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NLO mass effects in $b\bar{b}b\bar{b}$ production at the LHC

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In collaboration with G. Bevilacqua, M. Czakon, M. Krämer & M. Kubocz

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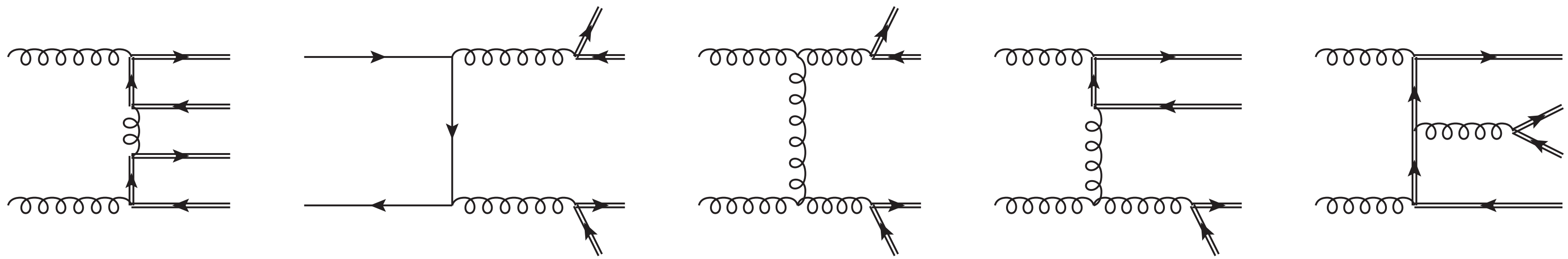
I am going to talk about…

- ❑ NLO QCD corrections to two bottom pairs with **HELAC-NLO**
  - ✧ α_s corrections to $\mathbf{pp \to b\bar{b}b\bar{b}}$ process at $\mathcal{O}(\alpha_s^4)$ **at the LHC**



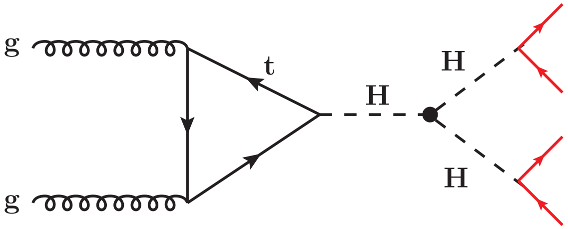
- ❑ Calculations can be performed in two different ways
  - ✧ 4-flavor scheme (4FS) with $\mathbf{m_b \neq 0}$
  - ✧ 5-flavor scheme (5FS) with $\mathbf{m_b = 0}$

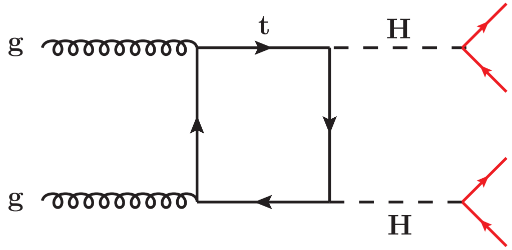
- ❑ Investigation of finite bottom quark mass effects
- ❑ Results with Catani- Seymour & Nagy-Soper subtraction schemes
- ❑ Summary & Outlook

Higgs Boson Analyses

- $\mathbf{b\bar{b}b\bar{b}}$ final state important in the SM Higgs boson studies at the LHC

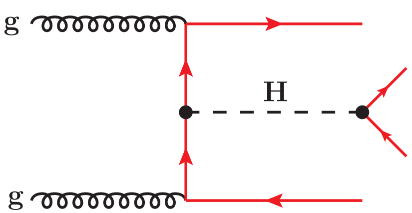
  - $\mathbf{pp \to H_{SM}H_{SM} \to b\bar{b}b\bar{b}}$: reconstruction of the Higgs potential, self couplings

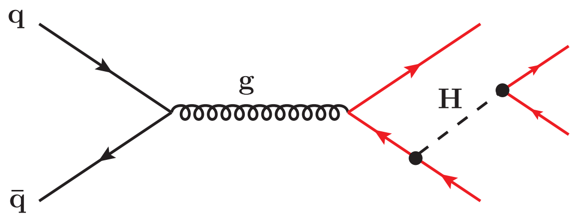




Djouadi, Kilian, Mühlleitner, Zerwas (1999)

  - $\mathbf{pp \to b\bar{b}H_{SM} \to b\bar{b}b\bar{b}}$: Higgs is radiated off (anti-)bottom, σ_{bbH} proportional to the bottom quark Yukawa coupling





Dittmaier, Krämer, Spira (2004)
Dawson, Jackson, Reina, Wackeroth (2004)

  - $\boldsymbol{\sigma}_{\mathbf{bbH/HH}} \approx$ **20/35 fb** comparing to the large QCD background $\boldsymbol{\sigma}_{\mathbf{bbbb}} \approx$ **137 pb**
    - no heavy objects decaying into bottom pairs ☑
    - efficient bottom quark tagging is needed ☒

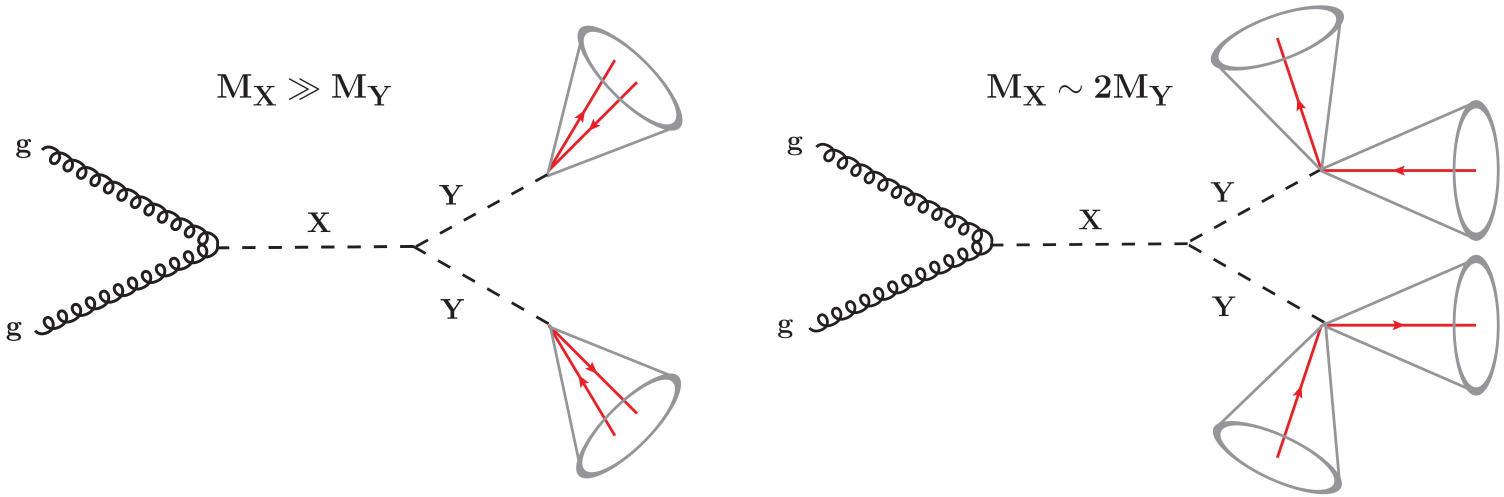
Searches For New Physics

- $\mathbf{b\bar{b}b\bar{b}}$ final state important in the New Physics searches at the LHC

$$\mathbf{pp \to X \to YY \to b\bar{b}b\bar{b}}$$

  - ✧ X: TeV scale resonance, some exotic particle e.g. H or A Higgs boson(s) from (…)MSSM, 2HDM, resonance from extra dimensions, G_{KK} massive Kaluza-Klein graviton, spin zero radion, …
  - ✧ Y: another massive particle e.g. either BSM particle or SM one (W, Z, H_{SM})
    - ➢ $\mathbf{M_X \gg M_y}$ boosted regime
    - ➢ $\mathbf{M_X \sim 2M_y}$ resolved four jet regime

Gouzevitch, Oliveir, Rojo, Rosenfeld, Salam, Sanz (2013)

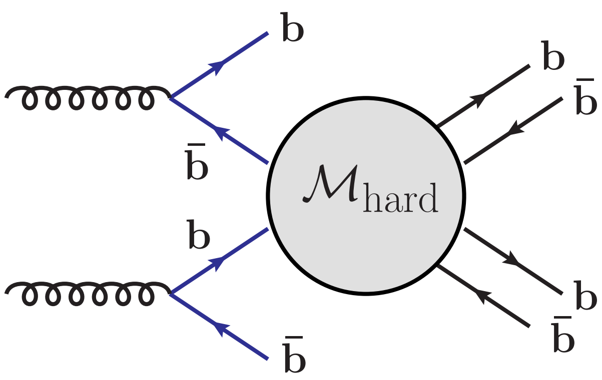


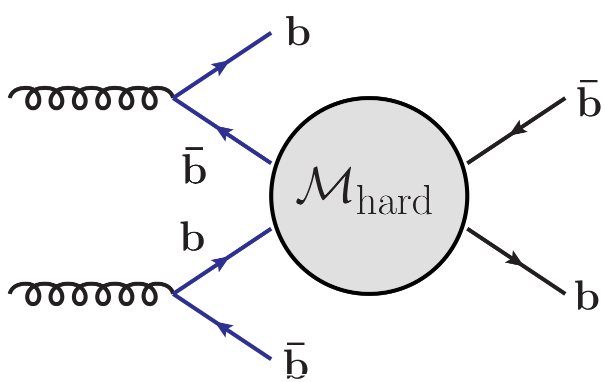
ACCURATE KNOWLEDGE OF THE SM BACKGROUND PLAYS A CRUCIAL ROLE !

Massive bottom [4FS]

- Bottom quarks appear only in the final state and are massive
- PDF does not contain bottom quark, **n_l= 4 (u, d, c, s)**
  - Do not enter in the computation of the running of $\alpha_\mathbf{s}$
  - Do not enter in the evolution of the PDFs

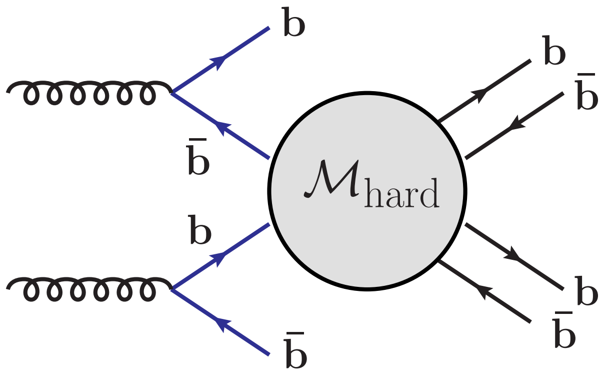
- Finite-m_b effects enter via:
  - Power corrections of the type $\mathcal{O}[(\mathbf{m_b}/\mathcal{Q})^\mathbf{n}]$
  - Logarithms of the type $\mathcal{O}[\log^\mathbf{n}(\mathbf{m_b}/\mathcal{Q})]$

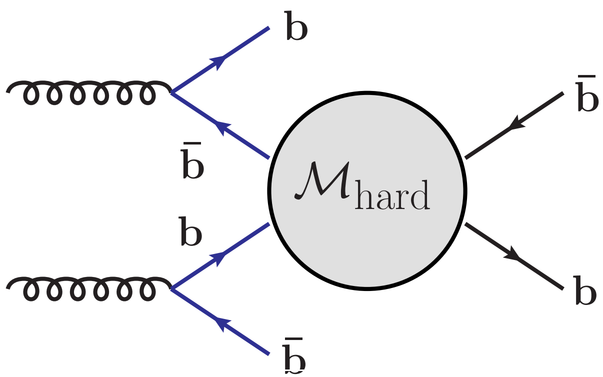




Massive bottom [4FS]

- At the LHC, typically $(\mathbf{m_b}/\mathcal{Q}) \ll \mathbf{1}$ and power corrections are suppressed
- While logarithms could be large (can be of initial or final state nature)
- For inclusive observables such as b-jets, logarithms can only originate from nearly collinear initial-state $\mathbf{g} \to \mathbf{b\bar{b}}$ splitting
- Large logarithms could spoil the convergence of the fixed order calculations
- Resummation could be needed





UP TO NLO ACCURACY POTENTIALLY LARGE LOGARITHMS

$$\log(\mathbf{m_b}/\mathcal{Q}) \to \log(\mathbf{p_{T,b}^{min}}/\mathcal{Q})\,, \qquad \mathbf{m_b} \ll \mathbf{p_{T,b}^{min}} \lesssim \mathcal{Q}$$

AND ARE LESS SIGNIFICANT NUMERICALLY

Massless bottom [5FS]

- Under the approximation that bottom quarks from splittings have small p_T towers of $\log^{\mathbf{n}}(\mathbf{m_b}/\mathcal{Q})$ explicitly resummed into bottom PDF
- For consistency with the factorization theorem, one should set **m_b = 0** in the calculation of the matrix element

- PDF contains bottom quark, **n_l= 5 (u, d, c, s, b)**
  - ✧ bottom quarks enter in the computation of the running of $\alpha_{\mathbf{s}}$
  - ✧ bottom quarks enter in the evolution of the PDFs

- To all orders in perturbation theory two schemes are identical
- The way of ordering the perturbative expansion is different and at any finite order the results might not match

- 5FS is suitable for inclusive observables, 4FS is more accurate for exclusive ones

Maltoni, Ridolfi, Ubiali (2012)
Harlander, Krämer, Schumacher (2011)
Frederix, Re, Torrielli (2012)
...

4FS vs. 5FS

- Calculation for 5FS with massless bottom quarks

Binoth, Greiner, Guffanti, Reuter, Guillet, Reiter (2010)
Greiner, Guffanti, Reiter, Reuter (2011)

- Comparison between 5FS and 4FS offers an opportunity to study the impact of dominant all-order mass contributions

Our goals:

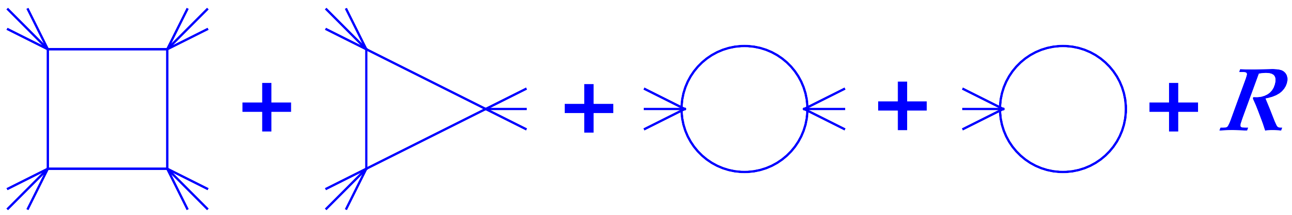
- Full NLO study of inclusive $\mathbf{pp \to b\bar{b}b\bar{b} + X}$ production with **HELAC-NLO**
- Comparative analysis of 5FS and 4FS results at the integrated and differential level
- First complete application of newly implemented Nagy-Soper subtraction scheme
- Both massive and massless cases can be tested

Bevilacqua, Czakon, Krämer, Kubocz, Worek (2013)
Bevilacqua, Czakon, Kubocz, Worek (2013)

HELAC-NLO

- Virtual corrections: reduction at the integrand level (OPP method)

Ossola, Papadopoulos, Pittau (2007)



$$\mathcal{A} = \sum \mathbf{d_{i_1 i_2 i_3 i_4}}\ \mathbf{Box} + \sum \mathbf{c_{i_1 i_2 i_3}}\ \mathbf{Triangle} + \sum \mathbf{b_{i_1 i_2}}\ \mathbf{Bubble} + \sum \mathbf{a_{i_1}}\ \mathbf{Tadpole} + \mathbf{R}$$

- **HELAC-1LOOP** *Hameren, Papadopoulos, Pittau (2009)*
  - Automatic evaluation of one loop amplitude and rational terms

Ossola, Papadopoulos, Pittau (2008)
Draggiotis, Garzelli, Papadopoulos, Pittau (2009)

- **CutTools**
  - Reduction of tensor integrals and determination of coefficients

- **OneLOop** *van Hameren (2011)*
  - Evaluation of scalar integrals

HELAC-NLO

- Real emission corrections: implementation of Catani-Seymour dipoles

$$\sigma_{\mathbf{NLO}} = \int_{\mathbf{m}} \mathbf{d}\sigma^{\mathbf{B}} + \int_{\mathbf{m+1}} \mathbf{d}\sigma^{\mathbf{R}} + \int_{\mathbf{m+1}} \mathbf{d}\sigma^{\mathbf{A}} - \int_{\mathbf{m+1}} \mathbf{d}\sigma^{\mathbf{A}} + \int_{\mathbf{m}} \mathbf{d}\sigma^{\mathbf{V}}$$

$$\sigma_{\mathbf{NLO}} = \int_{\mathbf{m}} \mathbf{d}\sigma^{\mathbf{B}} + \int_{\mathbf{m+1}} \left[\mathbf{d}\sigma^{\mathbf{R}} - \mathbf{d}\sigma^{\mathbf{D}}\right] + \int_{\mathbf{m}} \left[\mathbf{d}\sigma^{\mathbf{V}} + \mathbf{d}\sigma^{\mathbf{I}} + \mathbf{d}\sigma^{\mathbf{KP}}\right]$$

- **HELAC-DIPOLES**
  - ✧ Massless and massive cases — *Czakon, Papadopoulos, Worek (2009)*
  - ✧ Extended for arbitrary helicity eigenstates of the external partons
  - ✧ Phase space restriction on the dipoles phase space is included

Bevilacqua, Czakon, Kubocz, Worek (2013)

  - ✧ Alternative Nagy-Soper subtraction scheme fully implemented and tested
  - ✧ Massless and massive cases
  - ✧ Random polarization and color sampling of the external partons
  - ✧ Comparative study on efficiency & speed performed

CS vs. NS

CATANI-SEYMOUR

$$\{\mathbf{p_i}, \mathbf{p_j}\} \to \tilde{\mathbf{p}}_\mathbf{i} \;;\; \{\mathbf{p_k}, \mathbf{R}, \mathbf{Q}\} \to \{\tilde{\mathbf{p}}_\mathbf{k}, \mathbf{R}, \mathbf{Q}\}$$

$$\mathbf{p_i} + \mathbf{p_j} + \mathbf{p_k} = \tilde{\mathbf{p}}_\mathbf{i} + \tilde{\mathbf{p}}_\mathbf{k}$$

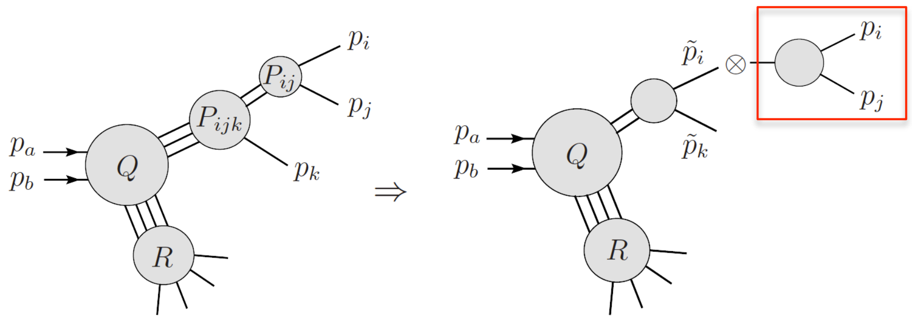
- ✧ Easier dipole integration ☑
- ✧ Cubic growth of subtraction terms ☒

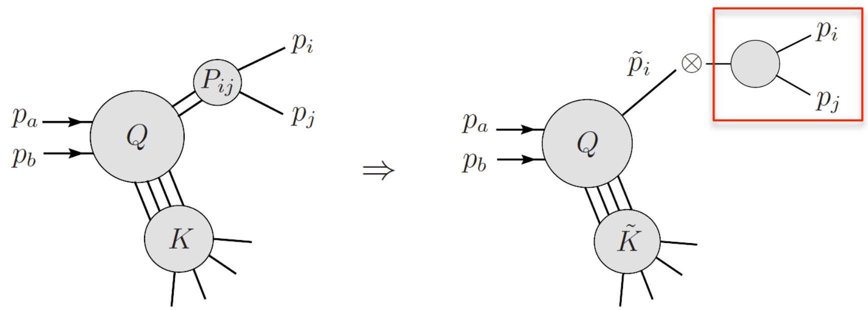
NAGY-SOPER

$$\{\mathbf{p_i}, \mathbf{p_j}\} \to \tilde{\mathbf{p}}_\mathbf{i} \;;\; \{\mathbf{K}, \mathbf{Q}\} \to \left\{\tilde{\mathbf{K}}, \mathbf{Q}\right\}$$

$$\mathbf{p_i} + \mathbf{p_j} + \mathbf{K} = \tilde{\mathbf{p}}_\mathbf{i} + \tilde{\mathbf{K}}$$

- ✧ More complex dipole integration ☒
- ✧ Quadratic growth of subtraction terms ☑





- ❑ Splitting functions have equal singular limits, but different non-singular parts
- ❑ Different number of mappings from (m + 1) to m-parton kinematics
- ❑ Different dipole phase space factorization and kinematics

CS vs. NS

Catani-Seymour

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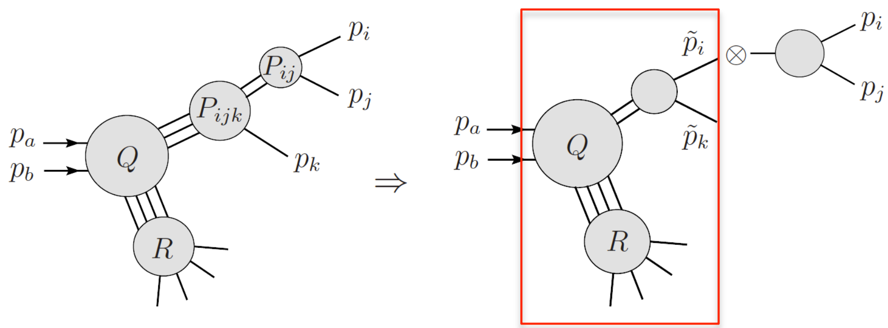

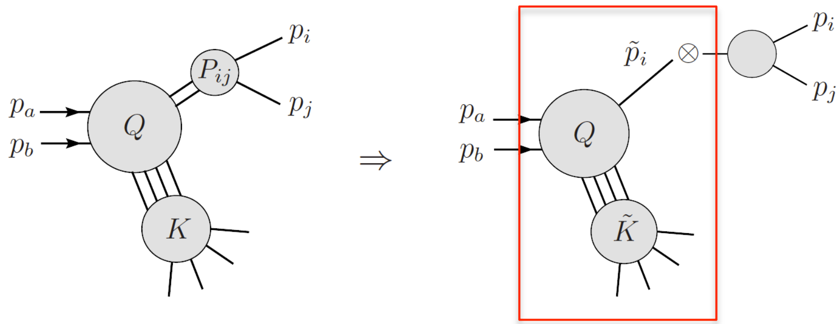

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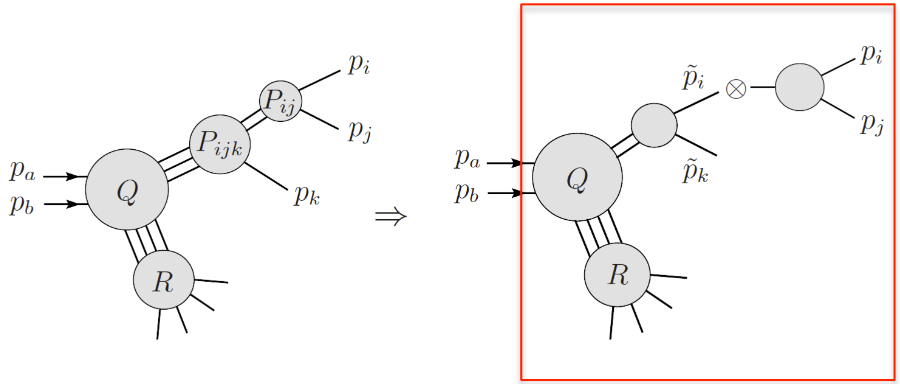

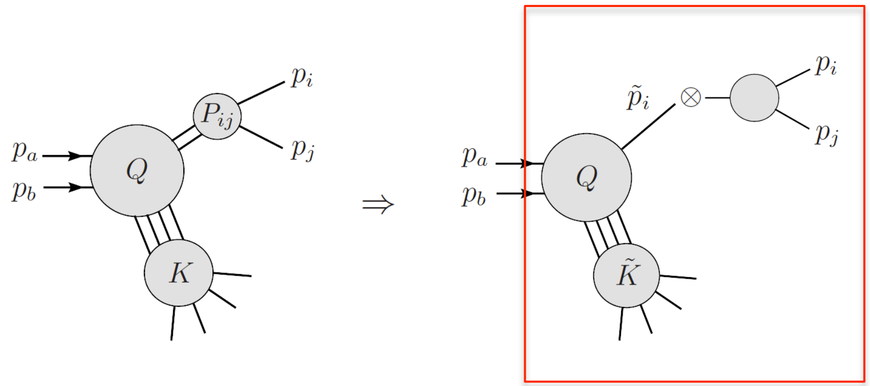

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CS vs. NS

Catani-Seymour

$$\{p_i, p_j\} \to \tilde{p}_i \; ; \; \{p_k, R, Q\} \to \{\tilde{p}_k, R, Q\}$$

$$p_i + p_j + p_k = \tilde{p}_i + \tilde{p}_k$$

- ✧ Easier dipole integration ☑
- ✧ Cubic growth of subtraction terms ☒

Nagy-Soper

$$\{p_i, p_j\} \to \tilde{p}_i \; ; \; \{K, Q\} \to \left\{\tilde{K}, Q\right\}$$

$$p_i + p_j + K = \tilde{p}_i + \tilde{K}$$

- ✧ More complex dipole integration ☒
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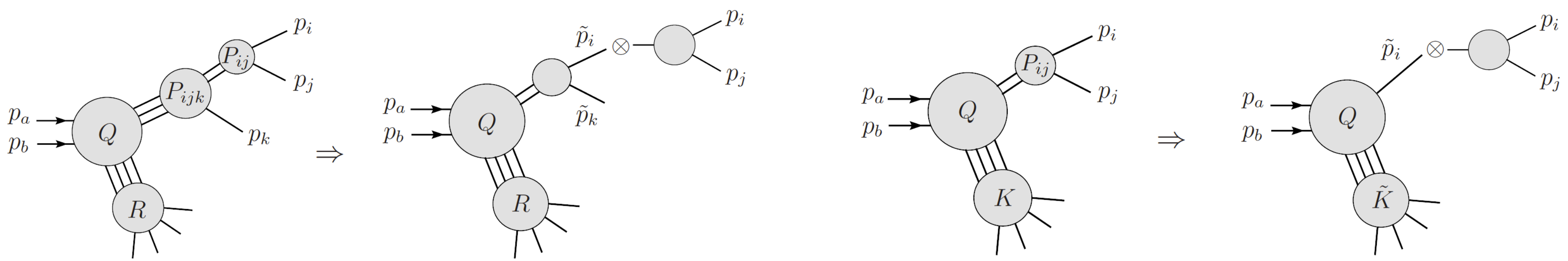

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- ❑ Different number of mappings from (m + 1) to m-parton kinematics
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Setup For Numerical Analysis

- Cuts selection for the LHC

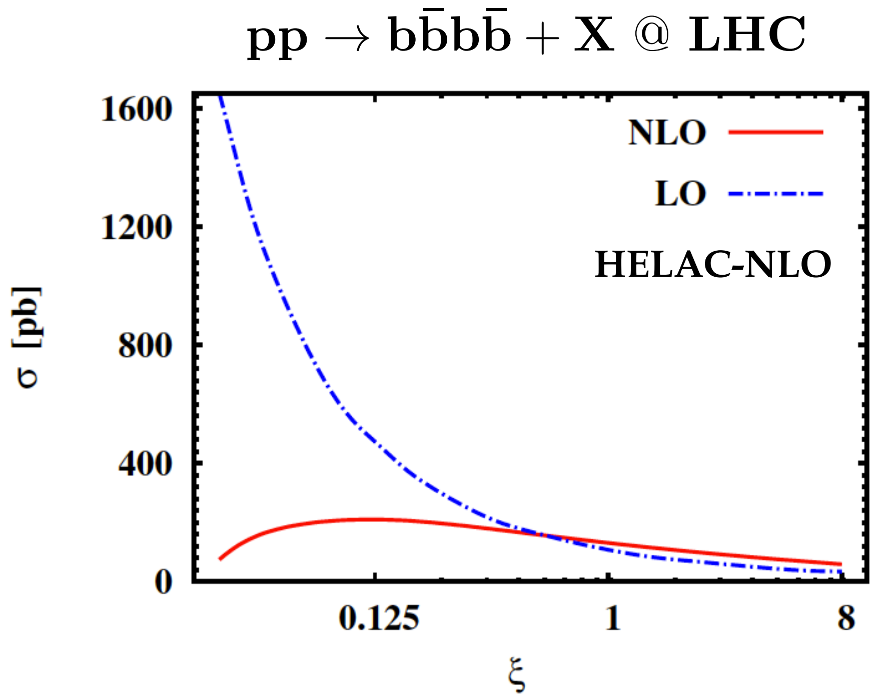
$$\sqrt{s} = 14\,\mathrm{TeV}, \quad p_{T,b} > 30\,\mathrm{GeV}, \quad |y_b| < 2.5, \quad \Delta R_{bb} > 0.4, \quad \mathrm{anti} - k_T$$

- Scale choice

$$\mu_R = \mu_F = \mu_0 = H_T, \qquad H_T = \sum m_{T,b}, \quad m_{T,b} = \sqrt{m_b^2 + p_{T,b}^2}$$

- Color & helicity treatment
  - Sum over color and helicity configurations performed with MC sampling
- One-loop
  - LO+V result obtained by reweighting a sample of Born unweighted events
- Checks
  - Real emission: cross-check between NS and CS subtraction
  - Real emission: restriction on the phase space of the subtraction (CS)
  - Virtual corrections: check of Ward identity

Integrated Cross Sections [5FS]



- Scale dependence
- 5FS LO & NLO cross sections

- Residual scale uncertainty
- **29% at NLO**
- **57% at LO**

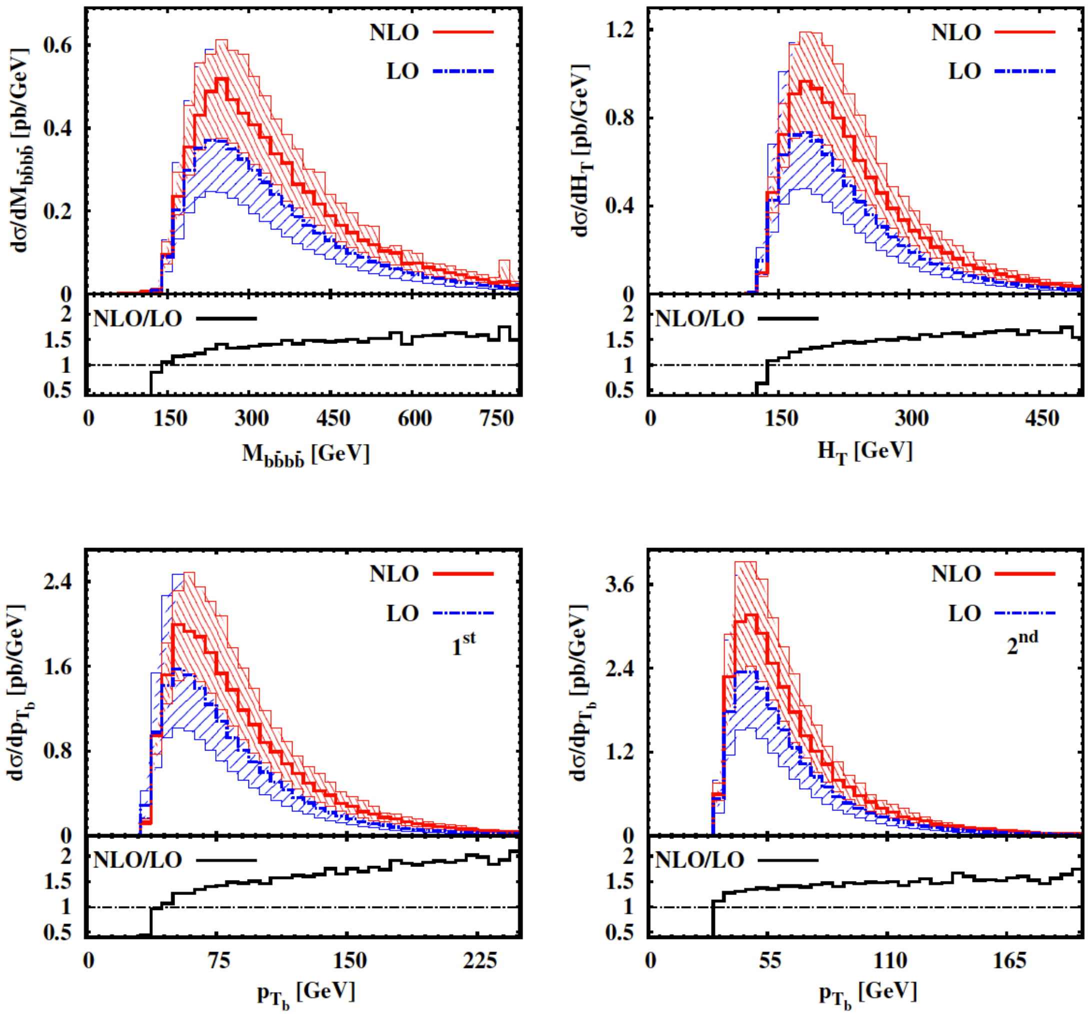
- PDF uncertainty **7% (11%)**

$pp \to b\bar{b}b\bar{b} + X$	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]	$K = \sigma_{\rm NLO}/\sigma_{\rm LO}$
CT09MC1/CT10	$106.9^{+61.5\,(57\%)}_{-36.4\,(34\%)}$	$123.6^{+35.6\,(29\%)}_{-26.6\,(22\%)}$	1.15
MSTW2008LO/NLO	$99.9^{+58.7\,(59\%)}_{-34.9\,(35\%)}$	$136.7^{+38.8(28\%)}_{-30.9\,(23\%)}$	1.37

Bevilacqua, Czakon, Krämer, Kubocz, Worek (2013)

Differential Cross Sections [5FS]

$$\mathbf{pp \to b\bar{b}b\bar{b} + X \text{ @ } LHC}$$



- ❑ Infrared-safe observables
- ❑ Theoretical uncertainties
- ❑ Differential K-factors

Size of the Higher Order Effects Depends on the Kinematics

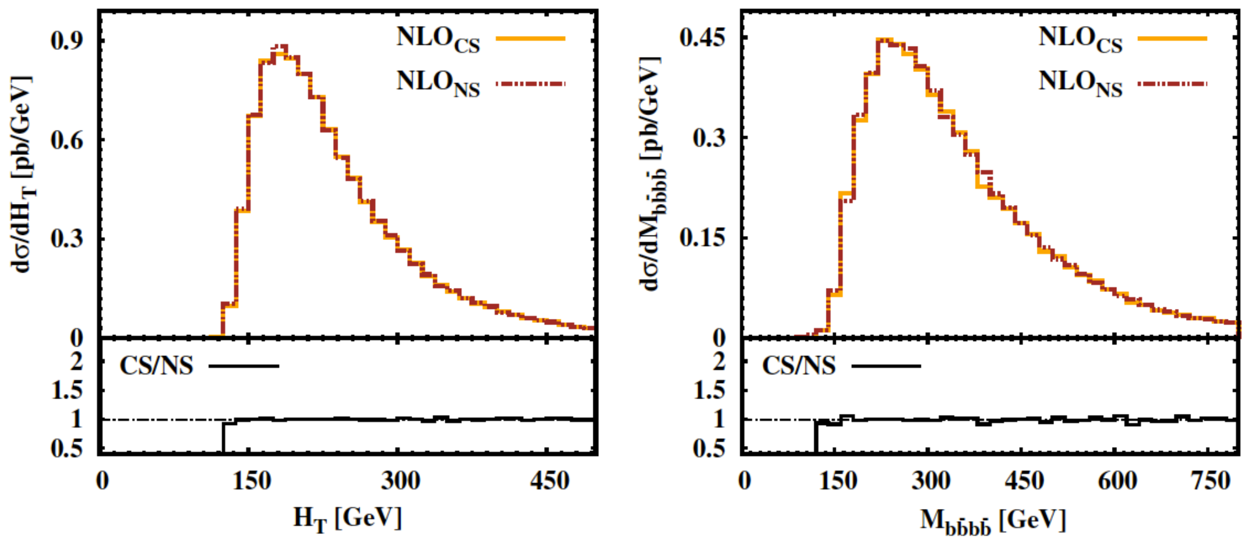
Not Sufficient to Rescale LO Prediction with an Inclusive K-factor

Bevilacqua, Czakon, Krämer, Kubocz, Worek (2013)

CS vs. NS [5FS]

- Comparison between two schemes for the inclusive and differential cross sections

$pp \to b\bar{b}b\bar{b} + X$	$\sigma^{\text{CS}\,(\alpha_{\text{max}}=1)}_{\text{NLO}}$ [pb]	$\sigma^{\text{CS}\,(\alpha_{\text{max}}=0.01)}_{\text{NLO}}$ [pb]	$\sigma^{\text{NS}}_{\text{NLO}}$ [pb]
CT10	123.6 ± 0.4	124.9 ± 0.9	124.8 ± 0.3
MSTW2008NLO	136.7 ± 0.3	136.1 ± 0.5	137.6 ± 0.5



Agreement Between Two Schemes
Validation of the Implementation of the NS Scheme

Integrated Cross Sections [4FS]

- Cross section predictions in LO and NLO for $\mu = H_T$ and **m_b=4.75 GeV**
- K-factor and residual scale dependence at NLO similar to 5FS results
- Validation of the implementation of the NS scheme for massive fermions

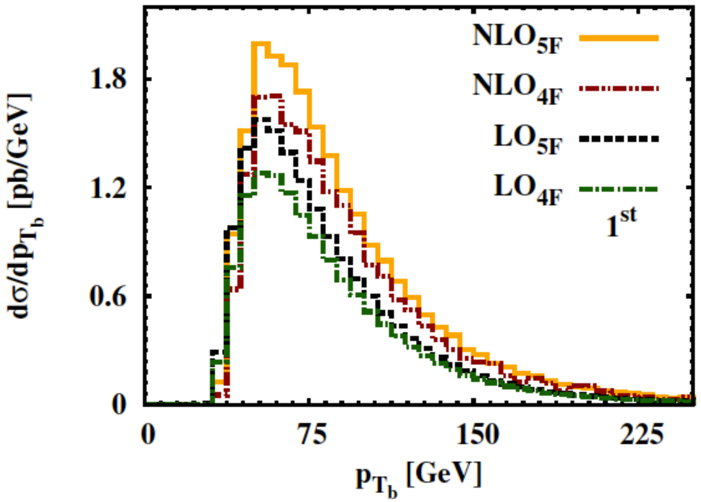
$pp \to b\bar{b}b\bar{b} + X$	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]	$K = \sigma_{\rm NLO}/\sigma_{\rm LO}$
MSTW2008LO/NLO (4FS)	$84.5^{+49.7(59\%)}_{-29.6(35\%)}$	$118.3^{+33.3(28\%)}_{-29.0(24\%)}$	1.40

$pp \to b\bar{b}b\bar{b} + X$	$\sigma_{\rm NLO}^{\rm CS\,(\alpha_{max}=1)}$ [pb]	$\sigma_{\rm NLO}^{\rm CS\,(\alpha_{max}=0.01)}$ [pb]	$\sigma_{\rm NLO}^{\rm NS}$ [pb]
MSTW2008NLO (4FS)	118.3 ± 0.5	118.2 ± 0.7	118.0 ± 0.5

- Comparing with 5FS bottom mass effects decrease the cross section by:
  - **18% at LO** & **16% at NLO**
  - Genuine bottom mass effects, for **$p_{T,b}$ > 30 GeV** of the order **~10%**
  - Strong dependence on $p_{T,b}$ cut, for **$p_{T,b}$ > 100 GeV** only **~1%**
  - Scheme dependence **~5%**, different PDFs and α_s

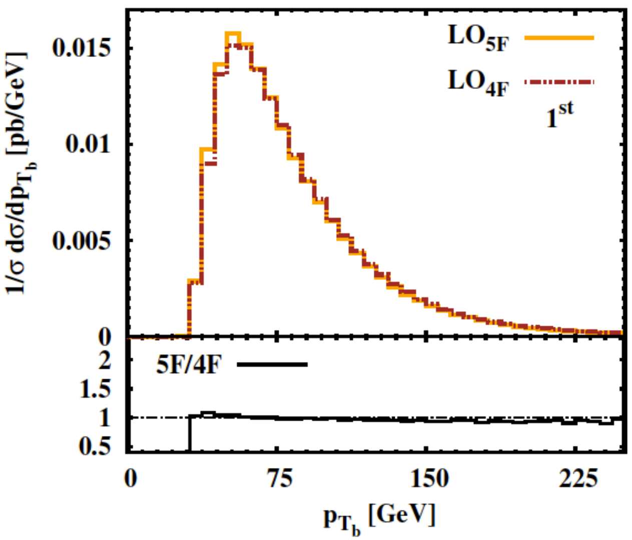
Bevilacqua, Czakon, Krämer, Kubocz, Worek (2013)

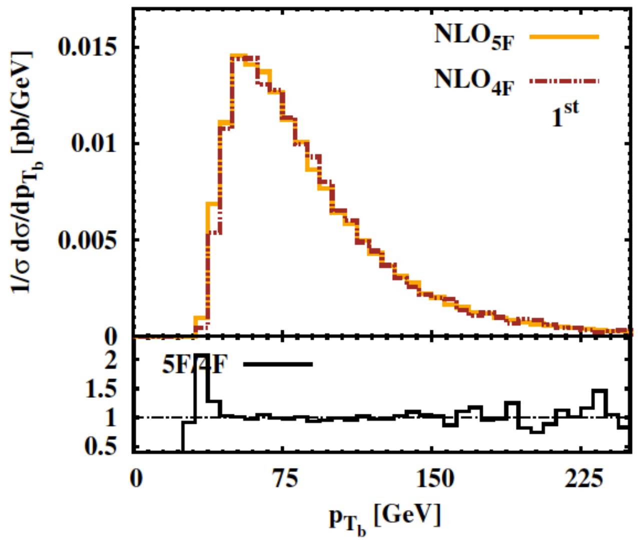
5FS vs. 4FS



- ❑ Transverse momentum of the hardest bottom jet in 5FS & 4FS
- ❑ Absolute prediction at LO and NLO
- ❑ Predictions normalized to inclusive cross sections

Shape Differences Very Small





Bevilacqua, Czakon, Krämer, Kubocz, Worek (2013)

Comparison CS vs. NS

Process	Nr. of Dipoles Catani-Seymour	Nr. of Subtractions Nagy-Soper	Nr. of Feynman Diagrams
$gg \to t\bar{t}b\bar{b}g$	55	11	341
$gg \to t\bar{t}t\bar{t}g$	30	6	682
$gg \to b\bar{b}b\bar{b}g$	90	18	682
$gg \to t\bar{t}ggg$	75	15	1240

Process	t^{CS} [msec]	t^{NS} [msec]	t^{RE} [msec]
$gg \to t\bar{t}b\bar{b}g$	24.8	13.2	6.5
$gg \to t\bar{t}t\bar{t}g$	35.7	18.5	11.2
$gg \to b\bar{b}b\bar{b}g$	26.6	16.2	10.1
$gg \to t\bar{t}ggg$	214.8	108.2	48.7

Bevilacqua, Czakon, Kubocz, Worek (2013)

Number of CS and NS subtraction terms and Feynman diagrams

The CPU time needed to evaluate the subtracted real emission for one phase space point

Intel 3.40 GHz & Intel Fortran

Comparison CS vs. NS

Process	$\varepsilon_{\rm SR}^{\rm CS\,(\alpha_{max}=0.01)}$ [pb]	$\varepsilon_{\rm SR}^{\rm CS\,(\alpha_{max}=1)}$ [pb]	$\varepsilon_{\rm SR}^{\rm NS}$ [pb]
$gg \to t\bar{t}b\bar{b}g$	$4.405 \cdot 10^{-5}$	$4.108 \cdot 10^{-5}$	$5.424 \cdot 10^{-5}$
$gg \to t\bar{t}t\bar{t}g$	$1.356 \cdot 10^{-7}$	$2.298 \cdot 10^{-8}$	$2.377 \cdot 10^{-8}$
$gg \to b\bar{b}b\bar{b}g$	$1.271 \cdot 10^{-3}$	$1.494 \cdot 10^{-3}$	$2.027 \cdot 10^{-3}$
$gg \to t\bar{t}ggg$	$7.560 \cdot 10^{-3}$	$2.290 \cdot 10^{-3}$	$6.507 \cdot 10^{-3}$

Bevilacqua, Czakon, Kubocz, Worek (2013)

Absolute error for subtracted real emission cross sections for dominant partonic subprocesses contributing at $\mathcal{O}(\alpha_s^5)$

BOTH SCHEMES, WITH THEIR DIFFERENT MOMENTUM MAPPINGS AND SUBTRACTION TERMS, HAVE SIMILAR PERFORMANCE

Comparison CS vs. NS

Full Color Summation

Process	$\sigma_{\mathrm{RE}}^{\mathrm{CS}\,(\alpha_{\max}=0.01)}$ [pb]	$\sigma_{\mathrm{RE}}^{\mathrm{CS}\,(\alpha_{\max}=1)}$ [pb]	$\sigma_{\mathrm{RE}}^{\mathrm{NS}}$ [pb]
$gg \to t\bar{t}b\bar{b}g$	$(28.43 \pm 0.13) \cdot 10^{-3}$	$(28.39 \pm 0.04) \cdot 10^{-3}$	$(28.59 \pm 0.06) \cdot 10^{-3}$
$gg \to t\bar{t}t\bar{t}g$	$(17.03 \pm 0.08) \cdot 10^{-5}$	$(16.98 \pm 0.02) \cdot 10^{-5}$	$(17.01 \pm 0.03) \cdot 10^{-5}$
$gg \to b\bar{b}b\bar{b}g$	$(65.71 \pm 0.30) \cdot 10^{-2}$	$(66.24 \pm 0.16) \cdot 10^{-2}$	$(66.06 \pm 0.22) \cdot 10^{-2}$
$gg \to t\bar{t}ggg$	$(87.91 \pm 0.17) \cdot 10^{-1}$	$(87.96 \pm 0.07) \cdot 10^{-1}$	$(88.16 \pm 0.08) \cdot 10^{-1}$

Random Color Sampling

Process	$\sigma_{\mathrm{RE,\,COL}}^{\mathrm{CS}\,(\alpha_{\max}=0.01)}$ [pb]	$\sigma_{\mathrm{RE,\,COL}}^{\mathrm{CS}\,(\alpha_{\max}=1)}$ [pb]	$\sigma_{\mathrm{RE,\,COL}}^{\mathrm{NS}}$ [pb]
$gg \to t\bar{t}b\bar{b}g$	$(28.91 \pm 0.32) \cdot 10^{-3}$	$(28.35 \pm 0.14) \cdot 10^{-3}$	$(28.77 \pm 0.14) \cdot 10^{-3}$
$gg \to t\bar{t}t\bar{t}g$	$(16.99 \pm 0.10) \cdot 10^{-5}$	$(17.00 \pm 0.03) \cdot 10^{-5}$	$(17.01 \pm 0.04) \cdot 10^{-5}$
$gg \to b\bar{b}b\bar{b}g$	$(67.01 \pm 0.64) \cdot 10^{-2}$	$(65.71 \pm 0.50) \cdot 10^{-2}$	$(67.00 \pm 0.66) \cdot 10^{-2}$
$gg \to t\bar{t}ggg$	$(88.05 \pm 0.45) \cdot 10^{-1}$	$(88.04 \pm 0.37) \cdot 10^{-1}$	$(87.76 \pm 0.31) \cdot 10^{-1}$

Bevilacqua, Czakon, Kubocz, Worek (2013)

Real emission cross sections for dominant partonic subprocesses contributing to the subtracted real emissions at $\mathcal{O}(\alpha_s^5)$

Comparison CS vs. NS

Random Helicity Sampling

Process	$\sigma^{\rm NS}_{\rm RE}$ [pb]	$\varepsilon^{\rm NS}_{\rm RE}$ [%]
$gg \to t\bar{t}b\bar{b}g$	$(28.59 \pm 0.06) \cdot 10^{-3}$	0.22
$gg \to t\bar{t}t\bar{t}g$	$(17.01 \pm 0.03) \cdot 10^{-5}$	0.19
$gg \to b\bar{b}b\bar{b}g$	$(66.06 \pm 0.22) \cdot 10^{-2}$	0.33
$gg \to t\bar{t}ggg$	$(88.16 \pm 0.08) \cdot 10^{-1}$	0.09

Random Polarization Sampling

Process	$\sigma^{\rm NS}_{\rm RE,\,POL}$ [pb]	$\varepsilon^{\rm NS}_{\rm RE,\,POL}$ [%]
$gg \to t\bar{t}b\bar{b}g$	$(28.50 \pm 0.06) \cdot 10^{-3}$	0.21
$gg \to t\bar{t}t\bar{t}g$	$(17.01 \pm 0.03) \cdot 10^{-5}$	0.19
$gg \to b\bar{b}b\bar{b}g$	$(66.23 \pm 0.20) \cdot 10^{-2}$	0.30
$gg \to t\bar{t}ggg$	$(88.16 \pm 0.07) \cdot 10^{-1}$	0.08

Bevilacqua, Czakon, Kubocz, Worek (2013)

Real emission cross sections for dominant partonic subprocesses contributing to the subtracted real emissions at $\mathcal{O}(\alpha_s^5)$

Results are shown for random helicity & polarization sampling

Both Approaches are Similar in Efficiency

Summary

- ❑ NLO QCD corrections to $\mathbf{pp \to b\bar{b}b\bar{b} + X}$ @ **LHC**
- ❑ Calculation with massive and massless bottom quarks
- ❑ Genuine bottom mass effects **~10%**, scheme dependence **~5%**
- ❑ Shapes differences very small

- ❑ Results obtained within the **HELAC-NLO** framework (publicly available)

Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek (2013)

- ❑ New process calculated next to:

$$\mathbf{pp(p\bar{p}) \to t\bar{t}b\bar{b} + X}\,, \quad \mathbf{pp(p\bar{p}) \to t\bar{t}jj + X}\,, \quad \mathbf{pp(p\bar{p})} \to \ell^+\nu_\ell\ell^-\bar{\nu}_\ell\mathbf{b\bar{b} + X}\,, \quad \mathbf{pp \to t\bar{t}t\bar{t} + X}$$

- ❑ Validation of the new Nagy-Soper subtraction scheme for all cases
- ❑ Implemented in the **HELAC-DIPOLES** software (publicly available)

Next Step

- **Matching HELAC-NLO onto the Nagy-Soper Shower**

- **Motivations**

  - ✧ Parton shower with quantum interference
  - ✧ Improved treatment of parton spin & subleading color
  - ✧ Parton shower based on the approximation of strongly ordered virtualities of successive parton splittings

Z. Nagy and D. Soper,
JHEP 0709 (2007) 11
JHEP 0803 (2008) 030
JHEP 0807 (2008) 025
JHEP 1206 (2012) 044

- **What is Required**

  - ✧ Complete Nagy-Soper subtraction at NLO - **HELAC-DIPOLES**
  - ✧ Matching of the fixed order calculation onto the Nagy-Soper parton shower

Backup Slides

Comparison [5FS]

- Comparison with results already presented in the literature

Greiner, Guffanti, Reiter, Reuter (2011)

$\sigma_{\rm LO}^{[8]}$ [pb]	$\sigma_{\rm LO}$ [pb]
94.88 ± 0.14	94.74 ± 0.20

LO cross sections in comparison with the previously published results, evaluated with CTEQ6.5 PDF set instead of CTEQ6M PDF set

Bevilacqua, Czakon, Krämer, Kubocz, Worek (2013)

$\sigma_{\rm NLO}^{[8]}$ [pb]	$\sigma_{\rm NLO}^{[8],\,\rm corr.}$ [pb]	$\sigma_{\rm NLO}^{\rm CS\,(\alpha_{max}=0.01)}$ [pb]	$\sigma_{\rm NLO}^{\rm CS\,(\alpha_{max}=1)}$ [pb]	$\sigma_{\rm NLO}^{\rm NS}$ [pb]
140.48 ± 0.64	143.75 ± 0.67	143.70 ± 0.44	144.35 ± 0.53	144.73 ± 0.62

- $\sigma^{\rm NLO}_{pp\to b\bar{b}b\bar{b}+X}$ in comparison with the previously published result & corrected one
- Scale setting corrected in previously published results

CORRECTED RESULTS AGREE WITH OUR CALCULATION