

Accurate predictions for b-jets at the Tevatron and LHC

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Theory Division, CERN

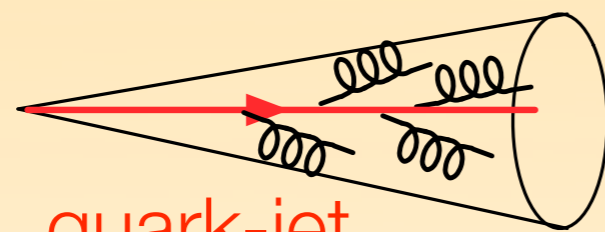
3rd Hera-LHC Workshop, DESY Hamburg, March 13th 2007

work done in collaboration with Andrea Banfi and Gavin Salam

Flavour of jets

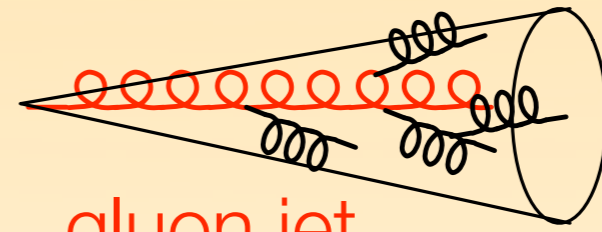
 intuitive definition easy:

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



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

$\sim C_F$



gluon jet
(no flavour)

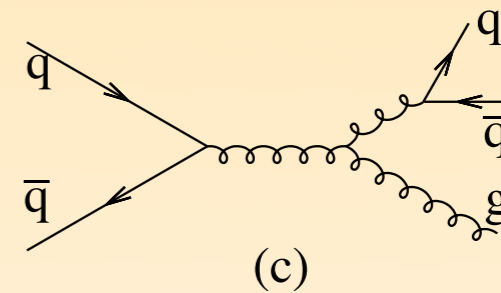
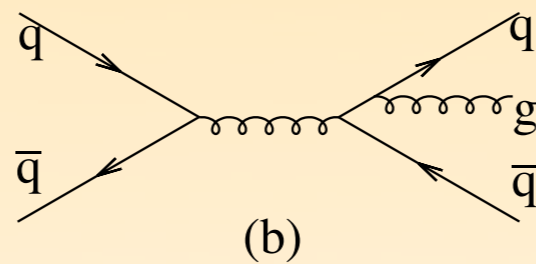
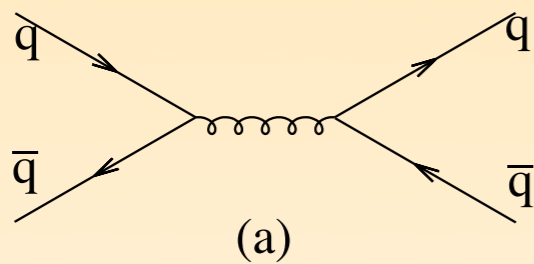
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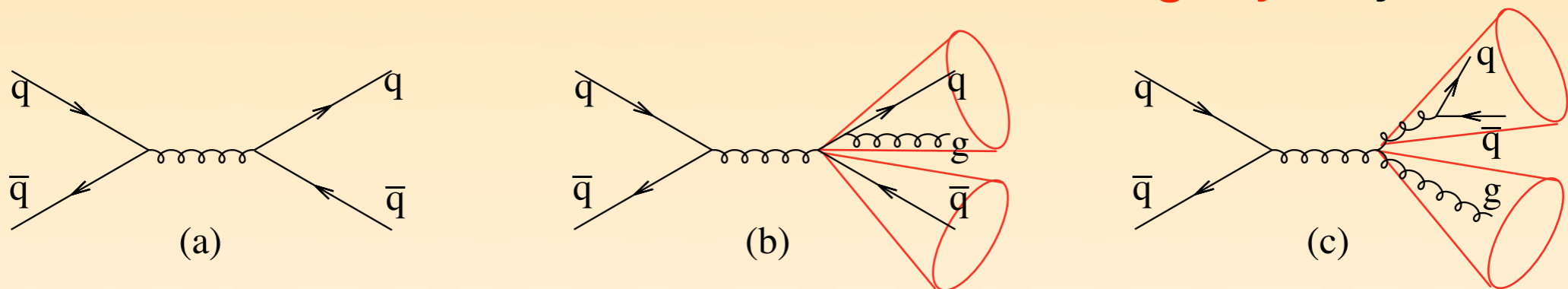
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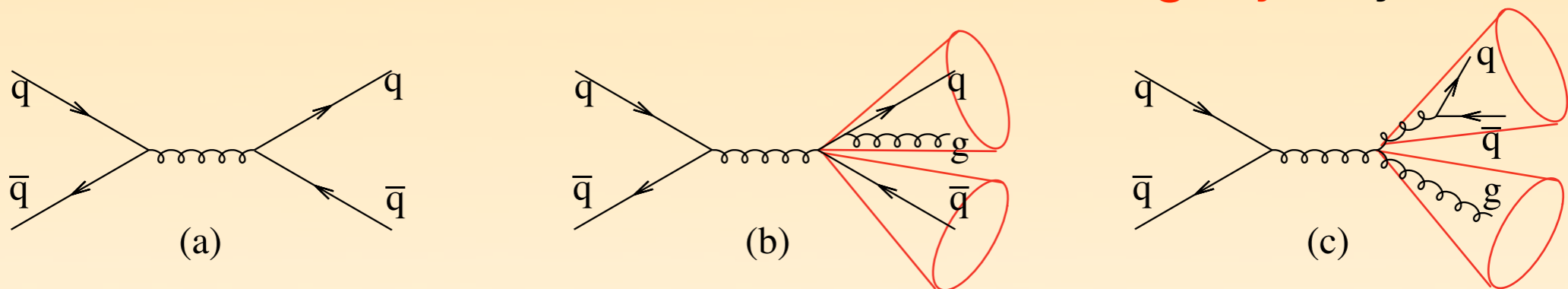
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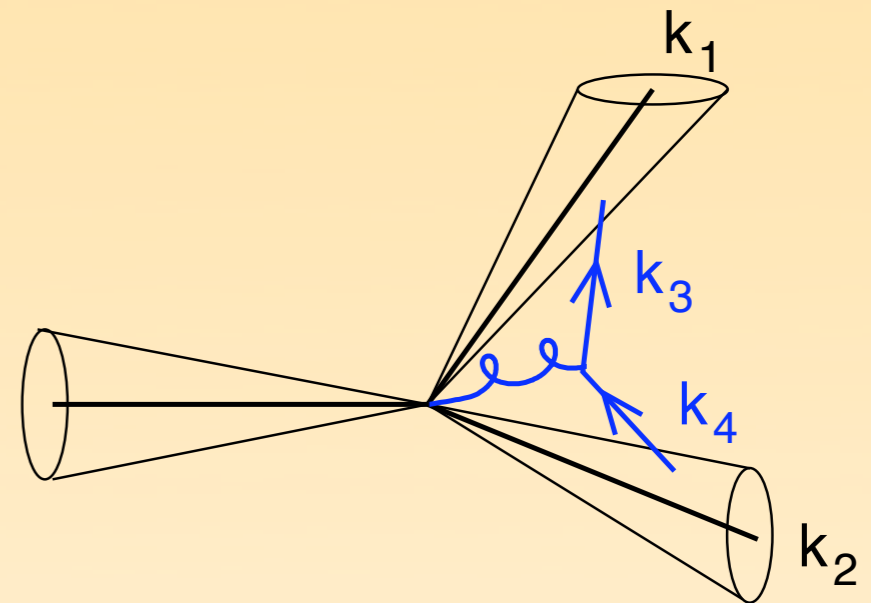
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📌 the problem: the jet-flavour so defined ***IR-unsafe beyond NLO***

Infrared unsafety of jet-flavour

Example:

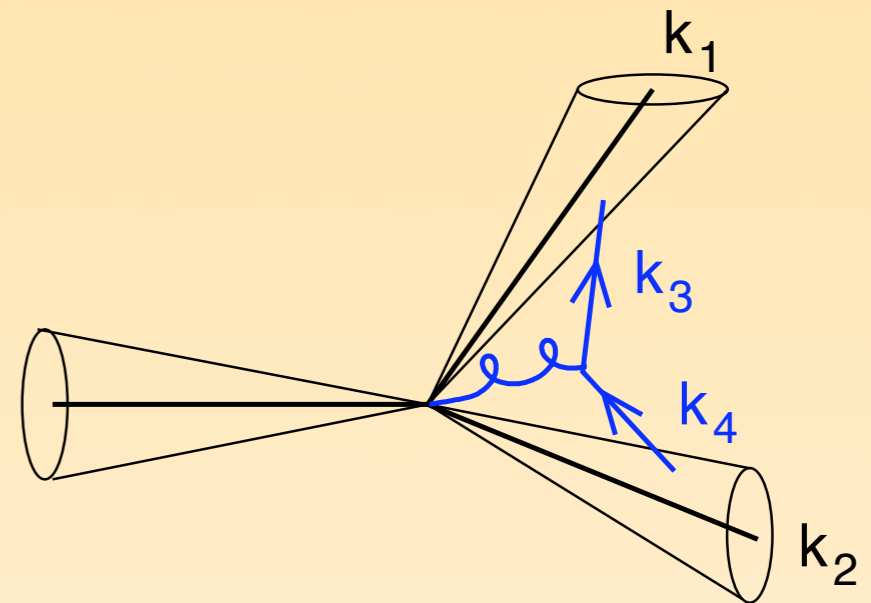
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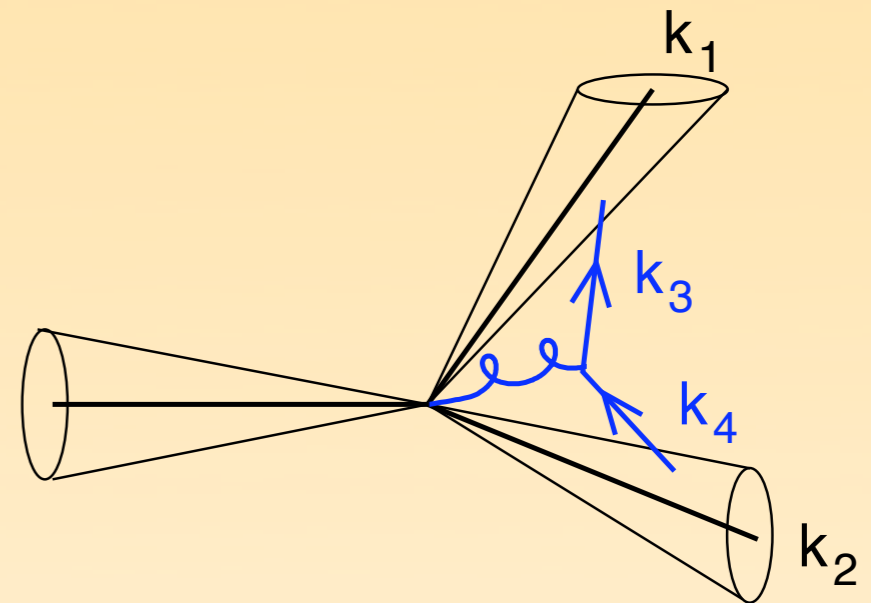


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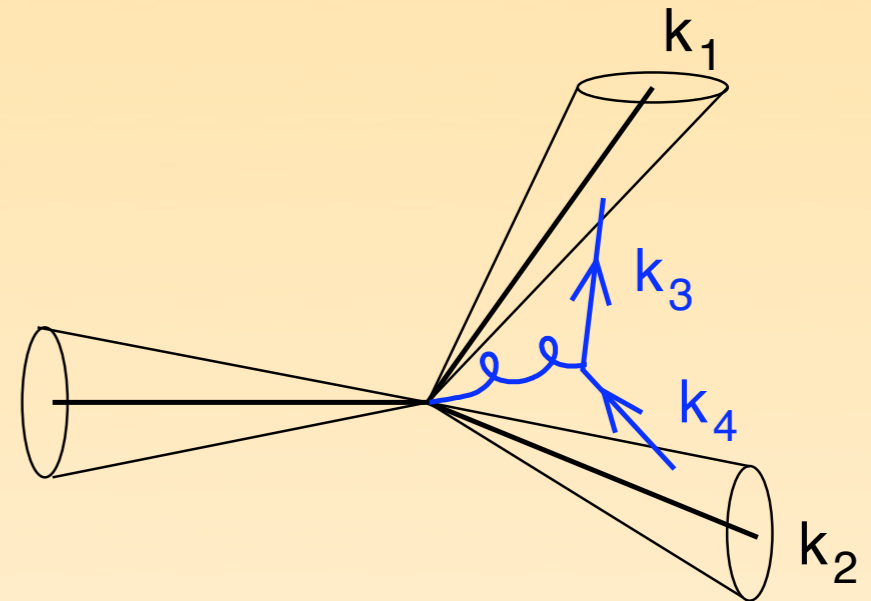
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- 1) how can one define it sensibly, i.e. make it IR-safe ?
- 2) why do we care about jet-flavour \Rightarrow e.g. application to b-jets

Origin of infrared unsafety

Take k_t -algorithm [similar considerations apply to Cone, Cambridge...]
Recombine close particles according to the distance measure

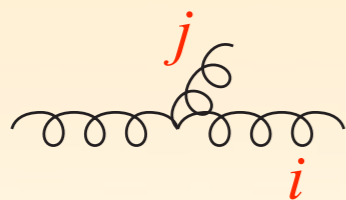
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This distance reflects the structure of the divergences of QCD matrix elements for *gluon emission: soft and collinear divergence*



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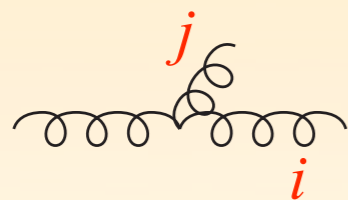
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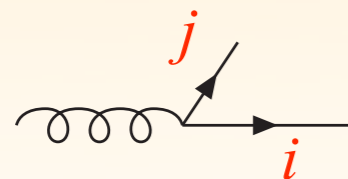
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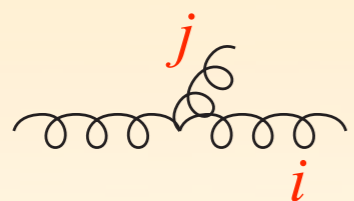
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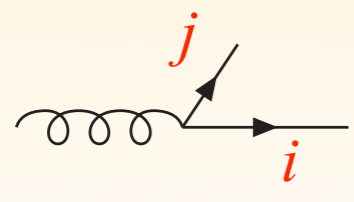
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Infrared safe jet-flavour

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]

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

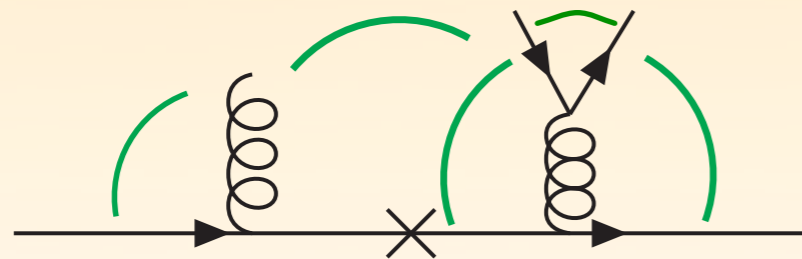
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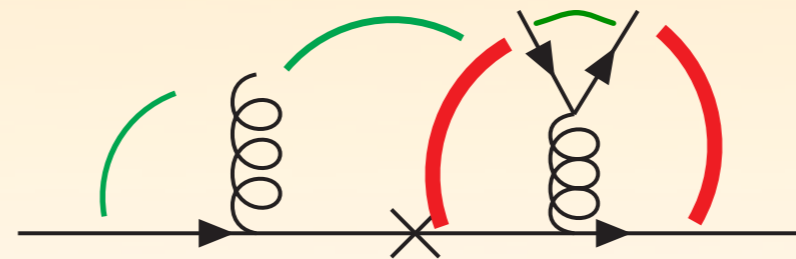
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Normal k_t algorithm



Recombination depends on angle

Flavour k_t algorithm



— small distance
— large distance

Bad recombinations strongly suppressed

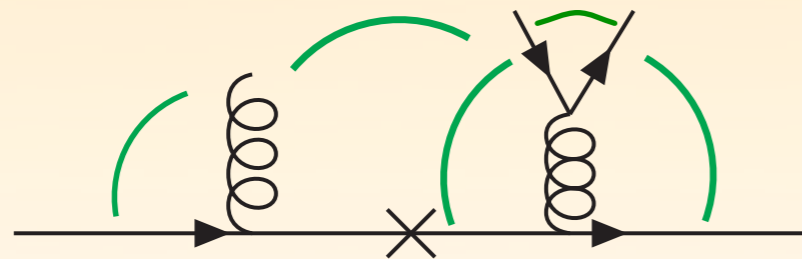
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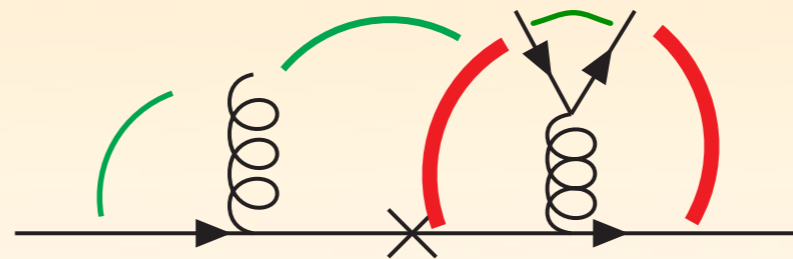
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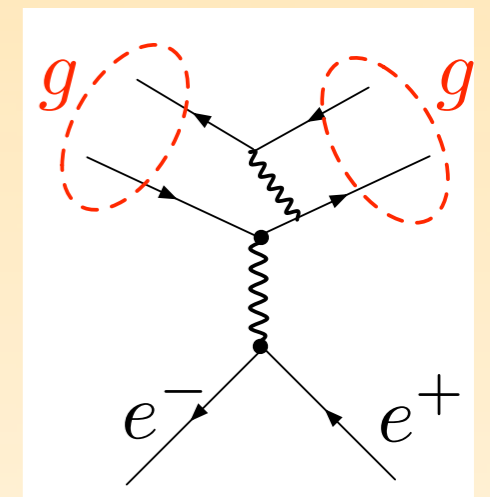
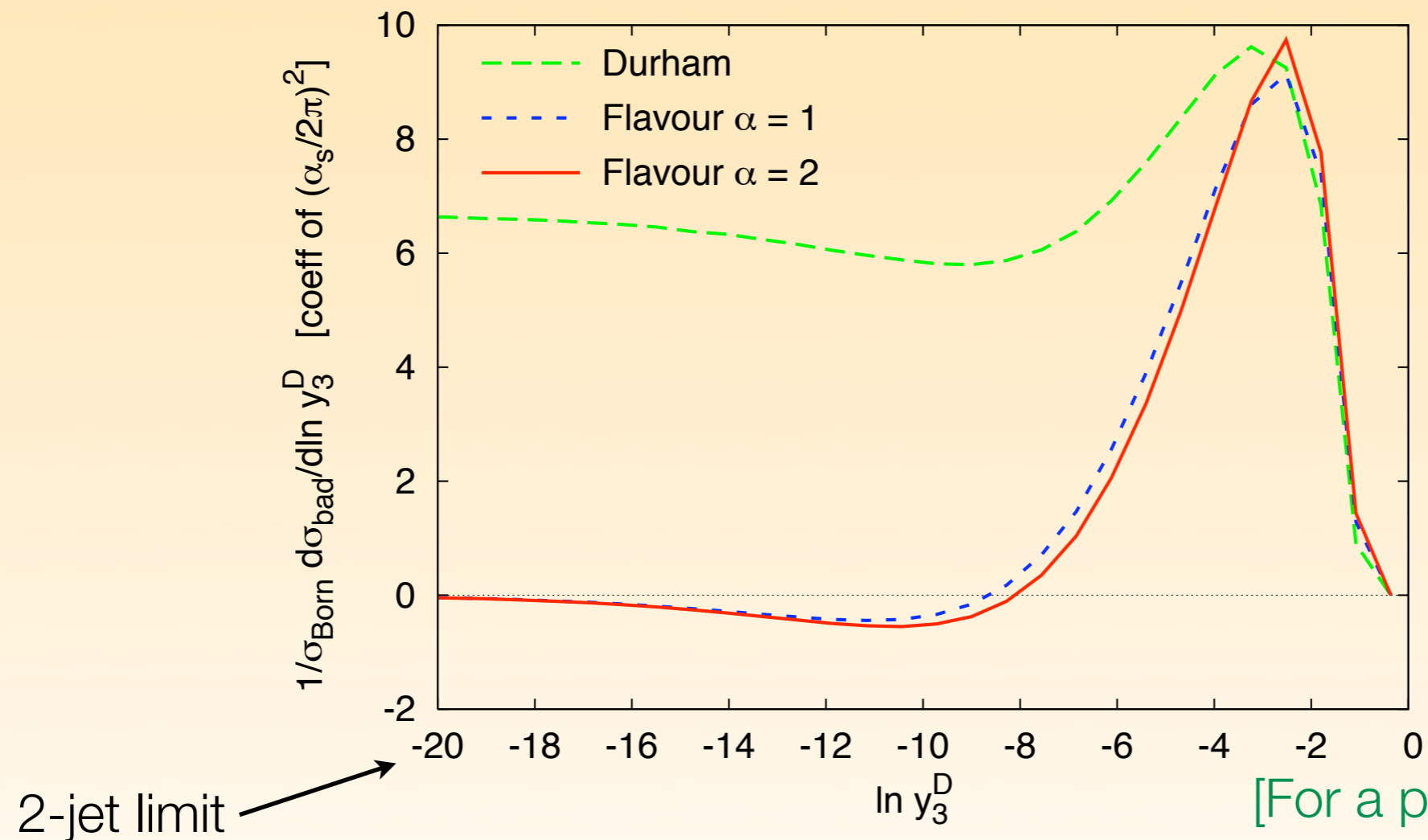
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Infrared safe?

Illustration of IR-safety at fixed order

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



[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:

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

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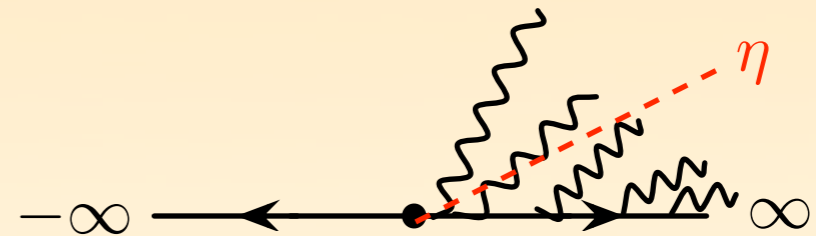
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Transverse scale for beam at positive rapidity:

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

⇒ particles already emitted from the beam



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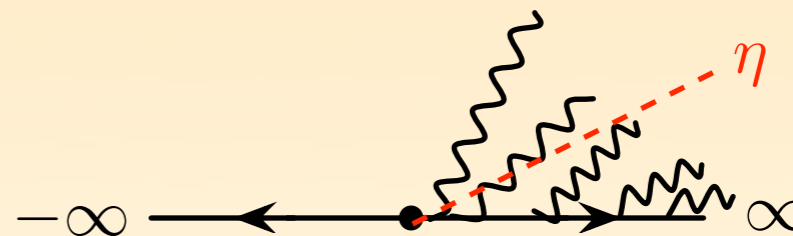
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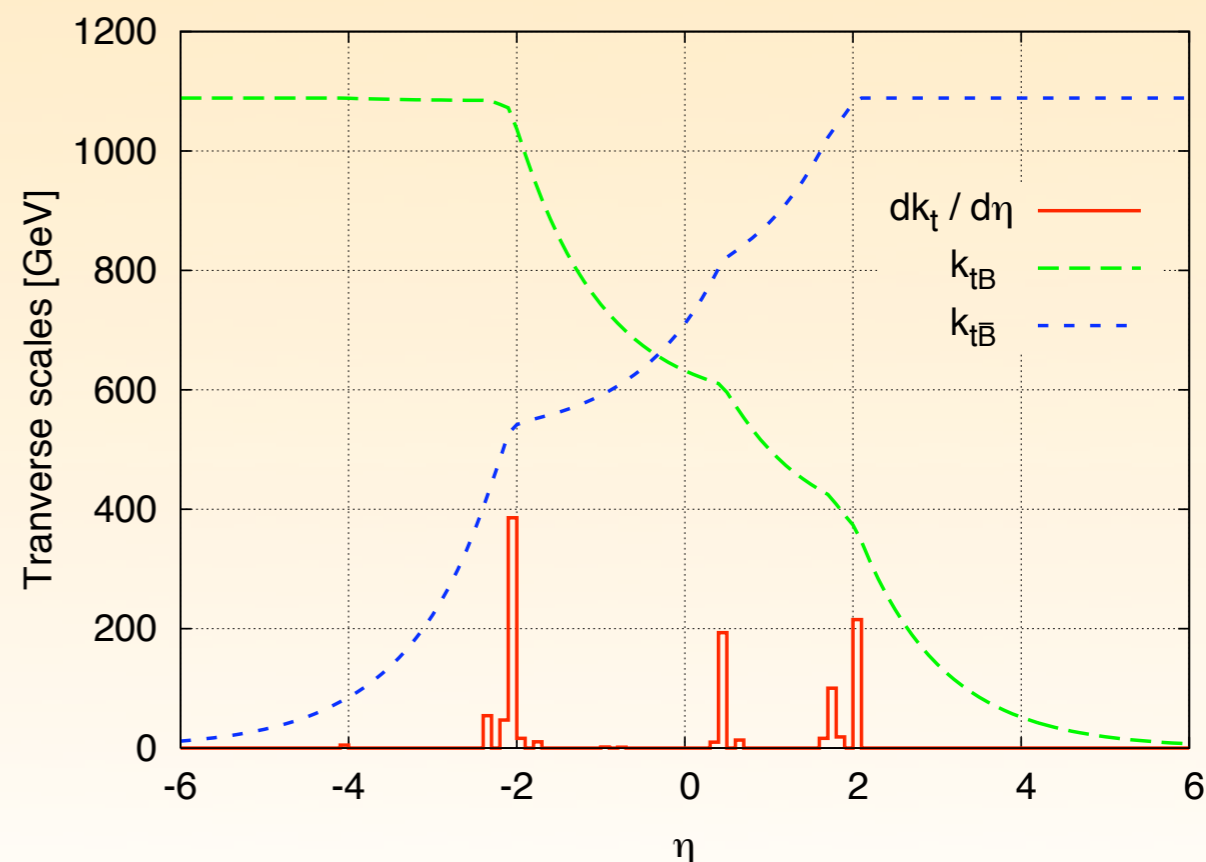
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$$k_{t,B} \equiv k_{t,\text{right}}(\eta) + k_{t,\text{left}}(\eta)$$



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Run flavour algorithm treating as flavourless light quarks and gluons

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How well are b-jets known at hadron colliders?

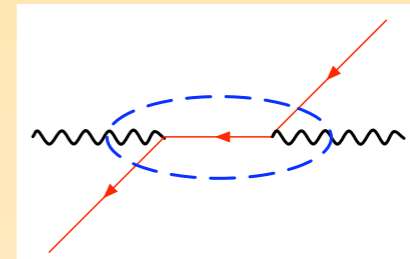
MCFM and MC@NLO predict heavy quark production at NLO

Why do we care then?

NLO heavy quark production mechanisms

At LO:

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

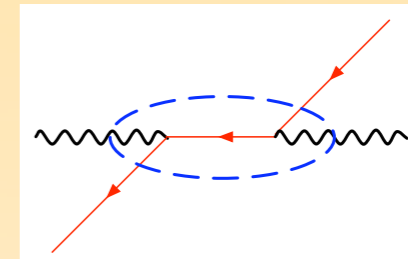


$\mathcal{O}(\alpha_s^2)$

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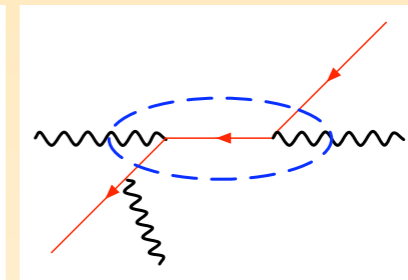
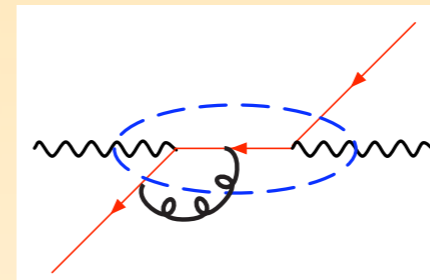
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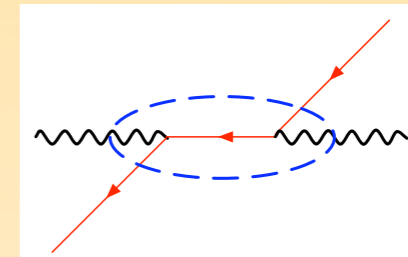
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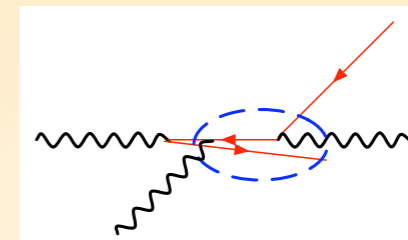
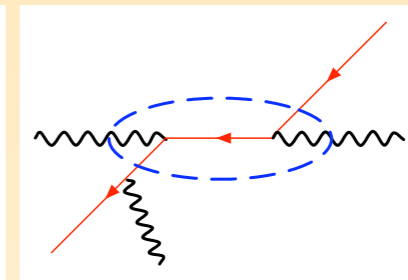
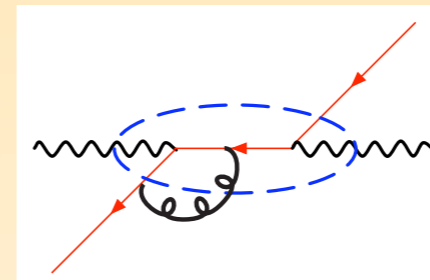
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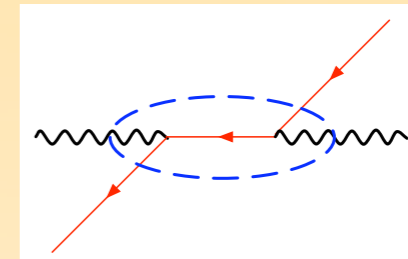
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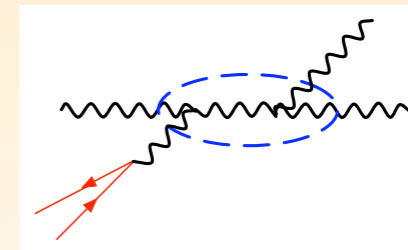
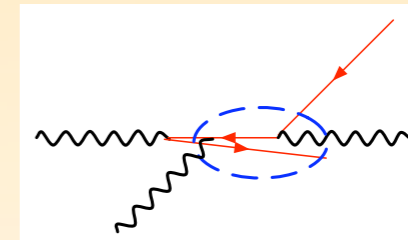
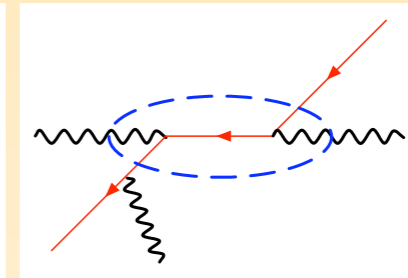
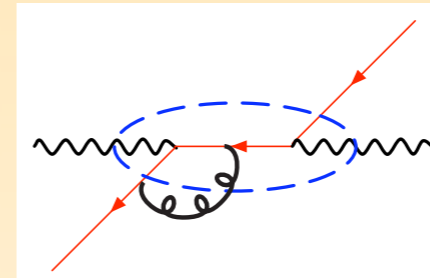
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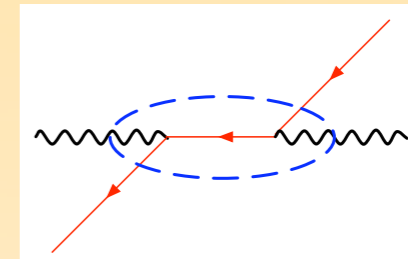
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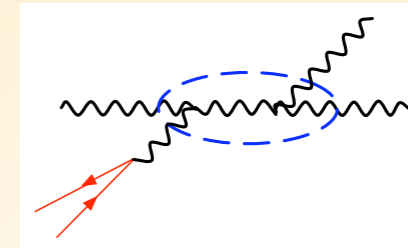
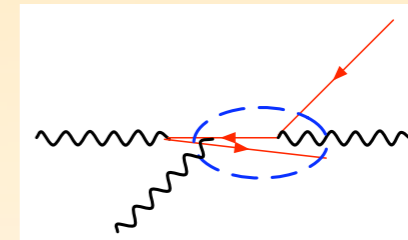
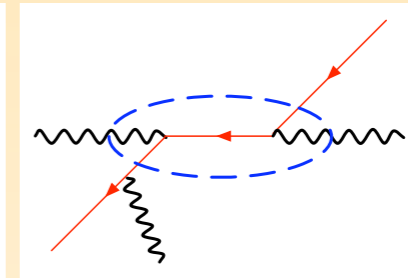
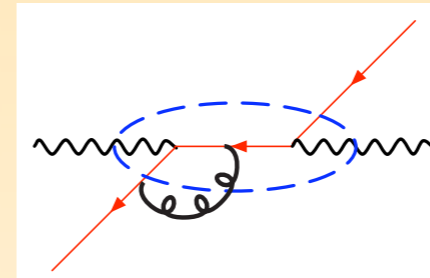
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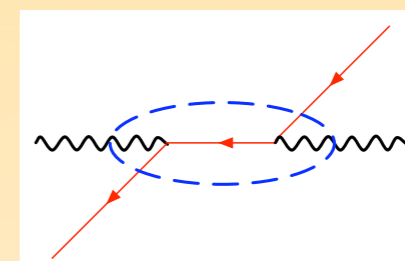


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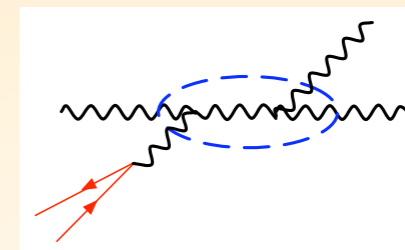
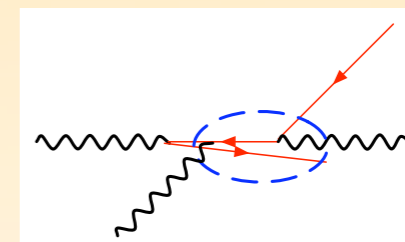
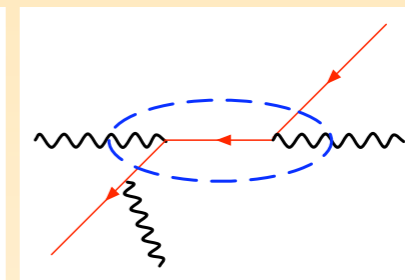
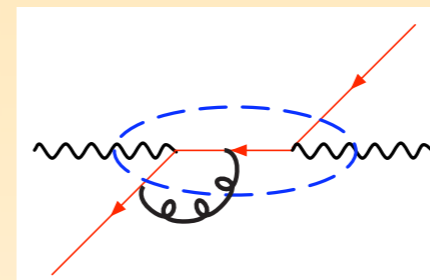
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- ▶ gluon splitting (GSP): $ll \rightarrow l(l \rightarrow b\bar{b})$

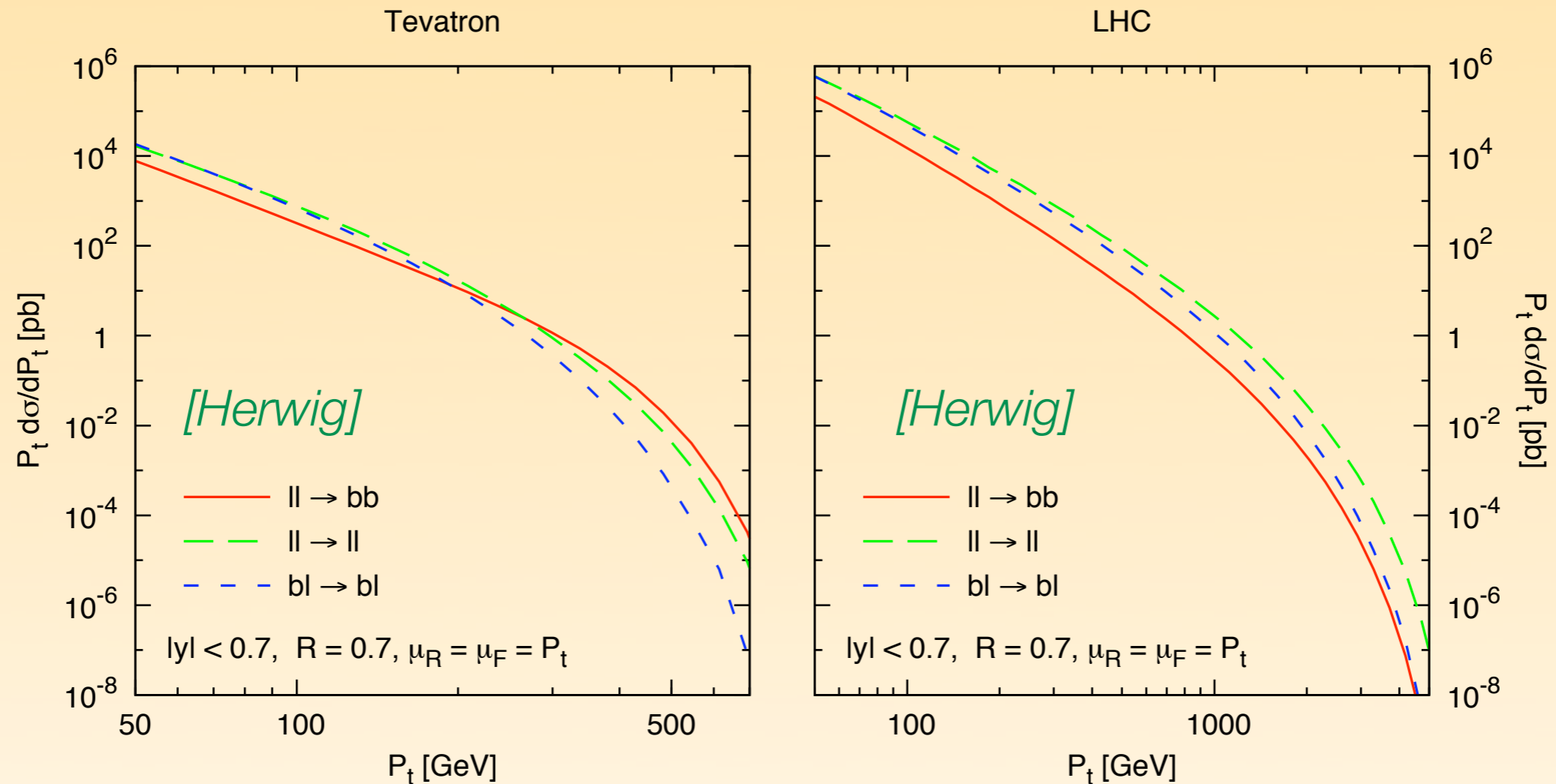


$\mathcal{O}(\alpha_s^3)$

⇒ 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



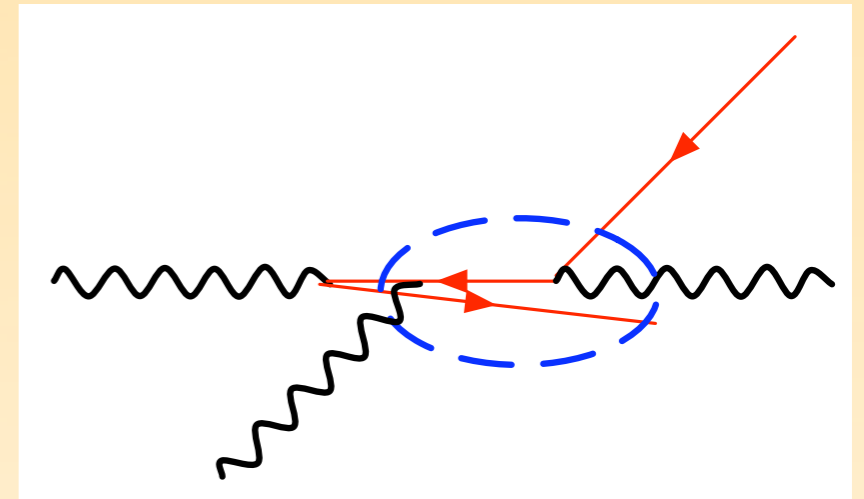
LO channel ($ll \rightarrow b\bar{b}$) nearly always smaller than NLO channels ($ll \rightarrow ll$ and $bl \rightarrow bl$).

Why are higher order channels so large?

Logarithmic enhancements

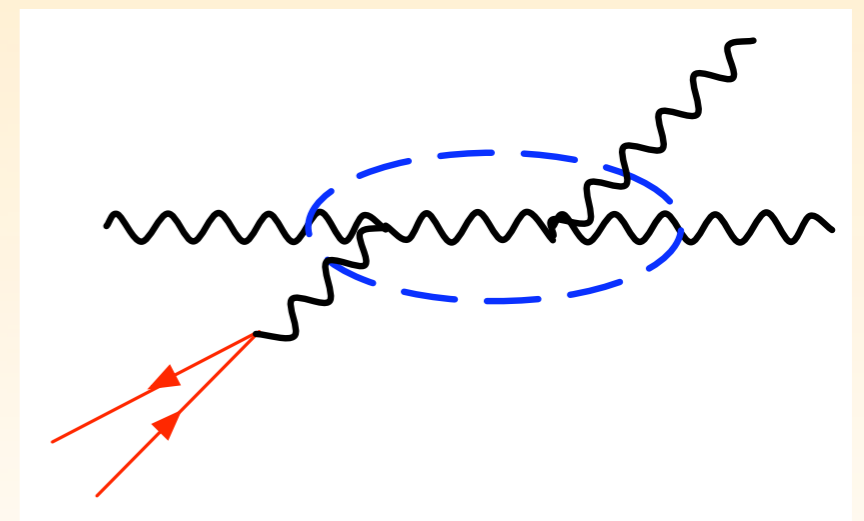
FEX:

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

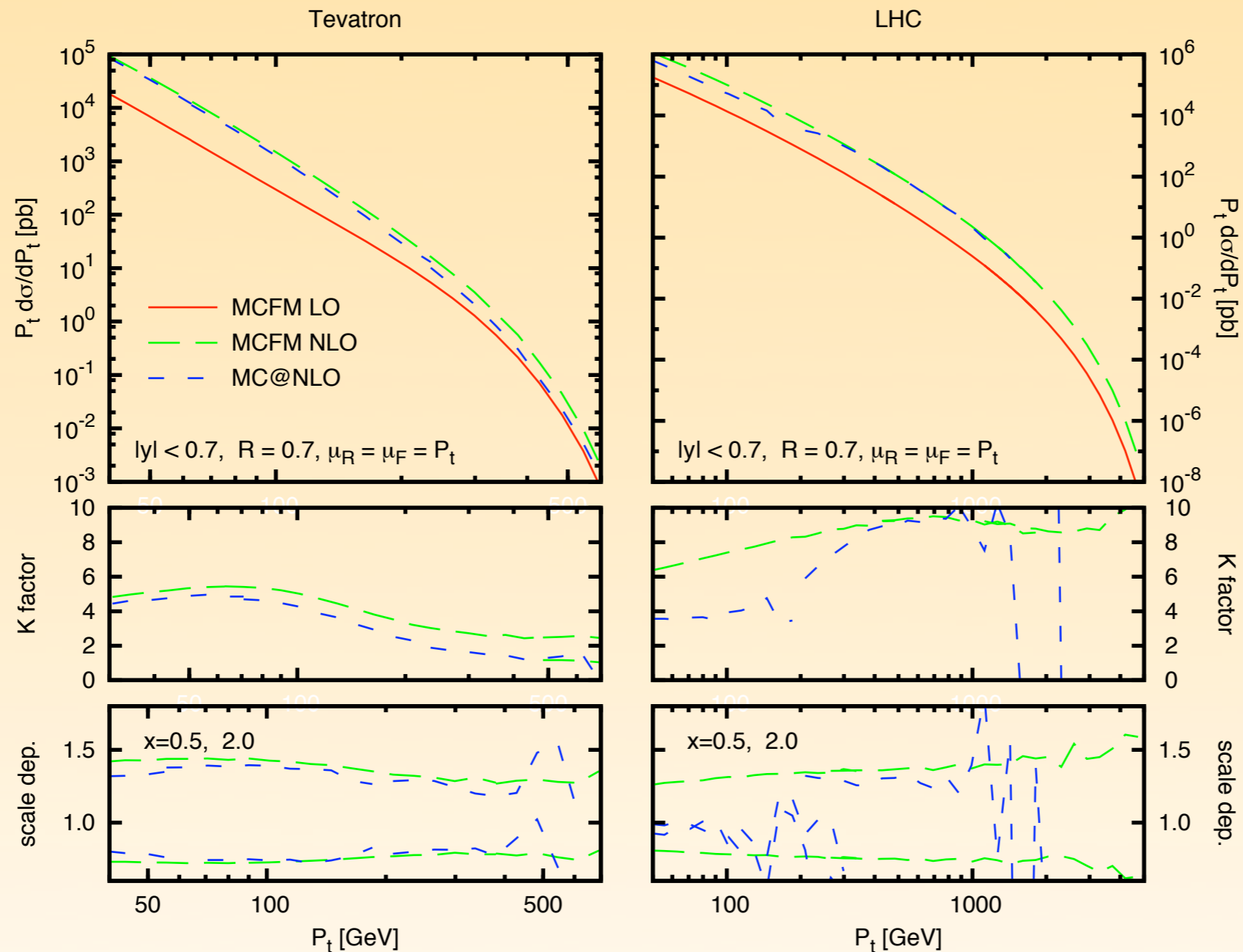


GSP:

- ▶ hard process $\mathcal{O}(\alpha_s^2)$
 - ▶ collinear splitting $\mathcal{O}(\alpha_s \ln(P_t/m_b))$
 - ▶ n soft/collinear gluons $\mathcal{O}((\alpha_s \ln^2(P_t/m_b))^n)$
- $\Rightarrow \mathcal{O}(\alpha_s^2 \cdot \alpha_s^n \ln^{2n-1}(P_t/m_b))$



Inclusive b-jets with standard kt-jet algorithm

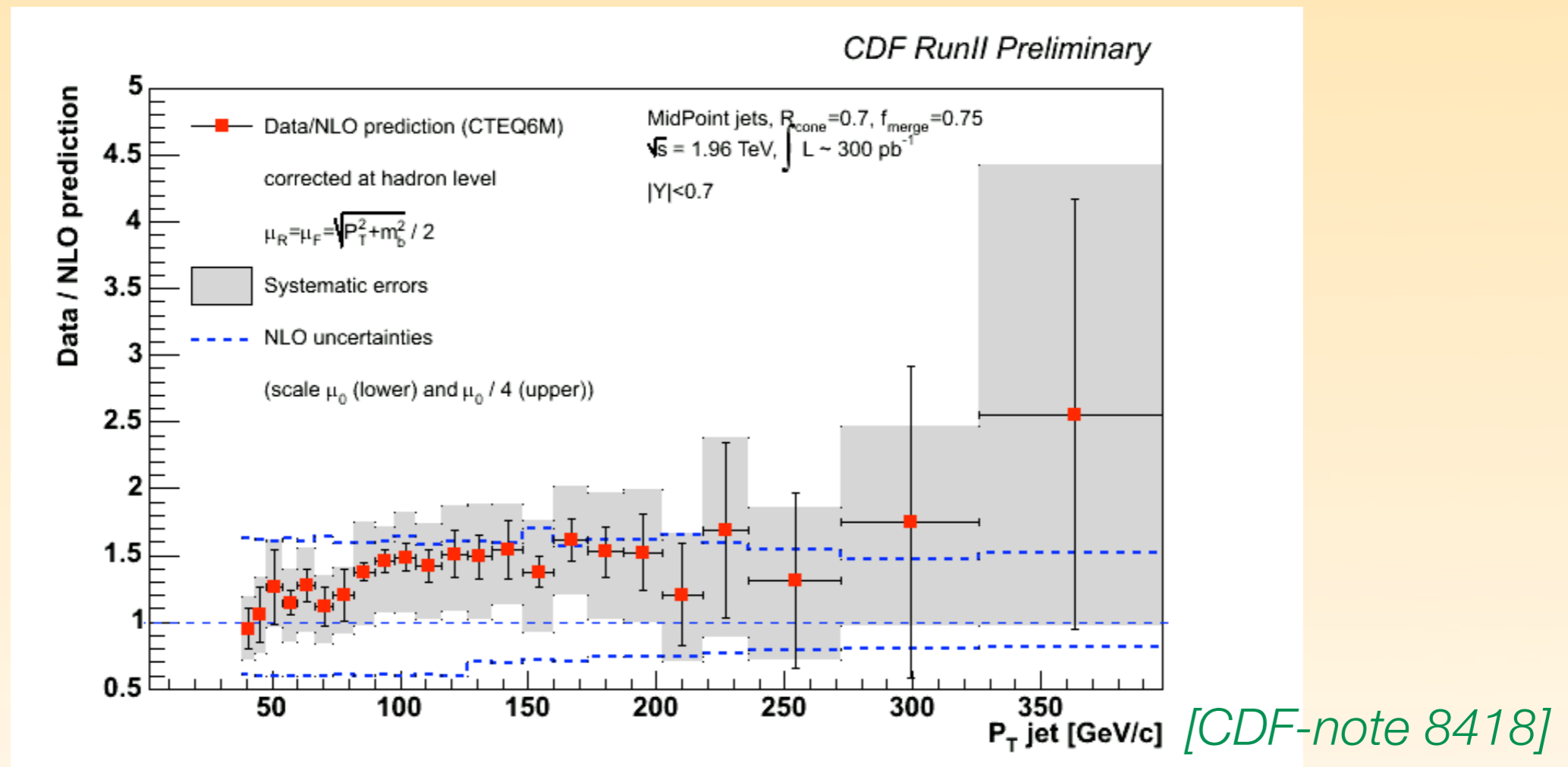


preliminary

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

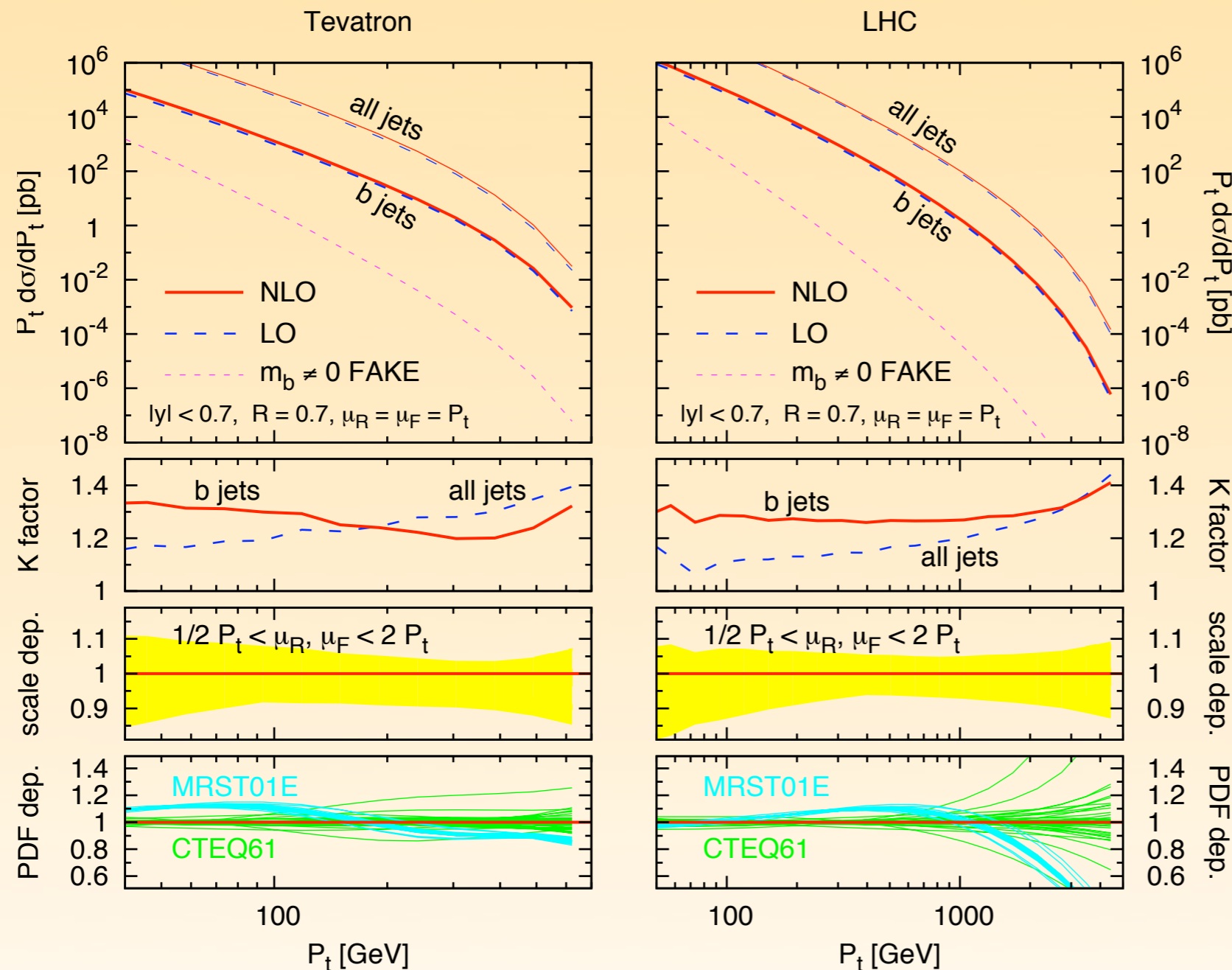
NLO vs data for b-jet inclusive cross section

With standard cone jet-algorithm



⇒ with MC@NLO $\sim 40\text{-}60\%$ uncertainty
experimental errors smaller than theoretical ones

b-jet spectrum with flavour algorithm



preliminary

⇒ NLO moderate effect $\sim 30\%$

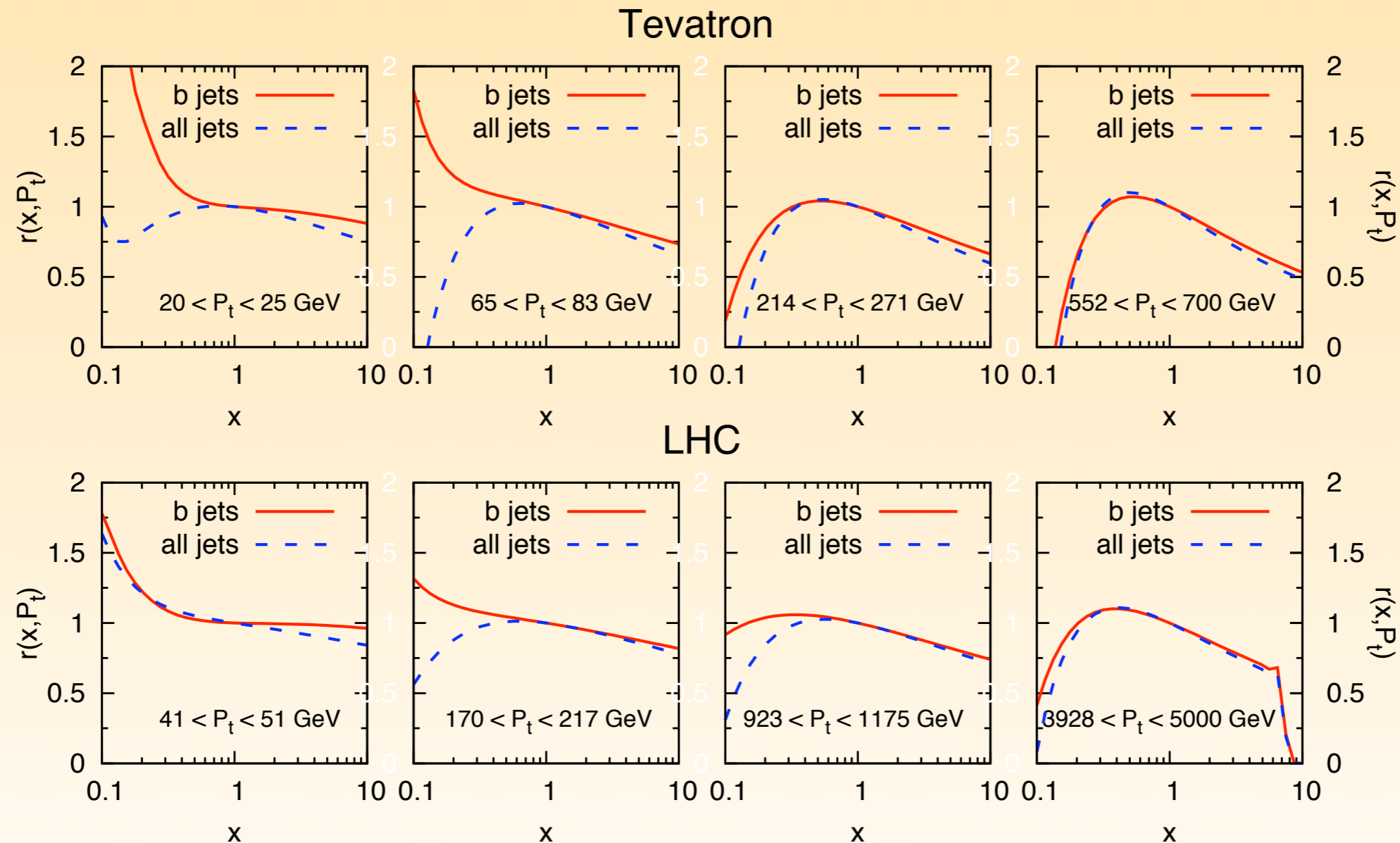
⇒ considerable reduction of TH uncertainties

⇒ 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

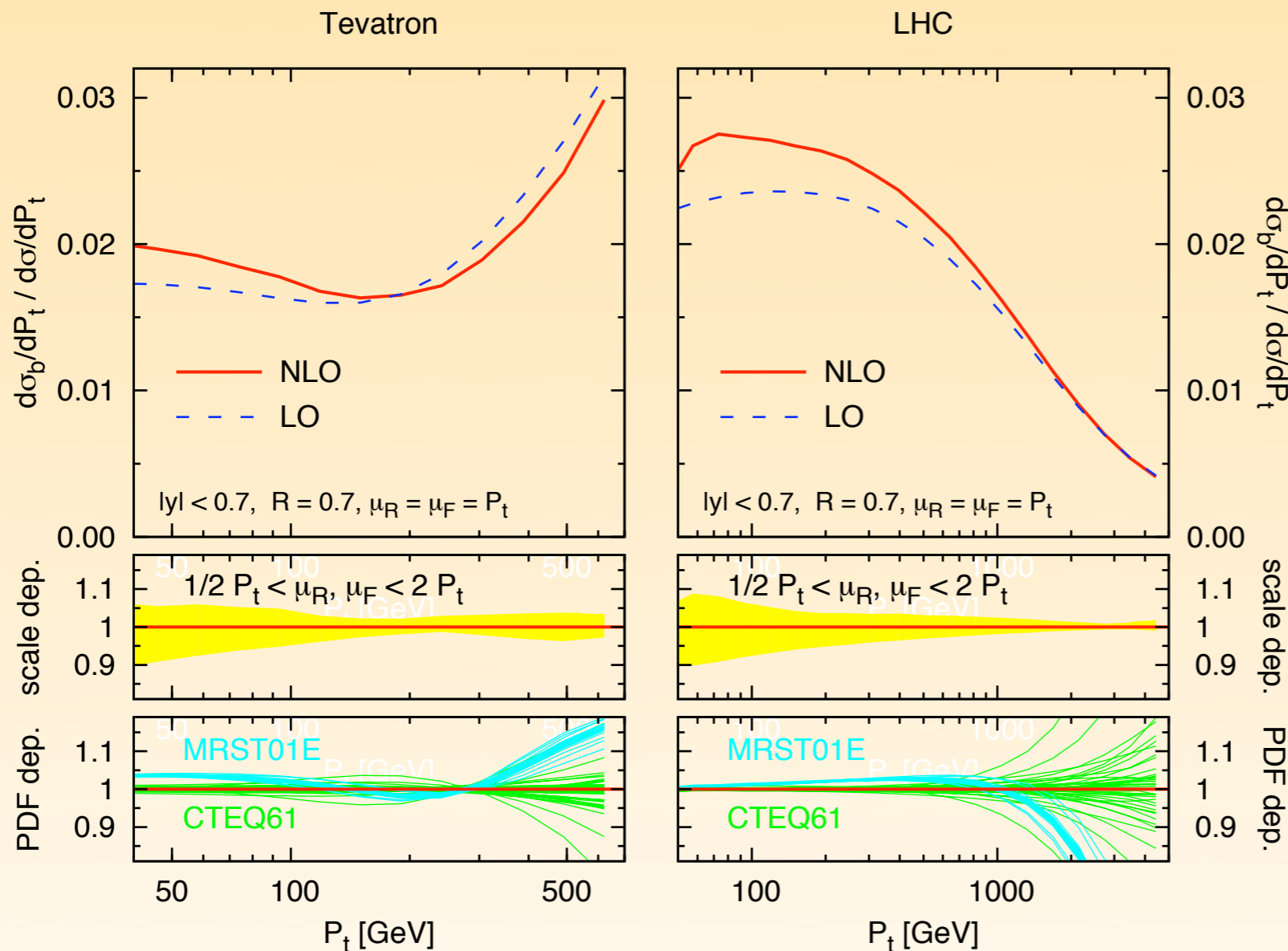
Sensitivity to scale variations

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 P_t



⇒ 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 P_T 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

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- ▶ cross-sections have **large logs** $\alpha_s^2 \cdot (\alpha_s \ln(P_t/m_b))^n$ due to **initial state collinear branchings** (FEX)

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- ▶ **logarithms from initial state gluon branchings** to $b\bar{b}$ can be resummed in b -PDFs

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- ▶ 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

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

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

☞ match multi-leg NLO with analytical resummations

[e.g. CAESAR+NLOJET]

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[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_{FB}^b , see Weinzierl '06]

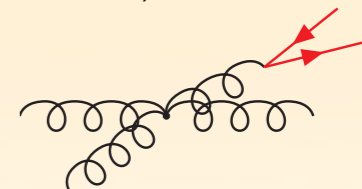
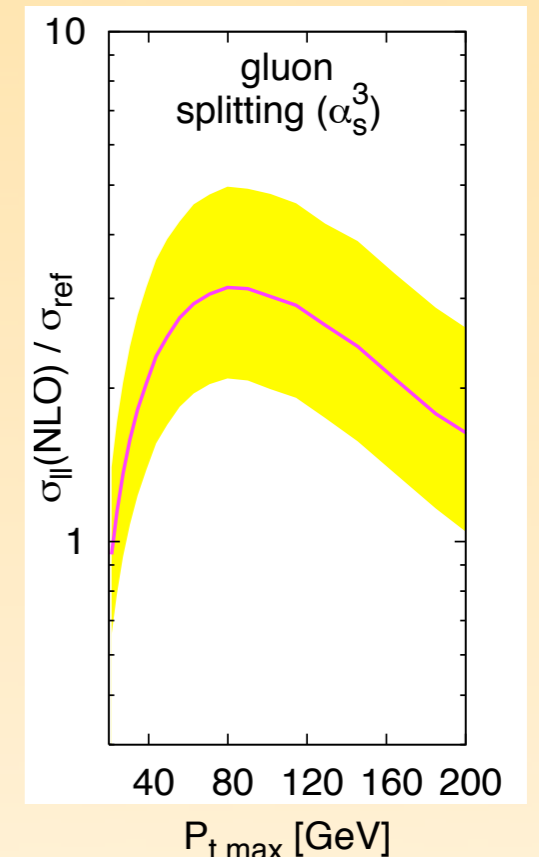
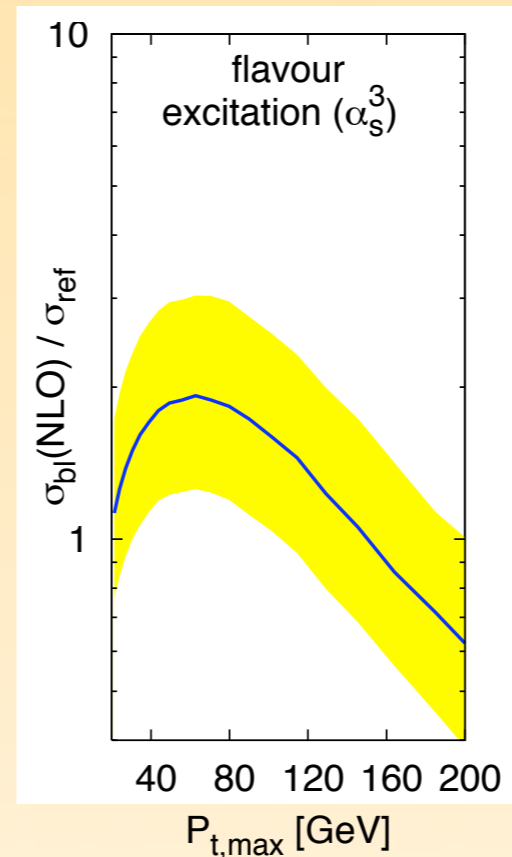
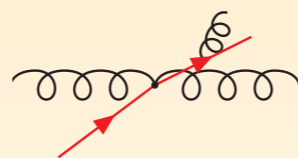
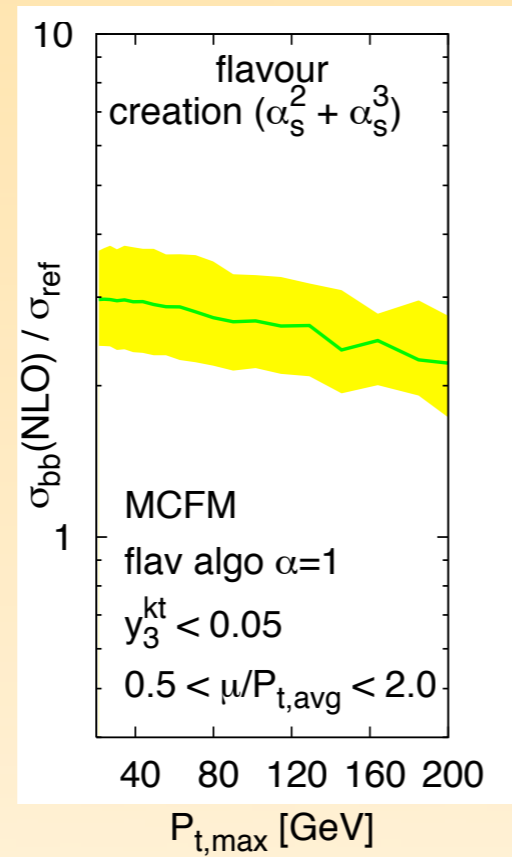
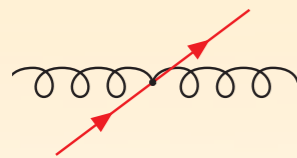
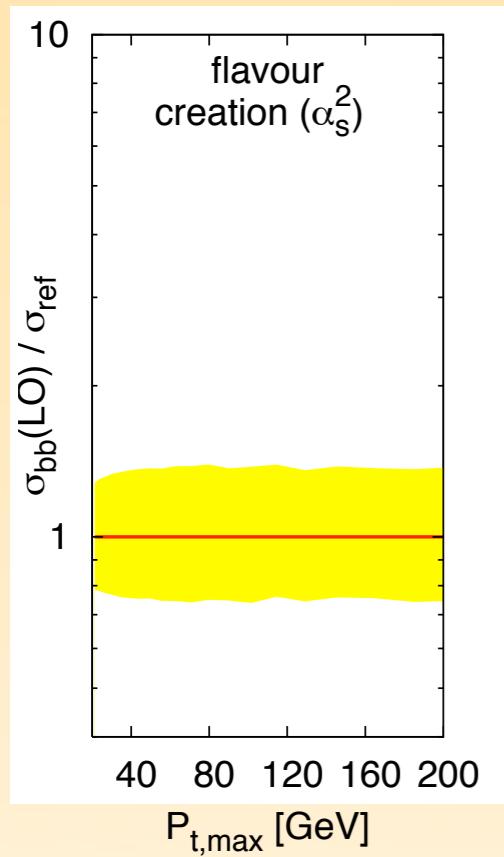
Conclusions

- ☑ 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%

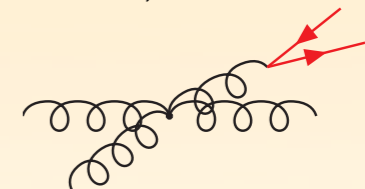
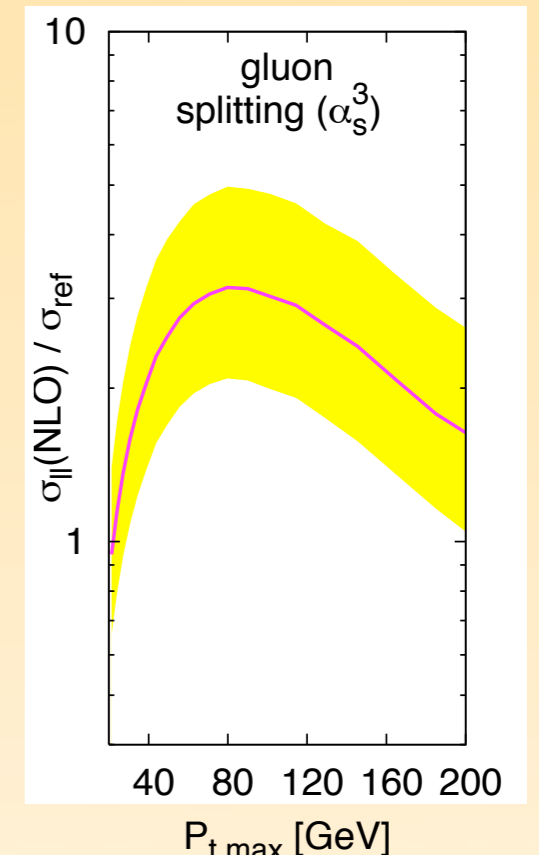
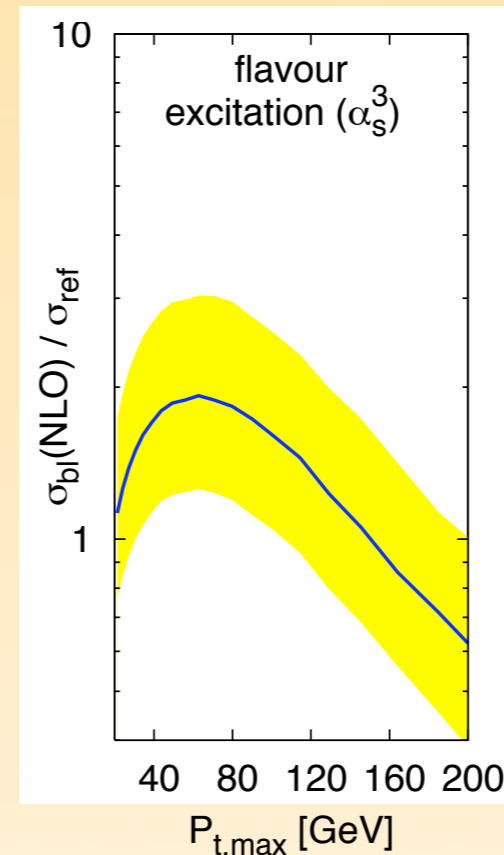
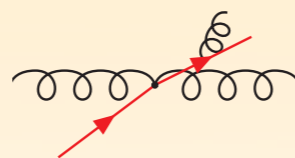
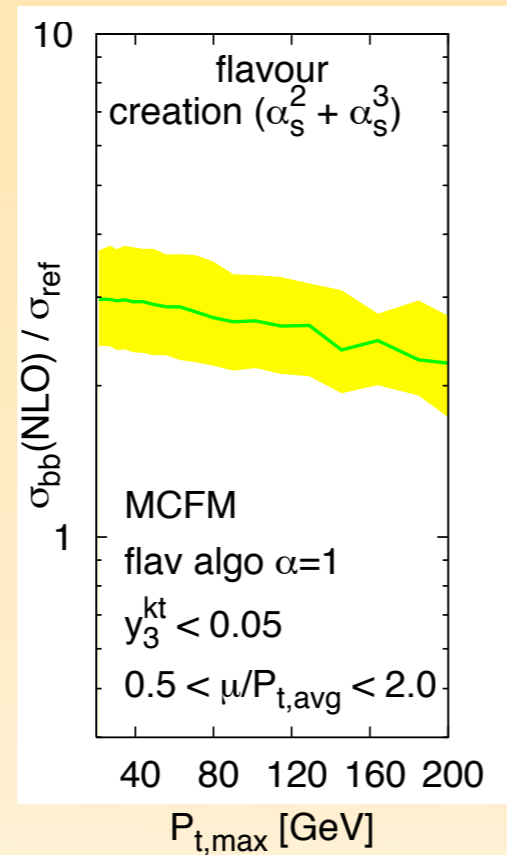
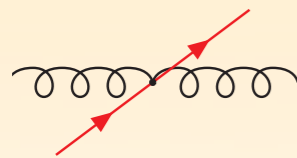
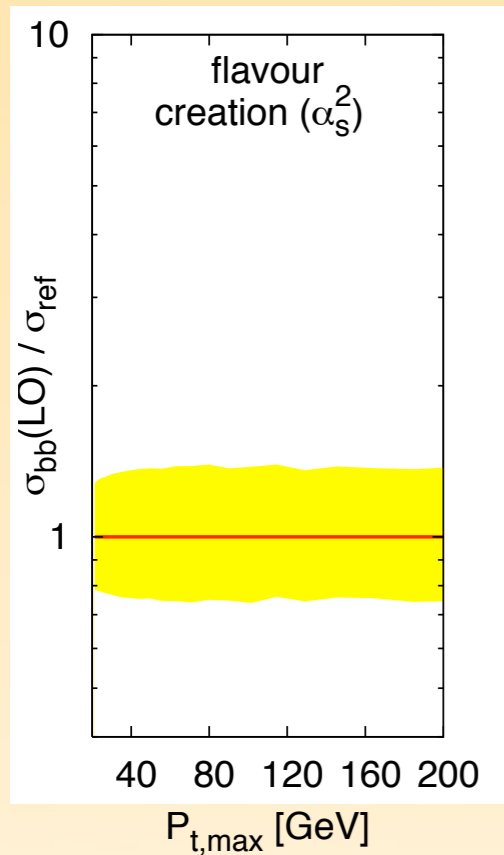
We look forward to further experimental investigations in this direction

Extra slides

b-production

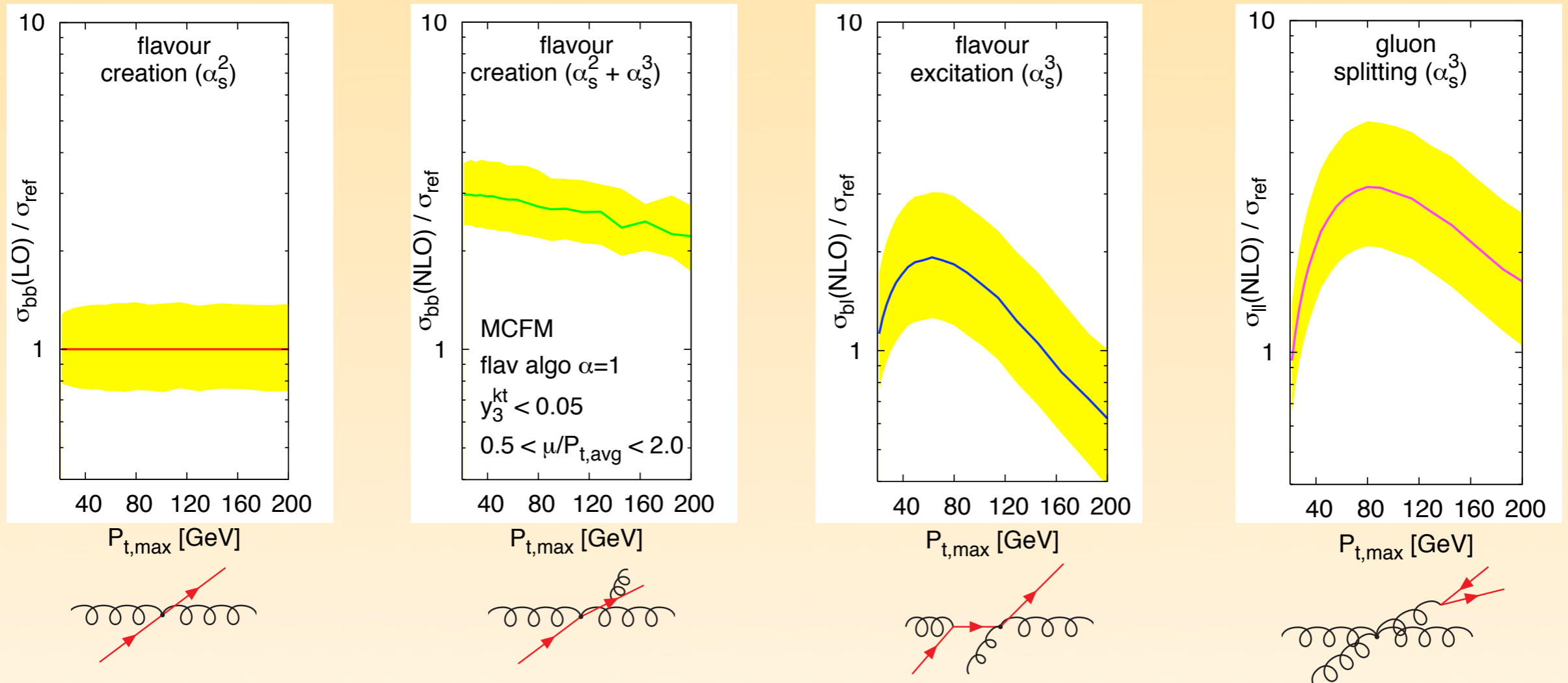


b-production



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

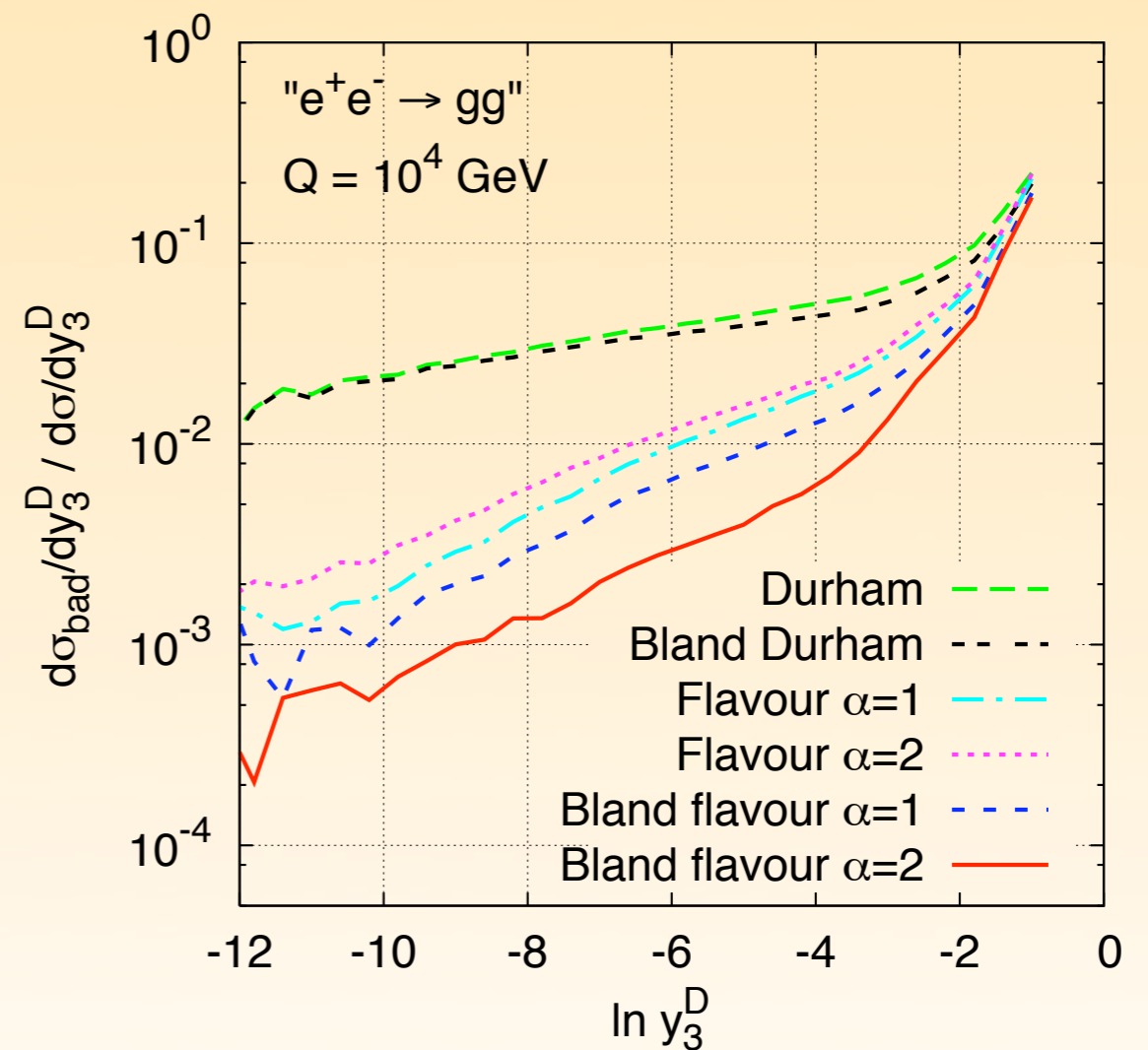
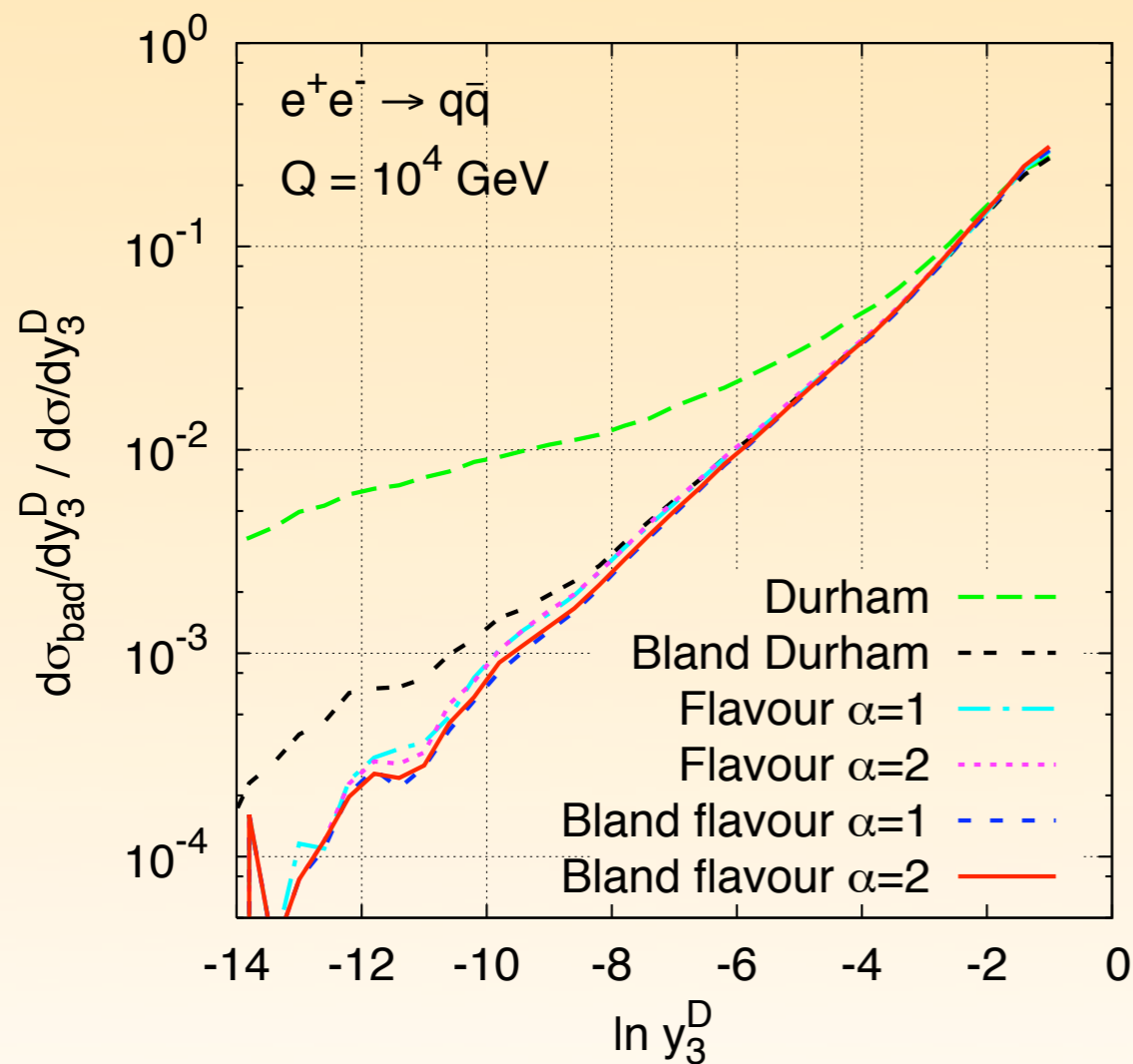
b-production



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

All-order IR-safety

Flavour misidentification of $ee \rightarrow qq$ (gg) events with Herwig



All-order IR-safety

Flavour misidentification of $qq \rightarrow qq, qg, gg$ events

