Splitting Kernels with Heavy Flavour

based on

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

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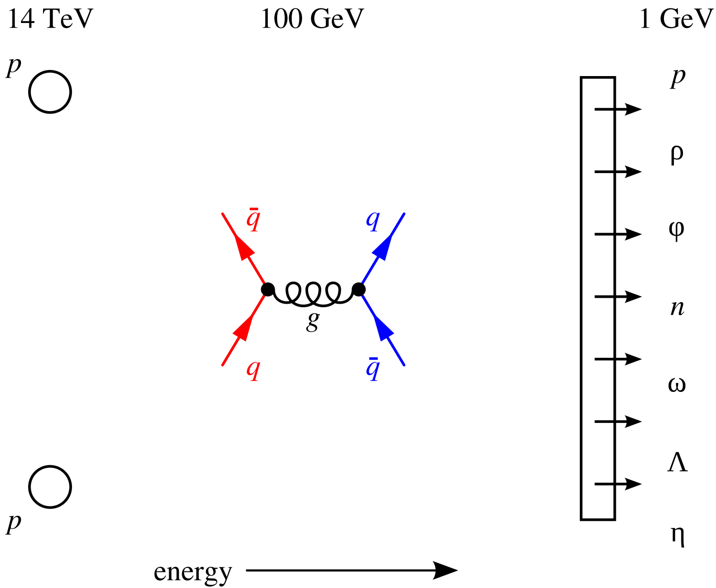
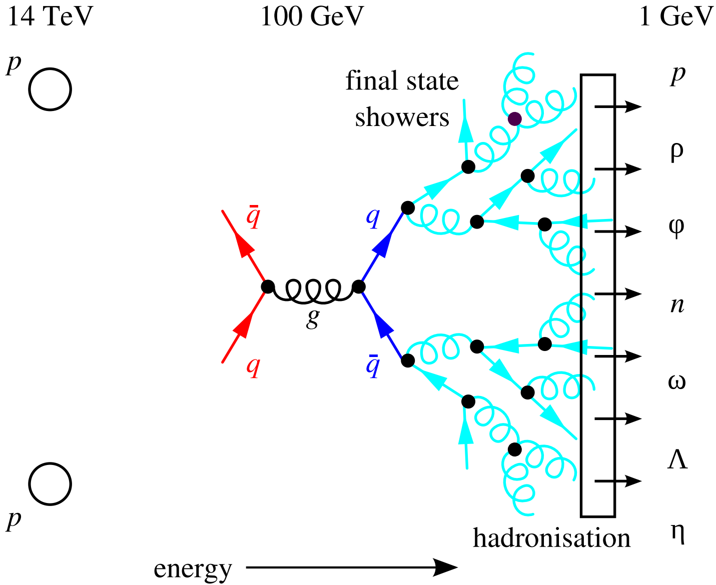
LHCb Implications Workshop

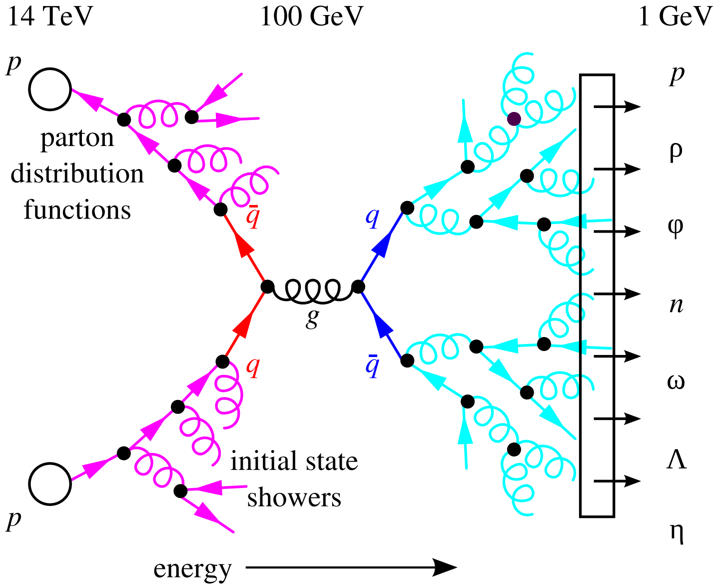
The Problem with QCD



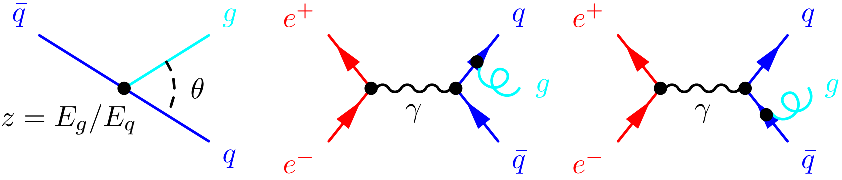
The Problem with QCD



The Problem with QCD



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 $\mathcal{P}_i$

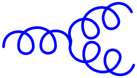
$$\mathrm{d}\sigma \approx \sigma \sum_i \frac{\mathrm{d}\theta^2}{\theta^2}\mathcal{P}_i\left(z, \alpha_s\right)\,\mathrm{d}z$$

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

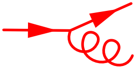
Sudakovs and Splitting Kernels

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

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



$g \to gg$



$q \to qg$

$g \to qq$

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

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

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

Reverse Engineering with Jets

- try to unfold initial hard partons from final state particles
  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

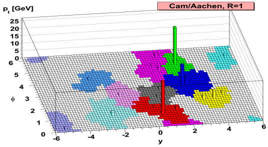
$$d_{ij} = \min(p_{\mathrm{T}i}^{2p}, p_{\mathrm{T}j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = p_{\mathrm{T}i}^{2p}$$

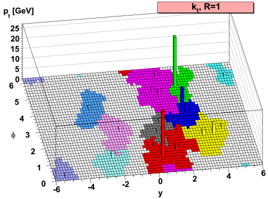
1. select minimum d
2. if d_{ij}, combine particle i and j
3. if d_{iB}, consider particle as jet and remove from clustering
4. terminate if no particles otherwise return to 1

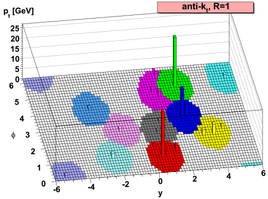
Flavours of Sequential Clustering

Cambridge/Aachen	k_t	anti-k_t

arXiv:1111.6097





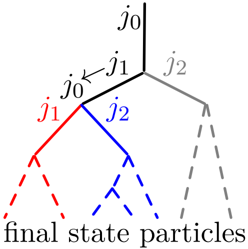


$p = 0$	$p = 1$	$p = -1$

- 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}

SoftDrop and Jet Sub-structure

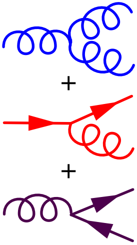
- what happens with boosted topology when $Q_{\text{hard}} \gg Q_{\text{obs}}$, *e.g.* $W, Z, H \to q\bar{q}$?
- anti-k_t produces a single jet → need jet sub-structure
- use jet sub-structure technique like SoftDrop



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

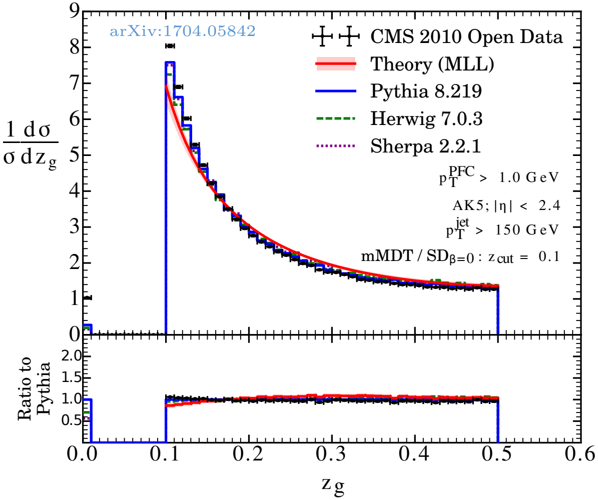
1. create fat anti-k_t jets
2. build Cambridge/Aachen tree for each fat jet
3. split j_0 into sub-jets j_1 and j_2
4. if j_1 and j_2 fulfil SoftDrop condition, terminate
5. otherwise, assign j_0 to larger p_{T} sub-jet and return to 3

Averaged Massless Splittings



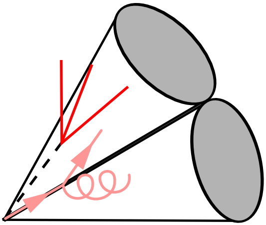
$$= \frac{1-z}{z} + \frac{z}{1-z} + \frac{1}{2}$$

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

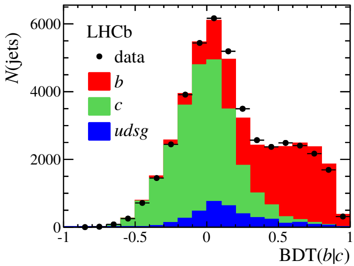


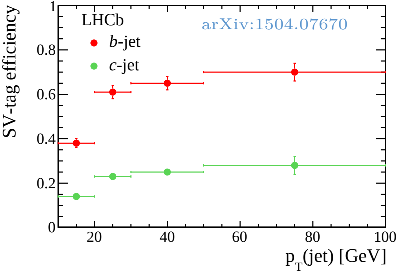
- SoftDrop provides direct access to the hardest $1 \to 2$ splitting

Enter LHCb



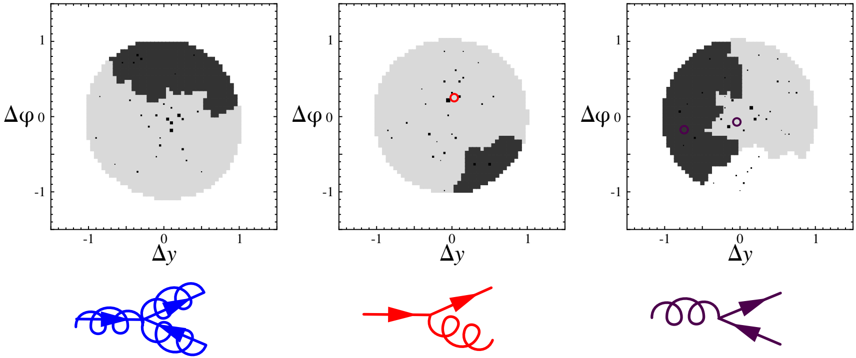
- can we access the individual splittings?
- tag sub-jets to determine the splitting kernel
- excellent secondary c/b tagging with LHCb provides ideal experimental probe





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 $p_{\text{T}}^{\text{tag}}/(p_{\text{T}1} + p_{\text{T}2}) > 0.05$



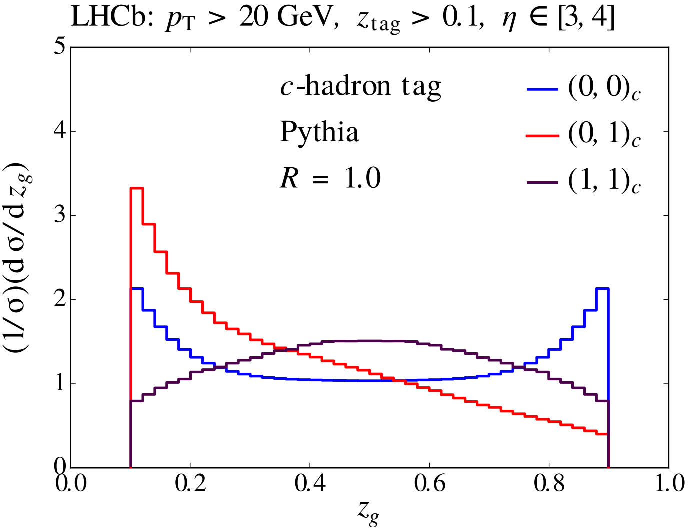
$(0, 0)_Q$ $(0, 1)_Q$ $(1, 1)_Q$

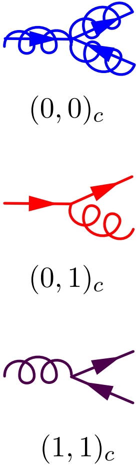
Some Numbers

	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 $\rightarrow$ minimal contamination
- efficiency of tagging well understood from data

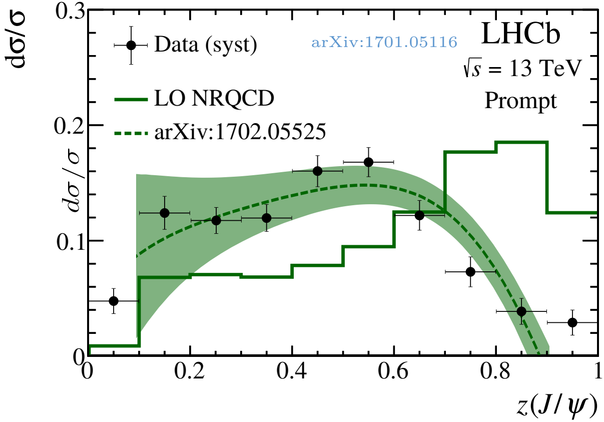
Heavy Flavour Splittings

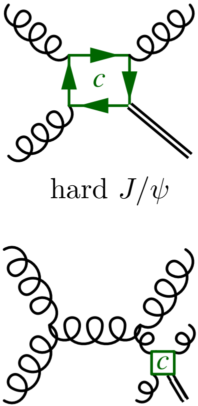




Problems with Quarkonia

- how should quarkonia be treated in the parton shower?
- PYTHIA only showers $J/\psi^{(8)}$ with $q \to qg$

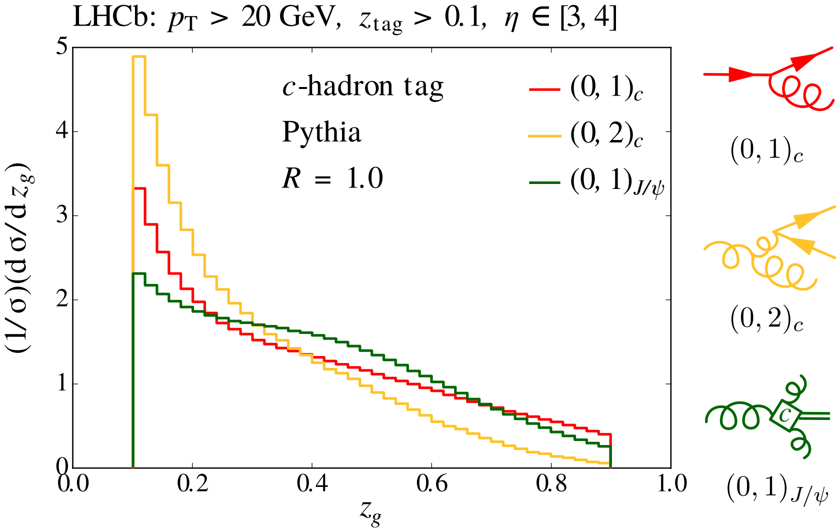




hard J/ψ

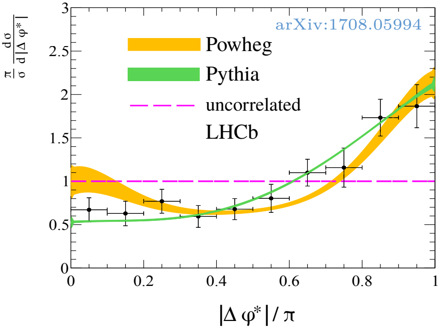
shower J/ψ

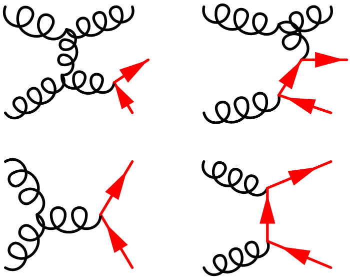
Quarkonia Splitting



Heavy Flavour Production

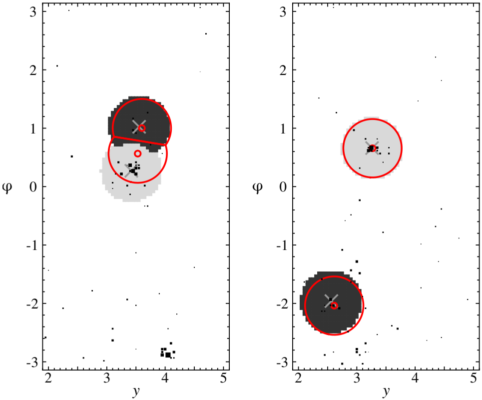
- understanding heavy flavour production critical for many signals
- two approaches typically taken
  1. hadron-level: good angular properties, poor energy proxy
  2. tagged jet-level: poor angular properties, good energy proxy





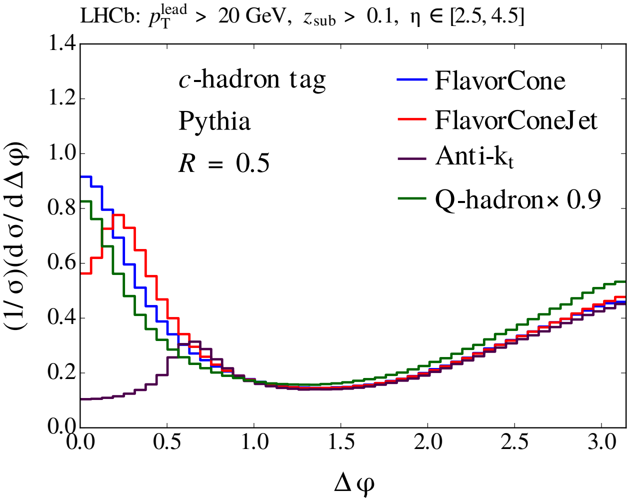
FlavorCone

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

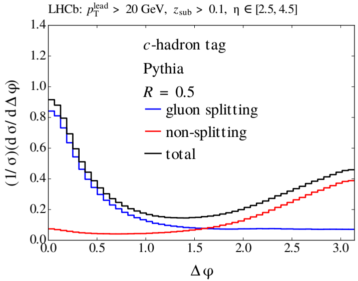


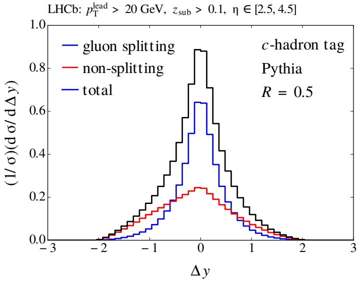
1. given n tags define n jet-axes
2. particles outside of R with an jet-axis is not clustered
3. remaining particles are clustered with nearest axis
4. jet momenta is sum of constituents

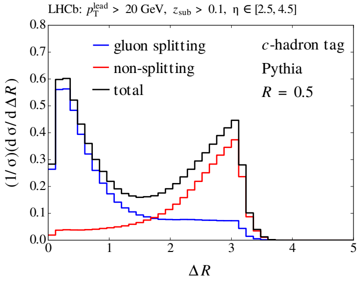
Comparison

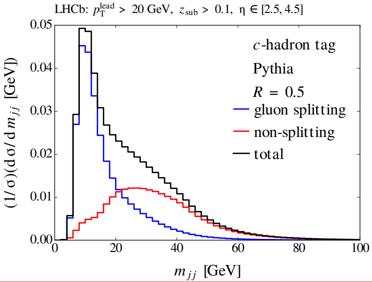

LHCb: $p_T^{lead} > 20$ GeV, $z_{sub} > 0.1$, $\eta \in [2.5, 4.5]$
c-hadron tag
Pythia
R = 0.5
FlavorCone
FlavorConeJet
Anti-k_t
Q-hadron× 0.9
$(1/\sigma)(d\sigma/d\Delta\varphi)$
$\Delta\varphi$
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Variable Discrimination









Outlook

- SoftDrop allows access to fundemental $1 \to 2$ QCD splittings
  - could help shed further light on quarkonia
- FlavorCone provides both good angular and energy properties for studying $Q\bar{Q}$ production
- LHCb's tagging capabilities provide a unique opportunity to probe fundemental QCD

Thank you!