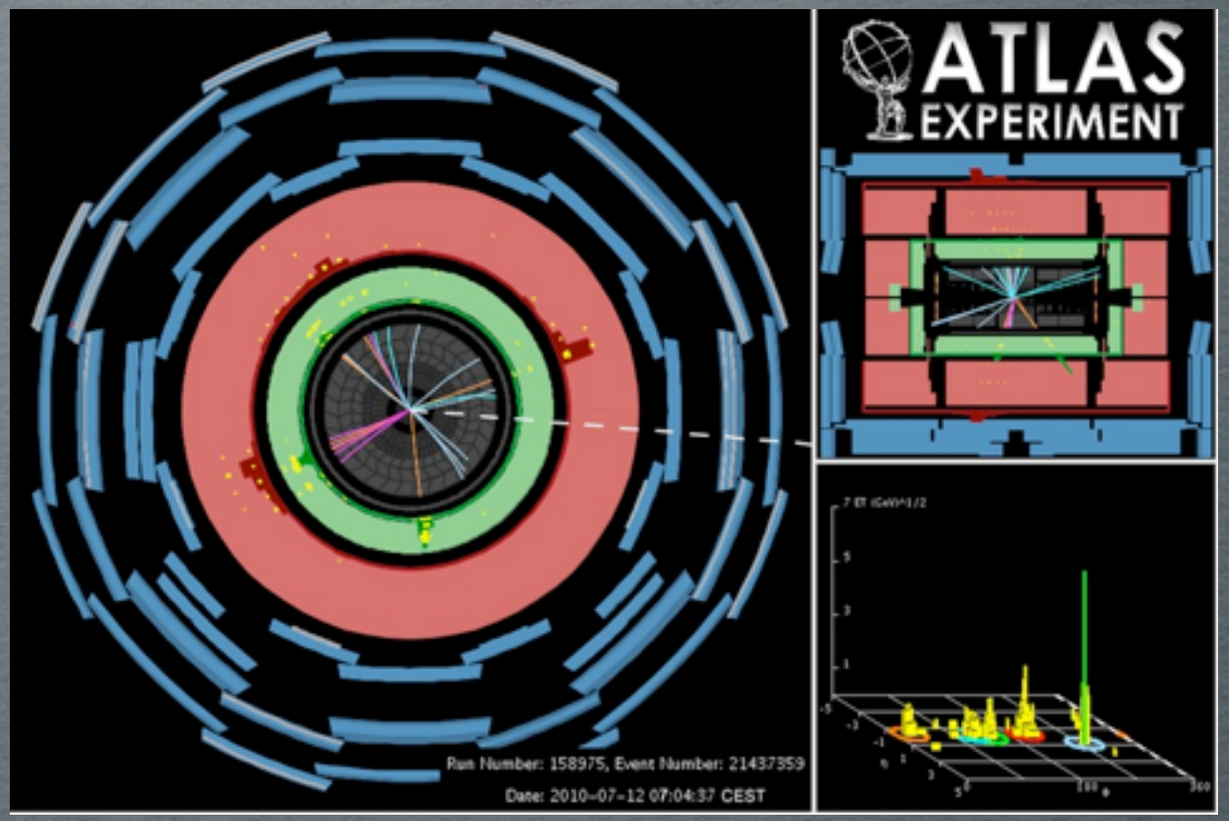
Flavored jets



Andrea Banfi
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in collaboration with
Gavin Salam and Giulia Zanderighi

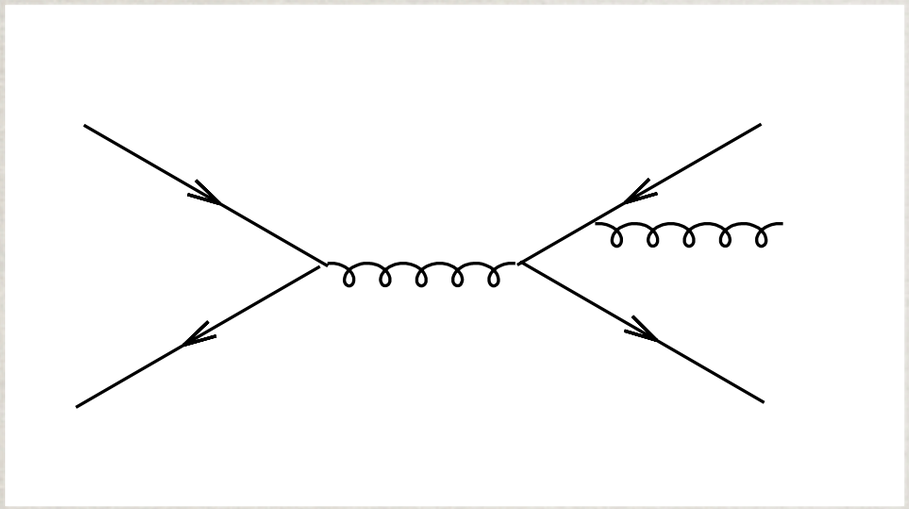
Outline

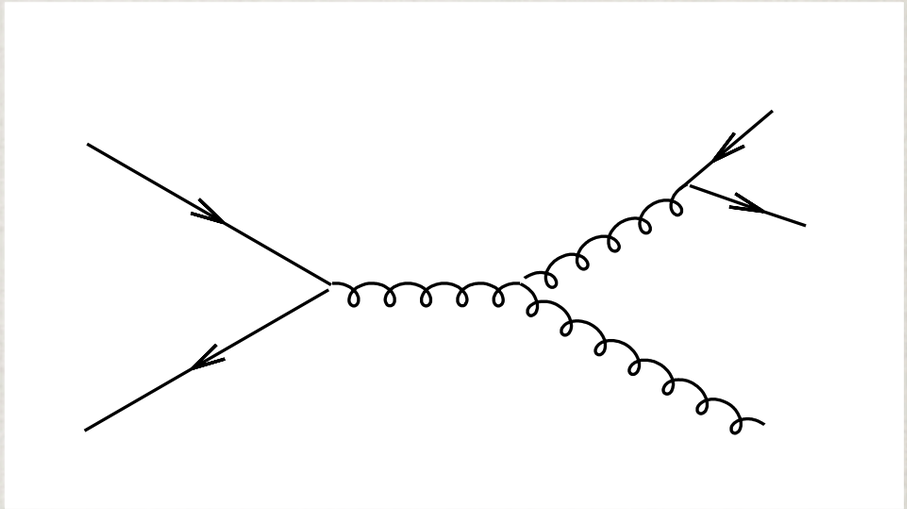
- IR safe definition of jet flavor
  - Problems in reconstructing jet flavor
  - The k_t-flavor algorithm in e^+e^- and hadron collisions
  - IR safety tests at parton level
  - Extension of k_t-flavor at hadron level

- Application of k_t-flavor to heavy quark production
  - IR safe separation of heavy quark production channels
  - Accurate determination of b-jet and c-jet p_t spectra
  - Discussion on experimental feasibility

Jet flavor beyond LO

- Problem: map the flavor of the final state $\rightarrow$ tree-level flavor





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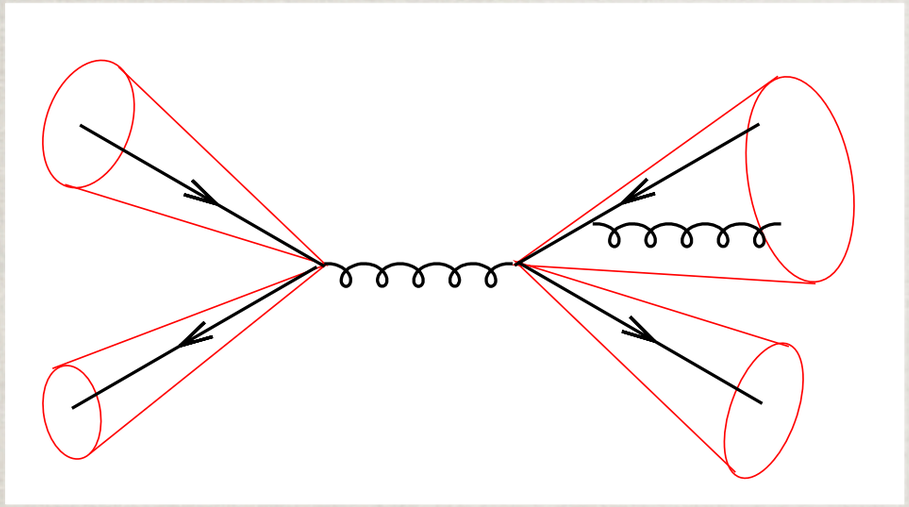

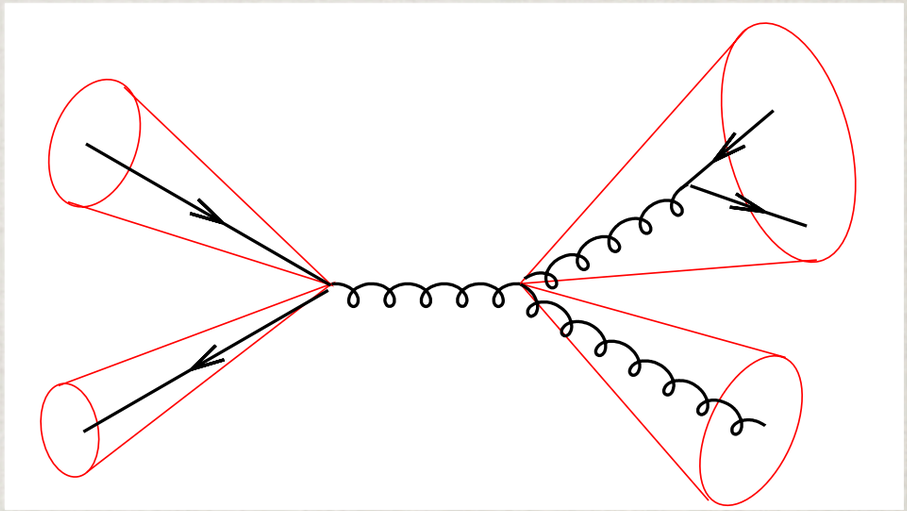

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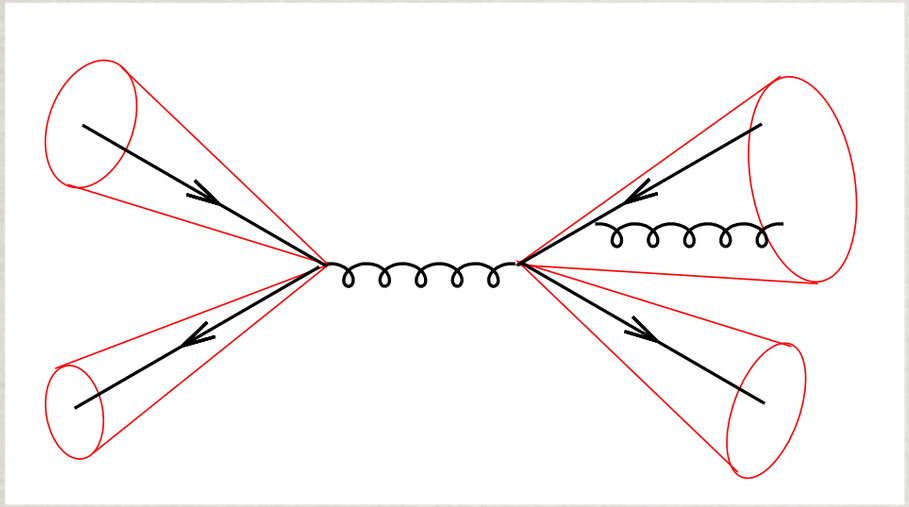

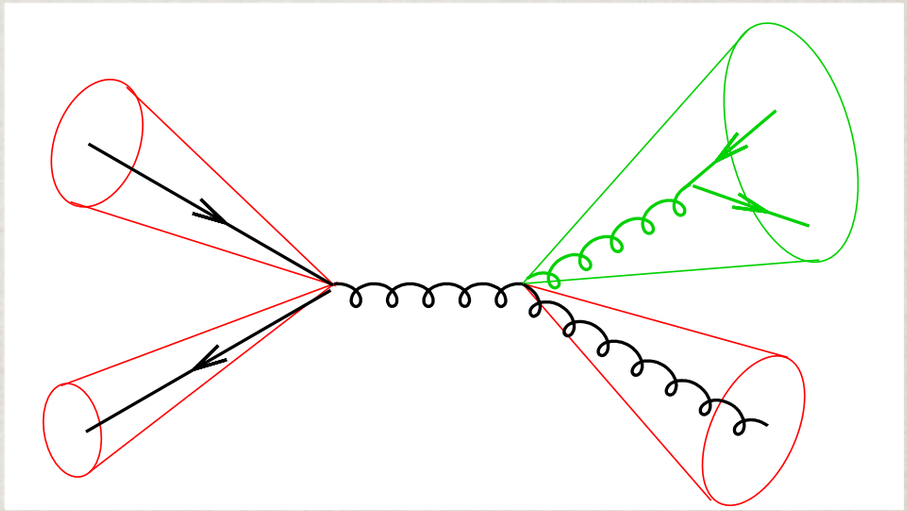

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$$u = (0, 1, 0, 0, 0, 0) \qquad \bar{u} = (0, -1, 0, 0, 0, 0) \qquad u, \bar{u} \in \text{jet}$$

Jet flavor beyond LO

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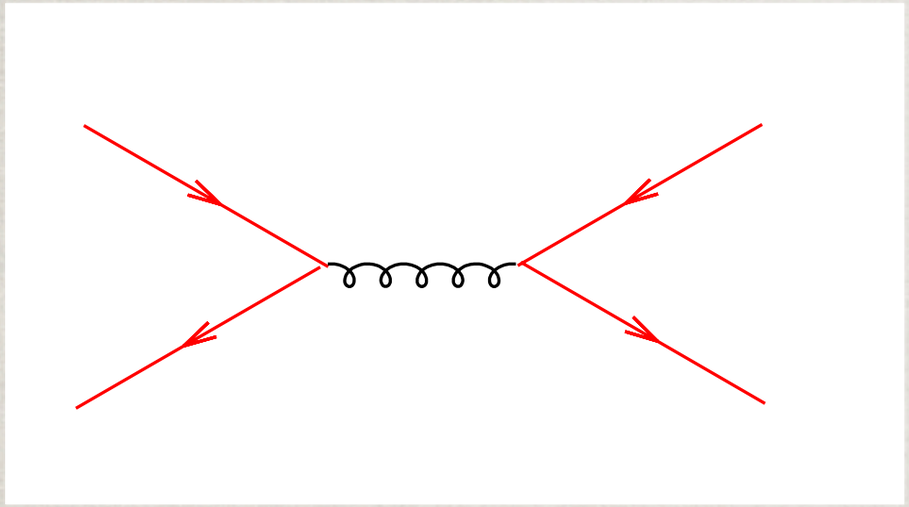

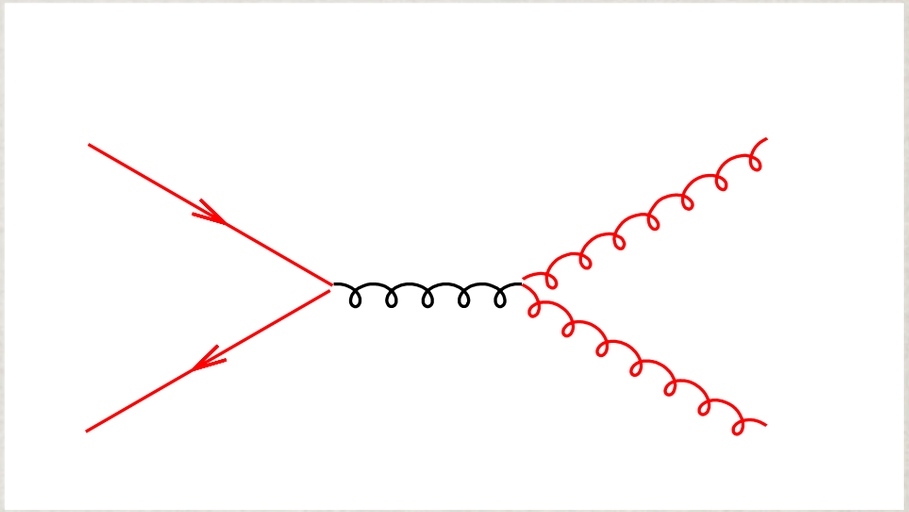

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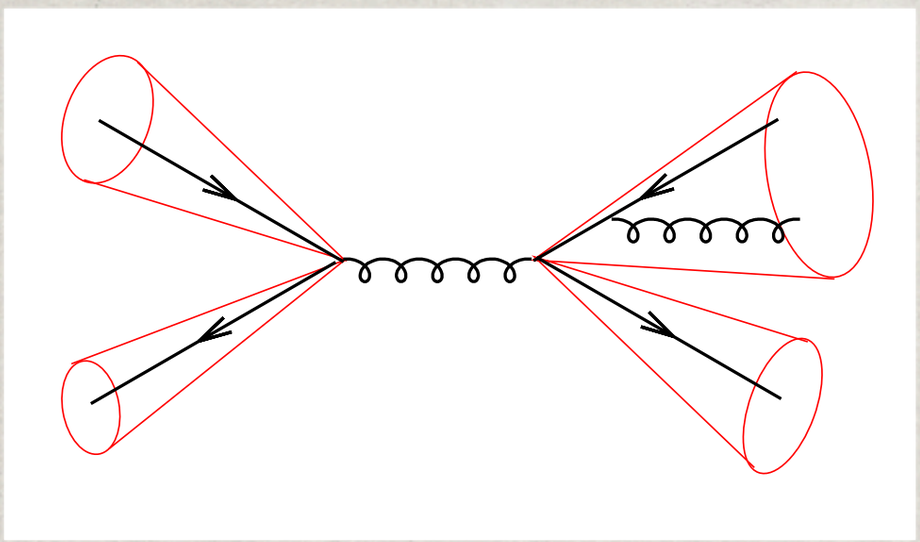
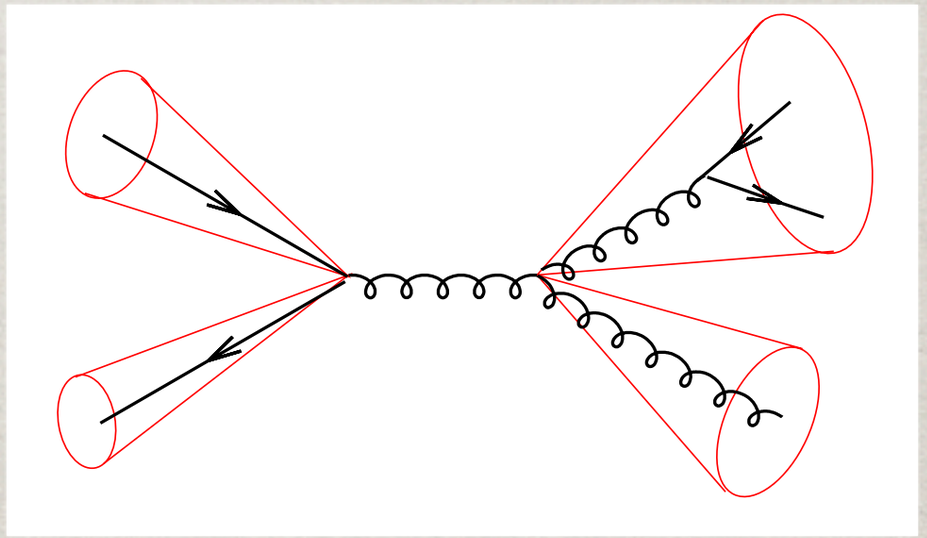
$$f_{\text{jet}} = u + \bar{u} = (0, 0, 0, 0, 0, 0) = g$$

Jet flavor at NLO

- Consider first only final-state jets
- At NLO, any IR safe jet algorithm is also an IR safe flavor algorithm
  - Soft/collinear gluons do not change the flavor of a jet
  - Collinear $q\bar{q}$ pairs are always recombined into the same jet



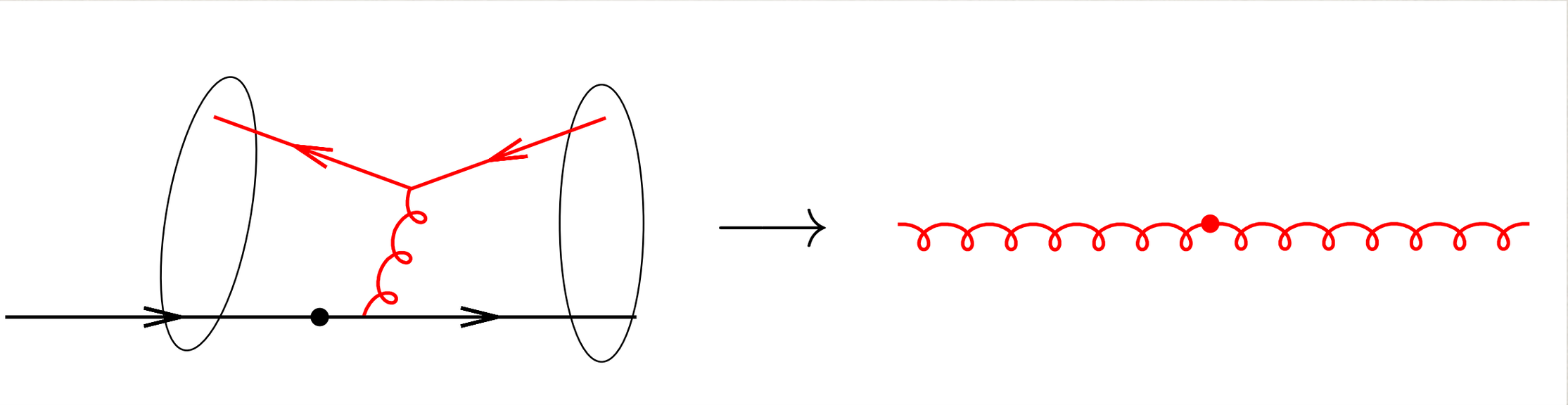


- The only problem left is to attribute a flavor to beam jets (see later)

Jet flavor beyond NLO

- Beyond NLO, soft large angle $q\bar{q}$ pair can be clustered into different jets, thus spoiling the reconstruction of jet flavor

- Example in e^+e^- : start from $e^+e^- \to q\bar{q}$ and after recombination of jet flavor end up with $e^+e^- \to gg$

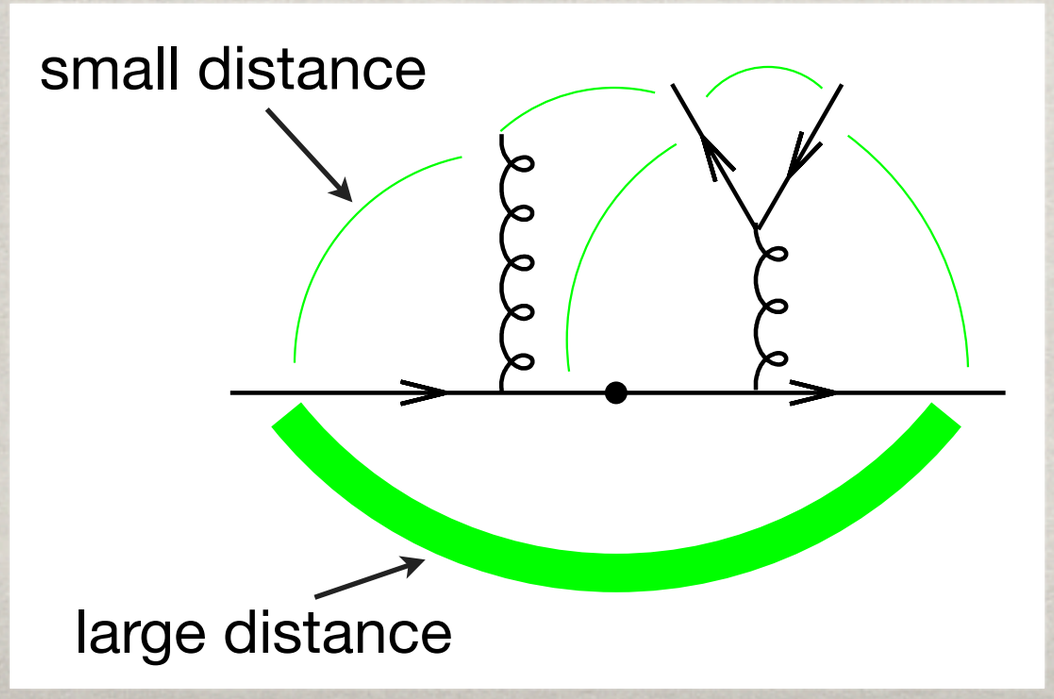


- The flavor of a jet is IR safe $\Leftrightarrow$ soft quarks and hard quark jets are never recombined

Flavor of final state jets

- Problem with the k_t-algorithm: distance is tailored to the splitting $q \to qg$, which has both collinear and soft singularities

$$dP_{q\to q_i g_j} \sim \frac{dE_j}{\min(E_i, E_j)} \frac{d\theta_{ij}^2}{\theta_{ij}^2} \qquad d_{ij} = 2(1-\cos\theta_{ij}) \times \min(E_i^2, E_j^2)$$



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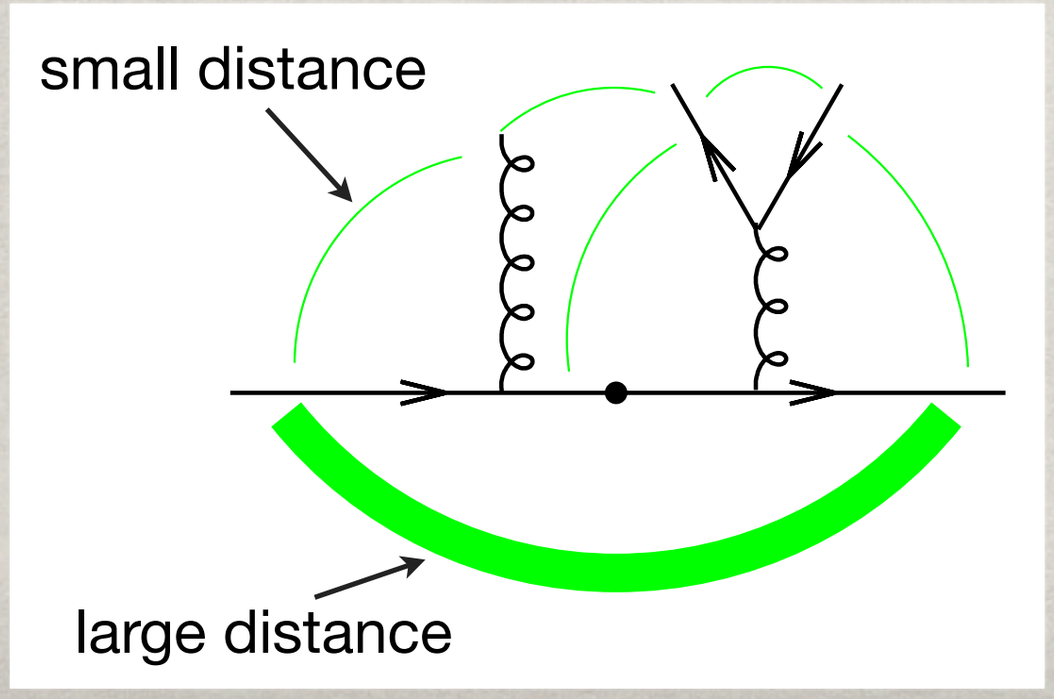
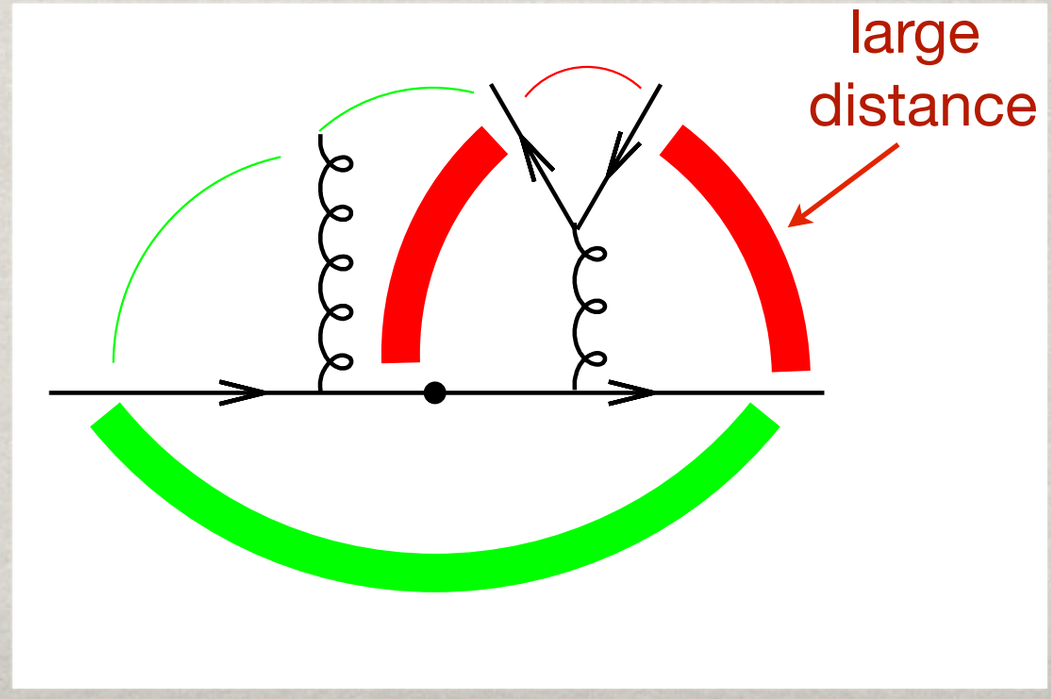
- The splitting $g \to q\bar{q}$ has no soft singularity $\Rightarrow$ modify d_{ij} when the softer parton is a quark

$$dP_{g\to q_i \bar{q}_j} \sim \frac{dE_j}{\max(E_i, E_j)} \frac{d\theta_{ij}^2}{\theta_{ij}^2} \qquad d_{ij} = 2(1-\cos\theta_{ij}) \times \max(E_i^2, E_j^2)$$



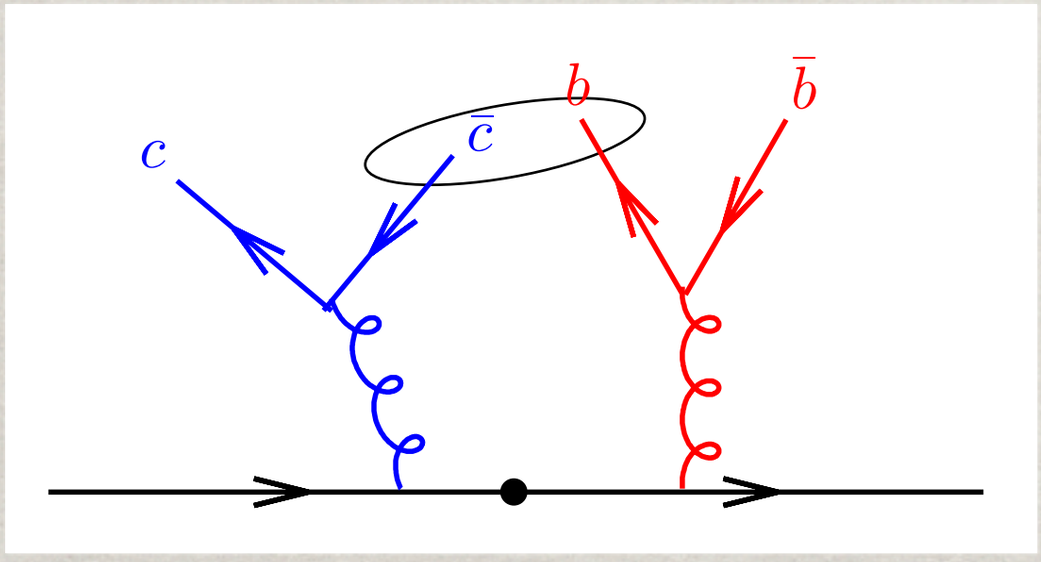


Kt-flavor algorithms in e+e-

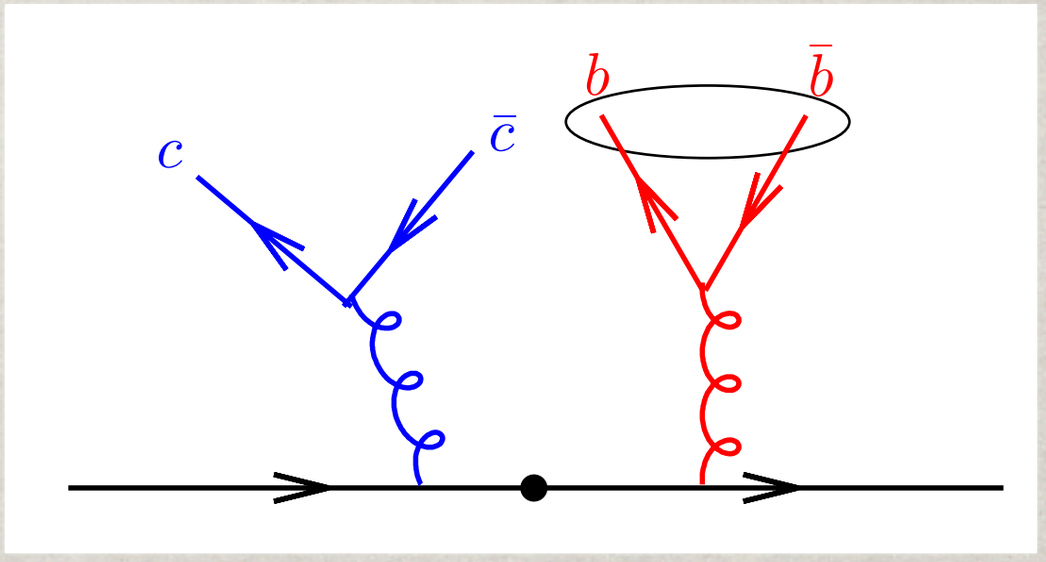
- Class of IR safe k_t-flavor algorithms ($0 < \alpha \leq 2$ is a parameter)

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

- Optional: allow only flavor bland recombinations $\Leftrightarrow$ strictly forbid recombinations of $q\bar{q}$ pairs whose net flavor is non-zero



flavor non-bland recombination

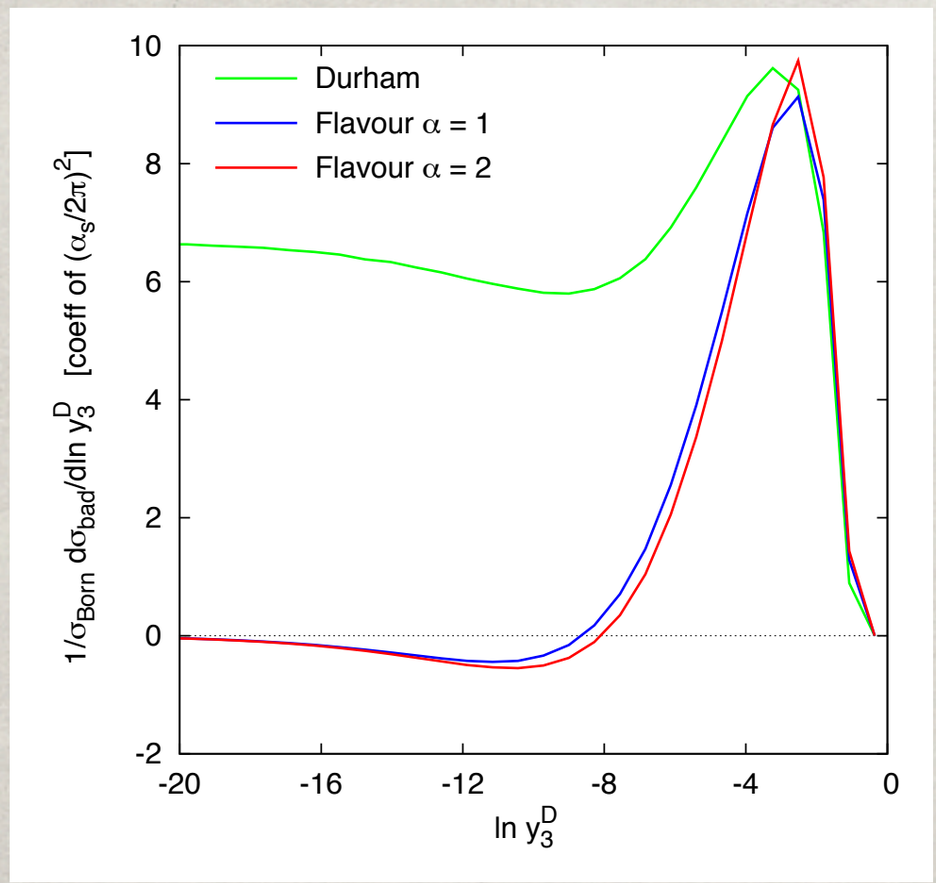


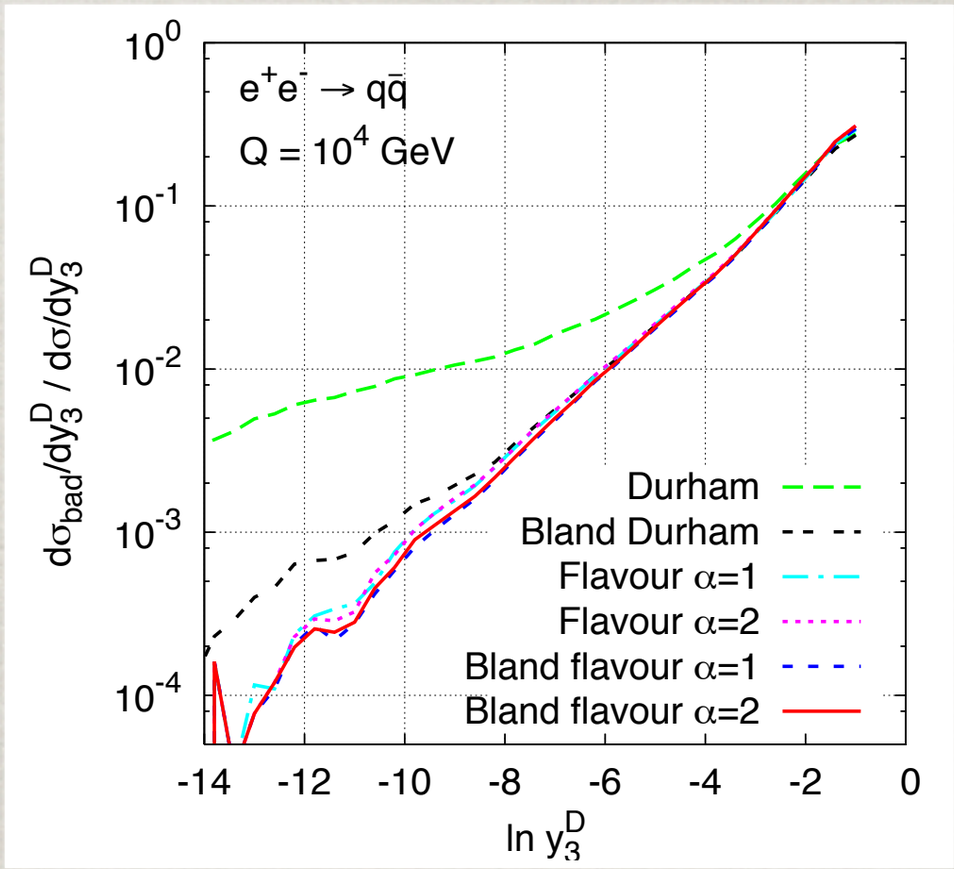
flavor bland recombination

[AB Salam Zanderighi '06]

Tests of IR safety in e+e-

- Generate multi-parton configurations in e^+e^- and cluster to 2 jets
- Compute fraction $\sigma_{\rm bad}(y_3)$ of misidentified events (e.g. $e^+e^- \to gg$)
- IR safety at NNLO (EVENT2) $\Leftrightarrow$ $\sigma_{\rm bad} \to 0$ for $y_3^D \to 0$
- IR safety at all orders (HERWIG) $\Leftrightarrow$ $\sigma_{\rm bad}$ scales differently for $y_3^D \to 0$



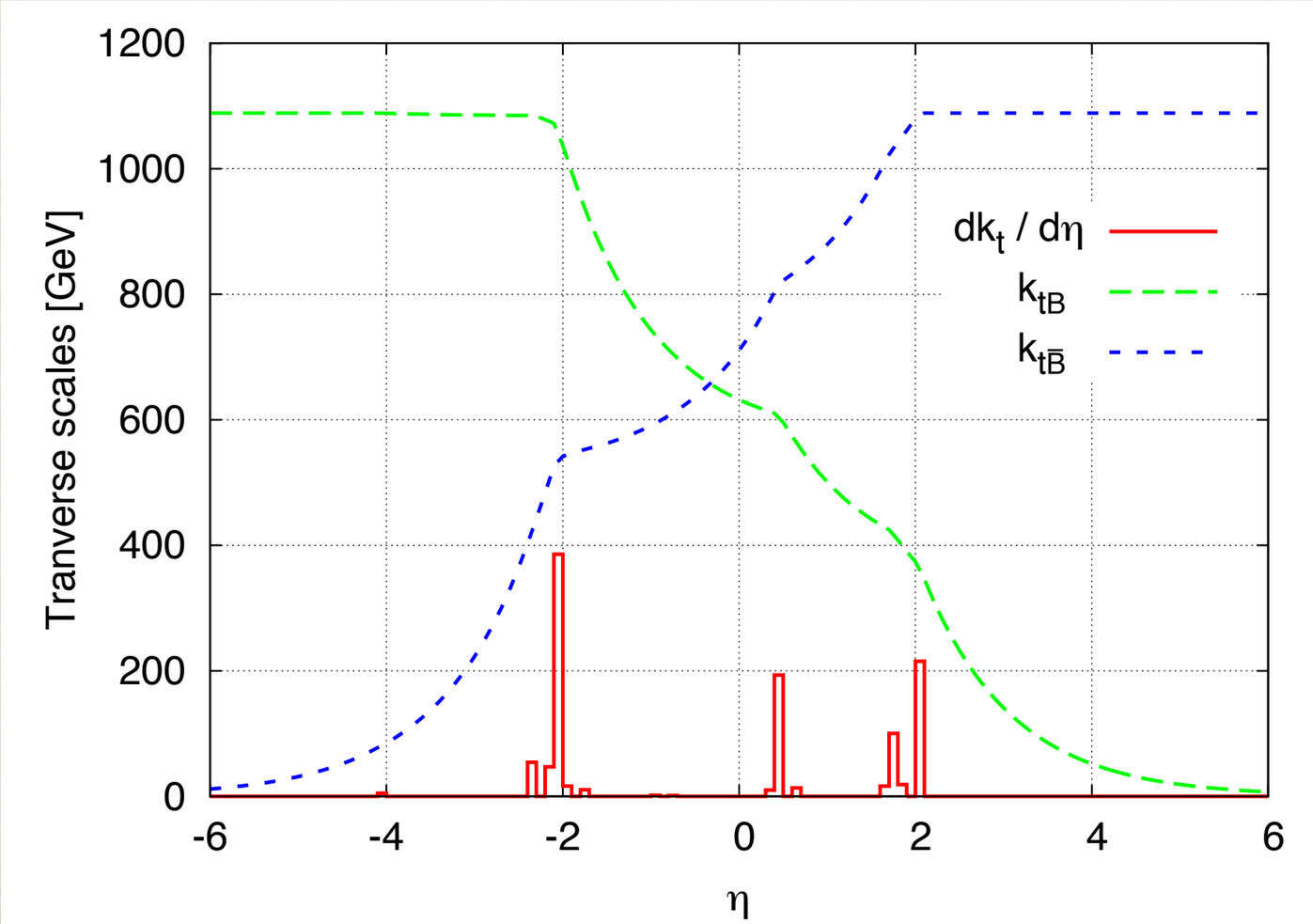


The "kt of the beam"

- Extension of the flavor-k_t algorithm to hadron collisions requires a boost invariant definition of the k_t of a beam

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

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



Kt-flavor algorithm in HH

- The distance between a pair of final-state partons is a boost-invariant extension of the definition for e^+e^- annihilation

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

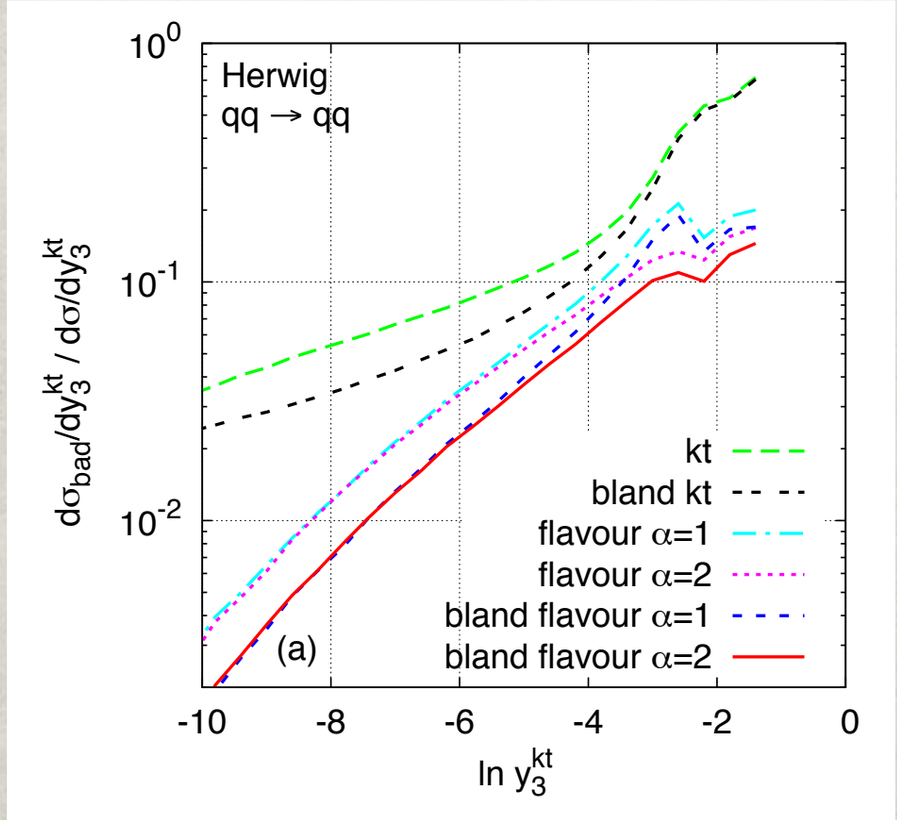
- Having introduced k_{tB} $(\eta \to \infty)$ and $k_{t\bar{B}}$ $(\eta \to -\infty)$ we can define a distance between a parton and each beam

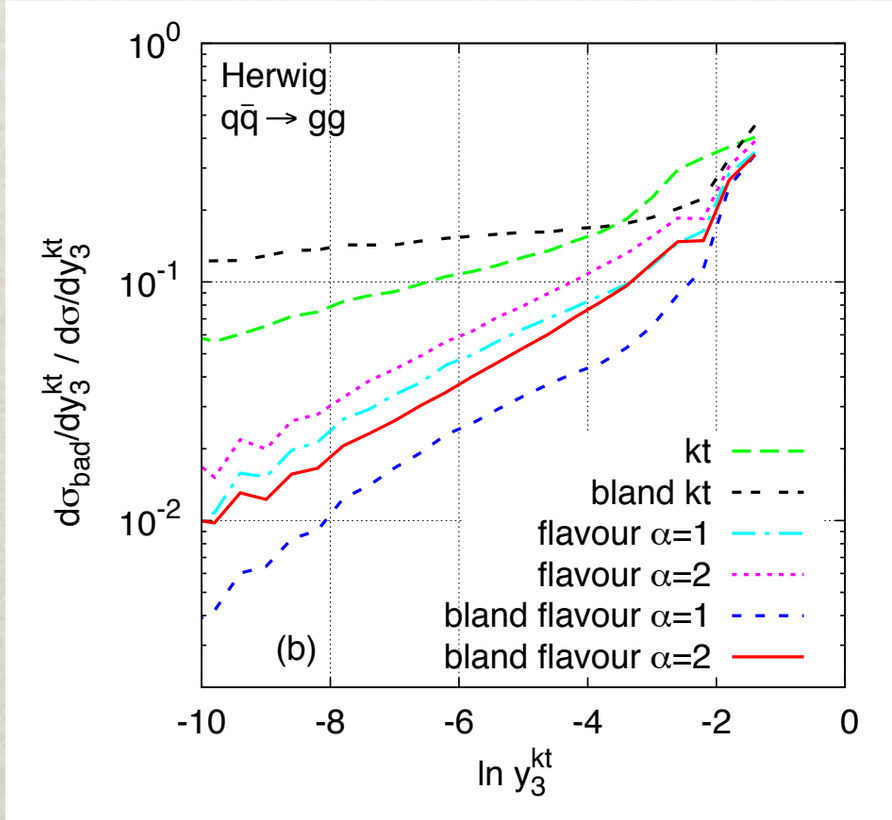
$$d_{iB}^{(F)} = \begin{cases} \min(k_{ti}, k_{tB})^2 & \text{i flavourless} \\ \max(k_{ti}, k_{tB})^\alpha \ \min(k_{ti}, k_{tB})^{2-\alpha} & \text{i flavoured} \end{cases}$$

- Note: from a flavor perspective, the anti-k_t is worse than k_t because distances with harder partons are smaller

Tests of IR safety in HH

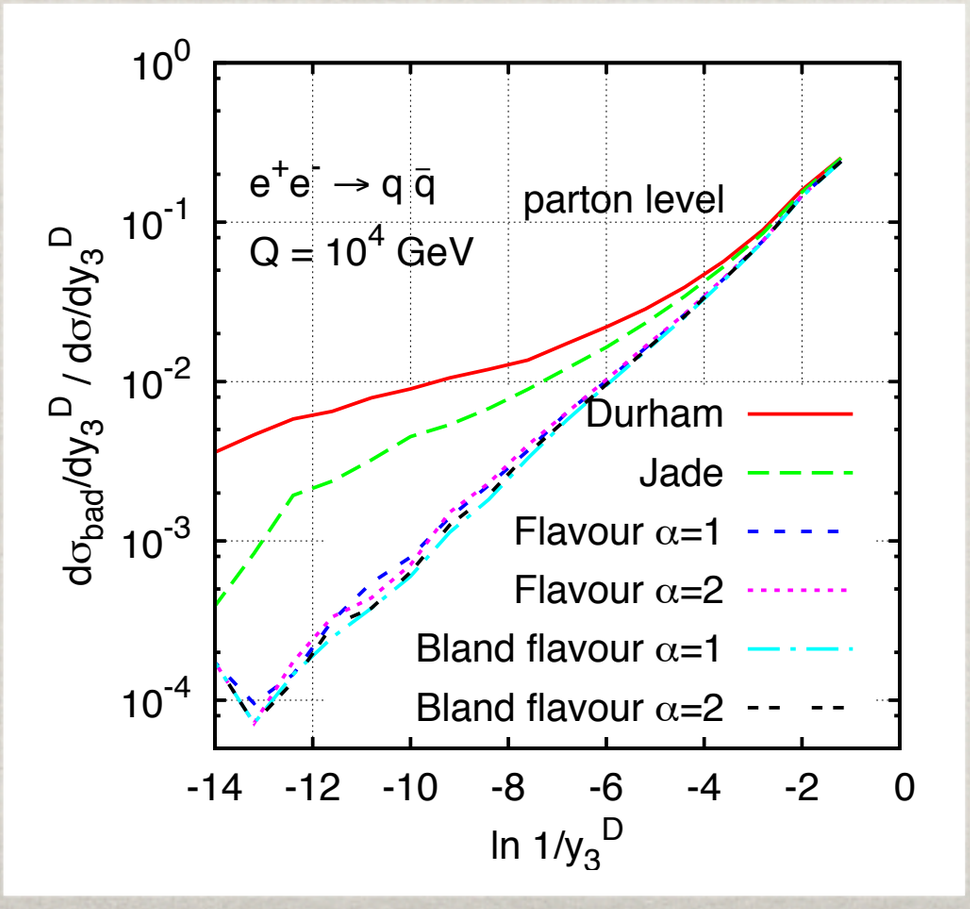
- The algorithm was never tested with fixed-order programs, no flavor information available that time
- Today testable using Z+1jet codes looking for misidentified $gg \to Z$, requires extension of k_{tB} and $k_{t\bar{B}}$ to events with non-QCD particles
- Tests with Monte Carlo event generators show the importance of the flavor blandness requirement for efficient flavor determination

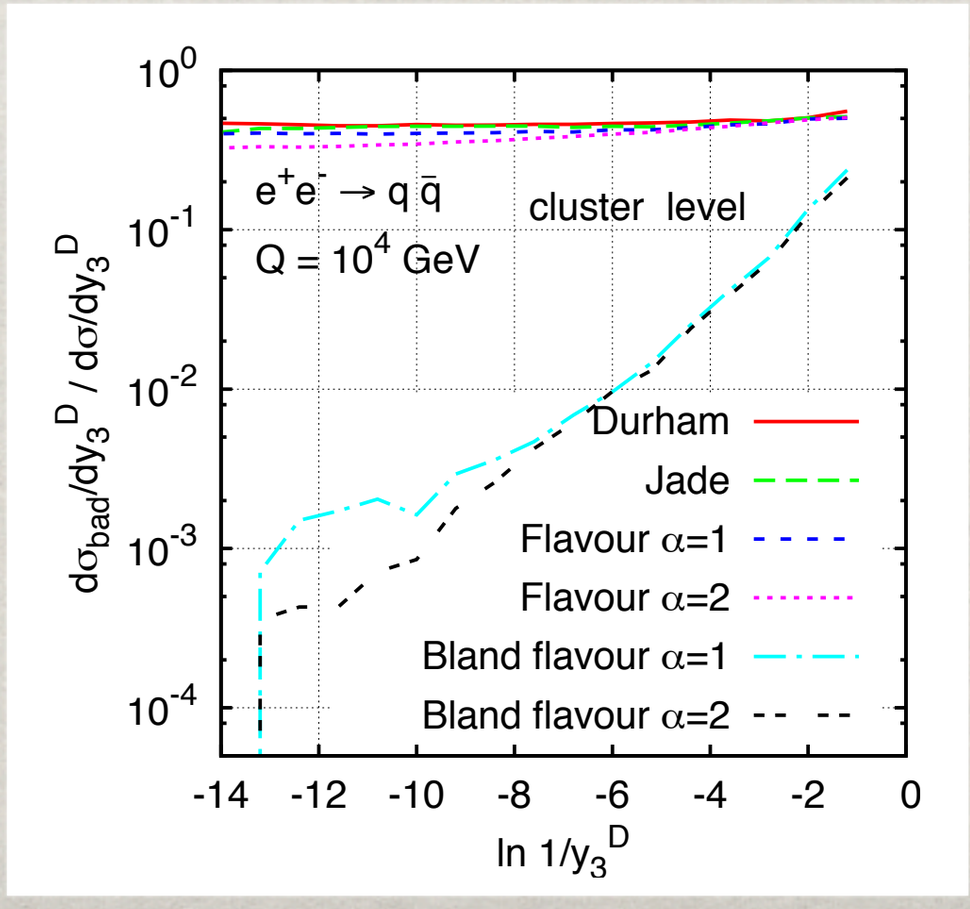




Jet flavor at hadron level

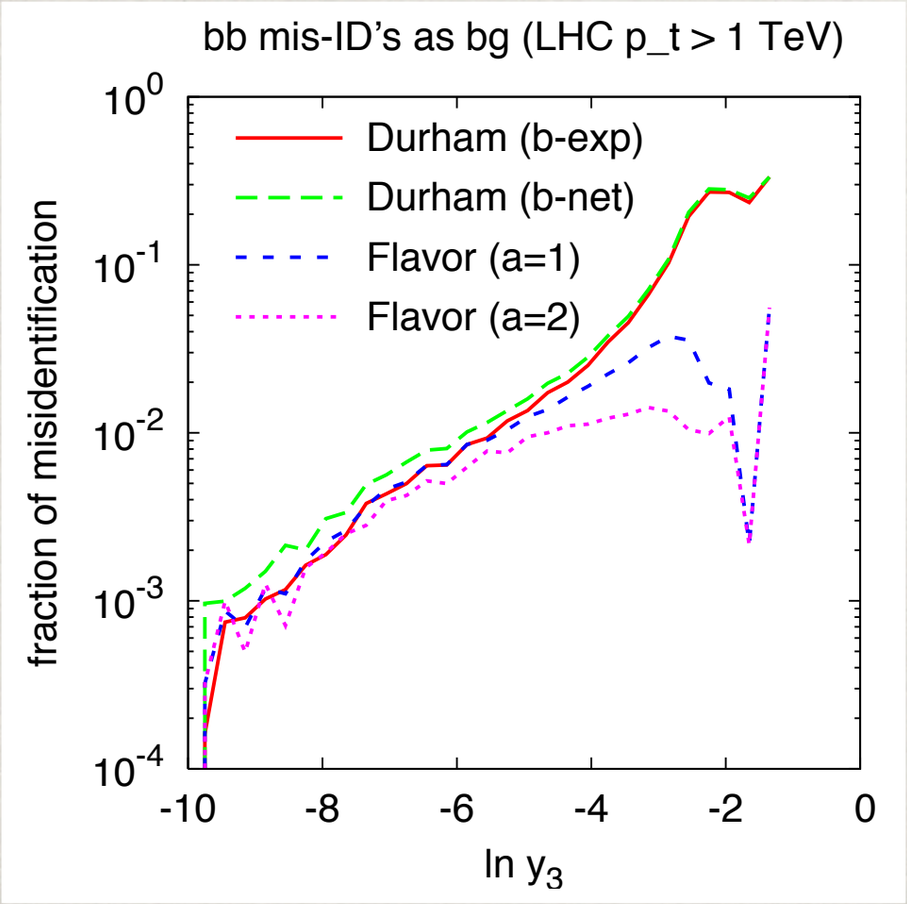
- The Monte Carlo tests for the k_t-flavor algorithm so far are at parton level only $\Rightarrow$ does the algorithm work at hadron level as well?
- At cluster level, when every gluon splits into a $q\bar{q}$ pair, all algorithms break down except those with flavor bland recombination
- More work is needed for a full hadron level algorithm (for instance, hadrons themselves are non-bland flavor combinations)

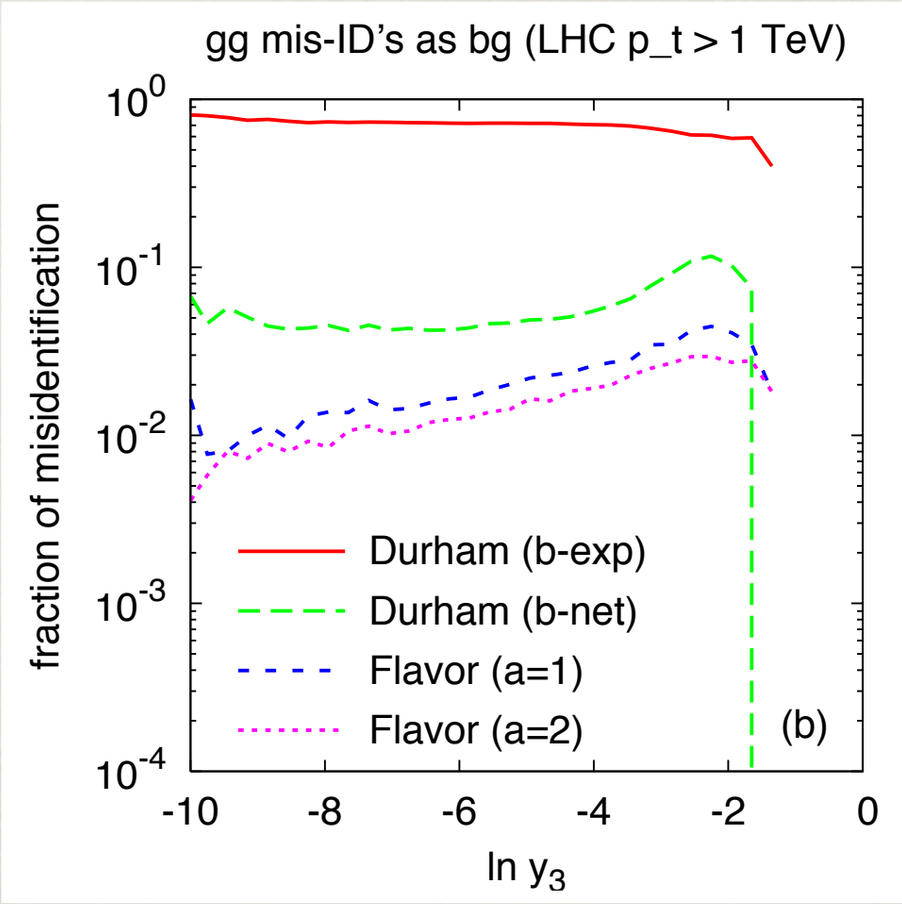




Heavy flavored jets

- A special case in which flavor algorithms can be successfully applied at hadron level is that of heavy flavored jets
- Strategy: only jets having a net b-flavor are treated as flavored, the others are considered gluon jets
- Experimental definition of b-jets (any jet with a b-tagging) is IR unsafe for $m_b \to 0$, mainly due to unresolved collinear splittings $g \to b\bar{b}$

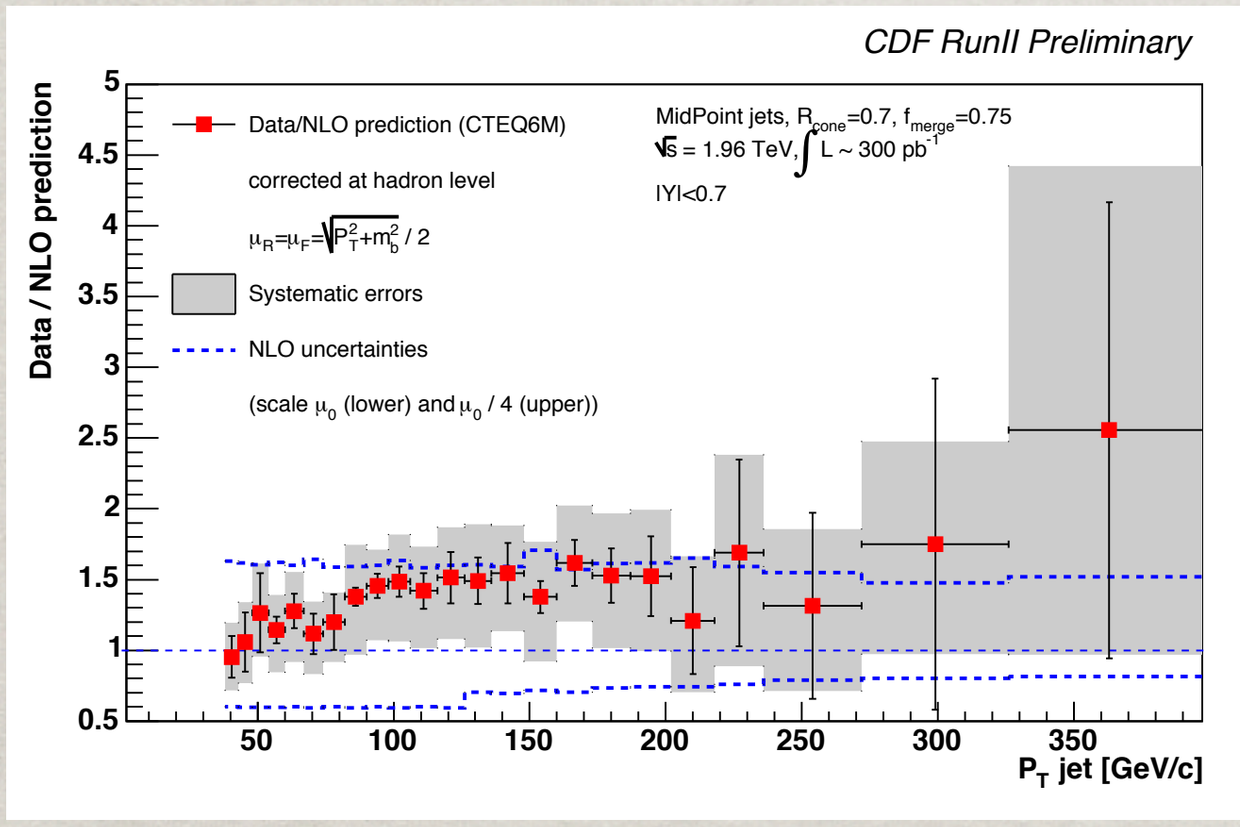


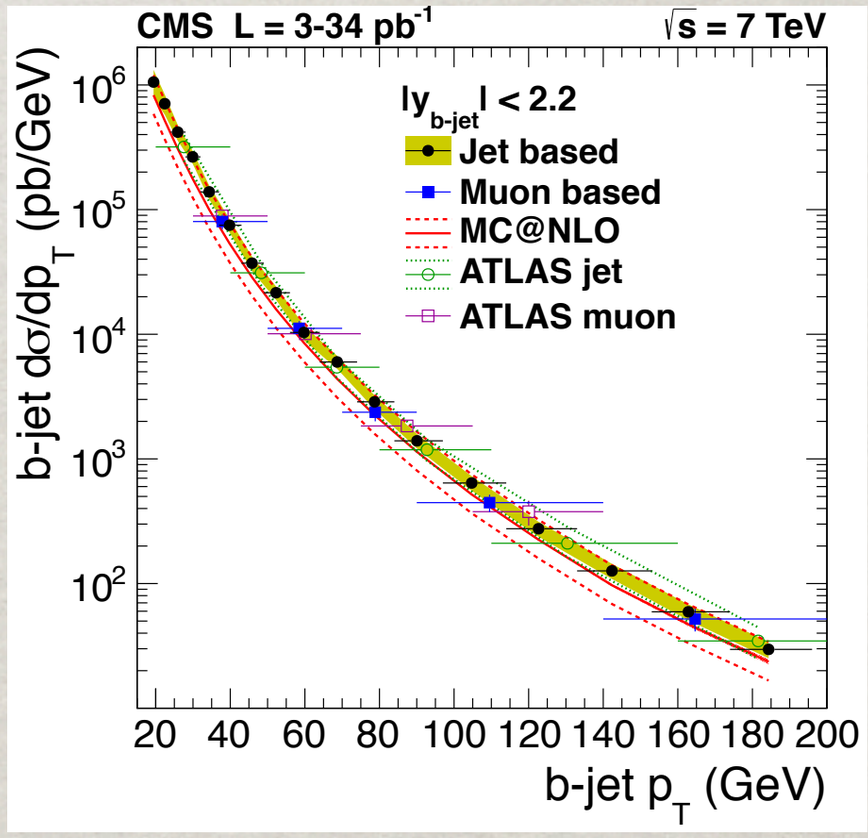


Comparison of NLO and experiment

- The IR unsafety of the current experimental definition of b-jets reflects into large uncertainties in NLO predictions

- NLO inclusive b-jet p_t-spectra have renormalisation scale uncertainties of order 40-50%, and poor comparison to data

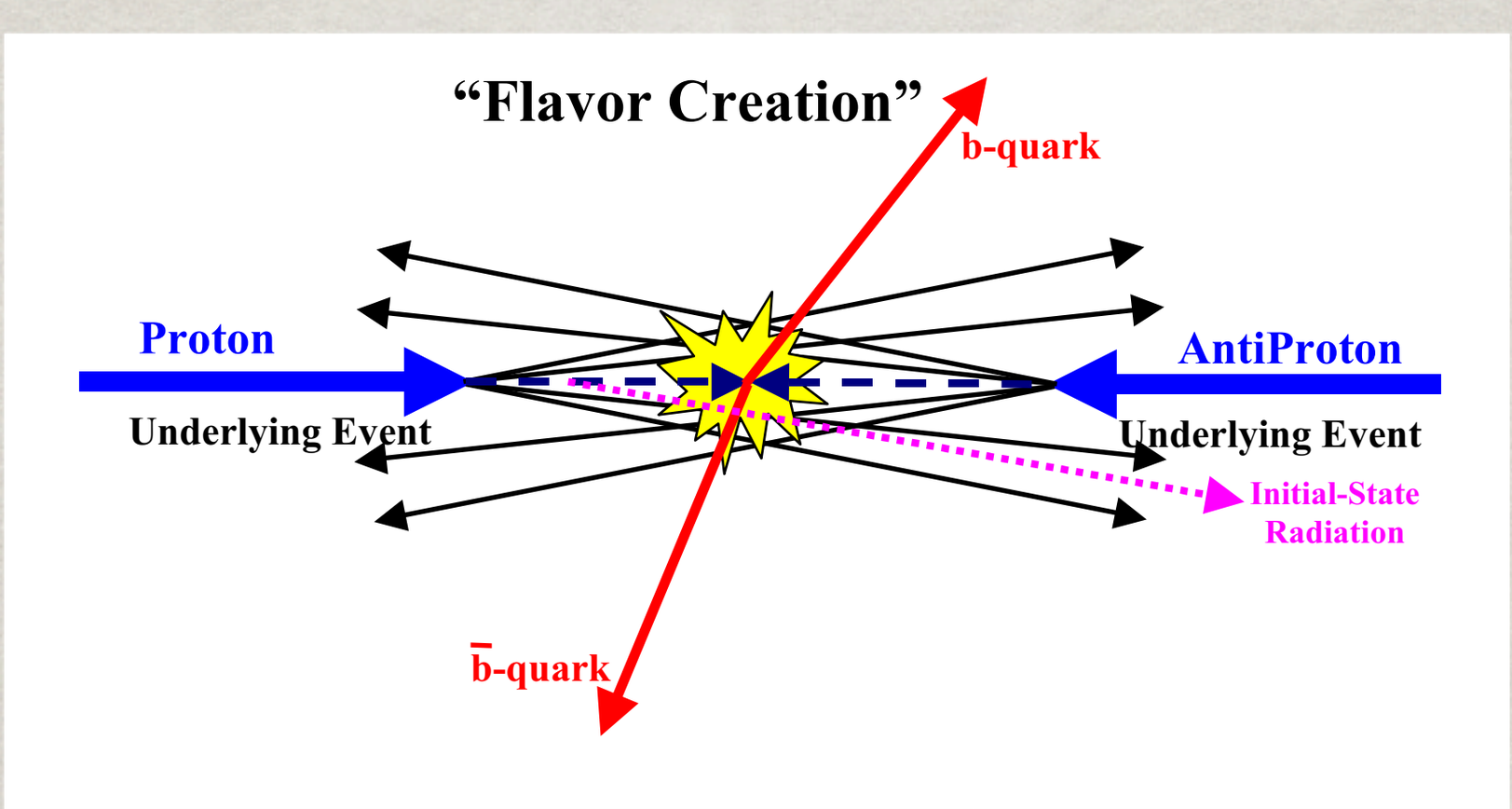




- Is it possible to exploit an IR safe flavor determination to reduce theoretical uncertainties in b-jet cross sections?

Flavor production mechanisms

- Flavor creation: $\alpha_s^2 + \alpha_s^3 \Rightarrow$ well described by NLO QCD



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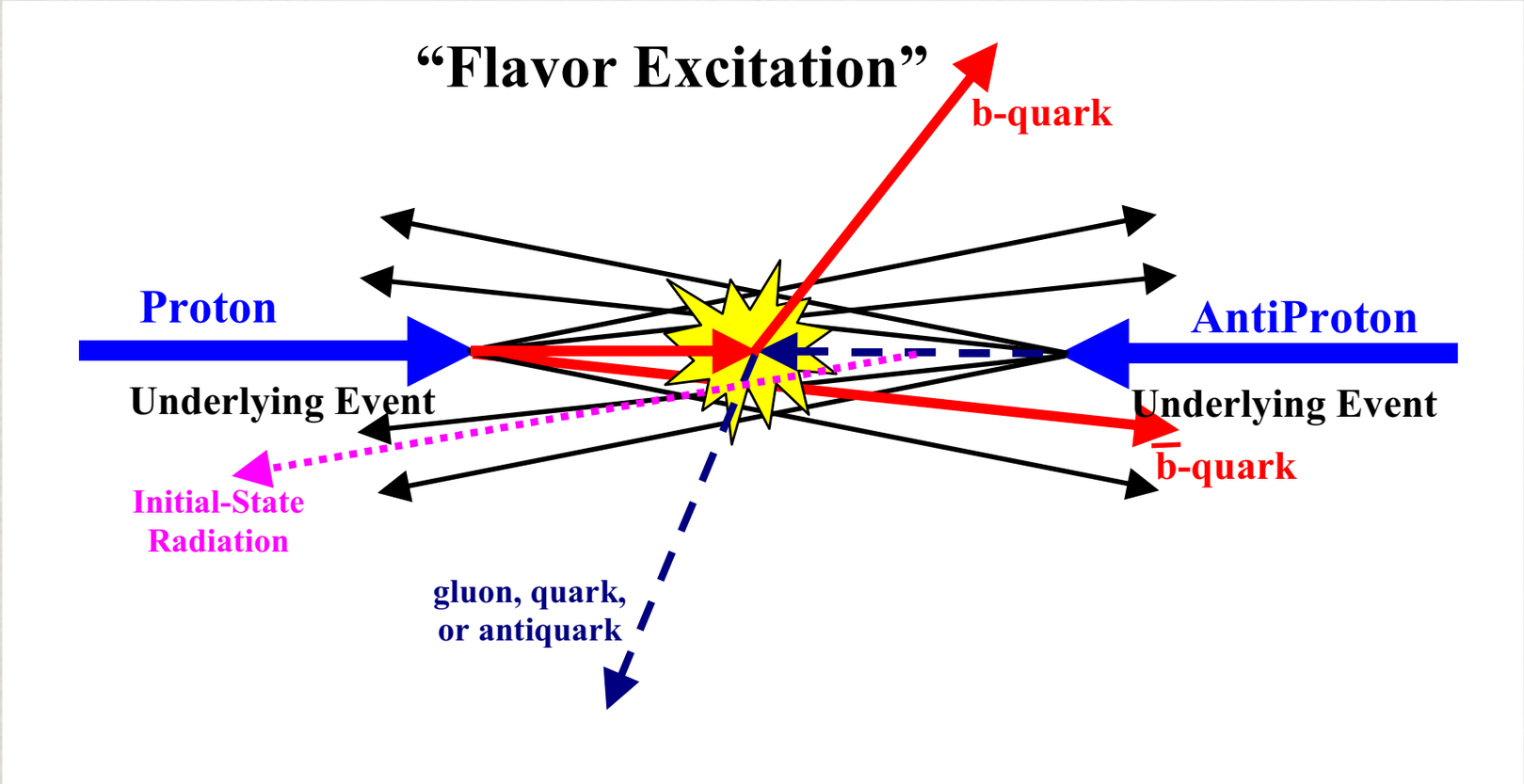

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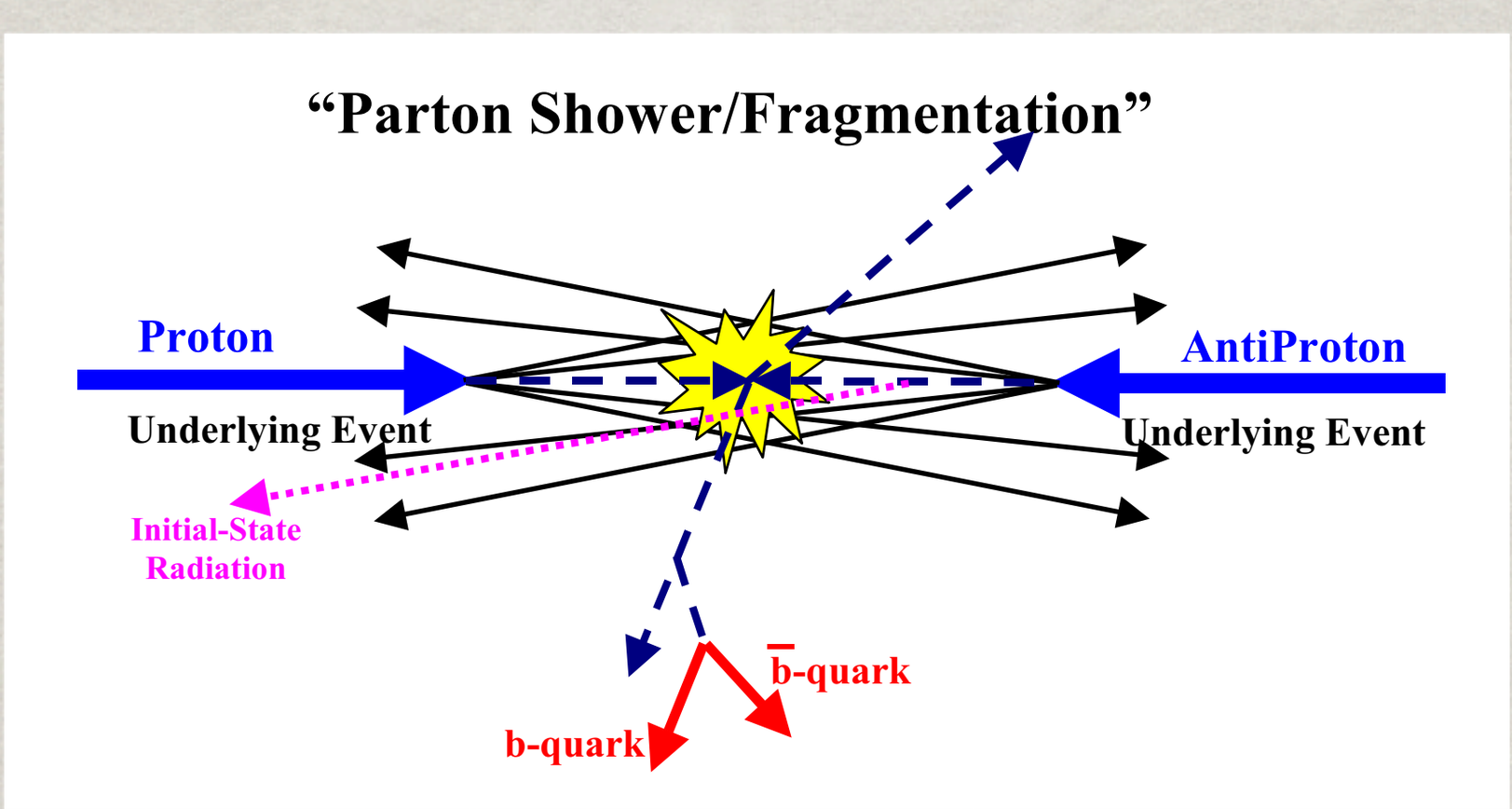
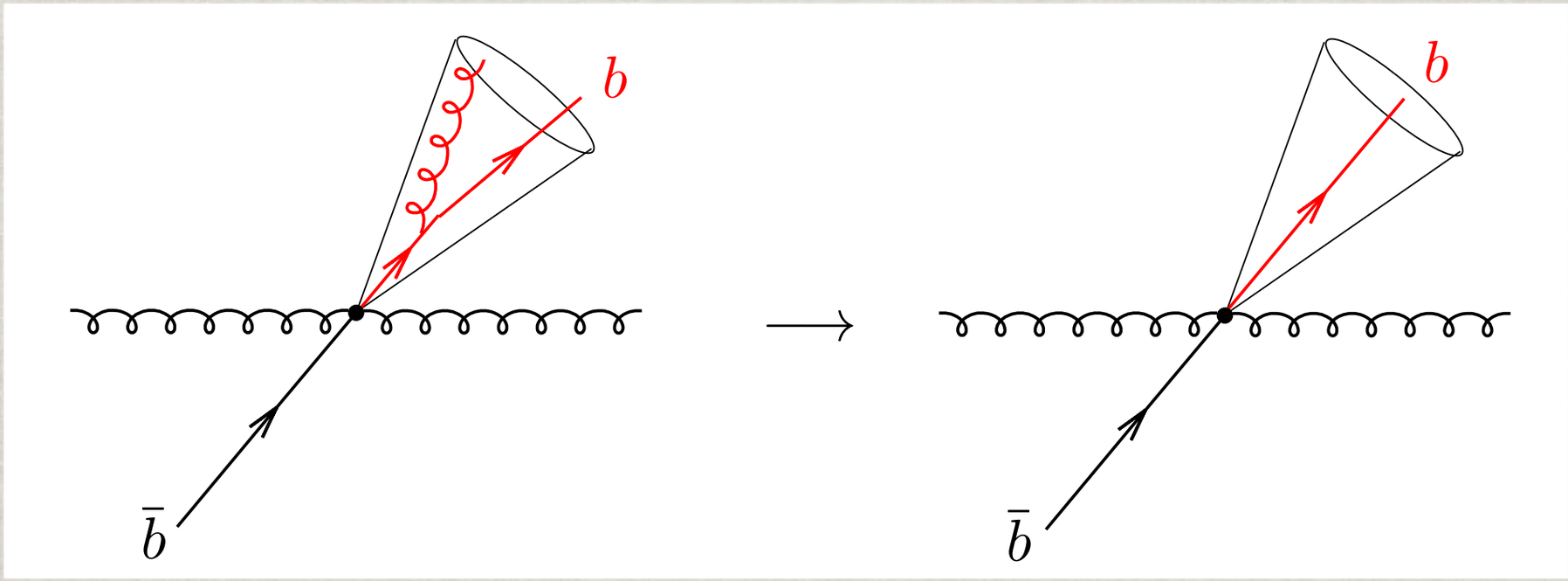
- Gluon splitting: $\alpha_s^2 \times \alpha_s \ln(p_t/m_b) \Rightarrow \alpha_s^n \ln^{2n-1}(p_t/m_b)$ soft and collinear logarithms, which need to be resummed at all orders

[Seymour '94]



Flavor-kt for b-jet pt spectra

- Separation of flavor channels can be exploited to reduce the uncertainty in fixed-order calculations [AB Salam Zanderighi '07]
  - Flavor creation: $q\bar{q} \to b\bar{b}$, $gg \to b\bar{b}$ or $b\bar{b} \to b\bar{b}$ can be computed with massive or massless b-quarks



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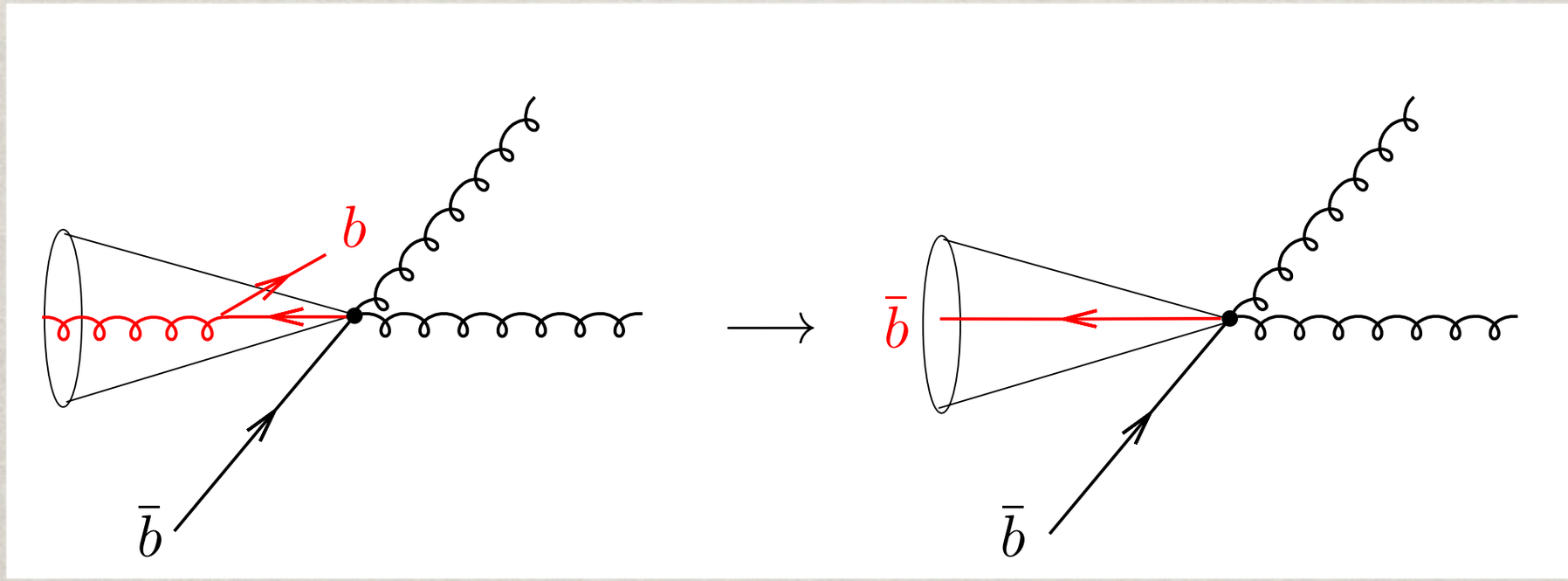

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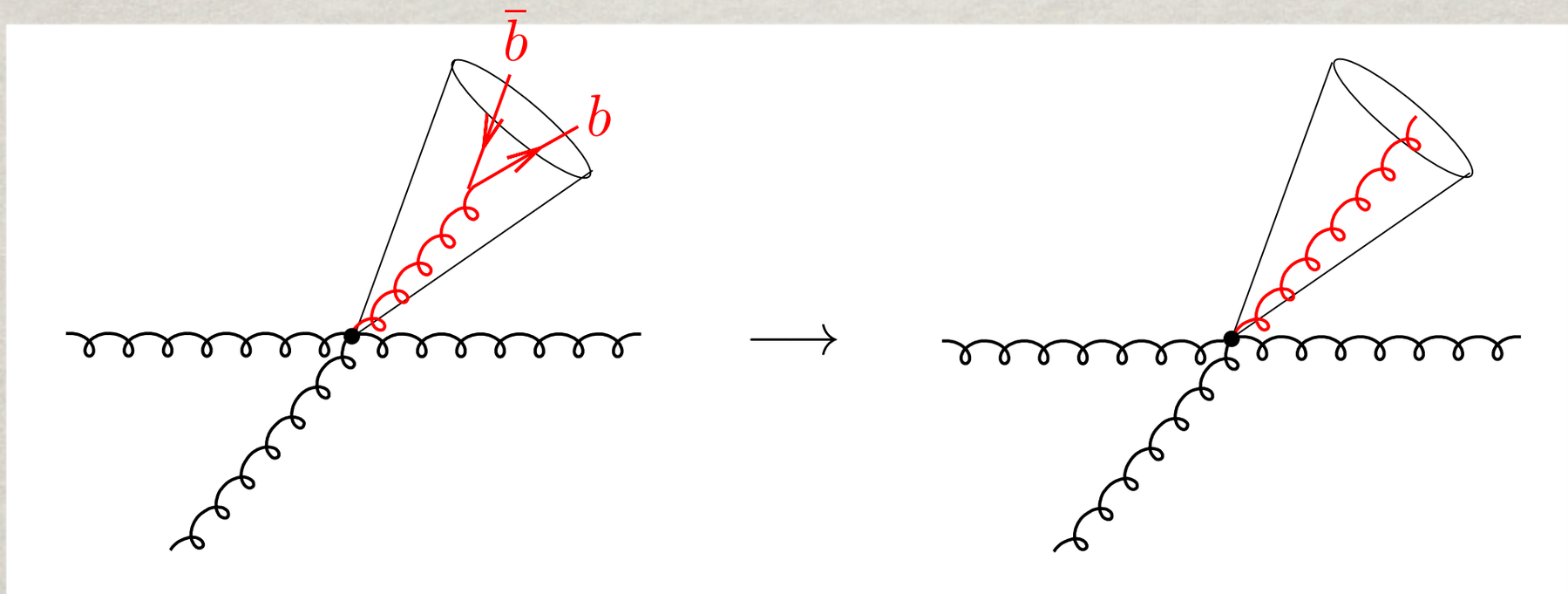

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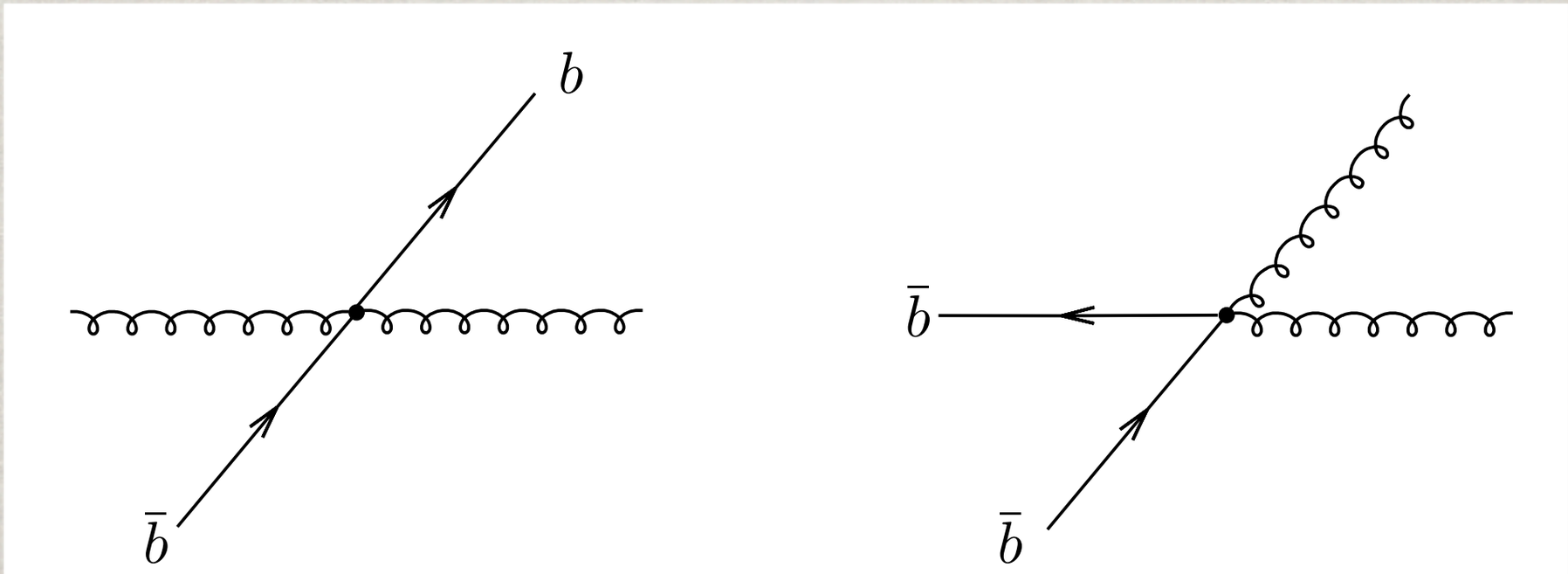
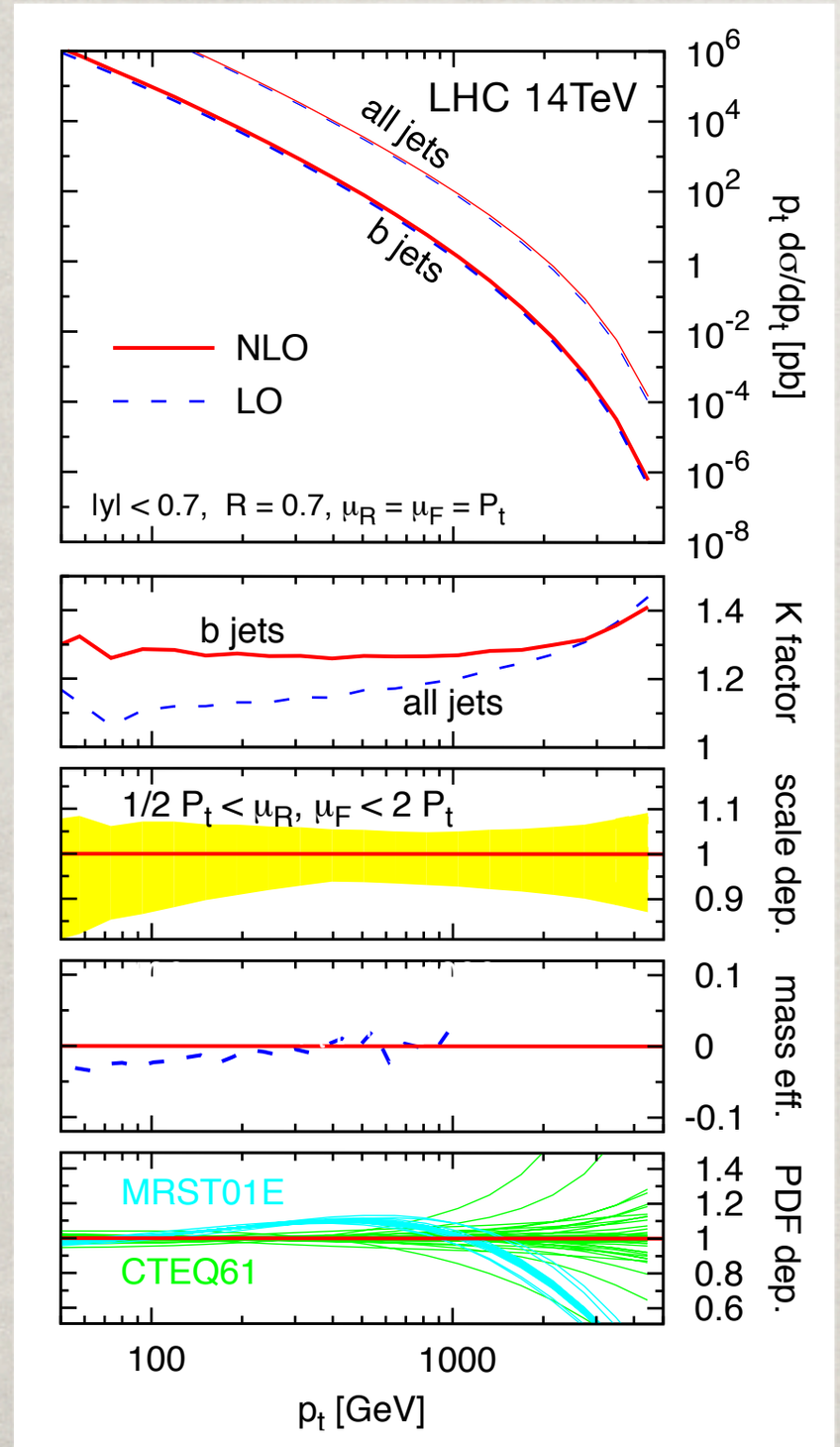
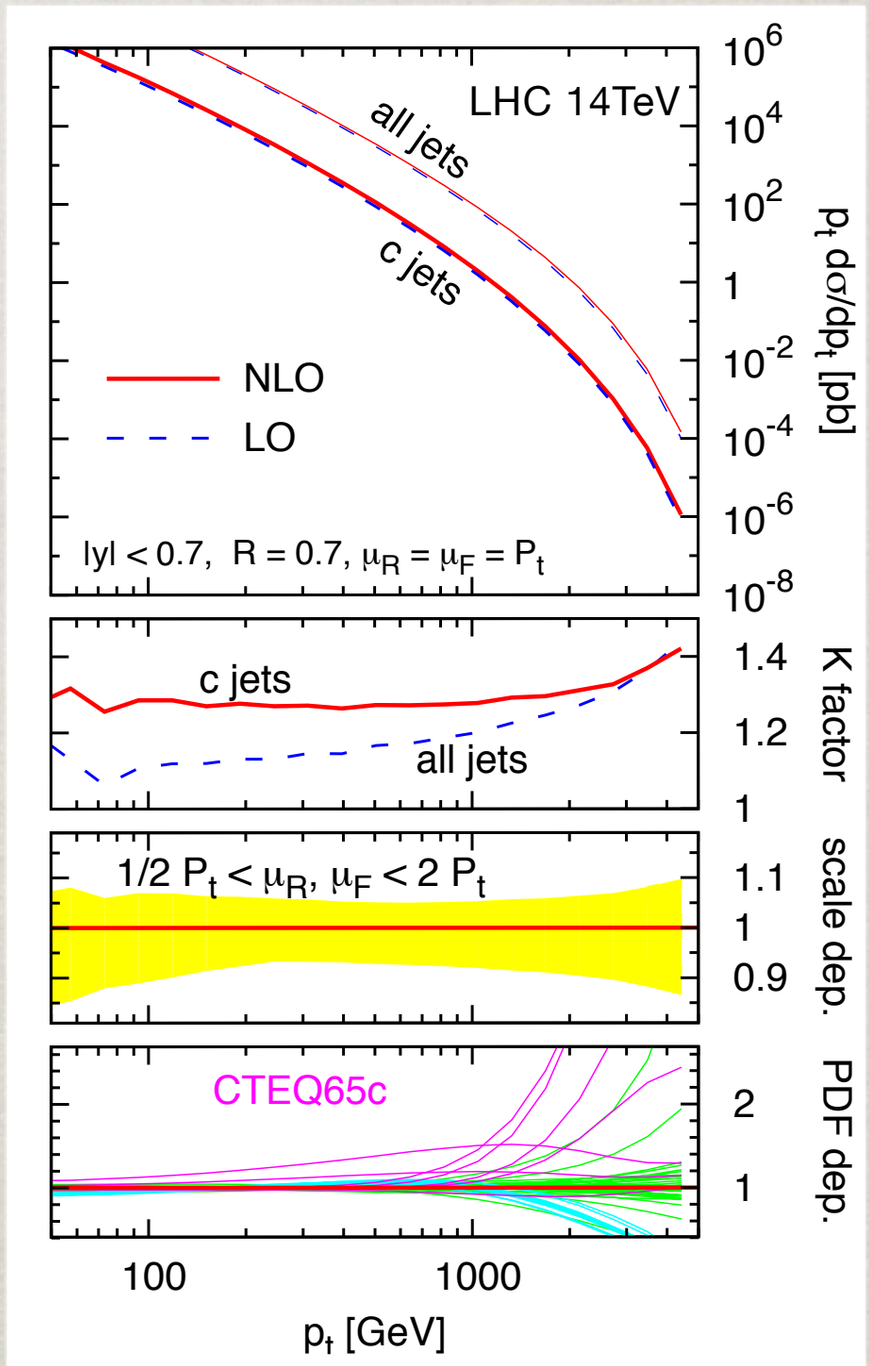


- True NLO calculations can be performed with massless b-quarks

Heavy flavored jets at the LHC

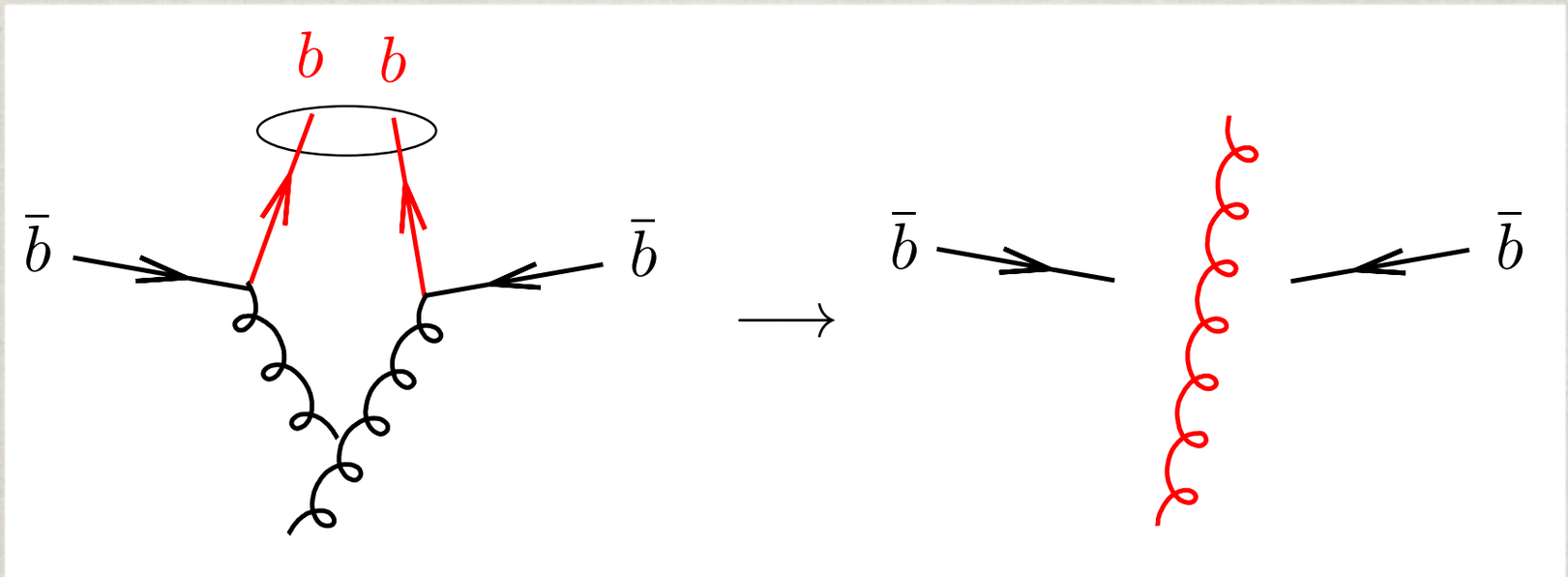
- Large pdf uncertainties at high p_t: constrain heavy flavor pdfs?





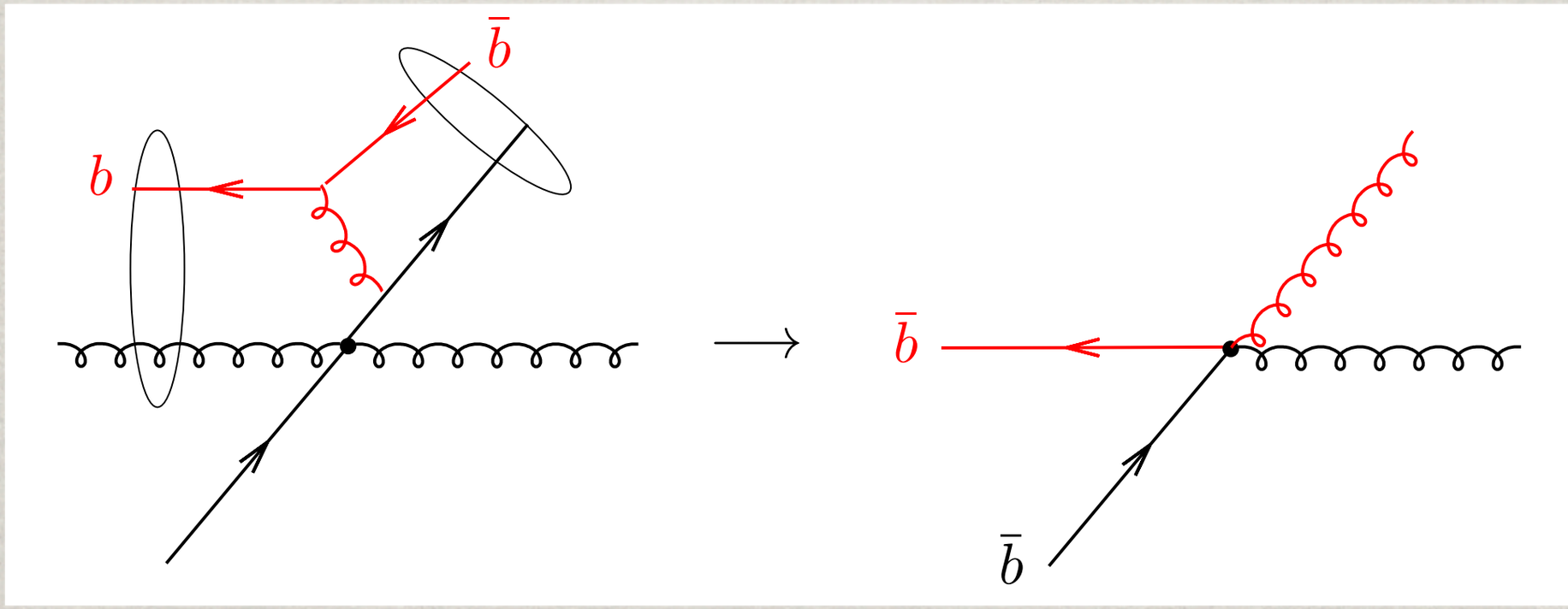
B-charge determination

- Strict flavor recombination requires knowledge of the exact b-flavor of jets, i.e. b and $\bar{b}$ need to be distinguished $\Rightarrow$ experimentally tricky
- Workaround: add extra flavor recombination rule $b + b = g$
- Since the matrix element for producing a collinear bb pair is non-singular, the k_t-flavor algorithm remains IR safe



Non-flavor jet algorithms

- At NLO, any collinear safe jet algorithm (anti-k_t, Cambridge-Aachen, k_t) gives the same b-jets as a k_t-flavor algorithm
- Measurements obtained with standard algorithms can be compared to NLO calculations, provided flavor recombination is done correctly
- Differences arise starting from NNLO, non-flavor algorithms have extra logarithms $\alpha_s^2 \times \alpha_s^n \ln^{n-1}(p_t/m_b)$ [Marchesini Mueller '03, Marchesini Onofri '04]



Experimental feasibility (I)

- Flavor algorithms can be used only if it is possible to identify more than one b-flavored particle inside each jet

- Given a number of b-tagged jets, here is a simplified estimate of true b-jets $b_{\rm true}$ out of jets with one b-tag $b_{\rm meas}$ and two b-tags $g_{\rm meas}$

  ϵ = efficiency for single b- tagging

  $\epsilon^2\eta$ = efficiency for double b- tagging in the same jet $\Rightarrow g_{\rm meas} = \epsilon^2\eta\, g_{\rm true}$

$$b_{\rm meas} = \epsilon\, b_{\rm true} + [1 - \epsilon^2\eta - (1-\epsilon)^2]\, g_{\rm true}$$

both b's tagged

both b's mistagged

$$b_{\rm true} = \frac{b_{\rm meas}}{\epsilon} - \frac{2-\epsilon(1+\eta)}{\epsilon^2\eta}\, g_{\rm meas}$$

- This estimate has an associated uncertainty

$$\left(\frac{\delta b_{\rm true}}{b_{\rm true}}\right)^2 = \left[(2f-1)\left(\frac{\delta\epsilon}{\epsilon}\right)\right]^2 + \left[(2-\epsilon)\, f\left(\frac{\delta\eta}{\eta}\right)\right]^2 \qquad f = \frac{g_{\rm true}}{b_{\rm true}}$$

Experimental feasibility (II)

- The key issue seems to be how well we understand efficiencies
- Example of what you get for a 100 GeV b-jet at the Tevatron and LHC

	$g_{\rm true}/b_{\rm true}$	ϵ	$\delta\epsilon/\epsilon$	$\delta\eta/\eta$	$\delta b_{\rm true}/b_{\rm true}$
Tevatron	0.75	50%*	10%	10%	12%
LHC	1.00	70%**	10%	10%	16%

* CDF coll. hep-ex/0412006

** CMS coll. arXiv:1202.4617

- Other real life issues that should be taken into account
  - b-tagging here is performed before the jet clustering, but there is no problem in reclustering fat jets obtained with traditional algorithms
  - dependence of efficiencies on jet rapidity and azimuth
  - energy scale uncertainties

Current status and perspectives

- k_t-flavor algorithms have been around for quite some years
- It is available on request as a plugin of FASTJET
- General k_t-flavor algorithms can be used to identify the Born flavor of a partonic event $\Rightarrow$ useful for perturbative QCD studies
- More ideas needed to extend flavor algorithms at hadron level, exception is heavy flavored jets
- With k_t-flavor algorithms we can obtain accurate QCD predictions for heavy-flavored jets
- Experimental feasibility of jet-flavor measurements should be seriously considered

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Thank you for your attention