Heavy Flavour Jets with LHCb

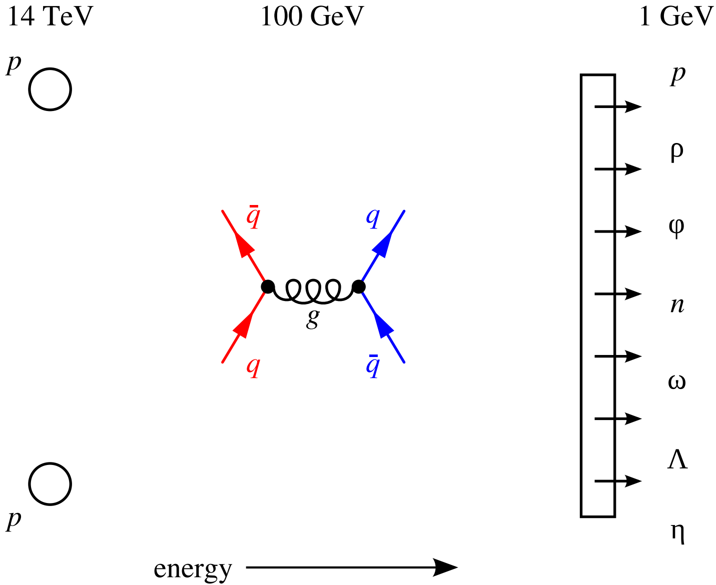
Philip Ilten

UNIVERSITY OF BIRMINGHAM

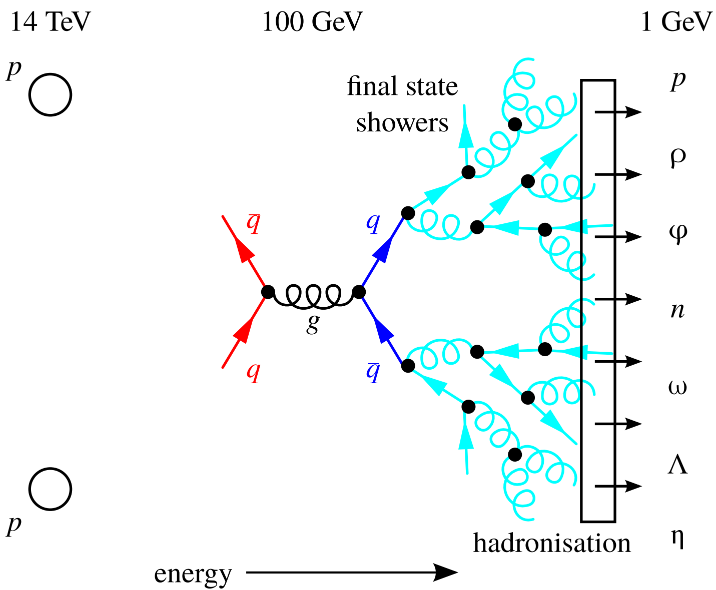
November 29, 2017

Edinburgh Seminar

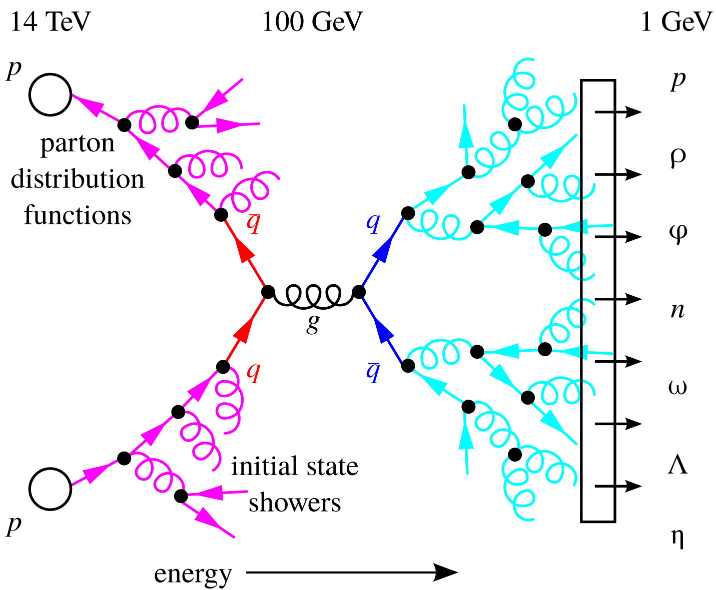
QCD at the LHC



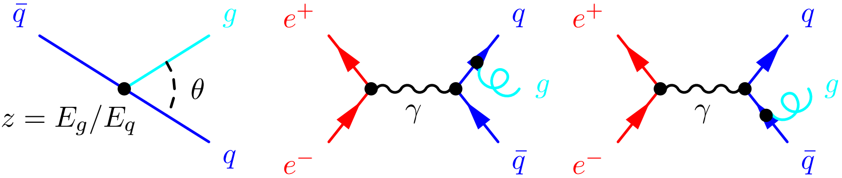
QCD at the LHC



QCD at the LHC



Factorising QCD



$$\mathrm{d}\sigma \approx \sigma \left(\frac{2\,\mathrm{d}\cos\theta}{\sin^2\theta}\right)\left(\frac{\alpha_s}{2\pi}\right)\left(\frac{N_c^2-1}{2N_c}\right)\left(\frac{1+(1-z)^2}{z}\right)\mathrm{d}z$$

- factorise into general form given any splitting kernel $\mathcal{P}_i$

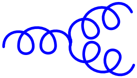
$$\mathrm{d}\sigma \approx \sigma \sum_i \frac{\mathrm{d}\theta^2}{\theta^2}\mathcal{P}_i\left(z, \alpha_s\right)\mathrm{d}z$$

- diverges when collinear ($\theta \to 0, \pi$) or infrared ($z \to 0$)

Sudakovs and Splitting Kernels

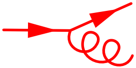
$$\Delta(Q_1^2, Q^2) = \exp\left[-\int_{Q^2}^{Q_1^2} \frac{1}{q^2} \int_{Q_0^2/q^2}^{1-Q_0^2/q^2} \mathcal{P}_i(z, \alpha_s)\, \mathrm{d}z\, \mathrm{d}q^2\right]$$

1. pick a random number $r \in [0, 1]$
2. solve $\Delta(Q_1^2, Q^2) = r$ for Q^2
3. if $Q > Q_0$ generate emission and repeat from 1
4. if $Q \leq Q_0$ terminate shower



$g \to gg$

$$\frac{1-z}{z} + \frac{z}{1-z} + z(1-z)$$



$q \to qg$

$$\frac{1-z}{z} + \frac{z}{2} - 2\mu$$

$g \to qq$

$$z^2 + (1-z)^2 + \mu^2$$

Reverse Engineering with Jets

- unfold final state particles to initial hard partons
  1. collinear safe → collinear emission changes nothing
  2. infrared safe → soft emission changes nothing
  3. insensitive to non-perturbative effects
  4. applicable to both parton and hadron level
- inclusive sequential clustering is algorithm of choice at LHC

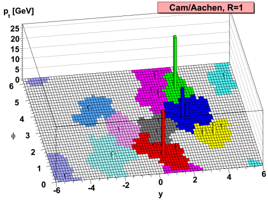
$$d_{ij} = \min(p_{\mathrm{T}i}^{k}, p_{\mathrm{T}j}^{k})\frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = p_{\mathrm{T}i}^{k}$$

1. select minimum d
2. if d_{ij}, combine particle i and j
3. if d_{iB}, consider particle as jet and remove from clustering
4. terminate if no particles otherwise return to 1

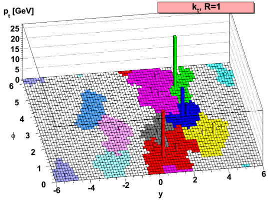
Flavours of Sequential Clustering

Cambridge/Aachen | k_t | anti-k_t

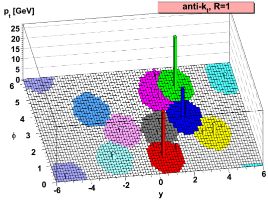
arXiv:1111.6097



$k = 0$



$k = 2$



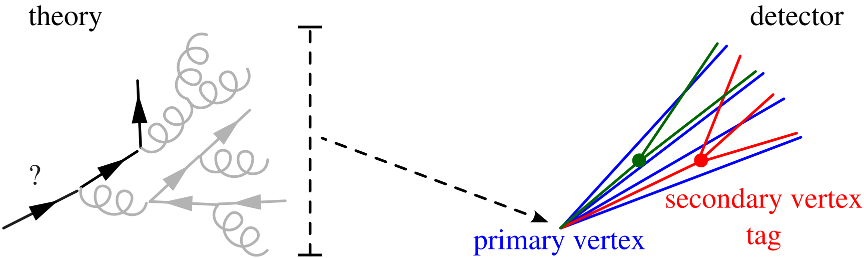
$k = -2$

- Cambridge/Aachen considers only geometry
- k_t and anti-k_t also consider momentum
- anti-k_t provides circular jets in R at high-p_T

Tagging a Jet

LHCb, JINST 10 (2015) P06013

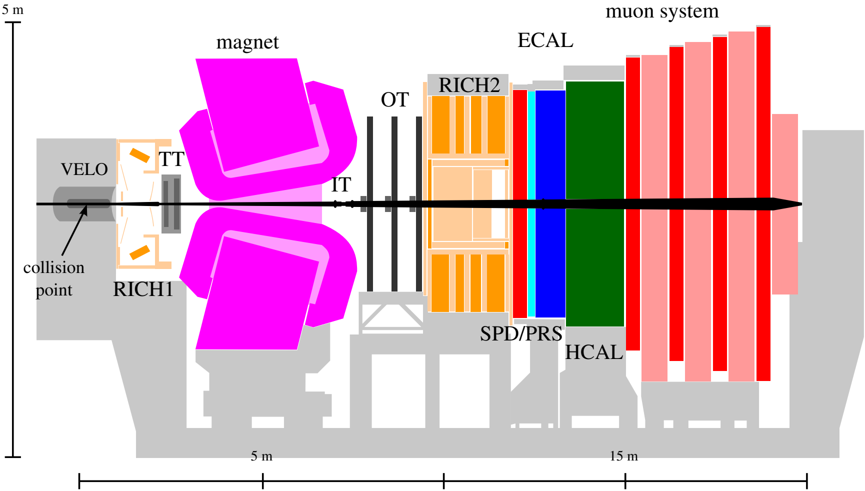
From Theory to Detector



- jet properties depend on initiating parton

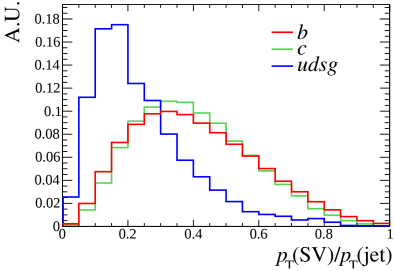
	c-hadron	b-hadron
mass	2 GeV	5 GeV
lifetime ($c\tau$)	0.1 mm	0.5 mm
multiplicity	≈ 2	≈ 3

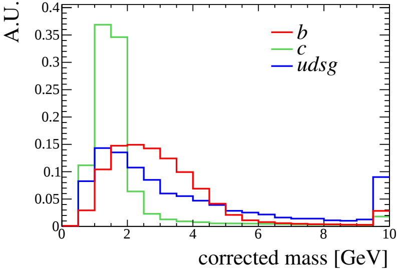
Enter LHCb

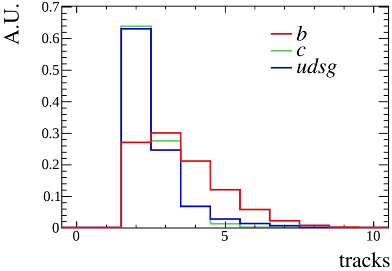


1. good momentum and mass resolution
2. excellent secondary vertex resolution

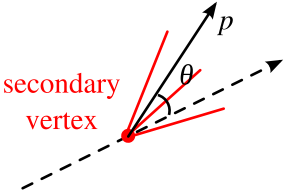
Tagging Ingredients





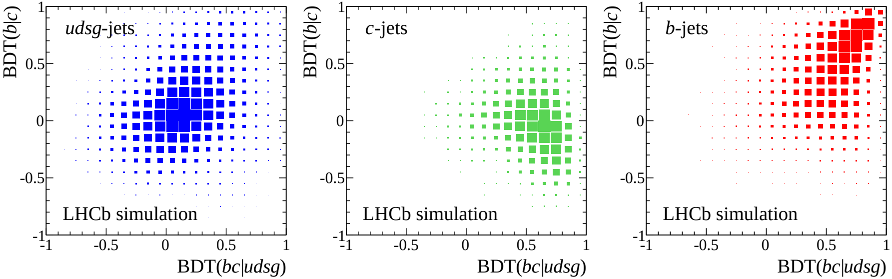


$$M_{\rm cor} = \sqrt{M^2 + p^2 \sin^2\theta} + p \sin\theta$$

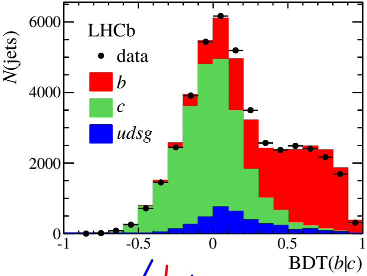


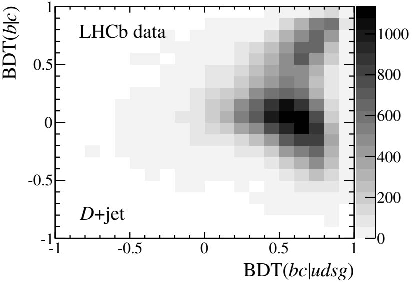
A Pinch of Machine Learning

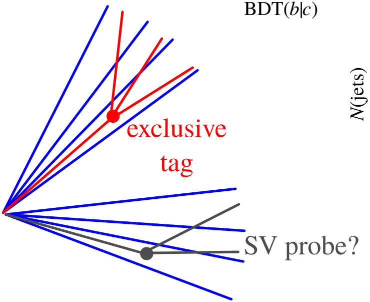
- 10 total observables (3 jet related) input to boosted decision trees
- two BDTs: *udsg vs. cb* and *c vs. b*
- fit 2-dimensional distribution of the two BDTs

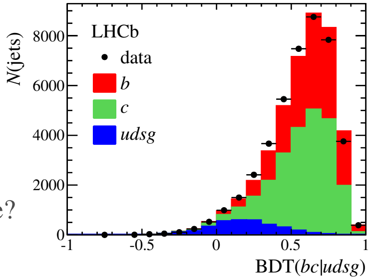


Tag and Probe





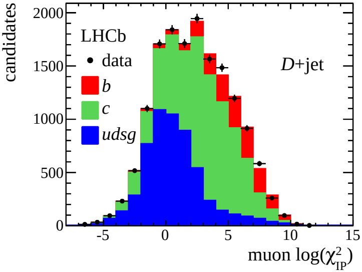


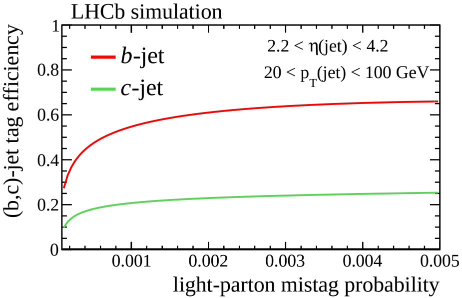


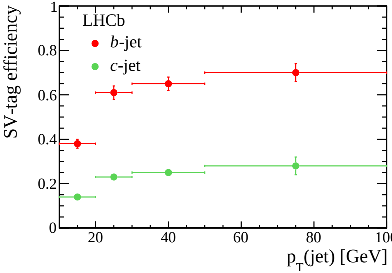
Efficiencies

$$\frac{N(\text{probe SV})}{N(\text{total})}$$

- $N(\text{probe SV})$ from BDT fit
- $N(\text{total})$ from hardest χ^2_{IP} fit







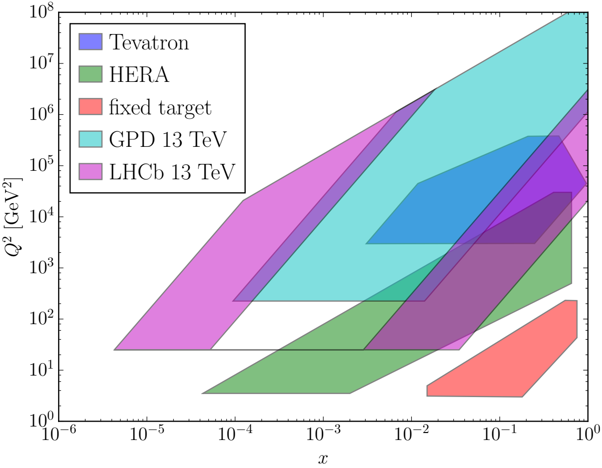
Vector Boson with a Jet

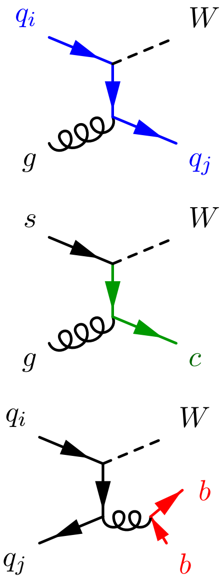
LHCb, Phys. Rev. D 92 (2015)

LHCb, Phys. Rev. Lett. 115 (2015)

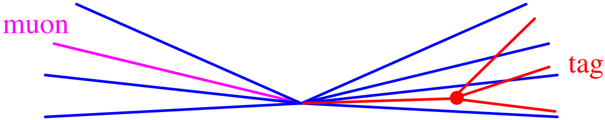
Boettcher, Ilten and Williams,
Phys. Rev. D 93 (2016)

Probing the Proton



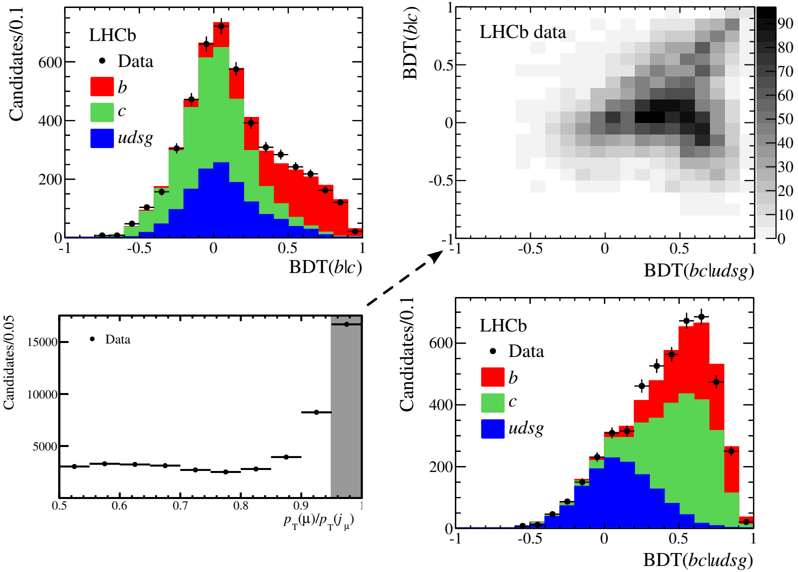


W with a Jet

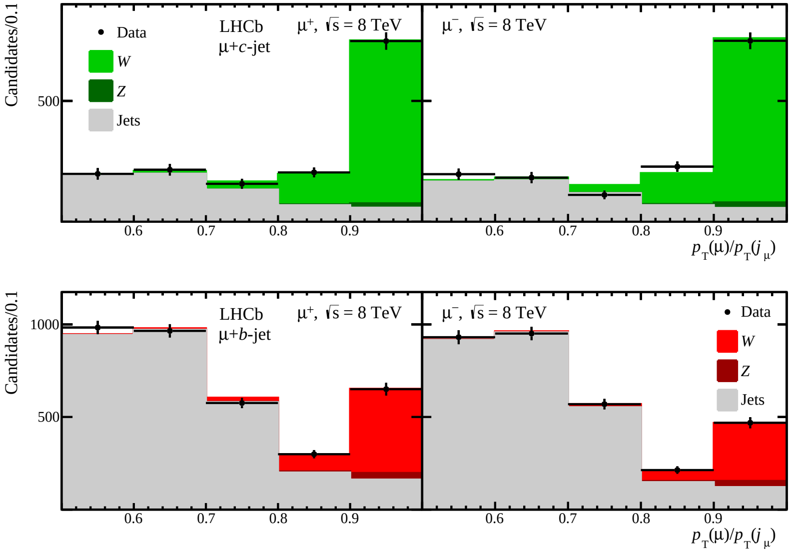


1. trigger on a high p_T muon
2. build jets in the event
3. require jet containing muon j_μ and tagged jet j
4. bin data as a function of isolation, $p_\mathrm{T}(\mu)/p_\mathrm{T}(j_\mu)$
5. determine flavour in each isolation bin with BDT fit
6. fit isolation to determine signal

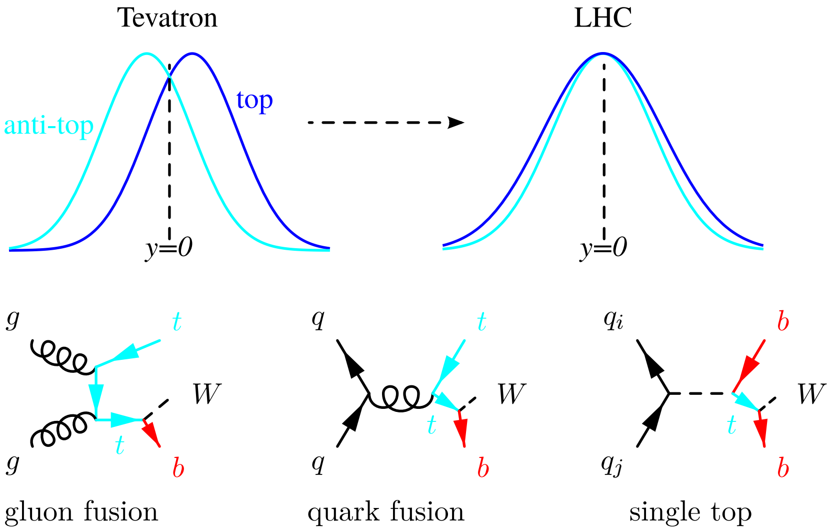
Flavour Determination



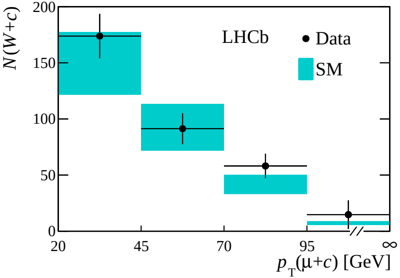
Signal Determination



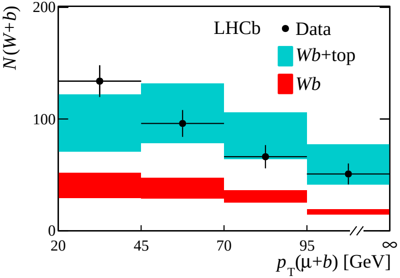
Topping the W

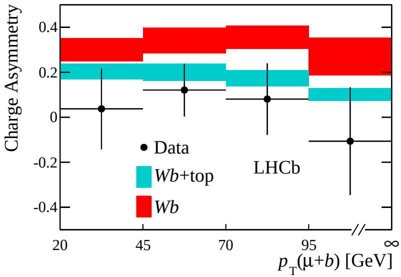


A Tricky Background

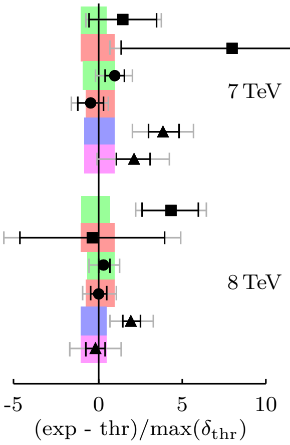


- constrain Wb with Wj
- scale with Wb/Wj theory
- validate with Wc



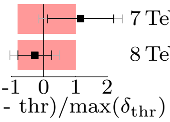


Putting Everything Together



$-0.09 \pm 0.08 \pm 0.04$	$\mathcal{A}(Wc)$
$0.51 \pm 0.20 \pm 0.09$	$\mathcal{A}(Wb)$
$5.80 \pm 0.44 \pm 0.75$	$\sigma(Wc)/\sigma(Wj) \times 10^2$
$0.66 \pm 0.13 \pm 0.13$	$\sigma(Wb)/\sigma(Wj) \times 10^2$
$6.61 \pm 0.19 \pm 0.33$	$\sigma(W^- j)/\sigma(Zj)$
$10.49 \pm 0.28 \pm 0.53$	$\sigma(W^+ j)/\sigma(Zj)$

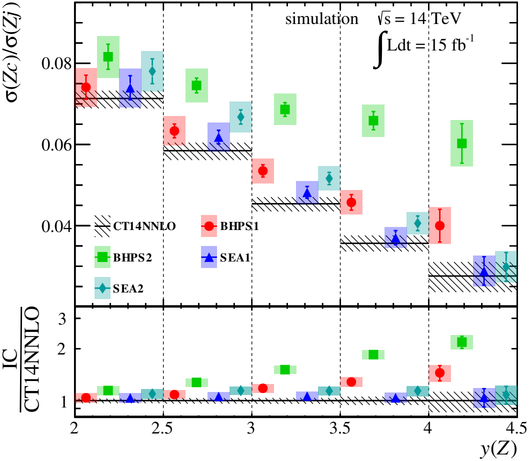
$-0.01 \pm 0.05 \pm 0.04$	$\mathcal{A}(Wc)$
$0.27 \pm 0.13 \pm 0.09$	$\mathcal{A}(Wb)$
$5.62 \pm 0.28 \pm 0.73$	$\sigma(Wc)/\sigma(Wj) \times 10^2$
$0.78 \pm 0.08 \pm 0.16$	$\sigma(Wb)/\sigma(Wj) \times 10^2$
$6.02 \pm 0.13 \pm 0.30$	$\sigma(W^- j)/\sigma(Zj)$
$9.44 \pm 0.19 \pm 0.47$	$\sigma(W^+ j)/\sigma(Zj)$

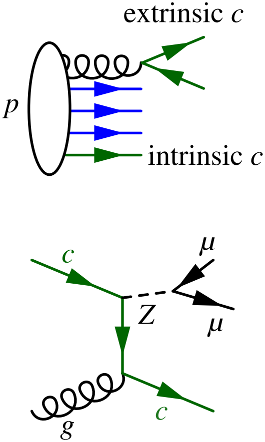


7 TeV $239 \pm 53 \pm 41$ [fb]

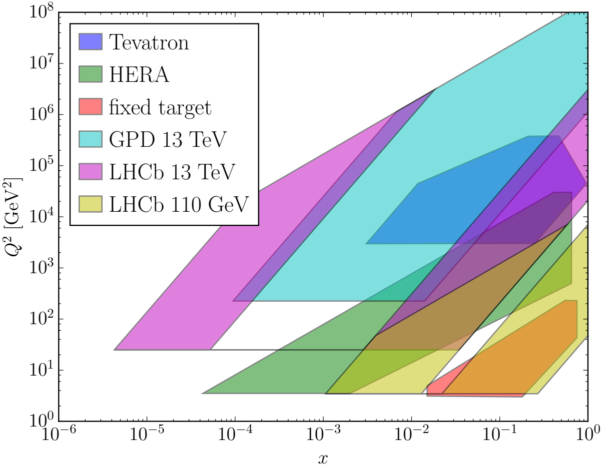
8 TeV $289 \pm 43 \pm 49$ [fb]

Intrinsic Charm





Bonus Intrinsic Charm

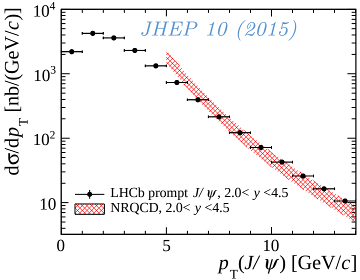


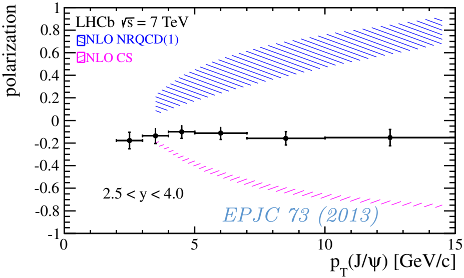
type	time
pNe	30m
PbNe	30m
pNe	12h
pHe	7h
pAr	20h
pAr	11h
PbAr	100h
pHe	20h
pHe	87h

J/ψ in a Jet

LHCb, Phys. Rev. Lett. 118 (2017)

The Polarization Puzzle

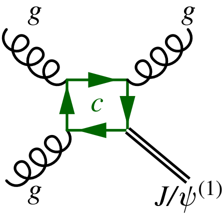


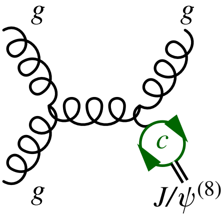


colour singlet

low p_T

longitudinal pol.





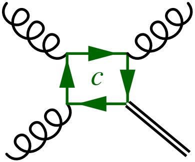
colour octet

high p_T

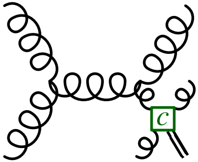
transverse pol.

A Tale of Two Pictures

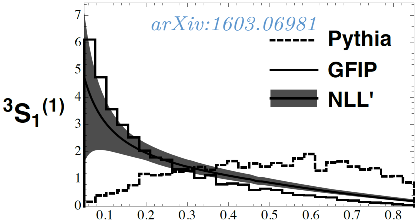
1. NRQCD hard process, octet states showered with QCD splittings
2. shower with NRQCD splittings, match with hard process



hard production



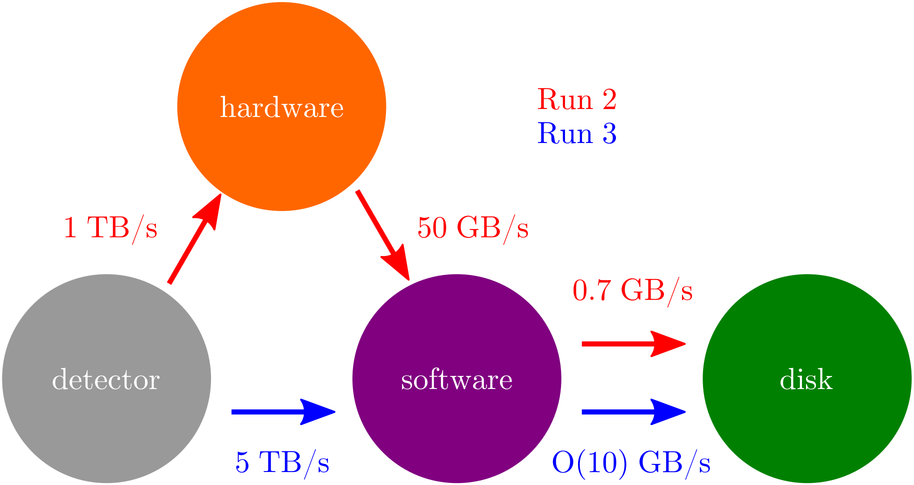
shower production



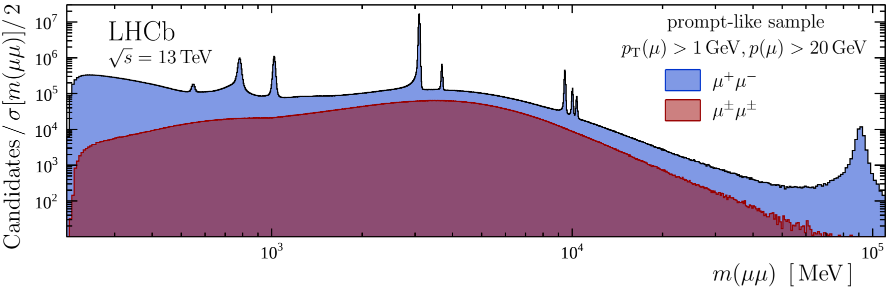
- build $J/\psi \to \mu\mu$ candidates
- build jets with J/ψ input
- select jets with J/ψs
- $z \equiv p_T(J/\psi)/p_T(\text{jet})$

LHCb Trigger

- real-time calibration and full event reconstruction in Run 2
- full detector readout in Run 3

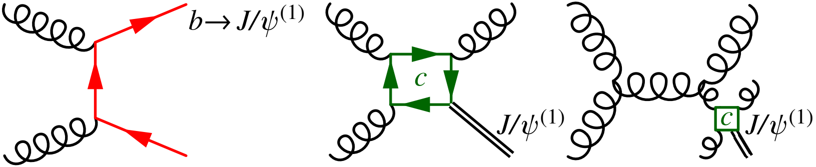


Dimuon Trigger

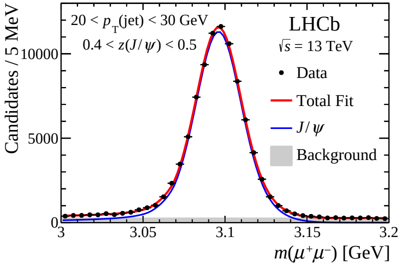


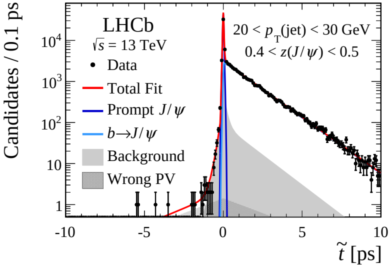
- fully reconstructed event written to disk, including particle flow
- jets can be fully reconstructed, sans hadronic calorimetry

Prompt and Displaced



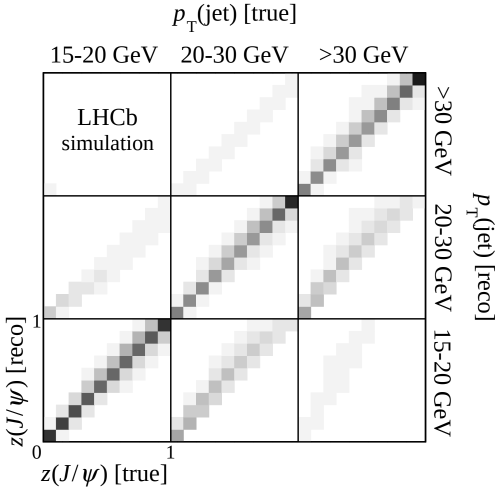
- determine J/ψ signal yield with mass fits
- separate prompt (direct) from displaced ($b \to J/\psi$) yields with pseudo-lifetime fits, $\tilde{\tau} \equiv (x_z - x_z(\text{PV}))m/p_z$



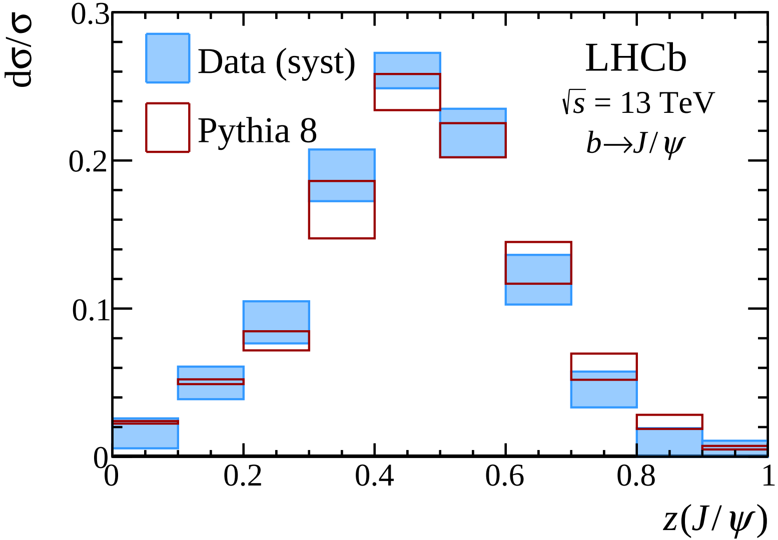


Unfolding

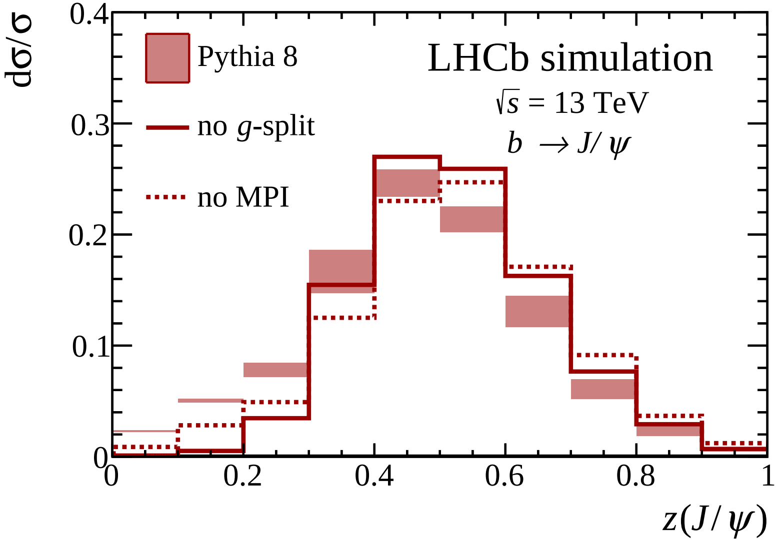
- correct for z resolution and $p_{\mathrm{T}}(j)$ resolution, $\approx 20 - 25\%$
- perform 2D unfolding in z and $p_{\mathrm{T}}(j)$ (iterative D'Agostini)



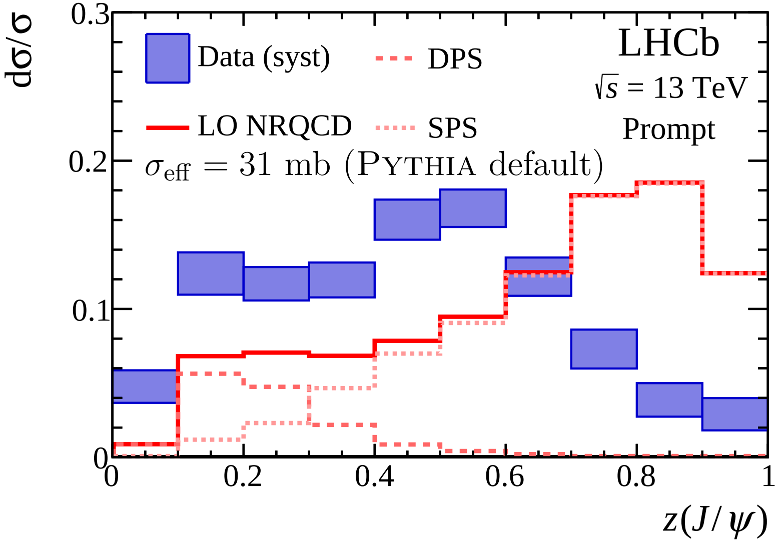
Displaced Results



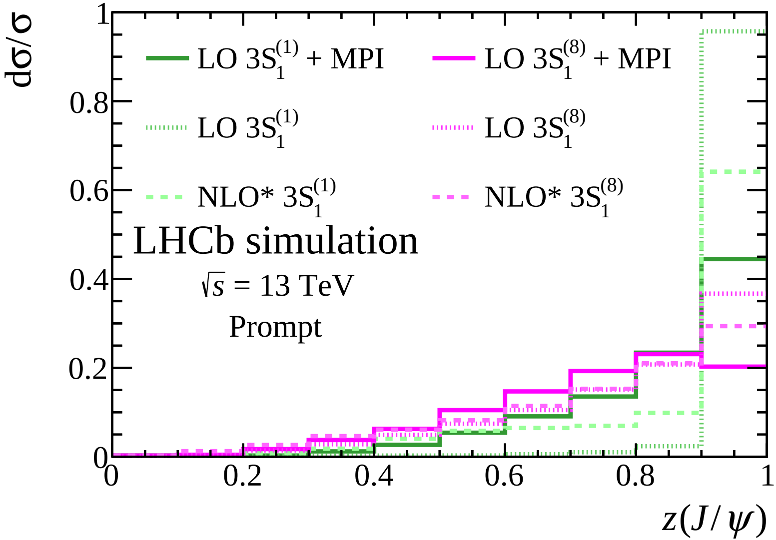
Displaced Results



Prompt Results



Prompt Results

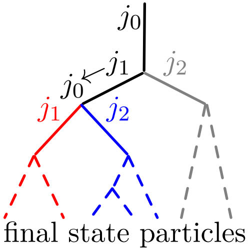


Jets in a Jet?

Ilten, Rodd, Thaler and Williams,
Phys. Rev. D 96 (2017)

SoftDrop and Jet Sub-structure

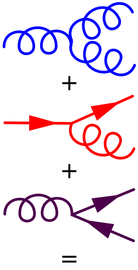
- what happens with boosted topology when $Q_{\text{hard}} \gg Q_{\text{obs}}$, *e.g.* $W, Z, H \to q\bar{q}$?
- anti-k_t produces a single jet → need jet sub-structure
- use jet sub-structure technique like SoftDrop



$$\frac{\min(p_{\text{T}1}, p_{\text{T}2})}{p_{\text{T}1} + p_{\text{T}2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

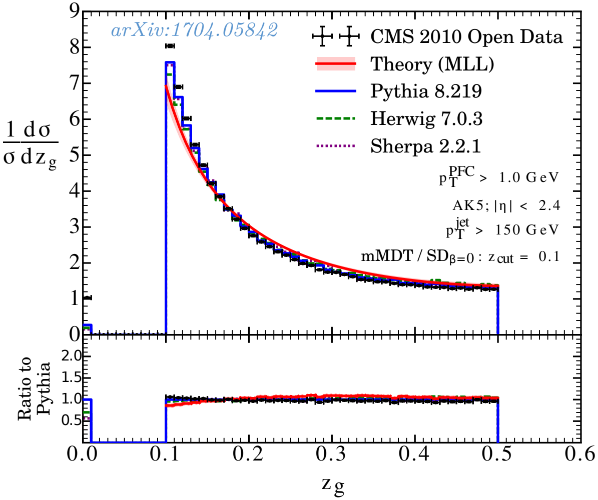
1. create fat anti-k_t jets
2. build Cambridge/Aachen tree for each fat jet
3. split j_0 into sub-jets j_1 and j_2
4. if j_1 and j_2 fulfil SoftDrop condition, terminate
5. otherwise, assign j_0 to larger p_{T} sub-jet and return to 3

Averaged Massless Splittings



$$\frac{1-z}{z} + \frac{z}{1-z} + \frac{1}{2}$$

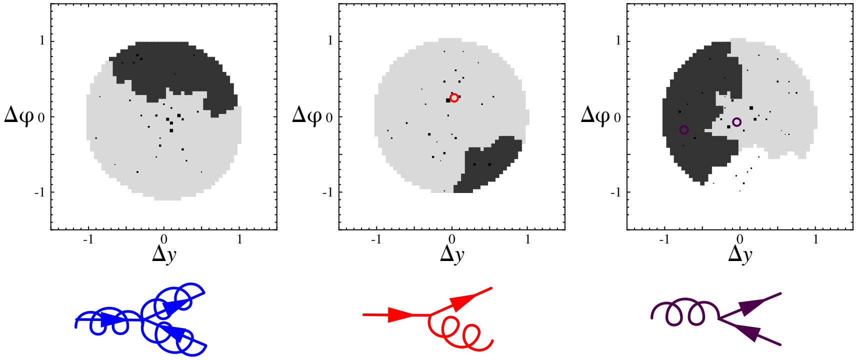
$$z_g \equiv \frac{p_{T1}}{p_{T1} + p_{T2}}$$



- SoftDrop provides direct access to the hardest $1 \to 2$ splitting

Jet Anatomy

1. find all tags in event and treat as *ghosts*
2. build anti-k_t jets with $R = 1$, including tags
3. apply SoftDrop with $z_{\text{cut}} > 0.1$ and $\beta = 0$
4. consider sub-jet tagged if $p_{\text{T}}^{\text{tag}}/(p_{\text{T1}} + p_{\text{T2}}) > 0.05$



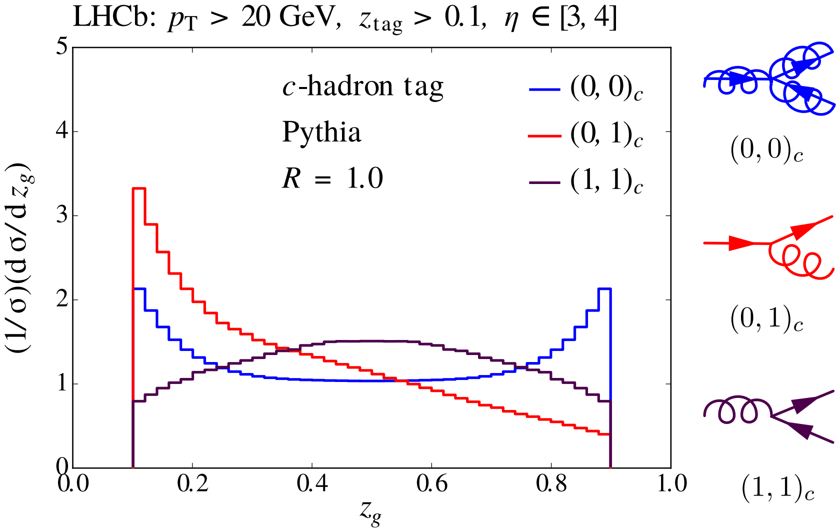
$(0, 0)_Q$ $(0, 1)_Q$ $(1, 1)_Q$

Some Numbers

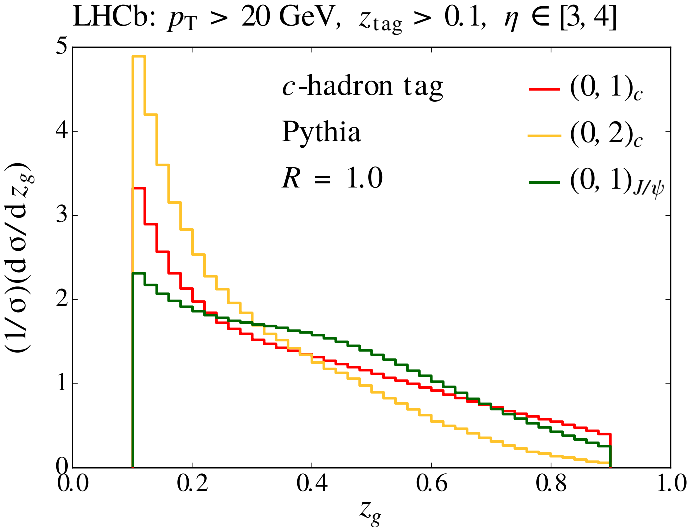
	σ(Pythia) [μb]	σ(Herwig++) [μb]
$(0,0)_c$	9.96×10^2	5.28×10^2
$(0,1)_c$	7.56×10^1	2.64×10^1
$(1,1)_c$	6.87×10^0	2.87×10^0
$(0,2)_c$	1.00×10^1	5.64×10^0
other_c	8.86×10^{-1}	2.47×10^{-1}
$(0,0)_b$	1.07×10^3	5.52×10^2
$(0,1)_b$	1.34×10^1	9.58×10^0
$(1,1)_b$	8.40×10^{-1}	5.03×10^{-1}
$(0,2)_b$	9.50×10^{-1}	5.94×10^{-1}
other_b	1.13×10^{-2}	7.75×10^{-3}

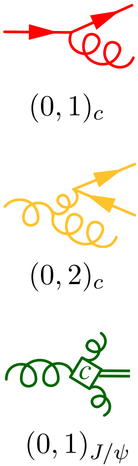
- missed tags migrate category up → minimal contamination
- efficiency of tagging well understood from data

Heavy Flavour Splittings



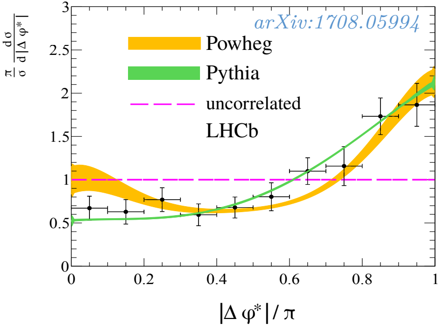
Quarkonia Splitting

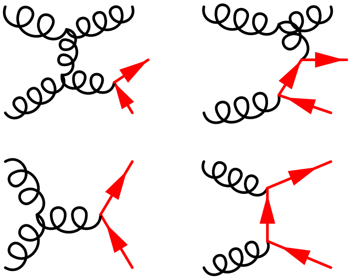




Heavy Flavour Production

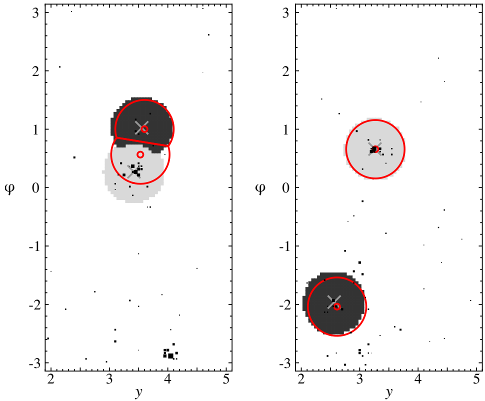
- understanding heavy flavour production critical for many signals
- two approaches typically taken
  1. hadron-level: good angular properties, poor energy proxy
  2. tagged jet-level: poor angular properties, good energy proxy





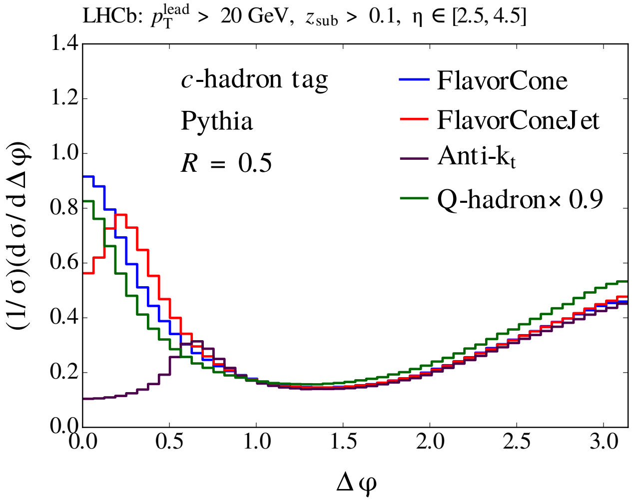
FlavorCone

- good angular properties, good energy proxy
- collinear and infrared safe by jet-axis definition



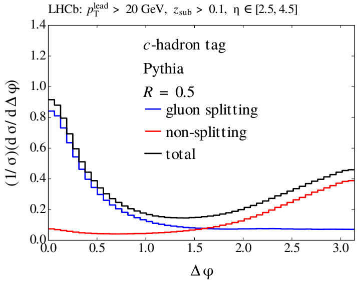
1. given n tags define n jet-axes
2. particles outside of R with an jet-axis is not clustered
3. remaining particles are clustered with nearest axis
4. jet momenta is sum of constituents

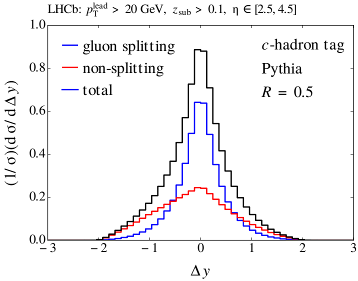
Comparison

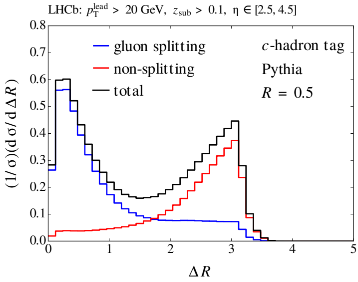


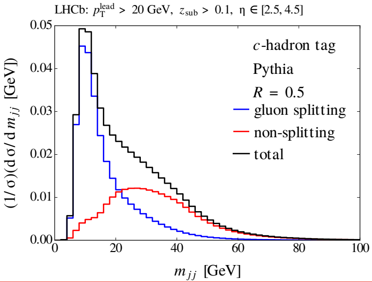
LHCb: $p_T^{lead} > 20$ GeV, $z_{sub} > 0.1$, $\eta \in [2.5, 4.5]$
c-hadron tag
Pythia
$R = 0.5$
FlavorCone
FlavorConeJet
Anti-k_t
Q-hadron× 0.9
$(1/\sigma)(d\sigma/d\Delta\varphi)$
$\Delta\varphi$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.5
1.5
2.0
2.5
3.0

Variable Discrimination









Outlook

- LHCb's tagging capabilities provide a unique probe of QCD
  - valence and strange quark PDFs
  - top asymmetry
  - intrinsic charm
  - NRQCD in the context of jets
- SoftDrop allows access to fundamental $1 \rightarrow 2$ QCD splittings
- FlavorCone provides both good angular and energy properties for studying $Q\bar{Q}$ production

Thank you!