Infrared safe definition of jet flavour

Jet-flavour algorithms at parton level

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Quark and gluon jets

- In the literature 376 papers with 'quark/gluon jet' in title
- Physically a quark/gluon jet = a jet initiated by a quark/gluon
- Experimentalists try determination of jet flavour
  - Discriminate quark/gluon jets using kinematical properties [jet profile, subjet multiplicity]
  - Jet charge = weighted charge of particles in a jet

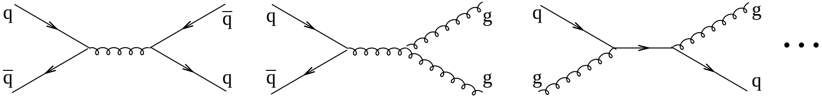
$$Q_{\rm jet} = \sum_{i \in \rm jet} q_{ti} Q_i / \sum_{i \in \rm jet} q_{ti}$$

All experimental definitions are practical but IR unsafe

- Hints of theoretical problems in IR safety and flavour
  - Feynman is alleged to have said "impossible"
  - Flavour insensitive definition of observable suggested [Nagy, Soper]

Subprocess decomposition

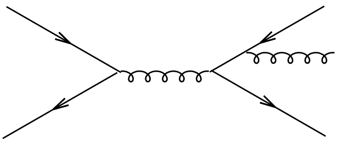
It is useful to decompose a QCD process into subprocesses

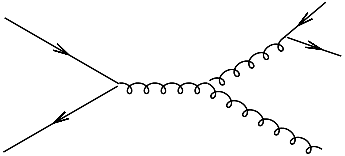


- to attribute more physical meaning to higher-order calculations
  [which subprocess gets largest contribution]
- to know relative numbers of quark and gluon jets
  [multiplicity studies, MC tuning]
- to combine matrix elements and parton shower
  [CKKW]
- to match analytical resummations to fixed order
  [CAESAR+NLOJET++]

Jet flavour at parton level beyond LO

Problem: map final state momenta $\rightarrow$ Born momenta





- Flavour decomposition is ambiguous beyond LO $\Rightarrow$ Interference
- Cluster of event into jets provides a mapping into a Born event
- Jet flavour = net flavour of particles in the jet

$$u = (0,1,0,0,0,0), \quad \bar{u} = (0,-1,0,0,0,0) \qquad u, \bar{u} \in \text{jet}$$

$$f_{\text{jet}} = u + \bar{u} = (0,0,0,0,0,0) = g$$

Ambiguity can be removed only in soft/collinear limit

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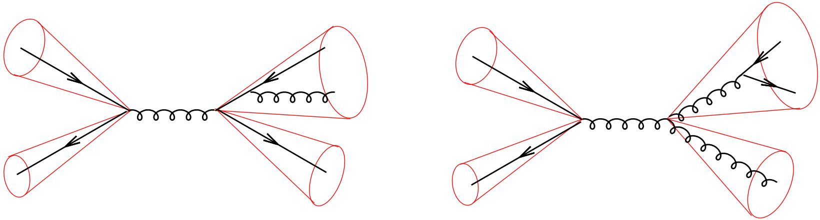

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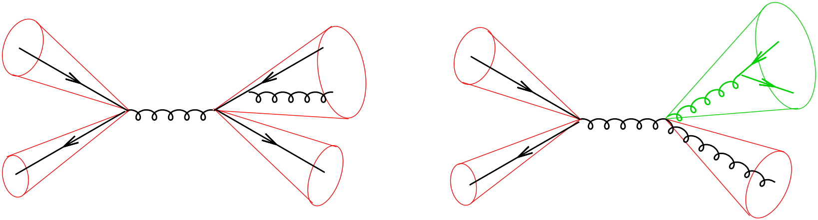

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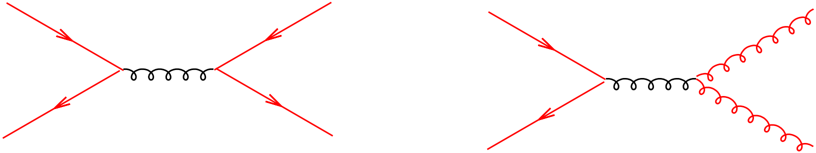

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Jet flavour and infrared safety

At NLO any IR safe jet algorithm is also an IR safe flavour algorithm

- Soft/collinear gluons do not change the flavour
- Collinear $q\bar{q}$ pairs are always recombined together

Beyond NLO soft large angle $q\bar{q}$ pairs can be clustered into different jets thus spoiling the reconstruction of jet flavour

IR safety $\Leftrightarrow$ soft quarks and hard partons never recombined

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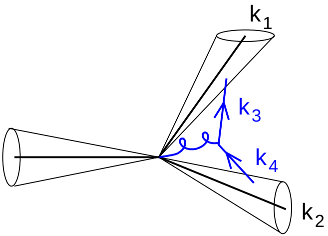

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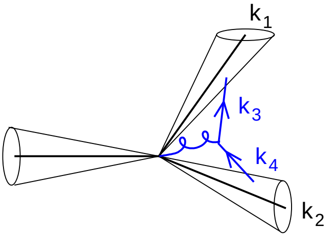


IR safety $\Leftrightarrow$ soft quarks and hard partons never recombined

Jet flavour algorithms in e^+e^-

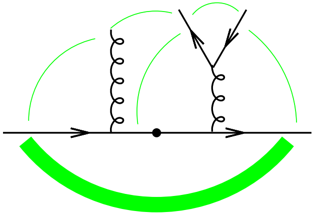
Durham algorithm

- Soft gluon emission $g \to g_i g_j$

$$[dk_j]|M^2(k_j)| \sim \frac{dE_j}{\min(E_i, E_j)} \frac{d\theta_{ij}^2}{\theta_{ij}^2}$$

- $d_{ij}^{(D)} \to 0$ for $\theta_{ij} \to 0$ and $E_j \to 0$

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



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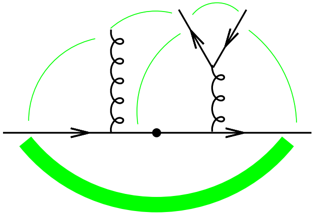

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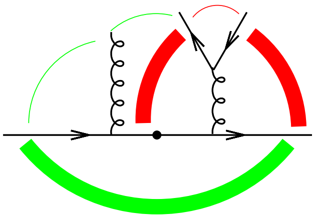

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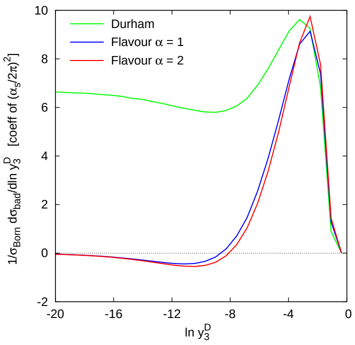
Class of IR safe algorithms identified by $\alpha \in (0, 2]$

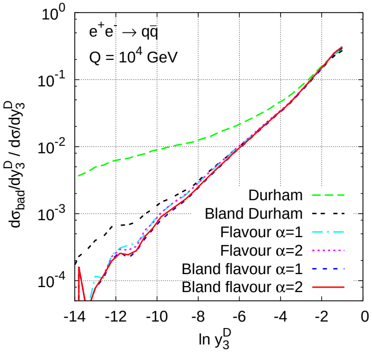
$$d_{ij}^{(F)} = 2(1-\cos\theta_{ij}) \times \begin{cases} \max(E_i, E_j)^\alpha \min(E_i, E_j)^{2-\alpha} & \text{softer of } i, j \text{ flavoured} \\ \min(E_i^2, E_j^2) & \text{softer of } i, j \text{ flavourless} \end{cases}$$

Optional: flavour blandness $\Leftrightarrow$ Recombine only $q\bar{q}$ with no net flavour

Tests of IR safety in e^+e^- annihilation

- Generate multi-parton configurations in e^+e^- and cluster to 2 jets
- Compute fraction of misidentified events $\sigma_{\rm bad}$ as a function of y_3^D
- IR safety at fixed order (EVENT2) $\Leftrightarrow$ $\sigma_{\rm bad}$ vanishes for $y_3 \to 0$
- IR safety at all orders (HERWIG) $\Leftrightarrow$ different scalings for $y_3 \to 0$





Jet flavour in hadron-hadron collisions

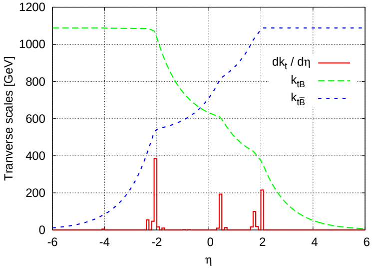
- Distance d_{ij} is modified to have boost invariance

$$d_{ij}^{(F)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}, k_{tj})^{\alpha} \min(k_{ti}, k_{tj})^{2-\alpha} & \text{softer of } i, j \text{ flavoured} \\ \min(k_{ti}^2, k_{tj}^2) & \text{softer of } i, j \text{ flavourless} \end{cases}$$

- Need a distance wrt B $(\eta \to \infty)$ and $\bar{B}$ $(\eta \to -\infty)$

$$d_{iB}^{(F)} = \begin{cases} \max(k_{ti}, k_{tB}(\eta_i))^{\alpha} \min(k_{ti}, k_{tB}(\eta_i))^{2-\alpha} & i \text{ flavoured} \\ \min(k_{ti}^2, k_{tB}^2(\eta_i)) & i \text{ flavourless} \end{cases}$$

- $k_{tB}(\eta)$ and $k_{t\bar{B}}(\eta)$ monotonic functions of η that saturate at the typical hardness of the event

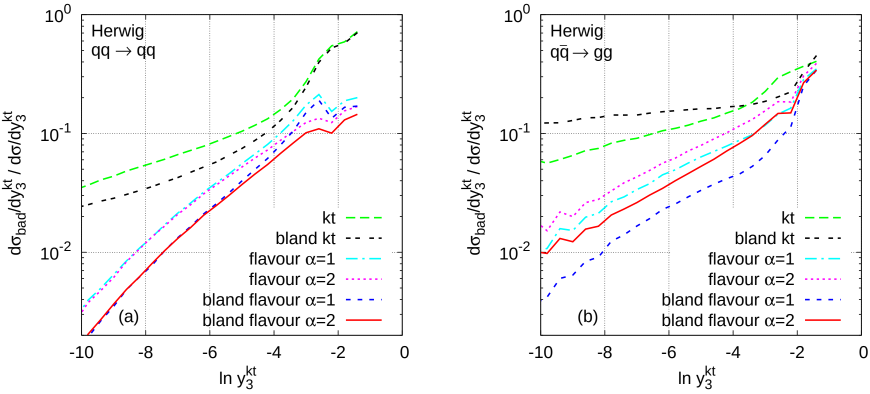


$$k_{tB} = \sum_i k_{ti}(\Theta(\eta_i - \eta) + \Theta(\eta - \eta_i) e^{\eta_i - \eta})$$

$$k_{t\bar{B}} = \sum_i k_{ti}(\Theta(\eta - \eta_i) + \Theta(\eta_i - \eta) e^{\eta - \eta_i})$$

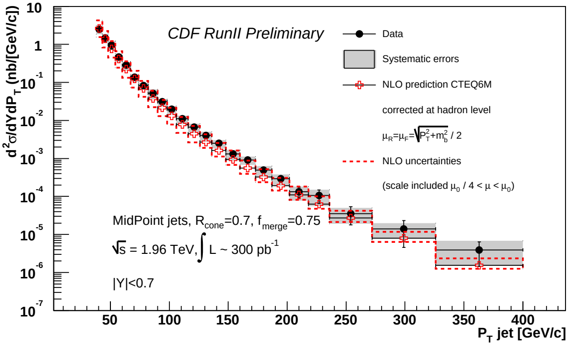
Tests of IR safety in hadron-hadron collisions

- IR safety tests impossible at fixed order at the moment
    - Missing flavour information in fixed order programs
    - Missing two-loop virtual correction to each subprocess
- Tests with HERWIG ⇒ Importance of flavour blandness



Heavy-flavour jets

- The algorithm has been designed to work at parton level
- At hadron level the algorithm can be used for heavy flavour jets
- Experimental definition of b-jet = jet containing b-flavour
- Comparisons to NLO of inclusive p_T spectra have large renormalisation scale uncertainties ($\sim 40 - 50\%$)



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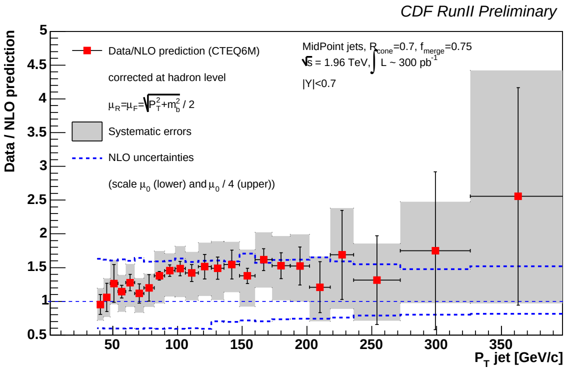
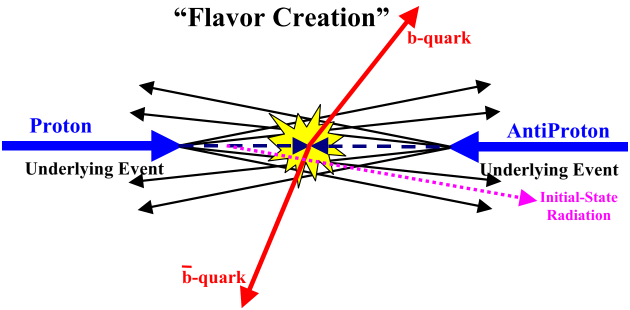


Flavour production mechanisms at hadron colliders

- Flavour creation $\alpha_s^2 + \alpha_s^3 \Rightarrow$ well described by NLO QCD
- Flavour excitation $\alpha_s^2 \times \alpha_s \ln E_T/m_b \Rightarrow \alpha_s^n \ln^n E_T/m_b$ in b pdf
- Gluon splitting $\alpha_s^2 \times \alpha_s \ln E_T/m_b \Rightarrow$ all order $\alpha_s^n \ln^{2n-1} E_T/m_b$



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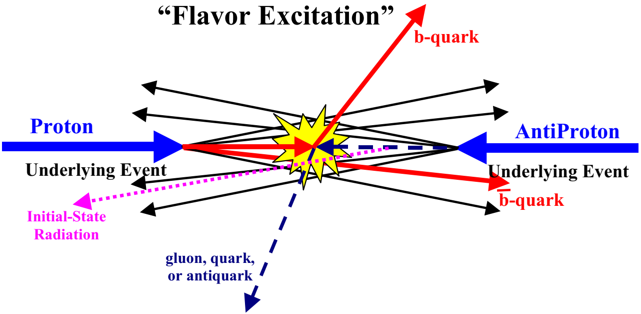

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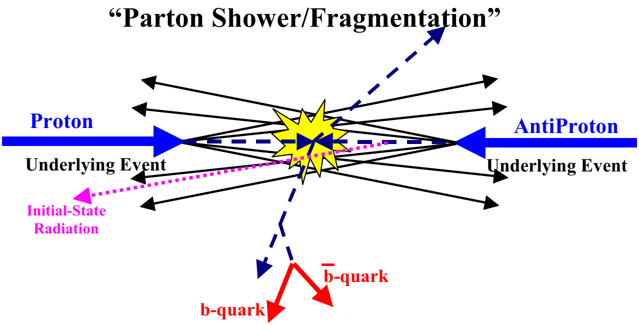
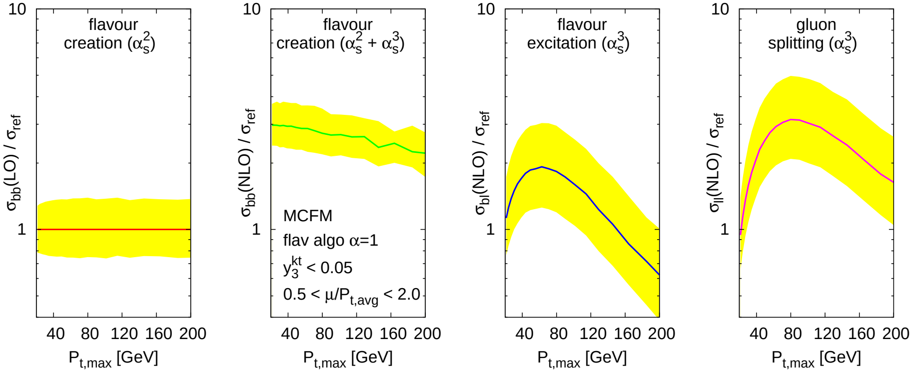


Theoretical uncertainties in NLO calculation

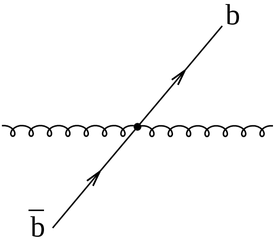
- Tevatron RunII $\sqrt{s} = 1.96$TeV
- Dijet events with $P_{t,\max} > 30$GeV and $|\eta_{\rm jet}| < 1$
- NLO predictions obtained with MCFM

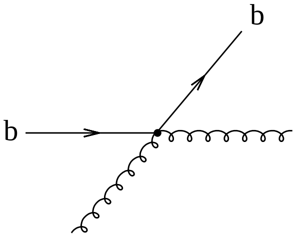


IR safe calculations of b-jet E_T spectra

- IR safe flavour algorithms $\Rightarrow$ no gluon splitting contributions
- Dijet cross sections calculable at NLO, eventually with MC@NLO
- Reduced theoretical uncertainties in inclusive jet cross sections
- IR safe cross sections calculable with NLO programs with massless partons (i.e. setting $m_b = 0$)
- New phenomenological studies feasible

[b parton densities, F_2^b, F_2^c, ...]





Summary

- We have a variant of k_t algorithm with IR safe determination of jet flavour
- Algorithm acts differently for quarks and gluons
  - designed for parton level
  - not practical at hadron level for light flavours (maybe JADE?)
- Matching of analytical resummations as soon as flavour info in fixed order programs will become available

  [Nagy, work in progress]
- Applications at hadron level for heavy flavour studies are under investigation . . .