MadFKS

automation of the FKS subtraction method

Rikkert Frederix

University of Zurich

HP2.3rd, Florence, September 14 - 17, 2010

Next-to-leading order

$$\sigma^{\text{NLO}} = \int_{m+1} d^{(d)}\sigma^{R} + \int_{m} d^{(d)}\sigma^{V} + \int_{m} d^{(4)}\sigma^{B}$$

'Real emission'
NLO corrections

'Virtual' or 'one-loop'
NLO corrections

'Born' or 'LO'
contribution

Why automate?

- To save time

  NLO calculations can take a long time. It would be nice to spend this time doing phenomenology instead.

- To reduce the number of bugs in the calculation

  Having a code that does everything automatically will be without* bugs once the internal algorithms have been checked properly.

- To have all processes within one framework

  To learn how to use a new code for each process is not something all our (experimental) colleagues are willing to do.

IR divergence

$$\sigma^{\rm NLO} = \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(d)}\sigma^V + \int_m d^{(4)}\sigma^B$$

- Real emission -> IR divergent
- (UV-renormalized) virtual corrections
  -> IR divergent
  - After integration, the sum of all contributions is finite (for infrared-safe observables)
  - To see this cancellation the integration is done in a non-integer number of dimensions:
    Not possible with a Monte-Carlo integration

Subtraction terms

$$\sigma^{\text{NLO}} = \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(d)}\sigma^V + \int_m d^{(4)}\sigma^B$$

Subtraction terms

$$\sigma^{\text{NLO}} = \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(d)}\sigma^V + \int_m d^{(4)}\sigma^B$$

$$\sigma^{\text{NLO}} = \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^A\right] + \int_m \left[d^{(4)}\sigma^B + \int_{\text{loop}} d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^A\right]_{\epsilon=0}$$

- Include subtraction terms to make real emission and virtual contributions separately finite
- All can be integrated numerically

MadFKS

In collaboration with Stefano Frixione, Fabio Maltoni & Tim Stelzer, arXiv: 0908.4247

FKS subtraction

$$\sigma^{\mathrm{NLO}} = \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^A \right] + \int_m \left[d^{(4)}\sigma^B + \int_{\mathrm{loop}} d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^A \right]_{\epsilon=0}$$

- FKS subtraction: Frixione, Kunszt & Signer 1996.
- Also known as "residue subtraction"
- Based on partitioning the phase space such that each partition has at most one soft and/or collinear divergence
- Use simple plus-distributions to regulate the divergences
- Are relevant formulae can be found in our MadFKS paper, arXiv:0908.4247

FKS -- technicalities

- Naive scaling of the number of subtraction terms is n^2 (as opposed to n^3 of CS dipoles). Can be greatly reduced by using symmetry of the matrix elements
  - Adding additional gluons does not lead to more phase-space partitions
- In a given phase space partition, Born amplitudes need be computed only once for each real-emission event, and can be used for the Born and collinear, soft and soft-collinear counter events (and their remainders)
- Trivially extended to BSM physics. Massive particles have only soft singularity which is independent of the spin

MadFKS

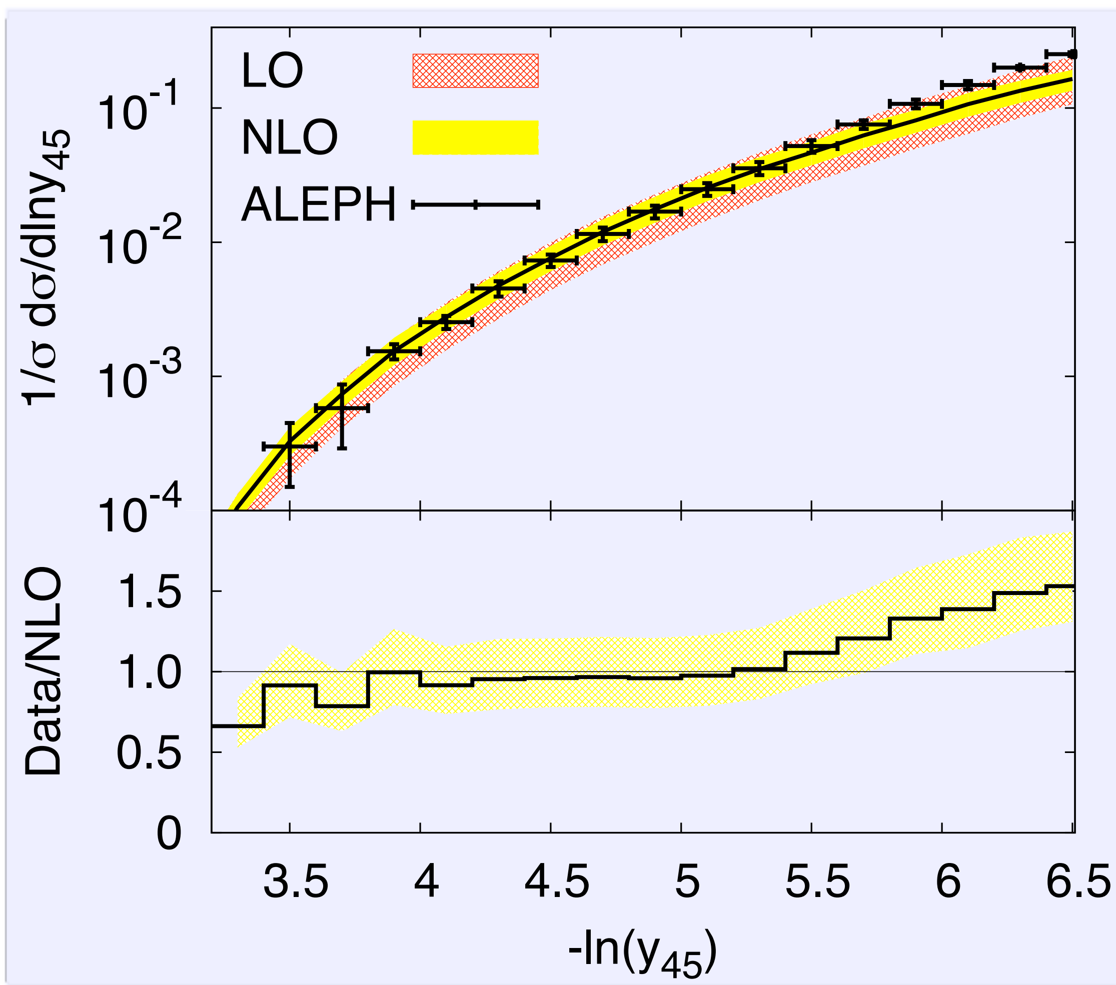
- Automatic FKS subtraction for QCD within the MadGraph/MadEvent framework
- Given the (n+1) process, it generates the real, all the subtraction terms and the Born processes
- Completely general & all automatic, using the same user-friendly interface as MadGraph
- MadFKS works also for any BSM physics model implemented in MadGraph, e.g. MSSM
- Color-linked Borns generated by MadDipole *RF, Gehrmann & Greiner*
- MC-ing over helicities possible; only more efficient for high-multiplicity final states
- Phase-space generation for the (n)-body is the same as in standard MG. It has been heavily adapted to generate (n+1)-body emission events at the same time

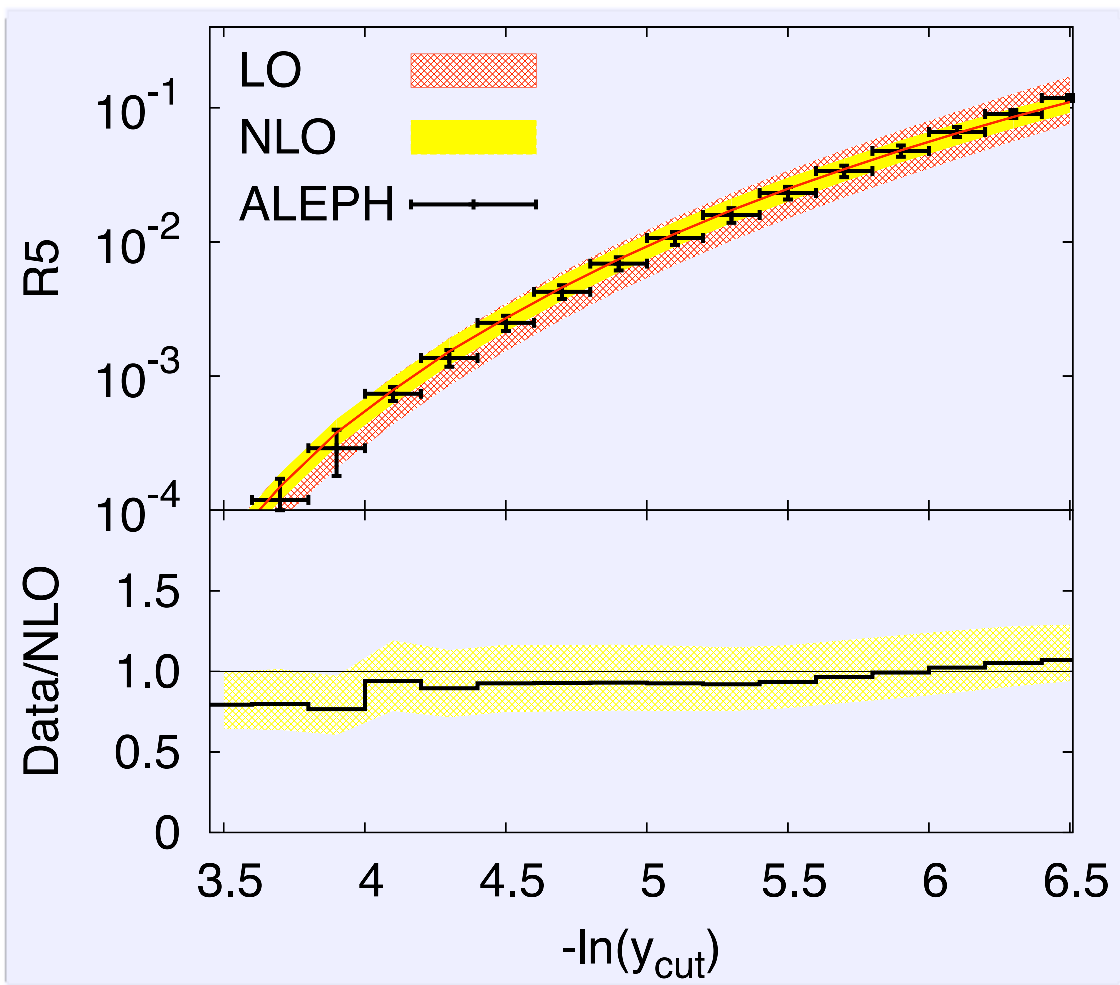
Full NLO

- Of course, to get the total NLO results, the finite parts of the virtual corrections should be included as well
- Interface to link with the virtual corrections following the Binoth-Les Houches Accord
  - Standardized way to link MC codes to one-loop programs
- We are also working on an interface to CutTools
  In collaboration with Hirschi, Garzelli & Pittau

5 jets at LEP @ NLO

RF, Frixione, Melnikov, Zanderighi arXiv:1008.5313

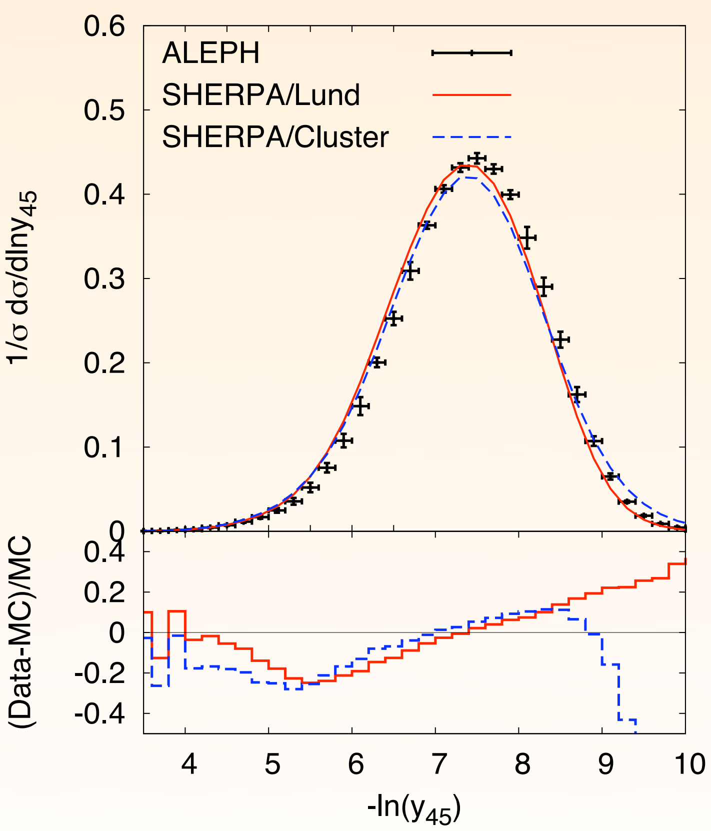


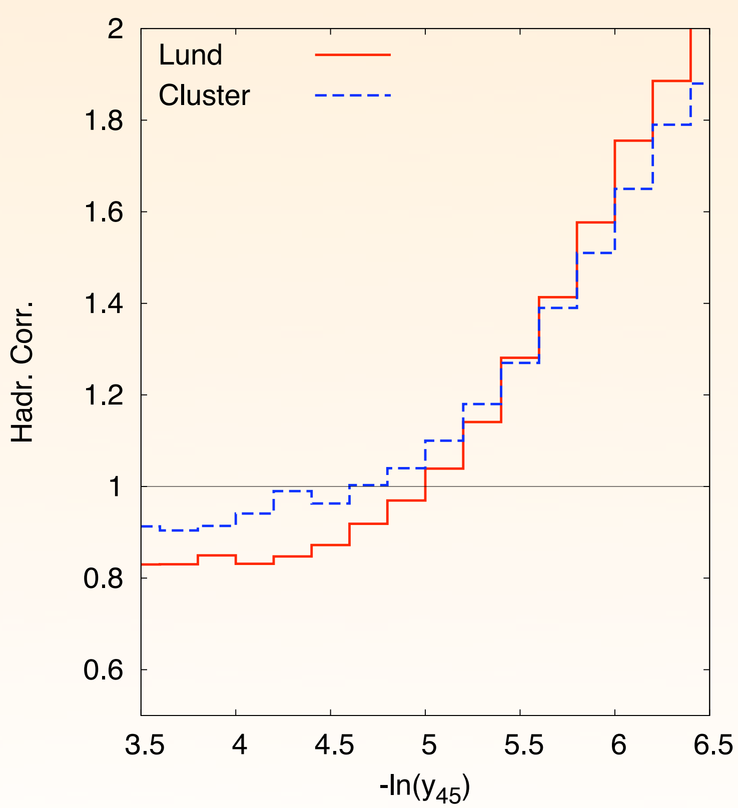


- Durham jet algorithm
- Scale dependence: +45% -30% at LO; ±20% at NLO
- LO and NLO bands overlap (LO uses $\alpha_s(M_Z)$=0.130)
- Point-by-point agreement with BlackHat (*Berger et al.*) for the virtuals

Hadronization corrections

- Historically, for LEP, hadronization corrections have been estimated by using Ariadne, Herwig & Pythia, which are tuned to data
- However, they are based on 2→2 and 2→3 matrix elements. Therefore, for these 5 jet observables, they rely strongly on the showers.
- We have estimated the hadronization corrections using Sherpa, with CKKW matching up to 5 hard partons
- Corrections are mild up to $-\ln(y_{45}) \sim 6$





α_s EXTRACTION

	LEP1, hadr. $\sigma_{tot}^{-1} d\sigma/dy_{45}$, R_5	LEP1, no hadr. $\sigma_{tot}^{-1} d\sigma/dy_{45}$, R_5
stat.	$^{+0.0002}_{-0.0002}$	$^{+0.0002}_{-0.0002}$
syst.	$^{+0.0027}_{-0.0029}$	$^{+0.0027}_{-0.0029}$
pert.	$^{+0.0062}_{-0.0043}$	$^{+0.0068}_{-0.0047}$
fit range	$^{+0.0014}_{-0.0014}$	$^{+0.0005}_{-0.0005}$
hadr.	$^{+0.0012}_{-0.0012}$	–
$\alpha_s(M_Z)$	$0.1159^{+0.0070}_{-0.0055}$	$0.1163^{+0.0073}_{-0.0055}$

	LEP2, no hadr. $\sigma_{tot}^{-1} d\sigma/dy_{45}$	LEP2, no hadr. R_5	LEP2, no hadr. $\sigma_{tot}^{-1} d\sigma/dy_{45}$, R_5
stat.	$^{+0.0020}_{-0.0022}$	$^{+0.0022}_{-0.0025}$	$^{+0.0015}_{-0.0016}$
syst.	$^{+0.0008}_{-0.0009}$	$^{+0.0012}_{-0.0012}$	$^{+0.0008}_{-0.0008}$
pert.	$^{+0.0049}_{-0.0034}$	$^{+0.0029}_{-0.0020}$	$^{+0.0029}_{-0.0020}$
fit range	$^{+0.0038}_{-0.0038}$	$^{+0.0030}_{-0.0030}$	$^{+0.0028}_{-0.0028}$
$\alpha_s(M_Z)$	$0.1189^{+0.0066}_{-0.0057}$	$0.1120^{+0.0050}_{-0.0047}$	$0.1155^{+0.0044}_{-0.0039}$

- Statistical uncertainties negligible at LEP1; larger at LEP2
- Systematic and Perturbative uncertainties larger at LEP1 than LEP2, fit range uncertainties are opposite
- Uncertainties from hadronization corrections already negligible at LEP1, not even considered for LEP2
- Correlations between bins and LEP energies taken into account conservatively

$$\alpha_s(M_Z) = 0.1156^{+0.0041}_{-0.0034}$$

α_s extraction -- correlations

- Statistical uncertainties are uncorrelated between different center-of-mass energies. At a given c.o.m. energy, y_{45} is uncorrelated, while R_5 is assumed to be fully correlated.
- Systematic uncertainties are assumed to be fully correlated at a given c.o.m. energy and between all LEP2 energies, however completely uncorrelated between LEP1 and LEP2.
- Perturbative uncertainties are assumed to be fully correlated.
- Hadronization uncertainties (considered only at LEP1) are assumed to be fully correlated.

Comparison with other measurements

Observable	$\alpha_s(M_Z)$	Ref.
τ decays	0.1197 ± 0.0016	S. Bethke
Υ decays	0.119 ± 0.0055	N. Brambilla *et al.*
3 jet observables	0.1224 ± 0.0039	G. Dissertori *et al.*
jets in DIS	0.1198 ± 0.0032	H1 collaboration
DIS	0.1142 ± 0.0021	J. Blümlein
thrust	0.1135 ± 0.0011	R. Abbate *et al.*
lattice	0.1183 ± 0.0008	HPQCD collaboration
EW fits	0.1193 ± 0.0028	H. Flacher *et al.*
world average	0.1184 ± 0.0007	S. Bethke
$e^+e^- \to$ five jets	0.1156 ± 0.0038	RF, S. Frixione, K. Melnikov & G. Zanderighi

- Uncertainty competitive with other measurements
- Slightly smaller than world average, but consistent within uncertainties

Virtual corrections

In collaboration with Valentin Hirschi and
Maria-Vittoria Garzelli & Roberto Pittau

Virtual corrections

- Interface using the Binoth-LHA is available
- For more flexibility (e.g. massive particles & BSM) we also started working on generating the virtual corrections ourselves
- Using the OPP method as implemented in CutTools

Ossola, Papadopoulos & Pittau

Implementation

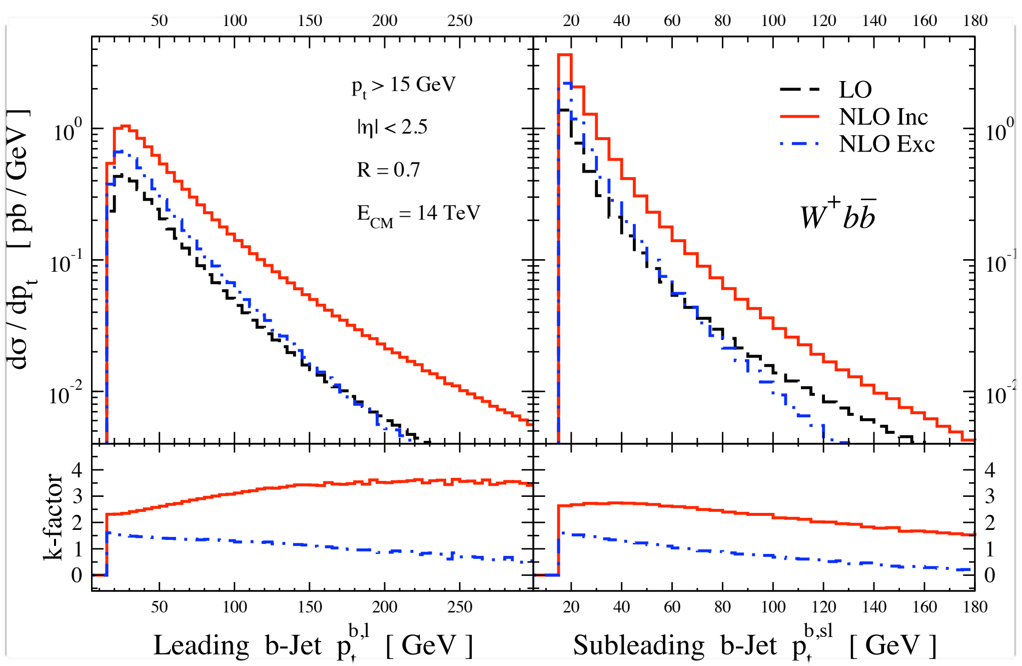
- MadGraph generates the loop diagrams by cutting one of the particles in the loop: simple tree-level diagrams remain
  → Passed to CutTools
- NLOComp filters duplicates and sets-up the interference with the Born diagrams: computation of the color factors.
- Ghosts also needed
- R2 terms are computed using tree-level Feynman Rules
  Draggiotis, Garzelli, Papadopoulos & Pittau
- Point-by-point agreement found with MCFM (and private codes): Drell-Yan, 2-jet production, top pair, W/Z+1 jet...
- Not yet optimized in any way. This will be done only in the MGv5 framework

Wbb associated production

- First new results with MadFKS+NLOComp/CutTools
- $pp \to W^+(\to e^+\nu_e)b\bar{b},$ with massive b's
- *Similar calculation by Febres Cordero, Reina & Wackeroth*
- However, here the W boson decay is included, and stable enough to generate results without cuts on the bottom quarks

Wbb Results

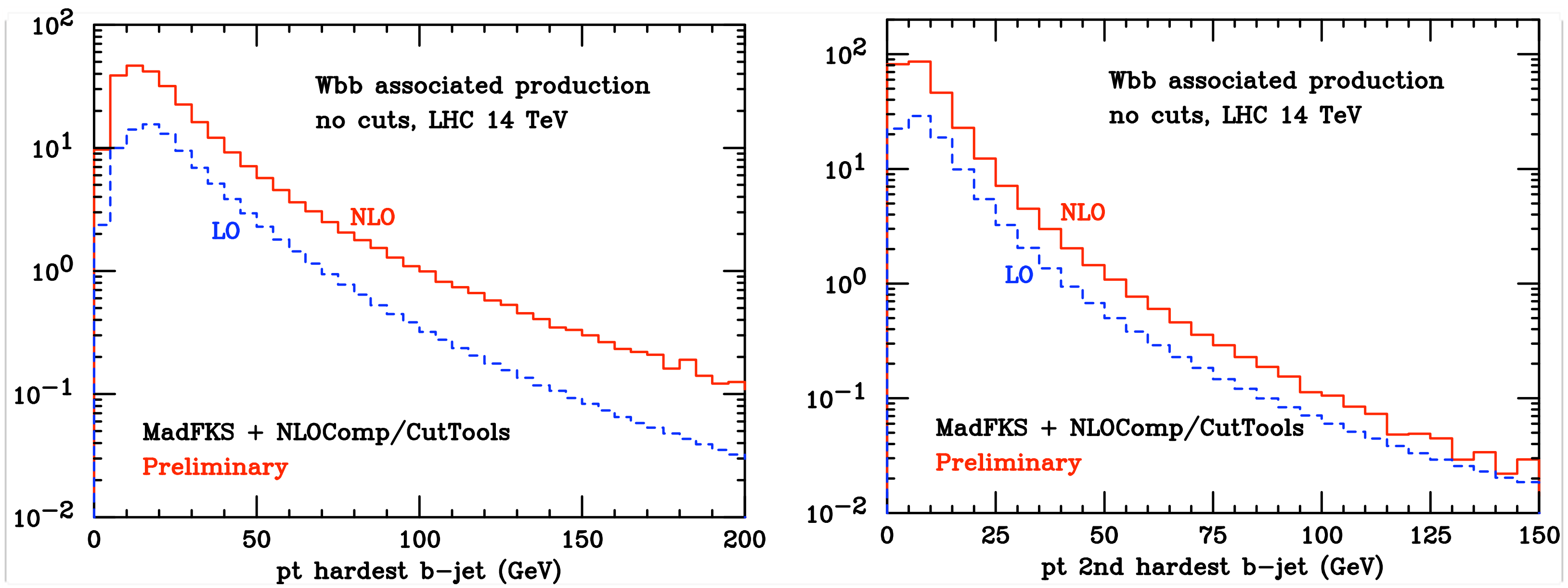
Febres Cordero et al.

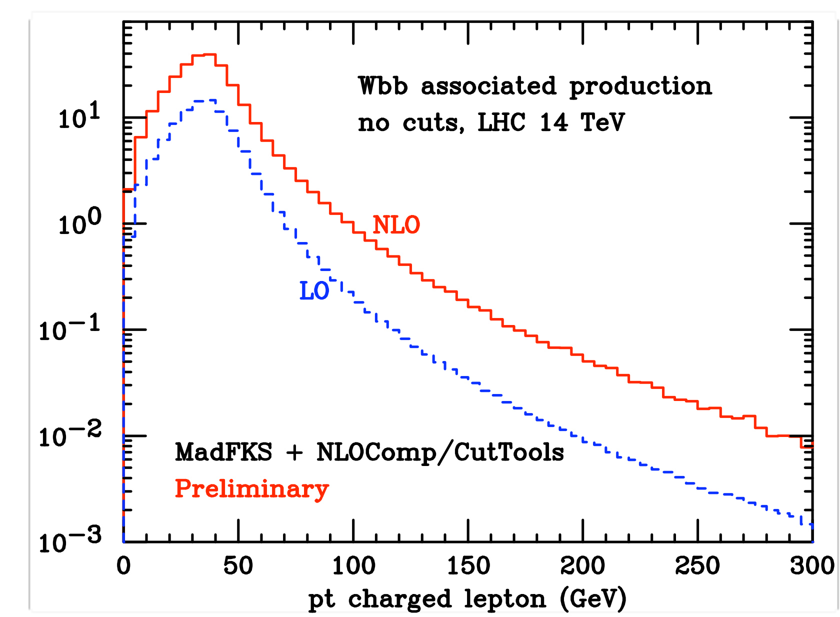


- Transverse momentum of the hardest and 2nd hardest b-jets regulated by the b quark mass
- W boson decay included
- Unfortunately, slight disagreement between calculations when cuts are also applied to our results

work in progress

RF, Frixione, Garzelli, Hirschi, Maltoni & Pittau





Matching to a Parton Shower

In collaboration with Stefano Frixione & Paolo Torrielli

Automation of MC@NLO

$$d\sigma^{(\mathbb{H})}_{\text{MC@NLO}} = d\phi_{n+1}\left(\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(\text{MC})}(\phi_{n+1})\right)$$

$$d\sigma^{(\mathbb{S})}_{\text{MC@NLO}} = \int_{+1} d\phi_{n+1}\left(\mathcal{M}^{(b+v+rem)}(\phi_n) - \mathcal{M}^{(c.t.)}(\phi_{n+1}) + \mathcal{M}^{(\text{MC})}(\phi_{n+1})\right)$$

- In black: pure NLO, fully tested in MadFKS
- In red: already implemented for Herwig 6;
  Pythia and Herwig++ are work in progress
  - FKS is based on a collinear picture, so are the MC counter terms: branching structure is for free
  - Automatic determination of color partners
  - Automatic computation of leading-color matrix elements
  - Works also when MC-ing over helicities

MadFKS matched to parton shower

- In MadFKS many process fully tested and working *(e.g. e^+e^- to jets, Drell-Yan, top pair production, ...)*

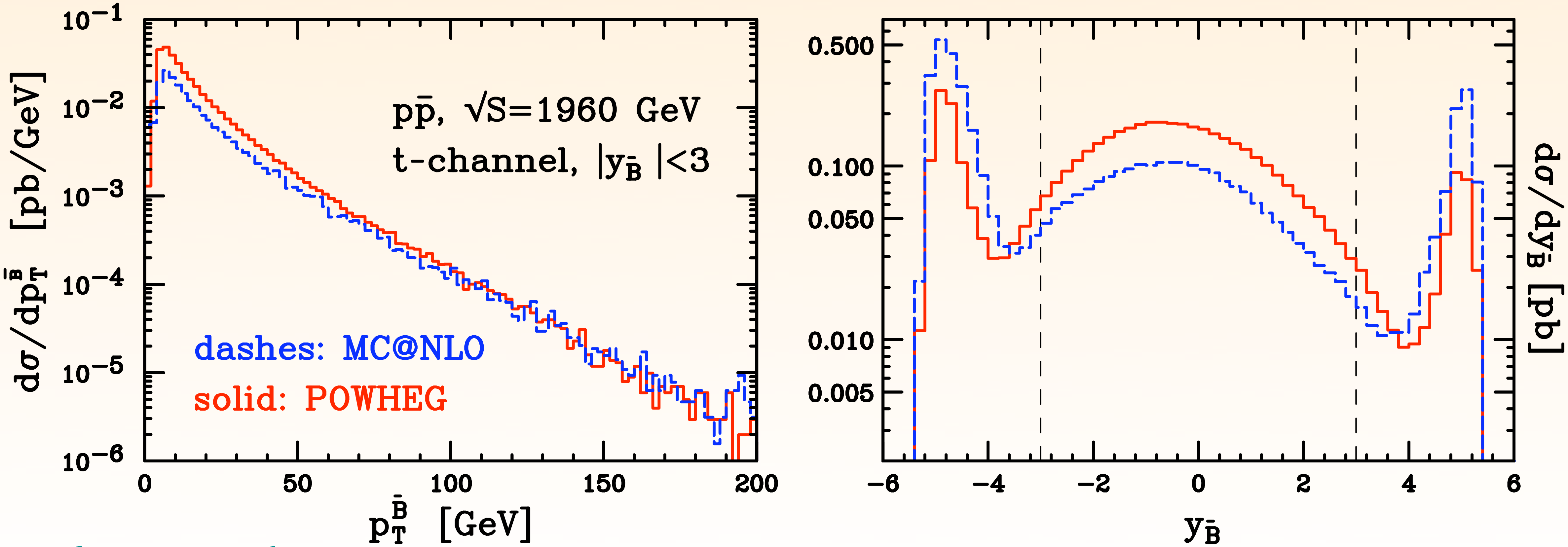
- New result: t-channel single top production

T-CHANNEL SINGLE TOP

- Already implemented in MC@NLO and POWHEG

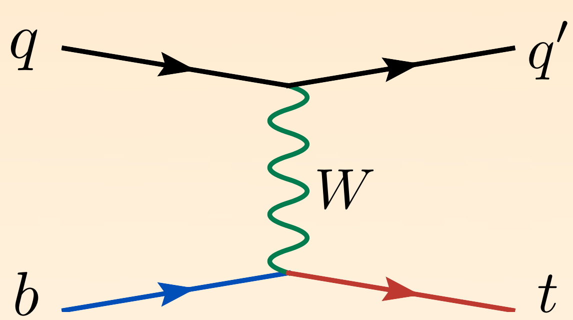
Frixione, Laenen, Motylinski & Webber (2006); Alioli, Nason, Oleari & Re (2009)

- However, due to the massless initial state b quark in the fixed order calculation, some strange behavior at low p_T and for forward B hadrons

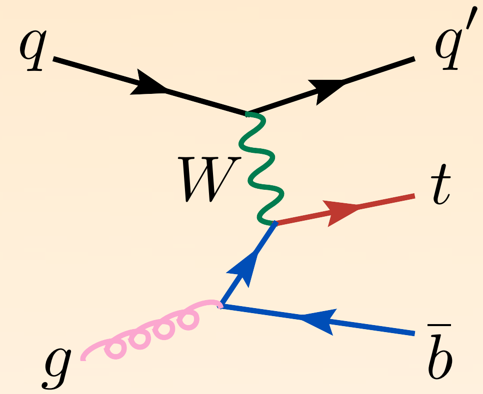


Initial state b quark

- "Standard" way of looking at this process



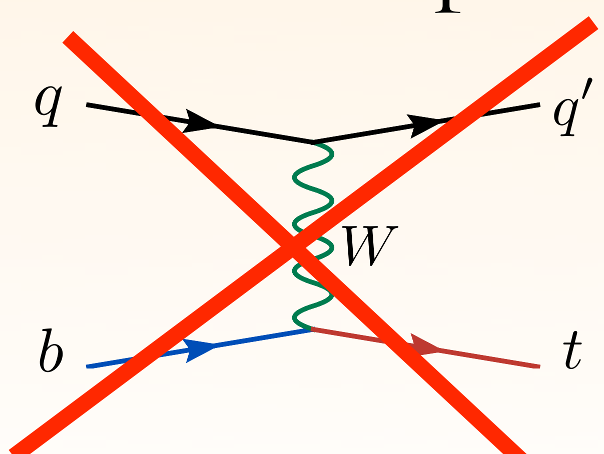
leading order



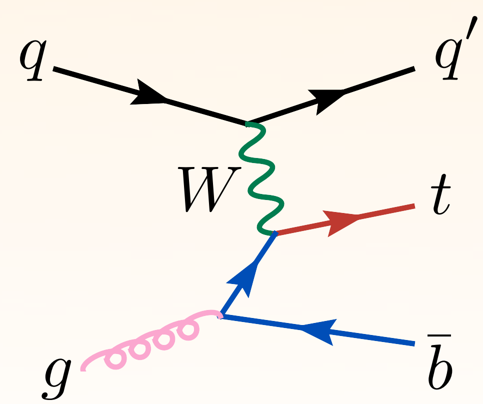
(contribution to) NLO

5-flavor scheme

- But there is an equivalent description with no bottom PDF and an explicit gluon splitting to b quark pairs



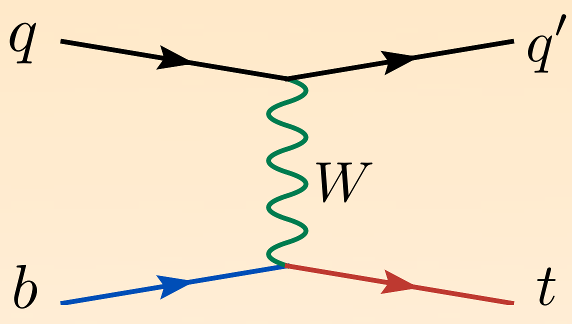
Does not exist



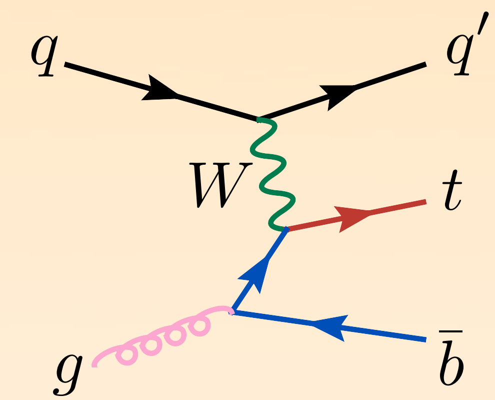
(part of) leading order

4-flavor scheme

The two schemes



5-flavor scheme: "2 → 2"



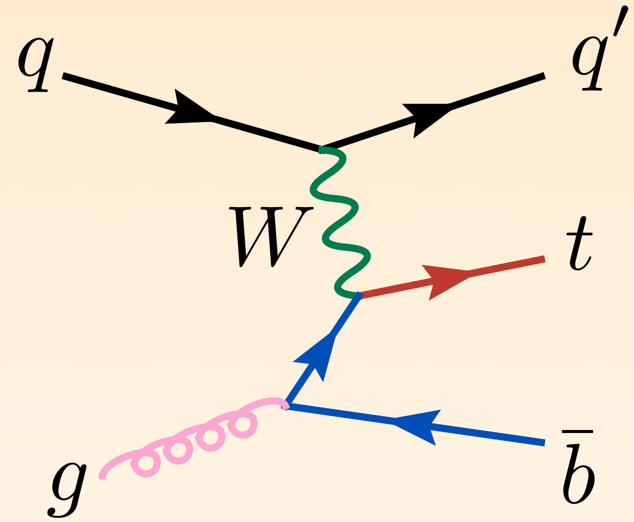
4-flavor scheme: "2 → 3"

- At all orders both description should agree; otherwise, differ by:
  - evolution of logarithms in PDF: they are resummed
  - available phase space
  - approximation by large logarithm

Four-flavor scheme

Campbell, RF, Maltoni, Tramontano (2009)

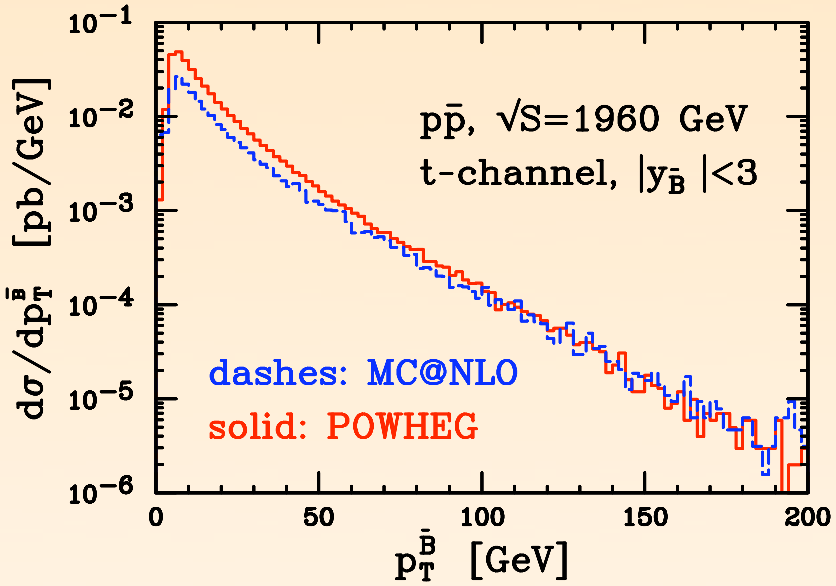
- Use the 4-flavor $(2 \rightarrow 3)$ process as the Born and calculate NLO
  - Much harder calculation due to extra mass and extra parton
  - Spectator b for the first time at NLO

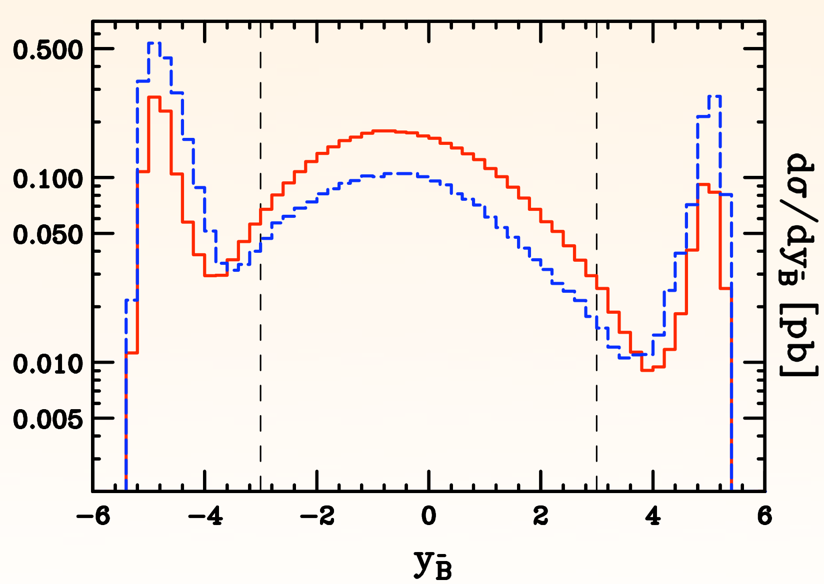


- Process implemented in the *MCFM-v5.7* parton-level NLO code
  - Starting point for future NLO+PS beginning at $(2 \rightarrow 3)$

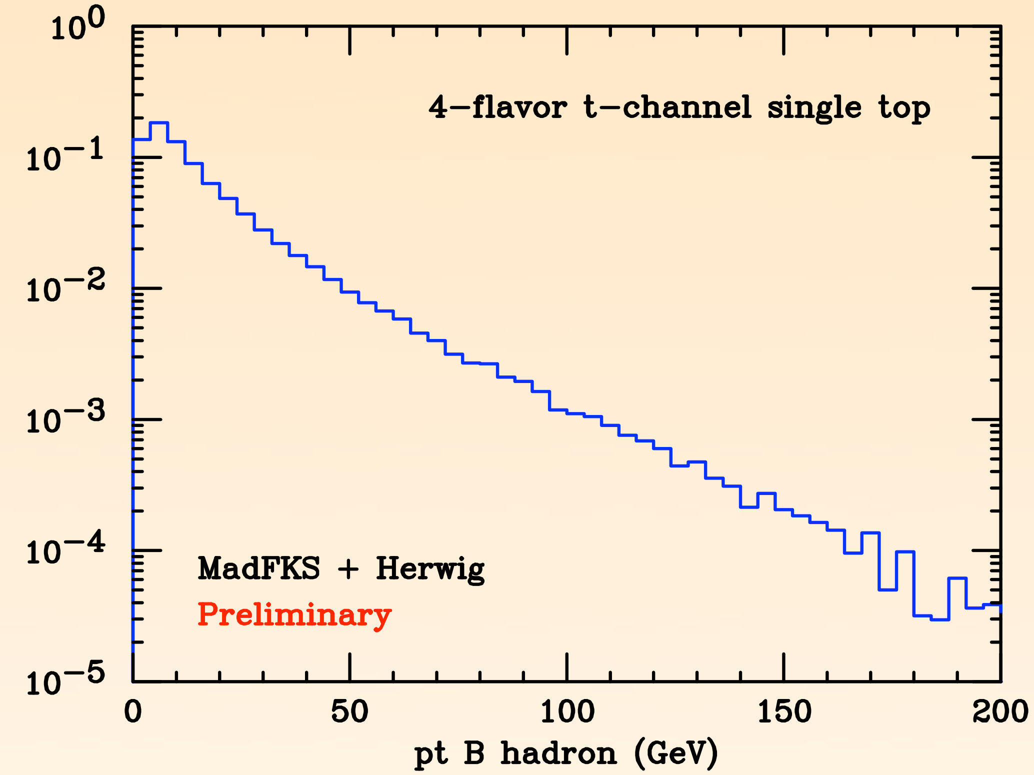
NLO 4 FLAVOR + SHOWER

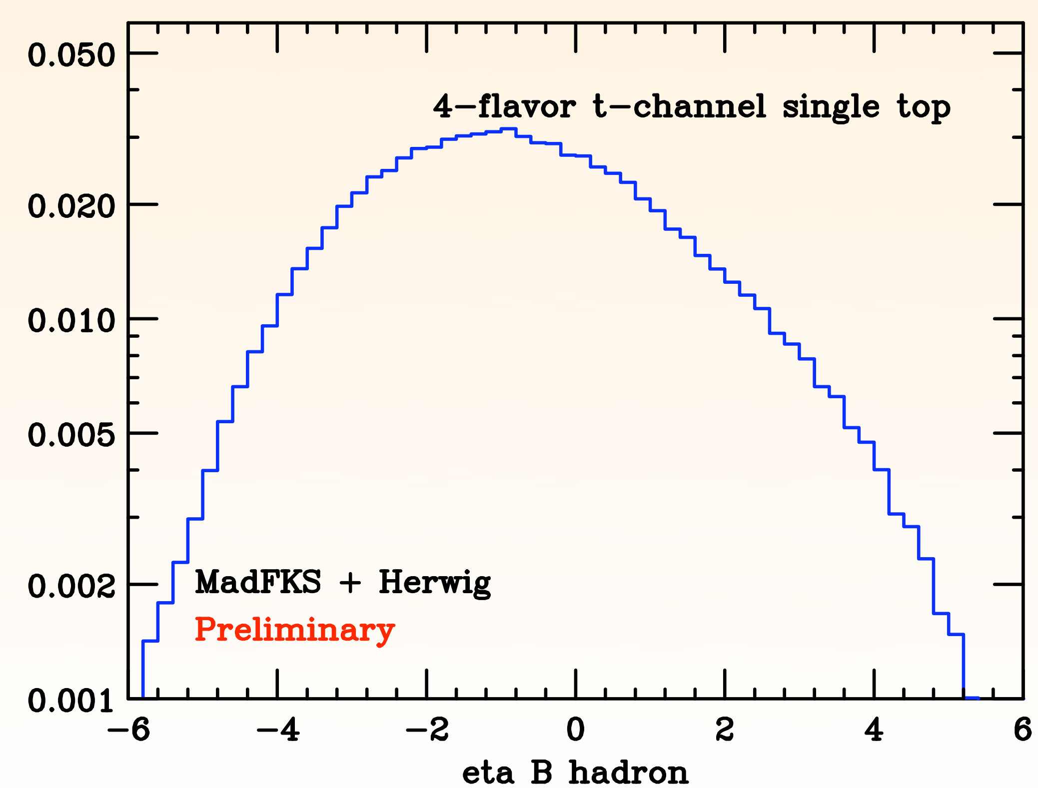
5-flavor scheme





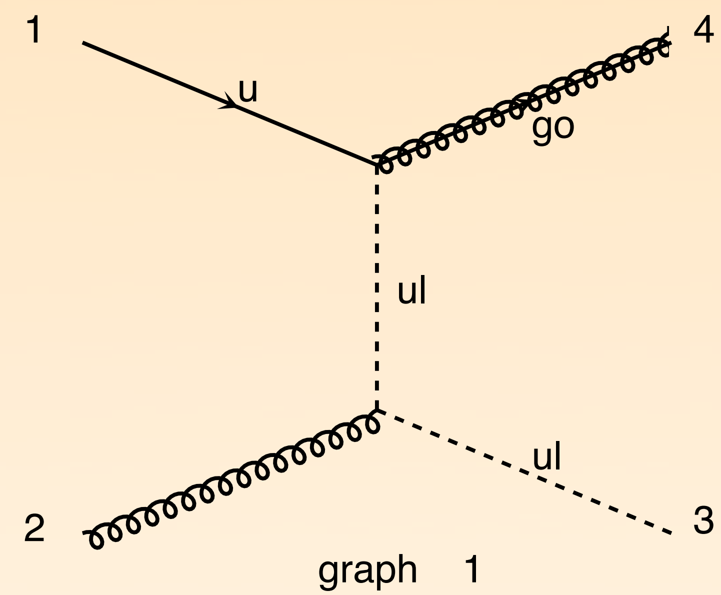
4-flavor scheme

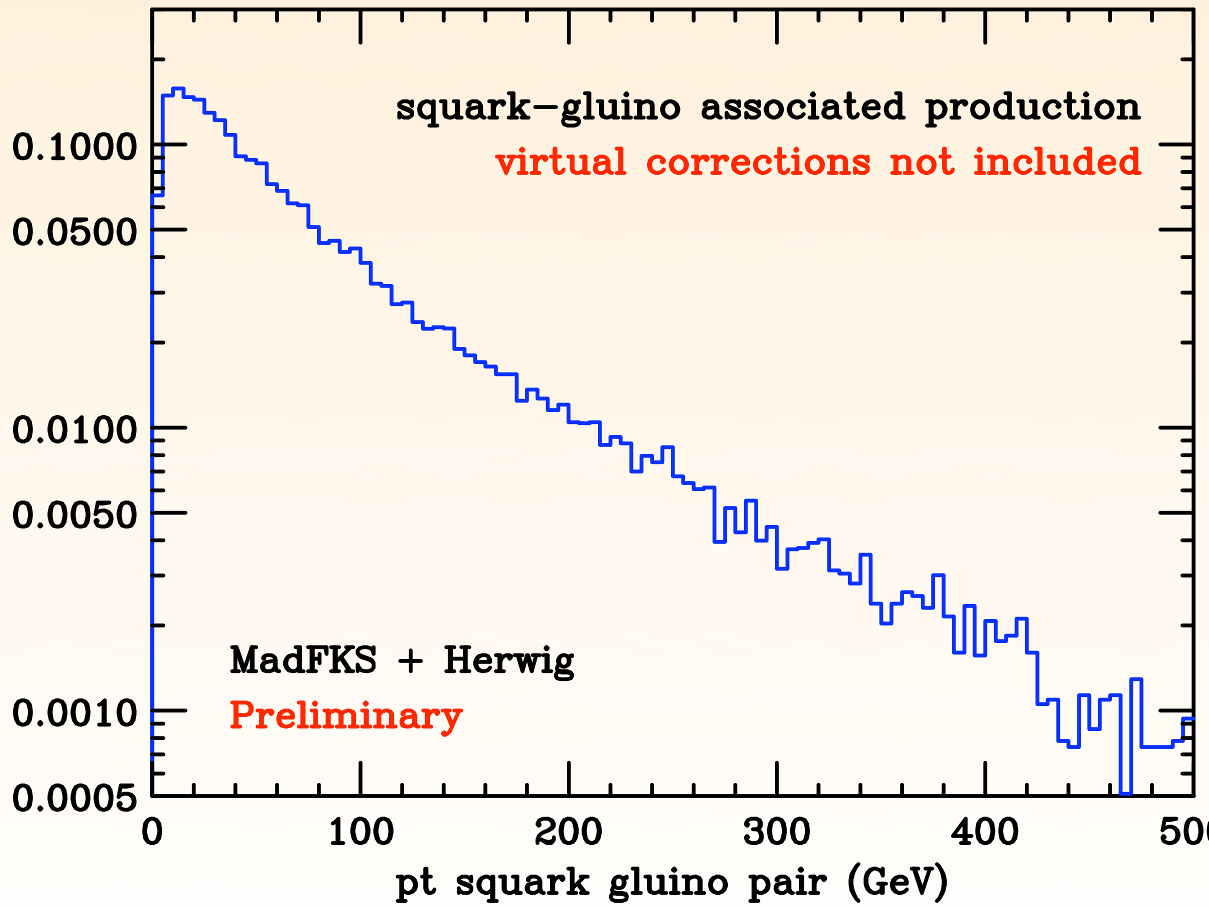


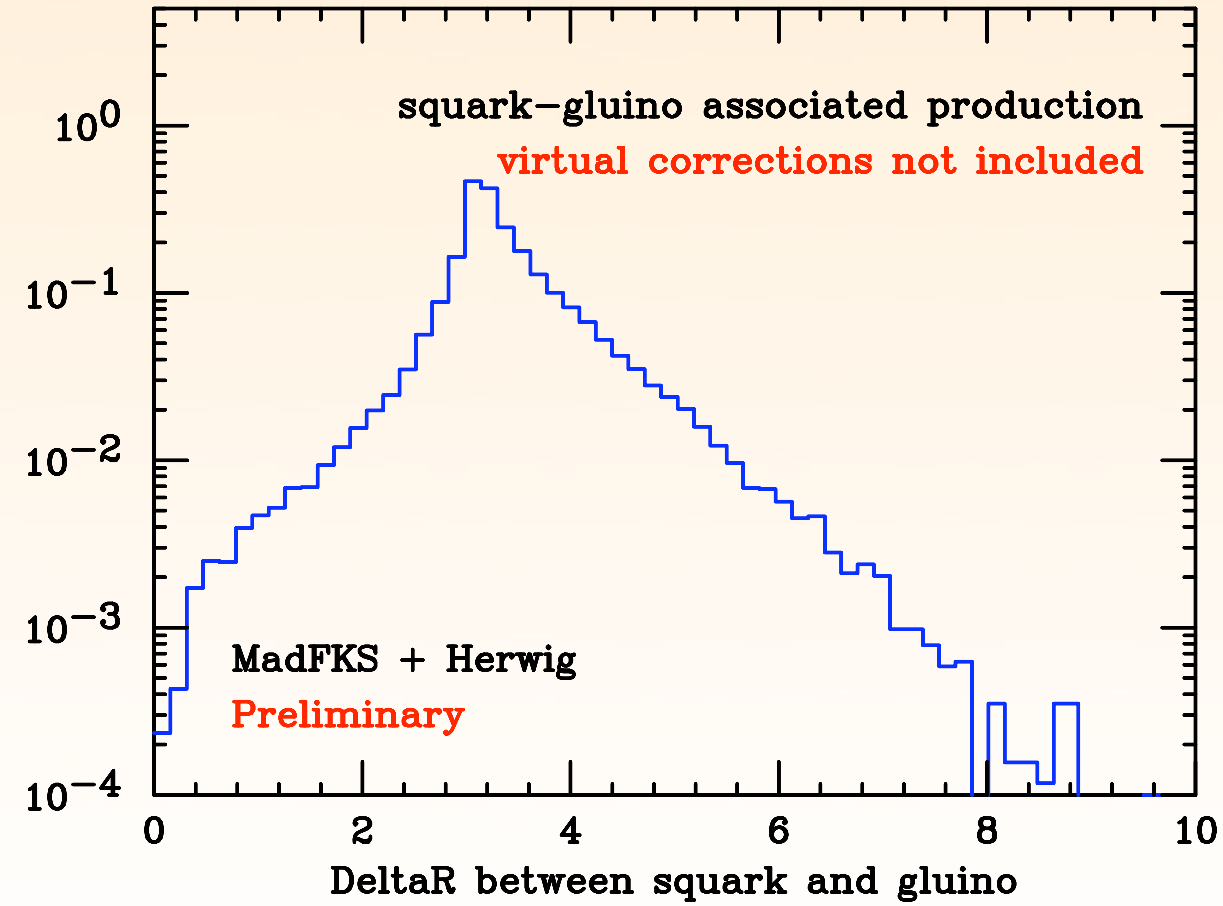


Also BSM

- squark-gluino associated production
- real emission corrections included, but virtual correction not (yet)







To conclude

- For any QCD NLO computation (SM & BSM) MadFKS takes care of:
  - Generating the Born, real emission, subtraction terms, phase-space integration and overall management of symmetry factors, subprocess combination etc.
- Using NLOComp+CutTools and virtual corrections are being automated
- With the shower subtraction terms, interface to showers to generate automatically unweighted events with NLO precision is working with Herwig and work in progress with Pythia and Herwig++
- **First physics results at NLO are being produced within the MadGraph/MadEvent framework using the MadFKS code**