Event simulation for colliders – A basic overview

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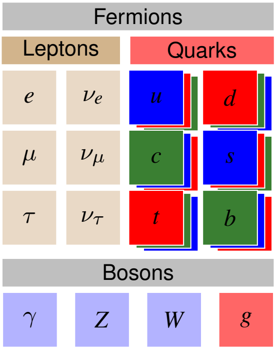
Contents

- Setting the stage: Event description at hadron colliders.
- Fixed order calculations.
- [Parton showers, just briefly]
- Interacing FO and PS.

Aim at a rather mixed audience: Overview on event simulation and basic calculational concepts.
Probably somewhat biased topic selection.
Will not quite agree with my promised abstract.
I appologize in advance if not all necessary contributions are properly cited.

Setting the stage ...

- Three of the four fundamental forces in nature are very well described by the Standard Model (SM) of particle physics.



The Standard Model

Unified theory of $\overbrace{\text{EM, weak}}^{\text{electroweak}}$ and strong interactions.

Matter sector (spin $\frac{1}{2}$ fermions):

- Leptons: Electroweakly interacting
- Quarks: Electroweakly and strongly interacting
  Each comes in three "colors", i.e.
  the charges of Quantum Chromo Dynamics (QCD)
- Particles and anti-particles

Gauge bosons (spin 1):

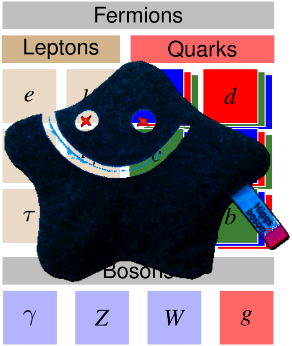
Electroweak mediators:

- Photon γ, Z^0-boson, W^+- and W^--boson

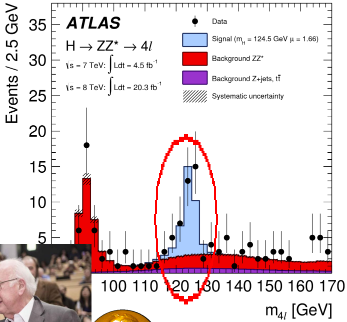
Mediators of "color":

- Gluons g (there are 8 types)

- Three of the four fundamental forces in nature are very well described by the Standard Model (SM) of particle physics.
- On July 4th 2012 the ATLAS and CMS experiments at the Large Hadron Collider (LHC), CERN, announced to have found the supposed Higgs particle.



The Higgs boson

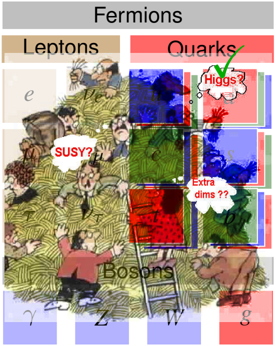


October 8th 2013:
Nobel prize to Englert and Higgs.

Image: http://www.particlezoo.net/

Image (Higgs announcement July 4th, 2012): M. Brice, CERN

- Three of the four fundamental forces in nature are very well described by the Standard Model (SM) of particle physics.
- On July 4th 2012 the ATLAS and CMS experiments at the Large Hadron Collider (LHC), CERN, announced to have found the supposed Higgs particle.
- Measurements of the Higgs properties and searches for physics beyond the Standard Model (BSM physics) continue.

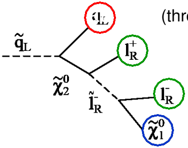


New physics beyond the SM

Supersymmetry (SUSY), extra dimensions, composite models, dark matter candidates, ...

If existing: Expected at high energies.

Signatures: Missing energy (if not interacting), leptons and QCD radiation (through rather long decay chains)



- Search new particles at high energies, with a lot of associated additional radiation.
- Measure the properties of newly discovered particles in this environment at high precision.

⇒ Need sophisticated computational techniques, theoretically and experimentally.

Setting the stage ...

As theorists, we are interested in describing events at colliders with as best as possible accuracy.

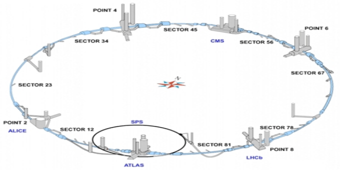


Image courtesy: CERN

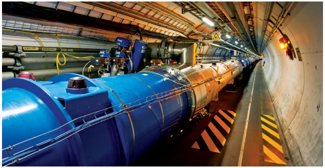


Image courtesy: CERN

Start with a simple recipe: Take two hadrons (say protons) and collide them at very high energies.

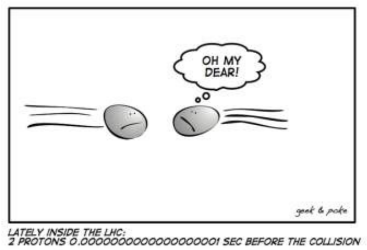


Image courtesy: Geek & Poke

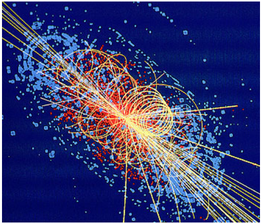


Image courtesy: CERN

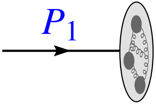
The rough picture of such an event simulation is as follows ...

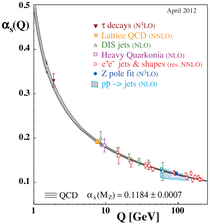
Factorization of hadronic cross sections:

$$\sum_{a,b} \int dx_1 dx_2 \quad f_a(x_1) f_b(x_2)$$

$$\alpha_s(Q) \propto 1/\log(\frac{Q^2}{\Lambda^2})$$

P_1





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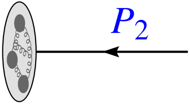
P_2



$f_a(x_1)$

pdf's cannot
be determined
from first principles

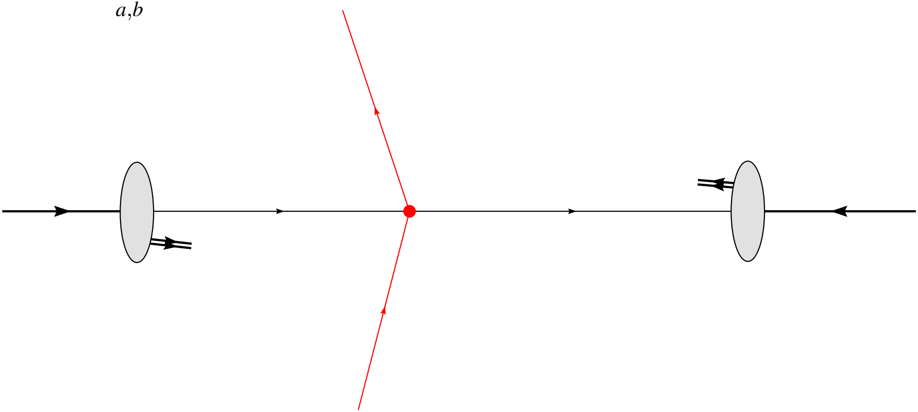
$f_b(x_2)$

Parton picture of the protons at high energies (QCD: Asymptotic freedom); resolve quarks and gluons.
E.g. parton a with momentum fraction x_1 of proton P_1 comes with probability density $f_a(x_1)$

Image courtesy: S. Gieseke, KIT

Factorization of hadronic cross sections:

$$\sigma = \sum_{a,b} \int dx_1 dx_2 \quad f_a(x_1) f_b(x_2) \quad \hat{\sigma}_{ab \to X}(\hat{s}; \{p_X\})$$

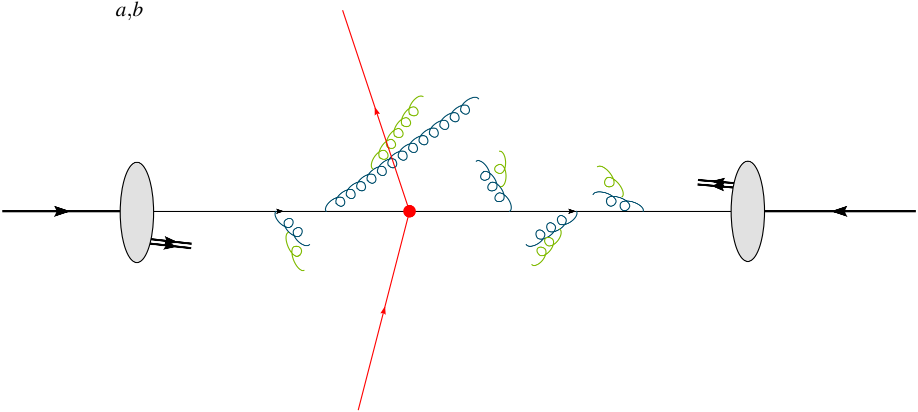


Parton picture of the protons at high energies (QCD: Asymptotic freedom); resolve quarks and gluons.
E.g. parton a with momentum fraction x_1 of proton P_1 comes with probability density $f_a(x_1)$
Single hard interaction between partons: Hard matrix elements; determine from fundamental principles.

Image courtesy: S. Gieseke, KIT

Turn inclusive cross sections into exclusive particle states.

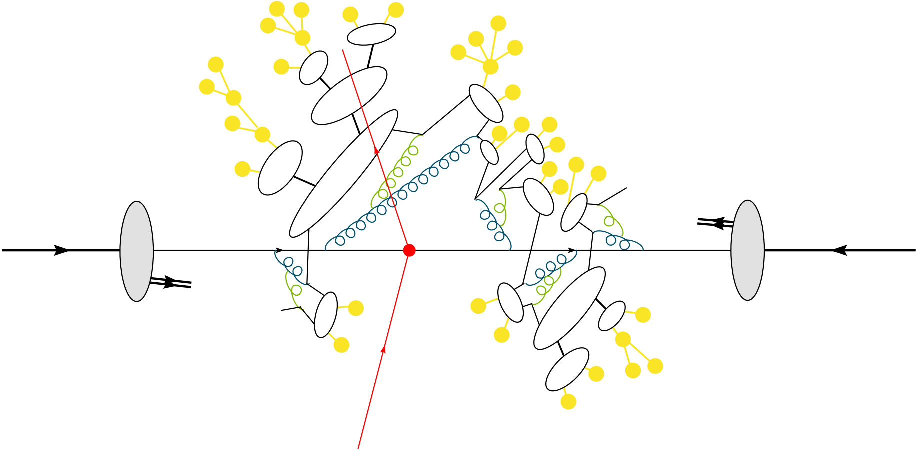
$$\sigma = \sum_{a,b} \int dx_1 dx_2 \quad f_a(x_1) f_b(x_2) \otimes \hat{\sigma}_{ab \to X}(\hat{s}; \{p_X\}) \otimes PS$$



Parton picture of the protons at high energies (QCD: Asymptotic freedom); resolve quarks and gluons.
Single hard interaction between partons: Hard matrix elements; determine from fundamental principles.
QCD radiation: Parton showers in initial and final state; evolution determined from first principles.

Image courtesy: S. Gieseke, KIT

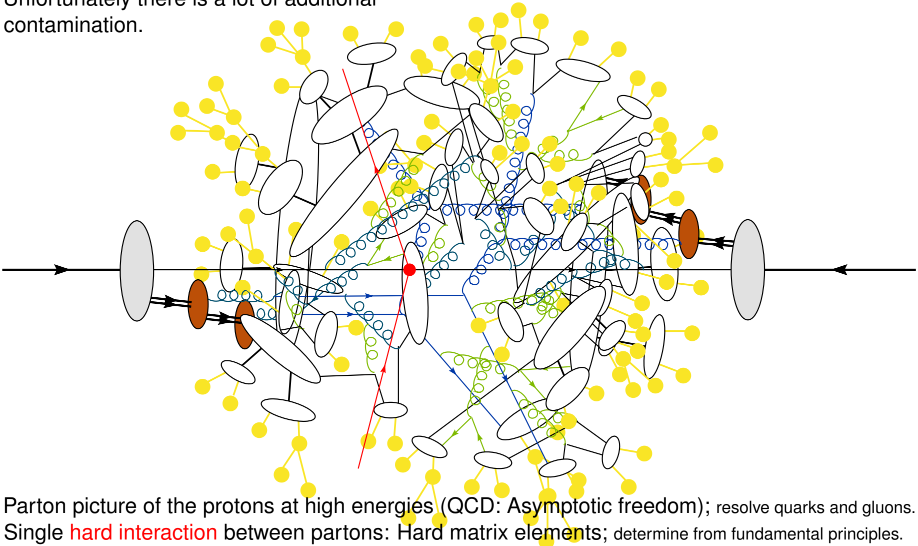
Form physical states in the end.



Parton picture of the protons at high energies (QCD: Asymptotic freedom); resolve quarks and gluons.
Single hard interaction between partons: Hard matrix elements; determine from fundamental principles.
QCD radiation: Parton showers in initial and final state; evolution determined from first principles.
Hadronization and hadron decays (QCD: Confinement); no first principles, needs modelling.

Image courtesy: S. Gieseke, KIT

Unfortunately there is a lot of additional contamination.

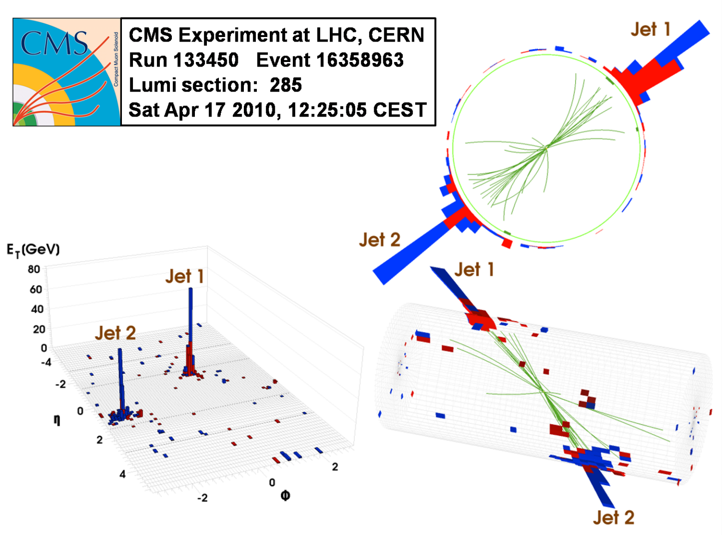


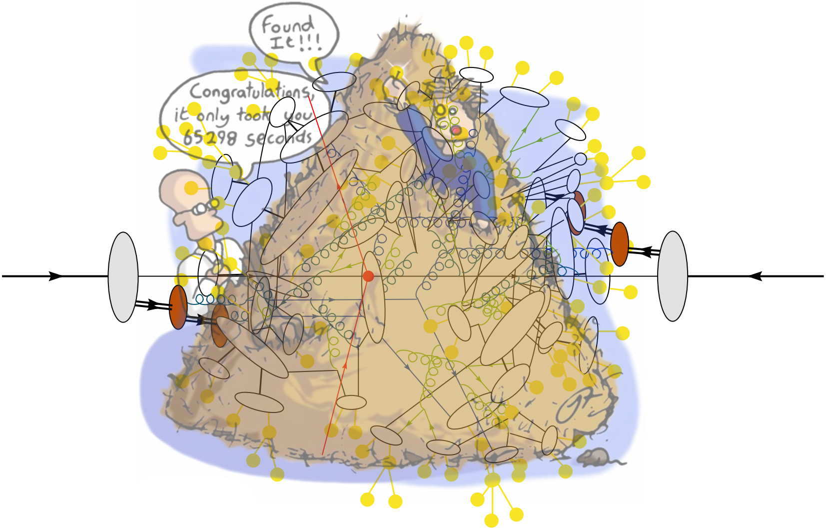
Parton picture of the protons at high energies (QCD: Asymptotic freedom); resolve quarks and gluons.
Single hard interaction between partons: Hard matrix elements; determine from fundamental principles.
QCD radiation: Parton showers in initial and final state; evolution determined from first principles.
Hadronization and hadron decays (QCD: Confinement); no first principles, needs modelling.
Multiple parton interactions (MPI) / Underlying events; modelling of soft QCD.

Image courtesy: S. Gieseke, KIT

Setting the stage ...

- QCD prefers events with collimated bunches of soft and collinear particles: Jets.
- Cone or cluster algorithms to determine, which partonic configurations end up in jets.
- Measurements of events with distinct particles in association with many jets.





Background	$pp \to VV + 2jets$	$V + 3jets$	$VVb\bar{b}$	$t\bar{t}b\bar{b}$	$t\bar{t} + 2jets$
Signal	$VBF \to H \to VV$	NP	$VBF \to H \to VV, t\bar{t}H$, NP	$t\bar{t}H$	$t\bar{t}H$

Aim at precision predictions for multi-jet events!

Image courtesy: S. Gieseke, KIT
www.jolyon.co.uk

$$\langle O\rangle \propto \sum_{a,b} \underbrace{\int dx_1 f_a(x_1) \int dx_2 f_b(x_2)}_{\text{pdf's}} \sum_n \underbrace{\int d\phi_n}_{\substack{\text{final state}\\ \text{phase space integral}\\ \text{(numerically)}}} \underbrace{O(p_1,\dots,p_n)}_{\substack{\text{observable}\\ \text{(infrared safe)}}} \underbrace{|\mathcal{A}_{n+2}|^2}_{\substack{\text{amplitude squared}\\ \text{(perturbatively)}}}$$

Phase space integration numerically through Monte Carlo methods.

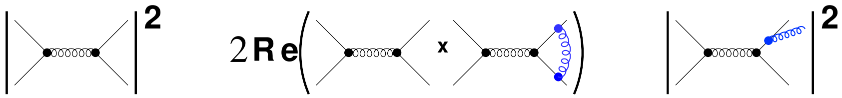
$O(\dots)$ IR safe:

$$O_{n+1}(p_1,\dots,p_i,\dots,p_j,\dots,p_{n+1}) \xrightarrow{p_i||p_j} O_n(p_1,\dots,p_i+p_j,\dots,p_{n+1}) \quad \text{collinear safety}$$

$$O_{n+1}(p_1,\dots,p_i,\dots,p_{n+1}) \xrightarrow{|p_i|\to 0} O_n(p_1,\dots,\not{p}_i,\dots,p_{n+1}) \quad \text{soft safety}$$

$$O_n(p_1,\dots,p_i,\dots,p_j,\dots,p_n) \xrightarrow{p_i \cdot p_j \to 0} 0 \quad \text{regulating Born}$$

Amplitudes $\mathcal{A}$ calculated in perturbation theory. We need $|\mathcal{A}|^2$:



At leading order (LO):

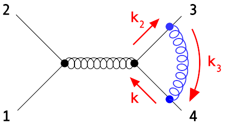
Only **B**orn amplitudes (here α_s^2)

At next-to-leading order (NLO):

One-loop amplitudes (**V**irtual) and Born-like amplitudes with additional parton (**R**eal) (here $\alpha_s^2 \alpha_s$)

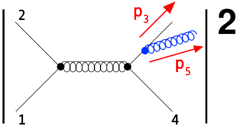
$$\langle O \rangle^{LO} + \langle O \rangle^{NLO} = \int_n O_n B + \int_n O_n V + \int_{n+1} O_{n+1} R$$

V Contains the loop integral $V \propto \int_{loop} dV$.



- Loop integration over d^4k leads to divergences:
  - Collinear ($k_i || k_j$),
  - soft ($|k_i| \to 0$),
  - ultraviolet ($|k| \to \infty$).

R Additional real emission.



- Integration over real emission phase space leads to divergences:
  - Collinear ($p_3 || p_5$),
  - soft ($|p_5| \to 0$).

- Ultraviolet singularities are removed by renormalization.
- The same regularization (e.g. dimensional regularization, $4 \to D = 4 - 2\varepsilon$) is required for the divergences.

$$\frac{-A_V}{\varepsilon} + \frac{-B_V}{\varepsilon^2} + F_V \qquad \text{vs.} \qquad \frac{A_R}{\varepsilon} + \frac{B_R}{\varepsilon^2} + F_R$$

- For IR safe observables, $V + R$ is finite, i.e. the IR poles cancel; only finite terms remain.

$$\frac{-A}{\varepsilon} + \frac{-B}{\varepsilon^2} + F_V \qquad \text{vs.} \qquad \frac{A}{\varepsilon} + \frac{B}{\varepsilon^2} + F_R$$

A combined Monte Carlo integration of both NLO terms in four dimensions is impossible, due to different phase space dimensions.

In the subtraction method, we rewrite the NLO observable:

$$\langle O\rangle^{NLO} = \int_{n+1} \left(O_{n+1}R - O_n A\right) + \int_{n} \left(O_n V + O_n \int_{+1} A\right)$$

- A has the same pointwise singular behaviour as R. Remember that $O_{n+1} \to O_n$ in the soft/collinear limit: $O_n A$ acts as local counterterm to $O_{n+1}R$.
- Analytical integrability over the one-parton sub-space in D dimensions. Leading to collinear and soft divergences (poles in ε).
- Separate numerical Monte Carlo integration of both brackets possible.

The singular part of the subtraction term is fixed. The finite part can be chosen. Various variants:

- Residue subtraction: [Frixion, Kunszt, Signer '95; Del Duca, Somogyi Trocsanyi '05; Frixione '11]
- Dipole subtraction: [Catani, Seymour '96; Phaf, Weinzierl '01; Catani, Dittmaier, Seymour, Trocsanyi '02; Dittmaier, Kasprzik '08; Papadopoulos, Worek '09; Goetz, Schwan, Weinzierl '12]
- Antenna subtraction: [Kosower '97; Gehrmann-de Ridder, Gehrmann, Glover '05; Daleo, Gehrmann, Maitre '06; Gehrmann-de Ridder, Ritzmann '09]
- Nagy-Soper subtraction: [Nagy, SOper '07; Chung, Kramer, Robens '10; Bevilacqua, Czakon, Kubocz, Worek '13]

Automated implementations: [Weinzierl '05; Gleisberg, Krauss '07; Seymour, Tevlin '08; Hasegawa, Moch, Uwer '08; Frederix, Gehrmann, Greiner '08; Czakon, Papadopoulos, Worek '09; Gieseke, Plaetzer '12]

The subtraction method lets us integrate the two NLO pieces separately, in a generic way.

Constructing and calculating each of the two pieces is still quite complicated.

The virtual correction:

- Traditional one-loop tensor reduction:
  - Can always reduce tensor integrals to scalar integrals.
  - Need to avoid Gram determinants.
- Cut-based methods:
  - Basis of scalar integrals known.
  - Coefficients obtained from tree-like objects.
  - Solve linear system of equations numerically.
- Numerical method with subtraction and contour deformation:
  - Introduces local one-loop subtraction terms.
  - Scales like Born computation.
  - Numerical implementation of contour deformation into complex plane.

Tensor reduction:

- In general we have tensor integrals of the form

$$I_{n,a}(\{p_i\},\{m_i\})^{\alpha_1\dots\alpha_{2a}} = \int d^D k \frac{k^{\alpha_1}\dots k^{\alpha_{2a}}}{\prod_{i=1}^{n}\left(k_i^2 - m_i^2 + i\delta\right)^n}$$

  Always reducable to linear combinations of scalar integrals.

  Price to pay: Introduction of inverse Gram determinants.

  Reducing triangle tensor rank 2 integral:

  $|G|^{-1} \propto (p_1^2 p_2^2 - (p1.p2)^2)^{-1}$, which tends to large values whenever $p_1||p_2$.

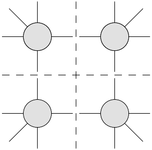
- Several solutions, based on different reduction schemes or expansion around small Gram determinants in critical regions have been proposed:

  [Denner, Dittmaier; Binoth, Guillet, Heinrich, Pilon, Schubert; del Aguila, R. Pittau; van Hameren, Vollinga, Weinzierl; Cascioli, Maierhoefer, Pozzorini; Fleischer, Riemann, Yundin]

Cut techniques:

- Basis of scalar integrals to decompose one-loop amplitude known.
- For massless amplitude need only coefficients in front of bubble, triangle and box:

$$A_n^{(1)} = \sum_{i,j} c_{i,j} I_2^{(ij)} + \sum_{i,j,k} c_{ijk} I_3^{(ijk)} + \sum_{i,j,k,l} c_{ijkl} I_4^{(ijkl)} + R_n$$



Box coefficients from quadruple cut.

After box contributions has been subtracted: Triangle coefficients from triple cuts.

After also triangle contributions subtracted: Bubble coefficients from double cuts.

Rational part R from D dimensional cuts.

[Britto, Cachazo, Feng; Forde, Ossola, Papadopoulos, Pittau; Anastasiou, Britto, Feng, Kunszt, Mastrolia; Ellis, Giele, Kunszt, Melnikov; Badger, Sattler, Yundin; ...]

- Predecessor versions:

[Cutkosky '60 (Cutkosky rule); Bern, Dixon, Dunbar, Kosower '94; Bern, Morgan '95; Bern, Dixon, Kosower, Weinzierl '96 ($e^+e^- \to 4\,\text{partons}$)]

The numerical approach by virtual subtraction: $V \equiv \int_{loop} dV_{bare} + V_{CT}$ (undo renormalization)

$$\sigma^{NLO} = \underbrace{\int_{n+1} \left(R - A\right)}_{\sigma^{NLO}_{real}} + \underbrace{\int_{n,loop} \left(dV_{bare} - L\right)}_{\sigma^{NLO}_{virtual}} + \underbrace{\int_{n} \left(V_{CT} + \int_{loop} L + \int_{+1} A\right)}_{\sigma^{NLO}_{insertion}}$$

- L matches dV_{bare} locally in the ultraviolet (UV), soft und collinear regions.
- Explicit poles from $\int_{loop} L$ cancel against IR–poles from $\int_{+1} A$ and UV–poles from V_{CT}.
- σ^{NLO}_{real}, $\sigma^{NLO}_{virtual}$ and $\sigma^{NLO}_{insertion}$ separately MC integrable. Well suited for automatization.
- Combined numerical integration in $\sigma^{NLO}_{virtual}$ over phase space of n final state particles plus 4-dimensional loop integral.

Course of action:

- Efficient construction of the one-loop integrand.
- Subtraction terms for collinear, soft and UV singular parts of integrand of one-loop amplitude.
- Idea not quite new [Nagy, Soper '03], but only on graph-by-graph basis.
- Contour deformation for the 4-dim. one-loop integral, to escape into complex plane.
- Generalization and application to $e^+e^- \to 7\,\mathrm{jets}$ in leading color approximation [arXiv:1111.1733]. See also [Assadsolimani, Becker, Goetz, CR, Schwan, Weinzierl '10 - '14]

QCD Feynman rules consist of two algebraic parts: A color part and a kinematical part.

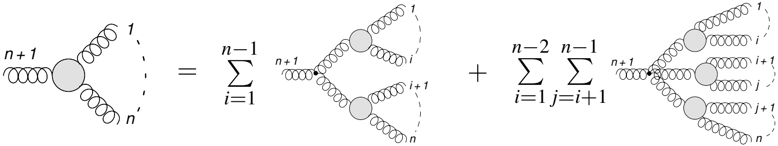
In an amplitude we may collect all terms with the same color.
E.g. tree–level n–gluon amplitude:
[Berends, Giele; Mangano, Parke; Bern, Kosower; ...]

$$\Big[f^{abe} f^{ecd} (g^{\mu\lambda} g^{\nu\rho} - g^{\mu\rho} g^{\nu\lambda}) + f^{ace} f^{ebd} (g^{\mu\nu} g^{\lambda\rho} - g^{\mu\rho} g^{\nu\lambda}) + f^{ade} f^{ebd} (g^{\mu\nu} g^{\lambda\rho} - g^{\mu\lambda} g^{\nu\rho}) \Big]$$

$$\mathcal{A}_n^{(0)}(g_1, \ldots, g_n) = g^{n-2} \sum_{\sigma \in S_n / Z_n} 2Tr[T^{\sigma_1} \ldots T^{\sigma_n}] A_n^{(0)}(g_{\sigma_1}, \ldots, g_{\sigma_n})$$

Partial amplitude $A_n^{(0)}(g_{\sigma_1}, \ldots, g_{\sigma_n})$:

- Sub–set of color–stripped diagrams, all with the
- same cyclic ordering $(g_{\sigma_1}, \ldots, g_{\sigma_n})$ of the external legs.
- Can be computed efficiently with the help of recursions:



gg → $(n-2)$g	$(n-2)$	2	3	4	5	...	8
# Unordered Feynman diagrams		4	25	220	2485	...	10525900
# Ordered diagrams (partial amplitude)		3	10	36	133	...	7335

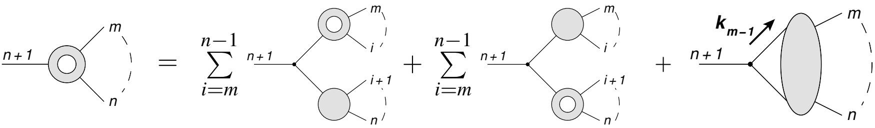
Important: caching of identical sub–currents!

Color–ordered one–loop partial amplitudes $A_i^{(1)}$.
Further decompose partial amplitudes into cyclic ordered primitive amplitudes P_j:
[Bern, Dixon, Kosower '95]

$$\mathcal{A}_n^{(1)} = \sum_i C_i^{(1)} A_i^{(1)} = \sum_i C_i^{(1)} \sum_j F_{ij} P_j$$

For arbitary numbers of quark-pairs: [CR, Weinzierl, arXiv:1310.0413].

Primitive one–loop amplitudes can also be constructed by recursive methods:



- The explicit one–loop term can be constructed from cutting open the loop.
- This reduces the computational complexity of the problem to tree–level complexity, i.e. scaling with the number n of legs behaves as $\sim n^4$.

For more details see [Becker, CR, Weinzierl, arXiv:1205.2096].

Originaly introduced through recursive Dyson–Schwinger equations [van Hameren et al. '09].

Also other groups use such an approach to construct their integrands [Pozzorini et al. '12].

FO (NLO) automatization

- The last years have witnessed tremendous progress in one-loop calculations (“NLO revolution”).
- NLO multi-leg automation basically solved. Many approaches are available.
- The so-called experimenter’s wishlist (stated in 2005) retired about 2 years ago.
- Tensor reduction programs:

  Golem95 [Binoth, Cullen, Greiner, Guffanti, Guillet, Heinrich, Karg, Kauer, Reiter, Reuter]

  MadGolem [Binoth, Goncalves Netto, Lopez-Val, Mawatari, Plehn, Wigmore]

  NLOX [Reina, Schutzmeier]

  OpenLoops [Cascioli, Maierhoefer, Pozzorini]

  PJFry [Fleischer, Riemann, Yundin]
- Programs based on cut techniques:

  BlackHat [Bern, Dixon, Febres-Cordero, Ita, Kosower, LoPresti, Maitre, Ozeren, Hoeche]

  GoSam [Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano]

  HelacNLO [Bevilacqua, Czakon, Garzelli, van-Hameren, Kardos, Papadopoulos, Pittau, Worek]

  MadLoop [Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau]

  NJet [Badger, Biedermann, Uwer, Yundin]

  OpenLoops [Cascioli, Maierhoefer, Pozzorini]

  Rocket [Ellis, Giele, Kunszt, Melnikov, Zanderighi]

Process ($V \in \{Z, W, \gamma\}$)	Status
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti WZ jet, $W\gamma$ jet completed by Campanario et al.
2. $pp \to$ Higgs+2 jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier Interference QCD-EW in VBF channel
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello and WWZ by Hankele/Zeppenfeld see also Binoth/Ossola/Papadopoulos/Pittau VBFNLOmeanwhile also contains WWW, ZZW, ZZZ, $WW\gamma$, $ZZ\gamma$, $WZ\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$, $\gamma\gamma\gamma$, $W\gamma\gamma j$
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek
5. $pp \to V$+3 jets	W+3 jets calculated by the Blackhat/Sherpa and Rocket collaborations Z+3jets by Blackhat/Sherpa
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek
7. $pp \to VV\,b\bar{b}$,	Pozzorini et al. Bevilacqua et al.
8. $pp \to VV$+2jets	W^+W^++2jets, W^+W^-+2jets, relevant for VBF $H \to VV$ VBF contributions by (Bozzi/)Jäger/Oleari/Zeppenfeld
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al.
10. $pp \to V+4$ jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets, Z+4jets see also HEJfor W + $n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures, Bevilacqua/Worek
$pp \to W\gamma\gamma$ jet	Campanario/Englert/Rauch/Zeppenfeld
$pp \to$ 4/5 jets	Blackhat+Sherpa/NJets

Closed

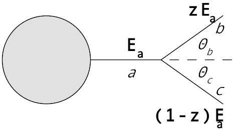
Parton showers

Fixed order calculations not enough for event prediction in colliders:

- Want exclusive final state with many particles: FO matrix elements can only do a limited number of legs.
- Logarithmic enhancements in regions of low momenta, which need to be resummed to all orders in α_s. Parton showers can do this approximately, due to multiple emissions in the soft/collinear approximation.

Parton showers approximate the matrix element in the soft and collinear regions, where contributions are dominant:

$$|A_{n+1}|^2 \sim P(z)|A_n|^2$$



Rely thereby on the factorization of the $n+1$ particle state into n particles state times a splitting:

$$d\sigma_{n+1} = d\sigma_n \frac{dt}{t} dz P(z)$$

For small angles:
$p_a^2 = t = (p_b + p_c)^2 = z(1-z)E_a^2(\Theta_b + \Theta_c)^2$

Splitting function $P(z)$ enhanced for $z = 0, 1$.

Fast production of many-particle final states possible in enhanced regions.

Shower action on events, distributed according to a cross section $d\sigma(\phi_n, Q)$:

$$PS\Big[d\sigma(\phi_n, Q)\Big] = \Delta[\mu|Q] d\sigma(\phi_n, Q) + PS\Big[d\sigma(\phi_n, Q) P(\phi_n, Q) \frac{d\phi_{n+1}}{d\phi_n} \Delta[q|Q]\Big]$$

- Sudakov form factor $\Delta[\mu|Q]$: Probability for no emission between the scales Q and μ.
- Recursive algorithm: Generate next emission off the $n+1$ particle state.
- Shower cut-off at scale μ: Shower evolution from Q down to μ ($Q > q > \mu$).

Parton showers

Parton showers (PS)

- Good and necessary approximation in the soft/collinear regions. ✓
- Describe the hard regions badly. ✗

Matrix elements (ME)

- Do not work well in the soft regions, due to logarithmic enhancements, which can only be described properly through some sort of resummation. ✗
- Nice behaviour for large angle / hard radiation. ✓

Idea

- Combine PS and ME by correcting (or replacing) the "first few" emissions of the PS.
- What exactly is meant by "first few" depends on the ordering variable of the shower as it proceeds down the shower evolution.
- The more ME's get involved, the better. Hard regions by the ME's, soft regions by the PS.
- But: PS and ME's combined show overlapping contributions $\rightarrow$ double counting! ✗

LO merging

- ME's for hadron colliders describe in general inclusive cross sections.
- For example the inclusive 2 jet cross section in pp collision contains contributions from 2, 3, 4, ... jet events.
- Adding multiple ME's together cleary leads to double counting.
- This issue is addressed by merging: General prescription on how to make inclusive cross sections exclusive, before combining them.

  [CKKW, CKKW-L, MLM, ...]

  [Catani, Krauss, Kuhn, Webber; Loennblad; Loennblad, Prestel, Hamilton, Richardson, Tully; Hoeche, Krauss, Schumann, Siegert; ...]

NLO matching

- Goal of combining NLO ME's and PS.
- However, both ME's and PS contain NLO contributions.
- For example, looking at the first emission of a PS attached to some Born ME, and at the real emission correction to this ME $\rightarrow$ double counting.
- This issue is addressed by NLO matching: General prescription on how to construct an auxiliary NLO cross section, which returns the results without double counting when the PS is applied.

  [Powheg, MC@NLO, ...]

NLO merging

- Merges multiple NLO ME's + multiple LO ME's to the PS.

  [UNLOPS, MEPS@NLO, ...]

  [Lavesson, Loennblad; Prestel, Loennblad; Plaetzer; Hoeche, Krauss, Schoenherr, Siegert; ...]

Matrix element generators and General purpose event generators

Tree-level tools, Feynman diagrams

- [AMEGIC++, CompHEP, MADGRAPH, ...]

Tree-level tools, Recursions

- [ALPGEN, Comix, HELAC, O'Mega, ...]

ME Generators

- [VBFNLO, GoSam, NJet, OpenLoops, HEJ, Rocket, BlackHat, ...]

ME Generators + PS

- [Whizard, MadGraph_aMCNLO, ...]

IR subtraction tools

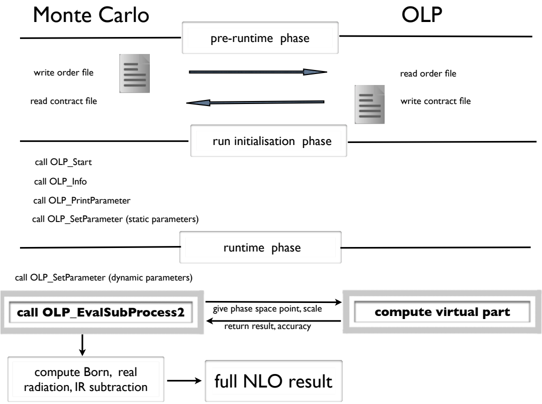
- [AMEGIC++, HELAC/PHEGAS, MadDipole, AutoDipole, MadFKS, Matchbox@Herwig++, ...]

General purpose events Generators

- Combine ME's, PS, hadronization and soft underlying physics in one simulation.
- All use different types of showers, different matching/merging prescriptions, different hadronization models, etc.
- [Pythia, Herwig++, Sherpa, ...]

Interfaces between event generators & matrix element generators

- Recent developments in (NLO) multi-leg automation make NLO multi-jet merging feasible.
- Combination of features of event generators and matrix element generators: Event generators need a way to access the matrix elements flexibly.
- An interface standard has been created, such that matrix elements can be accessed on a run-time basis (BLHA and BLHA2 [Binoth et al., arXiv:1001.1307; Alioli et al., arXiv:1308.3462]).
- Less error prone. The event generator steers the setup and provides for the phase space integration. The one-loop provider (OLP) provides the hard matrix elements. Simple communication through order/contract files and external function calls.



Some recent calculations

- Feasability study: NJet+Herwig++/Matchbox [arXiv:1405.1067]
- GoSam+Herwig++/Matchbox: $pp \rightarrow$Z+jet, NLO matched [arXiv:1405.1067]
- BlackHat+Sherpa: $pp \rightarrow$W+5jets @ NLO [arXiv:1304.1253]
- NJet+Sherpa: $pp \rightarrow$ 5jets @ NLO [arXiv:1309.6585]
- BlackHat+Sherpa: $pp \rightarrow$ 5jets @ NLO [arXiv:1112.3940]
- OpenLoops+Sherpa: $pp \rightarrow t\bar{t}$+2jets, NLO merged [arXiv:1402.6293]
- GoSam+Sherpa+MadEvent: H+3jets production in gluon fusion (NLO QCD) [arXiv:1307.4737]
- Herwig++/Matchbox: Electroweak H+3jets production (NLO QCD) [arXiv:1308.2932]

and many more ...

Summary

NLO calculations now in a state where tree-level was about 10 years ago.

- Many OLP projects, which wait to be applied to physics problems.
- Several MC generators to provide tree-level parts & integration.
- For those that don't, tree-level parts can also be provided by the OLPs.

Goals for OLPs

- Even more flexibility. E.g. in recovering exceptional phase space points for non-trivial processes.
- Keep up the high standards.
- ...

Goals for MCs

- Speed and efficiency in phase space integration and setup of the calculations.
- ...

Many thanks!

My apologies for not being able to cover everthing in more detail in this talk!