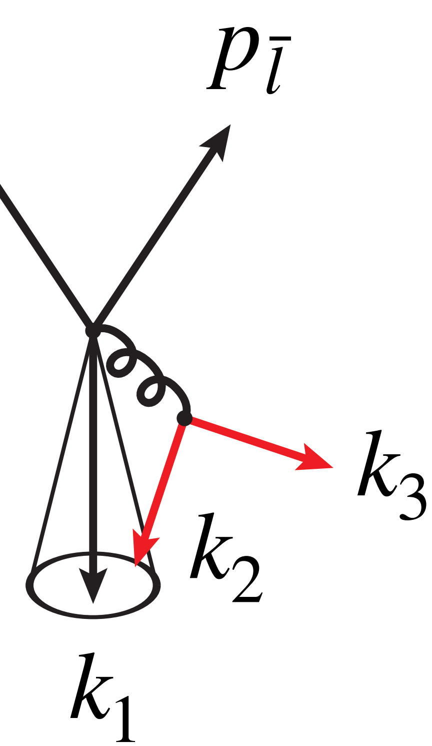


Heavy-flavour jets:

A roadmap towards precision physics

Rhorry Gauld

Jets and their substructure from LHC data

June 1st 2021

Netherlands Organisation for Scientific Research

Nikhef

Preliminaries

Identify the **flavour** & **kinematic** information of a hadronic jet

$\oplus$

Use this information to probe underlying physics effects

Preliminaries

Identify the **flavour** & **kinematic** information of a hadronic jet

$\oplus$

Use this information to probe underlying physics effects

Definition of a 'tag' and theory formalism depends on the goal

(i) **Absolute cross-sections of processes with flavoured jets**
This talk

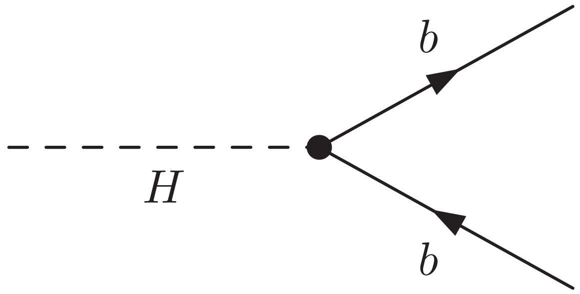
(ii) **Jet fragmentation**
Bauer, et al.:1312.5605, Bain et al. :1603.06891, 1610.06508, Dai et al. : 1805.06014, 2104.14707, Markis et al.:1807.09805

(iii) **Medium effects**:
Tao, Vitev: 1811.07905

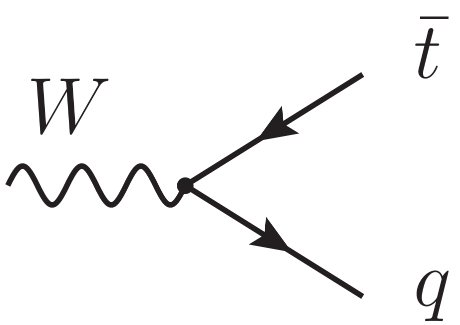
Preliminaries

Absolute cross-sections of processes with flavoured jets

(i) Higgs physics (hadronic decays)

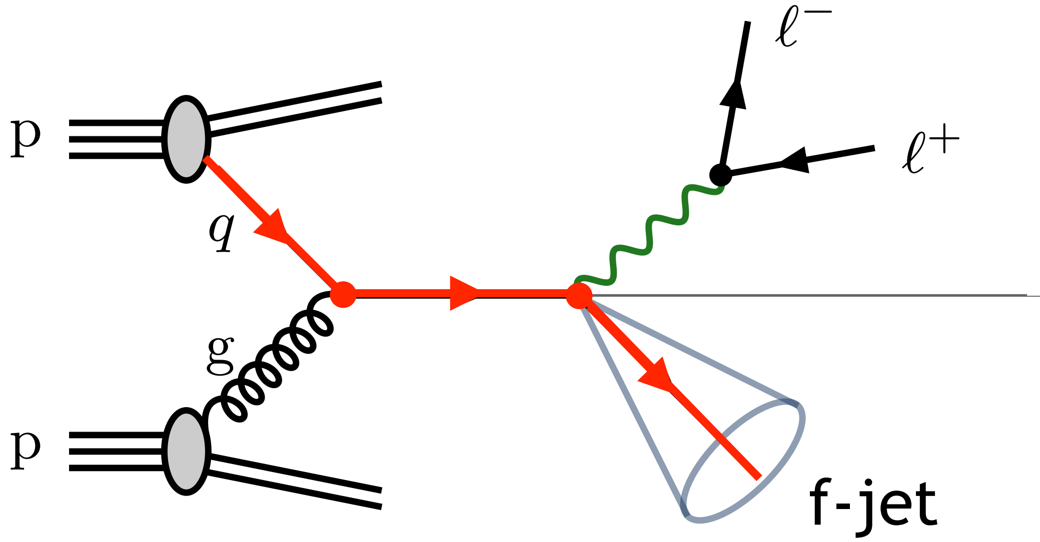


(ii) Top-quark physics ($|V_{tb}| \sim 1$)



(iii) New physics searches (f-jet $+E_T^{\mathrm{miss}}$)

(iv) Gauge-boson + heavy-flavour



Preliminaries

Absolute cross-sections of processes with flavoured jets

(i) Higgs physics (hadronic decays) [Higgs couplings]

(ii) Top-quark physics ($|V_{tb}| \sim 1$) [PDFs, α_s, BSM]

(iii) New physics searches (f-jet $+E_T^{\rm miss}$) [BSM]

(iv) Gauge-boson + heavy-flavour [PDFs, Theory framework]

Preliminaries

Absolute cross-sections of processes with flavoured jets

(i) Higgs physics (hadronic decays) [Higgs couplings]

(ii) Top-quark physics ($|V_{tb}| \sim 1$) [PDFs, α_s, BSM]

(iii) New physics searches (f-jet $+ E_T^{\text{miss}}$) [BSM]

(iv) Gauge-boson + heavy-flavour [PDFs, Theory framework]

in-direct (decays)

direct

Preliminaries

Absolute cross-sections of processes with flavoured jets

(i) Higgs physics (hadronic decays) [Higgs couplings]

(ii) Top-quark physics ($|V_{tb}| \sim 1$) [PDFs, α_s, BSM]

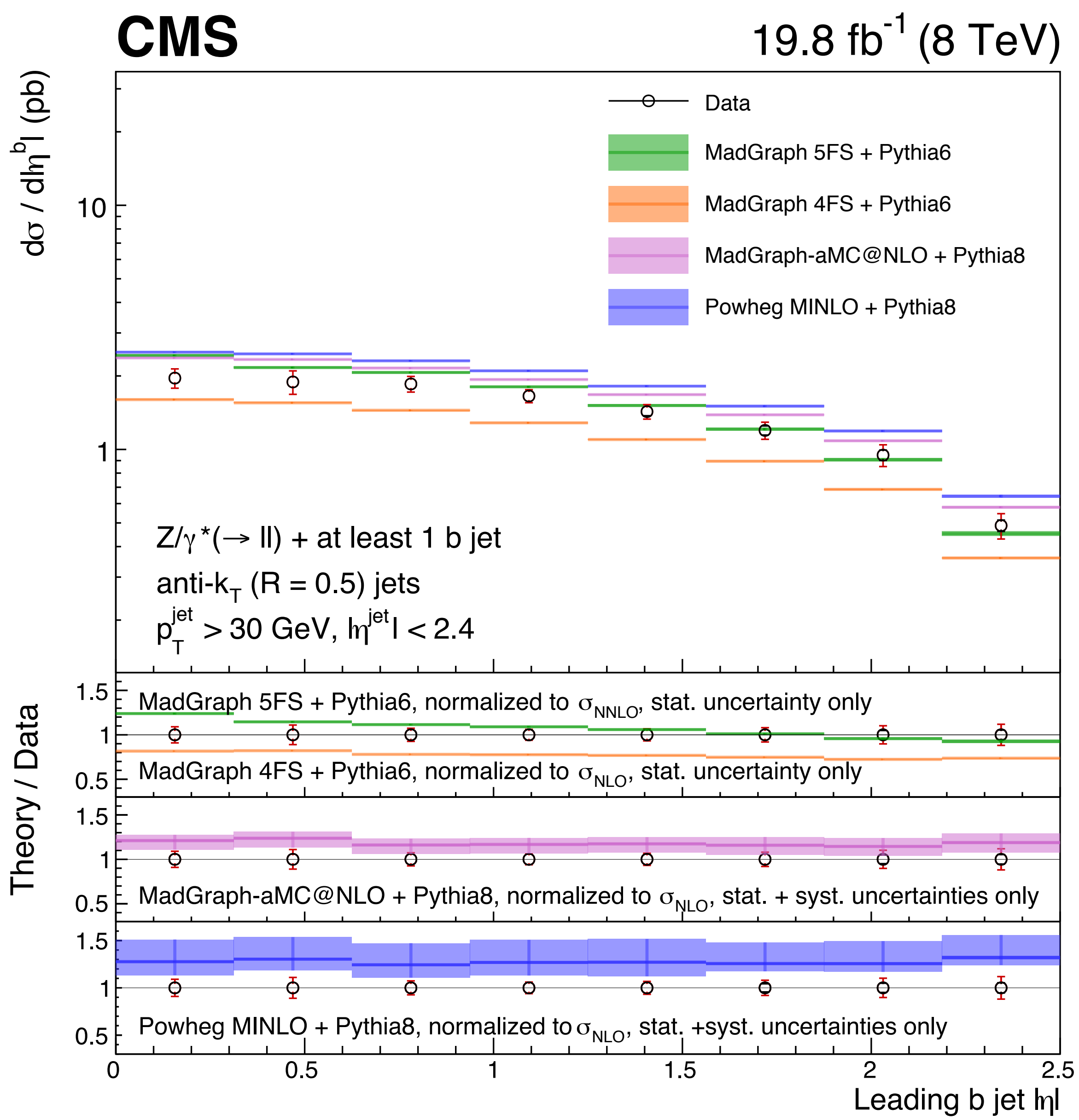
(iii) New physics searches (f-jet $+E_T^{\text{miss}}$) [BSM]

(iv) Gauge-boson + heavy-flavour [PDFs, Theory framework] [Dominant background for (i)-(iii)]

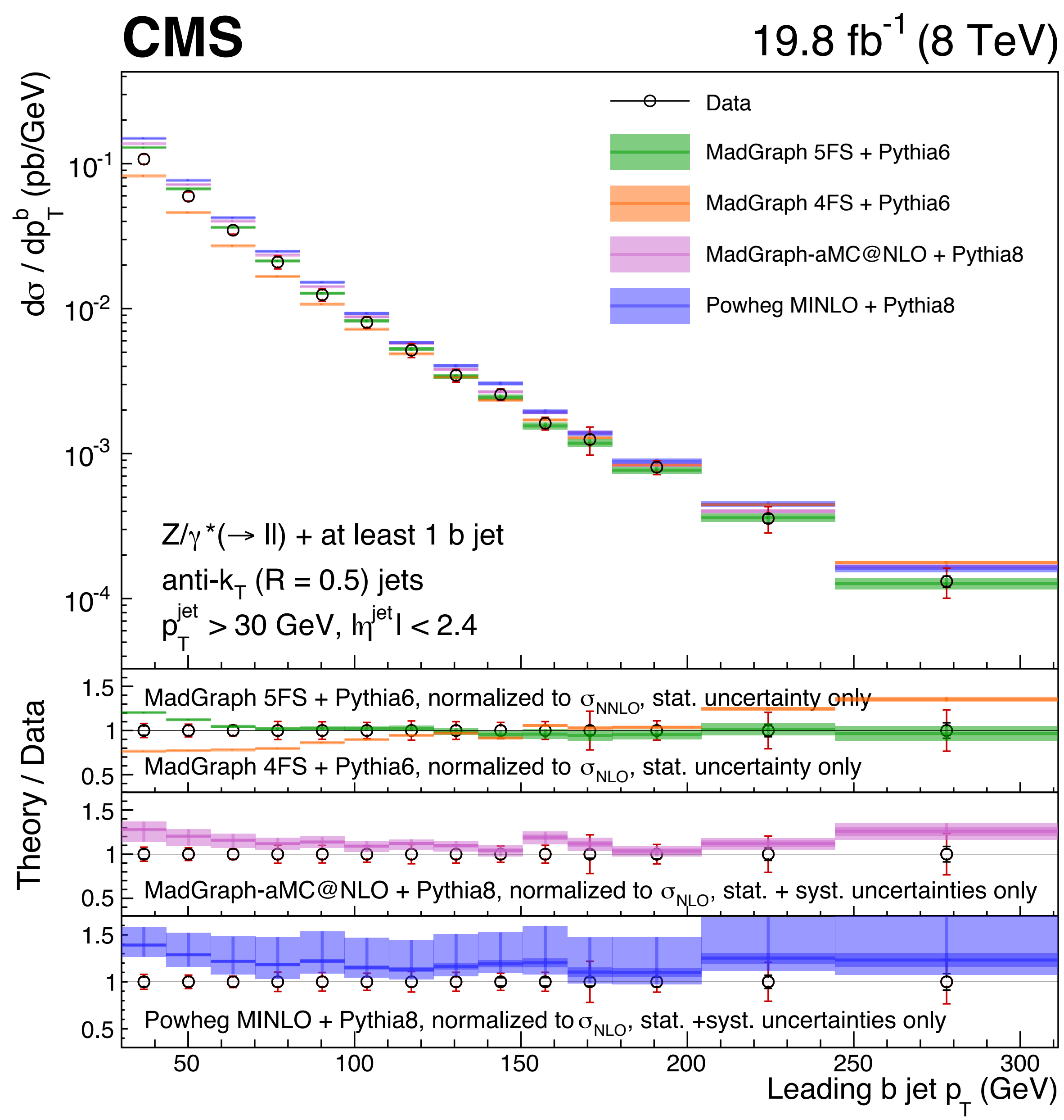
in-direct (decays)

direct

(Our) alternative motivation



η_b



$p_{T,b}$

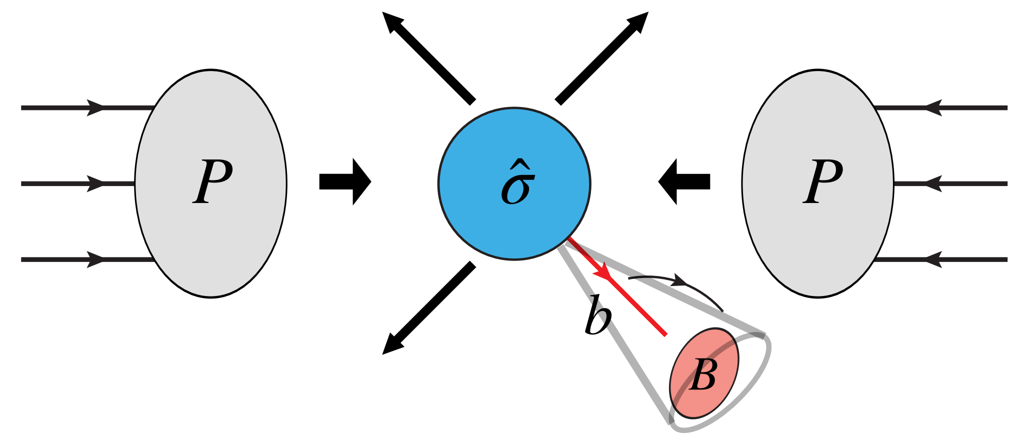
CMS Run I (8 TeV) measurement of $pp \to Z + b - \mathrm{jet(s)}$ Eur. Phys. J. C 77, 11 (2017) 751

"Our" NNLOJET [Gauld, Gehrmann-De Ridder, Glover, Huss, Majer] *PRL* 125 (2020) 22, 222002

Overview of remainder of talk

Direct heavy-flavour production

- The 'flavour scheme'
- Heavy-flavour PDFs

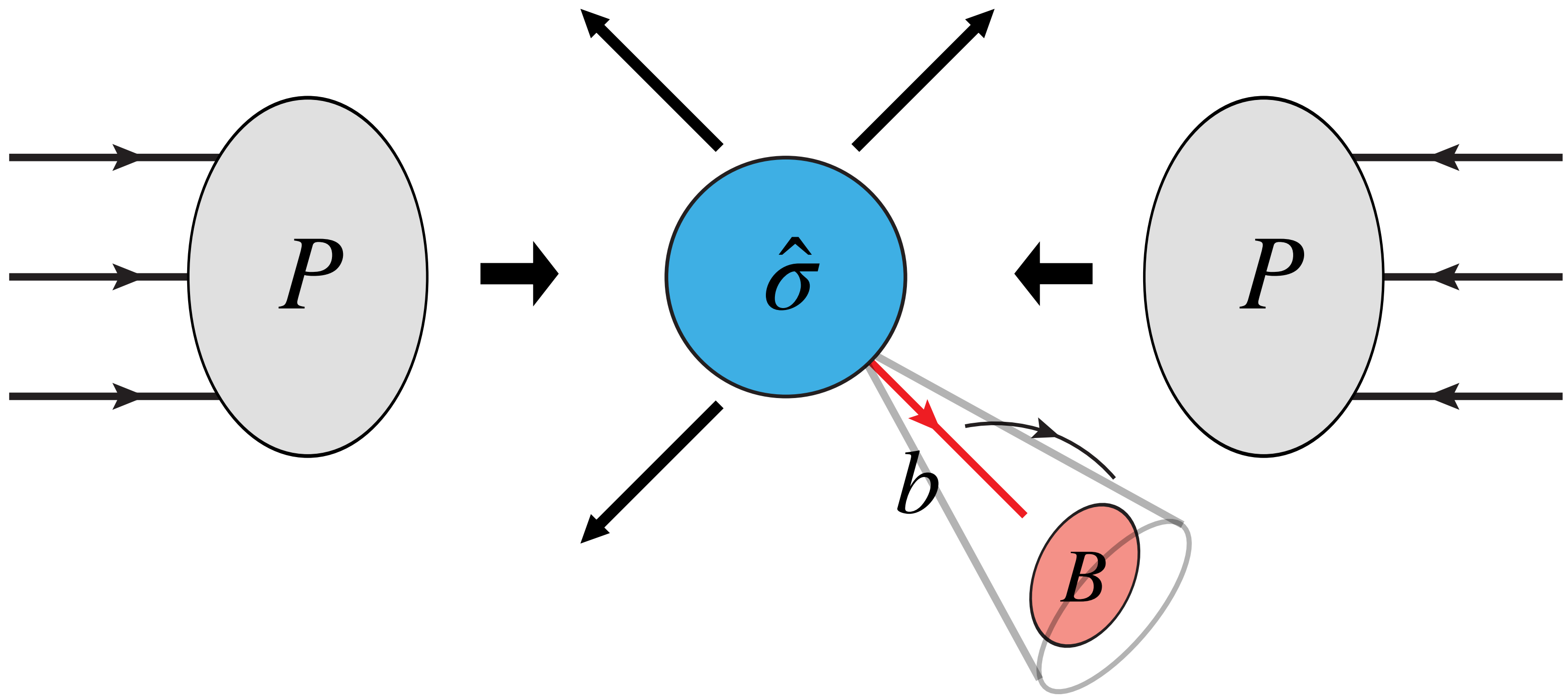


Flavoured jets & perturbative computations

- **I**nfra**R**ed and **C**ollinear safety
- Theory state-of-the-art

Theory meets experiment

Anatomy of heavy-flavour processes



Factorisation theorem

$$\mathrm{d}\sigma_{pp\to X} = \sum_{i,j} \int \mathrm{dx}_1 \mathrm{dx}_2\, f_i(x_1)\, f_j(x_2)\, \mathrm{d}\hat{\sigma}_{ij\to\hat{X}}(\hat{s},\ldots)\, T(\hat{X}\to X)$$

Partonic cross-section

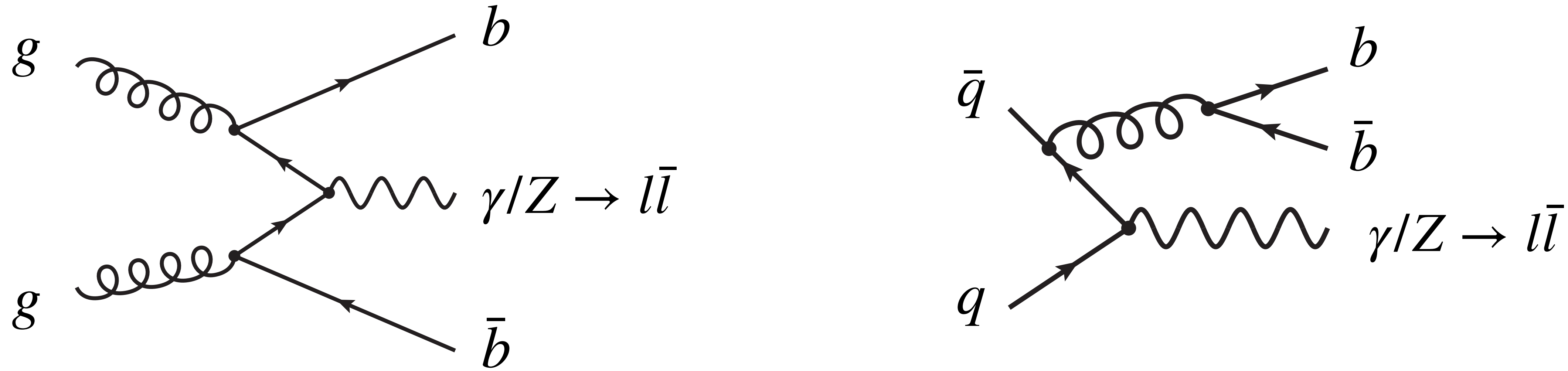
$$\mathrm{d}\hat{\sigma}_{ij\to\hat{X}} = \mathrm{d}\hat{\sigma}^{\mathrm{LO}}_{ij\to\hat{X}} + \alpha_s\, \mathrm{d}\hat{\sigma}^{\mathrm{NLO}}_{ij\to\hat{X}} + \alpha_s^2\, \mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{ij\to\hat{X}} + \ldots$$

At fixed-order, define parton-level jets [corrected with $T(\hat{X}\to X)$]

[from NLO+PS for example]

A theoretical bypass: Z+b-jet

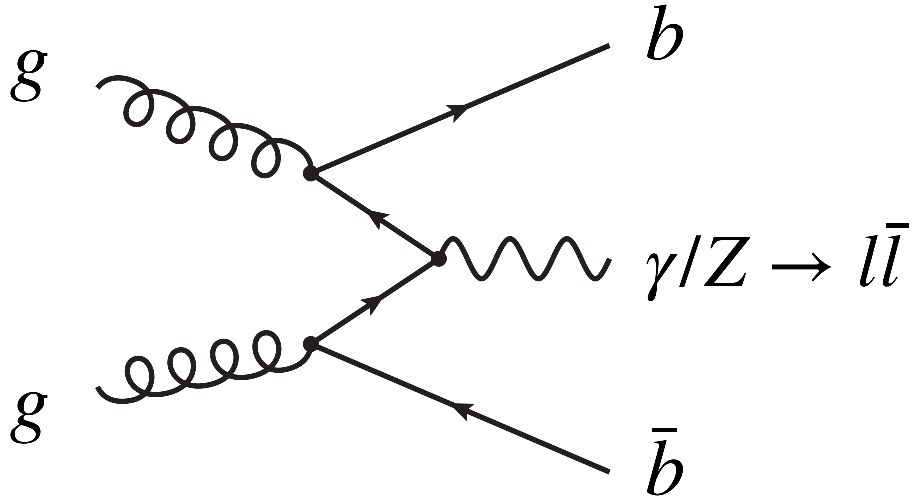
Computed in a scheme: e.g. "4fs" aka ZM-VFNS ($n_f^{\max} = 4$)

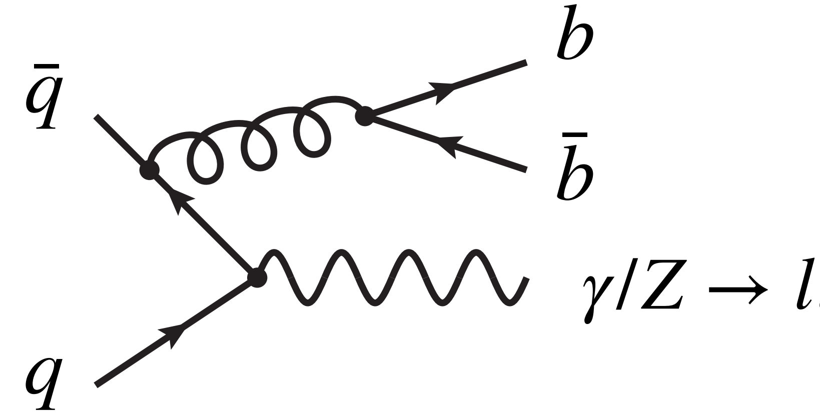


LO computation in 4fs $\mathcal{O}(\alpha_s^2)$, $\mathrm{d}\hat{\sigma}_{ij}^{\mathrm{LO}} \sim \int \mathrm{d}\phi_{\hat{X}} \, |M_{ij\to\hat{X}}|^2$

A theoretical bypass: Z+b-jet

Computed in a scheme: e.g. “4fs” aka ZM-VFNS ($n_f^{\max} = 4$)

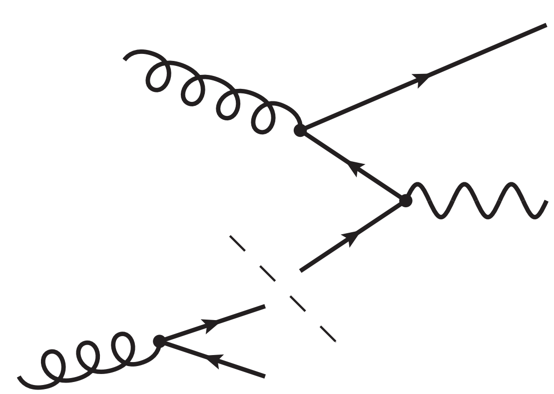




LO computation in 4fs $\mathcal{O}(\alpha_s^2)$, $\mathrm{d}\hat{\sigma}_{ij}^{\mathrm{LO}} \sim \int \mathrm{d}\phi_{\hat{X}} \, |M_{ij\to\hat{X}}|^2$

$$\mathrm{d}\sigma^{4fs} = \mathrm{d}\sigma^{m_b=0} \quad + \quad \mathrm{d}\sigma^{\ln[m_b]} \quad + \quad \mathrm{d}\sigma^{m_b}$$

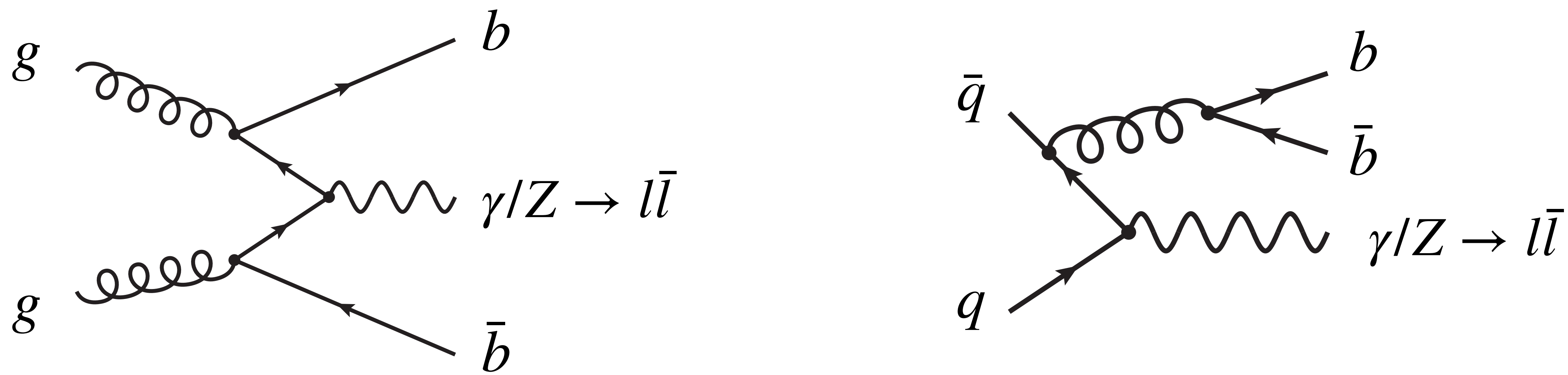
Massless component
$\mathcal{O}(\alpha_s^2 n_f)$ in 5fs



$\mathcal{O}(m_b^2)$ effects
exact kinematics

A theoretical bypass: Z+b-jet

Computed in a scheme: e.g. "4fs" aka ZM-VFNS ($n_f^{\max} = 4$)



LO computation in 4fs $\mathcal{O}(\alpha_s^2)$, $\mathrm{d}\hat{\sigma}_{ij}^{\mathrm{LO}} \sim \int \mathrm{d}\phi_{\hat{X}} \, |M_{ij\to\hat{X}}|^2$

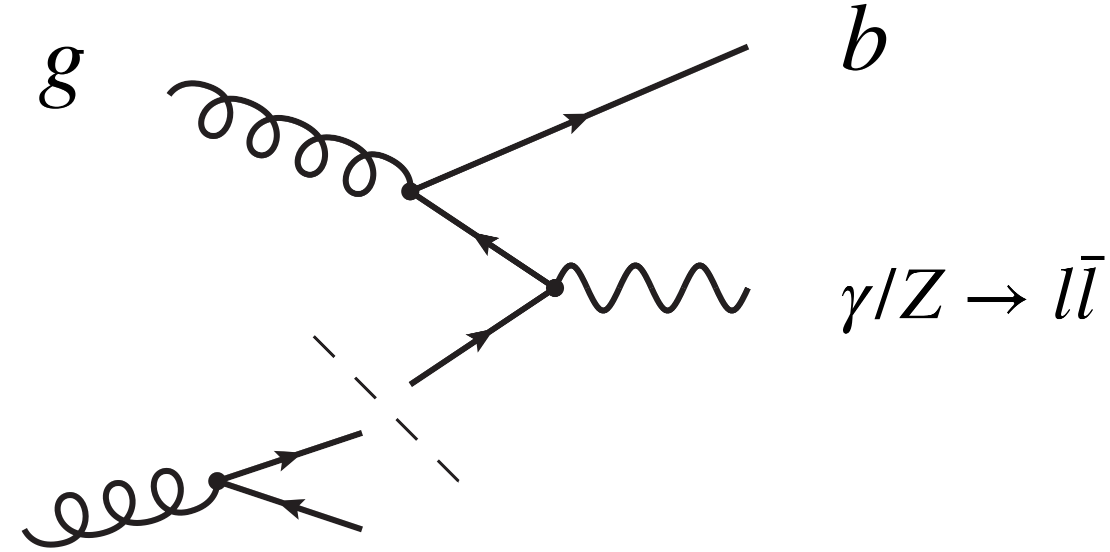
$$\mathrm{d}\sigma^{4fs} = \mathrm{d}\sigma^{m_b=0} \quad + \quad \mathrm{d}\sigma^{\ln[m_b]} \quad + \quad \mathrm{d}\sigma^{m_b}$$

100% = **-32%** **+135%** **-3%**

The b-quark PDF

Clearly, we wish to understand the logarithmic part (it is the largest)

$$\mathrm{d}\sigma^{\ln[m_b]} \sim$$



$$\mathrm{d}\sigma^{\ln[m_b]} \sim f_g(x_1, \mu_F^2) \otimes f_b^{(1)}(x_2, \mu_F^2) \otimes \mathrm{d}\hat{\sigma}^{m_b=0}_{bg\to Zb}$$

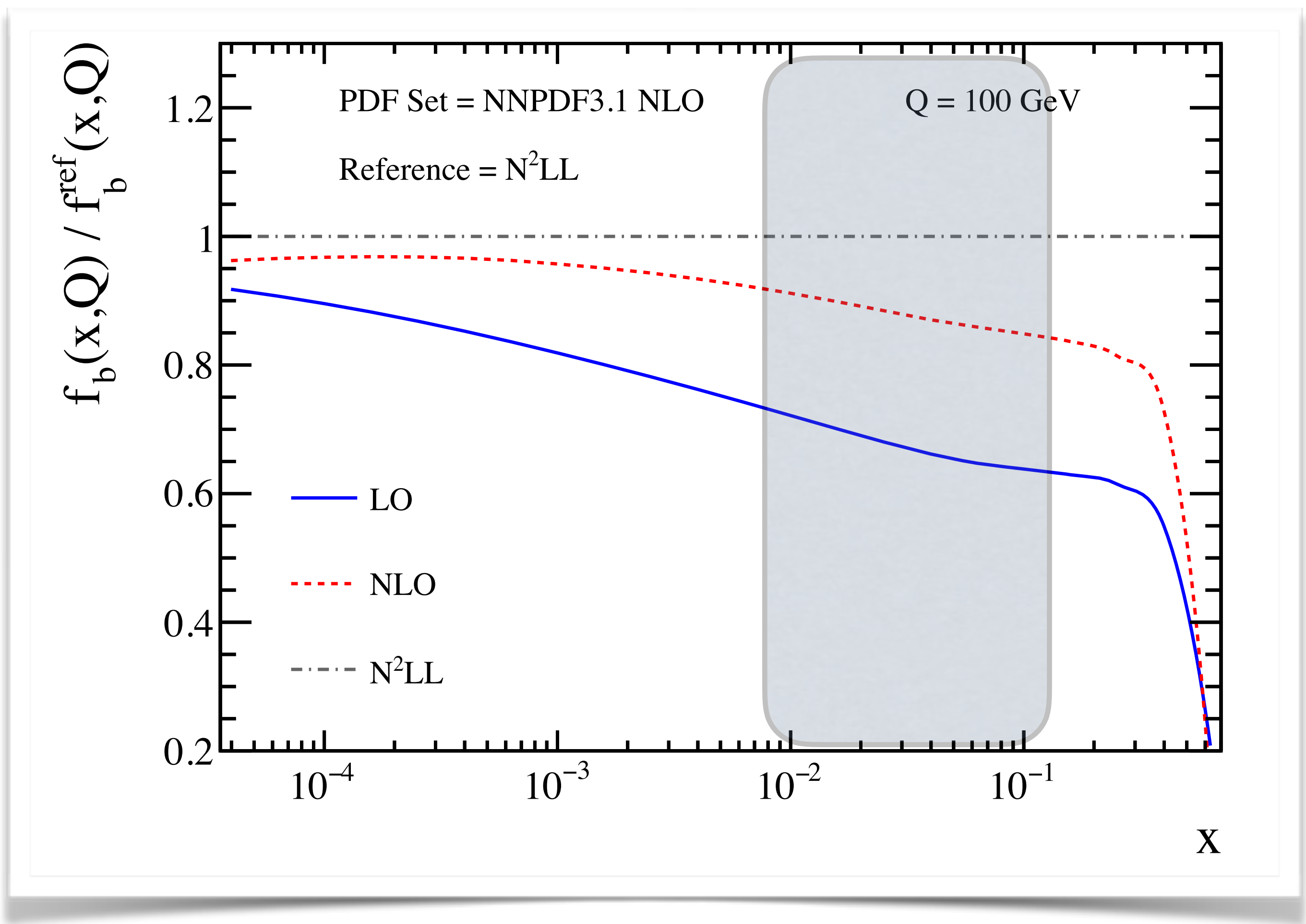
the fixed-order b-quark pdf

$$f_b^{(1)}(x, \mu_F^2) = \frac{\alpha_s}{2\pi}\left(p^{(0)}_{g\to q} \otimes f_g\right)[x, m_b^2] \ \ln\left[\frac{\mu_F^2}{m_b^2}\right]$$

The b-quark PDF

Clearly, we wish to understand the logarithmic part (it is the largest)

We do know it well (use the renormalisation group, "PDF evolution")



I am showing fixed-order pdf versus a resummed one (PDF evolution)

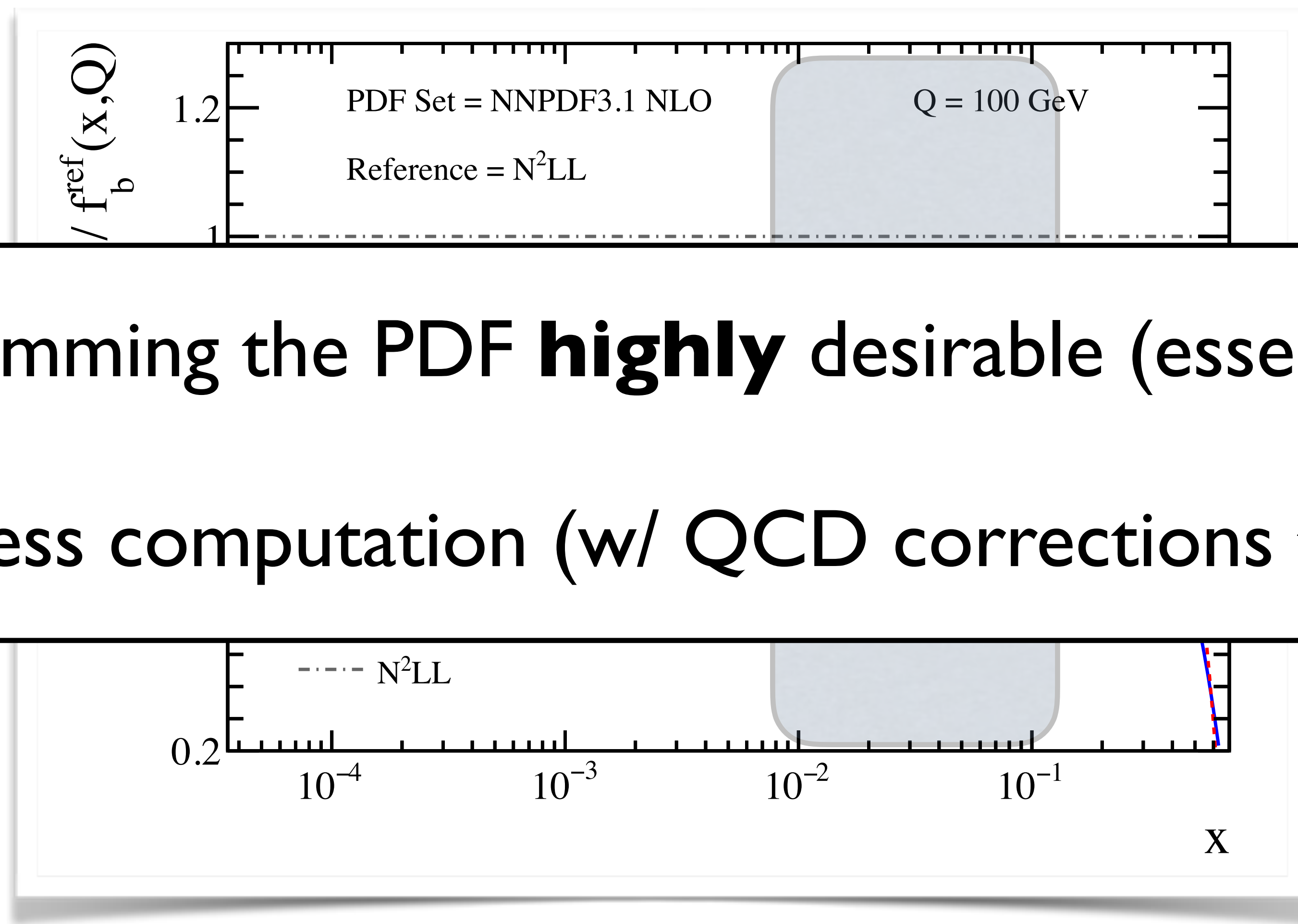
$\alpha_s^m \ln^n[\mu_F^2/m_b^2], \quad m \geq n$

Note! $\alpha_s \ln[m_Z^2/m_b^2] \approx 0.7$

The b-quark PDF

Clearly, we wish to understand the logarithmic part (it is the largest)

We do know it well (use the renormalisation group, "PDF evolution")



Resumming the PDF **highly** desirable (essential?)

aka: the massless computation (w/ QCD corrections to $\ln[m_b]$ part)

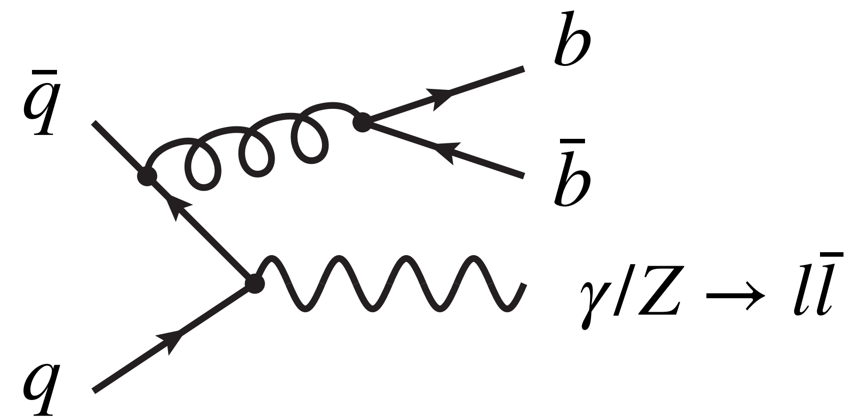
I am showing fixed-order pdf versus a resummed one (PDF evolution)

$\alpha_s^m \ln^n[\mu_F^2/m_b^2], \quad m \geq n$ Note! $\alpha_s \ln[m_Z^2/m_b^2] \approx 0.7$

InfraRed and Collinear safety

What happens if we apply anti-k_T alg. as in an experimental set-up

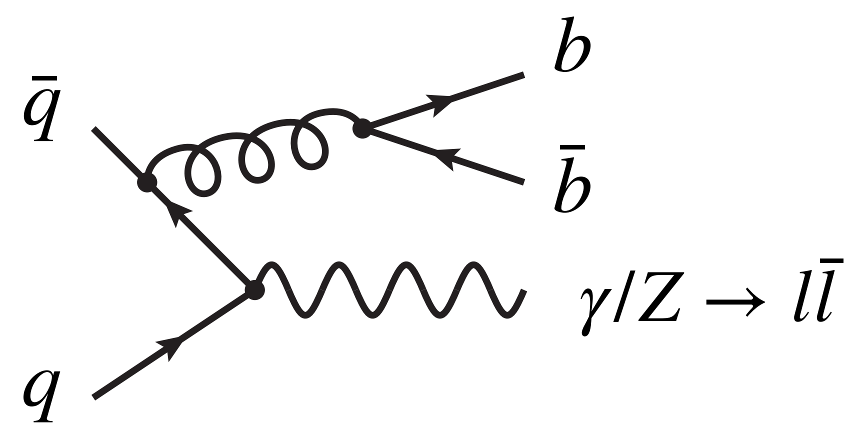
Collinear safety



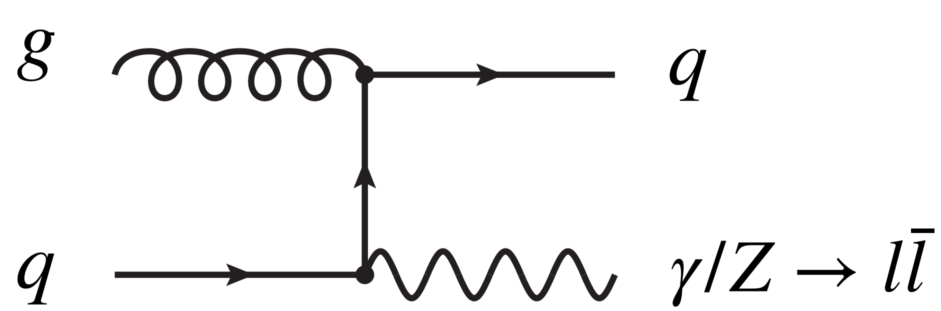
InfraRed and Collinear safety

What happens if we apply anti-k_T alg. as in an experimental set-up

Collinear safety



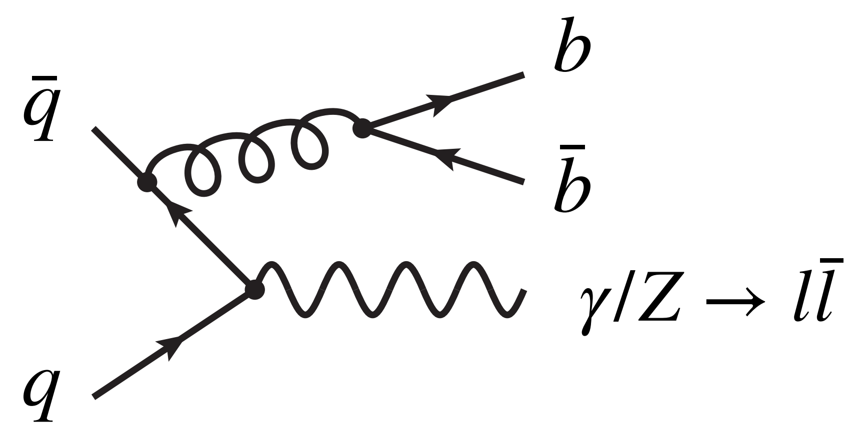
Soft safety



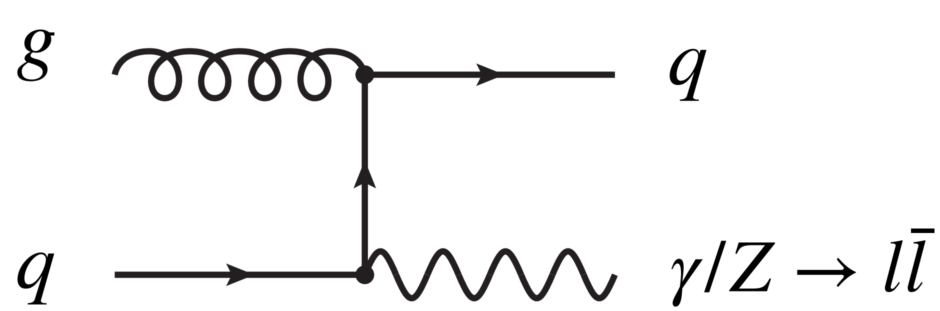
InfraRed and Collinear safety

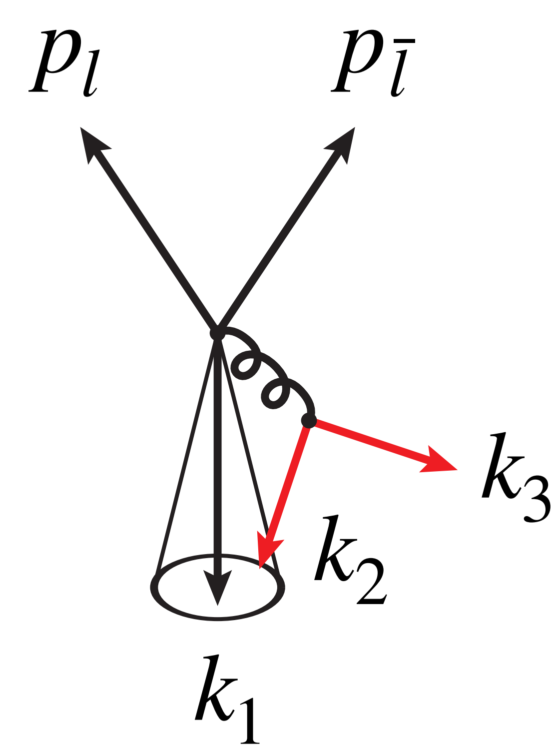
What happens if we apply anti-k_T alg. as in an experimental set-up

Collinear safety



Soft safety





Massless(5fs): infinite

Massive(4fs): finite, but contains large corrections like

$$C \propto \alpha_s \ln[Q^2/m_b^2]$$

$$S \propto \alpha_s^2 \ln^2[Q^2/m_b^2]$$

The flavour-k_T algorithm

Target: resummed heavy-flavour PDFs and avoid large "C, S" corrections

Theoretical Physics | Published: 19 May 2006

Infrared-safe definition of jet flavour

A. Banfi, G.P. Salam & G. Zanderighi

The European Physical Journal C - Particles and Fields **47**, 113–124(2006) | Cite this article

109 Accesses | **71** Citations | Metrics

(1) Quantum flavour assignment:

$$b = +1, \ \bar{b} = -1$$

(2) Flavour specific clustering

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}, k_{tj})^\alpha \min(k_{ti}, k_{tj})^{2-\alpha} & \text{softer of } i, j \text{ is flavoured,} \\ \min(k_{ti}, k_{tj})^\alpha & \text{softer of } i, j \text{ is unflavoured} \end{cases}$$

Note! anti-k_T clustering not well suited (preference of soft-hard clustering)

Theory state-of-the-art (f-jets @ NNLO)

$$\mathrm{d}\hat{\sigma}_{ij\to\hat{X}} = \mathrm{d}\hat{\sigma}^{\mathrm{LO}}_{ij\to\hat{X}} + \alpha_s\,\mathrm{d}\hat{\sigma}^{\mathrm{NLO}}_{ij\to\hat{X}} + \alpha_s^2\,\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{ij\to\hat{X}} + \ldots$$

$V + (H \to b\bar{b})$ — Ferrera et al. (1705.10304), Caola et al. (1712.06974), Gauld et al. (1907.05836)

$Z + \mathrm{b-jet}$ — Gauld et al. (2005.03016)

$W^{\pm} + \mathrm{c-jet}$ — Czakon et al. (2011.01011)

$t\bar{t}$ with PFF [B-hadrons] — Czakon et al. (2102.08267)

flavoured-jet algorithm applied

anti-k$_T$ algorithm applied (regulated by m_b , a tech. cut, or 'prescription')

$t\bar{t}$ with decay — Behring et al. (1901.05407), Czakon et al. (2008.11133)

$t, \bar{t}$ (t-chan with decay) — Berger et al. (1606.08463,1708.09405), Campbell et al. (2012.01574)

$V + (H \to b\bar{b})$ [4fs] — Behring et al. (2003.08321)

Apologies if I have missed some

Theory state-of-the-art (f-jets @ NNLO)

$$\mathrm{d}\hat{\sigma}_{ij\to\hat{X}} = \mathrm{d}\hat{\sigma}^{\mathrm{LO}}_{ij\to\hat{X}} + \alpha_s\,\mathrm{d}\hat{\sigma}^{\mathrm{NLO}}_{ij\to\hat{X}} + \alpha_s^2\,\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{ij\to\hat{X}} + \ldots$$

$V + (H \to b\bar{b})$ — Ferrera et al. (1705.10304), Caola et al. (1712.06974), Gauld et al. (1907.05836)

$Z + \mathrm{b-jet}$ — Gauld et al. (2005.03016)

$W^{\pm} + \mathrm{c-jet}$ — Czakon et al. (2011.01011)

$t\bar{t}$ with PFF [B-hadrons] — Czakon et al. (2102.08267)

flavoured-jet algorithm applied

anti-kT algorithm applied (regulated by m_b , a tech. cut, or 'prescription')

$t\bar{t}$ with decay — Behring et al. (1901.05407), Czakon et al. (2008.11133)

$t, \bar{t}$ (t-chan with decay) — Berger et al. (1606.08463,1708.09405), Campbell et al. (2012.01574)

$V + (H \to b\bar{b})$ [4fs] — Behring et al. (2003.08321)

Apologies if I have missed some

Theory meets experiment

$$\mathrm{d}\sigma_{pp\to X} = \sum_{i,j} \int \mathrm{dx}_1 \mathrm{dx}_2 \, f_i(x_1) \, f_j(x_2) \, \mathrm{d}\hat{\sigma}_{ij\to\hat{X}}(\hat{s}, \ldots) \, T(\hat{X} \to X)$$

Theory: parton-level flavour-k_T jets

Data: hadron-level anti-k_T jets

A correction (which may be small) **is** required for these calculations

Theory meets experiment

$$d\sigma_{pp\to X} = \sum_{i,j} \int dx_1 dx_2\, f_i(x_1)\, f_j(x_2)\, d\hat{\sigma}_{ij\to\hat{X}}(\hat{s},\ldots)\, T(\hat{X}\to X)$$

Theory: parton-level flavour-k_T jets

Unfold data with RooUnfold

Includes:

$T(\hat{X}\to X)$

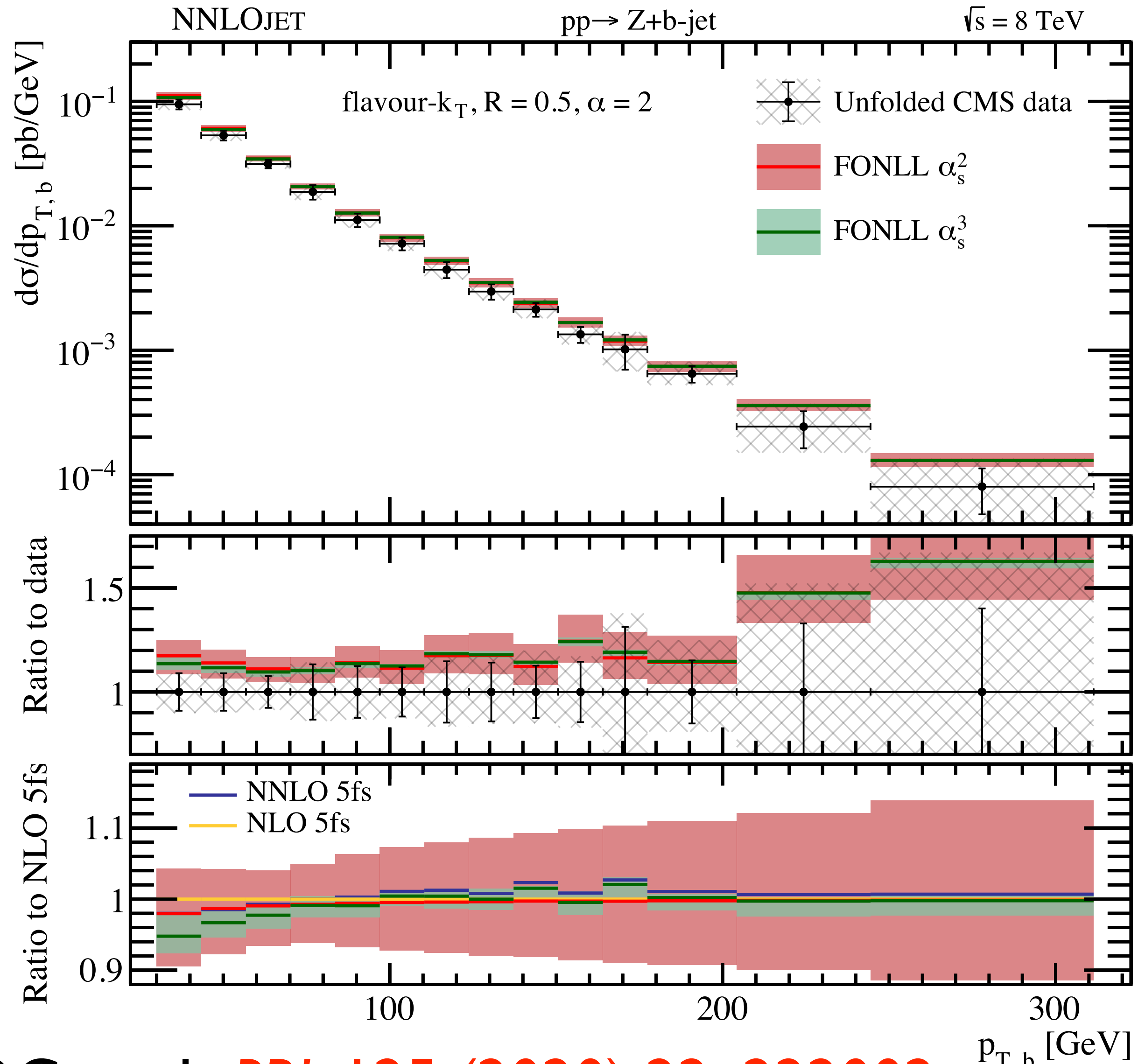
Model: NLO+PS

(4fs and 5fs)

Data: hadron-level anti-k_T jets

A correction (which may be small) **is** required for these calculations

Theory meets experiment



← (2-3)% unc.

$p_{T,b}$

Exact m_b effects included

RG et al., *PRL* 125 (2020) 22, 222002

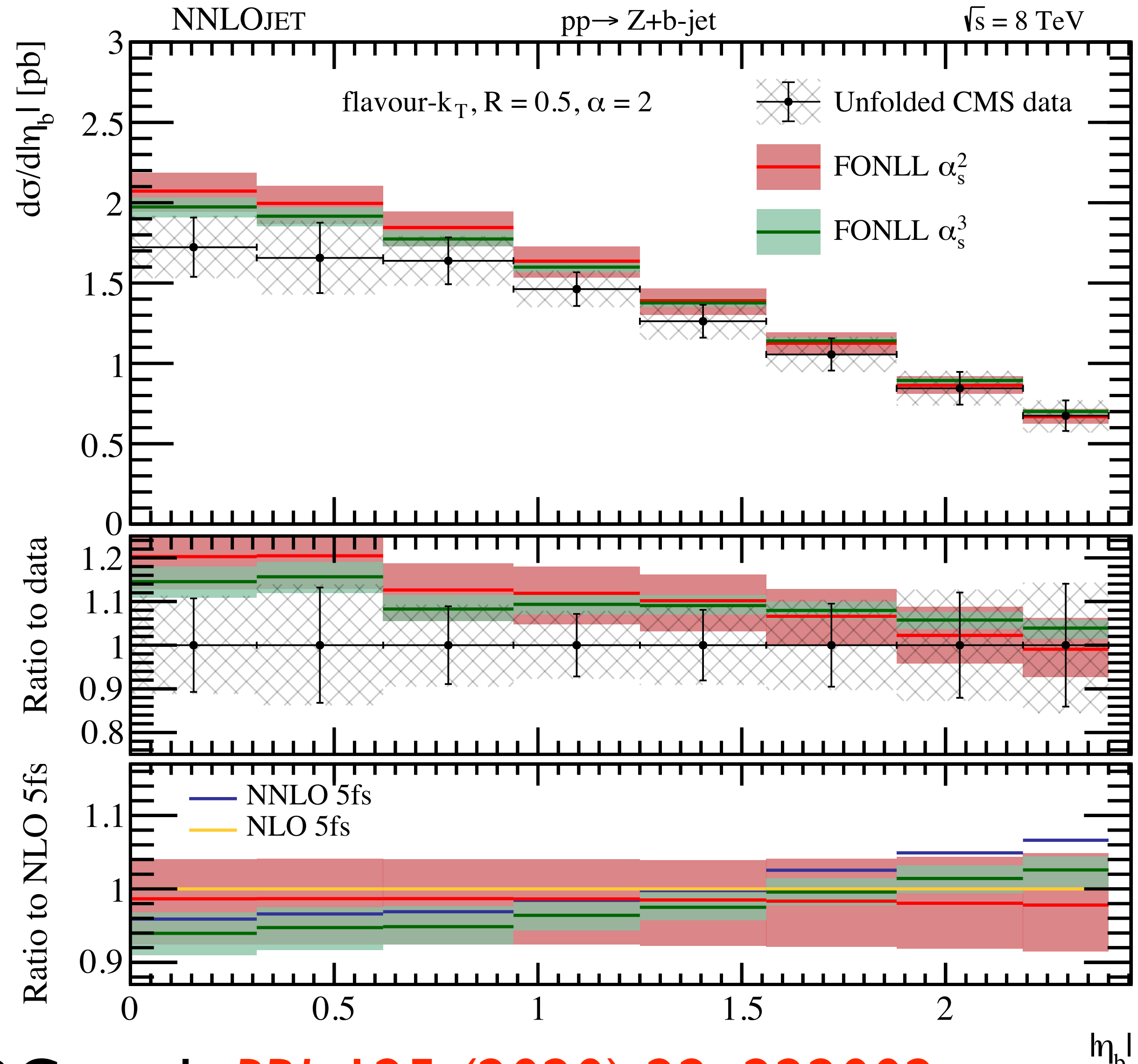
		m_b	$\mathcal{O}(\alpha_s^3)$
$\chi^2/N_{\rm dat}$	1.9	1.7	1.5

NLO (5fs)

$$\chi^2 = \sum_{\rm bins} \frac{(\sigma_{\rm theory} - \sigma_{\rm data})^2}{\delta\sigma_{\rm data}^2}$$

Note: used smaller uncertainty in χ^2

Theory meets experiment



← (2-3)% unc.

η_b

RG et al., *PRL* 125 (2020) 22, 222002

Exact m_b effects included →

		m_b	$\mathcal{O}(\alpha_s^3)$
$\chi^2/N_{\rm dat}$	2.0	1.6	1.0
	NLO (5fs)		

$$\chi^2 = \sum_{\rm bins} \frac{(\sigma_{\rm theory} - \sigma_{\rm data})^2}{\delta\sigma^2_{\rm data}}$$

Note: used smaller uncertainty in χ^2

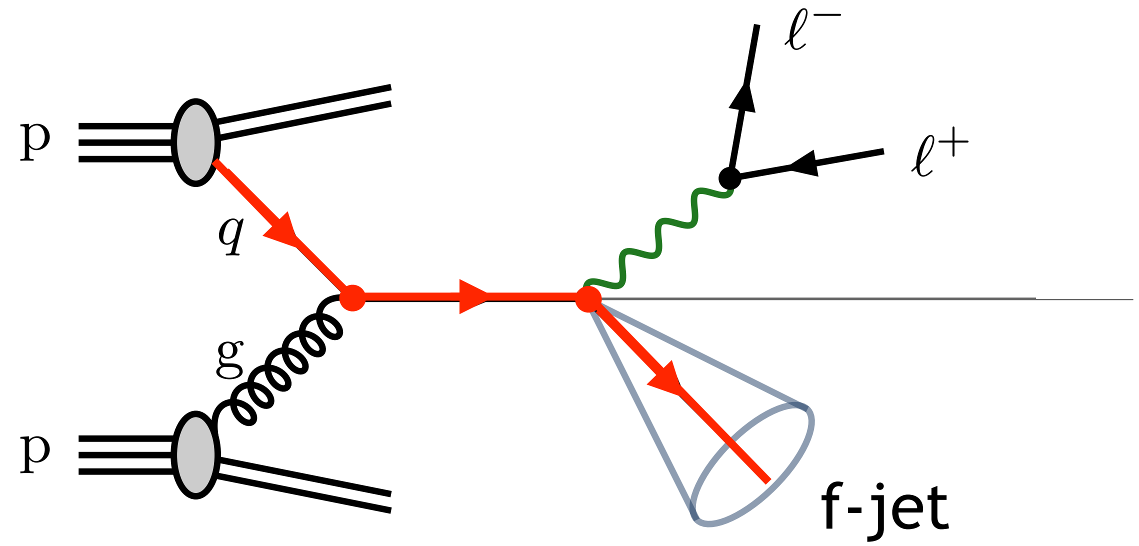
Summary: Part 1

Direct heavy-flavour production (V+f-jet)

(i) Resumming heavy-flavour PDF essential (computation in VFNS)

(ii) Demands the use of a <u>flavoured</u>-jet algorithm (or ad hoc prescription)

(iii) Theoretically well motivated (avoiding the collinear even-tags)



Critical for probing the proton flavour via: $V + \mathrm{f} - \mathrm{jet}\,, \quad V = W^{\pm}, \gamma, Z$

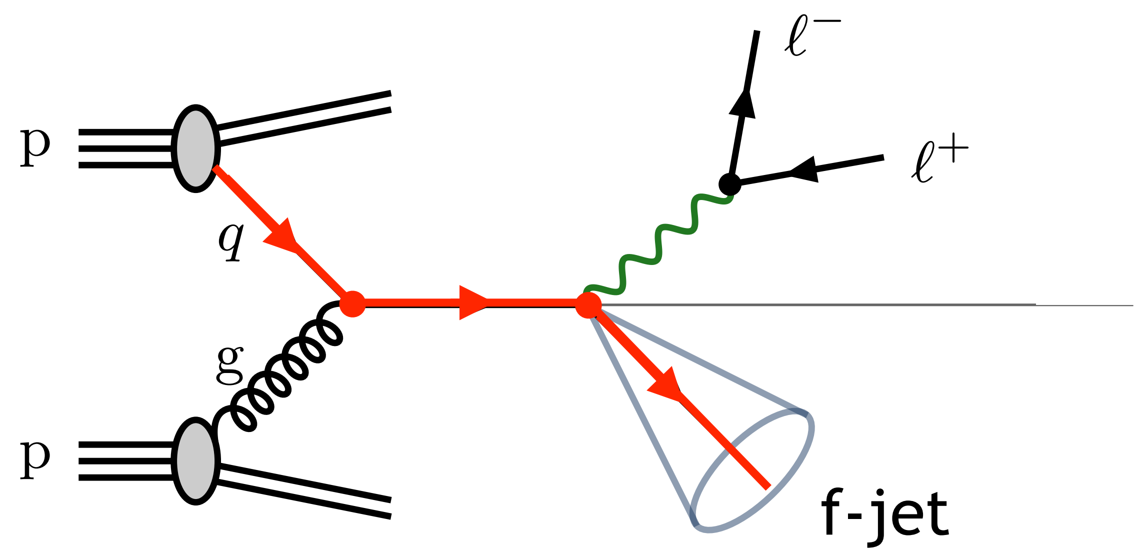
Summary: Part 1

Direct heavy-flavour production (V+f-jet)

(i) Resumming heavy-flavour PDF essential (computation in VFNS)

(ii) Demands the use of a <u>flavoured</u>-jet algorithm (or ad hoc prescription)

(iii) Theoretically well motivated (avoiding the collinear even-tags)



Critical for probing the proton flavour via: $V + \mathrm{f} - \mathrm{jet}\,, \quad V = W^{\pm}, \gamma, Z$

This alone motivates (i.e. the Roadmap to precision)

(a) [Exp.] Feasibility of applying a flavour-dependent jet alg. in data

(b) [Cont.] Will we have to rely on unfolding? How reliable is NLO+PS

Summary: Part 2

Collinear safety (even-tags)

(i) Unique assignment of $b = 1$ and $\bar{b} = -1$ to avoid collinear log or $1/\epsilon$

(ii) Manifests as double/even-tagged jets in practice

(iii) Critical issue for all fixed-order (anti-k_T or flavour-k_T)

(iv) Even if its impact is small for `signal' (VH) its large for background (Vj)

Summary: Part 2

Collinear safety (even-tags)

(i) Unique assignment of $b=1$ and $\bar{b}=-1$ to avoid collinear log or $1/\epsilon$

(ii) Manifests as double/even-tagged jets in practice

(iii) Critical issue for all fixed-order (anti-k_T or flavour-k_T)

(iv) Even if its impact is small for `signal' (VH) its large for background (Vj)

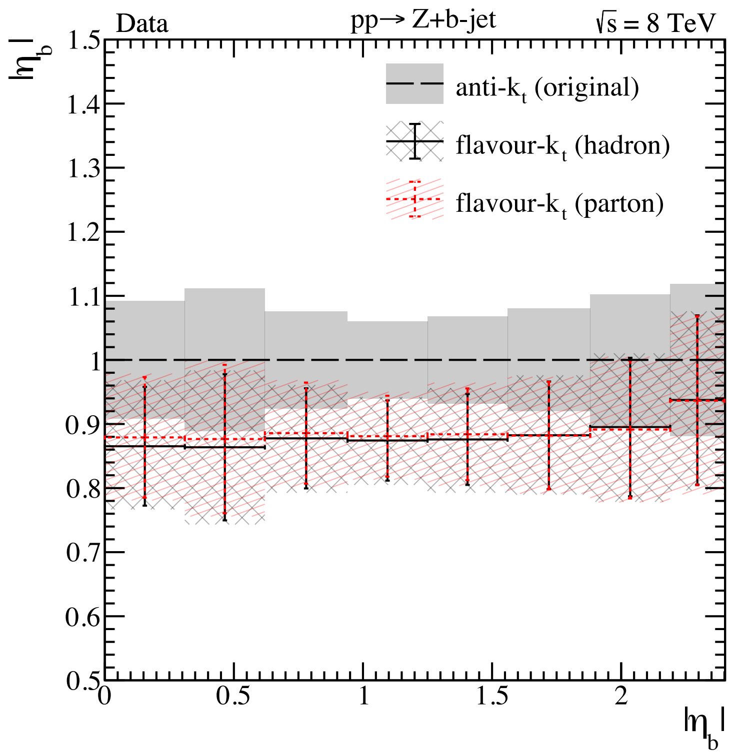
My questions (also related to Part 1), and part of the Roadmap:

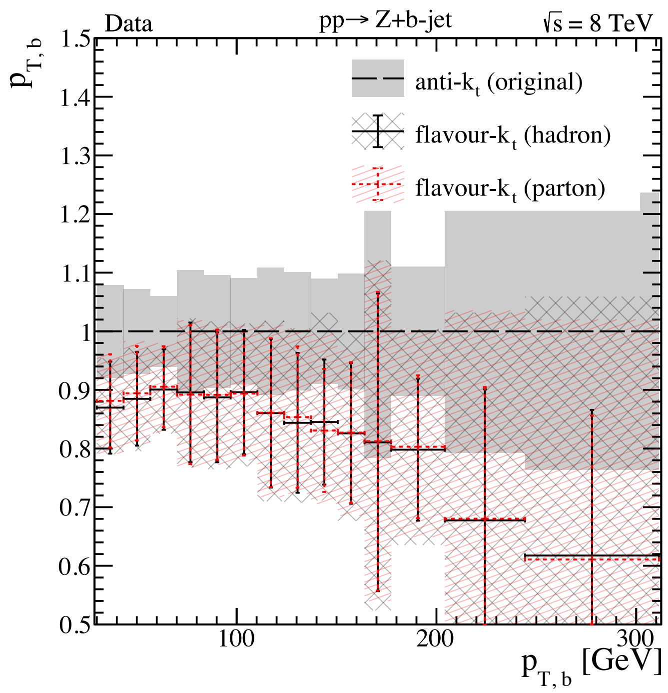
(a) How well can we isolate even-tagged anti-k_T jets in data (ϵ_{tag}^2)

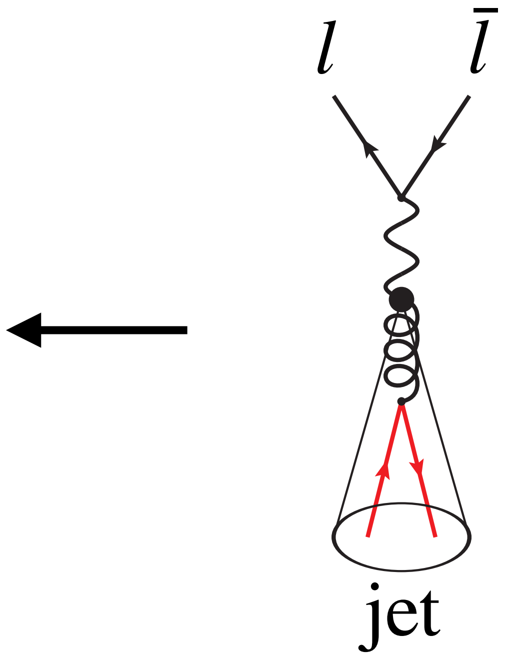
(b) To what extent does NLO+PS describe the double-tag enriched regions

(c) Are V+heavy-flavour control regions double-tag enriched? No I guess

(d) Is higher (fixed / logarithmic) accuracy needed — e.g. NNLO+(NLL PS)







Unfolding correction ~10% for Z+b-jet (grows for large $p_{T,b}$)

Questions/comments and discussion encouraged!

Whiteboard

Whiteboard

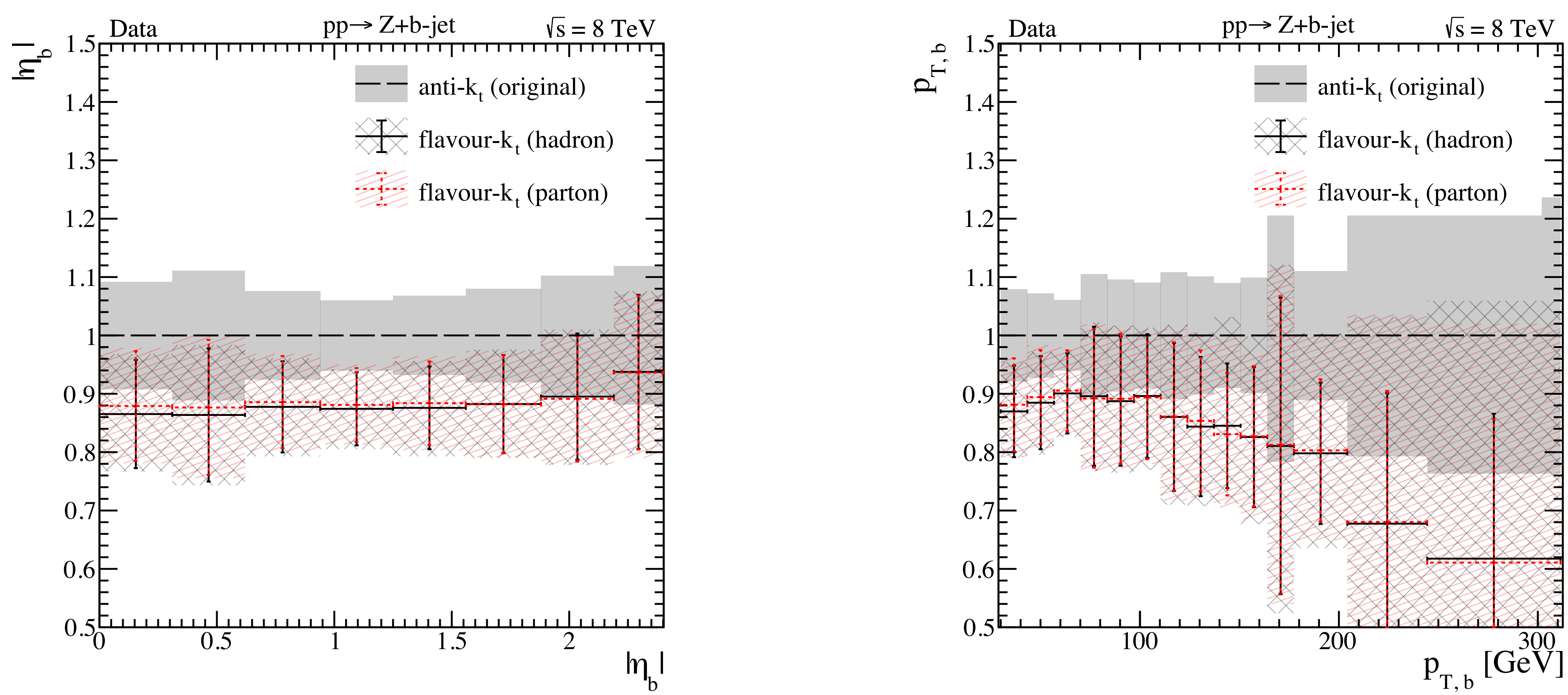
Size of unfolding correction

How to account for theory-experiment mismatch?

Use an NLO + Parton Shower prediction (which can evaluate both)

1) Prediction at parton-level, flavour-k_T algorithm **(Theory)**
2) Prediction at hadron-level, anti-k_T algorithm **(Experiment)**

Calculate an "Unfolding" correction from 2) Experiment → 1) Theory



We use RooUnfold (following the procedure used in the exp. analyses)

NNLO flavoured jet cross-sections

Primarily challenge: dealing with flavour

$$\mathrm{d}\hat{\sigma}_{ij,\mathrm{NLO}} = \int_{n+1} \left[\mathrm{d}\hat{\sigma}^{R}_{ij,\mathrm{NLO}} - \mathrm{d}\hat{\sigma}^{S}_{ij,\mathrm{NLO}}\right] + \int_{n} \left[\mathrm{d}\hat{\sigma}^{V}_{ij,\mathrm{NLO}} - \mathrm{d}\hat{\sigma}^{T}_{ij,\mathrm{NLO}}\right], \qquad (2.1)$$

Generic structure of higher-order terms (see arXiv: 1907.05836)

$$\mathrm{d}\hat{\sigma}^{R}_{ij,\mathrm{NLO}} = \mathcal{N}^{R}_{\mathrm{NLO}}\, \mathrm{d}\Phi_{n+1}\left(\{p_3,\ldots,p_{n+3}\};p_1,p_2\right)\, \frac{1}{S_{n+1}} \times \left[M^{0}_{n+3}\left(\{p_{n+3}\},\{f_{n+3}\}\right)\; J^{(n+1)}_{n}(\{p_{n+1}\},\{f_{n+1}\})\right]. \qquad (2.2)$$

Jet function acts on flavour and momenta of reduced MEs. In general (i, j, k) $\xrightarrow[\text{momentum}]{\text{flavour}}$ (I, K)

$$\mathrm{d}\hat{\sigma}^{S}_{ij,\mathrm{NLO}} = \mathcal{N}^{R}_{\mathrm{NLO}} \sum_{k} \mathrm{d}\Phi_{n+1}\left(\{p_3,\ldots,p_{n+3}\};p_1,p_2\right)\, \frac{1}{S_{n+1}} \times \left[X^{0}_{3}(\cdot,k,\cdot)\; M^{0}_{n+2}\left(\{\tilde{p}_{n+2}\},\{\tilde{f}_{n+2}\}\right)\; J^{(n)}_{n}\left(\{\tilde{p}_{n}\},\{\tilde{f}_{n}\}\right)\right], \qquad (2.3)$$

The ~ functions denoted mapped (in soft/collinear limits) momenta/flavour sets

Flavour-k_T Jet algorithm

Original work: Banfi, Salam, Zanderighi et al. hep-ph/0601139

These details from — (arXiv: 1907.05836)

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}, k_{tj})^\alpha \min(k_{ti}, k_{tj})^{2-\alpha} & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}, k_{tj})^\alpha & \text{softer of } i,j \text{ is unflavoured,} \end{cases} \tag{2.4}$$

and

$$d_{i\overset{(-)}{B}} = \begin{cases} \max(k_{ti}, k_{t\overset{(-)}{B}}(y_i))^\alpha \min(k_{ti}, k_{t\overset{(-)}{B}}(y_i))^{2-\alpha} & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}, k_{t\overset{(-)}{B}}(y_i))^\alpha & \text{softer of } i,j \text{ is unflavoured.} \end{cases} \tag{2.5}$$

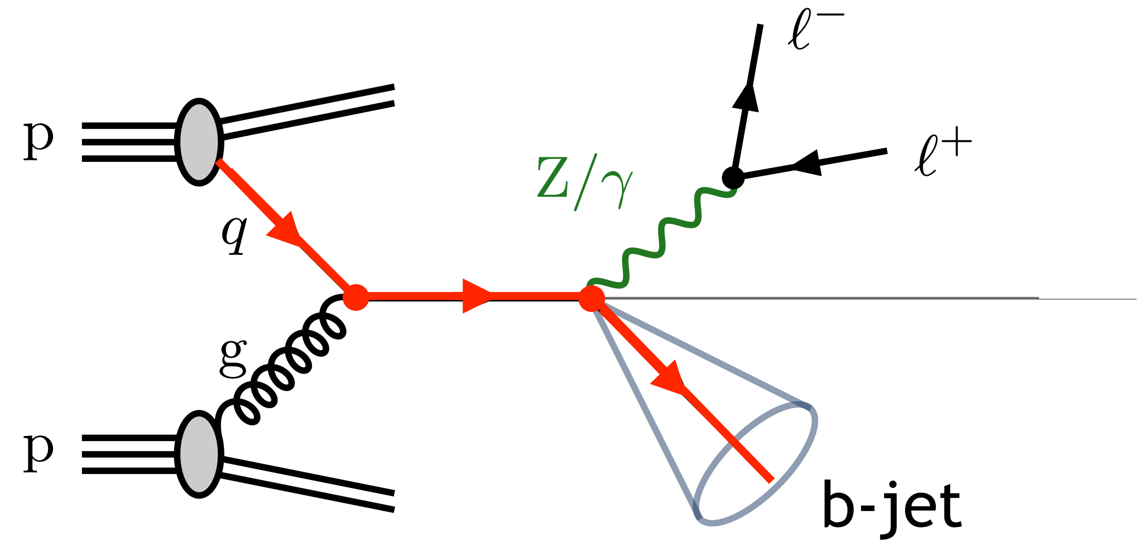
Introduction of a beam momentum, controls clusterings

$$k_{tB}(y) = \sum_i k_{ti} \left(\Theta(y_i - y) + \Theta(y - y_i)\, \mathrm{e}^{y_i - y}\right), \tag{2.6}$$

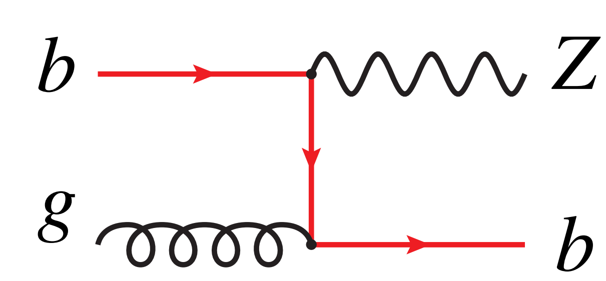
$$k_{t\bar{B}}(y) = \sum_i k_{ti} \left(\Theta(y - y_i) + \Theta(y_i - y)\, \mathrm{e}^{y - y_i}\right), \tag{2.7}$$

The massless NNLO calculation

$$\mathrm{d}\hat{\sigma}_{ij\to\hat{X}} = \mathrm{d}\hat{\sigma}^{\mathrm{LO}}_{ij\to\hat{X}} + \alpha_s\,\mathrm{d}\hat{\sigma}^{\mathrm{NLO}}_{ij\to\hat{X}} + \alpha_s^2\,\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{ij\to\hat{X}} + \ldots$$



At LO: 4 distinct channels, $\mathrm{d}\hat{\sigma}^{\mathrm{LO}}_{ij} \sim \int \mathrm{d}\phi_{\hat{X}}\,|M_{ij\to\hat{X}}|^2$



At NNLO: 1000 distinct channels (amplitudes also become very complicated)

Use a "flavoured dressed" version of the computation of $Z + 1j$ @ NNLO

Gehrmann-De Ridder et al., https://arxiv.org/abs/1507.02850

PRL 117, 022001 (2016)

The massless NNLO calculation

$$\mathrm{d}\hat{\sigma}_{ij\to\hat{X}} = \mathrm{d}\hat{\sigma}^{\mathrm{LO}}_{ij\to\hat{X}} + \alpha_s\,\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{ij\to\hat{X}} + \alpha_s^2\,\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{ij\to\hat{X}} + \dots$$

Theory collaboration between CERN, Durham, Karlsruhe, Lisbon, Nikhef, Zurich

A (parton level) Monte Carlo generator, antenna subtraction formalism

(Gehrmann et al. 2005-2013)

My collaborators for this work, i.e. $pp \to Z + \mathrm{b}-\mathrm{jet}$, *PRL* 125 (2020) 22, 222002

RG

A. Gehrmann-De Ridder

E.W.N. Glover

A. Huss

I. Maier

The mass of the b-quark

$$m_b^{\text{pole}} \sim 5 \text{ GeV}$$

The NNLO QCD computation assumes $m_b = 0$, what does this mean

The b-quark is **active** in the running of α_s and PDF. Meaning?

$$\frac{d\alpha_s}{d\ln\mu} = -\beta_0 \frac{\alpha_s^2}{2\pi} + \mathcal{O}(\alpha_s^3)$$

$$\alpha_s(\mu_R) = \frac{\alpha_s(\mu_0)}{1 + \frac{\beta_0}{2\pi}\alpha_s(\mu_0)\ln[\mu_r^2/\mu_0^2]}$$

$$\beta_0 = \left(\frac{11}{6}c_a - \frac{2}{3}t_r n_f\right)$$

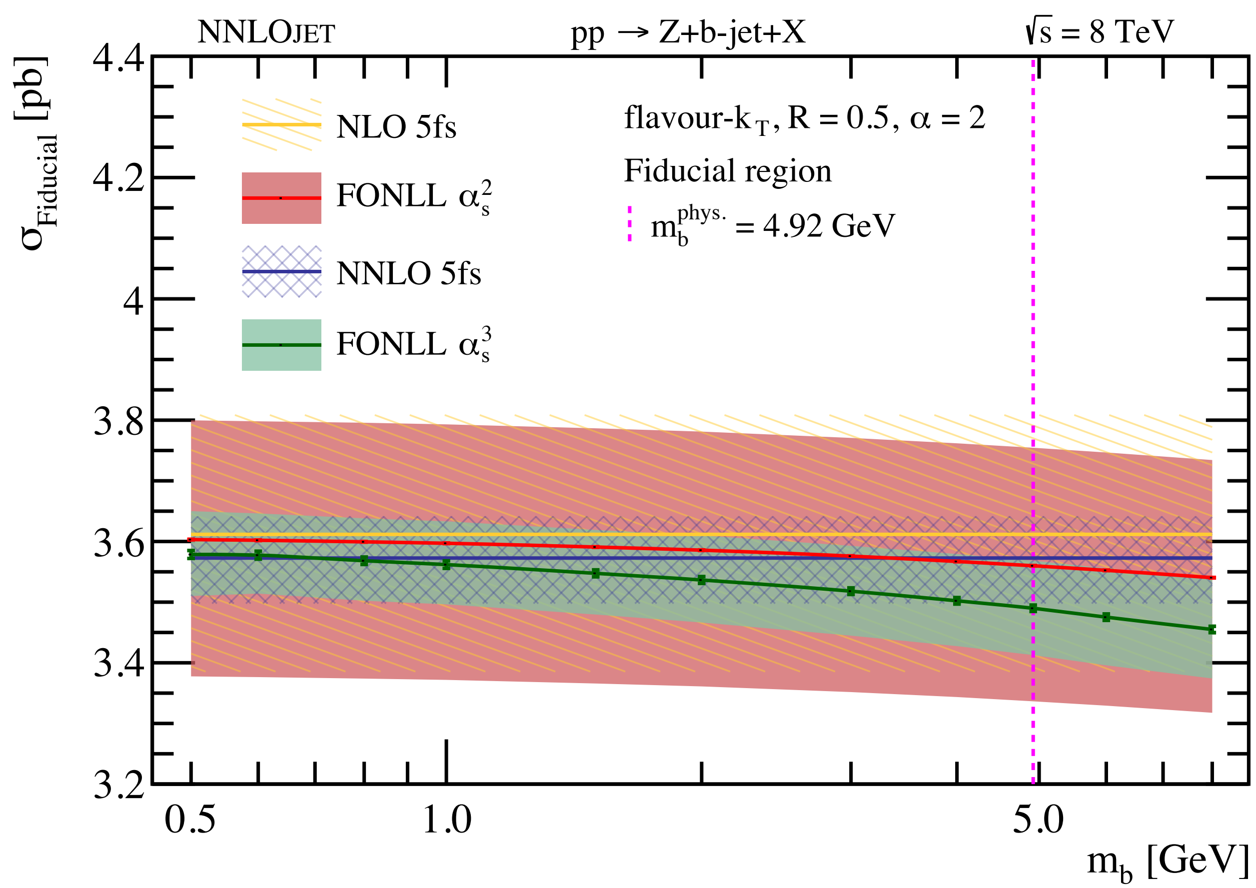
$$\frac{x}{1+Bx} \approx x\left(1 - Bx + B^2x^2\right) + \mathcal{O}(x^4)$$

Use of 'RG' improved perturbation theory to (re)sum $\ln[\mu_r/m_b]$ terms

Including mass corrections

Construct a massive variable flavour number scheme (M-VFNS)

$$d\sigma^{\mathrm{M-VFNS}} = d\sigma^{5fs} + \left(d\sigma^{4fs} - d\sigma^{4fs}_{m_b\to 0}\right)$$



$$d\sigma^{4fs} = d\sigma^{m_b=0} + d\sigma^{\ln[m_b]} + \left(d\sigma^{m_b}\right) \approx -3\,\%$$

aMC@NLO — dedicated computation

*M-VFNS = FONLL

The zero mass limit

$$\mathrm{d}\sigma^{GMVFNS} = \mathrm{d}\sigma^{m=0} + \left(\mathrm{d}\sigma^{m} - \mathrm{d}\sigma^{m\to 0}\right)$$

$$\mathrm{d}\sigma^{m} = \mathrm{d}\sigma^{m=0,n_f} + \mathrm{d}\sigma^{L[m]} + \mathrm{d}\sigma^{\mathcal{O}(m^2)}$$

$\mathrm{d}\sigma^{L[m]}$ is built from:

1) convolutions of a massless partonic cross section and OME
2) explicit virtual corrections, implicit via $\alpha_s^{n_f}$

Example: gg-channel at $\mathcal{O}(\alpha_s^2)$.

$$\mathrm{d}\sigma_{gg}^{L[m]} = \int \mathrm{d}x_1\, \mathrm{d}x_2\, g(x_1, \mu_F^2)\left[\hat{A}_{g\to b}(z, \mu_F^2/m_b^2) \otimes g(x_2/z, \mu_F^2)\right] \hat{\sigma}^{m=0}_{bg\to Zb}(\alpha_s(\mu_r), \mu_r, \mu_F, \hat{s})$$

$$f_b^{(1)}(x, \mu_F^2) = \int_x^1 g(x/z, \mu_F^2)\hat{A}_{gb} + \mathcal{O}(\alpha_s^2)\,, \quad \hat{A}_{gb} = \frac{\alpha_s(\mu_F^2)}{2\pi} P_{g\to q}(z)\, \ln[\mu_F^2/m_b^2]$$