Karlsruher Institut für Technologie

Parton level Monte Carlos, vector boson scattering and other fun work withTao

Dieter Zeppenfeld

TaoFest, May 14-15, 2026, Pittsburgh

KIT Center Elementary Particle and Astroparticle Physics - KCETA

40 years ago to the day: 1986 Madison Workshop
From Colliders to Supercolliders

First time I met Tao, who had helped organize the workshop

40 years ago to the day: 1986 Madison Workshop
From Colliders to Supercolliders

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Workshop excursion and picnic at Devil‘s Lake

What followed was a productive period of work with Tao and Vernon

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VOLUME 62, NUMBER 17 PHYSICAL REVIEW LETTERS 24 APRIL 1989

Large-p_T Weak-Boson Production at the Fermilab Tevatron

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[1] *Physics Department, University of Wisconsin, Madison, Wisconsin 53706*
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(Received 15 December 1988)

Perturbative QCD calculations of the processes $p\bar{p} \to W^{\pm}, Z + n$ jets ($n = 1,2,3$) with $W \to e\nu$ and $Z \to e\bar{e}$ decays are presented for comparison with forthcoming Fermilab Tevatron data at $\sqrt{s} = 1.8$ TeV. The $W,Z + 2$-jet results are compared with the corresponding $p\bar{p} \to WW$, WZ, and ZZ electroweak cross sections.

PACS numbers: 13.85.Qk, 12.38.Bx

- LO QCD simulations of W (or Z) production with additional jets
- Programming helicity amplitude tools (based on work with Kaoru)
- pre-HELAS, still the basic ingredient of VBFNLO amplitude calculations
- Important help from Bill Long to generate fast code

Including pheno work

ELSEVIER

Physics Letters B

Volume 220, Issue 3, 6 April 1989, Pages 464-470

Constraints on exotic particles from tevatron missing transverse momentum data

V. Barger [a], K. Hagiwara [a b], T. Han [a], D. Zeppenfeld [a]

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https://doi.org/10.1016/0370-2693(89)90904-0

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Abstract

The search at the Tevatron for events with large missing transverse momentum (*pstroke*;$_T$), which set mass bounds exceeding 73 GeV for both squarks and gluinos, implies significantly improved mass limits on other exotic particles. We study various sources for *pstroke*;$_T$ events: production of leptoquarks or their fermionic partners in E_6 models, Majorana leptogluons in composite models of quarks and leptons, and cosmions in a model which explains the solar neutrino and dark matter problems. The CDF data can already exclude neutral leptogluons with masses below 110 GeV, while an integrated luminosity of order 2 pb^{-1} would set lower mass bounds of order 100 GeV for the other exotic particles.

…some of which probably all 4 of us have forgotten about long time ago

More important: dijet + weak boson pairs → background to weak boson scattering

PHYSICAL REVIEW D VOLUME 41, NUMBER 9 1 MAY 1990

Pair production of $W^{\pm}$, γ, and Z in association with jets

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(Received 22 November 1989)

Amplitudes for the production of electroweak-gauge-boson pairs (any combination of γ, Z, or $W^{\pm}$) in association with up to two jets are given. The gauge bosons may be either real or virtual with subsequent decays into charged or neutral leptons. The amplitudes are presented in a form directly amenable to numerical evaluation. Representative cross sections are given for Fermilab Tevatron, CERN Large Hadron Collider, and Superconducting Super Collider center-of-mass energies.

… and then we explored forward jet tagging

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PHYSICAL REVIEW D VOLUME 44, NUMBER 5 1 SEPTEMBER 1991

Comparative study of the benefits of forward jet tagging in heavy-Higgs-boson production at the Superconducting Super Collider

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Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510

J. Ohnemus
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(Received 10 April 1991)

The event rate for production of a Higgs boson of mass ~ 1 TeV with decay $H \to ZZ \to 4$ charged leptons is of order 25 events per year at standard Superconducting Super Collider luminosity and the QCD background is of comparable size. By tagging a *single* forward jet of energy $E_j > 1$ TeV and rapidity $2 < |\eta_j| < 5$ from the $qq \to qqZZ$ process, the QCD background can be essentially eliminated, with about 10 Higgs-boson signal events per year remaining, which amounts to 70% of the $qq \to qqZZ$ signal rate. The experimental separation of the vector-boson scattering subprocess is thereby possible.

…. and central jet veto

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PHYSICAL REVIEW D VOLUME 44, NUMBER 9 1 NOVEMBER 1991

Single-forward-jet tagging and central-jet vetoing to identify the leptonic WW decay mode of a heavy Higgs boson

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D. Zeppenfeld
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(Received 30 May 1991)

We study the extraction of the heavy-Higgs-boson signal $H \to W^+W^- \to \bar{\ell}\nu, \ell\bar{\nu}$ ($\ell = e$ or μ) from the standard-model background at hadron supercolliders. By tagging a single forward jet with energy $E_j > 3$ TeV and pseudorapidity $3 < |\eta_j| < 5$ and by vetoing central jets of transverse momenta $p_{Tj} > 60$ GeV in the pseudorapidity range $0 < |\eta_j| < 3$, the QCD WWj and $t\bar{t}j \to WWb\bar{b}j$ backgrounds are suppressed. For $m_H = 1$ TeV there are about 46 signal events from electroweak-vector-boson scattering (of which 36 events are of Higgs-boson origin) at the Superconducting Super Collider (SSC) for an integrated luminosity of 10 fb^{-1} and 10 other events from the WWj and $t\bar{t}j$ backgrounds for $m_t = 140$ GeV. The experimental separation of the vector-boson-scattering subprocess is thereby possible. At the CERN Large Hadron Collider, with an $E_j > 2$ TeV jet energy cut, all cross sections are about a factor of 10 below the SSC values.

To be applied to weak boson scattering: WZjj

PHYSICAL REVIEW D VOLUME 46, NUMBER 5 1 SEPTEMBER 1992

Full tree-level calculation of the $qq \to qqWZ$ electroweak process at hadron supercolliders

V. Barger and Kingman Cheung
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T. Han
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A. Stange and D. Zeppenfeld
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(Received 23 December 1991)

We present a full standard model calculation of the $qq \to qqWZ$ electroweak process in pp collisions at the Superconducting Super Collider, including W and Z leptonic decay correlations. We also analyze the backgrounds to this signal from $Zt\bar{t} \to ZW +$ jets and $q\bar{q} \to WZ+$ jets. Single forward jet tagging and vetoing of events with ≥ 2 central jets can suppress the backgrounds with little effect on the signal. With 10 fb^{-1} integrated luminosity we expect 50 signal events and 30 background events.
PACS number(s): 13.85.Qk, 12.15.Cc, 12.15.Ji, 14.80.Er

… and search for a heavy Higgs at LHC and SSC

PHYSICAL REVIEW D VOLUME 48, NUMBER 11 1 DECEMBER 1993

Finding the leptonic WW decay mode of a heavy Higgs boson at hadron supercolliders

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[2] *Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208*
[3] *Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510*

(Received 13 May 1993)

We reanalyze the extraction of the heavy Higgs boson signal $H \to W^+W^- \to \bar{\ell}\nu, \ell\bar{\nu}$ ($\ell = e$ or μ) from the standard model background at hadron supercolliders, taking into account revised estimates of the top quark background. With new acceptance criteria the detection of the signal remains viable. Requiring a forward jet tag, a central jet veto, and a large relative transverse momentum of the two charged leptons yields $S/\sqrt{B} > 6$ for one year of running at the SSC or CERN LHC.

PACS number(s): 14.80.Gt, 13.85.Qk, 13.87.−a

At the time, weak boson fusion was thought to be useful for heavy Higgs search only. For light (SUSY) Higgs gluon fusion and Higgs-strahlung were the main anticipated search modes

Collaboration with Tao didn‘t quite stop when he moved to Davis

PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

$W\gamma\gamma$ production at the Fermilab Tevatron collider: Gauge invariance and radiation amplitude zero

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[1]*Department of Physics, State University of New York, Buffalo, New York 14260*
[2]*Department of Physics, University of California, Davis, California 95616*
[3]*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706*
(Received 19 February 1997)

The electroweak process $p\bar{p}\ell^{\pm}\nu\gamma\gamma$ is calculated at the tree level, including finite W width effects. In order to obtain a gauge-invariant amplitude, the imaginary parts of $WW\gamma$ triangle graphs and $WW\gamma\gamma$ box diagrams have to be included, in addition to resumming the imaginary contributions to the W vacuum polarization. We demonstrate the existence of a radiation amplitude zero in $p\bar{p}\to W^{\pm}\gamma\gamma\to\ell^{\pm}\nu\gamma\gamma$, and discuss how it may be observed in correlations of the $\gamma\gamma$ and lepton rapidities at the Fermilab Tevatron. [S0556-2821(97)04813-3]

PACS number(s): 12.15.Lk, 13.85.Qk, 14.70.Fm

In our albums I did not find any photos of Tao from these first ten years….-

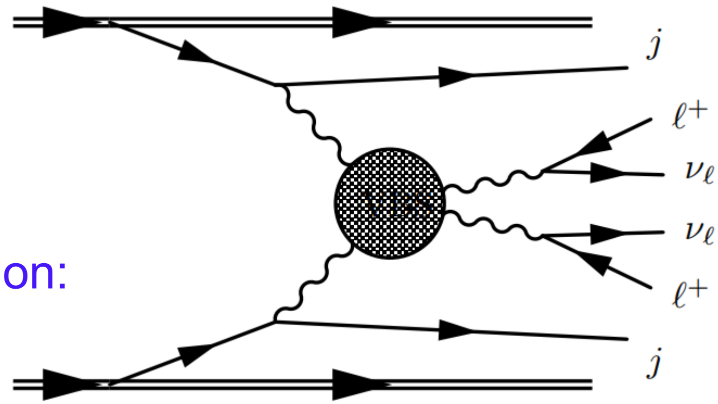
Barger/Olsson: Classical Mechanics at 25

1998: celebrating 25 years
of a great classical mechanics
textboook

… building on work with Tao

Early work on forward jet tagging and central jet veto led to studies of vector boson fusion and weak boson scattering

- Basic process: VV→VV
- accompanied by 2 quark jets
  = tagging jets
- Identify weak bosons by decay leptons
  (or hadronic V decay)
- Characteristic radiation pattern of gluon emission:
  suppresssed emission in central region
- Central jet veto suppresses background



Long standing problem: reliable modeling of VV+3 jets or H+3jets for signal and background. Need NLO QCD calculations for these proccesses

- H + 3 jets (PhD thesis of Terrance Figy)
- Z + 3 jets is excellent lab for experimental verification of NLO expectations
- W^+W^++3 jets recently calculated by Barbara Jäger et al.

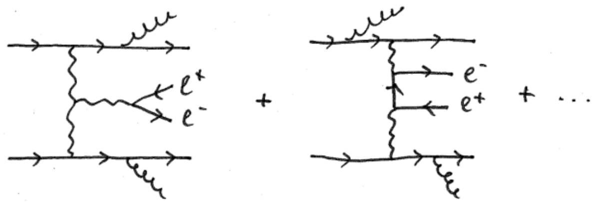
Speeding up NLO calculations: VBF Z+3jet as a case study

(work with T. Jezo and M. Löschner)

Many contributing subprocesses

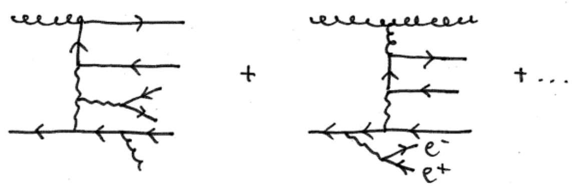
e.g. 1117 (118) Z+4 parton real emission processes with 5 (2) massless quark flavors

- Quark initiated



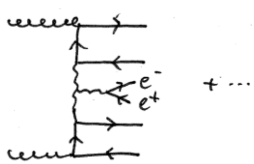
x4 for q→qbar
6 distinct flavor combinations

- qg initiated



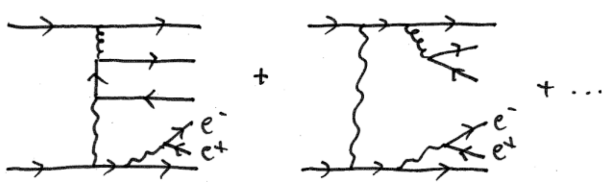
x4 for q→qbar, qg→gq
6 distinct flavor combinations

- gg initiated



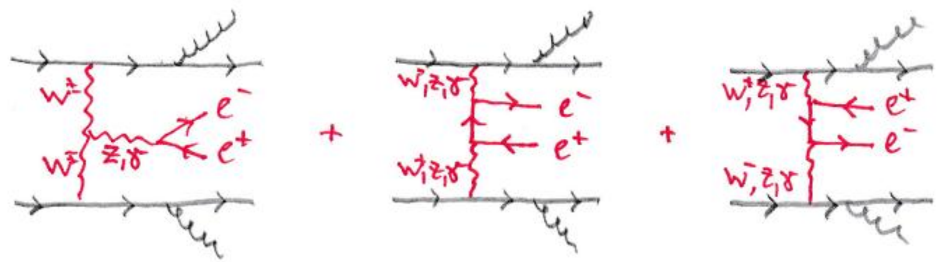
6 distinct flavor combinations

- 6 quark processes

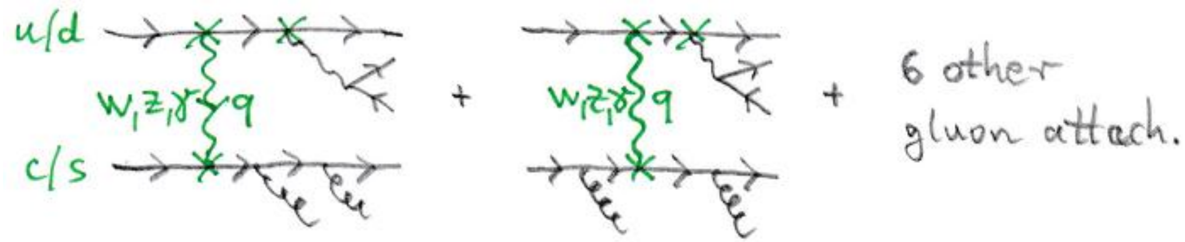


x4 for q→qbar
16 distinct flavor combinations

- Helas/MadGraph philosophy:
  generate separate amplitude programs for each distinct flavor structure;
  do crossing by sign factors in separate numerical evaluations
  ➔ no reuse of partial amplitudes
- VBFNLO philosophy: reuse partial amplitudes
  - leptonic tensors for VBF part: VV→leptons



  - do spinor/Lorentz structure common to various flavor combinations only once.
    e.g.

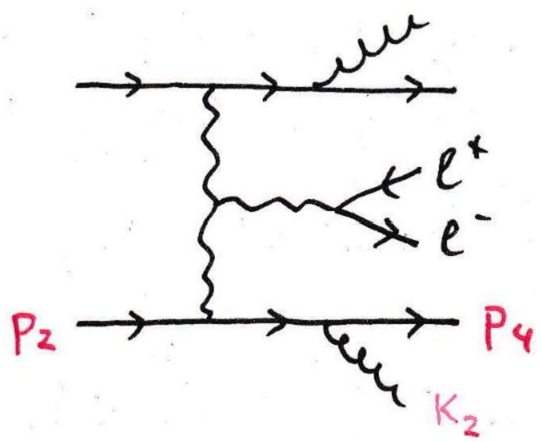


Multiply scalar factor containing flavor dependent couplings & boson propagators

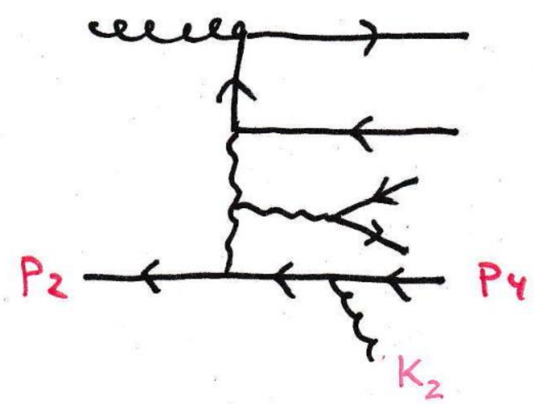
$$\mathcal{M} \sim g_Z \cdot g_{gg} * \text{couplings}(\text{hel.}, \text{flavor}) \frac{1}{q^2 - m^2}$$

- Result: VBFNLO code for tree level Z+4quark+2gluon amplitudes is 300 times faster than Helas routines generated with MadGraph-2
- Can we improve on this?
  - decay currents for Z→leptons and gamma→leptons are proportional to each other for given fermion helicities
  - Charge conjugation relates quark- and antiquark-lines of opposite chirality: same except for sign factor

- Result: VBFNLO code for tree level Z+4quark+2gluon amplitudes is 300 times faster than Helas routines generated with MadGraph-2
- Can we improve on this?
  - decay currents for Z→leptons and gamma→leptons are proportional to each other for given fermion helicities
  - Charge conjugation relates quark- and antiquark-lines of opposite chirality: same except for sign factor, for example



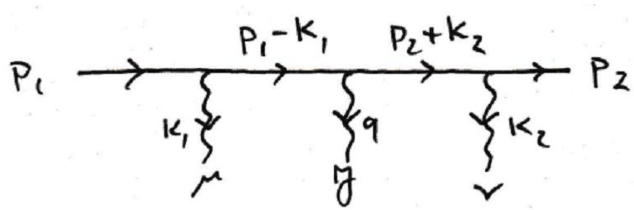
vs.



quark line vs. anti-quark line

Relating massless quark- to anti-quark-lines

Consider

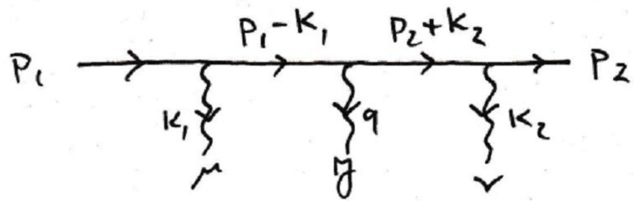


i.e. $\bar{u}(p_2)\,\gamma^\nu \frac{1}{\not p_2+\not k_2}\,\not q\, P_\sigma \frac{1}{\not p_1-\not k_1}\,\gamma^\mu\, u(p_1)$

of chirality σ: $P_\sigma = \frac{1}{2}(1+\sigma\gamma_5)$

Relating massless quark- to anti-quark-lines

Consider



i.e. $\underbrace{\bar{u}(p_2)}_{-v^T(p_2)C^{-1}}\gamma^\nu \frac{1}{\not{p}_2+\not{k}_2}\not{q}P_\sigma\frac{1}{\not{p}_1-\not{k}_1}\gamma^\mu \underbrace{u(p_1)}_{C\bar{v}^T(p_1)}$

of chirality σ: $P_\sigma = \frac{1}{2}(1+\sigma\gamma_5)$

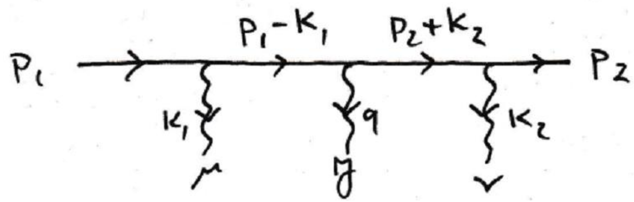
and use $C^{-1}\not{a}C = -\not{a}^T$

$$= -\bar{v}(p_1)(-\gamma^\mu)\frac{1}{-\not{p}_1+\not{k}_1}P_\sigma(-\not{q})\frac{1}{-\not{p}_2-\not{k}_2}(-\gamma^\nu)v(p_2)$$

$$= \bar{v}(p_1)\gamma^\mu\frac{1}{-\not{p}_1+\not{k}_1}\not{q}P_{-\sigma}\frac{1}{-\not{p}_2-\not{k}_2}\gamma^\nu v(p_2)$$

Relating massless quark- to anti-quark-lines

Consider



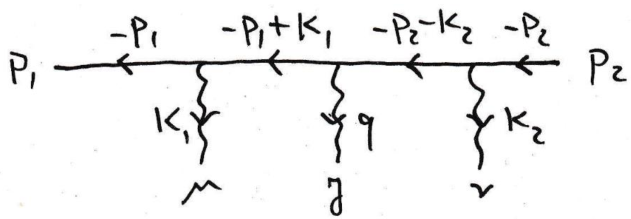
i.e. $\bar{u}(p_2)\,\gamma^\nu \frac{1}{\not p_2+\not k_2}\,\not J P_\sigma \frac{1}{\not p_1-\not k_1}\,\gamma^\mu u(p_1)$

with $\bar{u}(p_2) = -v^T(p_2)\,C^{-1}$ and $u(p_1) = C\,\bar{v}^T(p_1)$

of chirality σ: $P_\sigma = \frac{1}{2}(1+\sigma\gamma_5)$

$$= -\bar{v}(p_1)\,(-\gamma^\mu)\,\frac{1}{-\not p_1+\not k_1}\,P_\sigma(-\not J)\,\frac{1}{-\not p_2-\not k_2}\,(-\gamma^\nu)\,v(p_2)$$

and use $C^{-1}\not a\, C = -\not a^T$

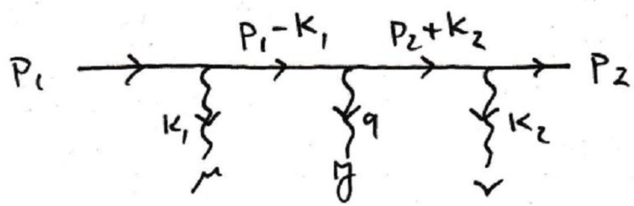


$$= \bar{v}(p_1)\,\gamma^\mu \frac{1}{-\not p_1+\not k_1}\,\not J P_{-\sigma}\,\frac{1}{-\not p_2-\not k_2}\,\gamma^\nu v(p_2)$$

fermion line (σ) = anti-fermion line(-σ) x $(-1)^{\#\text{ of propagators}}$

Relating massless quark- to anti-quark-lines

Consider



i.e. $\bar u(p_2)\,\gamma^\nu \frac{1}{\not p_2+\not k_2}\,\not q\, P_\sigma \frac{1}{\not p_1-\not k_1}\,\gamma^\mu\, u(p_1)$

with $\bar u(p_2) = -v^T(p_2)\,C^{-1}$ and $u(p_1) = C\,\bar v^T(p_1)$

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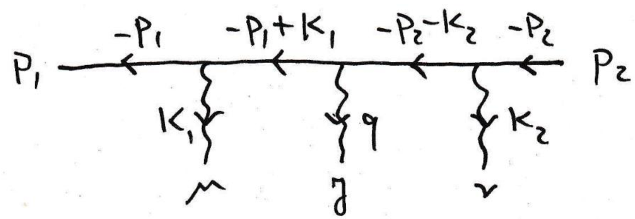

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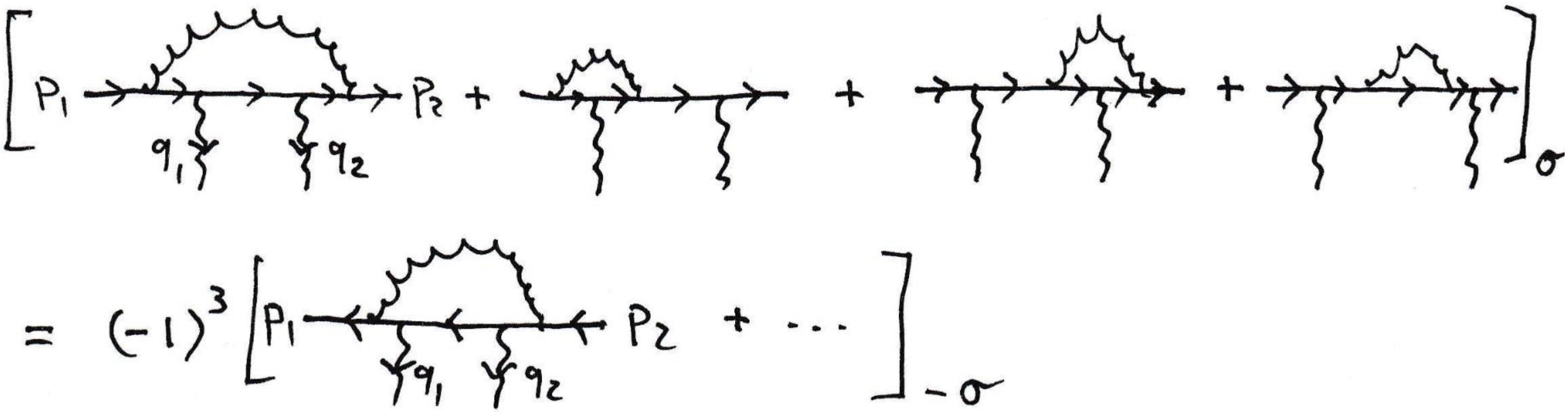
fermion line (σ) = anti-fermion line(-σ) x $(-1)^{\#\text{ of propagators}}$

Holds for loop diagrams as well

Example: boxline routine in VBFNLO

- VBFNLO has dedicated routines for the sum of loop graphs correcting individual fermion lines, e.g. qqVg, qqgV, qqVV lines



- Antiquark line with identical external momenta and gauge boson ordering does not need extra calculation
- Note sign difference of antiquark line with 3-gluon vertex (non-abelian box)
- Analogous results for quark lines with pentagons or hexagons
- Easy to implement when basic building blocks of amplitudes are currents or tensors representing entire quark lines

- Result: VBFNLO code for tree level Z+4quark+2gluon amplitudes is 300 times faster than Helas routines generated with MadGraph-2
- Can we improve on this?
  - decay currents for Z→leptons and gamma→leptons are proportional to each other for given fermion helicities
  - Charge conjugation relates quark- and antiquark-lines of opposite chirality: same except for sign factor
  - This charge conjugation relation also holds for loop amplitudes
  - Pauli interference for identical fermions enters at sub-percent level ➔ calculate interference contributions separately with reduced statistics and neglect fermion interchange in main Monte Carlo run
  - 1-loop corrections enter via interference with Born amplitude. After Catani-Seymour (CS) subtraction they are small compared to Born**2 and can be evaluated separately with substantially reduced statistics
  - Born amplitudes for a number of CS subtractions from real emission are identical (78 distinct subtraction configurations for Z+3jet VBF out of maximum total of 228): no need to recalculate the rest again

Combining quark and anti-quark scattering

- Do spinor calculation of amplitude
  - without coupling factors and 1-particle reducible gauge boson propagators
  - for one direction of fermion number flow only
- This yields stripped amplitudes. Obtain anti-quark from quark diagrams (of opposite chirality) by sign factors for groups of diagrams with same number of propagators on individual quark lines
- Coupling×propagator factors depend on external quark flavors, helicities and momenta
- Choose momentum assignments to maximize relationships between different subamplitudes/Feynman diagrams
- Don‘t calculate the same thing twice

Summary

Implementation in VBFNLO code for Z+3jet at NLO QCD resulted in

- Loop contributions take only ~5 times longer than Born for same statistical error
- Additional factor 5 speed increase in cross section calculation of sum of $qq \rightarrow Zqqgg$ processes
- >95% of CPU time is spent in (CS subtracted) real emission contributions => speedup of entire NLO code by factor 5

Summary

Implementation in VBFNLO code for Z+3jet at NLO QCD resulted in

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- >95% of CPU time is spent in (CS subtracted) real emission contributions => speedup of entire NLO code by factor 5

Could this be implemented in generators like MadGraph?

Message to Tao

I had a lot of fun working with you and discussing physics over the last 40 years

Messages to Tao

I had a lot of fun working with you and discussing physics over the last 40 years

Retirement is great:

No committees

No writing of grant proposals

No department meetings

But the fun with physics continues

Messages to Tao

I had a lot of fun working with you and discussing physics over the last 40 years

Thank you!!

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