NNLO QCD corrections to W+2 b-jet production

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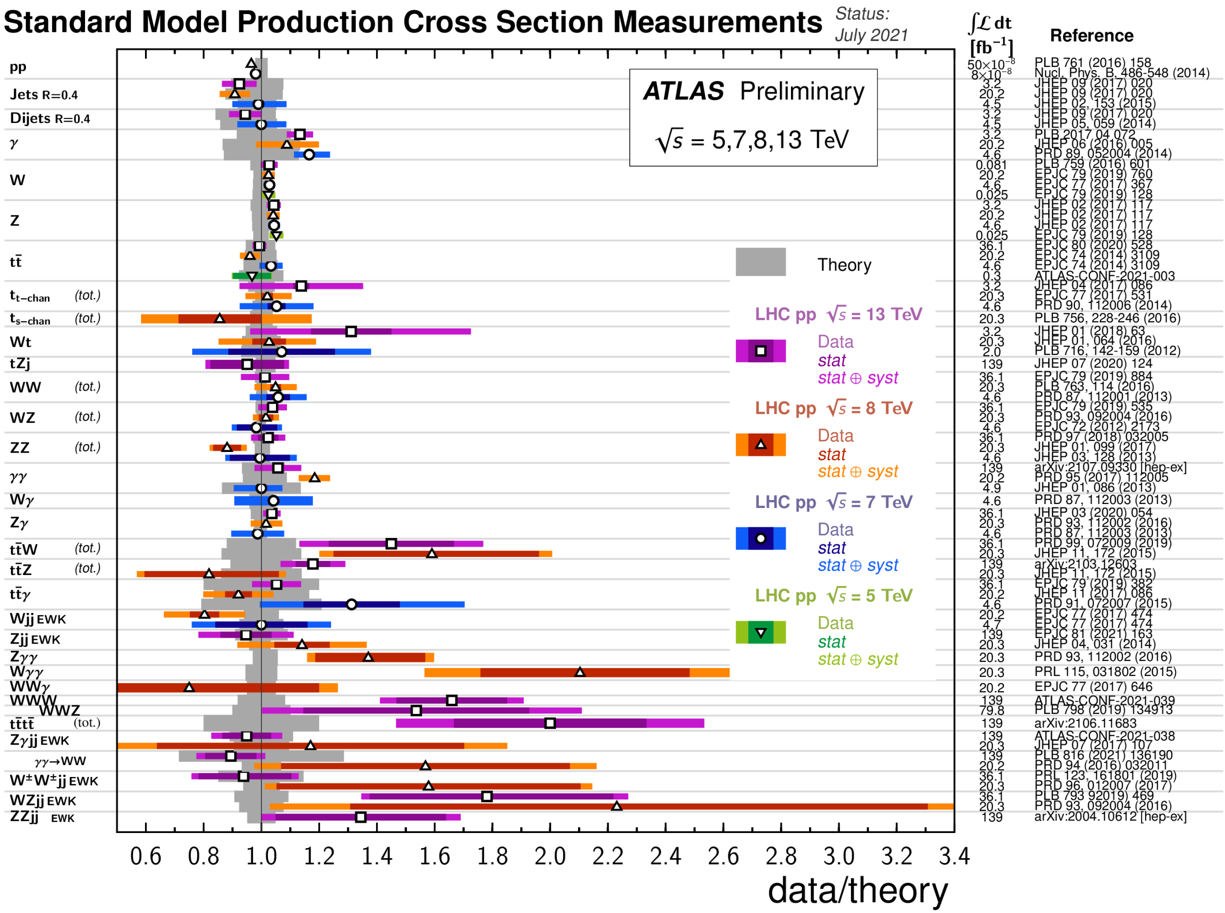
in collaboration with Bayu Hartanto, Andrei Popescu, Simone Zoia

based on: [2102.02516], [2205.01687] and [2209.03280]

Outline

- Introduction
- Sector-improved residue subtraction
- Two-loop five-point amplitude for ud → W (→lν) b bbar
- W+2 b-jet production @ LHC
  - Phenomenology and flavour jet definitions
- Summary and Outlook

SM measurements at the LHC



New physics around the corner?

Precise measurements
<->
Precise theory

Win-Win situation

- improved SM understanding
- search for indirect NP signals

Precision predictions

Resummation

Fixed order
perturbation theory

Parton-showers

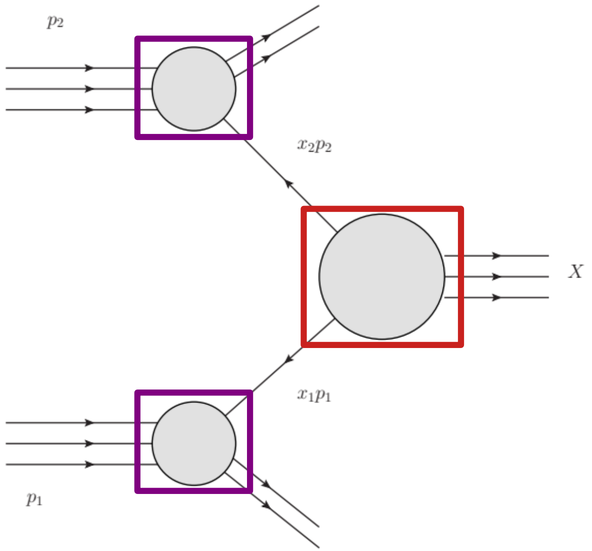
Precision theory predictions

Parametric input:
PDFs and αS

Soft physics:
MPI, colour reconnection,
...

Fragmentation/hadronisation

Perturbative QCD



Hadronic cross section:

$$\sigma_{h_1 h_2 \to X} = \sum_{ij} \int_0^1 \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \phi_{i,h_1}(x_1, \mu_F^2) \phi_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij \to X}(\alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

Parton distribution functions: δ~1-3%

Perturbative expansion of partonic cross section:

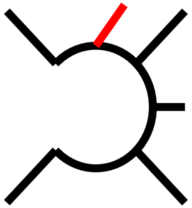
$$\hat{\sigma}_{ab \to X} = \hat{\sigma}^{(0)}_{ab \to X} + \hat{\sigma}^{(1)}_{ab \to X} + \hat{\sigma}^{(2)}_{ab \to X} + \mathcal{O}(\alpha_s^3)$$

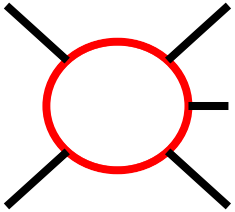
Typical uncertainties from scale variations: δLO ~20-30% δNLO ~5-20% δNNLO ~1-5%

Next-to-leading order case

Perturbative expansion of partonic cross section:

$$\hat{\sigma}_{ab\to X} = \hat{\sigma}^{(0)}_{ab\to X} + \hat{\sigma}^{(1)}_{ab\to X} + \hat{\sigma}^{(2)}_{ab\to X} + \mathcal{O}(\alpha_s^3)$$

Real corrections: 

Virtual corrections: 

$$\hat{\sigma}^{(1)}_{ab} = \hat{\sigma}^{\mathrm{R}}_{ab} + \hat{\sigma}^{\mathrm{V}}_{ab} + \hat{\sigma}^{\mathrm{C}}_{ab}$$

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$

$$\hat{\sigma}^{\mathrm{V}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n}\, 2\mathrm{Re} \left\langle \mathcal{M}^{(0)}_{n} \middle| \mathcal{M}^{(1)}_{n} \right\rangle \mathrm{F}_{n}$$

$$\hat{\sigma}^{\mathrm{C}}_{ab} = (\text{single convolution})\, \mathrm{F}_{n}$$

Each term separately infrared (IR) divergent.

→ KLN theorem: sum is finite for sufficiently inclusive observables and regularization scheme independent

Slicing and Subtraction

Central idea: Divergences arise from IR limits → Factorization!

Slicing:

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int_{\delta(\Phi)\geq\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} + \frac{1}{2\hat{s}} \int_{\delta(\Phi)<\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$

$$\approx \frac{1}{2\hat{s}} \int_{\delta(\Phi)\geq\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} + \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n \, \tilde{M}(\delta_c)\mathrm{F}_n + \mathcal{O}(\delta_c)$$

$$\ldots + \hat{\sigma}^{\mathrm{V}}_{ab} = \text{finite}$$

Subtraction:

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int \left(\mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} - \mathrm{d}\tilde{\Phi}_{n+1} \, \mathcal{S}\mathrm{F}_n \right) + \frac{1}{2\hat{s}} \int \mathrm{d}\tilde{\Phi}_{n+1} \, \mathcal{S}\mathrm{F}_n$$

$$\frac{1}{2\hat{s}} \int \mathrm{d}\tilde{\Phi}_{n+1} \, \mathcal{S}\mathrm{F}_n = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n \, \mathrm{d}\Phi_1 \, \mathcal{S}\mathrm{F}_n$$

Slicing:
- Conceptually simple
- Recycling of lower computations
- Non-local cancellations
  → computationally expensive

Subtraction:
- Conceptually more difficult
- Local subtraction → efficient
- Better numerical stability

Slicing and Subtraction

Central idea: Divergences arise from IR limits → Factorization!

Slicing:

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int_{\delta(\Phi)\geq\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} + \frac{1}{2\hat{s}} \int_{\delta(\Phi)<\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$

$$\approx \frac{1}{2\hat{s}} \int_{\delta(\Phi)\geq\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} + \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n\, \tilde{M}(\delta_c) \mathrm{F}_n + \mathcal{O}(\delta_c)$$

$$\ldots + \hat{\sigma}^{\mathrm{V}}_{ab} = \mathrm{finite}$$

Subtraction:

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int \left(\mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} - \mathrm{d}\tilde{\Phi}_{n+1}\, \mathcal{S}\mathrm{F}_n \right) + \frac{1}{2\hat{s}} \int \mathrm{d}\tilde{\Phi}_{n+1}\, \mathcal{S}\mathrm{F}_n$$

$$\frac{1}{2\hat{s}} \int \mathrm{d}\tilde{\Phi}_{n+1}\, \mathcal{S}\mathrm{F}_n = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n\, \mathrm{d}\Phi_1\, \mathcal{S}\mathrm{F}_n$$

Slicing:

qT-slicing [Catain'07],
N-jettiness slicing [Gaunt'15/Boughezal'15]

Subtraction:

Antenna [Gehrmann'05-'08], Colorful [DelDuca'05-'15],
Projetction [Cacciari'15], Geometric [Herzog'18],
Unsubtraction [Aguilera-Verdugo'19],
Nested collinear [Caola'17],
Sector-improved residue subtraction [Czakon'10-'14]

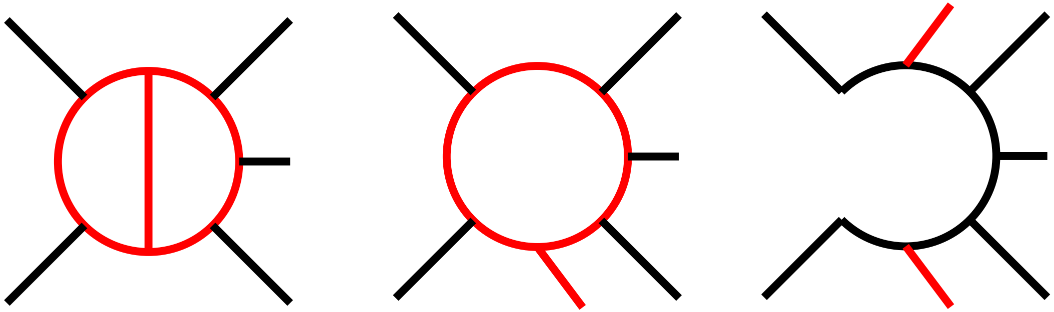
Partonic cross section beyond NLO

Perturbative expansion of partonic cross section:

$$\hat{\sigma}_{ab\to X} = \hat{\sigma}^{(0)}_{ab\to X} + \hat{\sigma}^{(1)}_{ab\to X} + \hat{\sigma}^{(2)}_{ab\to X} + \mathcal{O}(\alpha_s^3)$$

Contributions with different multiplicities and # convolutions:

$$\hat{\sigma}^{(2)}_{ab} = \hat{\sigma}^{\mathrm{VV}}_{ab} + \hat{\sigma}^{\mathrm{RV}}_{ab} + \hat{\sigma}^{\mathrm{RR}}_{ab} + \hat{\sigma}^{\mathrm{C2}}_{ab} + \hat{\sigma}^{\mathrm{C1}}_{ab}$$



$$\hat{\sigma}^{\mathrm{RR}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2} \left\langle \mathcal{M}^{(0)}_{n+2} \middle| \mathcal{M}^{(0)}_{n+2} \right\rangle \mathrm{F}_{n+2}$$

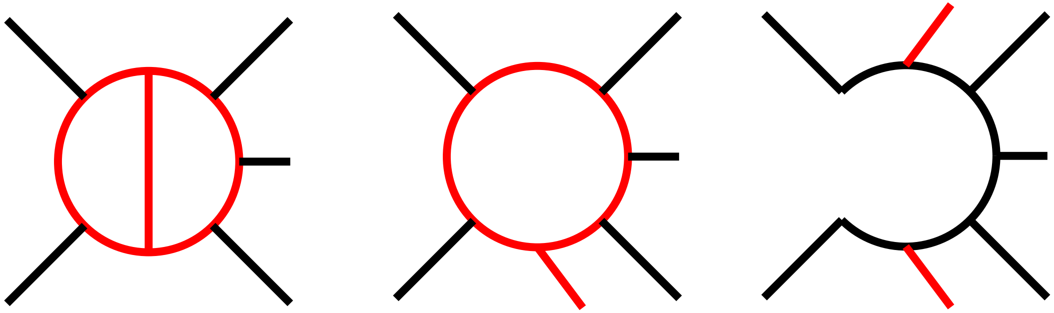
$$\hat{\sigma}^{\mathrm{RV}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1}\, 2\mathrm{Re} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(1)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$

$$\hat{\sigma}^{\mathrm{VV}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n} \left(2\mathrm{Re} \left\langle \mathcal{M}^{(0)}_{n} \middle| \mathcal{M}^{(2)}_{n} \right\rangle + \left\langle \mathcal{M}^{(1)}_{n} \middle| \mathcal{M}^{(1)}_{n} \right\rangle \right) \mathrm{F}_{n}$$

$$\hat{\sigma}^{\mathrm{C1}}_{ab} = (\text{single convolution})\, \mathrm{F}_{n+1}$$

$$\hat{\sigma}^{\mathrm{C2}}_{ab} = (\text{double convolution})\, \mathrm{F}_{n}$$

Sector-improved residue subtraction



Sector decomposition I

Considering working in CDR:

→ Virtuals are usually done in this regularization: $\hat{\sigma}_{ab}^{VV} = \sum_{i=-4}^{0} c_i \epsilon^i + \mathcal{O}(\epsilon)$

→ Can we write the real radiation as such expansion?

→ Difficult integrals, analytical impractical (except very simple observables)!

→ Numerics not possible, integrals are divergent → ε-poles!

How to extract these poles? → Sector decomposition!

Divide and conquer the phase space:

$$1 = \sum_{i,j} \left[\sum_k \mathcal{S}_{ij,k} + \sum_{k,l} \mathcal{S}_{i,k;j,l} \right] \quad \Rightarrow \quad \hat{\sigma}_{ab}^{\mathrm{RR}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2} \sum_{i,j} \left[\sum_k \mathcal{S}_{ij,k} + \sum_{k,l} \mathcal{S}_{i,k;j,l} \right] \left\langle \mathcal{M}_{n+2}^{(0)} \middle| \mathcal{M}_{n+2}^{(0)} \right\rangle \mathrm{F}_{n+2}$$

Sector decomposition II

Divide and conquer the phase space:

- Each $\mathcal{S}_{ij,k}/\mathcal{S}_{i,k;j,l}$ has simpler divergences.
  (Soft and collinear (w.r.t parton k,l) of partons i and j)
  Parametrization w.r.t. reference parton
  (makes divergences explicit:)

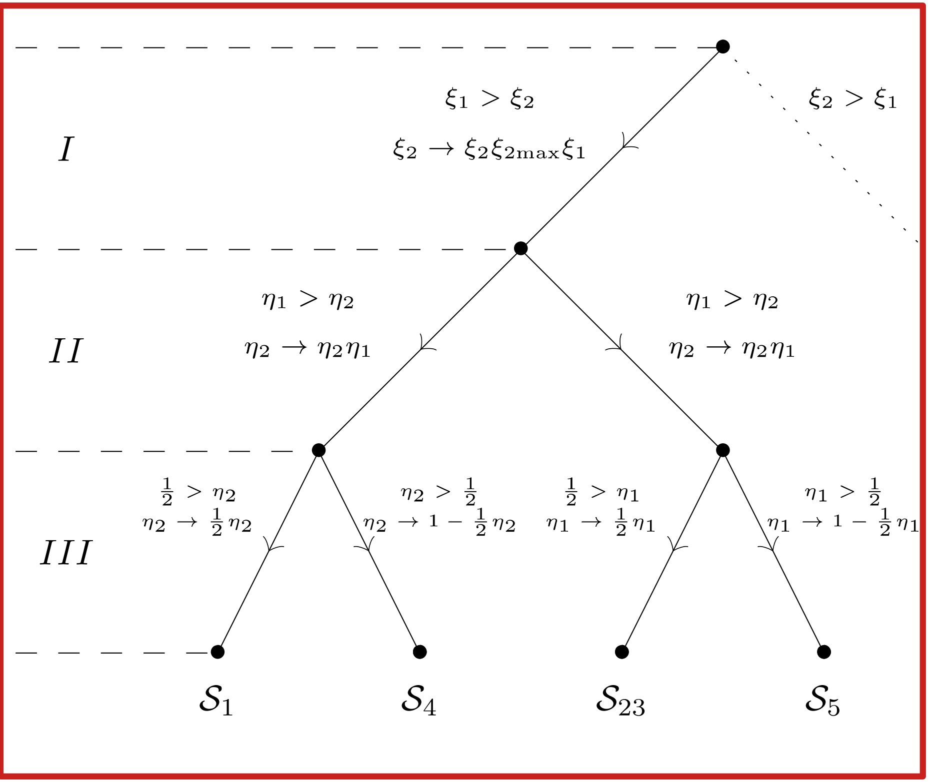
$$\hat{\eta}_i = \tfrac{1}{2}(1-\cos\theta_{ir}) \in [0,1] \qquad \hat{\xi}_i = \frac{u_i^0}{u_{\max}^0} \in [0,1]$$

- Example: Splitting function $\sim \dfrac{1}{s_{r1}} P(z)$

$$s_{r1} = (p_r + p_1)^2 = 2 p_r^0 u_{\max}^1 \xi_1 \eta_1$$

$$(p_r + u_1 + u_2)^2 = 2 p_r^0 (\xi_1 \eta_1 u_{\max}^1 + \xi_2 \eta_2 u_{\max}^2 + \xi_1 \xi_2 \frac{u_{max}^1 u_{max}^2}{p_r^0} \angle(u_1, u_2))$$

- Subdivide to factorize divergences
  → double soft factorization: $\theta(u_1^0 - u_2^0) + \theta(u_2^0 - u_1^0)$
  → triple collinear factorization



[Czakon'10,Caola'17]

Sector decomposition III

Factorized singular limits in each sector:

$$\frac{1}{2\hat{s}}\int \mathrm{d}\Phi_{n+2}\,\mathcal{S}_{kl,m}\left\langle \mathcal{M}^{(0)}_{n+2}\middle|\mathcal{M}^{(0)}_{n+2}\right\rangle \mathrm{F}_{n+2} = \sum_{\text{sub-sec.}}\int \mathrm{d}\Phi_n \prod \mathrm{d}x_i\, \underbrace{x_i^{-1-b_i\epsilon}}_{\text{singular}}\, \mathrm{d}\tilde{\mu}(\{x_i\}) \underbrace{\prod x_i^{a_i+1}\langle \mathcal{M}_{n+2}|\mathcal{M}_{n+2}\rangle}_{\text{regular}}\mathrm{F}_{n+2}$$

$$x_i \in \{\eta_1, \xi_1, \eta_2, \xi_2\}$$

Regularization of divergences:

$$x^{-1-b\epsilon} = \underbrace{\frac{-1}{b\epsilon}}_{\text{pole term}} + \underbrace{\left[x^{-1-b\epsilon}\right]_+}_{\text{reg. + sub.}}$$

$$\int_0^1 \mathrm{d}x\,\left[x^{-1-b\epsilon}\right]_+ f(x) = \int_0^1 \frac{f(x)-f(0)}{x^{1+b\epsilon}}$$

Finite NNLO cross section

$$\hat{\sigma}_{ab}^{\rm RR} = \frac{1}{2\hat{s}} \int {\rm d}\Phi_{n+2} \left\langle \mathcal{M}_{n+2}^{(0)} \middle| \mathcal{M}_{n+2}^{(0)} \right\rangle {\rm F}_{n+2}$$

$$\hat{\sigma}_{ab}^{\rm RV} = \frac{1}{2\hat{s}} \int {\rm d}\Phi_{n+1}\, 2{\rm Re} \left\langle \mathcal{M}_{n+1}^{(0)} \middle| \mathcal{M}_{n+1}^{(1)} \right\rangle {\rm F}_{n+1}$$

$$\hat{\sigma}_{ab}^{\rm VV} = \frac{1}{2\hat{s}} \int {\rm d}\Phi_{n} \left(2{\rm Re} \left\langle \mathcal{M}_{n}^{(0)} \middle| \mathcal{M}_{n}^{(2)} \right\rangle + \left\langle \mathcal{M}_{n}^{(1)} \middle| \mathcal{M}_{n}^{(1)} \right\rangle \right) {\rm F}_{n}$$

$$\hat{\sigma}_{ab}^{\rm C1} = (\text{single convolution})\, {\rm F}_{n+1}$$

$$\hat{\sigma}_{ab}^{\rm C2} = (\text{double convolution})\, {\rm F}_{n}$$

sector decomposition and master formula

$$x^{-1-b\epsilon} = \underbrace{\frac{-1}{b\epsilon}}_{\text{pole term}} + \underbrace{\left[x^{-1-b\epsilon}\right]_+}_{\text{reg. + sub.}}$$

$$\left(\sigma_F^{RR}, \sigma_{SU}^{RR}, \sigma_{DU}^{RR}\right) \quad \left(\sigma_F^{RV}, \sigma_{SU}^{RV}, \sigma_{DU}^{RV}\right) \quad \left(\sigma_F^{VV}, \sigma_{DU}^{VV}, \sigma_{FR}^{VV}\right) \quad \left(\sigma_{SU}^{C1}, \sigma_{DU}^{C1}\right) \quad \left(\sigma_{DU}^{C2}, \sigma_{FR}^{C2}\right)$$

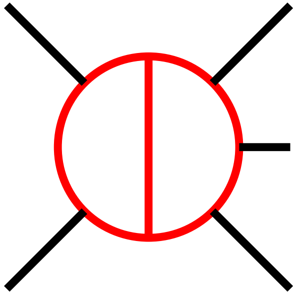
re-arrangement of terms → 4-dim. formulation [Czakon'14,Czakon'19]

$$\underline{\left(\sigma_F^{RR}\right)} \quad \underline{\left(\sigma_F^{RV}\right)} \quad \underline{\left(\sigma_F^{VV}\right)} \quad \underline{\left(\sigma_{SU}^{RR}, \sigma_{SU}^{RV}, \sigma_{SU}^{C1}\right)} \quad \underline{\left(\sigma_{DU}^{RR}, \sigma_{DU}^{RV}, \sigma_{DU}^{VV}, \sigma_{DU}^{C1}, \sigma_{DU}^{C2}\right)} \quad \underline{\left(\sigma_{FR}^{RV}, \sigma_{FR}^{VV}, \sigma_{FR}^{C2}\right)}$$

separately finite: ε poles cancel

Two-loop five-point amplitude

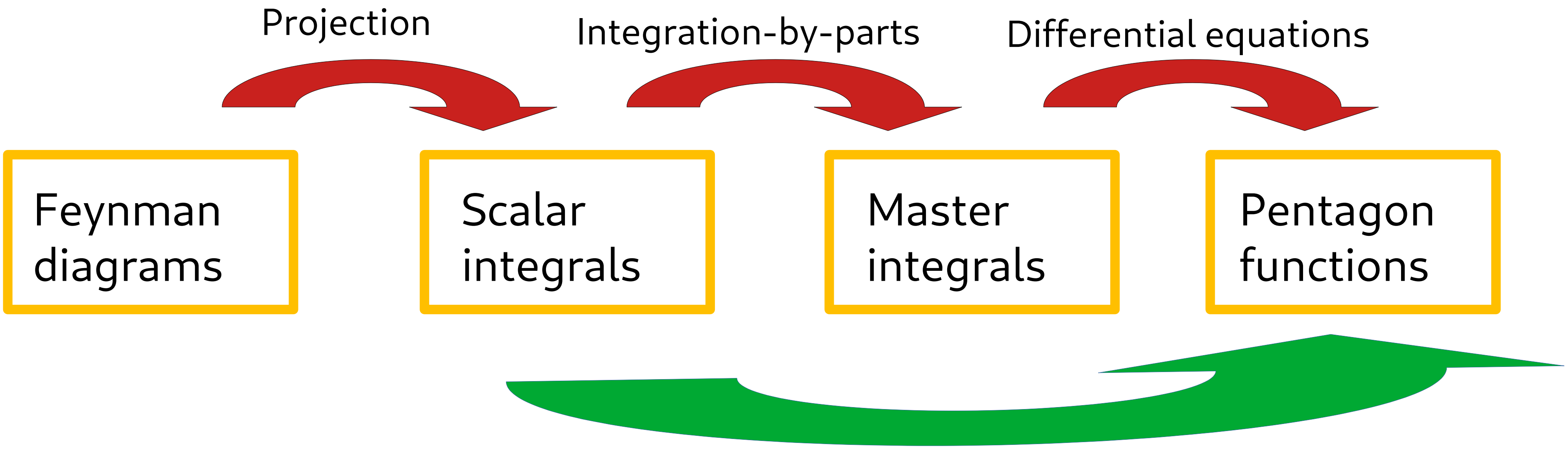
Massless:
[Chawdry'19'20'21] (3A+2j,2A+3j)
[Abreu'20'21] (3A+2j,5j)
[Agarwal'21] (2A+3j)
[Badger'21'] (5j,gggAA)



1 external mass:
[Abreu'21] (W+4j)
[Badger'21'22] (Hqqgg,W4q,WAjjj)

Overview

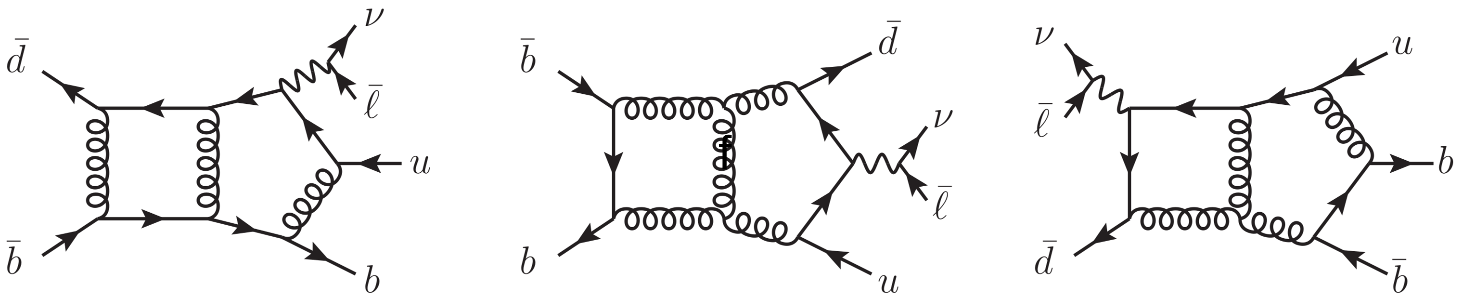
Old school approach:



Automated framework using finite fields to avoid expression swell based on FiniteFlow [Peraro'19]

Projection to scalar integrals

Generate diagrams (contributing to leading-colour) with QGRAF



Factorizing decay: $A_6^{(L)} = A_5^{(L)\mu} D_\mu P$

$$M_6^{2(L)} = \sum_{\text{spin}} A_6^{(0)^*} A_6^{(L)} = M^{(L)\mu\nu} D_{\mu\nu} |P|^2$$

Projection on scalar functions (FORM+Mathematica):
→ anti-commuting γ_5 + Larin prescription

$$M_5^{(L)} = \sum_{i=1}^{16} a_i^{(L)} v_i^{\mu\nu}$$

$$a_i^{(L)} = a_i^{(L),\text{even}} + \mathrm{tr}_5 a_i^{(L),\text{odd}}$$

$$a_i^{(L),p} = \sum_i c_{j,i}(\{p\},\epsilon)\mathcal{I}(\{p\},\epsilon)$$

Integration-By-Parts reduction

$$a_i^{(L),p} = \sum_i c_{j,i}(\{p\},\epsilon)\mathcal{I}(\{p\},\epsilon)$$

Prohibitively large number of integrals

$$\mathcal{I}_i(\{p\},\epsilon) \equiv \mathcal{I}(\vec{n}_i,\{p\},\epsilon) = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d}\prod_{k=1}^{11} D_k^{-n_{i,k}}(\{p\},\{k\})$$

Integration-By-Parts identities connect different integrals → system of equations
→ only a small number of independent "master" integrals

$$0 = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d} l_\mu \frac{\partial}{\partial l^\mu}\prod_{k=1}^{11} D_k^{-n_{i,k}}(\{p\},\{k\}) \quad \text{with} \quad l \in \{p\}\cap\{k\}$$

LiteRed (+ Finite Fields)

$$\longrightarrow \quad a_i^{(L),p} = \sum_i d_{j,i}(\{p\},\epsilon)\mathrm{MI}(\{p\},\epsilon)$$

Master integrals & finite remainder

Differential Equations: $\mathrm{d}\vec{\mathrm{MI}} = \mathrm{d}A(\{p\},\epsilon)\vec{\mathrm{MI}}$

Canonical basis: $\mathrm{d}\vec{\mathrm{MI}} = \epsilon \mathrm{d}\tilde{A}(\{p\})\vec{\mathrm{MI}}$

[Remiddi, 97]
[Gehrmann, Remiddi, 99]
[Henn, 13]

Simple iterative solution

$$\mathrm{MI}_i = \sum_w \epsilon^w \tilde{\mathrm{MI}}_i^w \quad \text{with} \quad \tilde{\mathrm{MI}}_i^w = \sum_j c_{i,j} m_j$$

Chen-iterated integrals
"Pentagon"-functions

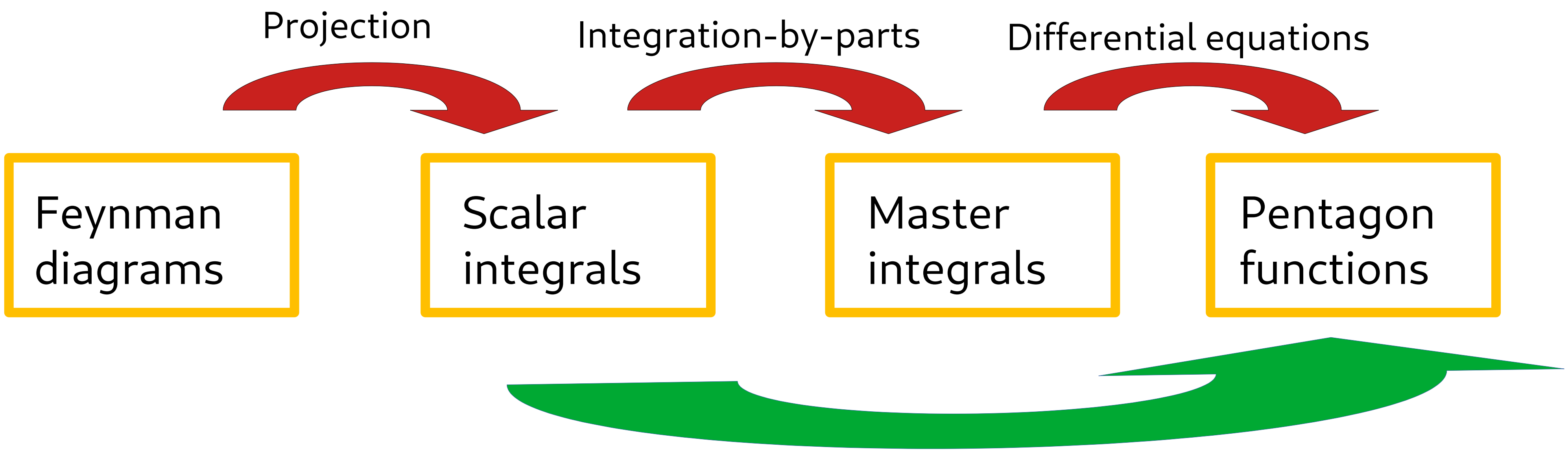
[Chicherin, Sotnikov, 20]
[Chicherin, Sotnikov, Zoia, 21]

Putting everything together (and removing of IR poles):

$$f_i^{(L),p} = a_i^{(L),p} - \text{poles} \qquad\qquad f_i^{(L),p} = \sum_j c_{i,j}(\{p\}) m_j + \mathcal{O}(\epsilon)$$

Overview

Old school approach:



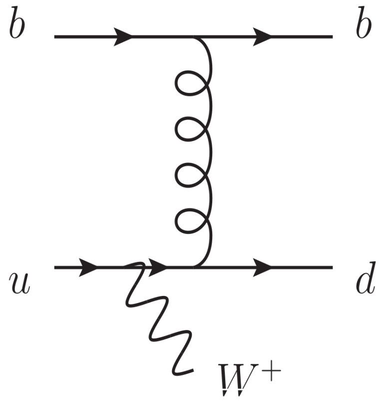
Automated framework using finite fields
to avoid expression swell based on
FiniteFlow [Peraro'19]

W+2 b-jet production @ LHC

W + b - jets

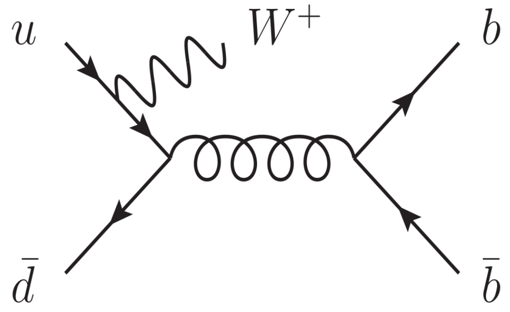
Motivation: → testing perturbative QCD: large NLO QCD corrections, 4FS vs. 5 FS
→ modelling of flavoured jets

W + 1b-jet



→ probe b quark PDFs

W + 2b-jet

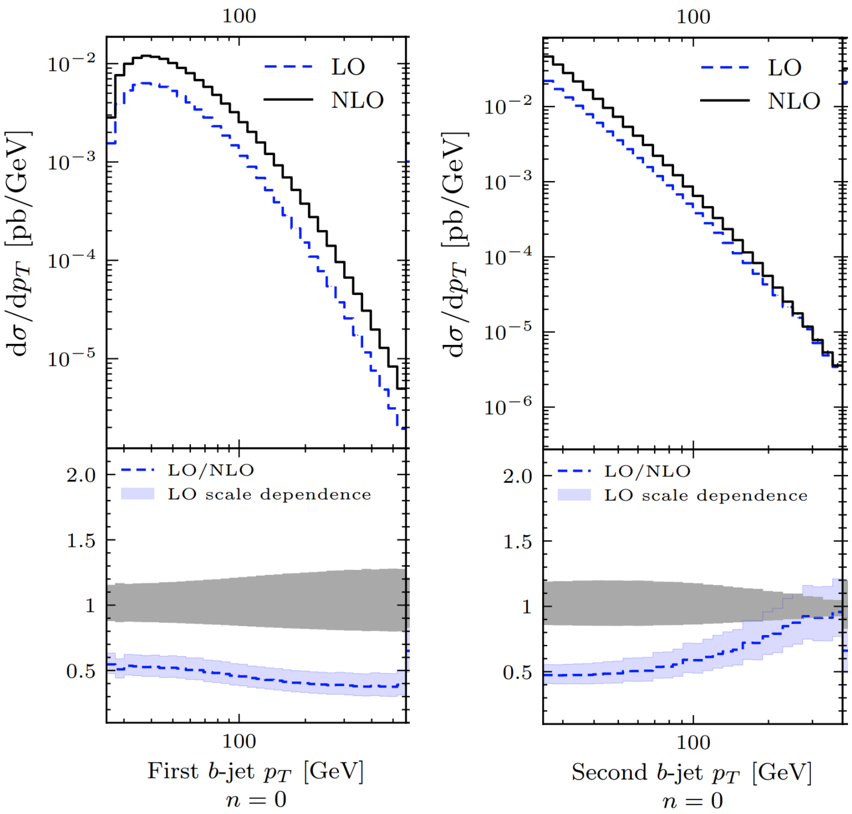


background for:
→ WH(H→ bb)
→ single top

Experiment: [D0,1210.0627,0410062] [ATLAS,1109.1470,1302.2929][CMS,1312.6608,1608.07561]
Theory W+1 b-jet: [Campbell et al,0611348,0809.3003][Caola et.al.,1107.3714]
Theory W+2 b-jet: mb=0 [Ellis et al,9810489] onshell W: [Cordero et al,0606102]W(lv)bb: [Campbell et al,1011.6647]
NLO+PS: [Oleari et al,1105.4488][Frederix et al,1110.5502] W(lv)bb: [Luisoni et al,1502.01213]
W(lv)bb+≤3j: [Anger et al, 1712.05721]

NLO QCD corrections

[Anger et al, 1712.05721]



- Large NLO QCD corrections + scale dependence
- Opening of qg-channel

- Computation of NNLO QCD corrections
  - Amplitudes:
    - Born: AvH library [Bury'15]
    - Oneloop: OpenLoops2 [Buccioni'19]
    - Twoloop [Bager'21,Hartanto'22]
  - Subtraction → Stripper [Czakon'10'14'19]

Setup

NNLO QCD corrections to Wbb production at the LHC
Hartanto, **Poncelet**, Popescu, Zoia 2205.01687

- LHC @ 8 TeV in 5 FS, NNPDF31, scale: $H_T = E_T(l\nu) + pT(b1) + pT(b2)$
- Phasespace definition to model **[CMS, 1608.07561]:**
  $pT(l) \geq 30$ GeV $|y(l)| < 2.1$ $pT(j) \geq 25$ GeV, $|y(j)| < 2.4$
- Inclusive (at least 2 b-jets) and exclusive (exactly 2 b-jets, no other jets) jet phase spaces (defined by the flavour-kT jet algorithm [Banfi'06])

- Inclusive:
  ~ +20% corrections
  ~ 7% scale dependence
- Exclusive:
  ~ + 6% corrections
  ~ 2.5% scale dependence (7-pt)
  Compare decorrelated model: [Steward'12]
  ~ 11% scale dependence

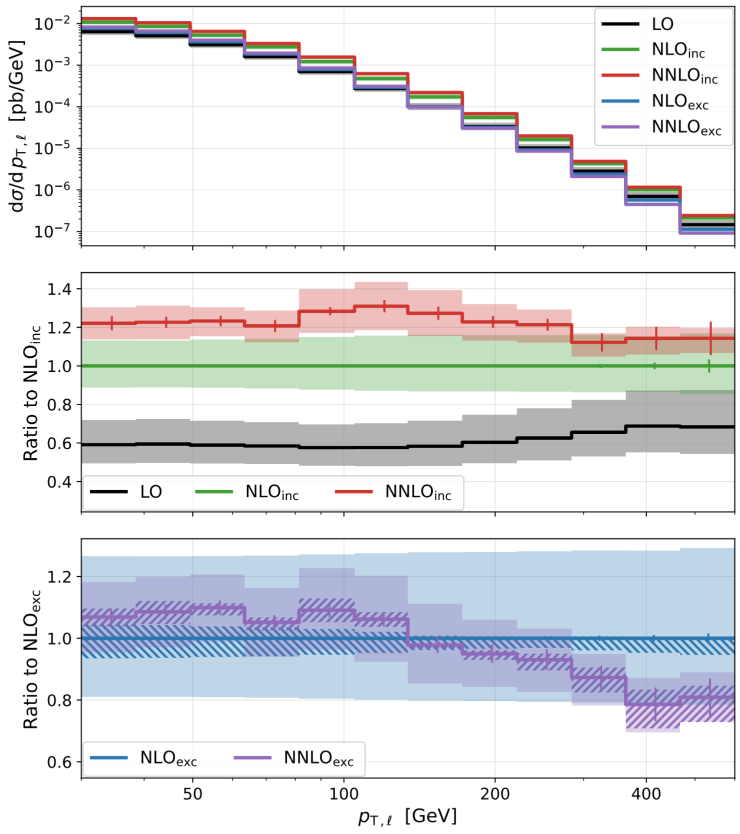
	inclusive [fb]	$\mathcal{K}_{\mathrm{inc}}$	exclusive [fb]	$\mathcal{K}_{\mathrm{exc}}$
σ_{LO}	$213.2(1)^{+21.4\%}_{-16.1\%}$	-	$213.2(1)^{+21.4\%}_{-16.1\%}$	-
σ_{NLO}	$362.0(6)^{+13.7\%}_{-11.4\%}$	1.7	$249.8(4)^{+3.9(+27)\%}_{-6.0(-19)\%}$	1.17
σ_{NNLO}	$445(5)^{+6.7\%}_{-7.0\%}$	1.23	$267(3)^{+1.8(+11)\%}_{-2.5(-11)\%}$	1.067

$$\sigma_{Wb\bar{b},\mathrm{excl.}} = \sigma_{Wb\bar{b},\mathrm{incl.}} - \sigma_{Wb\bar{b}j,\mathrm{incl.}}$$

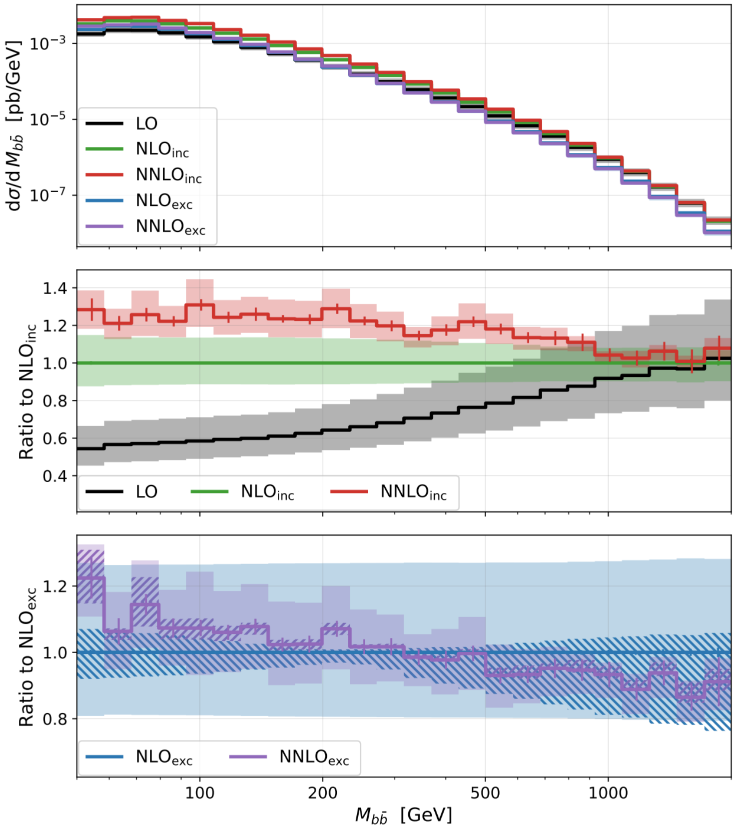
$$\Delta\sigma_{Wb\bar{b},excl.} = \sqrt{(\Delta\sigma_{Wb\bar{b},incl.})^2 + (\Delta\sigma_{Wb\bar{b}j,incl.})^2}$$

Differential cross sections

Transverse momentum of lepton



Invariant mass b-jet pair



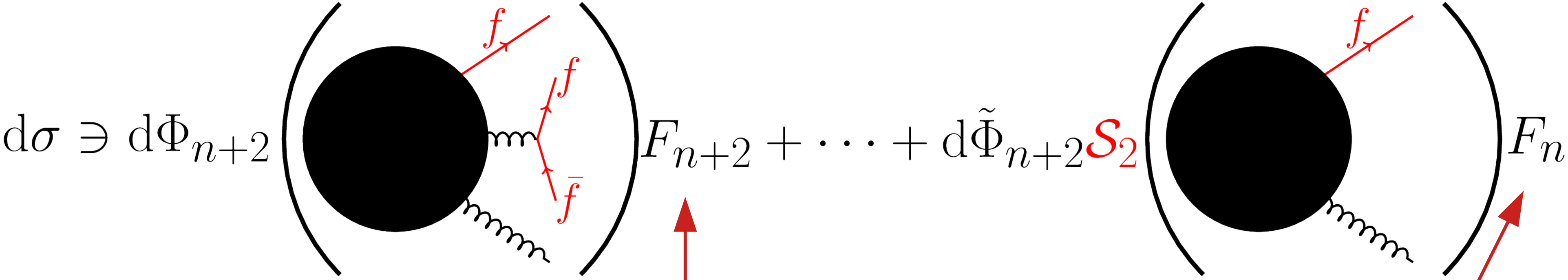
Fixed order flavoured jets beyond NLO

What is the problem with FO flavoured jets?

Example NNLO: double real radiation and subtraction

Double soft subtraction term:
Double soft function * tree ME

Double real matrix element



Flavour structure depends on the angular configuration

IR safety:
Have to match in double soft limit

Fixed flavour structure

- If F(n+2) does not treat the flavour pair appropriately:
  → double soft singularity not subtracted

➔ Implies correlated treatment of kinematics and flavour information

Solution: Modified jet algorithms

- Implies correlated treatment of kinematics and flavour information

Standard kT algorithm:

Pair distance:

$$d_{ij} = \min(k_{T,i}^2, k_{T,j}^2) R_{ij}^2$$

$$R_{ij}^2 = (\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2)/R^2$$

"Beam" distance for determination condition:

$$d_i = k_{T,i}^2$$

Flavour kT algorithm: **Infrared safe definition of jet flavor**, Banfi, Salam, Zanderighi hep-ph/0601139

Pair distance:

$$d_{ij} = R_{ij}^2 \begin{cases} \max(k_{T,i}, k_{T,j})^\alpha \min(k_{T,i}, k_{T,j})^{2-\alpha} & \text{softer of i,j is flavoured} \\ \min(k_{T,i}, k_{T,j})^\alpha & \text{else} \end{cases}$$

Beam distance:

$$d_{i,B} = \begin{cases} \max(k_{T,i}, k_{T,B}(y_i))^\alpha \min(k_{T,i}, k_{T,B}(y_i))^{2-\alpha} & \text{i is flavoured} \\ \min(k_{T,i}, k_{T,B}(y_i))^\alpha & \text{else} \end{cases}$$

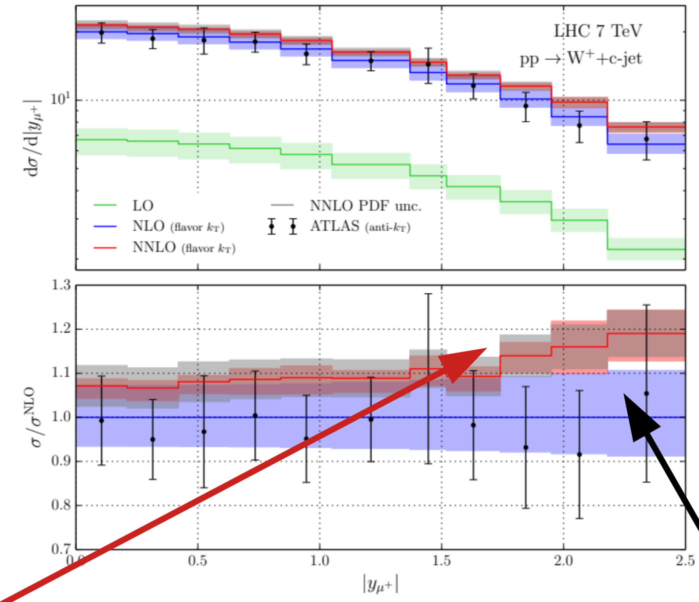
$$d_B(\eta) = \sum_i k_{T,i}(\theta(\eta_i - \eta) + \theta(\eta - \eta_i) e^{\eta_i - \eta}$$

$$d_{\bar{B}}(\eta) = \sum_i k_{T,i}(\theta(\eta - \eta_i) + \theta(\eta_i - \eta) e^{\eta - \eta_i}$$

Problem solved, isn't it?

Example: W+c-jet at NNLO QCD with flavour-kT

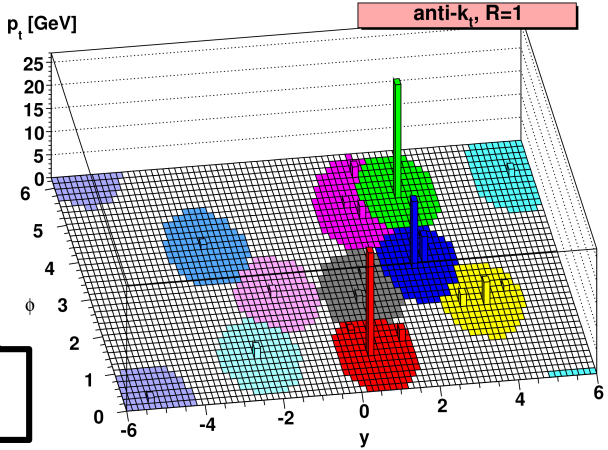
NNLO QCD predictions for W+c-jet production at the LHC
Czakon, Mitov, Pellen, **Poncelet** 2011.01011

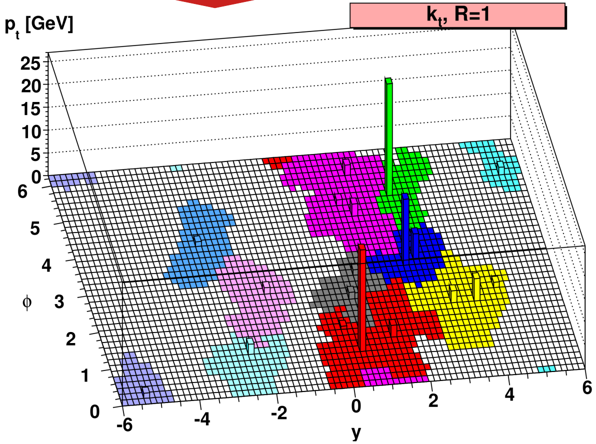


A proper comparison would require to unfold experimental data

→ (flavour-) kT and anti-kT cluster partonic jets differently → Non-trivial procedure.

Towards Jetography
Salam 0906.1833





NNLO QCD with flavour kT

ATLAS data with standard anti-kT

Old problem, new approaches

Renewed interest:

- Anti-kT + flv.-kT flavour matching:

  QCD-aware partonic jet clustering for truth-jet flavour labelling Buckley, Pollard 1507.00508

  Practical Jet Flavour Through NNLO Caletti, Larkoski, Marzani, Reichelt 2205.01109

  A dress of flavour to suit any jet Gauld, Huss, Stagnitto 2208.11138

- Fixed-order fragmentation:

  B-hadron production in NNLO QCD: application to LHC ttbar events with leptonic decays, Czakon, Generet, Mitov and Poncelet, 2102.08267

  A Fragmentation Approach to Jet Flavor Caletti, Larkoski, Marzani, Reichelt 2205.01117

- Modified anti-kT algorithm:

  Infrared-safe flavoured anti-kT jets, Czakon, Mitov, Poncelet 2205.11879

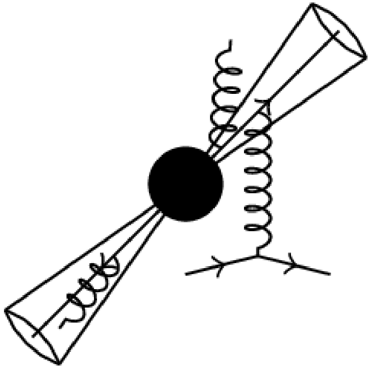
Proposed modification:
A soft term designed to modify the distance of flavoured pairs.

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases}$$

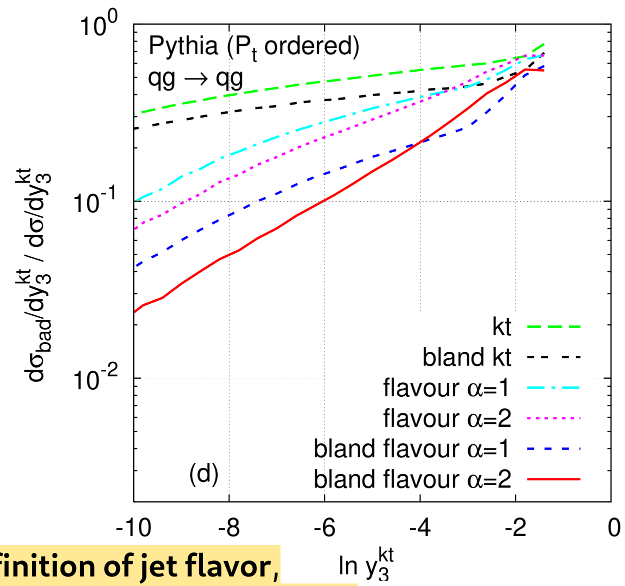
$$\mathcal{S}_{ij} = 1 - \theta(1-x)\cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_{T,i}^2 + k_{T,j}^2}{2a k_{T,\max}^2}$$

Tests of IR safety with parton showers

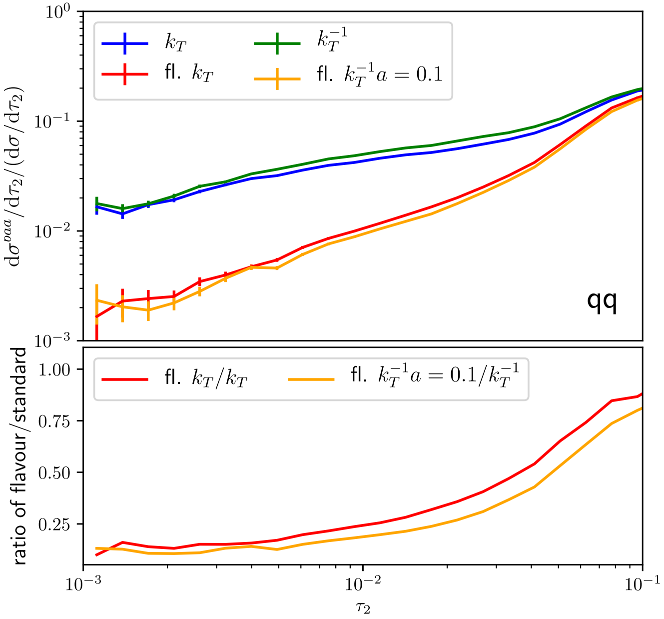
Dress tree-level di-jet events (definite flavour structure: “qq”, “qg” or “gg”) with radiation and study jet flavour (q or g) as function of kinematics.
In the di-jet limit the flavour needs to correspond to tree level flavours
→ misidentification rate needs to vanish in di-jet back-to-back limit



Flavour kT vs. kT:



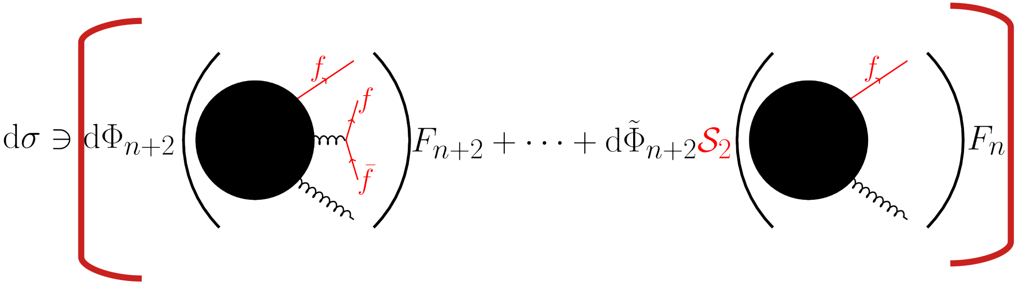
Flavour anti-kT:



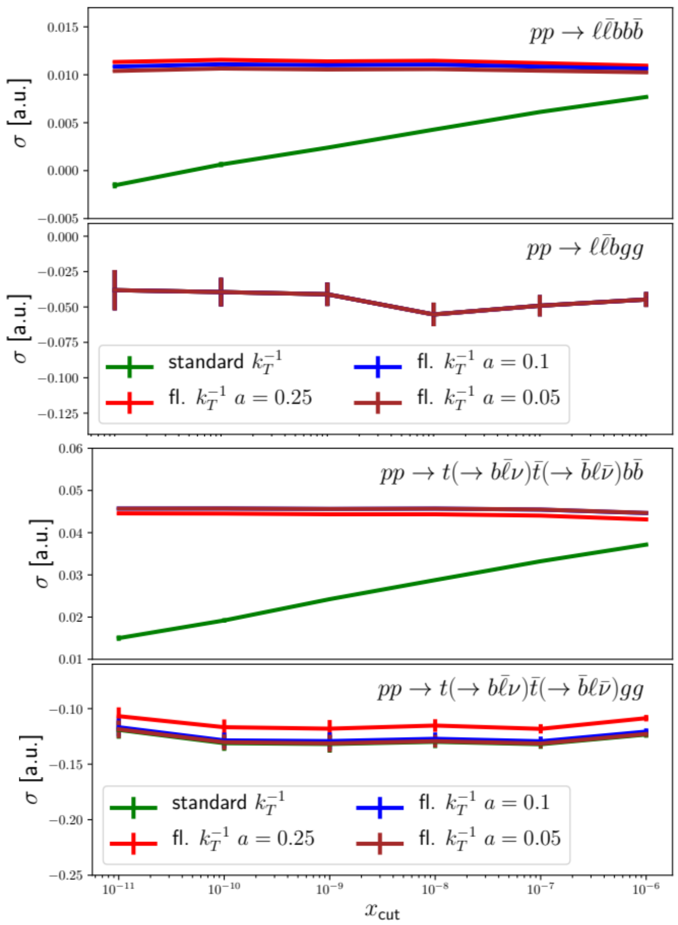
Infrared safe definition of jet flavor,
Banfi, Salam, Zanderighi hep-ph/0601139

Tests of IR safety with NNLO FO computations

IR sensitivity of jet cross sections on
(technical) IR regulating parameter x



$\theta(x - x_{\text{cut}})$



In the limit x_cut → 0:

IR safe jet flavour → no dependence on x_cut

IR non-safe jet flavour → logarithmic divergent

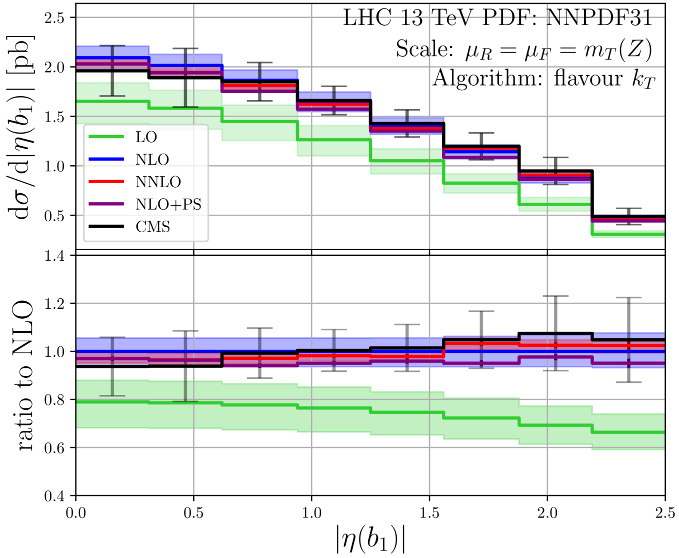
Z+b-jet Phenomenology: Tunable parameter

Benchmark process: pp → Z(ll) + b-jet

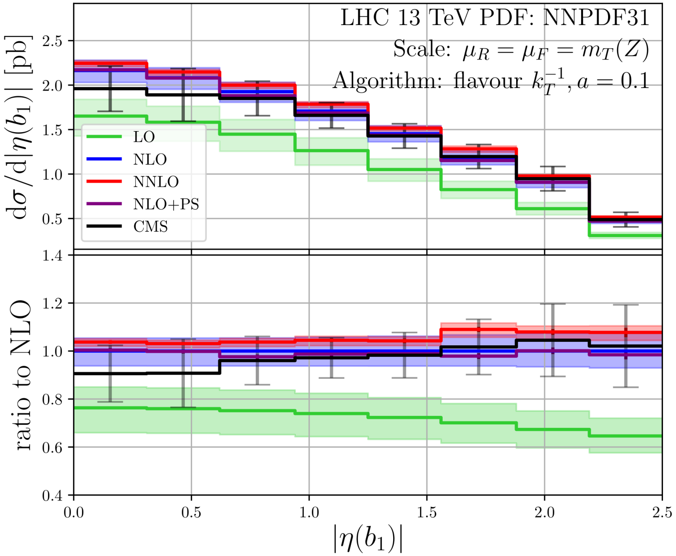
Tunable parameter a:

- Limit a → 0 <=> original anti-kT (IR unsafe)
- Large a <=> large modification of cluster sequence

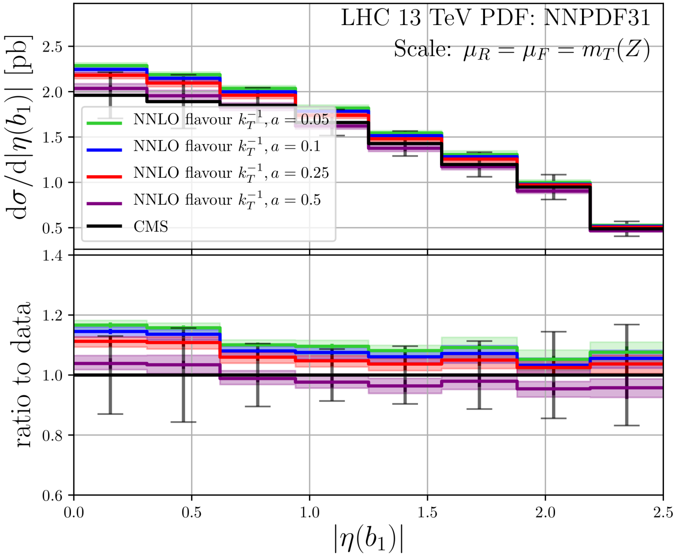
Flavour kT:



Flavour anti-kT: $a = 0.1$

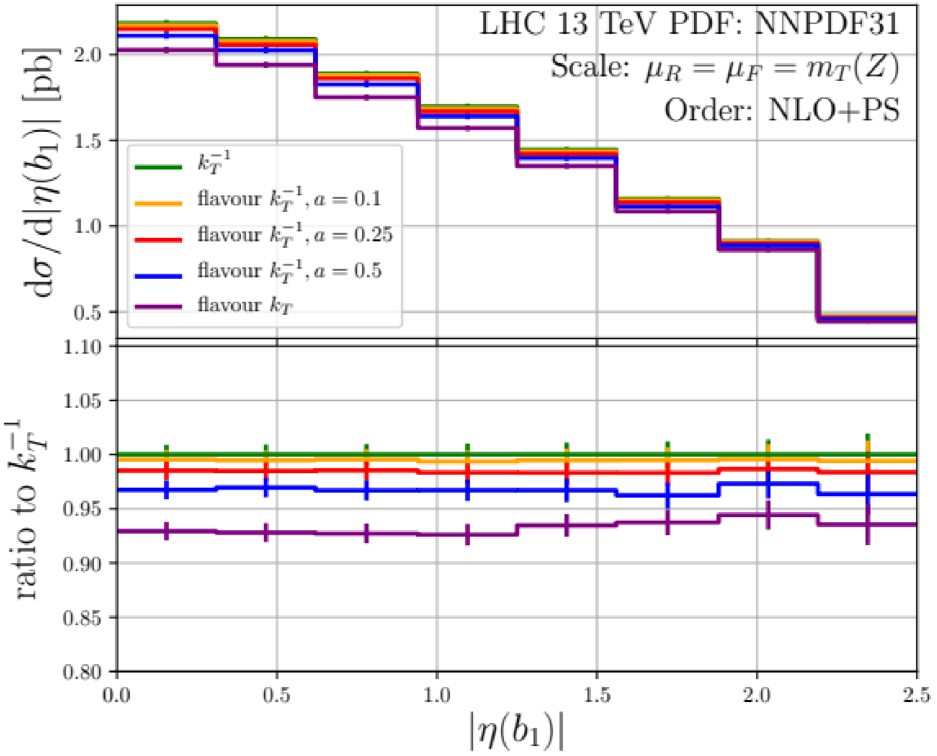


Comparison of different parameter a to data:



Z+b-jet Phenomenology: Tunable parameter II

What happens in the presence of many flavoured partons? → NLO PS



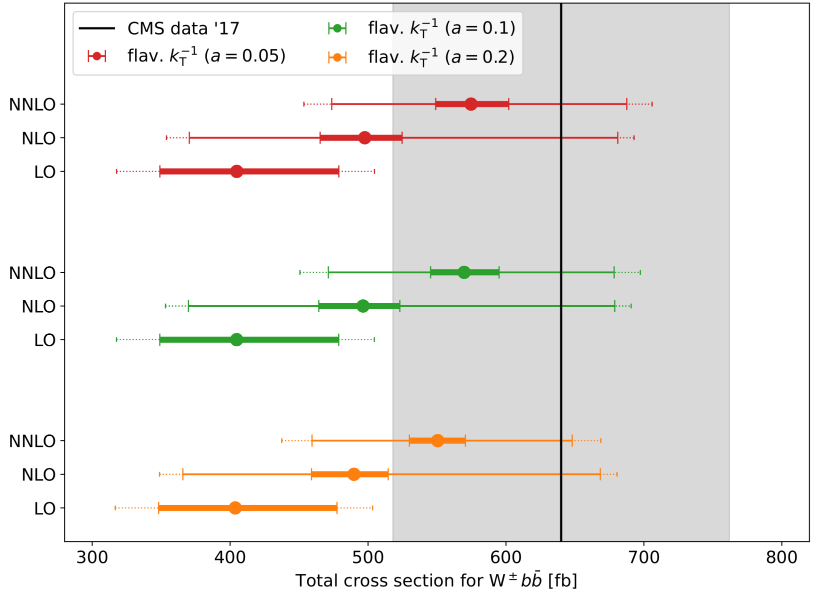
Tunable parameter a:

- Small a: Flavour anti-kT results are more similar to standard anti-kT → small unfolding factors
- Larger a: Larger modification of clustering

Good FO perturbative convergence + Small difference to standard anti-kT → a~0.1 is a good candidate

W+2 bjets: flavour anti-kT

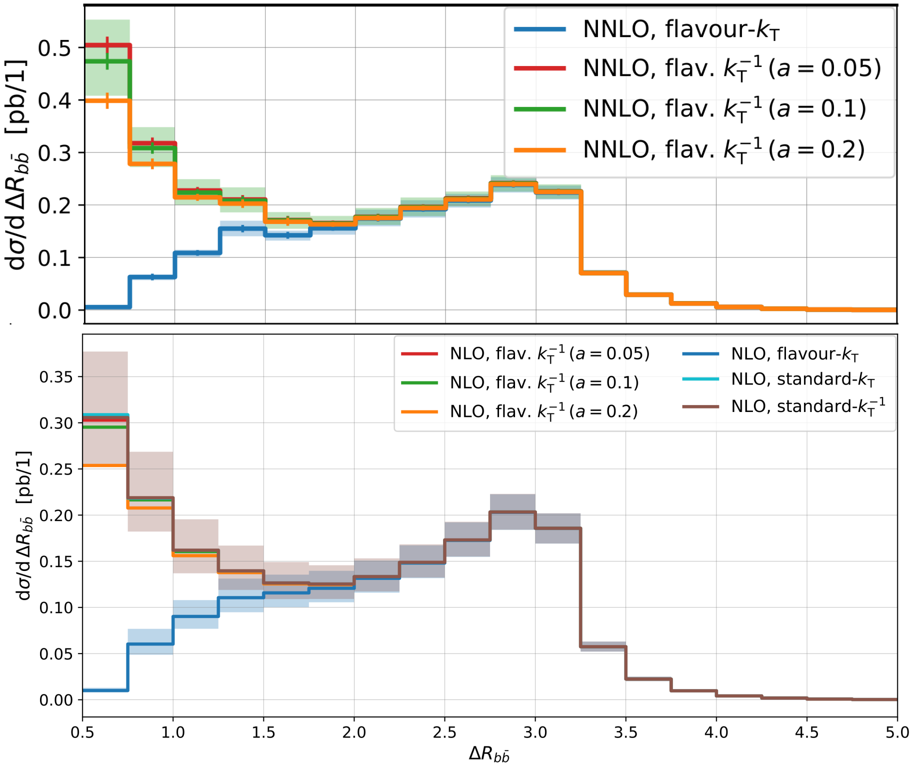
Flavour anti-kT algorithm applied to Wbb production at the LHC
Hartanto, **Poncelet**, Popescu, Zoia 2209.03280



Comparison to data

Measurement of the production cross section of a W boson in association with two b jets in pp collisions at \sqrt{s} = 8 TeV, CMS 1608.07561

(assumes small unfolding corrections → wip)



Significant differences between kT and anti-kT
In small DeltaR(bb) region? Beam-function?!

Summary & Outlook

Summary & Outlook

Summary

- Sector-improved residue subtraction scheme
- Two-loop five-point amplitudes with external mass
- NNLO QCD corrections to W+2b-jet production at the LHC
- Flavour sensitive jet-algorithms

Outlook

- Application of Stripper to further 5-point signatures
- Working towards non-planar contributions (also for 1 ext. mass)
  → See Abreu's summary at $(HP)^2$
- Flavour-tagging
  → more studies and comparisons between different algorithms needed

Backup

Improved phase space generation

Phase space cut and differential observable introduce

mis-binning : mismatch between kinematics in subtraction terms

→ leads to increased variance of the integrand

→ slow Monte Carlo convergence

New phase space parametrization [Czakon'19]:

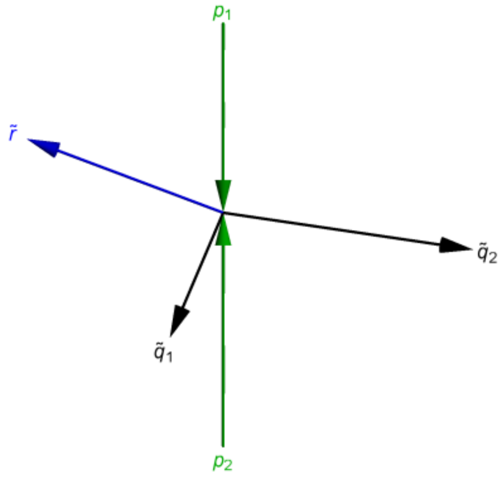
Minimization of # of different subtraction kinematics in each sector

Improved phase space generation

New phase space parametrization:

Minimization of # of different subtraction kinematics in each sector

Mapping from n+2 to n particle phase space: $\{P, r_j, u_k\} \to \left\{\tilde{P}, \tilde{r}_j\right\}$



Requirements:

- Keep direction of reference r fixed
- Invertible for fixed u_i : $\left\{\tilde{P}, \tilde{r}_j, u_k\right\} \to \{P, r_j, u_k\}$
- Preserve Born invariant mass: $q^2 = \tilde{q}^2\,,\ \ \tilde{q} = \tilde{P} - \sum_{j=1}^{n_{fr}} \tilde{r}_j$

Main steps:

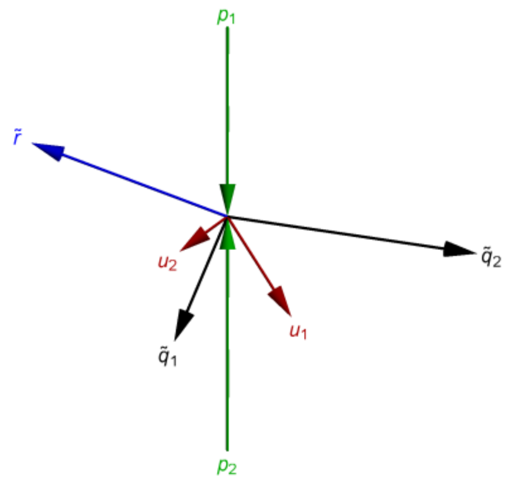
- Generate Born configuration
- Generate unresolved partons u_i
- Rescale reference momentum $r = x\tilde{r}$
- Boost non-reference momenta of the Born configuration

Improved phase space generation

New phase space parametrization:

Minimization of # of different subtraction kinematics in each sector

Mapping from n+2 to n particle phase space: $\{P, r_j, u_k\} \to \left\{\tilde{P}, \tilde{r}_j\right\}$



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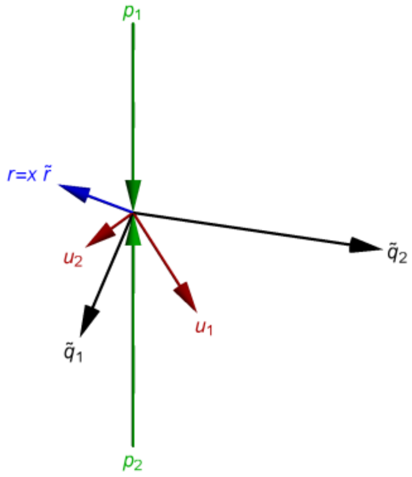

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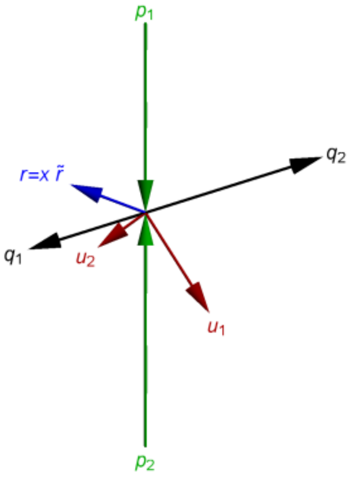

Requirements:

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Main steps:

- Generate Born configuration
- Generate unresolved partons u_i
- Rescale reference momentum $r = x\tilde{r}$
- Boost non-reference momenta of the Born configuration

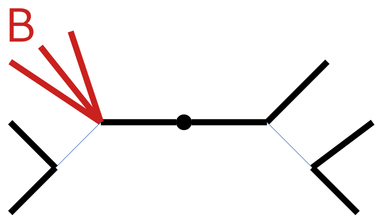
Further technical developments

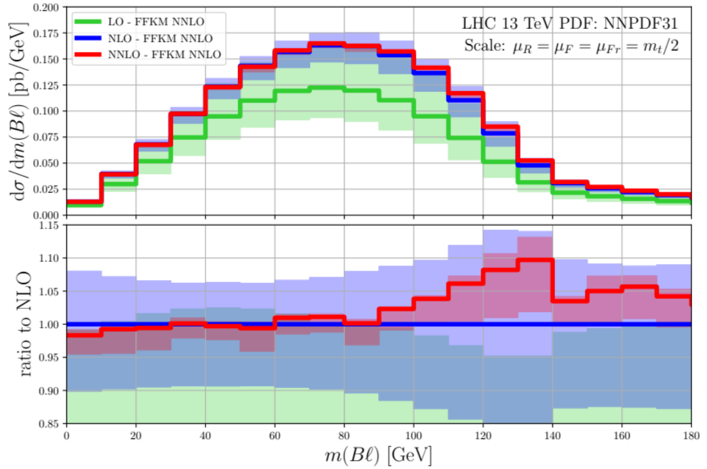
- Narrow-width-approximation and Double-Pole-Approximation for resonant particles:
  - Top-quark pairs + decays [Czakon'19'20]
  - W+W- polarization [Poncelet'21]
- Automated interfaces to OpenLoops, Recola and Njet
- Implementation of state-of-the-art twoloop matrix-elements:
  - 2→ 2(1) : pp → VV, pp→ Vj, pp → H (j), e+e- → jets, DIS
  - 2 → 3: Pp → 3γ, pp → 2γ + j, pp → 3j
- Fragmentation of massless partons into hadrons
  - First application to pp → tt +X → l+l- ν ν~ B + X (NWA) [Czakon'21]
- Countless small improvements in terms of organization and efficiency

Flavour tagging and fixed order fragmentation

- Fixed order QCD predictions with a final state hadron
- Partonic computation + transition of parton to hadron (collinear fragmentation of massless partons)
- Non-perturbative fragmentation function (similar to PDFs): Probability to find a hadron with a fraction x of a parton
- Advantage is that the hadrons momentum is measurable
  → usage as b-tag?
- Implementation in the STRIPPER framework through NNLO QCD:
  B-hadron production in NNLO QCD: application to LHC ttbar events with leptonic decays, Czakon, Generet, Mitov and Poncelet, 2102.08267

$$pp \to t\bar{t} \to B\ell\bar{\ell}\nu\bar{\nu}b + X$$

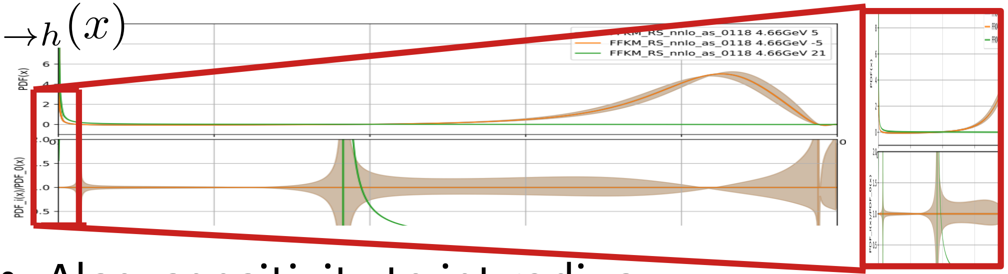




Subtleties

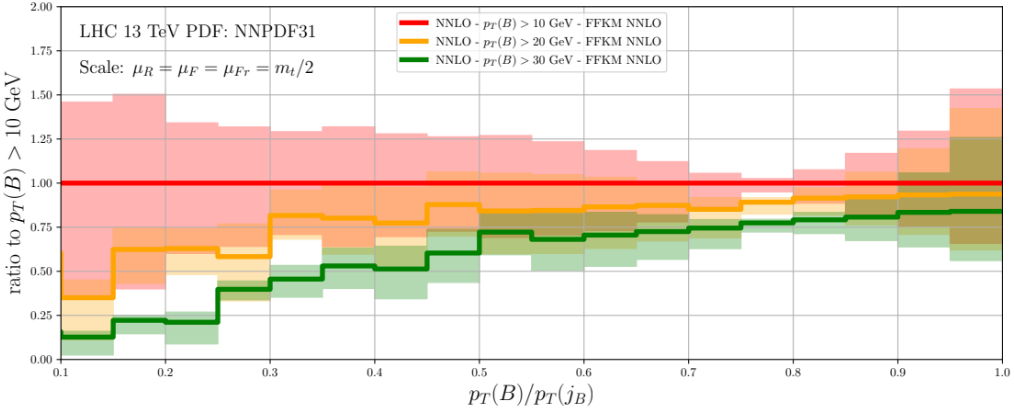
- pT(B) requirement necessary since NNLO fragmentation function divergent for x → 0 due to g → bbar splitting:

$D_{i\to h}(x)$



- Also: sensitivity to jet radius

→ Usage as b-tag needs tuning



Jet radius variation R = 0.8,0.6,0.4