Accurate predictions for heavy-quark jets at the Tevatron and LHC

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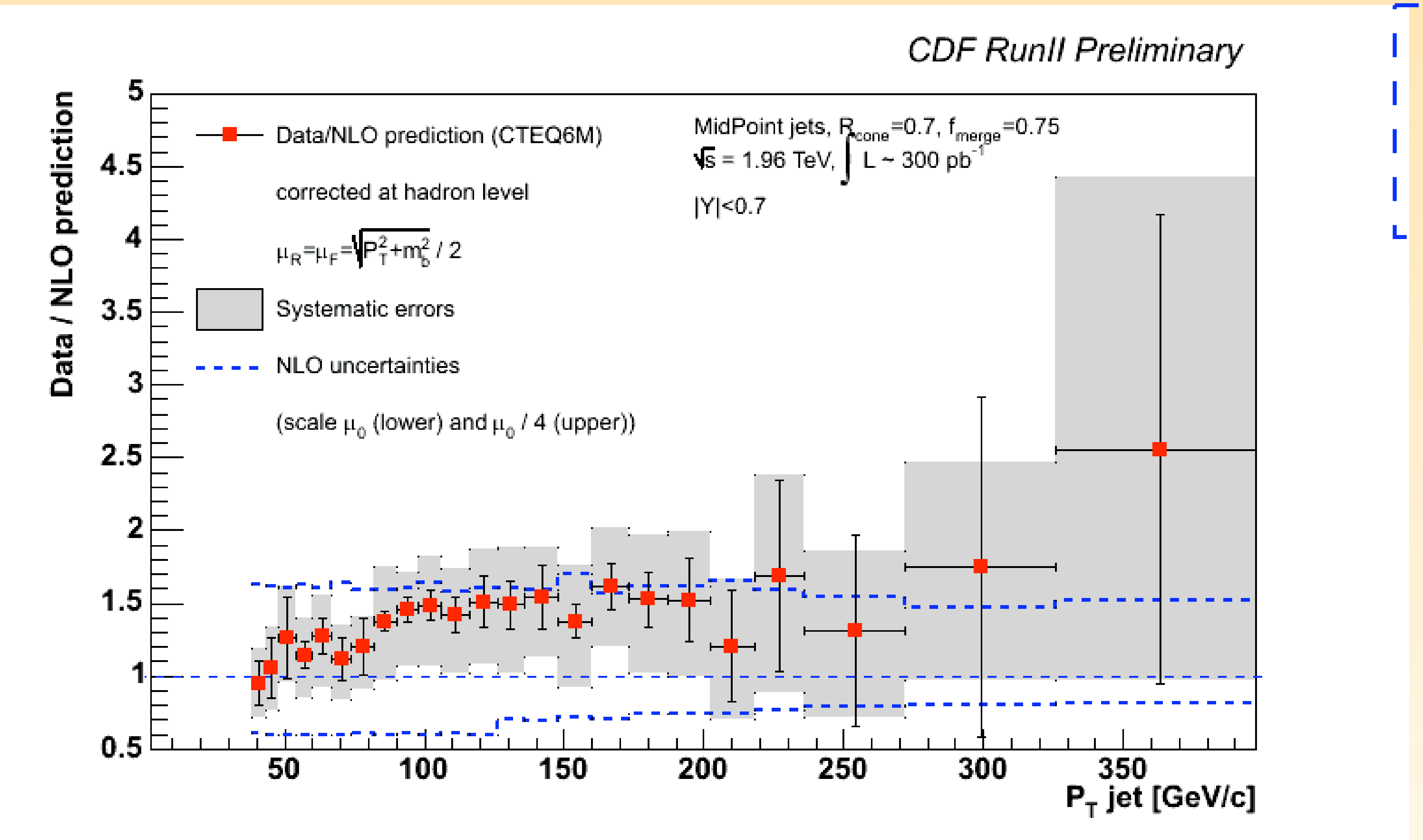
work done in collaboration with Andrea Banfi and Gavin Salam

Motivation

NLO vs data for b-jet inclusive cross section



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

[CDF-note 8418]

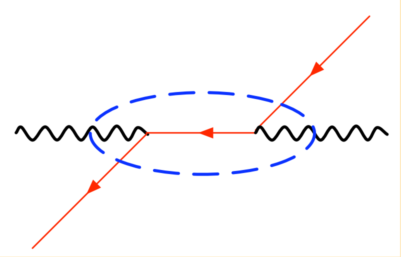
⇒ NLO calculation (MC@NLO) has ∼40-60% uncertainty

experimental errors smaller than theoretical ones

NLO heavy quark production mechanisms

At LO:

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



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

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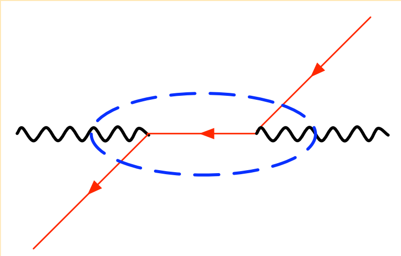

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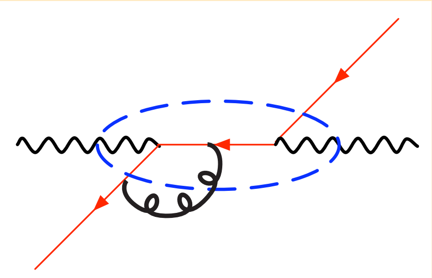

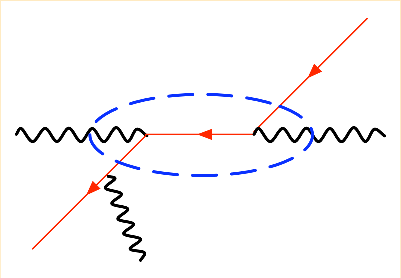

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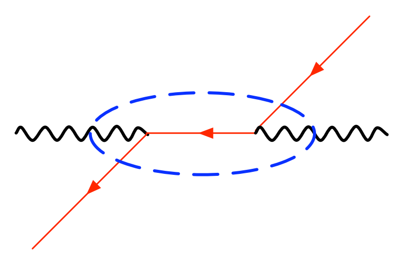

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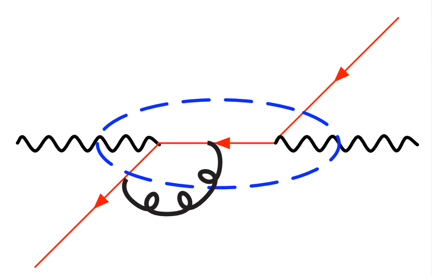

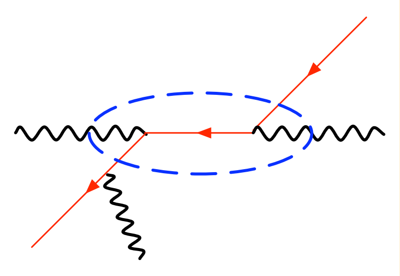

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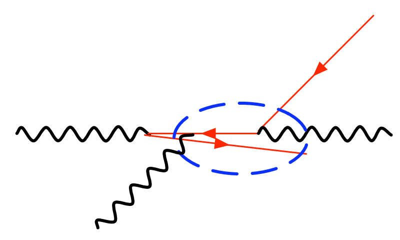

- flavour excitation (FEX): $l(l \to b\bar{b}) \to lb\bar{b}$

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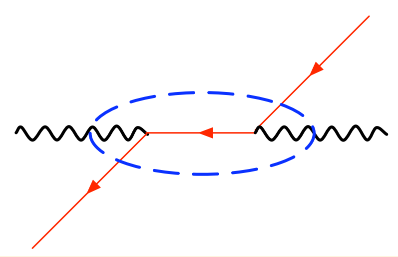

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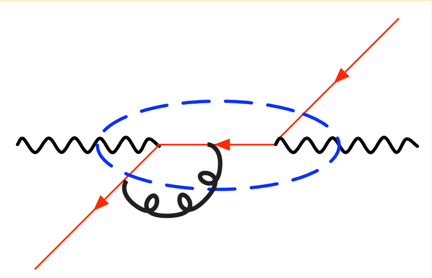

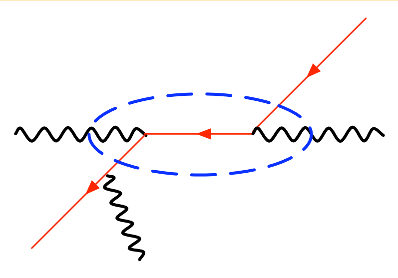

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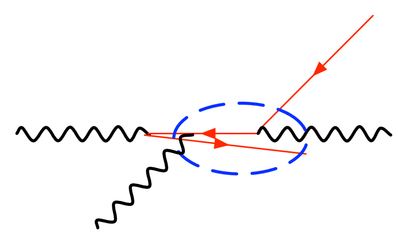

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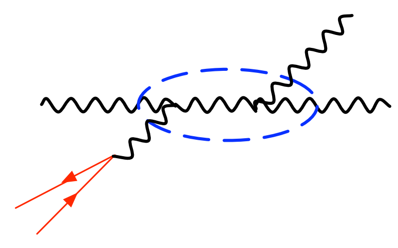

- gluon splitting (GSP): $ll \to l(l \to b\bar{b})$

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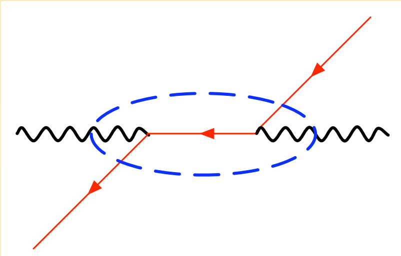

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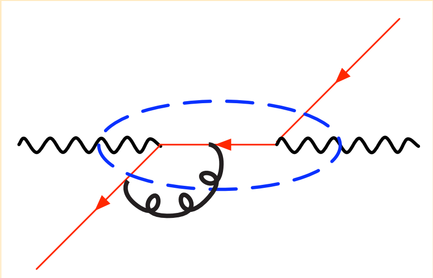

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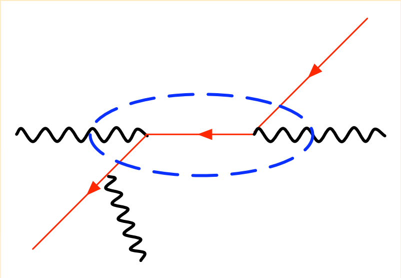

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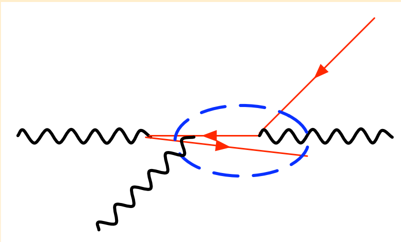

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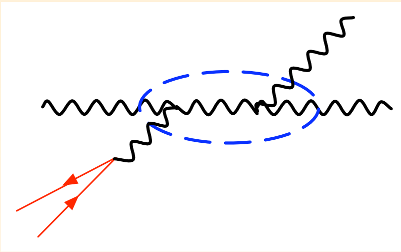
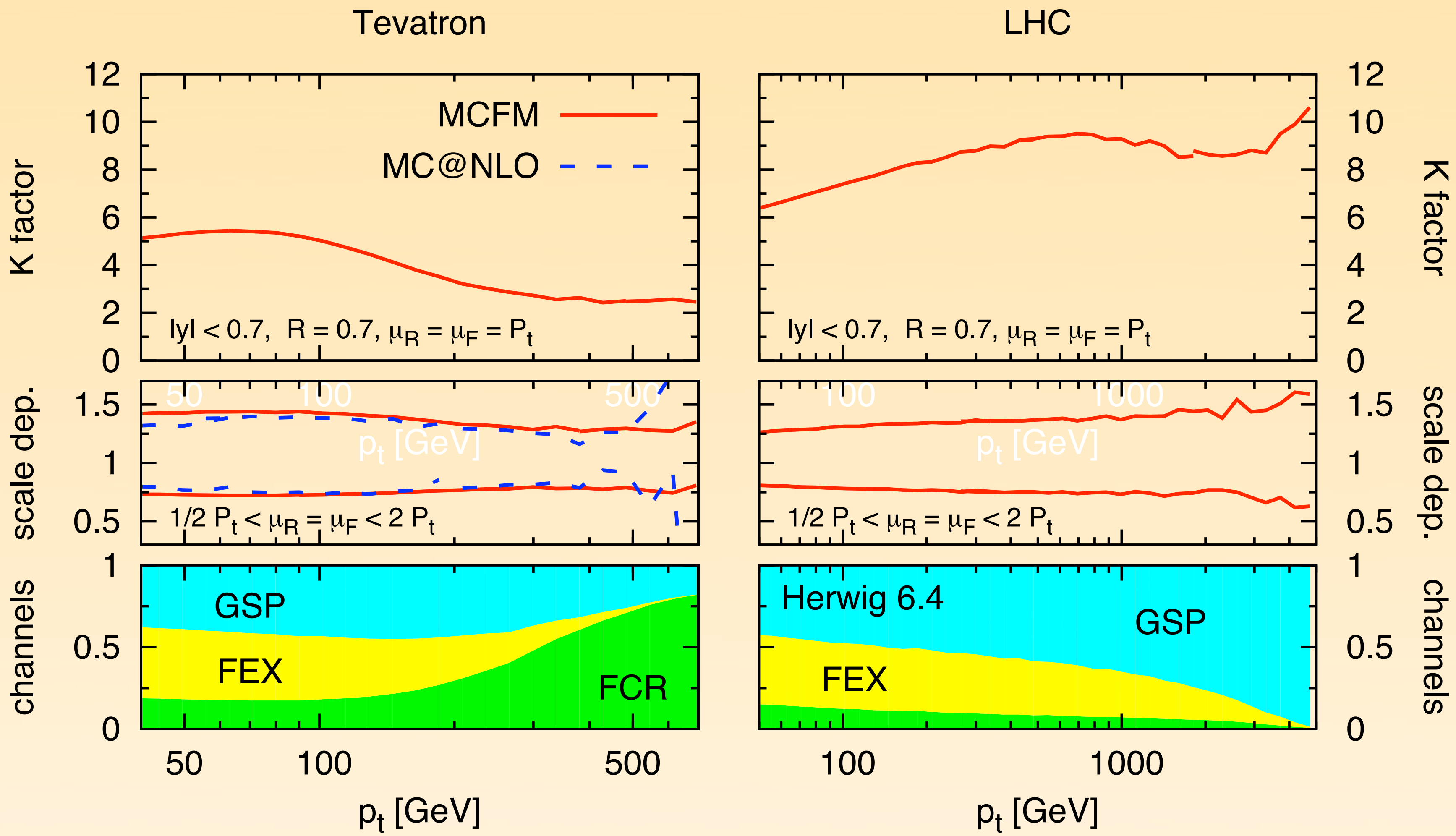


$\mathcal{O}(\alpha_s^3)$

$\Rightarrow$ two new channels open up at NLO

How important are those contributions?

NLO decomposition of b-jet spectrum



⇒ LO channel (FCR) nearly always smaller than NLO channels (GSP and FEX)

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

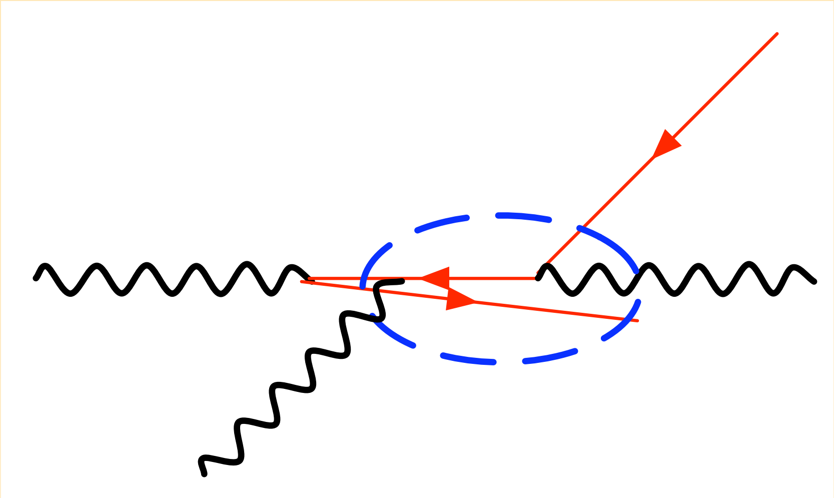
Why are higher order channels so large?

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

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



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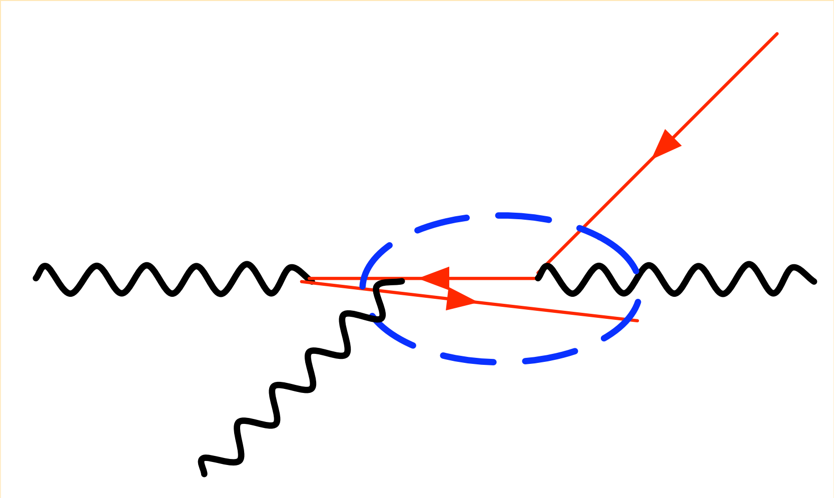
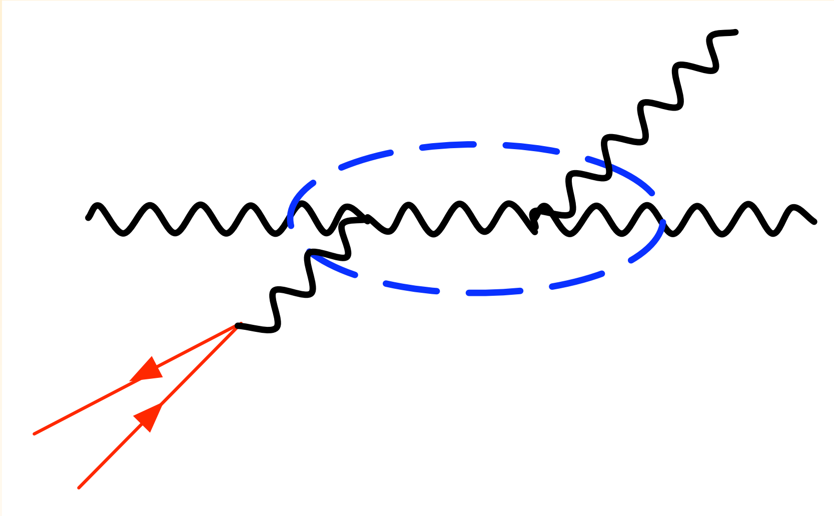


GSP:

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

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



Logarithmic enhancements

- origin of logarithms: collinear splittings of gluons into bb-pairs
- could eliminate these logarithms by defining a b-jet as a jet containing a net-number of b-quarks, i.e. remove gluon jets from b-jet spectra
- this would only partially cure the problem. Infrared logarithms due soft to large angle bb-pairs would survive.

⇒ switch instead to *an infrared safe flavour-kt algorithm*

Standard kt-algorithm

k_t-algorithm: recombine close particles according to distance measure

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

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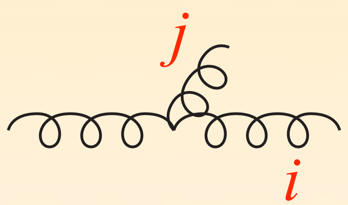
This distance reflects the structure of the divergences of QCD matrix elements for *gluon emission: soft and collinear divergence*



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

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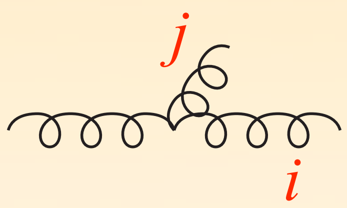

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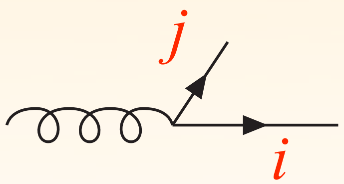

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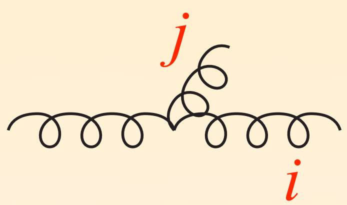

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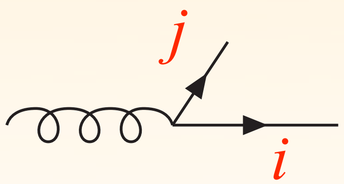

$$\sim \frac{\alpha_s T_R}{\pi}\frac{d\theta^2}{\theta^2}\frac{dE_j}{\max\{E_i, E_j\}} \qquad E_j \ll E_i,\ \theta \ll 1$$

Infrared safe flavour-algorithm

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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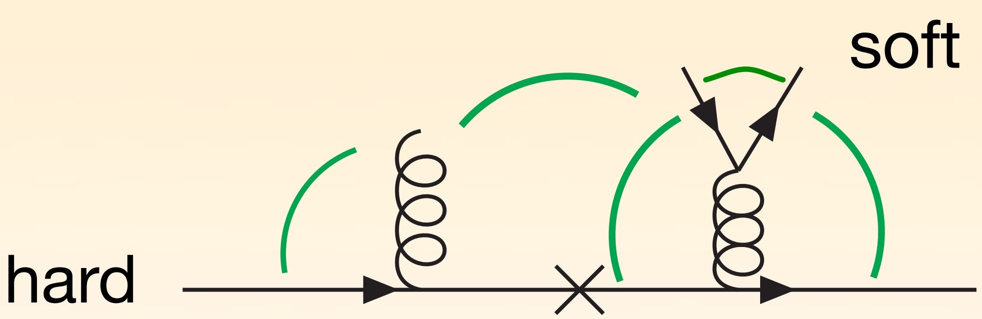
<u>*Normal k_t algorithm*</u>



Recombination depends on angle

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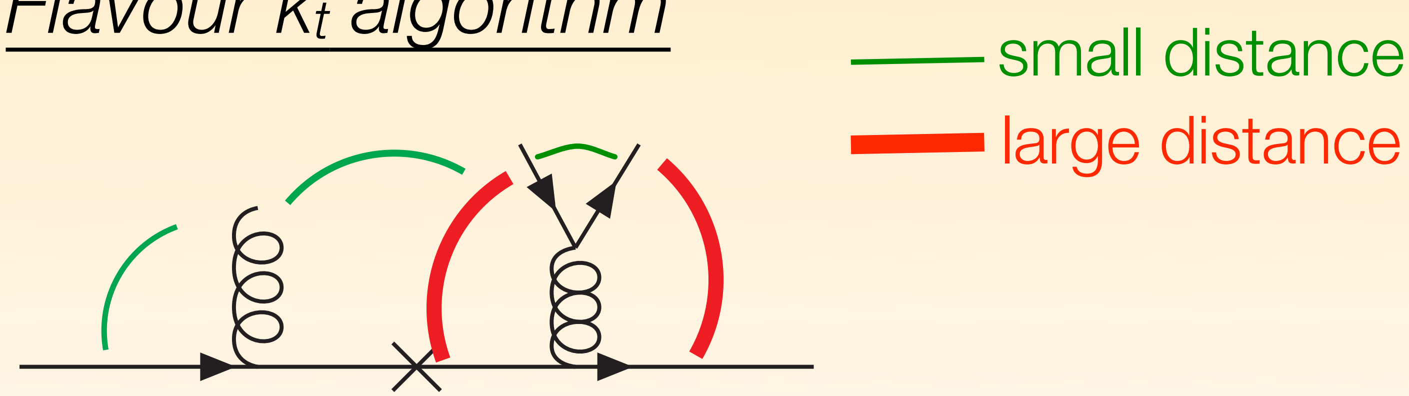

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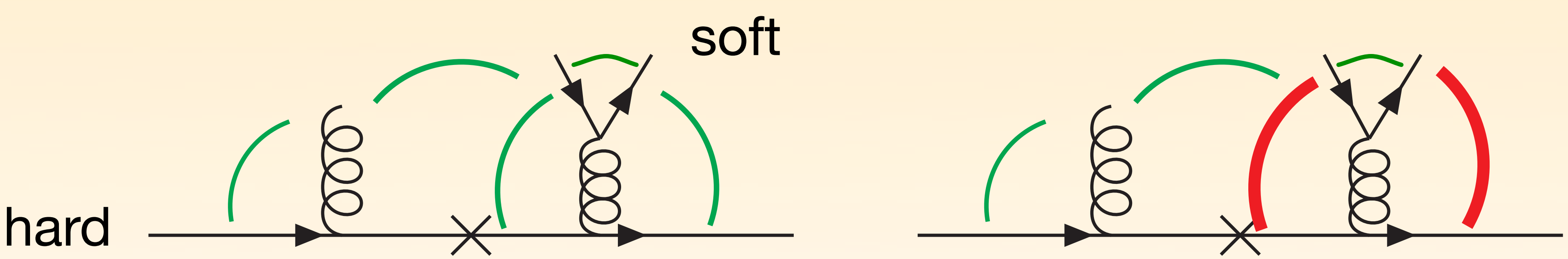
Normal k_t algorithm *Flavour k_t algorithm*

small distance
large distance



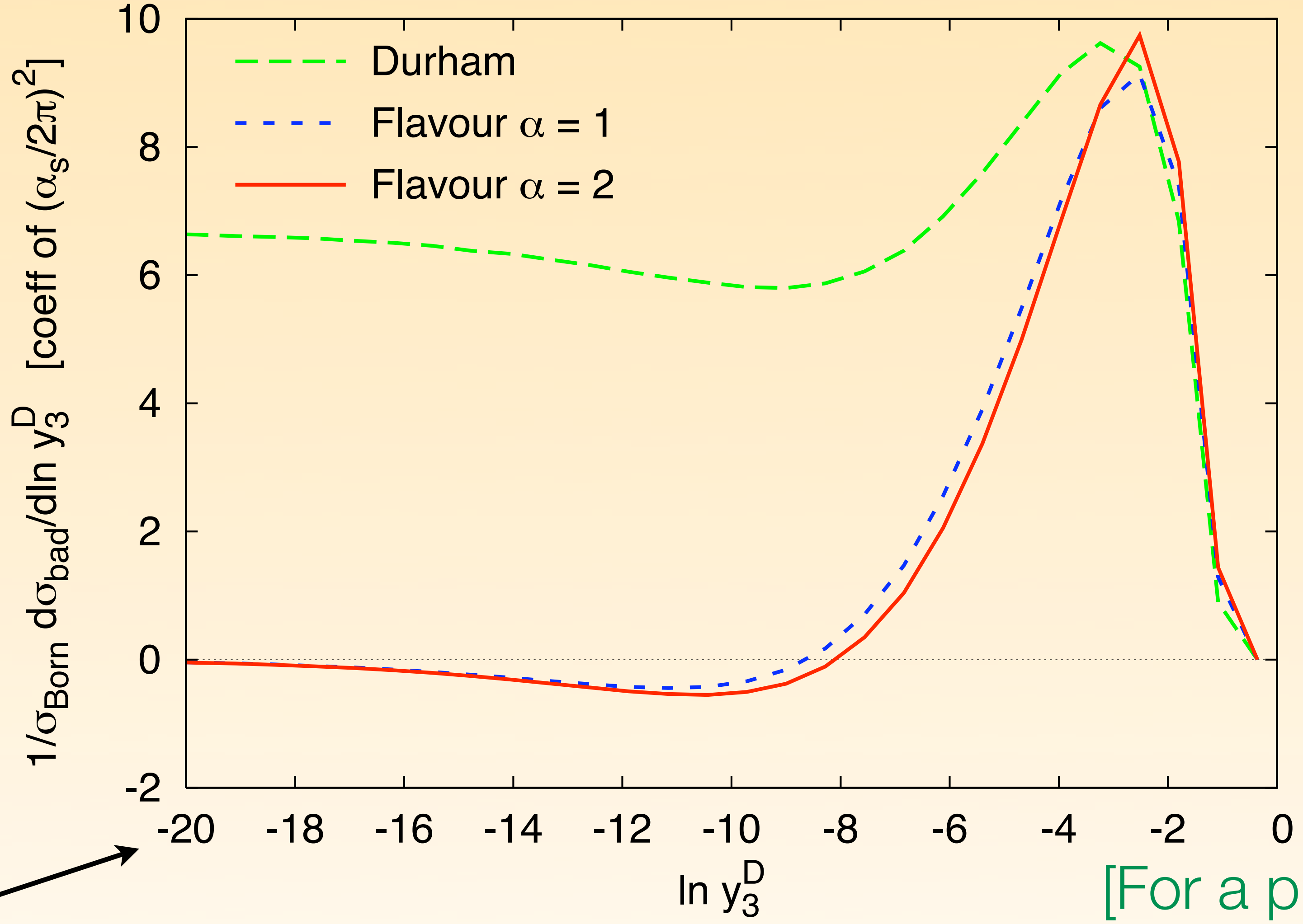
Recombination depends on angle

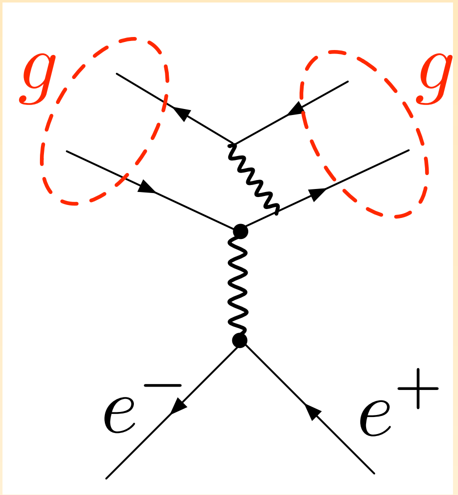
Infrared safe?

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*

Comparison of algorithms for b-jets

Standard algorithms (IR-unsafe):

- must keep finite m_b in PT calculation, FEX and GSP at LO

Flavour algorithms (IR-safe):

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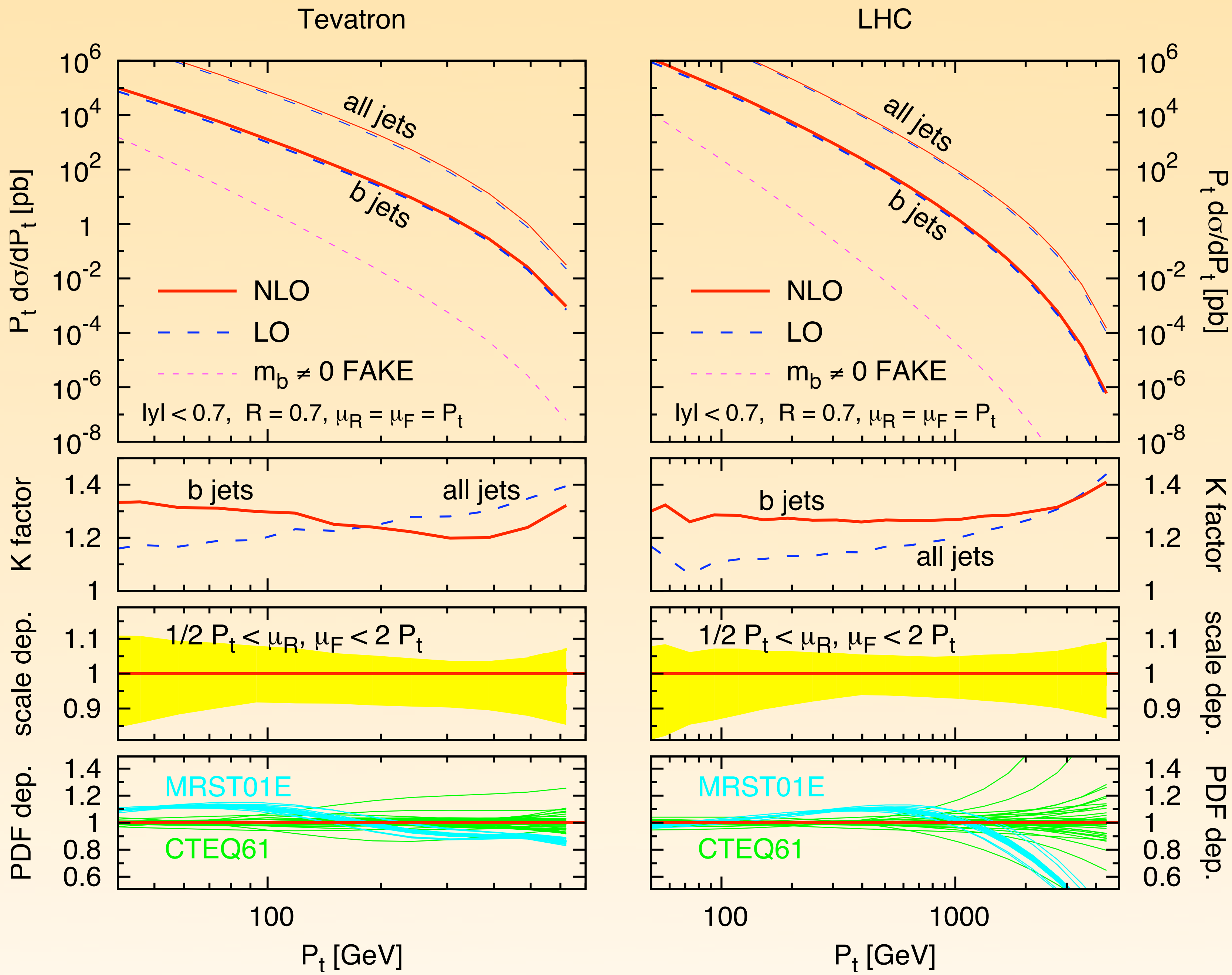
- cross-sections have large logs $\alpha_s^2 \cdot (\alpha_s \ln(P_t/m_b))^n$ due to initial state collinear branchings (FEX)

Flavour algorithms (IR-safe):

- full NLO massless QCD calculation (much simpler)
- 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

b-jet spectrum with flavour algorithm



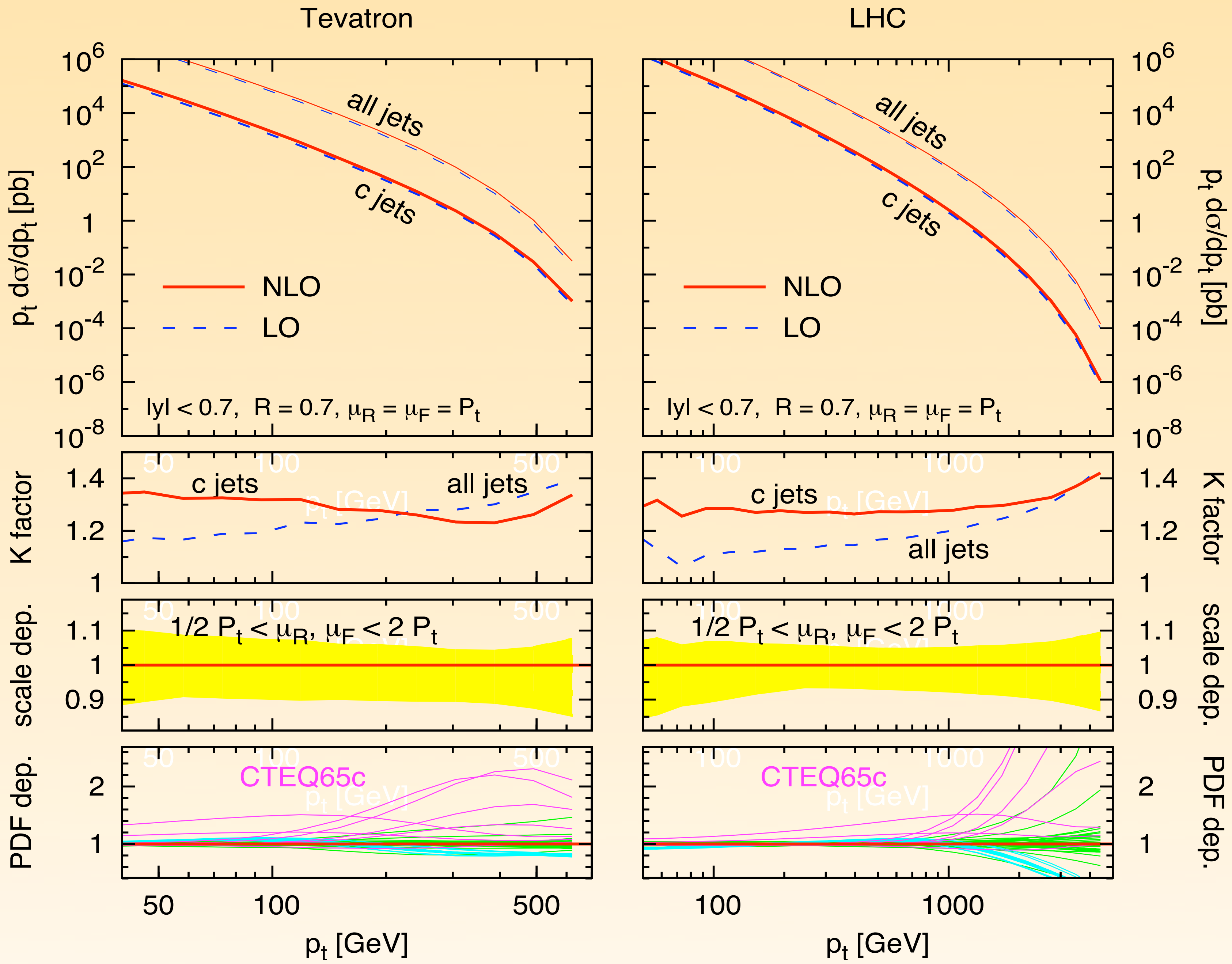
⇒ NLO: moderate effect ∼ 30%

⇒ considerable reduction of theory 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

charm-jet spectrum with flavour algorithm



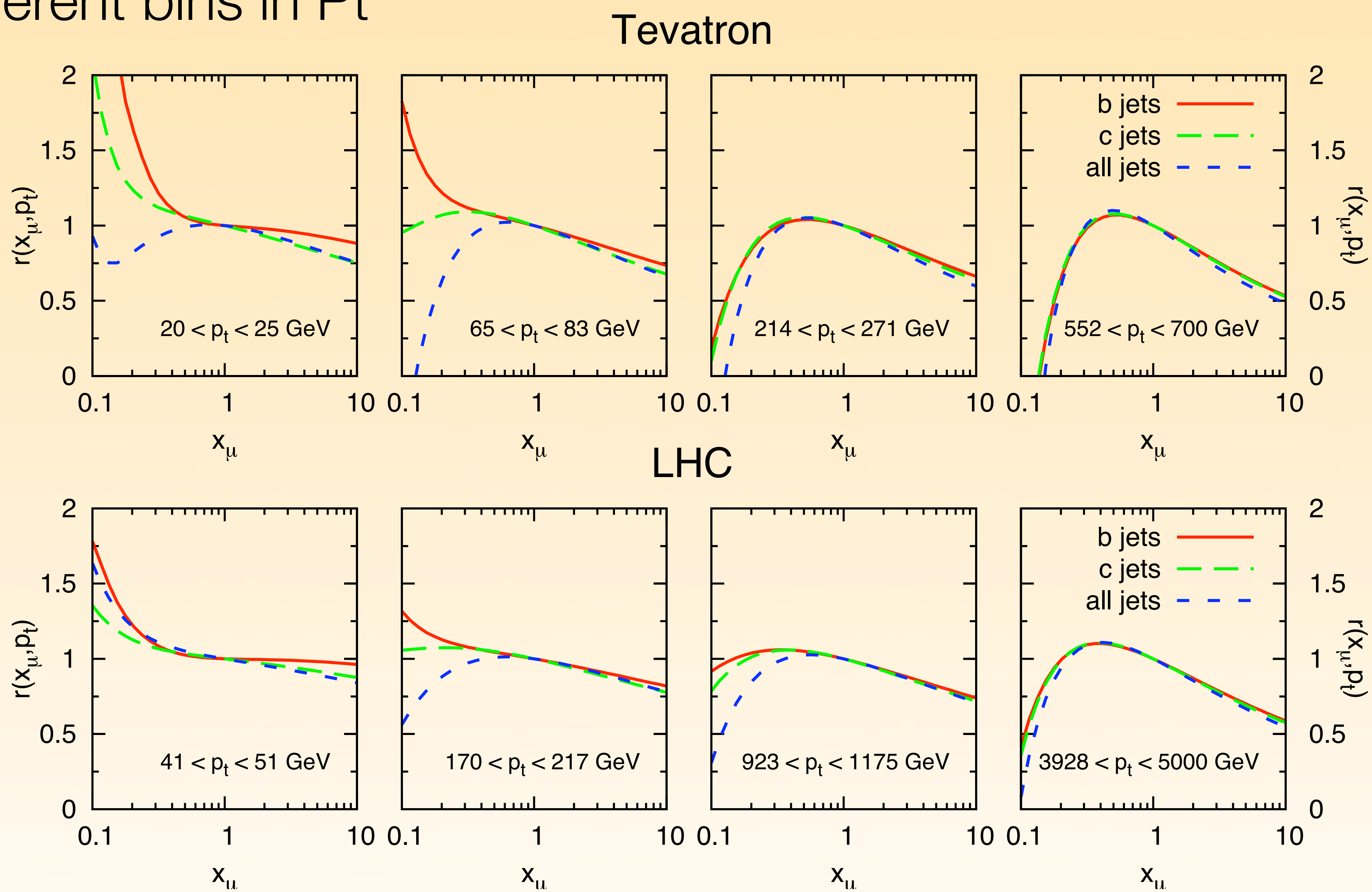
⇒ similar results as for b-jets

⇒ high sensitivity to possible intrinsic charm component of the proton

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

Sensitivity to scale variations

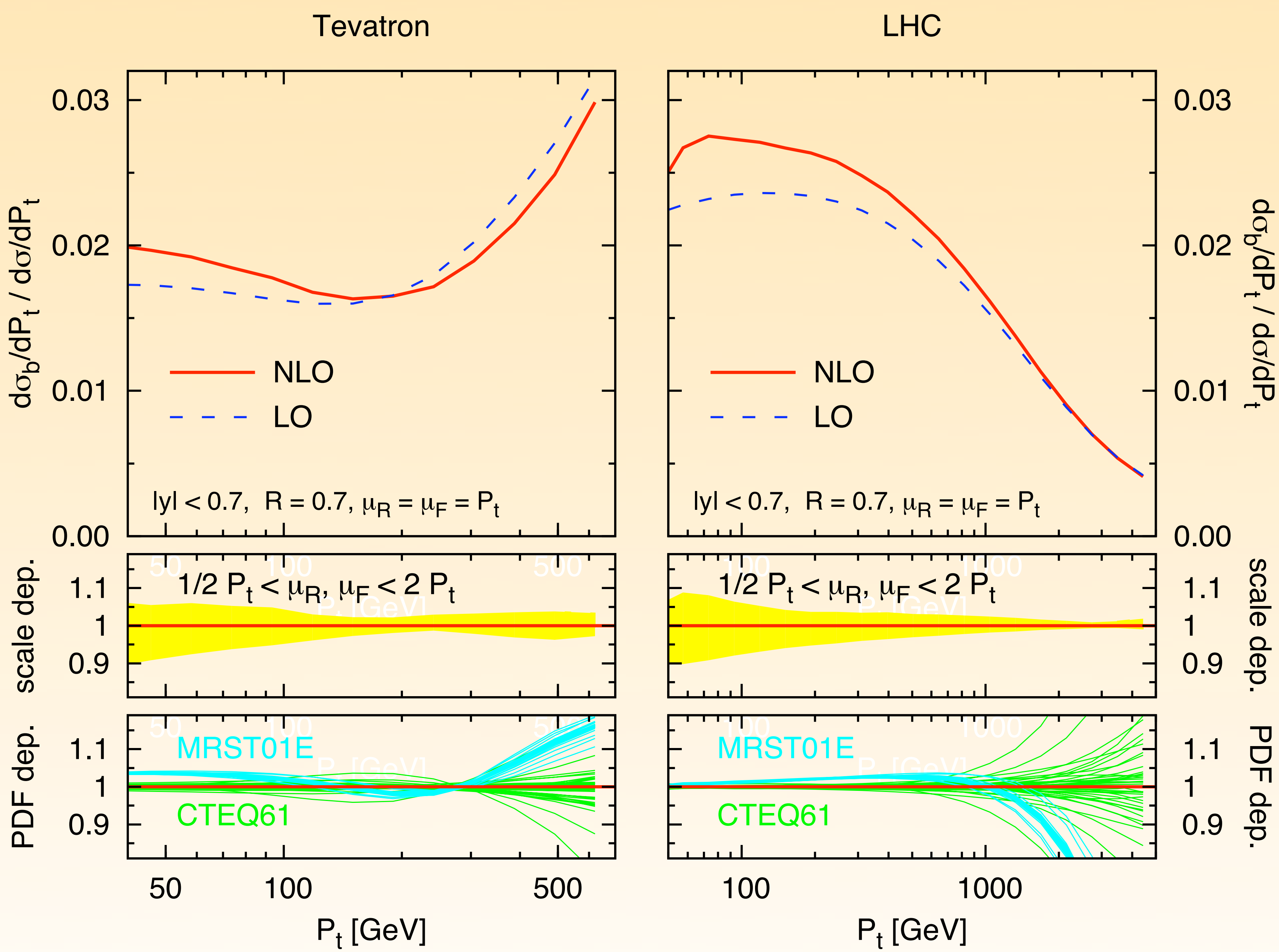
Look at the ratio $r(x, P_t) \equiv \sigma(\mu_R = \mu_F = xP_t)/\sigma(\mu_R = \mu_F = P_t)$
for different bins in Pt



$\Rightarrow$ heavy- and all-jets have the same sensitivity to scale variations

Ratios heavy-jets/all jets

b-jets



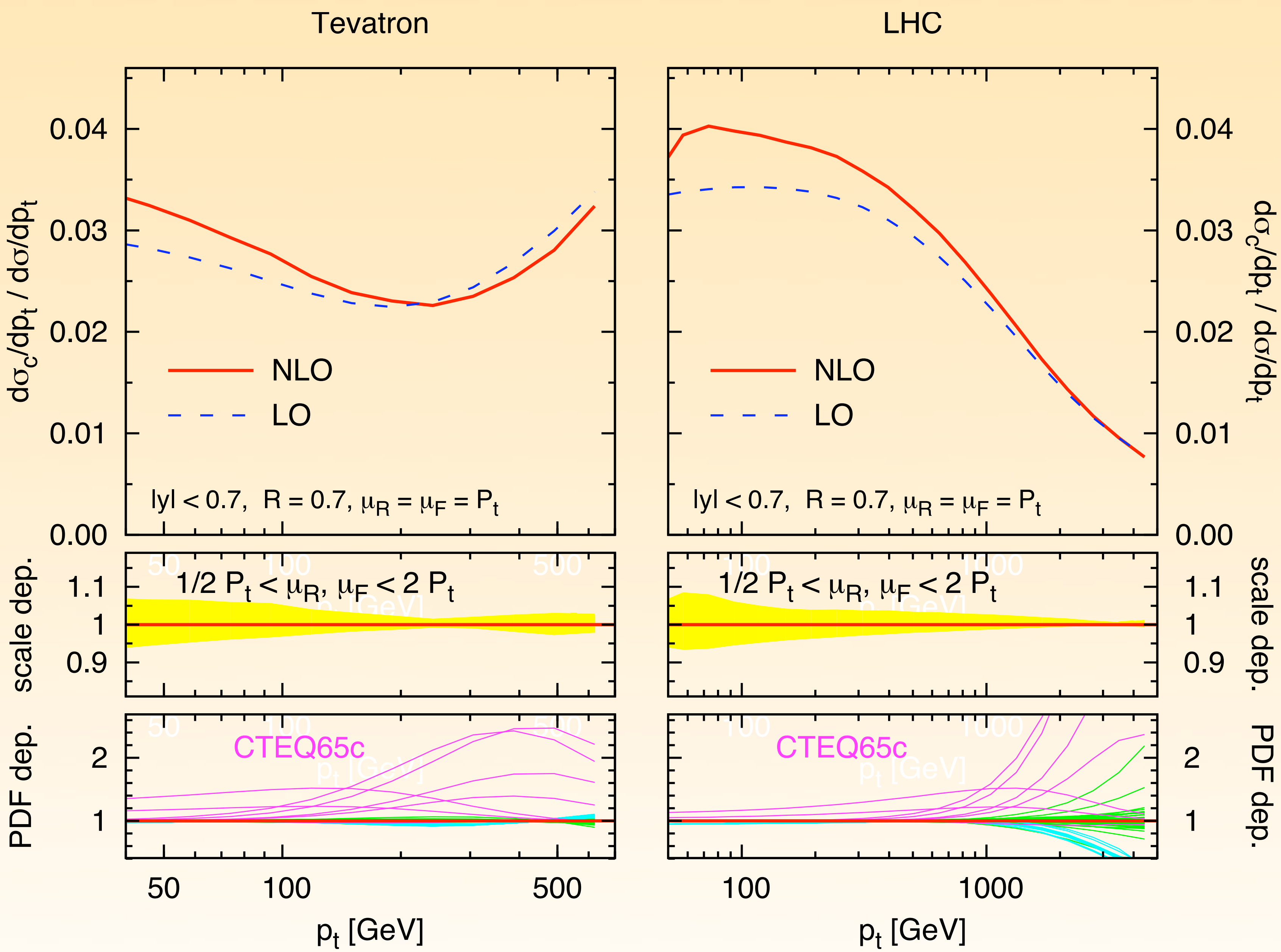
⇒ many common exp. uncertainties cancel in the ratio

⇒ theory uncertainty reduced in the ratio

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

Ratios heavy-jets/all jets

c-jets



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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^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)
- ☑ with IR-safe definition
  - give a true meaning to the decomposition into FC, FEX, GSP
  - reduced the theoretical uncertainties from 40-50% to 10-20%
- ☐ experimentally? must know efficiency for single & double tagging

We look forward to experimental investigations in this direction