to guide our choice of related uncertainties.
- ○ precise b-fragmentation → smaller uncertainties on the b-quark to b -jet transfer
- ○ a better understanding of $t \rightarrow b^{quark} \rightarrow b^{hadron}$ crucial for fully-leptonic template mass extractions ($m(\ell\mu)$ or $m(\ell, J/\psi)$)

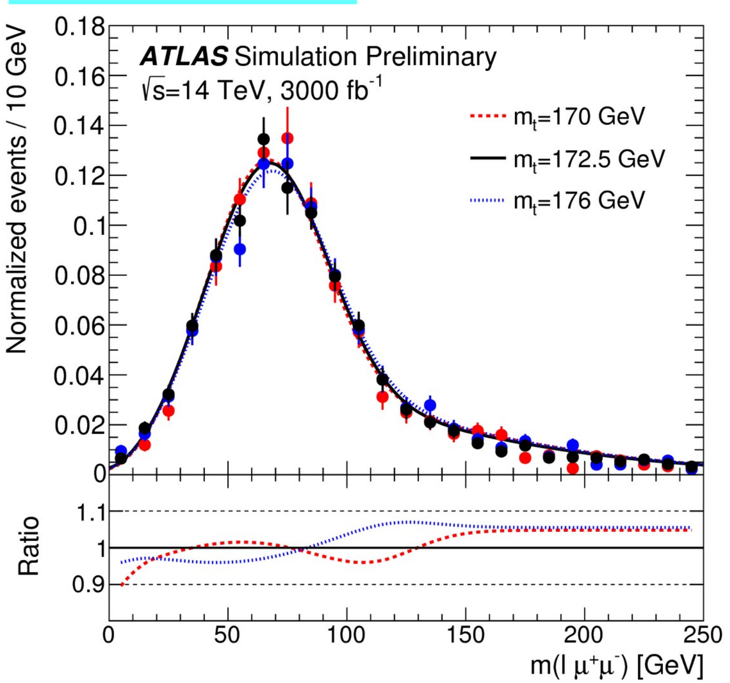
joint fragmentation+mass measurements in leptonic modes should be investigated

ATLAS-CONF-2019-046



CERN Yellow Report
arXiv:1902.04070

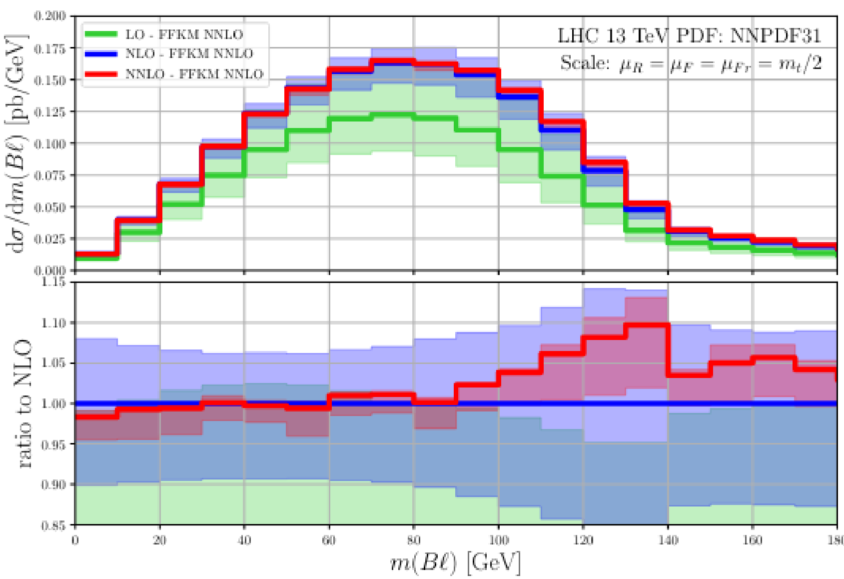
ATL-PHYS-PUB-2018-042

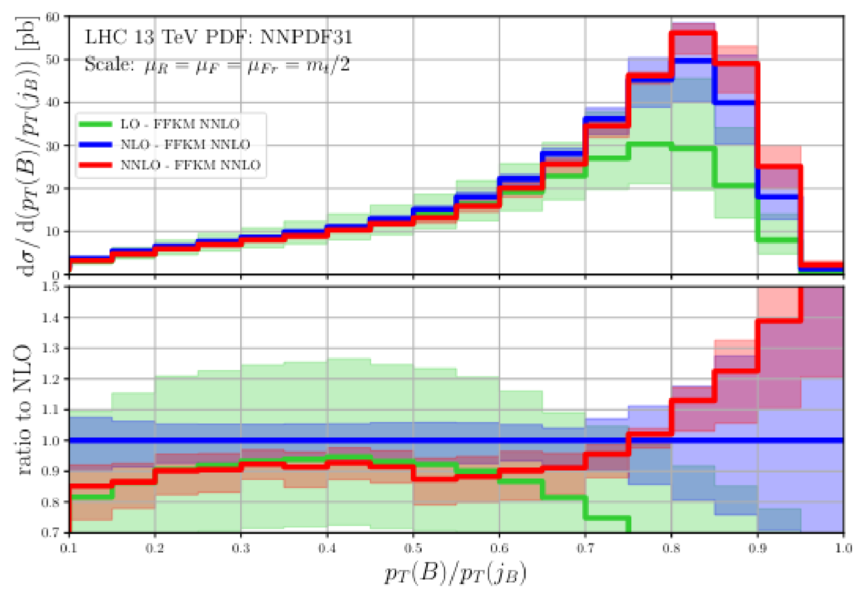


Status of analytic calculations

- Mitov et al. showed the first quasi-analytic calculations of similar distributions at TOP2020 and did recent publication
- will be very interesting to compare to unfolded data
- challenges for comparison:
  - calculations are for production of exclusive B-hadron species
  - jets are defined at parton-level in calculation
  - cannot use observables based on charged particles

arXiv:2102.08267





Conclusion

- **Measurements sensitive to jet fragmentation have grown far beyond direct measurements**
  - a multiple of angularities, correlation functions, substructure observables from both ATLAS and CMS (not covered here !)
  - use of track-based and all-particle reconstructions and dig into jet-flavour depence. Ghost-association of track-jets or reconstructed hadrons, esp. for b-quark studies
    - refitting r_b on LHC data
    - testing models using $t\bar{t}$ pairs

- **Ways to improve systematic uncertainties precision ? Most analyses only 36/fb so far !**

- **First ~analytic calculations of b -quark fragmentation in top-quark decays are on the horizon for comparison !**

- **Dawn of Run 3 a good time to revisit 7 TeV MC tunes & studies**

Backup slides