Accurate predictions for b-jets at the Tevatron and LHC

Giulia Zanderighi
Theory Division, CERN

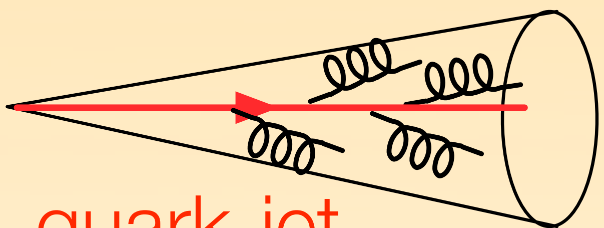
3rd Hera-LHC Workshop, DESY Hamburg, March 15th 2007

work done in collaboration with Andrea Banfi and Gavin Salam

Flavour of jets

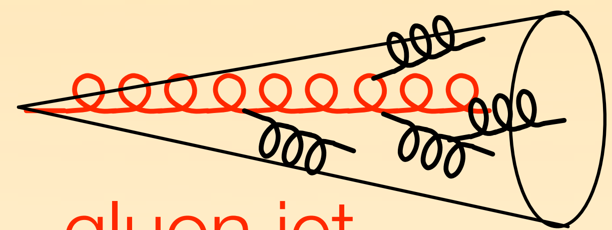
- <u>intuitive definition easy</u>:

flavour of a jet $\equiv$ *flavour of the parton initiating the jet*



$\sim C_F$

quark-jet
(u,d,c...)



$\sim C_A$

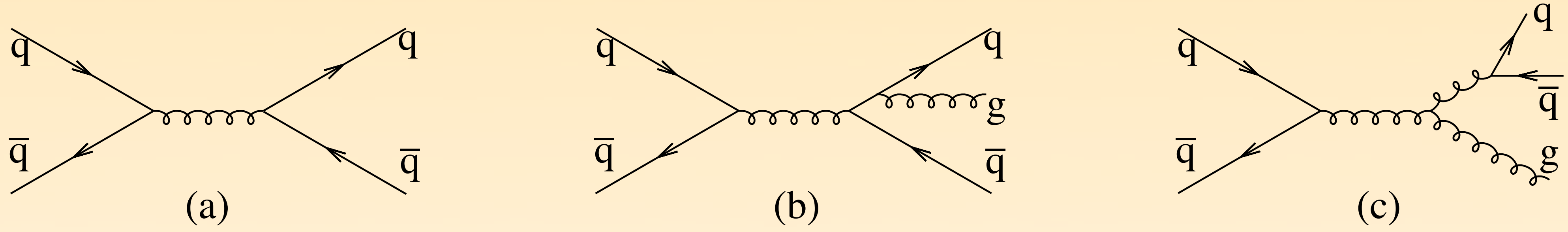
gluon jet
(no flavour)

Flavour of jets

- intuitive definition easy:

  flavour of a jet ≡ flavour of the parton initiating the jet

- yet because of interference there is an ambiguity beyond LO



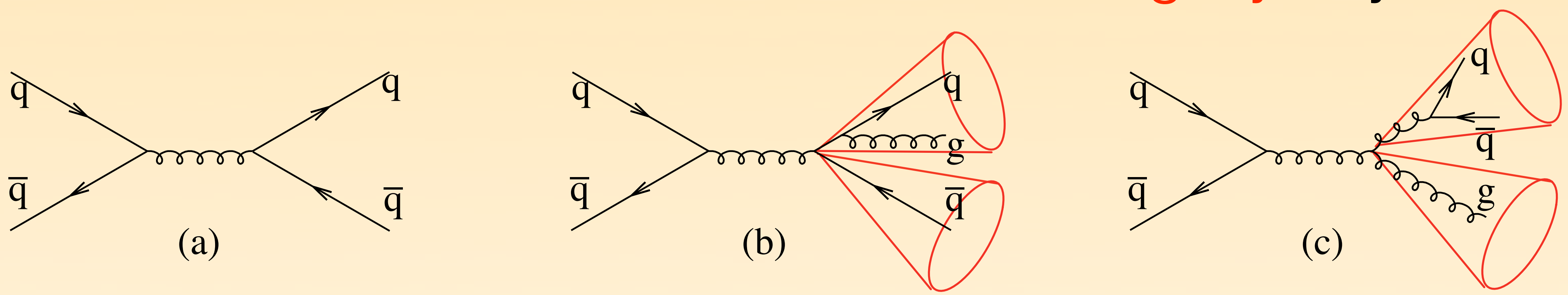
$q\bar{q}g$:correction to $q\bar{q} \to q\bar{q}$ or $q\bar{q} \to gg$?

Flavour of jets

- intuitive definition easy:

  flavour of a jet ≡ *flavour of the parton initiating the jet*

- yet because of interference there is an ambiguity beyond LO



$q\bar{q}g$: correction to $q\bar{q} \to q\bar{q}$ or $q\bar{q} \to gg$?

- no ambiguity in the soft-collinear limit $\Rightarrow$ cluster into jets and *define*

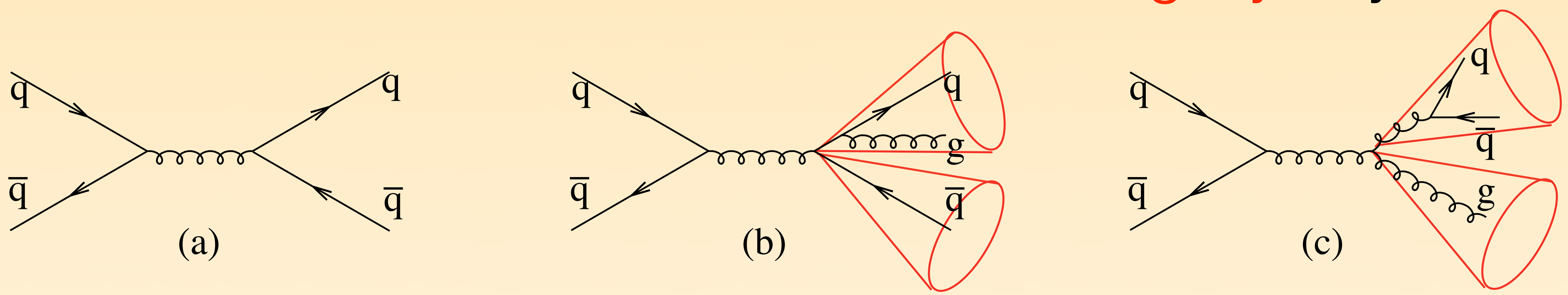
  flavour of a jet ≡ *net number of quarks in the jet*

Flavour of jets

- <u>intuitive definition easy</u>:

  flavour of a jet ≡ flavour of the parton initiating the jet

- yet because of interference there is an ambiguity beyond LO



$q\bar{q}g$:correction to $q\bar{q} \to q\bar{q}$ or $q\bar{q} \to gg$?

- no ambiguity in the soft-collinear limit $\Rightarrow$ cluster into jets and *define*

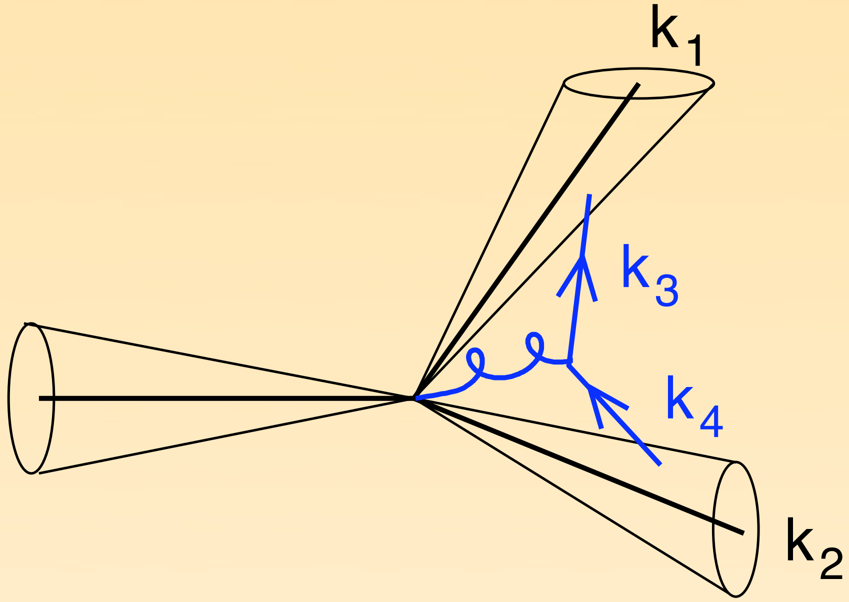
  flavour of a jet ≡ net number of quarks in the jet

- <u>the problem</u>: the jet-flavour so defined ***IR-unsafe beyond NLO***

Infrared unsafety of jet-flavour

Example:

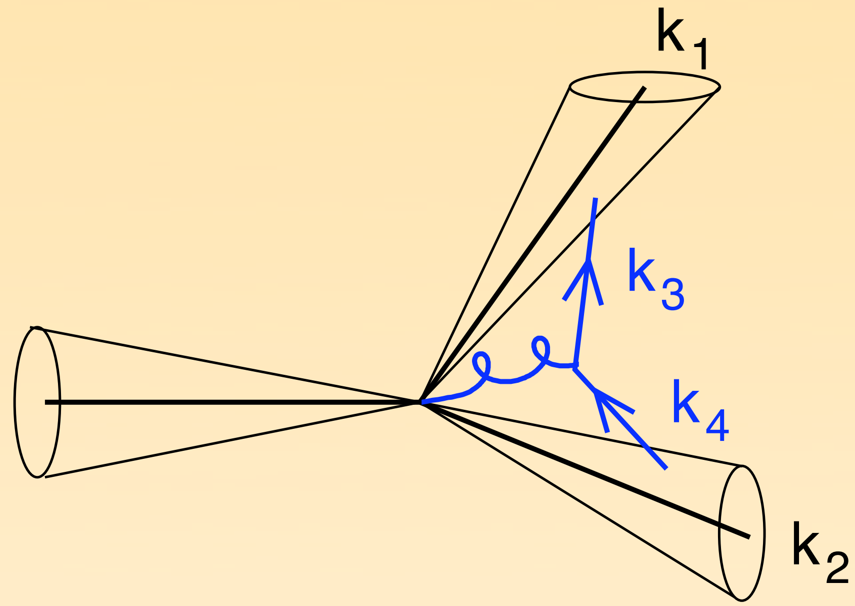
run k_t-algorithm: k_3 and k_4 will end up in different jets and *change the jet-flavour, no matter how soft the quarks 3 and 4 are* ⇒ *jet-flavour is IR unsafe*



Infrared unsafety of jet-flavour

Example:

run k_t-algorithm: k_3 and k_4 will end up in different jets and *change the jet-flavour, no matter how soft the quarks 3 and 4 are* ⇒ *jet-flavour is IR unsafe*

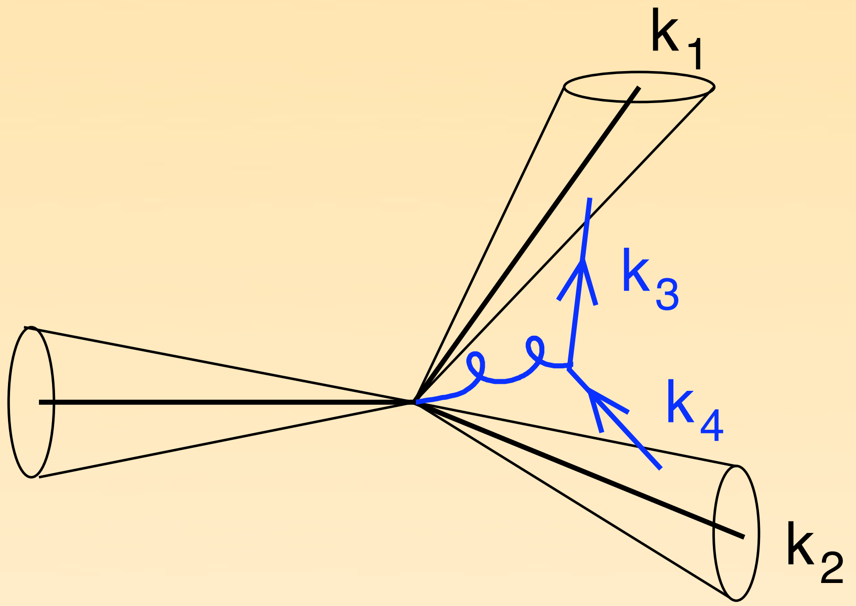


We know that IR-unsafe quantities should be avoided, yet in the literature there are $\sim$ 400 papers with "quark/gluon jet" in the title

Infrared unsafety of jet-flavour

Example:

run k_t-algorithm: k_3 and k_4 will end up in different jets and *change the jet-flavour, no matter how soft the quarks 3 and 4 are* ⇒ *jet-flavour is IR unsafe*



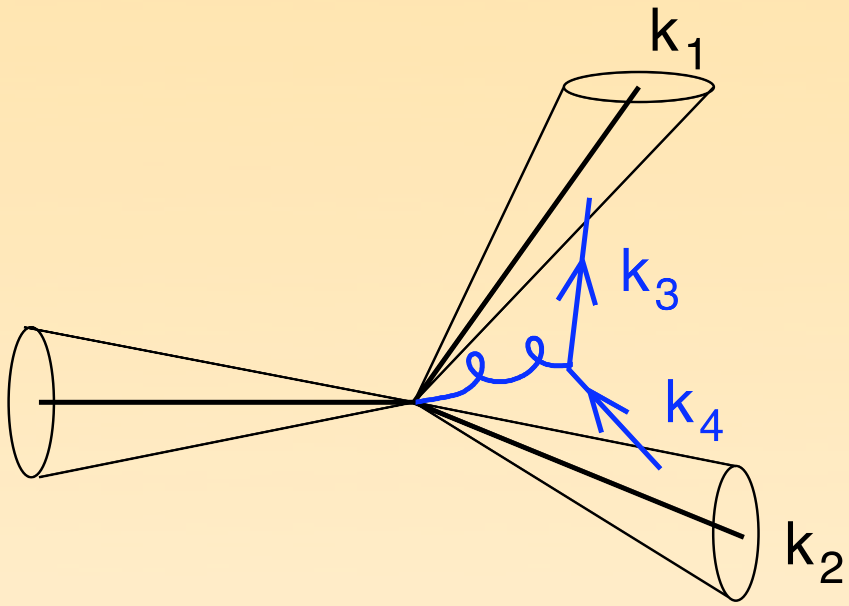
We know that IR-unsafe quantities should be avoided, yet in the literature there are $\sim$ 400 papers with “quark/gluon jet” in the title

1) how can one define it sensibly, i.e. make it IR-safe ?

Infrared unsafety of jet-flavour

Example:

run k_t-algorithm: k_3 and k_4 will end up in different jets and *change the jet-flavour, no matter how soft the quarks 3 and 4 are* ⇒ *jet-flavour is IR unsafe*



We know that IR-unsafe quantities should be avoided, yet in the literature there are $\sim$ 400 papers with "quark/gluon jet" in the title

1) how can one define it sensibly, i.e. make it IR-safe ?

2) why do we care about jet-flavour ⇒ e.g. application to b-jets

Origin of infrared unsafety

Take k_t-algorithm, recombine close particles according to the distance measure

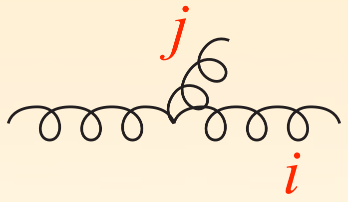
$$d_{ij} = \frac{2\min\{E_i, E_j\}}{Q^2}(1 - \cos\theta) \sim \frac{k_t^2}{Q^2}$$

Origin of infrared unsafety

Take k_t-algorithm, recombine close particles according to the distance measure

$$d_{ij} = \frac{2\min\{E_i, E_j\}}{Q^2}(1-\cos\theta) \sim \frac{k_t^2}{Q^2}$$

This distance reflects the structure of the divergences of QCD matrix elements for *gluon emission: soft and collinear divergence*



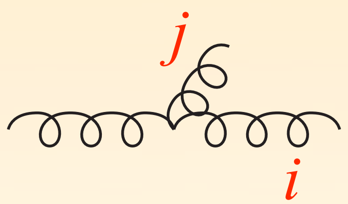
$$\sim \frac{\alpha_s C_A}{\pi}\frac{d\theta^2}{\theta^2}\frac{dE_j}{E_j} \qquad E_j \ll E_i,\ \theta \ll 1$$

Origin of infrared unsafety

Take k_t-algorithm, recombine close particles according to the distance measure

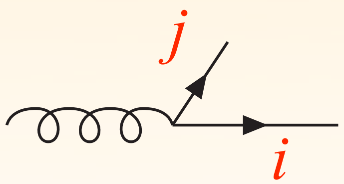
$$d_{ij} = \frac{2\min\{E_i, E_j\}}{Q^2}(1-\cos\theta) \sim \frac{k_t^2}{Q^2}$$

This distance reflects the structure of the divergences of QCD matrix elements for *gluon emission: soft and collinear divergence*



$$\sim \frac{\alpha_s C_A}{\pi}\frac{d\theta^2}{\theta^2}\frac{dE_j}{E_j} \qquad E_j \ll E_i,\ \theta \ll 1$$

However, for *quark production: only collinear divergence*



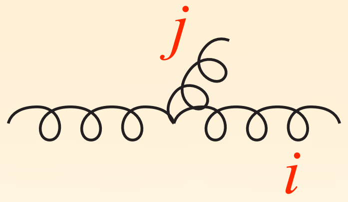
$$\sim \frac{\alpha_s T_R}{\pi}\frac{d\theta^2}{\theta^2}\frac{dE_j}{E_i} \qquad E_j \ll E_i,\ \theta \ll 1$$

Origin of infrared unsafety

Take k_t-algorithm, recombine close particles according to the distance measure

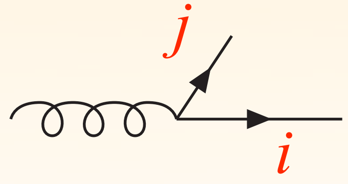
$$d_{ij} = \frac{2\min\{E_i, E_j\}}{Q^2}(1-\cos\theta) \sim \frac{k_t^2}{Q^2}$$

This distance reflects the structure of the divergences of QCD matrix elements for *gluon emission: soft and collinear divergence*



$$\sim \frac{\alpha_s C_A}{\pi}\frac{d\theta^2}{\theta^2}\frac{dE_j}{\min\{E_i, E_j\}} \qquad E_j \ll E_i,\ \theta \ll 1$$

However, for *quark production: only collinear divergence*



$$\sim \frac{\alpha_s T_R}{\pi}\frac{d\theta^2}{\theta^2}\frac{dE_j}{\max\{E_i, E_j\}} \qquad E_j \ll E_i,\ \theta \ll 1$$

Infrared safe jet-flavour

To construct IR-safe flavour modify the distance measure for quarks so as to respect the divergences of QCD matrix elements

[Banfi, Salam & GZ '06]

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

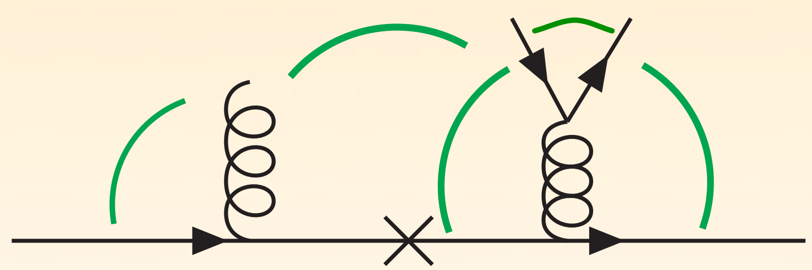
Infrared safe jet-flavour

To construct IR-safe flavour modify the distance measure for quarks so as to respect the divergences of QCD matrix elements

[Banfi, Salam & GZ '06]

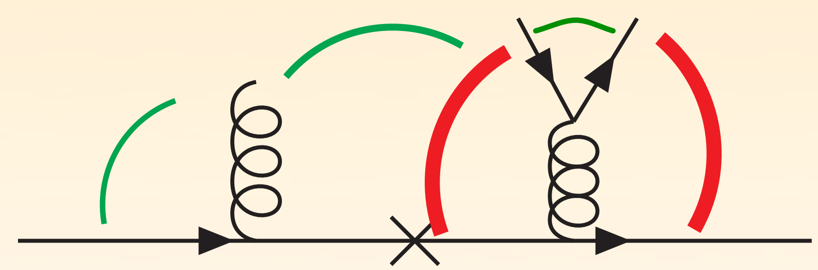
$$d_{ij}^{(F)} = \frac{2(1-\cos\theta)}{Q^2} \times \begin{cases} \min(E_i^2, E_j^2) & \text{softer of } i, j \text{ is flavourless (gluon)} \\ \max(E_i^2, E_j^2) & \text{softer of } i, j \text{ is flavoured (quark)} \end{cases}$$

Normal k_t algorithm



Recombination depends on angle

Flavour k_t algorithm



small distance

large distance

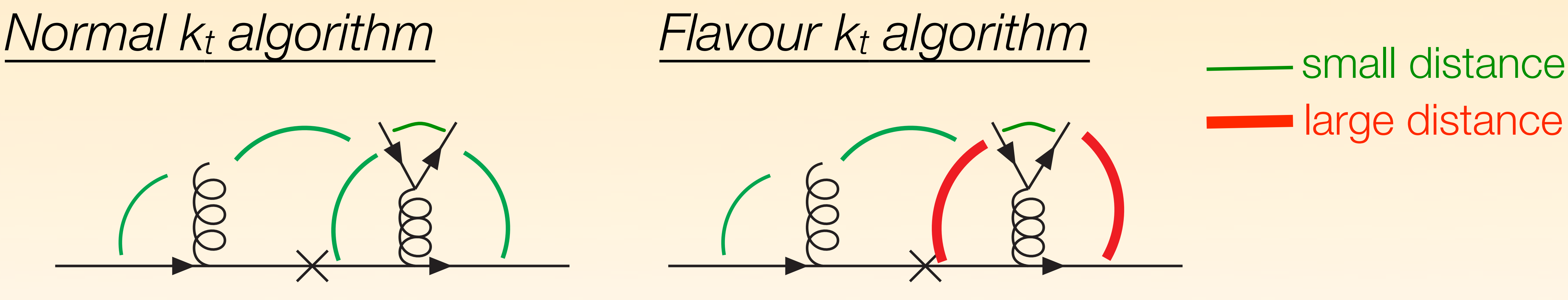
Bad recombinations strongly suppressed

Infrared safe jet-flavour

To construct IR-safe flavour modify the distance measure for quarks so as to respect the divergences of QCD matrix elements

[Banfi, Salam & GZ '06]

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



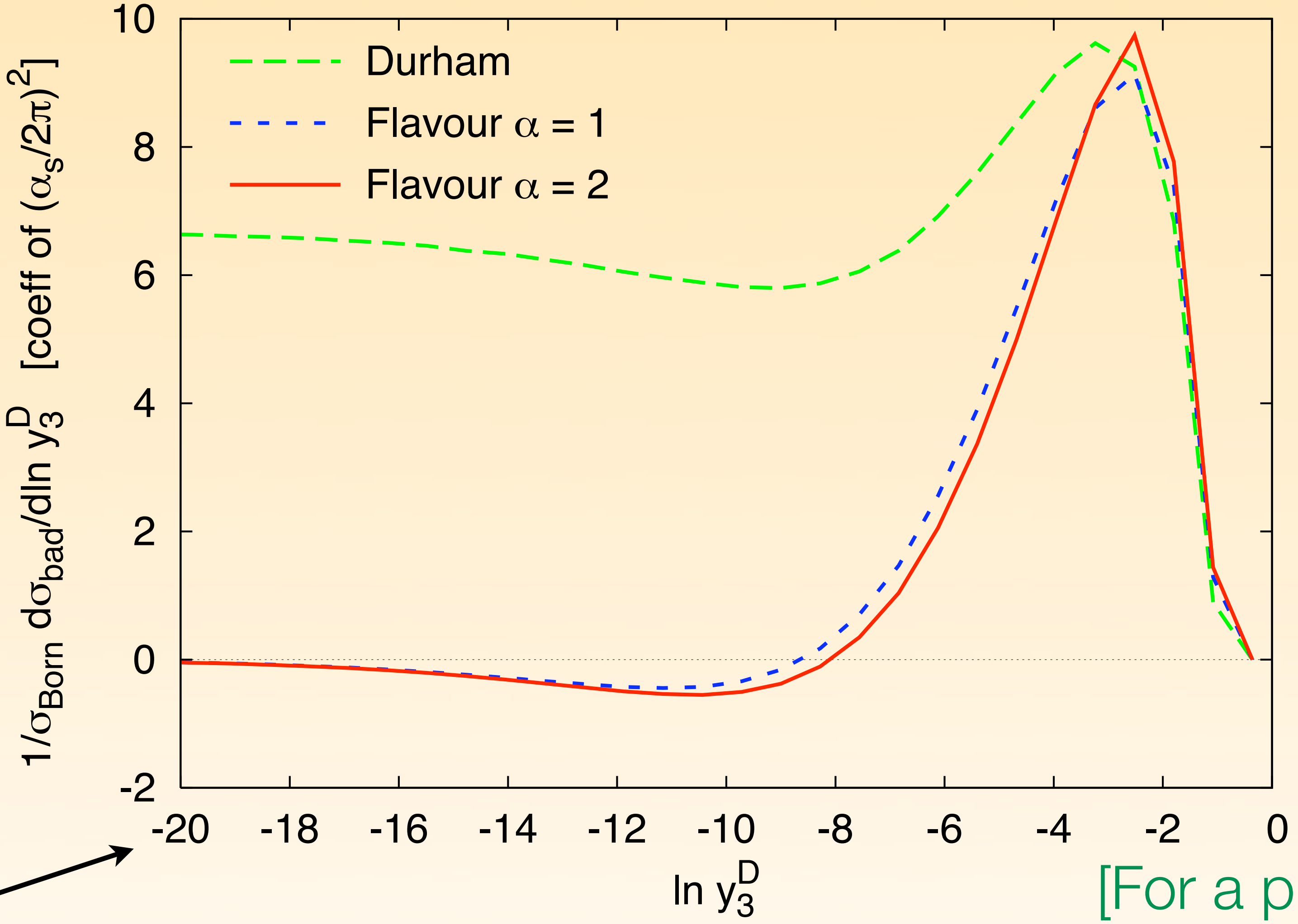
Recombination depends on angle

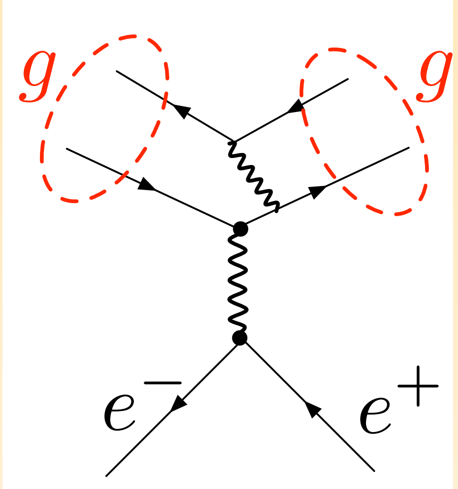
Infrared safe?

Bad recombinations strongly suppressed

Illustration of IR-safety at fixed order

Generate $e^+e^- \to q\bar{q}$ events with e.g. Event2 and look at the rate of misidentifications (events clustered as gg)





2-jet limit

[For a proof of IRsafety see App. A of hep-ph/0601139]

⇒ non-vanishing misidentification in 2-jet limit sign of IR-unsafety

Flavour algorithm for hadron colliders

Distance to the beam:

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

Flavour algorithm for hadron colliders

Distance to the beam:

?

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

Flavour algorithm for hadron colliders

Distance to the beam:

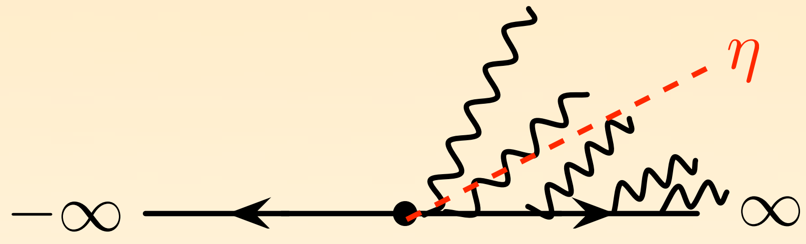
?

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

Transverse scale for beam at positive rapidity:

$$k_{\mathrm{t,right}}(\eta) \equiv \sum_i k_{t,i} \Theta(\eta_i - \eta)$$

⇒ particles already emitted from the beam



Flavour algorithm for hadron colliders

Distance to the beam:

?

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

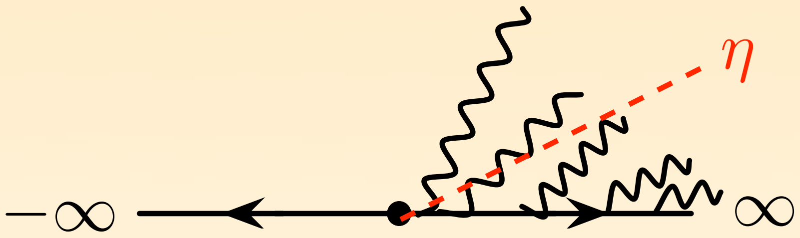
Transverse scale for beam at positive rapidity:

$$k_{\mathrm{t,right}}(\eta) \equiv \sum_i k_{t,i} \Theta(\eta_i - \eta)$$

⇒ particles already emitted from the beam

$$k_{\mathrm{t,left}}(\eta) \equiv \sum_i k_{t,i} e^{\eta - \eta_i} \Theta(\eta - \eta_i)$$

⇒ light-cone momentum left in the beam



Flavour algorithm for hadron colliders

Distance to the beam:

?

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

Transverse scale for beam at positive rapidity:

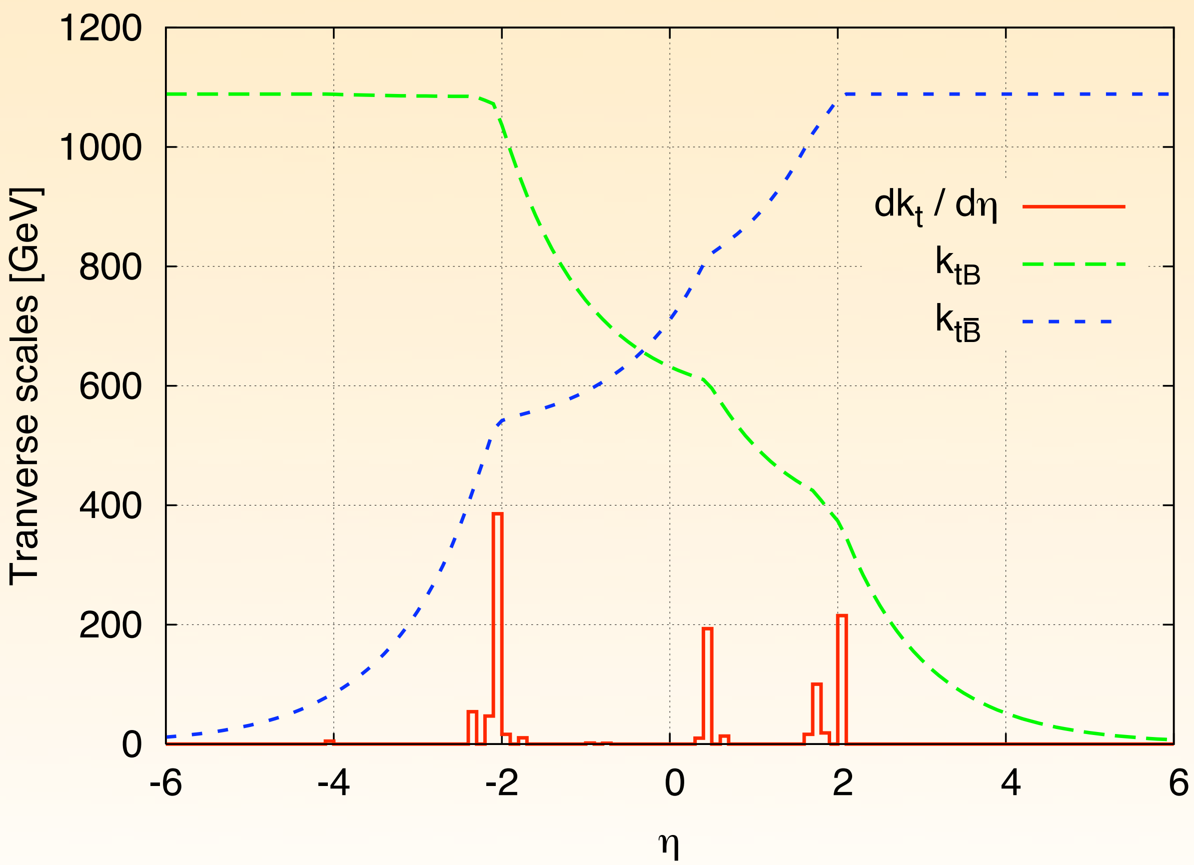
$$k_{\mathrm{t,right}}(\eta) \equiv \sum_i k_{t,i} \Theta(\eta_i - \eta)$$

⇒ particles already emitted from the beam

$$k_{\mathrm{t,left}}(\eta) \equiv \sum_i k_{t,i} e^{\eta - \eta_i} \Theta(\eta - \eta_i)$$

⇒ light-cone momentum left in the beam

$$k_{t,B} \equiv k_{\mathrm{t,right}}(\eta) + k_{\mathrm{t,left}}(\eta)$$



Flavour algorithm for b-jets

Run flavour algorithm treating as flavourless light quarks and gluons

Flavour algorithm for b-jets

Run flavour algorithm treating as flavourless light quarks and gluons

⇕

Compare with standard definition of b-jets:

b-jet ≡ any jet containing at least a b-quark

Flavour algorithm for b-jets

Run flavour algorithm treating as flavourless light quarks and gluons

Compare with standard definition of b-jets:

b-jet ≡ any jet containing at least a b-quark

How well are b-jets known at hadron colliders?

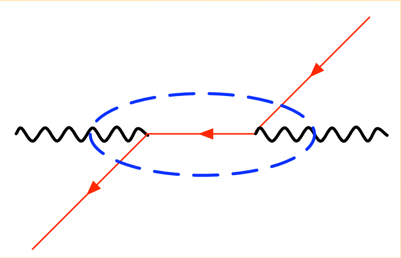
MCFM and MC@NLO predict heavy quark production at NLO

Why do we care then?

NLO heavy quark production mechanisms

At LO:

- flavour creation (FC): $ll \to b\bar{b}$

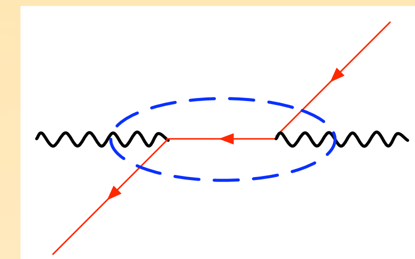


$\mathcal{O}(\alpha_s^2)$

NLO heavy quark production mechanisms

At LO:

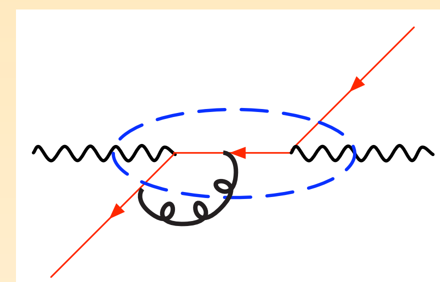
- flavour creation (FC): $ll \to b\bar{b}$

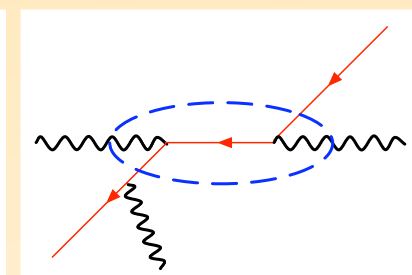


$\mathcal{O}(\alpha_s^2)$

At NLO:

- flavour creation (FC): $ll \to (b \to bl)\bar{b}$

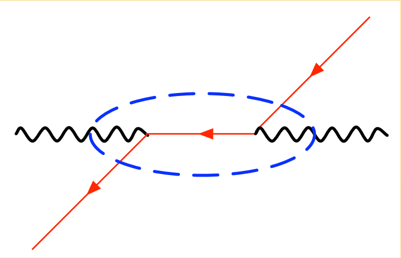




NLO heavy quark production mechanisms

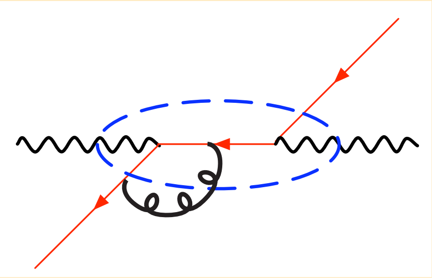
At LO:

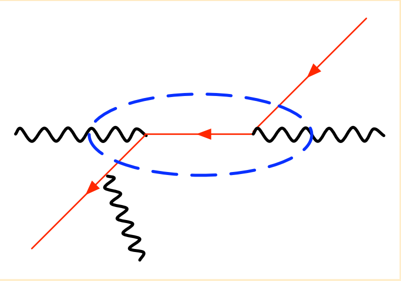
- flavour creation (FC): $ll \to b\bar{b}$



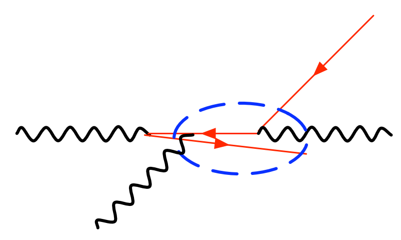
$\mathcal{O}(\alpha_s^2)$

At NLO:





- flavour creation (FC): $ll \to (b \to bl)\bar{b}$

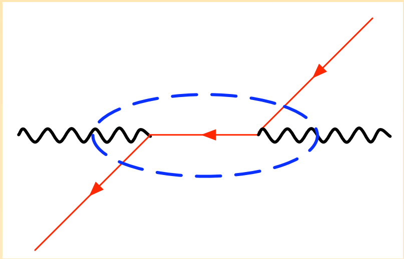


- flavour excitation (FEX): $l(l \to b\bar{b}) \to lb\bar{b}$

NLO heavy quark production mechanisms

At LO:

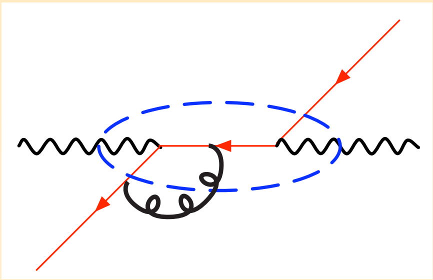
- flavour creation (FC): $ll \rightarrow b\bar{b}$

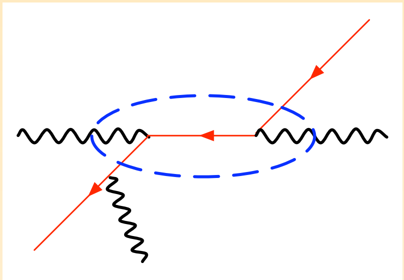


$\mathcal{O}(\alpha_s^2)$

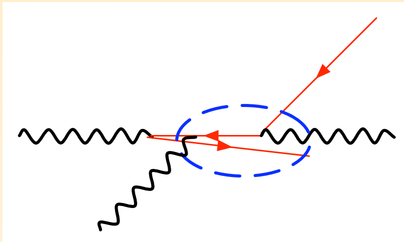
At NLO:

- flavour creation (FC): $ll \rightarrow (b \rightarrow bl)\bar{b}$

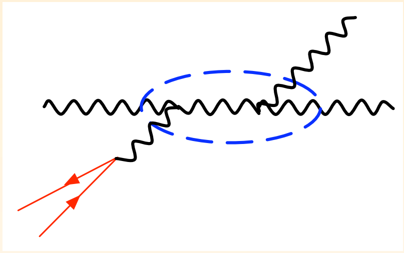




- flavour excitation (FEX): $l(l \rightarrow b\bar{b}) \rightarrow lb\bar{b}$



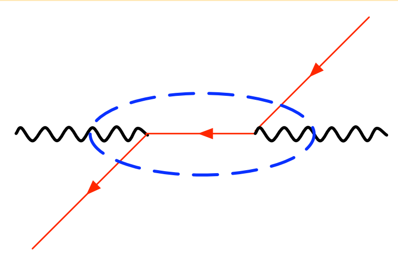
- gluon splitting (GSP): $ll \rightarrow l(l \rightarrow b\bar{b})$



NLO heavy quark production mechanisms

At LO:

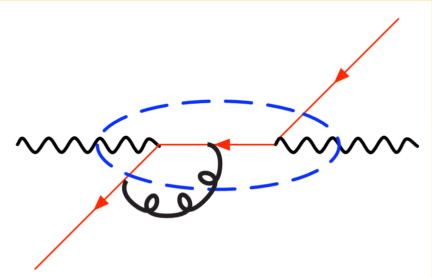
- flavour creation (FC): $ll \rightarrow b\bar{b}$

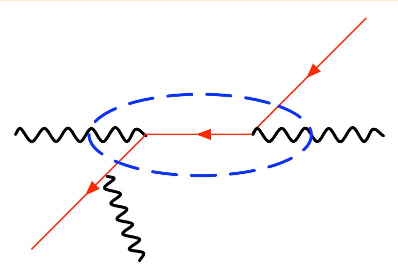


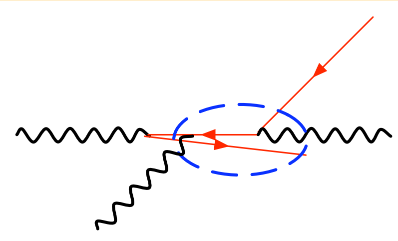
$\mathcal{O}(\alpha_s^2)$

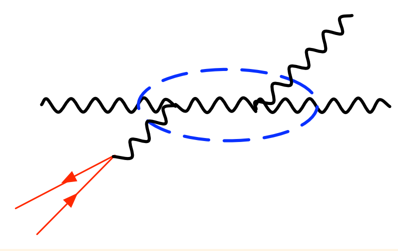
At NLO:

- flavour creation (FC): $ll \rightarrow (b \rightarrow bl)\bar{b}$
- flavour excitation (FEX): $l(l \rightarrow b\bar{b}) \rightarrow lb\bar{b}$
- gluon splitting (GSP): $ll \rightarrow l(l \rightarrow b\bar{b})$







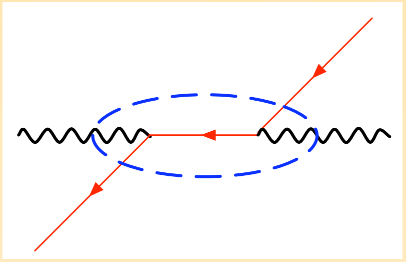


$\mathcal{O}(\alpha_s^3)$

NLO heavy quark production mechanisms

At LO:

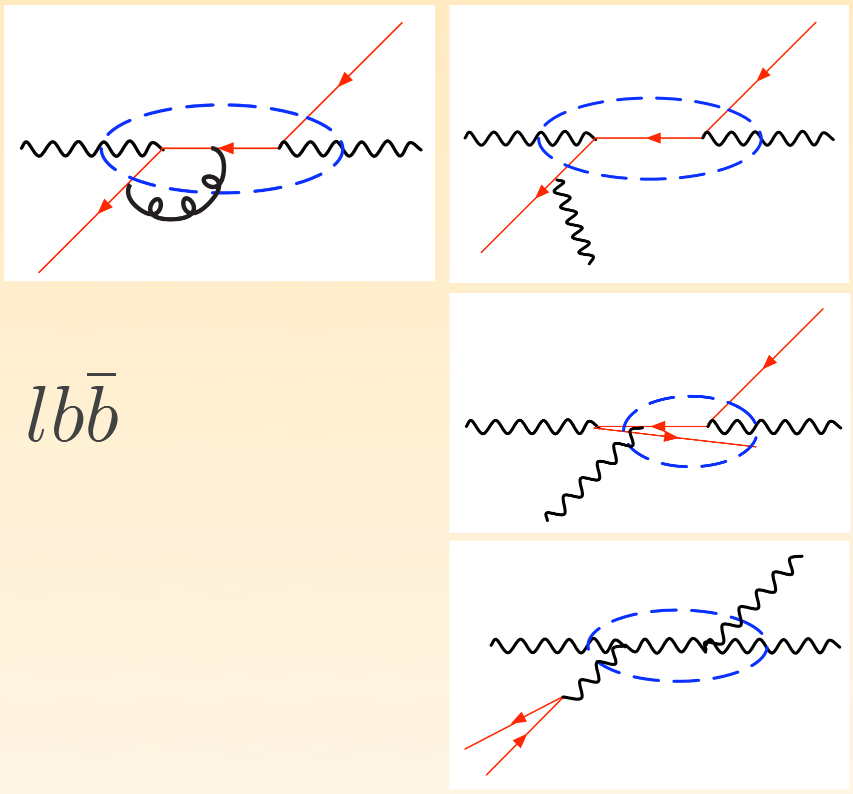
- flavour creation (FC): $ll \to b\bar{b}$



$\mathcal{O}(\alpha_s^2)$

At NLO:

- flavour creation (FC): $ll \to (b \to bl)\bar{b}$
- flavour excitation (FEX): $l(l \to b\bar{b}) \to lb\bar{b}$
- gluon splitting (GSP): $ll \to l(l \to b\bar{b})$

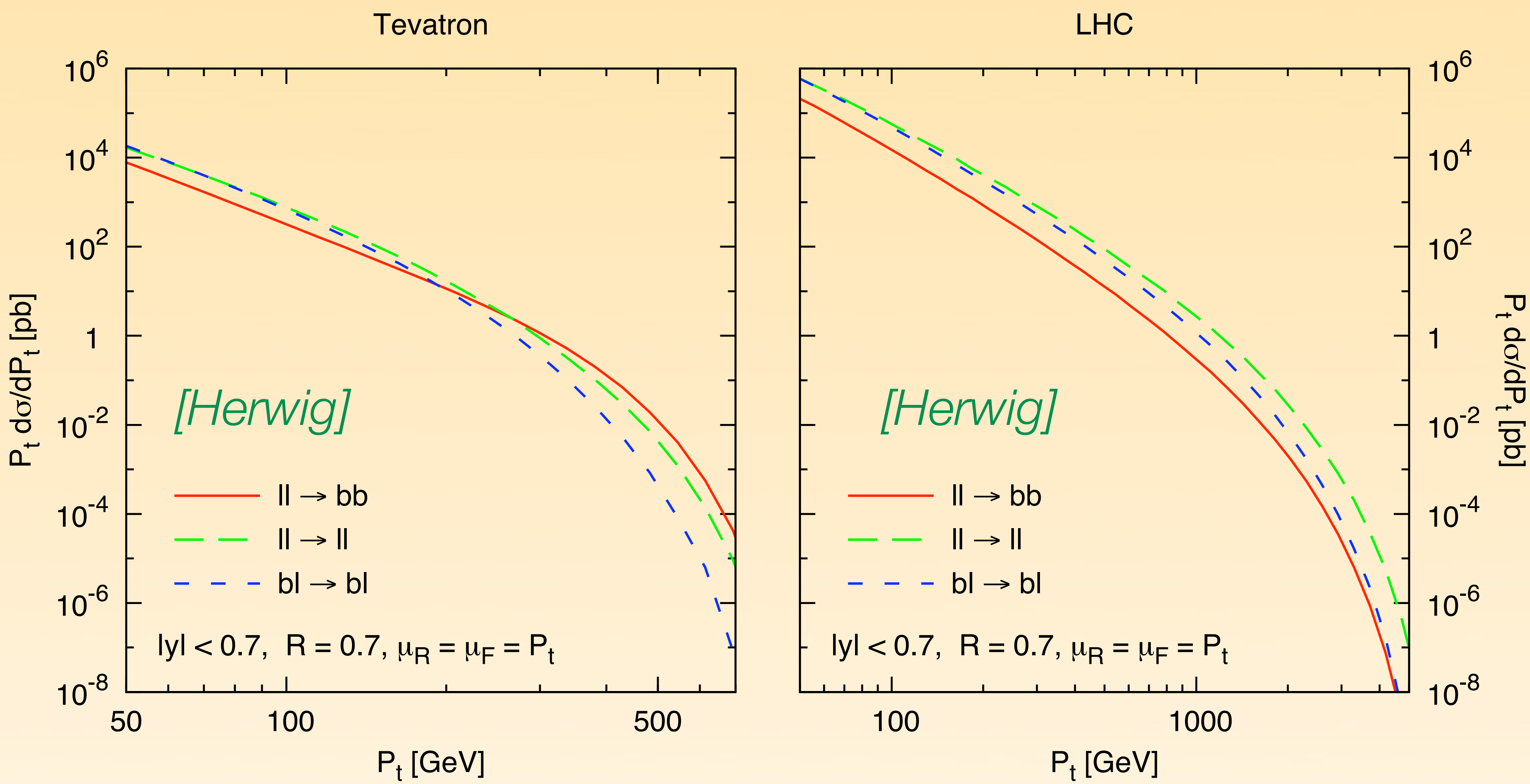


$\mathcal{O}(\alpha_s^3)$

⇒ two new channels open up at NLO

MCFM and MC@NLO have FC at NLO, but FEX and GSP at tree level.
How important are those contributions?

NLO decomposition of b-jet spectrum



LO channel ($ll \to b\bar{b}$) nearly always smaller than NLO channels ($ll \to ll$ and $bl \to bl$).

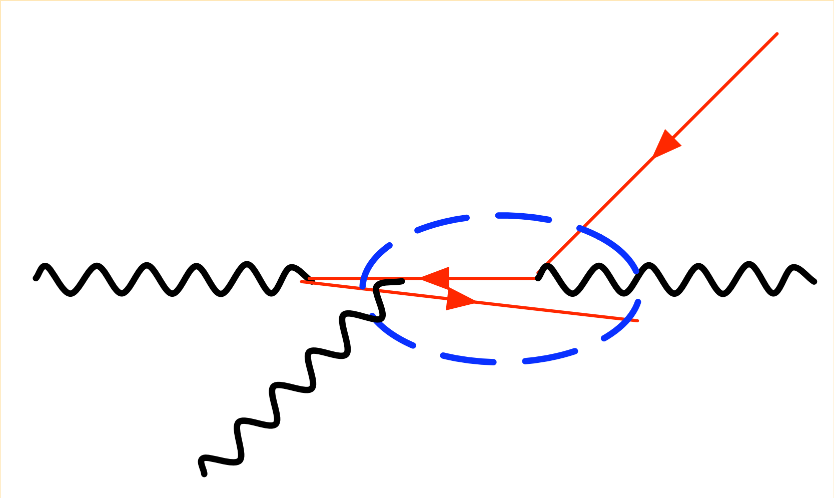
Why are higher order channels so large?

Logarithmic enhancements

FEX:

- hard process $\mathcal{O}(\alpha_s^2)$
- collinear splitting $\mathcal{O}\left(\alpha_s \ln(P_t/m_b)\right)$
- add n collinear gluons $\mathcal{O}\left((\alpha_s \ln(P_t/m_b))^n\right)$

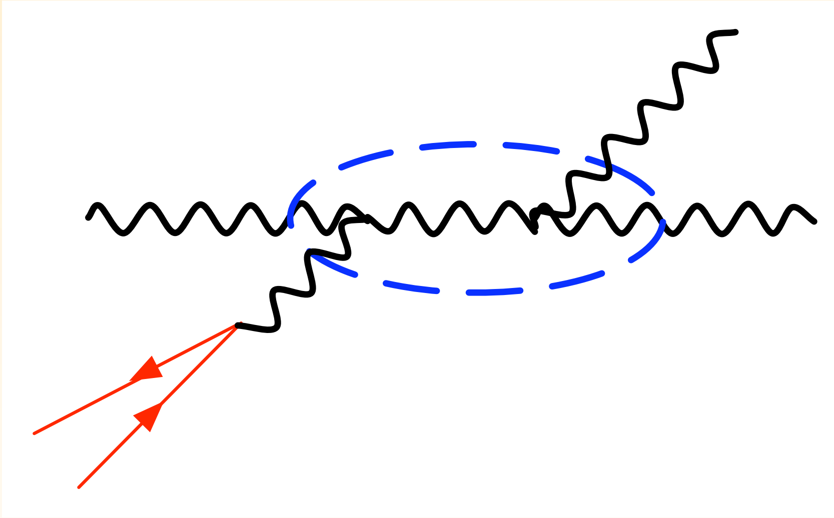
$\Rightarrow \mathcal{O}\left(\alpha_s^2 \cdot (\alpha_s \ln(P_t/m_b))^n\right)$



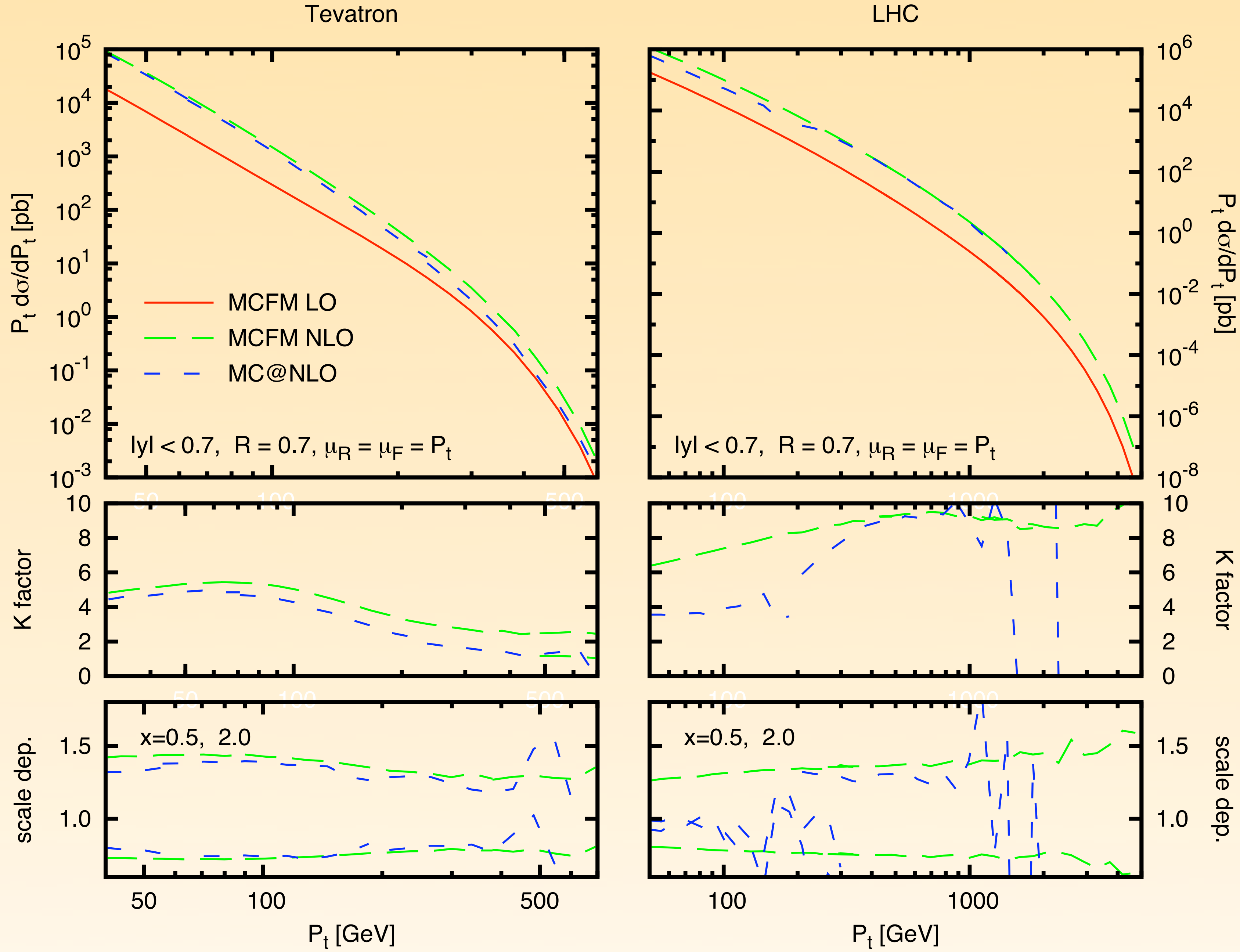
GSP:

- hard process $\mathcal{O}(\alpha_s^2)$
- collinear splitting $\mathcal{O}\left(\alpha_s \ln(P_t/m_b)\right)$
- n soft/collinear gluons $\mathcal{O}\left((\alpha_s \ln^2(P_t/m_b))^n\right)$

$\Rightarrow \mathcal{O}\left(\alpha_s^2 \cdot \alpha_s^n \ln^{2n-1}(P_t/m_b)\right)$



Inclusive b-jets with standard kt-jet algorithm

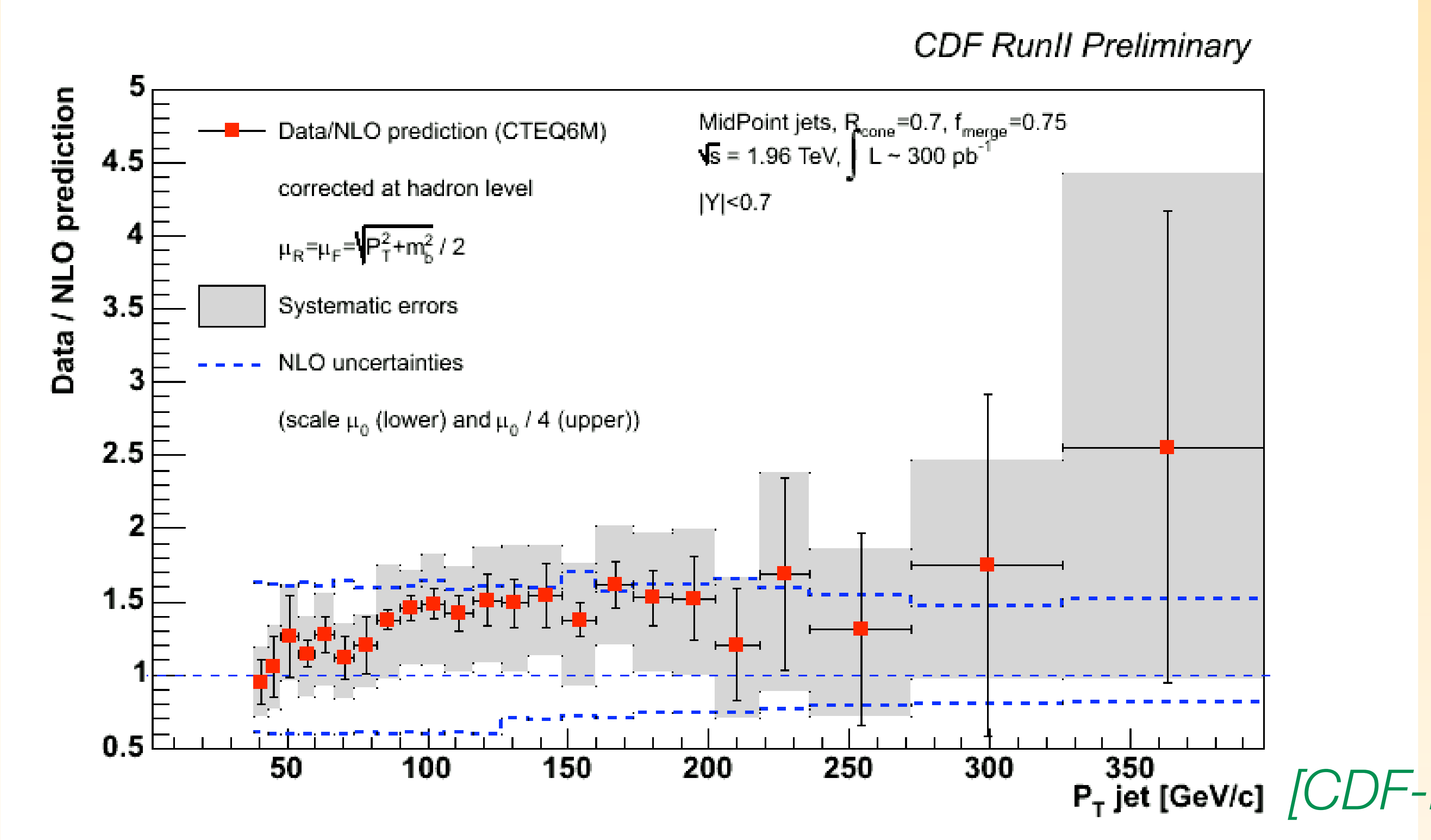


preliminary

⇒ large K-factors and uncertainties both with MCFM and MC@NLO

NLO vs date for b-jet inclusive cross section

With standard cone jet-algorithm

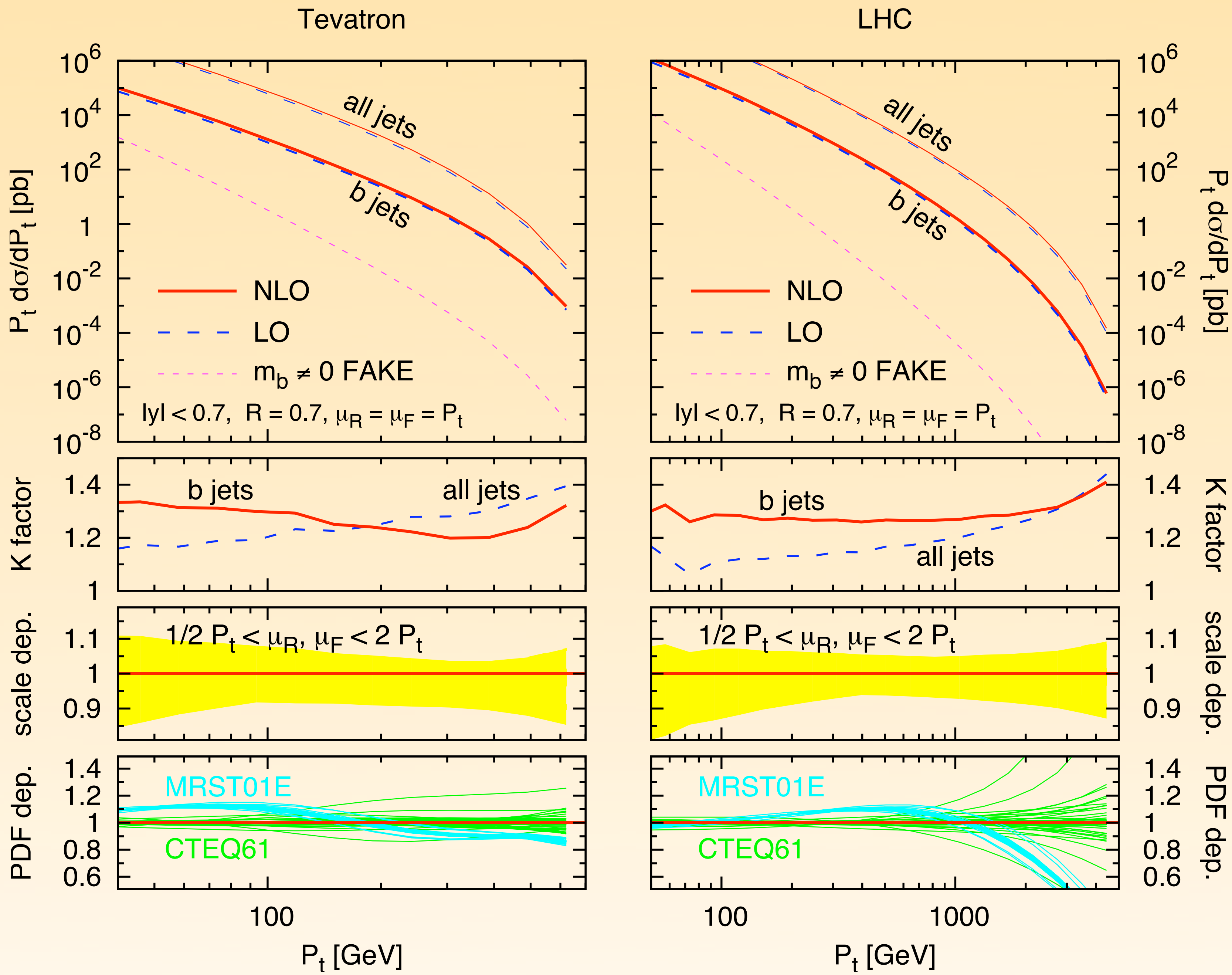


[CDF-note 8418]

⇒ with MC@NLO ∼40-60% uncertainty

experimental errors smaller than theoretical ones

b-jet spectrum with flavour algorithm



preliminary

⇒ NLO moderate effect ∼ 30%

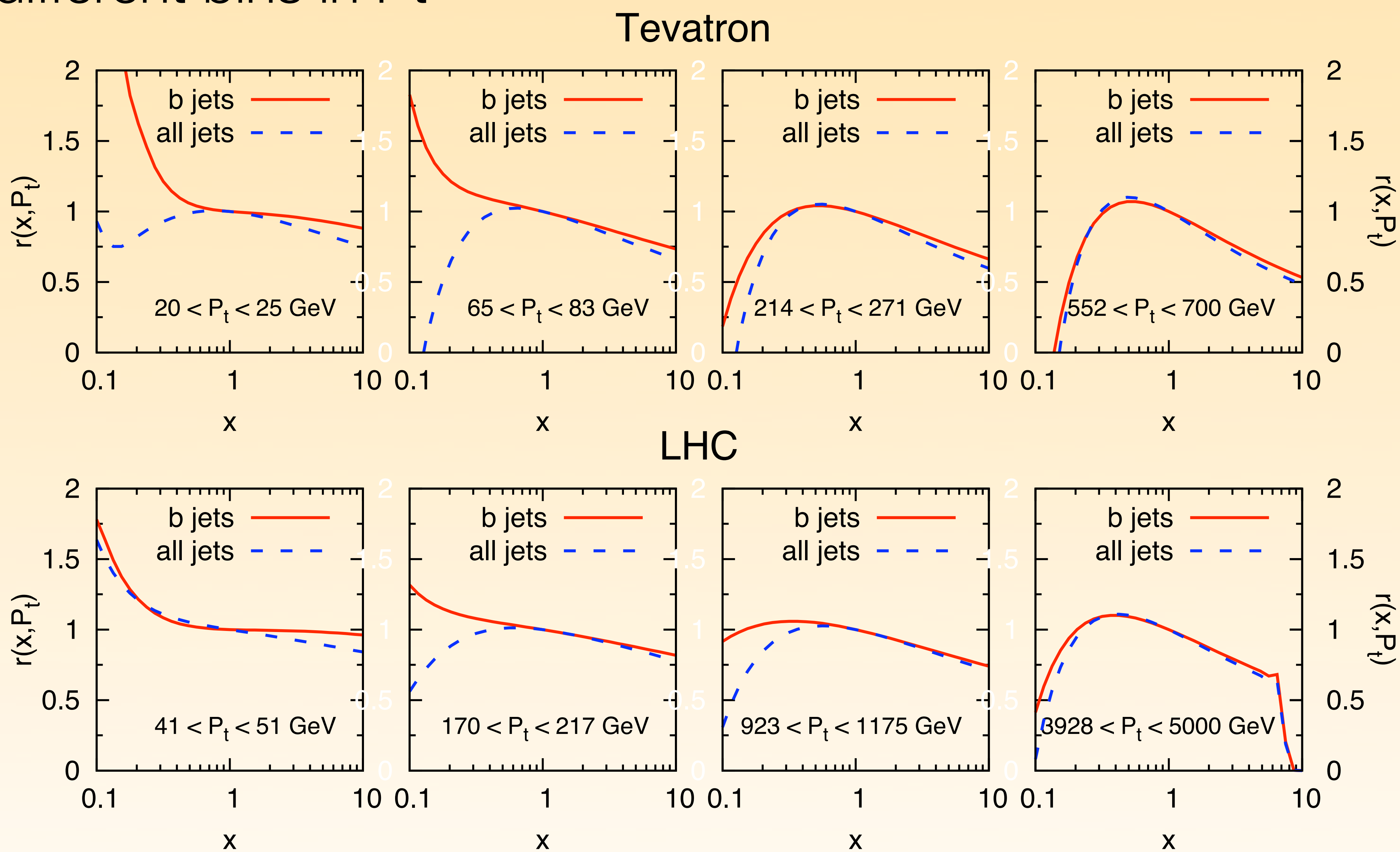
⇒ considerable reduction of TH uncertainties

⇒ largest uncertainties from PDFs at high P_t

NB: spectra obtained by extending NLOjet++ so as to have access to the flavour of incoming and outgoing partons

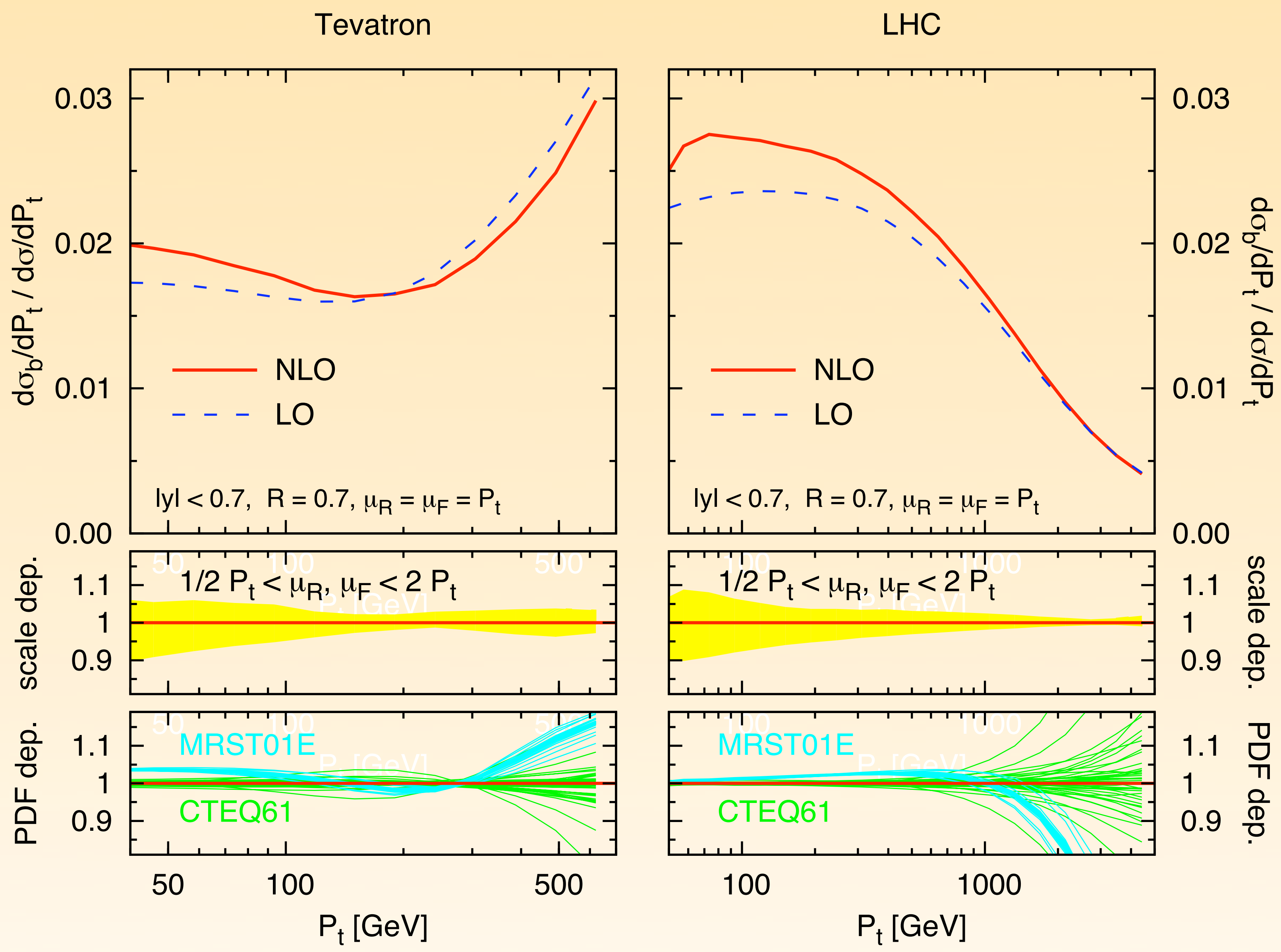
Sensitivity to scale variations

Look at the ratio $r(x, P_t) \equiv \sigma(\mu_R = \mu_F = xP_t)/\sigma(\mu_R = \mu_F = P_t)$ for different bins in Pt



⇒ b- and all-jets have the same sensitivity to scale variations

Ratios b-jets/all jets



⇒ many common exp. uncertainties cancel in the ratio

⇒ theory uncertainty reduced in the ratio

⇒ different behaviour at high PT due to different dominant sub-process

Comparison of algorithms for b-jets

Standard algorithms (IR-unsafe):

- cross-sections have large logarithms $\alpha_s^2 \cdot \alpha_s^n \ln(P_t/m_b)^{2n-1}$ due to gluon splitting (GSP)

Flavour algorithms (IR-safe):

- no large logs from gluon splitting, because gluon jets do not contribute to b-jet spectra

Comparison of algorithms for b-jets

Standard algorithms (IR-unsafe):

- cross-sections have large logarithms $\alpha_s^2 \cdot \alpha_s^n \ln(P_t/m_b)^{2n-1}$ due to gluon splitting (GSP)
- cross-sections have large logs $\alpha_s^2 \cdot (\alpha_s \ln(P_t/m_b))^n$ due to initial state collinear branchings (FEX)

Flavour algorithms (IR-safe):

- no large logs from gluon splitting, because gluon jets do not contribute to b-jet spectra
- logarithms from initial state gluon branchings to $b\bar{b}$ can be resummed in b-PDFs

Comparison of algorithms for b-jets

Standard algorithms (IR-unsafe):

- cross-sections have large logarithms $\alpha_s^2 \cdot \alpha_s^n \ln(P_t/m_b)^{2n-1}$ due to gluon splitting (GSP)
- cross-sections have large logs $\alpha_s^2 \cdot (\alpha_s \ln(P_t/m_b))^n$ due to initial state collinear branchings (FEX)
- must keep finite m_b in PT calculation, FEX and GSP at LO

Flavour algorithms (IR-safe):

- no large logs from gluon splitting, because gluon jets do not contribute to b-jet spectra
- logarithms from initial state gluon branchings to $b\bar{b}$ can be resummed in b-PDFs
- full NLO massless QCD calculation (much simpler)

Other applications of flavour-algorithms

Flavour algorithms allow one to give a meaning to decompositions into subprocesses beyond LO. Important to

Other applications of flavour-algorithms

Flavour algorithms allow one to give a meaning to decompositions into subprocesses beyond LO. Important to

☛ match multi-leg NLO calculations with Monte Carlo showers

[e.g. CKKW, MC@NLO, Nagy-Soper,Nason]

Other applications of flavour-algorithms

Flavour algorithms allow one to give a meaning to decompositions into subprocesses beyond LO. Important to

☛ match multi-leg NLO calculations with Monte Carlo showers

[e.g. CKKW, MC@NLO, Nagy-Soper,Nason]

☛ match multi-leg NLO with analytical resummations

[e.g. CAESAR+NLOJET]

Other applications of flavour-algorithms

Flavour algorithms allow one to give a meaning to decompositions into subprocesses beyond LO. Important to

☛ match multi-leg NLO calculations with Monte Carlo showers

[e.g. CKKW, MC@NLO, Nagy-Soper,Nason]

☛ match multi-leg NLO with analytical resummations

[e.g. CAESAR+NLOJET]

☛ count the relative number of quark vs gluon jets

[e.g. multiplicity studies, Monte Carlo tuning]

Other applications of flavour-algorithms

Flavour algorithms allow one to give a meaning to decompositions into subprocesses beyond LO. Important to

- ☛match multi-leg NLO calculations with Monte Carlo showers
  [e.g. CKKW, MC@NLO, Nagy-Soper,Nason]
- ☛match multi-leg NLO with analytical resummations
  [e.g. CAESAR+NLOJET]
- ☛count the relative number of quark vs gluon jets
  [e.g. multiplicity studies, Monte Carlo tuning]
- ☛use massless calculations to reduce uncertainties in b-quantities
  [e.g. forward-backward asymmetry A^b_{FB}, see Weinzierl '06]

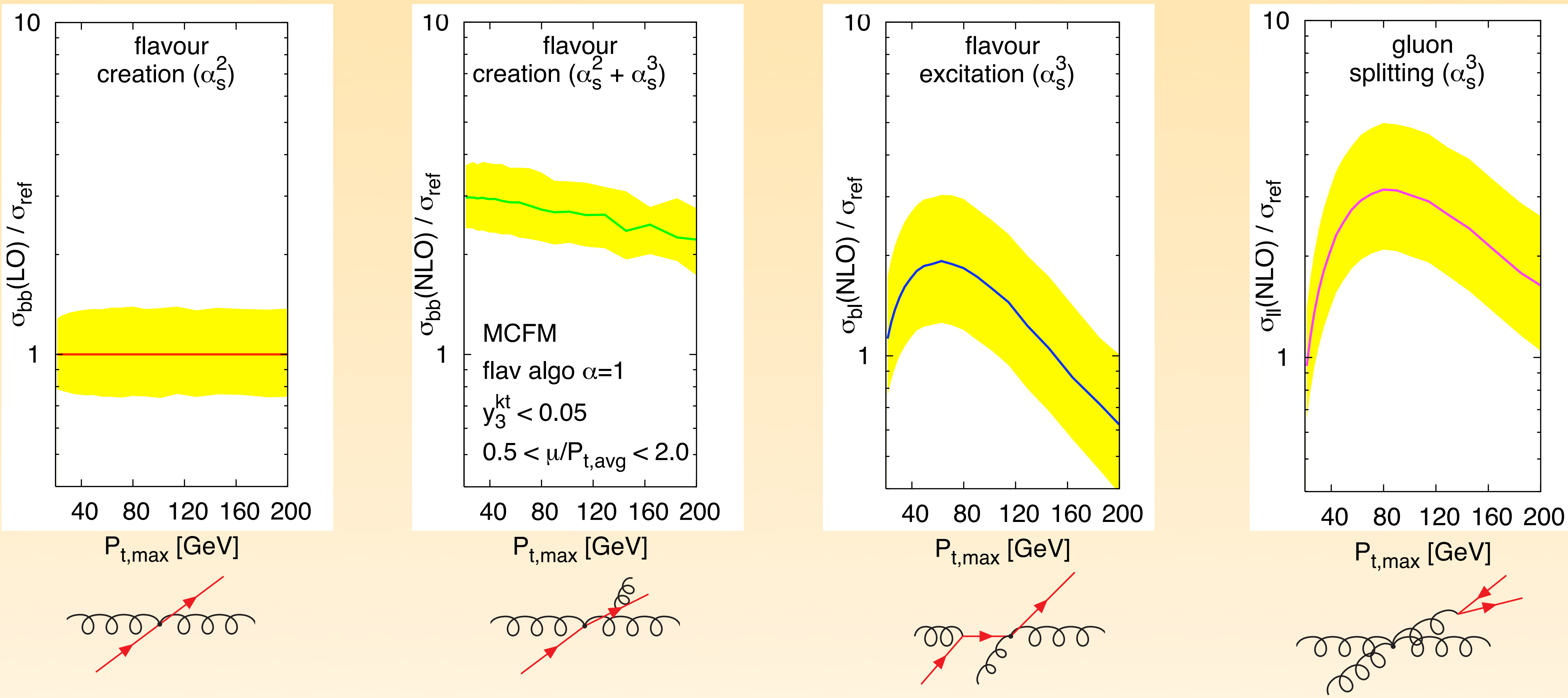
Conclusions

- ☑ we defined the flavour of jets in an IR-safe way
- ☑ we exploited IR-safety of the new definition of b-jets to improve on the current theoretical prediction by
  - removing or resumming all large logarithms
  - doing a true NLO massless calculation (no new channels at NLO)
- ☑ our IR-safe definition reduced the theoretical uncertainties from 40-50% to 10-20%

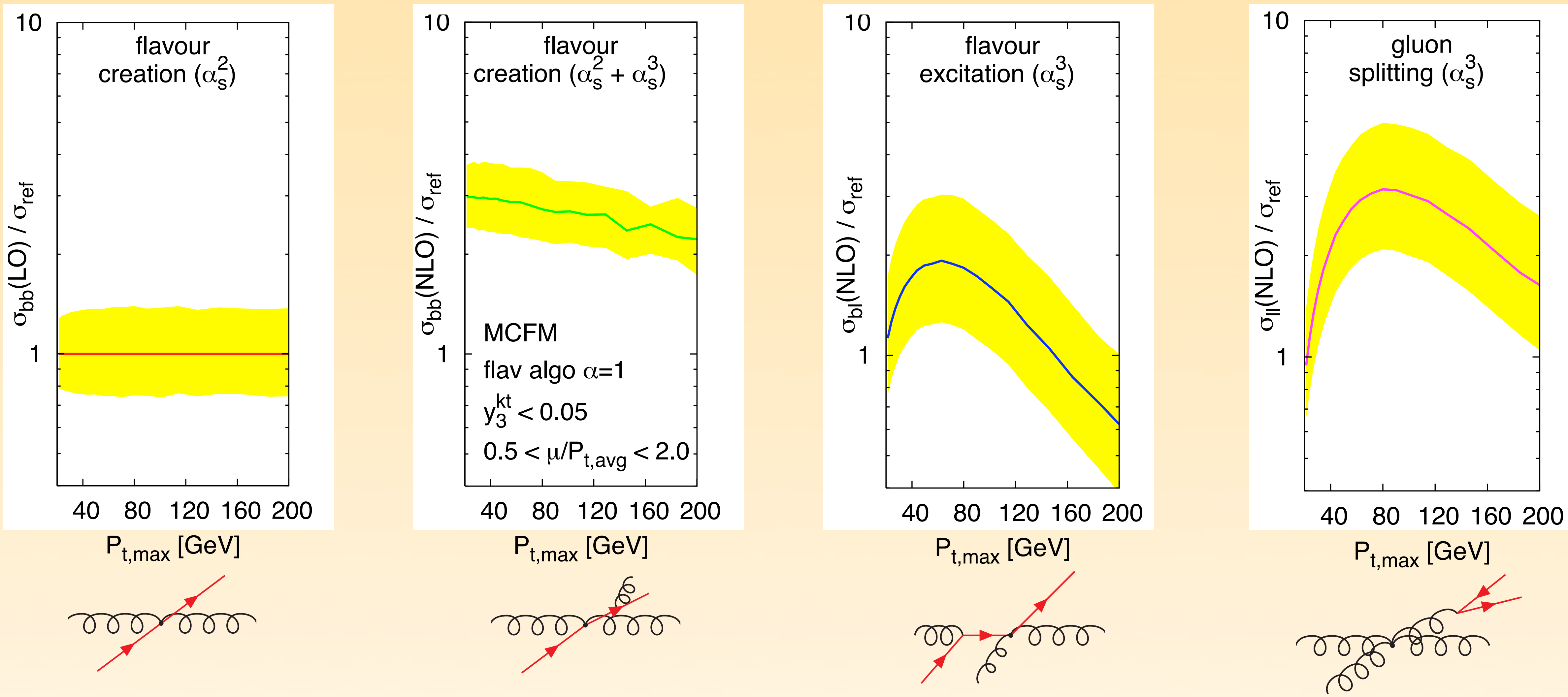
We look forward to further experimental investigations in this direction

Extra slides

b-production

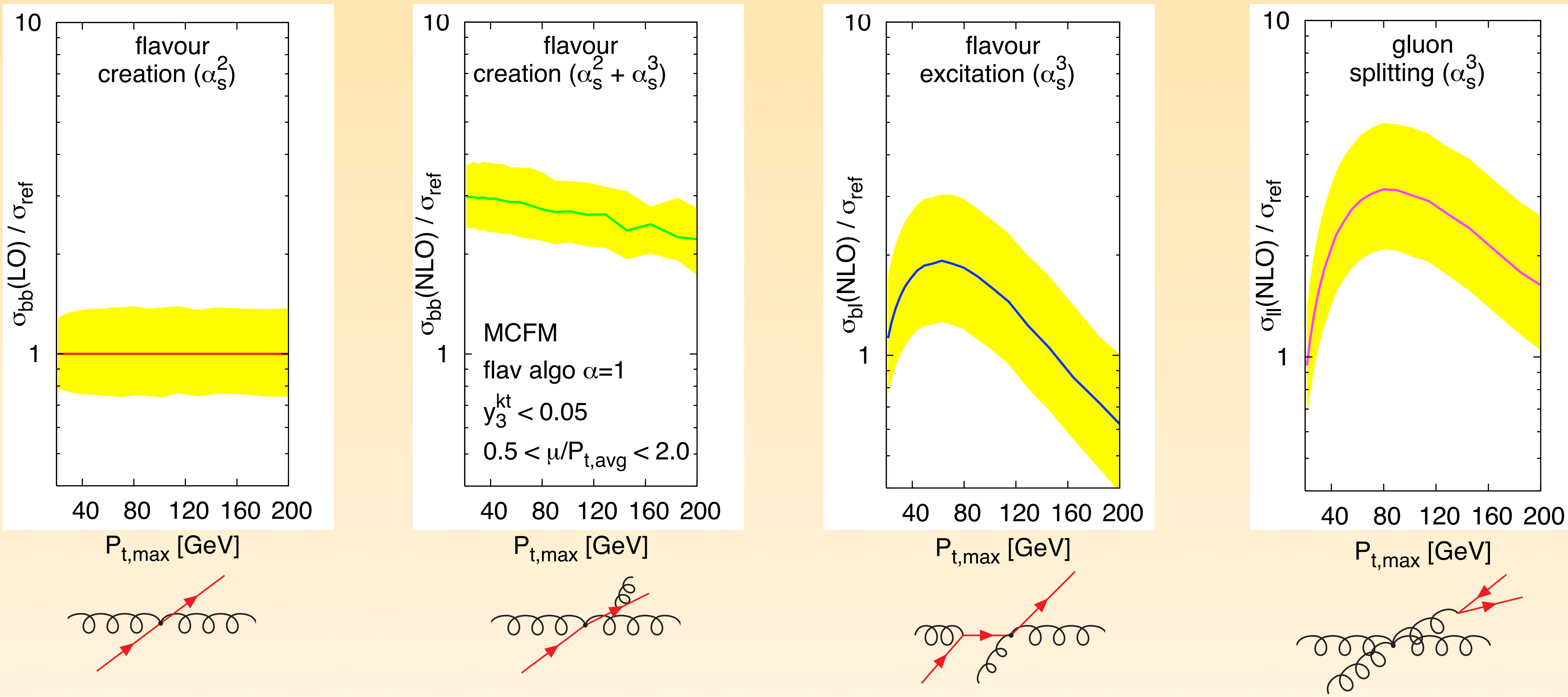


b-production



- flavour excitation (FEX) and gluon splitting (GSP) have large uncertainties

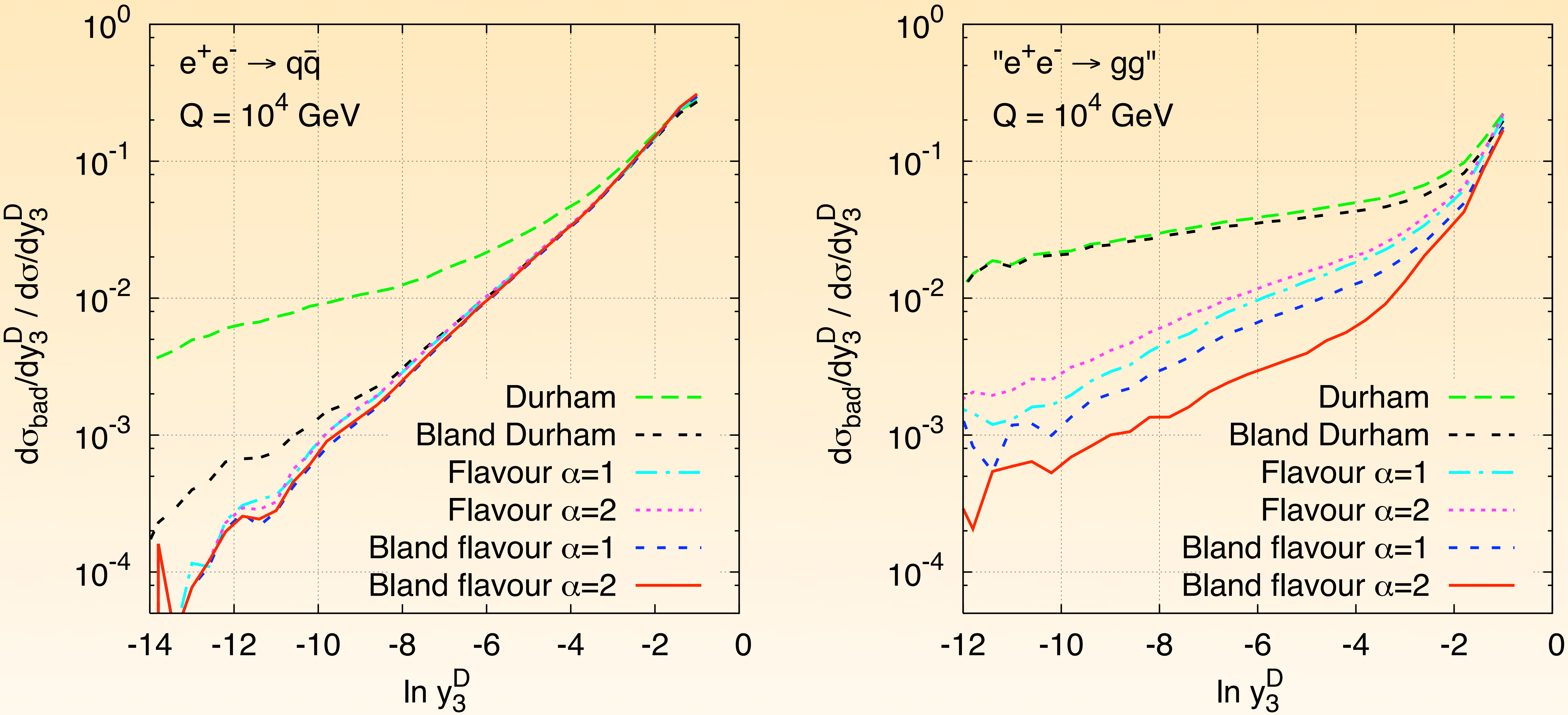
b-production



- flavour excitation (FEX) and gluon splitting (GSP) have large uncertainties
- with flavour algorithm: GSP contribution does not contribute and FEX is resummed in PDFs ⇒ reduce uncertainties

All-order IR-safety

Flavour misidentification of ee→qq (gg) events with Herwig



All-order IR-safety

Flavour misidentification of qq→qq,qg,gg events