A New Generator For Drell-Yan Process

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Monte-Carlo Generator

- is a **stochastic** simulation tool.
- is not an **Integrator** *(value of integral is a byproduct, main product – events)*
- any observable can be investigated *(filling histograms, density-plots etc.)*
- any cuts can be applied
- error estimate is reliable and stable
- easy for parallelization

LePaProGen

- is generator for Drell-Yan process:

$$p^+p^- \longrightarrow \gamma, Z \longrightarrow \mu^+\mu^-$$

- for “charged-current” Drell-Yan:

$$p^+p^- \longrightarrow W^+ \longrightarrow \mu^+\nu$$

- with one-loop **electroweak** corrections
- with exact hard QED Bremsstrahlung contribution:

$$p^+p^- \longrightarrow l^+l^- + \gamma$$

- QCD and double-Bremsstrahlung are in development: $p^+p^- \longrightarrow l^+l^- + \gamma/g + \gamma/g$

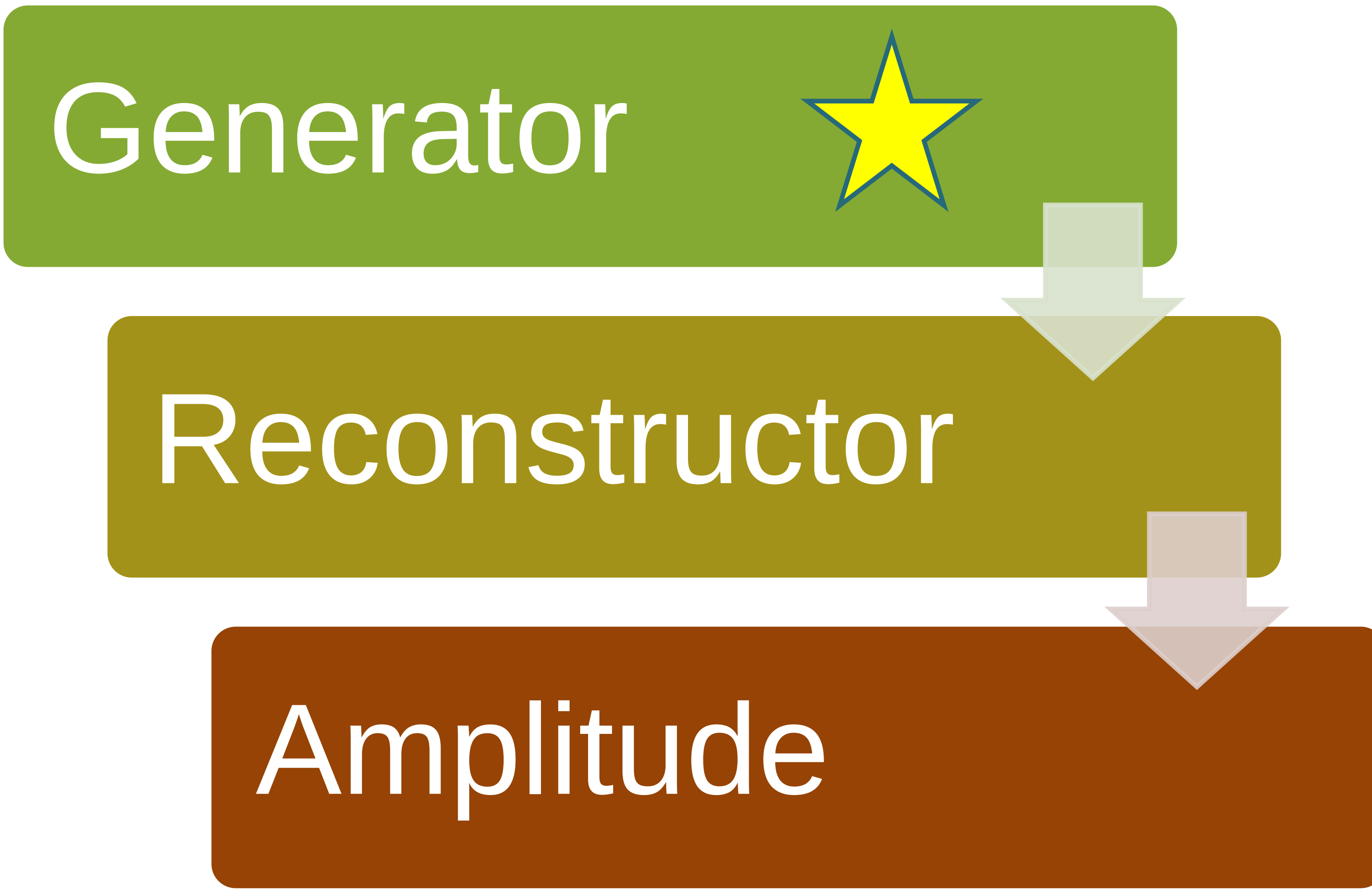
LePaProGen Interfaces

- can be **Pythia8** plug-in;
- Les Houches Accord (**LHA**) event format;
- **HepMC** output format;
- LHAPDF interface for parton density functions;
- variety of renormalization schemes;
- POWHEG-like matching (in preparation).

LePaProGen code structure

- Python module: processing of input settings, precalculation of all constants
- Mako template: optimized code generation for process chosen by user
- C++ code: modular architecture, high performance

LePaProGen structure



Importance Sampling

- to flatten a **peak** – change variable:

$$\frac{f(x)dx}{(x-x_0)^2+a^2} = \frac{f(x_0+a\ \tan\ \psi)d\psi}{a}$$

- in tree-level amplitude all peaks are due to **propagators**
- Can we parametrize phase-space by invariant variables, which appear in propogators?

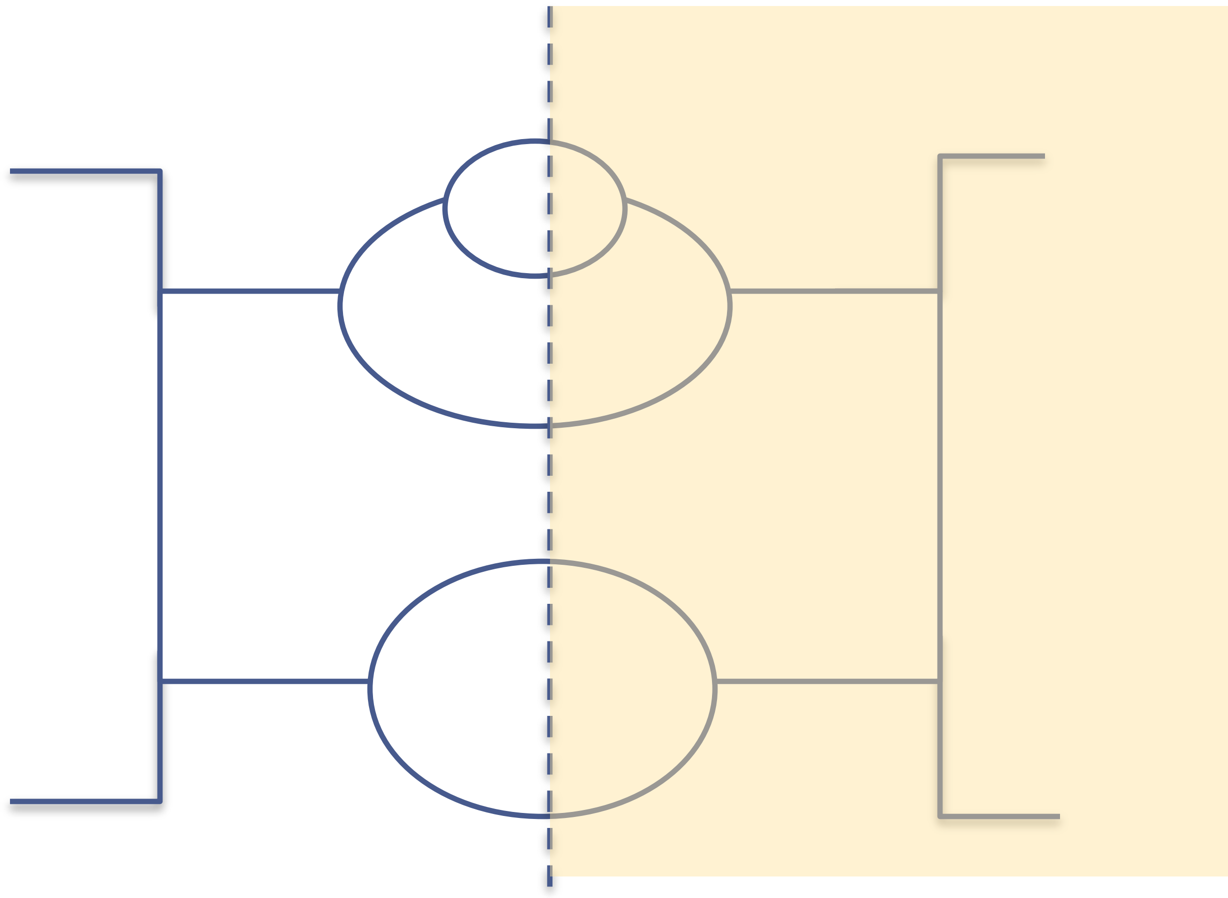
Cutting lines

- changing of variables is as simple, as taking integrals with δ-functions:

$$\int dR_n \left(\frac{1}{p^2 - m^2} \ldots \right) = \int ds' \frac{1}{s' - m^2} \left[\int dR_n \delta(p^2 - s') \ldots \right]$$

- problem now reduces to **« generalized unitarity »** integrals
- now all (intermediate and final) particles are **« on-shell »**
- what about « simple unitarity »?

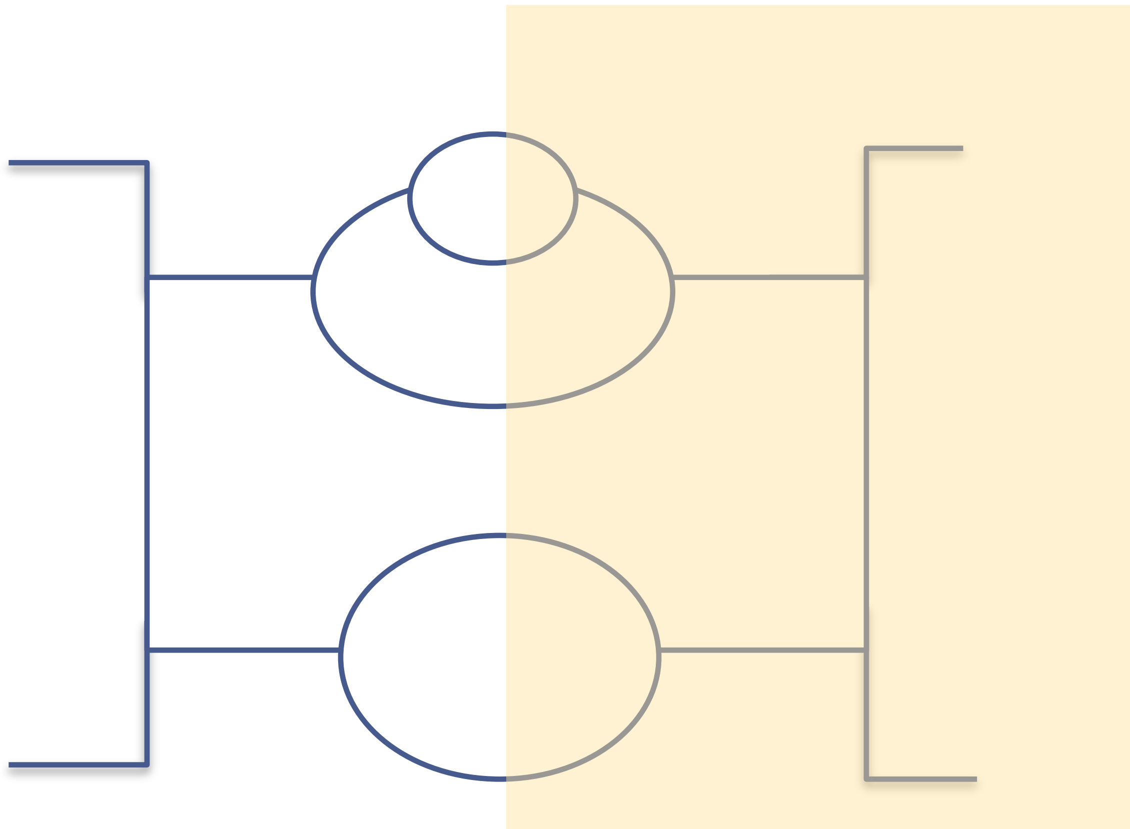
Optical Theorem



- squared amplitude is imaginary part of multi-loop diagram

Loop Contraction

- we are going to integrate loop-by-loop



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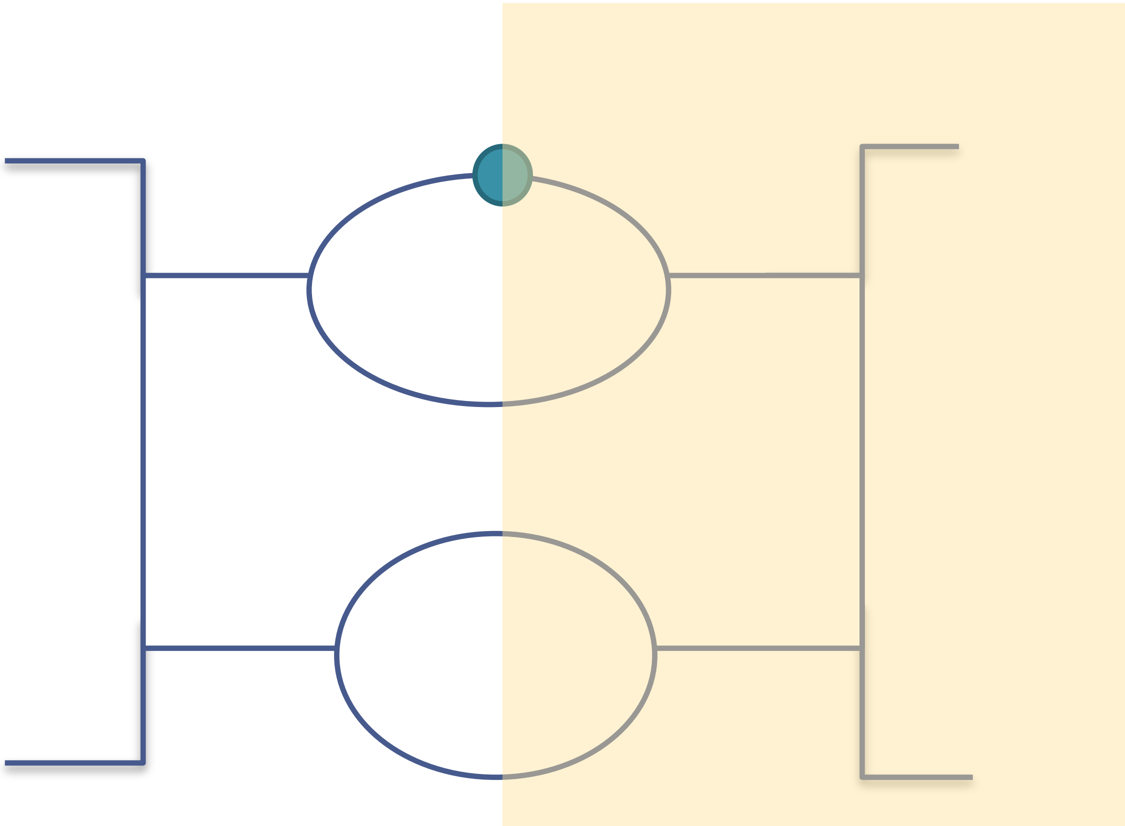

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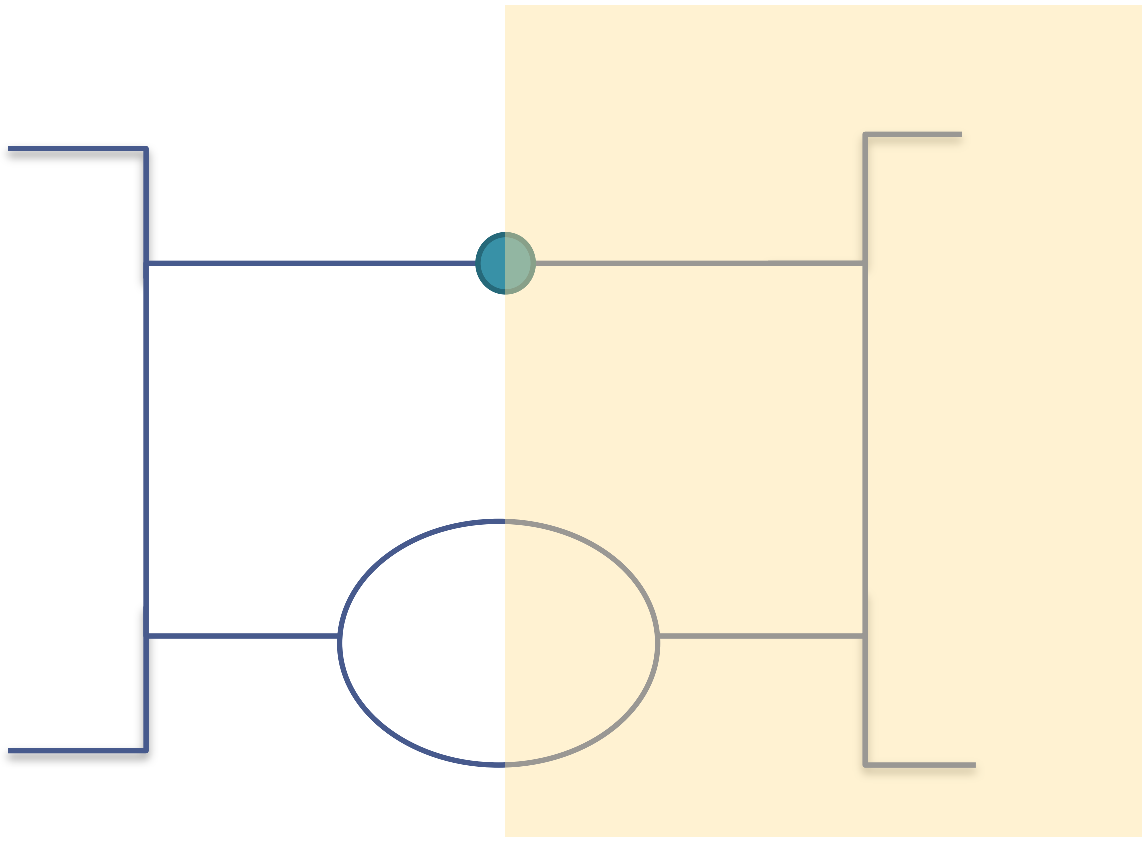

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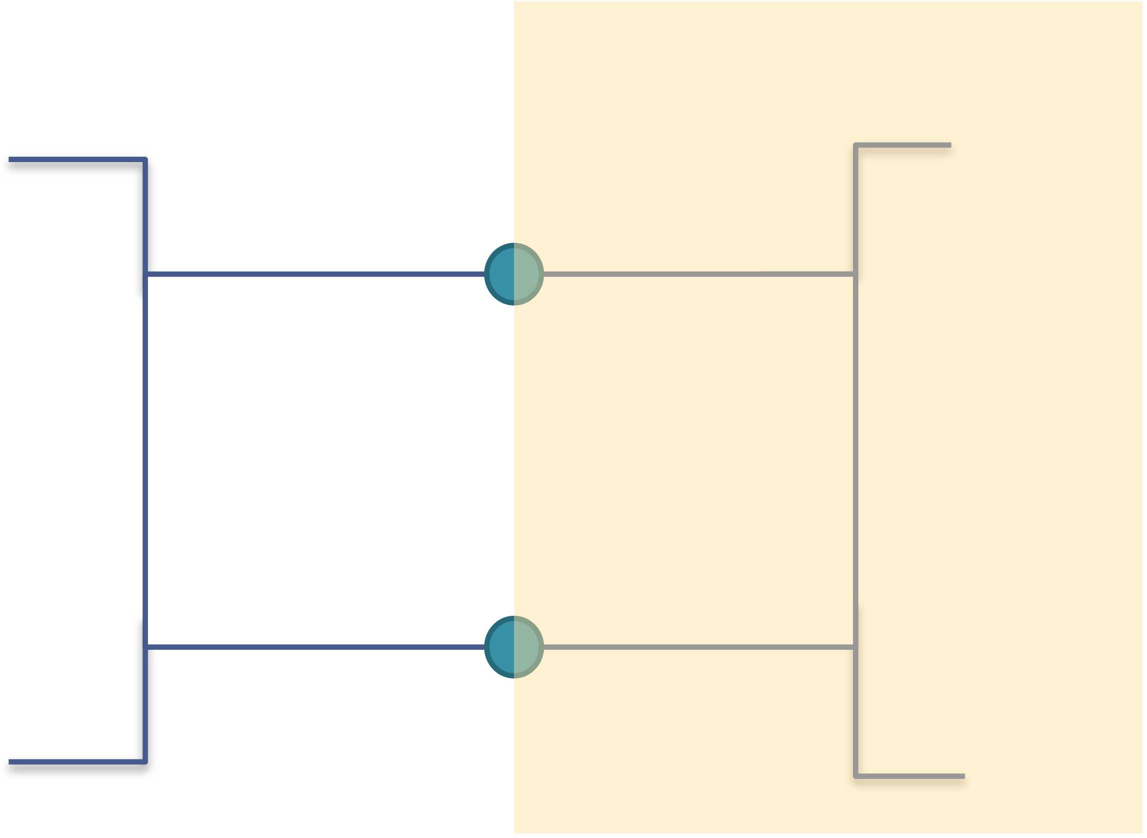

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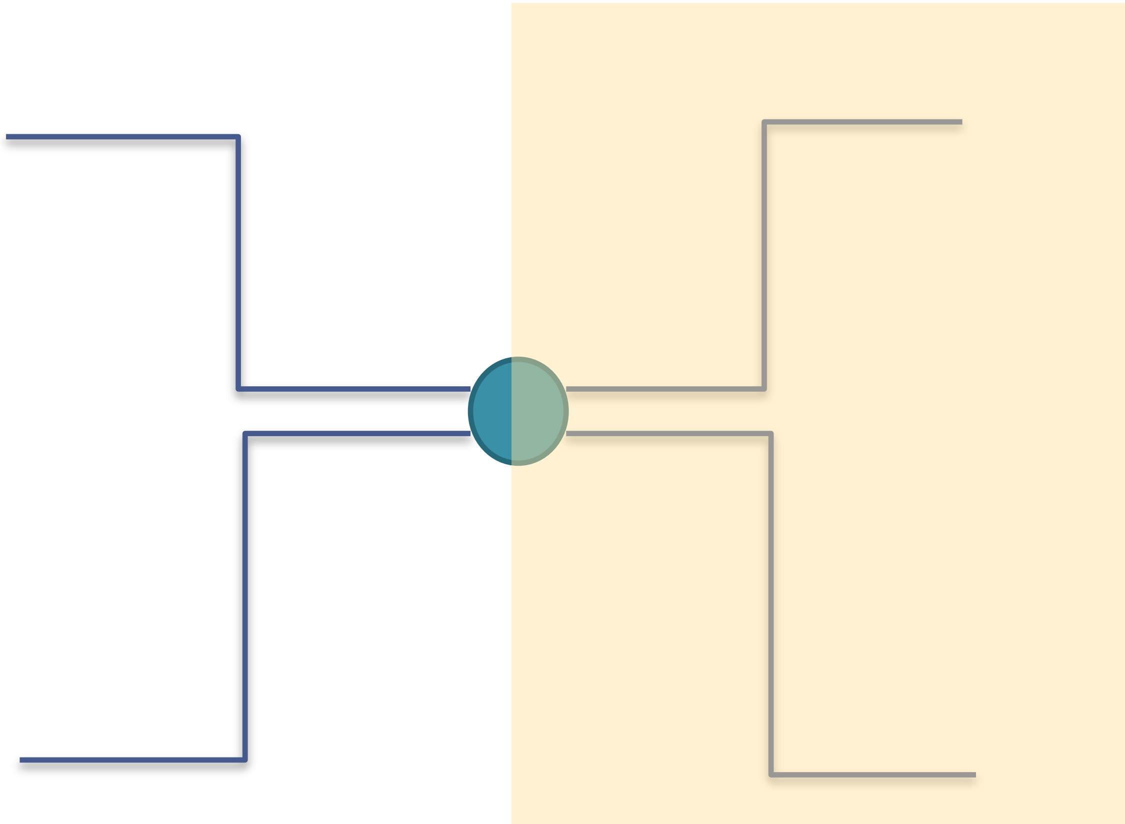
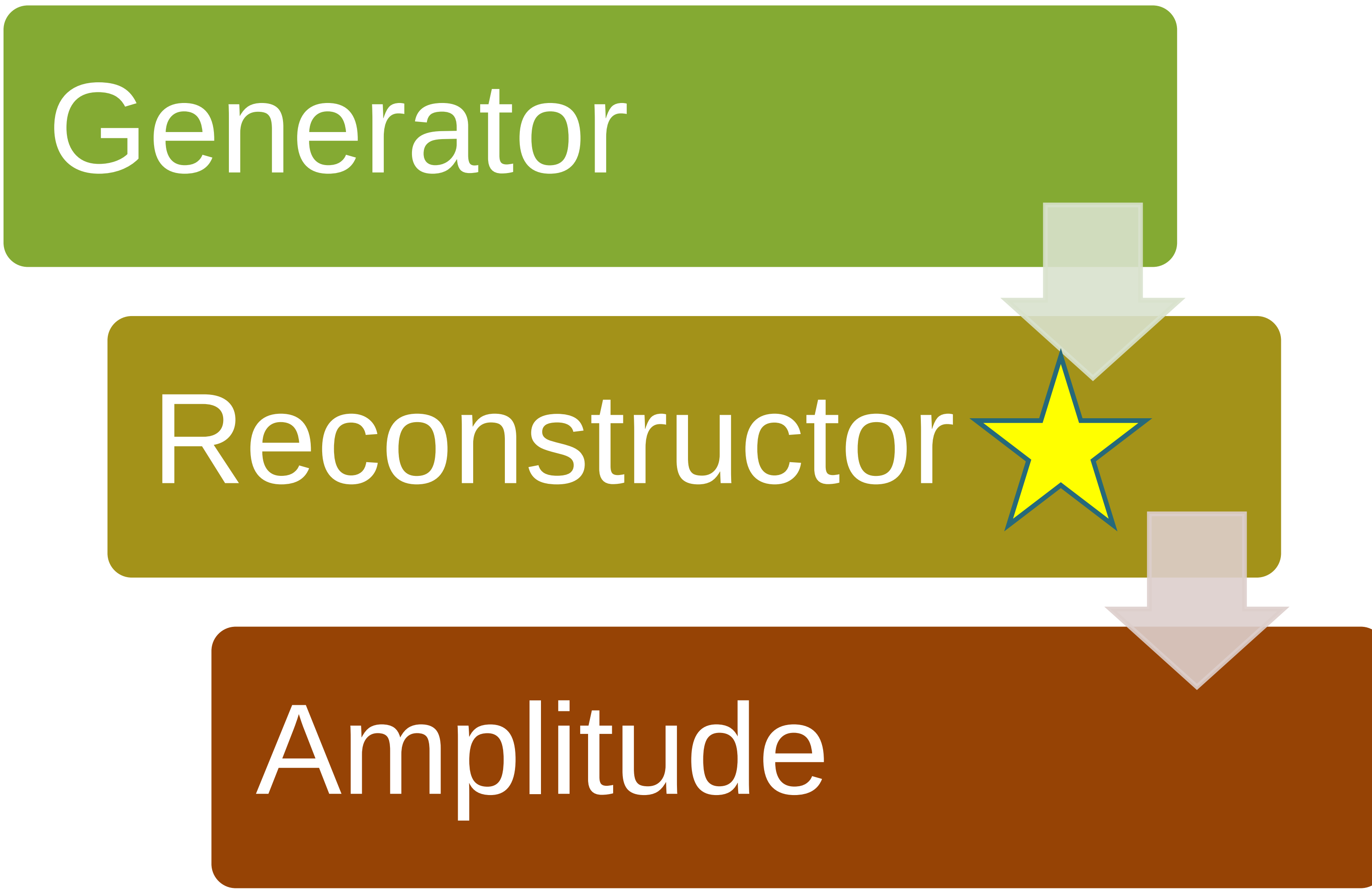


Loop Contraction

- It is generalization of recurrence relation for phase-space volume from [E. Byckling and K. Kajantie, Particle *Kinematics* (John Wiley, London; New York; Sydney; Toronto, 1973)]

LePaProGen structure



Reconstruction

- one-loop sub-diagrams used for reconstruction of the momentum, running in the loop
- reference frame and axes directions are fixed by external legs
- boosts and rotations can easily be performed by operators from *Clifford* algebra [Doran, Lasenby Geometric Algebra for Physicists]

Example of reconstruction

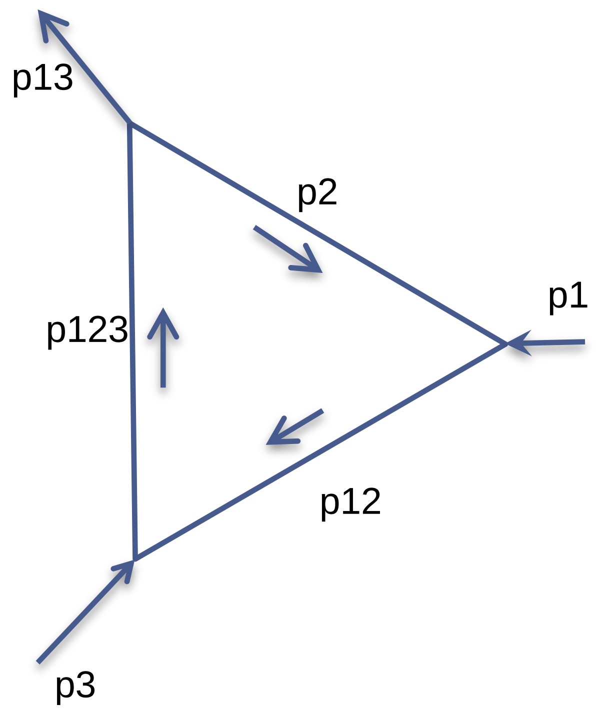
$$p_1 \cdot p_2 = \frac{s_{12} - s_1 - s_2}{2} \qquad p_2 \cdot p_{13} = \frac{s_{123} - s_{13} - s_2}{2}$$

$$G = p_1 \wedge p_{13}$$

$$\tilde{p}_1 = p_{13} G^{-1}$$

$$\tilde{p}_{13} = -p_1 G^{-1}$$

$$p_{2L} = \left(p_1 \cdot p_2\right) \tilde{p}_1 + \left(p_2 \cdot p_{13}\right) \tilde{p}_{13}$$



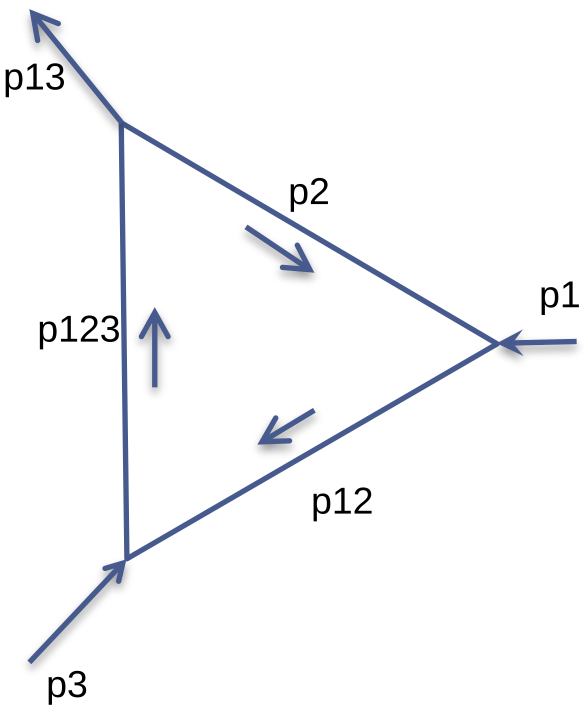
Example of reconstruction

$$n = \gamma_1 \sin\alpha + \gamma_2 \cos\alpha$$

$$p_{2T}^2 = p_{2L}^2 - s_2$$

$$G = p_1 \wedge p_{13} \qquad S = G\,\gamma_0 \wedge \gamma_3$$

$$p_2 = p_{2L} + \sqrt{p_{2T}^2}\,S^{1/2} n S^{-1/2}$$



Cuts and Limits

- for each “propagator” variable there are **limits**, which *must* be determined
- they **depend** on inner-loop masses and outer-loop variables
- limits can be modified by applying user **cuts**
- we adopt **interval arithmetic** package for doing this job

LePaProGen structure

Generator

Reconstructor

Amplitude

Amplitude

- The complete EW corrections at one-loop is calculated for single W and Z production.
- Supports different EW-schemes: $\alpha(0)$, $\alpha(MZ)$, $G\mu$.
- Bremsstrahlung amplitudes are generated using helicity amplitude technique by our MetaAmp package

MetaAmp

[R. Kleiss and W. J. Stirling, Nucl. Phys. B262 (1985) 235]

- Choose arbitrary vectors k_0 and k_1 such that $k_0^2 = 0, \quad k_0 \cdot k_1 = 0, \quad k_1^2 = -1$
- Construct spinors $u_+(k_0)$ and $u_-(k_0)$:

$$u_\lambda(k_0)\bar{u}_\lambda(k_0) = \omega_\lambda k_0, \quad u_\lambda(k_0) = \lambda k_1 u_{-\lambda}(k_0), \quad \omega_\lambda = \frac{1+\lambda\gamma_5}{2}$$

- Let $k_0 = \{1/2, 0, 0, 1/2\}, \quad k_1 = \{0, 1, 0, 0\}$, so

$$u_+(k_0) = \{1, 0, 0, 0\}^T \text{ and } u_-(k_0) = \{0, 0, 0, -1\}^T$$

$$u_\lambda(p) = \frac{\hat{p} \pm m}{\sqrt{2p \cdot k_0}} u_{-\lambda}(k_0)$$

MetaAmp

- Building blocks:

$$\langle pq\ldots k\rangle = \bar{u}_+(k_0)\,\hat{p}\hat{q}\ldots\hat{k}\,\omega\_u_+(k_0)$$

$$\langle pq\ldots k] = \bar{u}_+(k_0)\,\hat{p}\hat{q}\ldots\hat{k}\,\omega_+ u_-(k_0)$$

$$[pq\ldots k\rangle = \bar{u}_-(k_0)\,\hat{p}\hat{q}\ldots\hat{k}\,\omega_- u_+(k_0)$$

$$[pq\ldots k] = \bar{u}_-(k_0)\,\hat{p}\hat{q}\ldots\hat{k}\,\omega_+ u_-(k_0)$$

MetaAmp

- For Drell-Yan process:

$$D_{LR}(s) = Q(q)Q(\mu) + g_L(q)g_R(l)\frac{s}{s - M_Z + i\Gamma_Z M_Z}$$

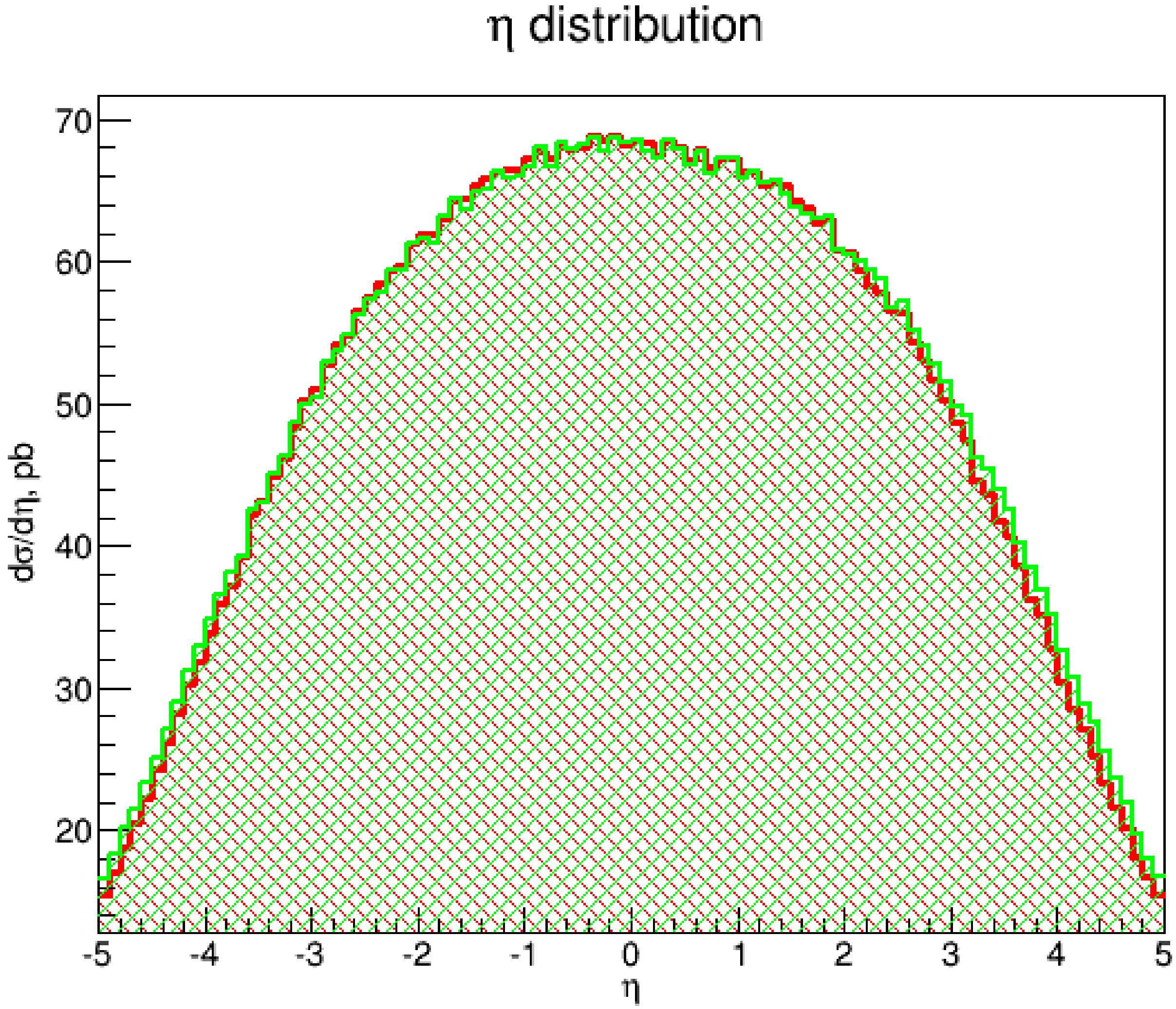
- Single bremsstrahlung amplitude:

$$A^{\gamma}_{+--+-} = 4e^3\delta^{i_1}_{i_2}\left[Q(l)D_{RR}(p_{12}^2)\left(\frac{1}{p_{45}^2}[p_2p_3\rangle\langle p_4p_5]\langle p_1p_{45}] - \frac{1}{p_{35}^2}[p_3]\langle p_1p_4][p_2p_3p_5]\right)\right.$$
$$\left. + Q(q)D_{RR}(p_{34}^2)\left(\frac{1}{p_{25}^2}[p_2]\langle p_1p_4][p_3p_2p_5] - \frac{1}{p_{15}^2}[p_2p_3\rangle\langle p_1p_5]\langle p_4p_{15}]\right)\right]$$

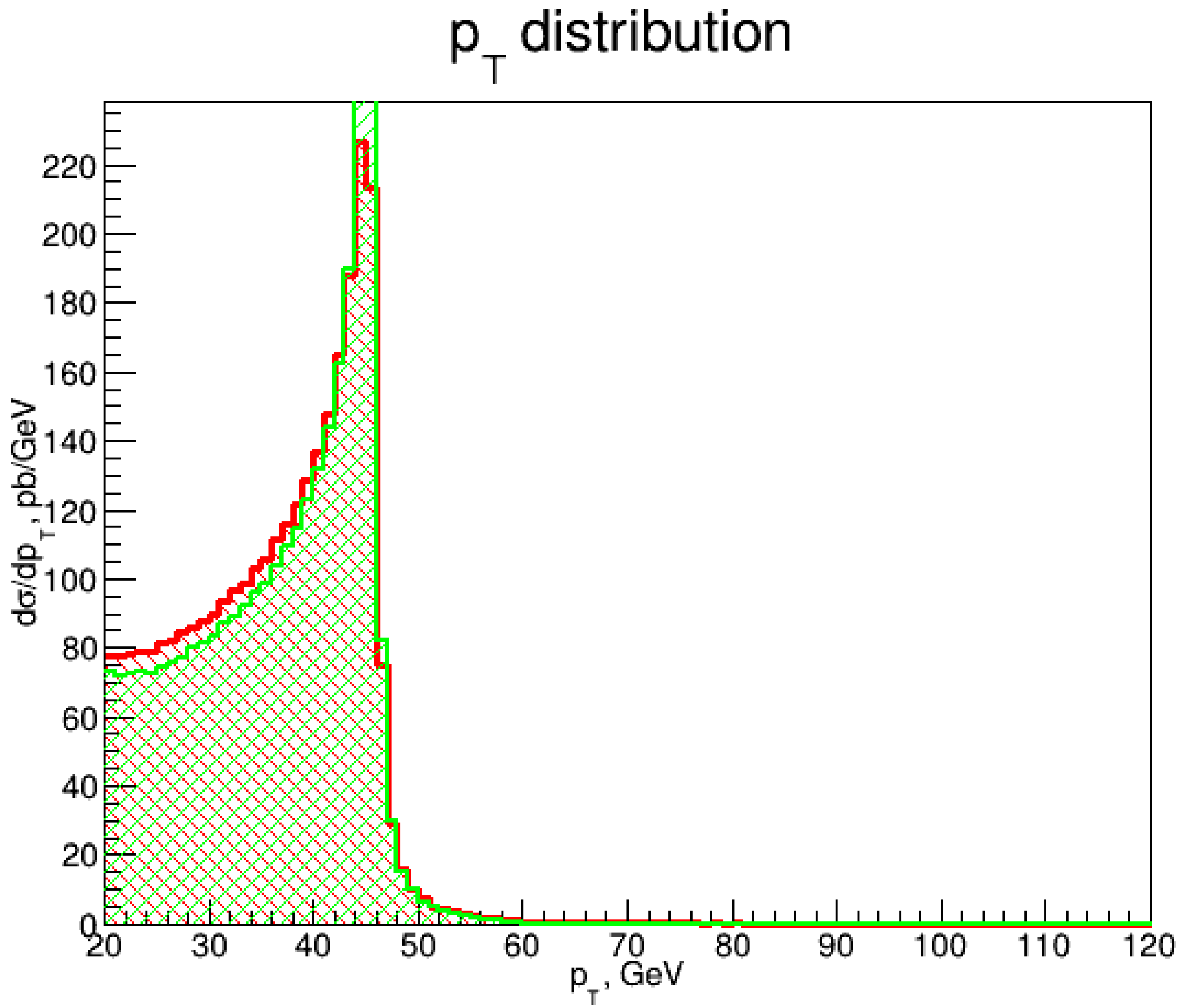
MetaAmp

- Uses FeynArts [Hahn] output to produce helicity amplitudes.
- Avoids spinors – all calculations performed in the algebra of Dirac matrices.
- Normalization terms are factorized out from amplitudes.

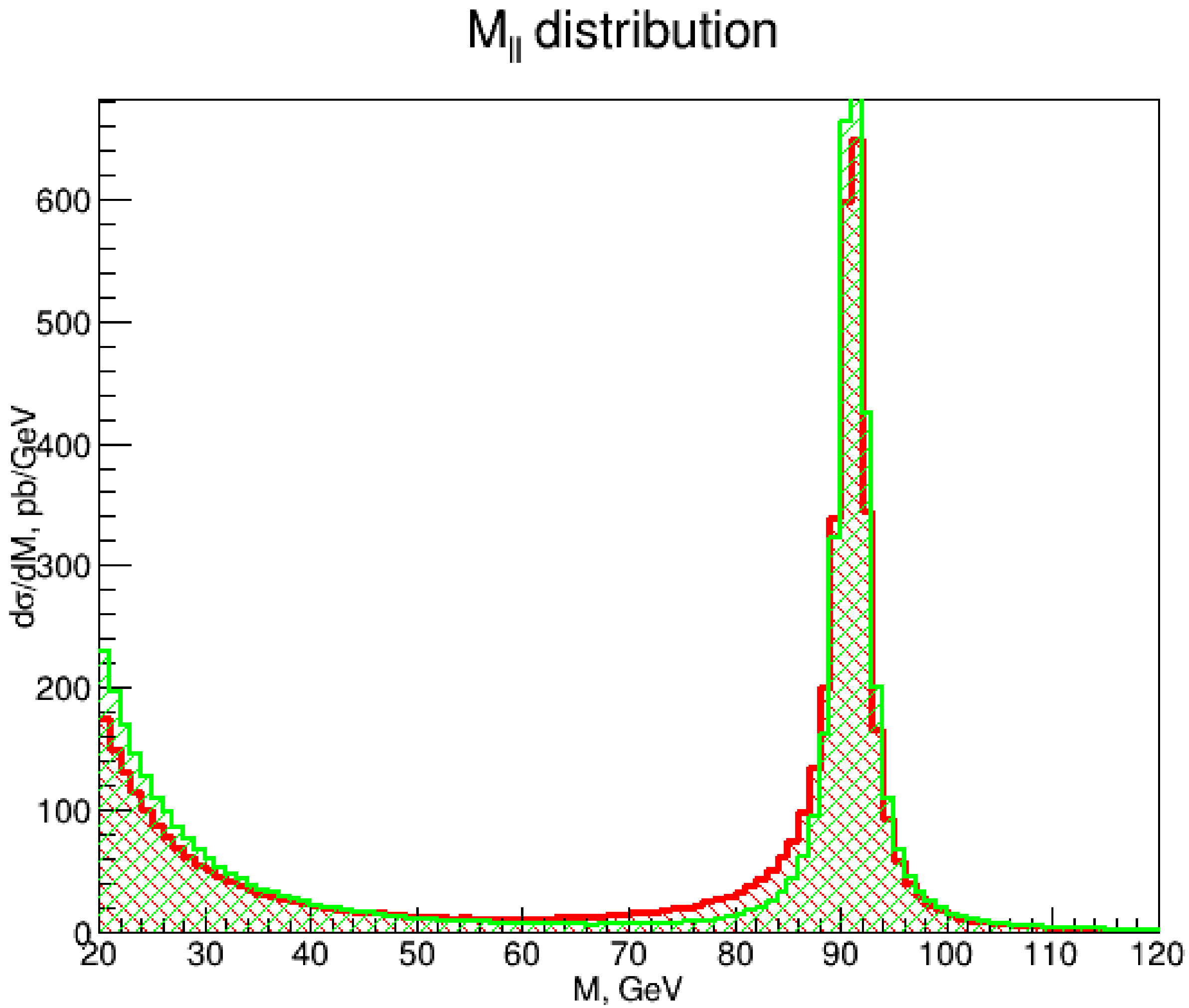
Some plots: *pseudo-rapidity*



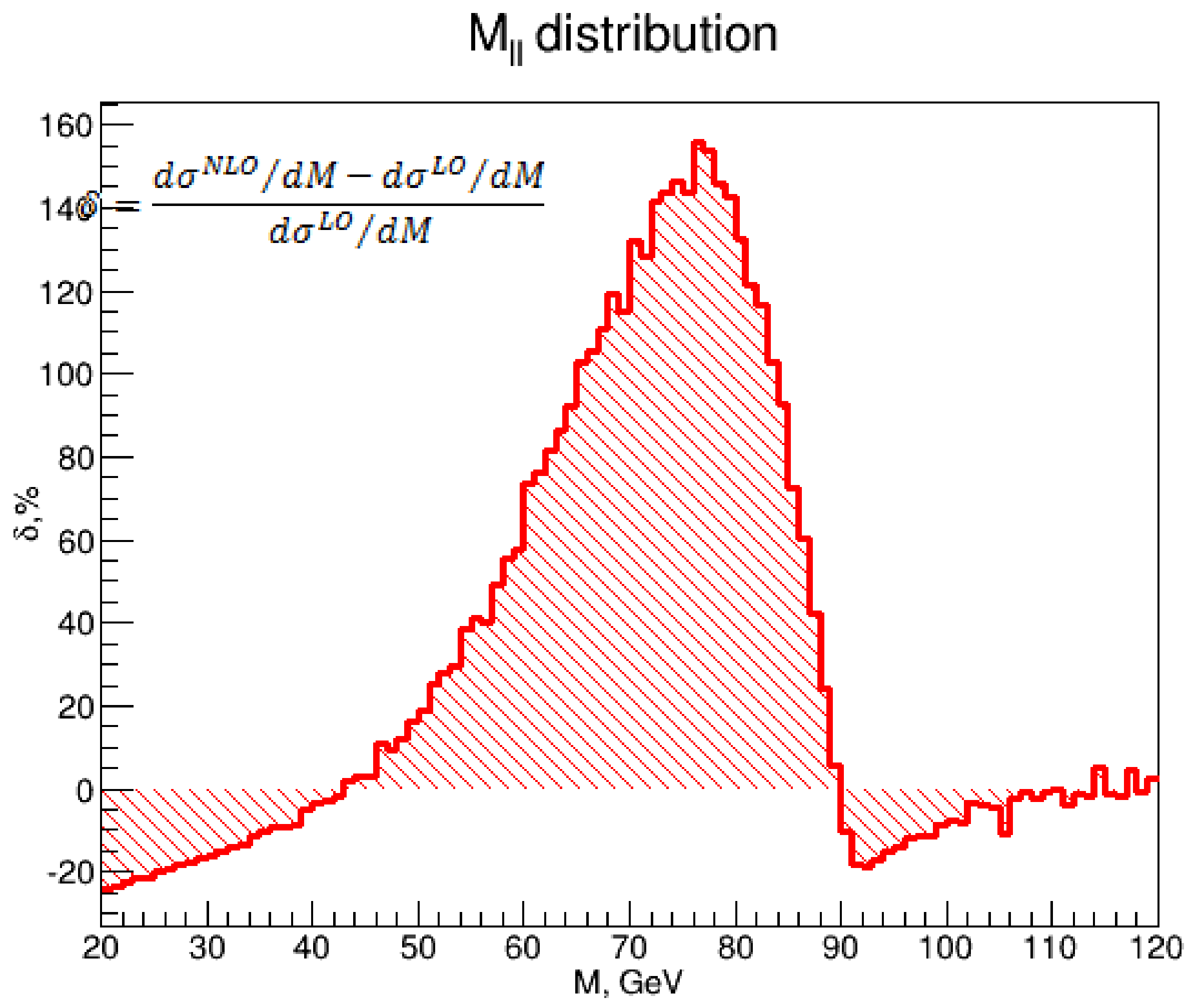
Some plots: *transverse momentum*



Some plots: *pair invariant mass*



Some plots: correction



Conclusions

- proposed method of generation and reconstruction is proved to be efficient
- all necessary interfaces for inclusion into CMS analysis infrastructure

next steps:

- comparison against other existing codes *(FEWZ, HORACE, WINHAC etc.)*
- matching with parton shower MCs

Thank you!