CASCADE event generator

09.11.2021

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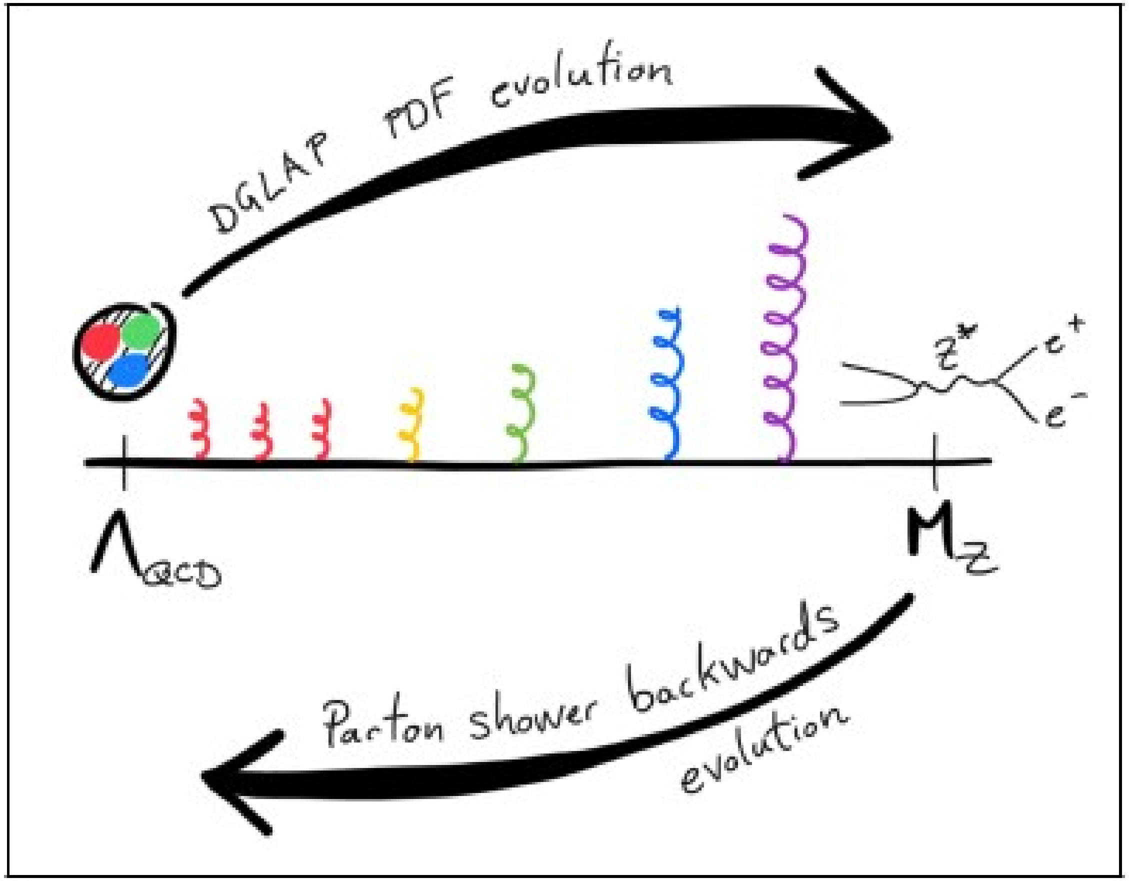
Virtual Monte-Carlo School 2021

8-12 November 2021 (on Zoom)

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

DESY.

Recall from Stefan's lecture

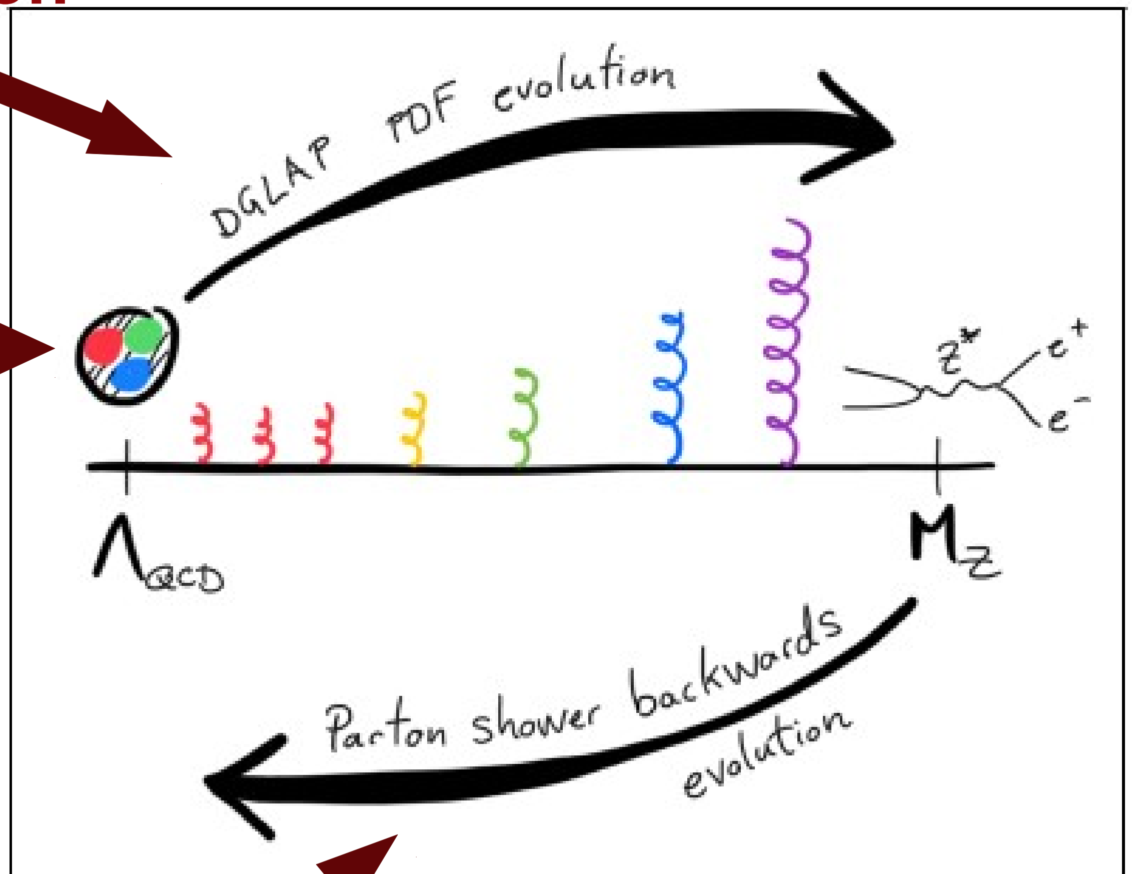


Recall from Stefan's lecture

CASCADE

TMD evolution

TMD



TMD parton shower

CASCADE

- Monte Carlo program based on TMDs, doing ISR and FSR
- Latest version CACADE 3.1.1 (https://cascade.hepforge.org/)
- Inputs **lhe** files (hard process):


```
<event>
 7      2 +3.4258351e+03 9.53459700e+01 7.54677100e-03 1.29039900e-01
        2 -1    0    0  503    0 -0.0000000000e+00 +0.0000000000e+00 +3.0198415593e+01 3.0198415593e+01 0.0000000000e+00 0.0000e+00 -1.0000e+00
       21 -1    0    0  501  502 +0.0000000000e+00 -0.0000000000e+00 -1.6043111285e+02 1.6043111285e+02 0.0000000000e+00 0.0000e+00 1.0000e+00
       23  2    1    2    0    0 +1.6819700231e+01 +2.6667373435e+01 -1.0597756437e+02 1.4466512520e+02 9.3288279956e+01 0.0000e+00 0.0000e+00
      -11  1    3    3    0    0 -2.6501879581e+01 -1.5727235559e+01 -6.3701790953e+01 7.0764494842e+01 0.0000000000e+00 0.0000e+00 1.0000e+00
       11  1    3    3    0    0 +4.3321579812e+01 +4.2394608994e+01 -4.2275773422e+01 7.3900630360e+01 0.0000000000e+00 0.0000e+00 -1.0000e+00
       21  1    1    2  503  502 -1.6491715594e+01 -7.7498171134e+00 -1.9004781331e+01 2.6329034581e+01 0.0000000000e+00 0.0000e+00 -1.0000e+00
        2  1    1    2  501    0 -3.2798463720e-01 -1.8917556322e+01 -5.2503515557e+00 1.9635368664e+01 0.0000000000e+00 0.0000e+00 -1.0000e+00
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>
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</mgrwt>
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<clus scale="   19.702">  2  7  1 -1</clus>
<clus scale="   93.288">  4  5 -1 -1</clus>
<clus scale="   18.222">  2  4  1 -1</clus>
</clustering>
</event>
```
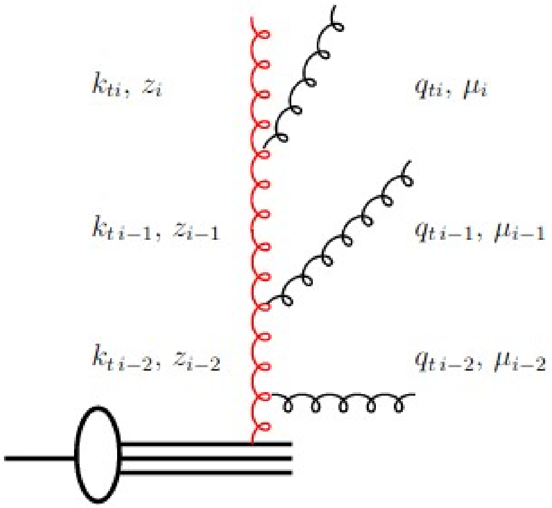


- Can be used to **shower events** (collinear and kt-dependent processes):
  - for collinear processes kt is added according to TMD, preserving mass of the system
  - for off-shell processes events are showered directly
- After shower events are hadronized and written in hepmc format for further analysis in **Rivet**

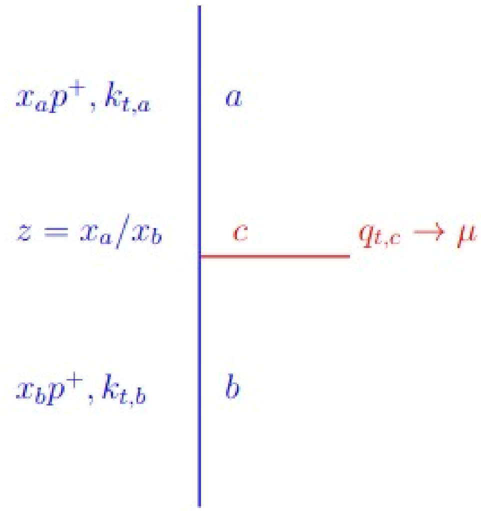
CASCADE: PB formulation of TMD evolution

- Starting at a scale μ_i, the algorithm samples the next scale μ_{i-1} at which a parton will be emitted

$$\Delta_S(x,\mu_i,\mu_{i-1})=\exp\left[-\int_{\mu_{i-1}}^{\mu_i}\frac{d\mu'}{\mu'}\frac{\alpha_s(\tilde{\mu}')}{2\pi}\sum_a\int dz P_{a\to bc}(z)\frac{x'\mathcal{A}_a(x',k_t',\mu')}{x\mathcal{A}_b(x,k_t,\mu')}\right]$$



- Continues until lowest scale (cutoff)
- Physics lies in mapping of evolution variables to splitting kinematics
- * TMD from splittings cumulative kt in forward evolution
- **ISR fully determined by TMD and its backward PB evolution**
- **PS exactly matches the evolution of the TMD**



In each splitting

$$\begin{aligned}\mathbf{k_{t,b}} &= \mathbf{k_{t,a}} + \mathbf{q_{t,c}}\\ &= \mathbf{k_{t,a}} + (1-z)\mu\end{aligned}$$

Total transverse momentum:

$$\mathbf{k_t} = \mathbf{k_{t,0}} + \sum_c \mathbf{q_{t,c}}$$

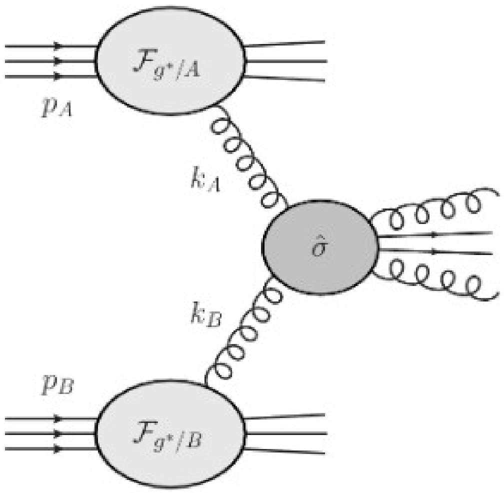
CASCADE + KaTie

k_T-factorization

$$\sigma_{AB\to q\bar{q}} = \int d^2k_{T\,A} \frac{dx_A}{x_A} \mathcal{F}(x_A, k_{T\,A})\; d^2k_{T\,B} \frac{dx_B}{x_B} \mathcal{F}(x_B, k_{T\,B})\; \hat{\sigma}_{g^*g^*}\left(\frac{m^2}{x_A x_B s}, \frac{k_{T\,A}}{m}, \frac{k_{T\,B}}{m}\right)$$

KaTie

- Parton level events with **off-shell initial state partons**
- Calculation **including TMD**
- Event files in the Les Houches format (LHE)



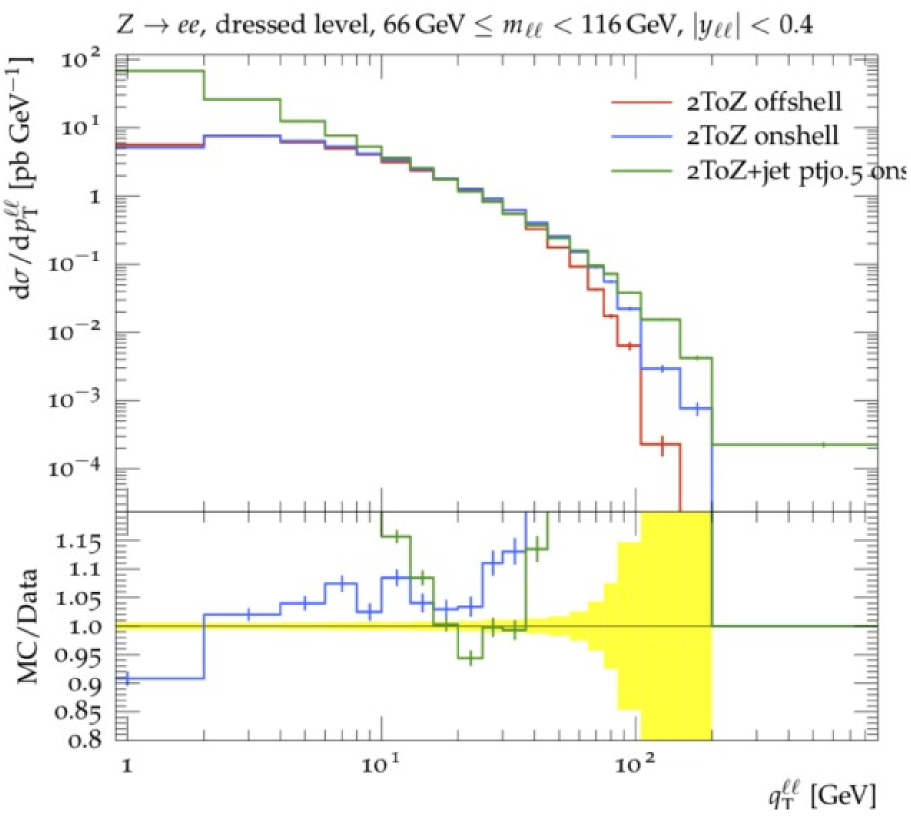
$$k_i^2 = k_{iT}^2 < 0$$

CASCADE

- Takes LHE files from KaTie
- **Showers** using **TMD evolution** and hadronizes

CASCADE + KaTie

- off-shell agrees with on-shell with TMD added (and keeping mass fixed) at small q_T
  - ➔ important check for application with collinear NLO calculation
- off-shell agrees with $2 \rightarrow 2$ on-shell at medium q_T
  - ➔ important check for merging different parton multiplicities



CASCADE + MC@NLO

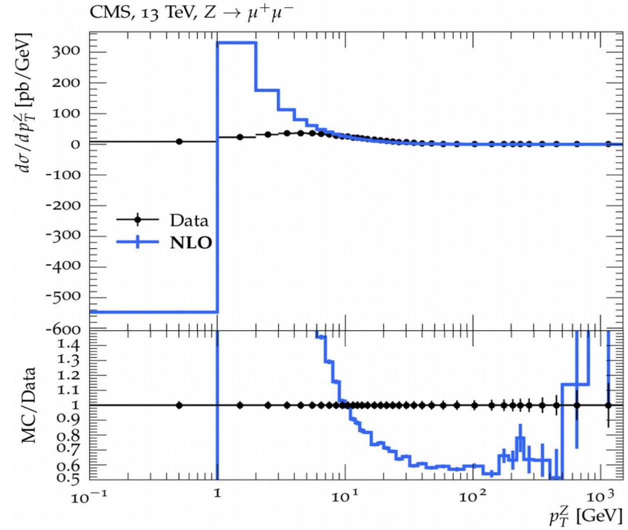
- Recall the MC@NLO formula:

$$\overline{\mathcal{B}} = \mathcal{B} + \left[\mathcal{V} + \int dp_t^2 \mathcal{R}^{PS}(p_t^2)\right] + \int dp_t^2 \left[\mathcal{R}(p_t^2) - \mathcal{R}^{PS}(p_t^2)\right]$$

The real emission is generated following the second term:

$$\mathcal{R}(p_t^2) - \mathcal{R}^{PS}(p_t^2)$$

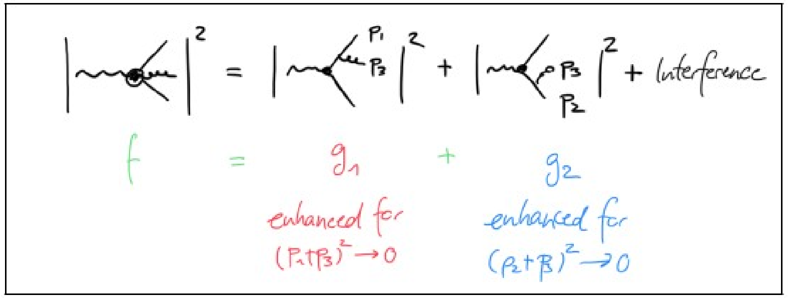
Divergences at NLO



MC@NLO

- **Real and virtual corrections**
- Includes **subtraction terms** (Parton shower dependent)
- Event files in the LHE format

Recall Stefan's points

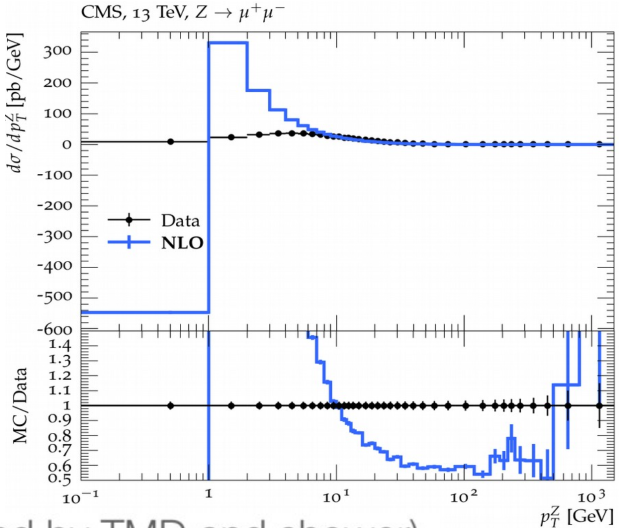


CASCADE

- Takes LHE files from MC@NLO
- Adds TMD
- **Showers** using **TMD evolution** and hadronizes

CASCADE + MC@NLO

Divergences at NLO



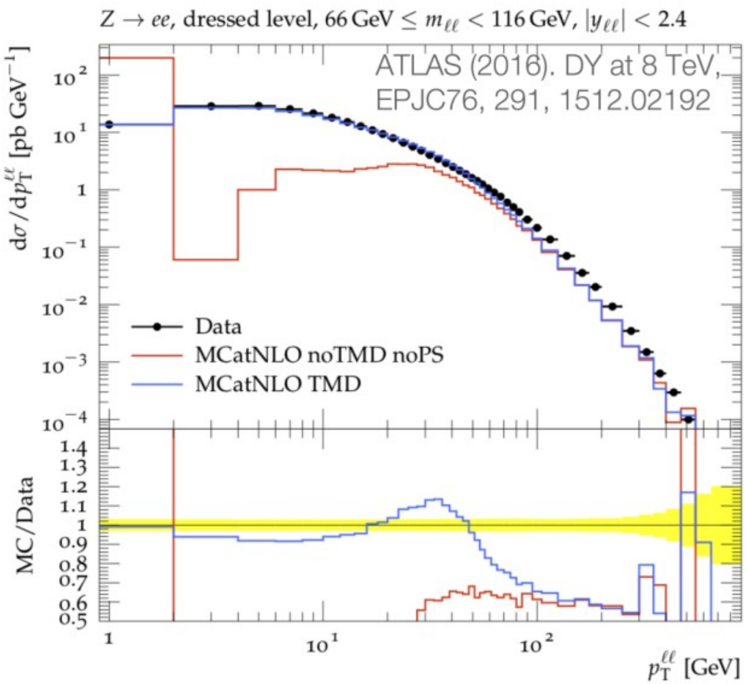
- Recall the MC@NLO formula:

$$\overline{\mathcal{B}} = \mathcal{B} + \left[\mathcal{V} + \int dp_t^2 \mathcal{R}^{PS}(p_t^2)\right] + \int dp_t^2 \left[\mathcal{R}(p_t^2) - \mathcal{R}^{PS}(p_t^2)\right]$$

The real emission is generated following the second term:

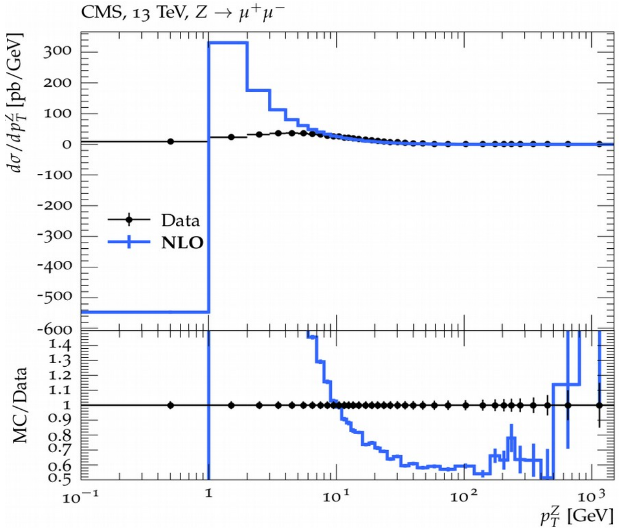
$$\mathcal{R}(p_t^2) - \mathcal{R}^{PS}(p_t^2)$$

- MC@NLO subtracts soft & collinear parts from NLO (added by TMD and shower)
- MC@NLO without shower unphysical
  - DY-process as example
  - low q_T region affected by subtraction of soft & collinear parts
    - to be filled by TMD (+ PS)
  - DY production very well described by TMD with MC@NLO
    - TMD fills low q_T part



CASCADE + POWHEG

Divergences at NLO



- Recall the POWHEG method:

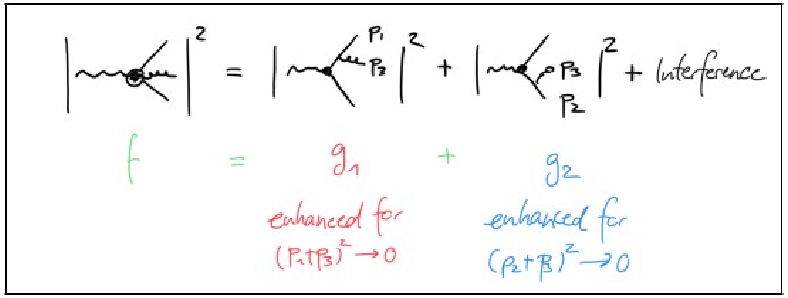
$$\overline{\mathcal{B}} = \overline{\mathcal{B}} \exp\left[-\int_{p^2_{t\min}} dp_t'^2 \frac{\mathcal{R}(p_t'^2)}{\mathcal{B}}\right] + \overline{\mathcal{B}} \int_{p^2_{t\min}} dp_t^2 \frac{\mathcal{R}(p_t^2)}{\mathcal{B}} \exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}(p_t'^2)}{\mathcal{B}}\right]$$

- Exponential suppression (as opposed to subtraction terms)
- Cut separating *n* and *n+1* contributions

POWHEG

- **Real and virtual corrections**
- Includes **supression** (Parton shower independent)
- Positive weighted events
- Event files in the LHE format

Recall Stefan's points

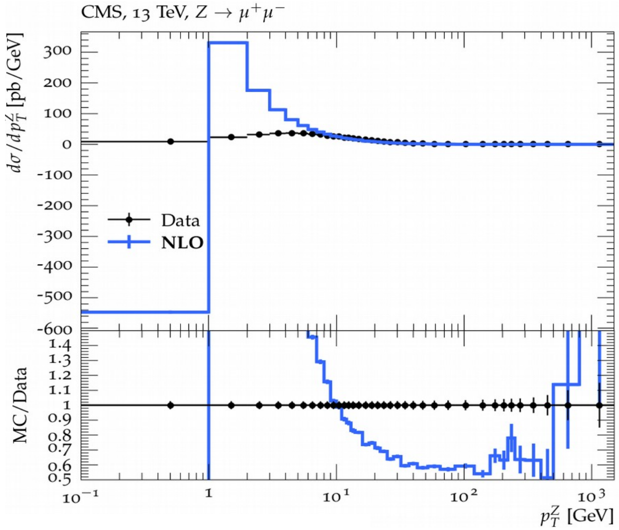


CASCADE

- Takes LHE files from POWHEG
- Adds TMD
- **Showers** using **TMD evolution** and hadronizes

CASCADE + POWHEG

Divergences at NLO

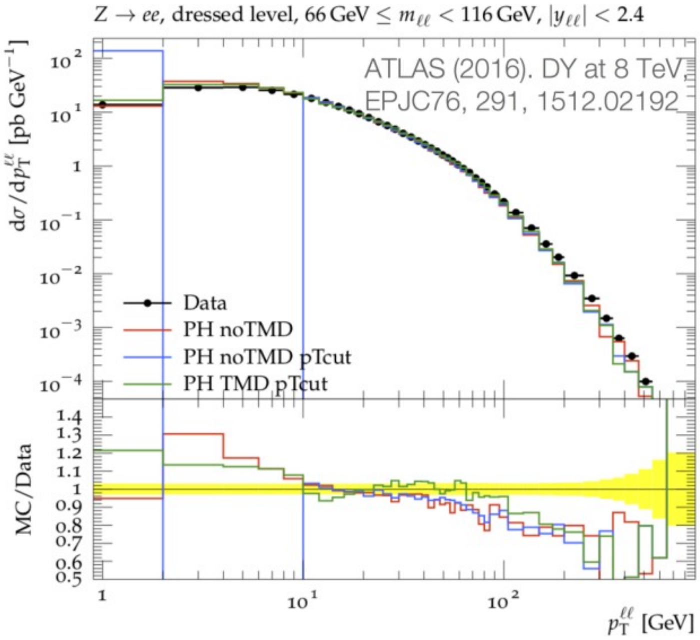


- Recall the POWHEG method:

$$\overline{\mathcal{B}} = \overline{\mathcal{B}} \exp\left[-\int_{p_{t\min}^2} dp_t'^2 \frac{\mathcal{R}(p_t'^2)}{\mathcal{B}}\right] + \overline{\mathcal{B}} \int_{p_{t\min}^2} dp_t^2 \frac{\mathcal{R}(p_t^2)}{\mathcal{B}} \exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}(p_t'^2)}{\mathcal{B}}\right]$$

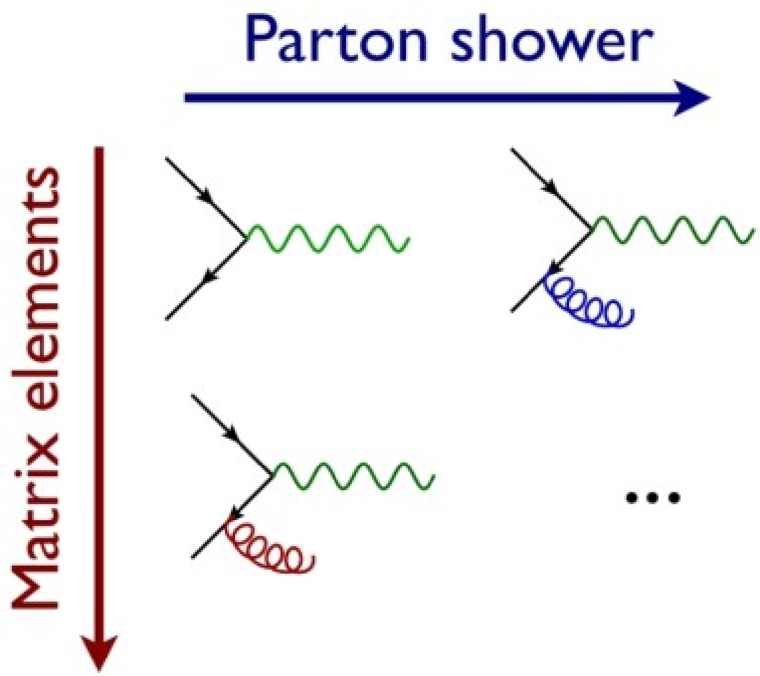
- Exponential suppression (as opposed to subtraction terms)
- Cut separating *n* and *n+1* contributions

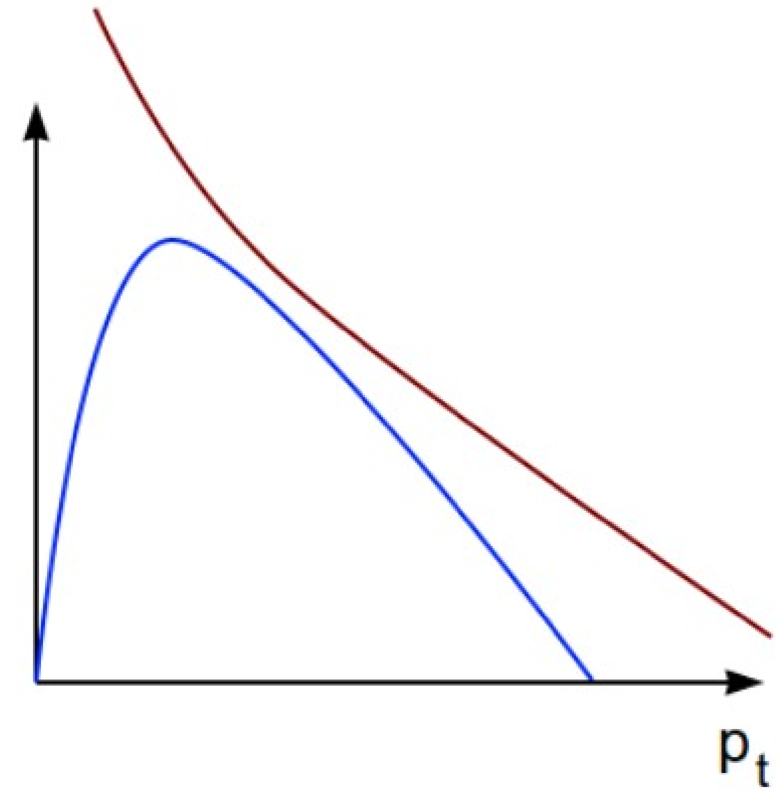
- POWHEG exponentiates real emission (soft part): Sudakov for 1st emission
  - DY-process as example
  - q_T cut applied (ptsqmin) to allow for contribution from TMD (and PS)
    - low q_T region filled by TMD + PS
    - large q_T by real emission
  - DY production described reasonably well with TMD + POWHEG with q_T cut
    - TMD fills low q_T part



CASCADE and multi-jet merging

∘ Z production as an example:



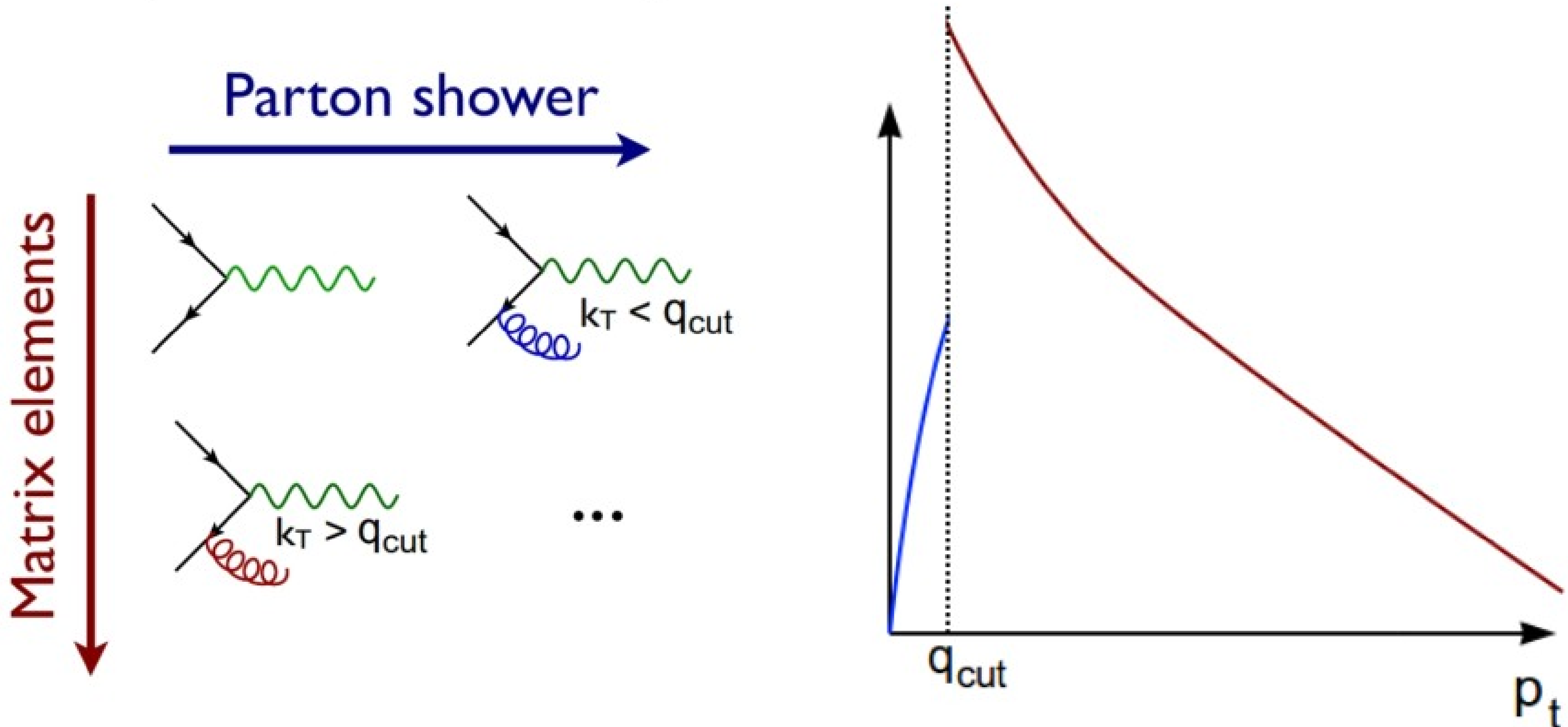


- 1st emission PS: $\mathcal{R}^{PS}(p_t^2) \times \exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}}\right]$

- 1st emission ME: $\mathcal{R}(p_t^2)$

CASCADE and multi-jet merging

◦ Z production as an example:

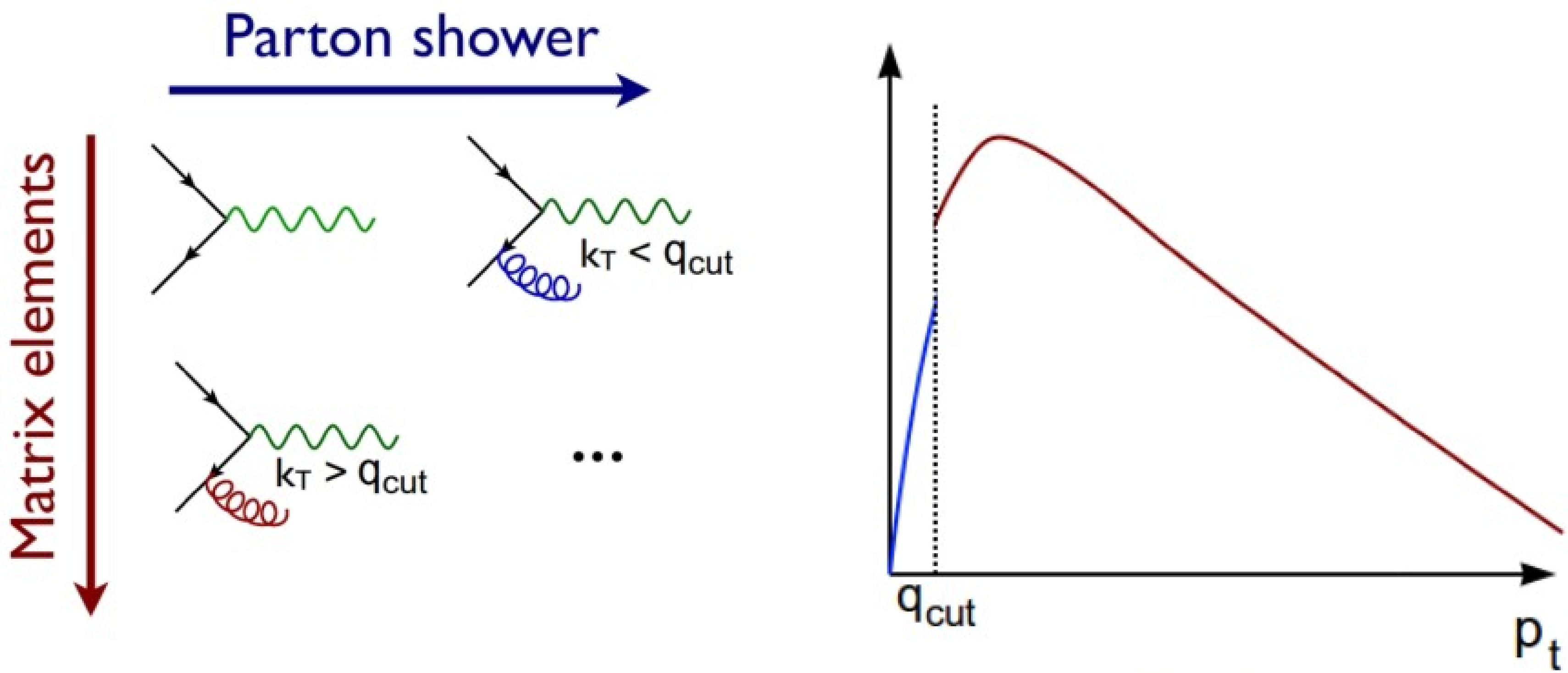


- 1st emission PS: $\mathcal{R}^{PS}(p_t^2) \times \exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}}\right]$

- 1st emission ME: $\mathcal{R}(p_t^2)$

CASCADE and multi-jet merging

- Z production as an example:



- 1st emission PS: $\mathcal{R}^{PS}(p_t^2) \times \exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}}\right]$
- 1st emission ME: $\mathcal{R}(p_t^2) \longrightarrow \mathcal{R}(p_t^2)\times\exp\left[-\int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}}\right]$

CASCADE and multi-jet merging

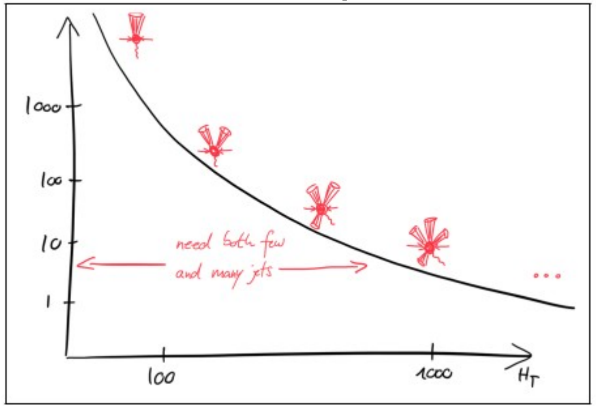
Madgraph

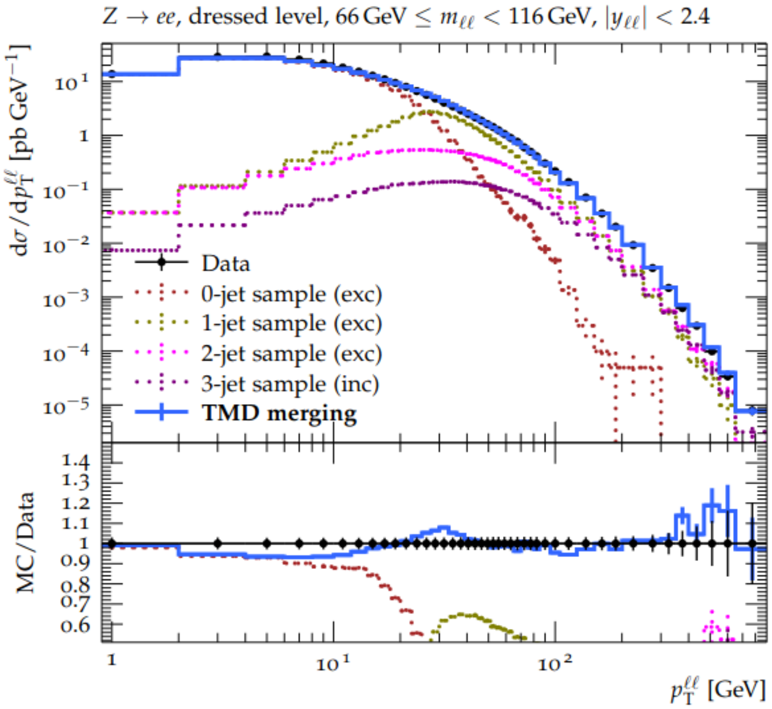
- ***n*, *n*+1, *n*+2, ... real corrections**
- Event files in the LHE format

CASCADE

- Takes LHE files from Madgraph
- Adds TMD
- **Showers** using **TMD evolution** and hadronizes
- **Divergent regions suppressed** by merging (Parton shower Sudakov)
- **Double counting** avoid by merging

Recall Stefan's points





CASCADE steering file (merging example)

```
&CASCADE_input                                ! Nr of events to process
NrEvents = -1                                ! Nr of events to process
Process_Id = -1                               ! Read LHE file
Hadronisation = 1                            ! Hadronisation on (=1)
SpaceShower = 1                              ! Space-like Parton Shower
SpaceShowerOrderAlphas=2                     ! Order alphas in Space Shower
TimeShower = 1                               ! Time-like Parton Shower
TimeLikeSplittingInSpaceShower = 1           ! Time-like splitting in Space Shower
ScaleTimeShower = 4                          ! Scale choice for Time-like Shower ! 1 is checked
!ScaleFactorFinalShower = 0.25                 ! scale factor for Final State Parton Shower
PartonEvolution = 3                          ! type of parton evolution in Space-like Shower
PartonDensity = 102200                      ! use TMDlib
lheInput = 'mg5.lhe'  ! LHE input file
lheHasOnShellPartons = 1                    ! = 0 LHE file has off-shell parton configuration
lheScale = 3                                ! Scale defintion for TMD: =0 use scalup, =1 use shat
!                                             0: use scalup
!                                             1: use shat
!                                             2: use 1/2 Sum pt^2 of final parton/particles
!                                             3: use shat for Born and 1/2 Sum pt^2 of final parton(particle)
!                                             4: use shat for Born and max pt of most forward/baward parton(particle)
!                                             5: use shat for Born and HT of final state particles (POWHEG)
&End

&CASCADE_MLM
Imerge = 1                                                 ! multijet-merging:=1 for MLM (=2 cckw)
! for pure MLM merging
iMLM = 1                                     ! iMLM=1: use old MLM merging
LHE_tmd = 1                                  ! LHE_tmd=1: use partons after kt added
rclus = 0.6                                 ! cluster radius for merging
etclus = 40.0
etaclmax = 5.4                               ! eta_max for cluster
MaxJEtsMerge = 4                             ! for merging, specify max nr of jets
&End
```

CASCADE steering file (merging example)

Main block

```
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```