Monte Carlo challenges for the multi-TeV muon collider

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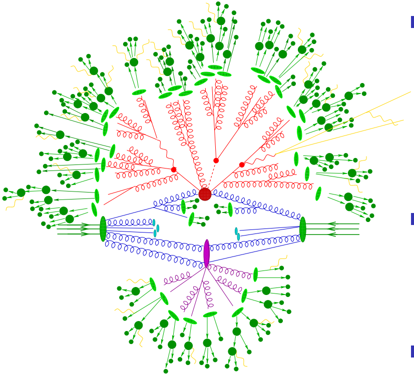
MC event generators for hadron colliders

Huge progress in MC development for hadron colliders



$gg \to t\bar{t}H$ from 0811.4622

- Hard process

  MC event generators with given perturbative accuracy: LO, NLO-QCD, NLO-QCD+NLO-EW, NNLO QCD

- Multiple $g/q/\gamma$ radiation

  Shower MC programs

- Non perturbative effects

  IS PDFs, hadronization, ...

three elements combined consistently to have sound predictions

MC event generators for hadron colliders: showers

Most used shower MC programs

- HERWIG: QCD and QED shower
- PYTHIA: QCD and QED shower
- PHOTOS: QED shower off resonances

can be run on LHE files for the hard scattering generated by other MC generators

- Built-in QCD and QED shower in SHERPA

MC event generators for hadron colliders: hard scattering

- @LO: ALPGEN, MADGRAPH, SHERPA, ...
  multi-purpose, multi-leg ($\sim$ up to 7-8 legs), typically supplemented with multi-jet merging strategies (CKKW, MLM,...)

- @NLO QCD with QCD PS matching according to the MC@NLO or POWHEG algorithms: MG5_aMC@NLO, POWHEG, SHERPA, H7 matchbox, ...

- @NLO QCD with multi-jet merging at NLO QCD (FxFx, MEPS@NLO, MiNLO, etc. strategies) for instance in MG5_aMC@NLO, POWHEG+MiNLO, H7, SHERPA, ...

- @NLO QCD+EW with QCD and QED PS matching only for very few processes in POWHEG

- @NNLO QCD with QCD PS matching (GENEVA, $\mathrm{NNLO_{PS}}$, MINNLO, UNNLOPS): available for a limited number of processes in GENEVA, POWHEG+MiNNLO, SHERPA, ...

Extremely short and incomplete overview!

MC event generators for high-energy μ colliders

In Principle

NO actual reason against having the same kind of development for MC for μ colliders

- people focused on hadronic environment because of LHC
- calculation of higher-order effects (main EW) more complicated/time-consuming, handling of large Sudakov corrections...

In Practice

only limited number of options with limited accuracy available

- LO multi-purpose event generators: MADGRAPH, SHERPA, WHIZARD
- shower MCs: HERWIG$^{(*)}$, PHOTOS, PYTHIA$^{(*)}$, SHERPA
- work in progress towards NLO EW+QED PS matching mainly in MG5_aMC@NLO, SHERPA
- precision tools from LEP era (only for $l^+l^- \to f\overline{f}$ or WW production)
- precision tools like BABAYAGA@NLO, MCMULE focus on low-energy collisions (QED corrections only)

$^{(*)}$ also implement $2 \to 2$ processes in lepton collider environment

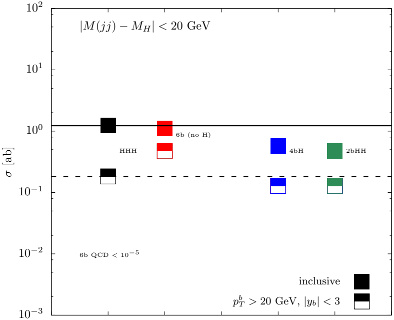
μ coll: main differences wrt hadr. coll.

initial states are muons!

- most relevant processes are EW ones (most relevant H.O. are EW)
- muons are elementary: in first approx no such things as PDFs. However, beyond LO, ISR photon radiation give rise to large collinear logs $\sim \frac{\alpha}{\pi} \log Q^2/m_\mu^2$ (5% for $Q \sim 10$ TeV):
  - in the context of precision physics should be resummed $\rightarrow$ structure functions/e-PDFs
  - Structure functions/e-PDFs are perturbative, computable (and computed). They are implemented in the MC generators available for the μ coll.
- potential beamstrahlung effects (from EM interaction among particle bounces, machine dependent). From first exploration negligible$^{(*)}$

$^{(*)}$ T. Ohl, talk at 1^{st} ECFA Workshop on e^+e^- Higgs/Electroweak/Top Factories

MC tools for HIGH-ENERGY μ-colls: challenges



- it is likely to have hard reactions with large multiplicities
- need efficient multileg event generators

$6b$ means $\mu^+\mu^- \to 3(b\bar{b})\nu\bar{\nu}$ not H-mediated, basically out of reach with available MC

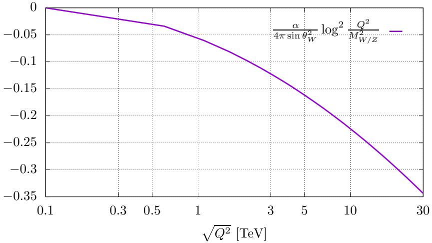
(in-house modified version of ALPGEN used for the simulation)

MC tools for HIGH-ENERGY μ-colls: challenges

- at high-energy gauge cancellations are crucial:
  - small violations could leas to huge numerical effects
  - consistent gauge-invariant algorithms for unstable $W/Z/H/t$, like the complex-mass scheme, should be used
- we might enter the Sudakov regime where virtual weak corrections might be $\sim$ several tens of percent (depending on process/observable/corner of phase space)
  - NLO EW corrections might be required for a large class of processes with many final state legs
  - automation unavoidable
  - available automated matrix-element calculators might require improvements$^{(*)}$

$^{(*)}$ currently $pp \to 4ljj$ at NLO including EW is probably the most complicated process computed with a not-too-unreasonable runtime

Again on Sudakov corrections



NLO EW corrections in the Sudakov limit dominated by $\log^2 \frac{Q^2}{M_V^2}$

Sudakov logs are the IR limit of virtual weak corrections (M_V being the *physical* cutoff)

If NLO EW corrections are huge, one should study the compensation from real W/Z radiation (should develop similar logs with opposite sign)

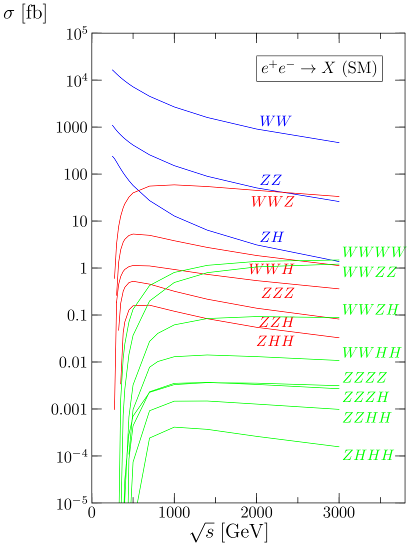
- always incomplete: Bloch Nordsieck violation effects hep-ph/0001142
- degree of cancellation strongly depend on the experimental setup (additional W/Z only included if the decay products are degenerate with the signature under consideration)

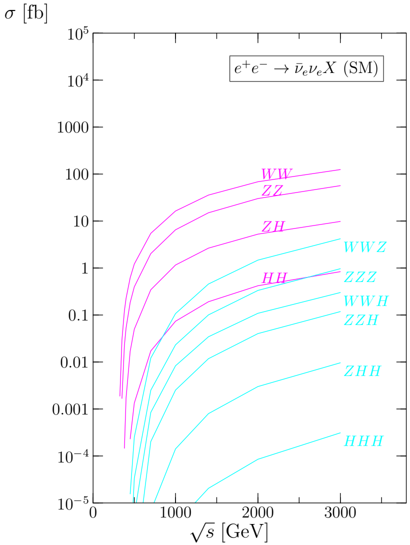
If NLO EW+real weak radiation still large, one could$^{(*)}$

- resum virtual weak logs hep-ph/0104232,hep-ph/0108221
- consider multiple real W/Z radiation (degenerate with the signal) $\sim$ weak showers 1401.5238

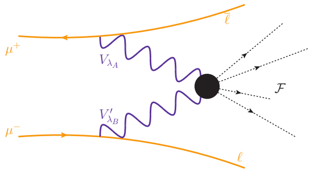
$^{(*)}$ there are explorations in the literature, but algorithms and technology not really ready for actual implementation in MC generators

effectively *high-luminosity weak boson colliders*





effectively *high-luminosity weak boson colliders*



$$\sigma(\mu^+\mu^- \to Fl\bar{l}) \sim f_{\text{coll}}\sigma(VV' \to F)$$

- f_{coll} is a *generalized* Weizsacker-Williams approx.
- can speed-up/simplify calculations
- implemented for in stance in MADGRAPH, WHIZARD
- validity limits at μ coll in 2111.02442

EW-PDF approach 2007.14300,2103.09844

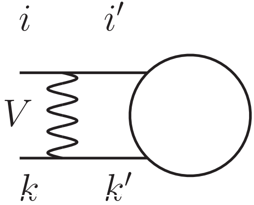
- resum collinear logs through DGLAP evolution
- represent the probability that μ emits a particle p through collinear splitting
- no public code available, not present in MC generators
- how to use them beyond LO?

Conclusions

- only few MC event generators for high-energy μ-colls available, generally only at LO accuracy
- in principle it is possible to transpose all the technology developed for high-precision generators for hadron colliders to the leptonic environment
- in practice, some new challenges arise, mainly connected to the large $\sqrt{s}$ and the large final-state multiplicities, Sudakov corrections

Backup Slides

$$\sum_{i,k}\sum_{i',k'}\sum_{V}$$



$$= \sum_{i,k}\sum_{i',k'}\sum_{V}\delta^{DL}\left(V; i, i'; k, k'\right) M_{\mathrm{Born}}\left(i', k'\right)$$

- $\delta^{DL} \propto \log^2 \frac{2p_i p_k}{M_V^2}$
- i' and k' may be $SU2$ transformed of i and k