Study of soft gluon resummation as a function of particle mass & center-of-mass energy in high-energy p-p collisions

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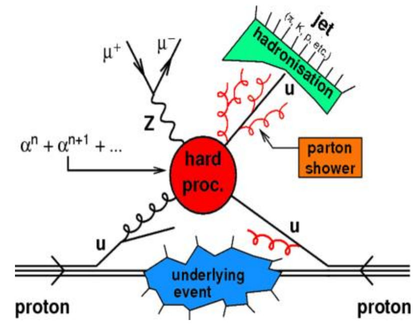
Introduction:

Description of an event in an accelerator is a bit tricky. As an example for investigating typical proton-proton collision there are many parts involved:

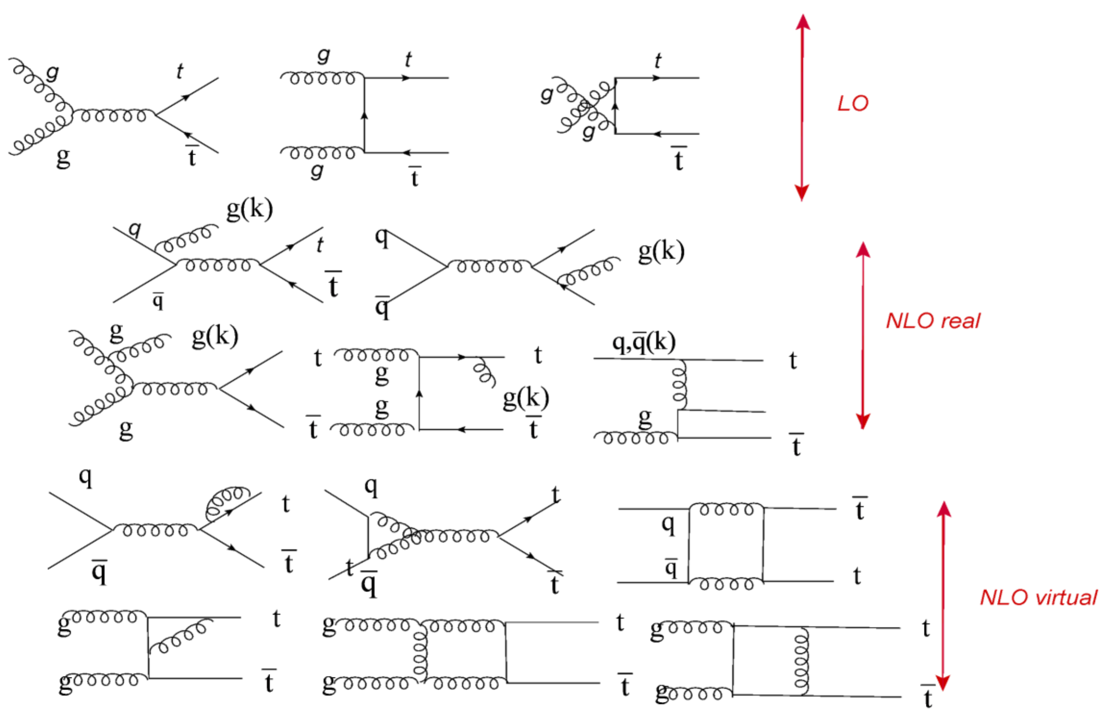
1. For incoming hadrons we should know about the parton distribution functions (PDFs), which are the momentum distribution functions of the partons within the proton and for expressing them we need fitting to data. They are necessary for calculating production cross sections at hadron colliders.
2. We have some initial- and final-state radiations (ISR and FSR) which are in the domain where perturbative calculations can be applied so we can use “QCD evolution equations for parton densities” (DGLAP).
3. Also hard processes occur, so we need matrix element calculation at LO, NLO, ... level.
4. Furthermore we should measure and interpret the underlying event which is the soft component of a collision which adds further particles to the overall event activity.
5. And at last to investigate the hadronization, fragmentation functions which represent the probability for a parton to fragment into a particular hadron, are needed.



In this project we are concerned only with the **second** and the **third** parts.

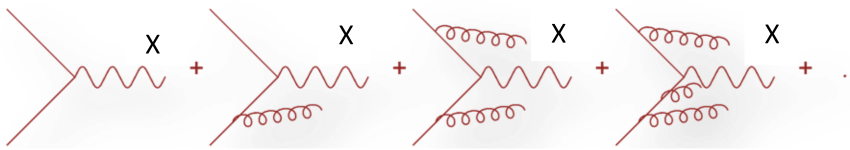
Hard scattering

For hard scattering processes the (differential) cross section can be expressed as: $\frac{d\sigma}{dQ_T^2} \sim \alpha_s + \alpha_s^2 + \alpha_s^3 + ...$
As an example the following picture is the top pair production up to NLO order at LHC:

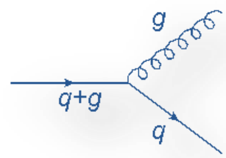


Initial and Final-state soft gluon radiations:

Soft gluons are very easy to radiate and this affects the p_T distribution of particle X:



Initial or final-state collinear and soft emission (always with $k_T > \Lambda_{QCD}$) are strongly enhanced, due to the vanishing denominator in the propagator of the parent:



$$\frac{1}{(q+g)^2 - m_q^2} = \frac{1}{2E_g E_q(1-\beta_q \cos\theta_{qg})}$$

soft divergence if $E_g \to 0$

collinear if $\theta_{qg} \to 0$ (only if $m_q = 0$)

So in some kinematics regions (e.g. at low Q) terms of the form: $\alpha_s^{\,n} \ln(Q^2/Q_T^{\,2}) = \alpha_s^{\,n} L$ are large. If L is large, the following terms are effectively of the same order:

$$\alpha_s(1+L) \sim \alpha_s^2(L^2+L^3) \sim \alpha_s^3(L^4+L^5)$$

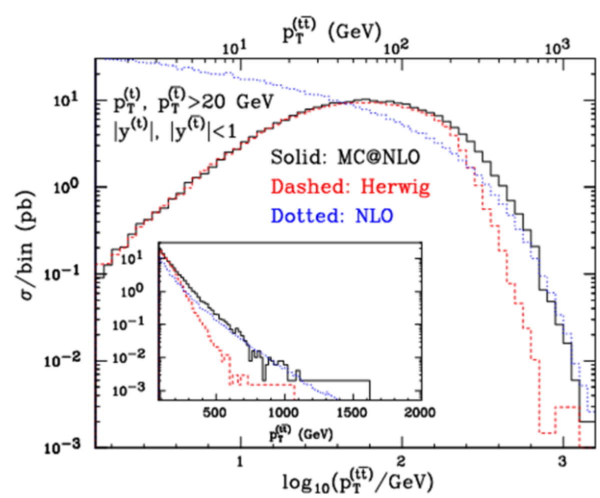
We need to re-order the terms of the perturbative expansion of differential cross section and use Log resummation instead of fixed-order calculation to preserve the convergence of the new perturbative sequence:

$$\frac{d\sigma}{dQ_T^2} = Q_T^{-2}\{\boxed{\alpha_s(1+L)} + \boxed{\begin{matrix}\alpha_s^2(L^2+L^3)\\ +\alpha_s^2(1+L)\end{matrix}} + \boxed{\begin{matrix}\alpha_s^3(L^4+L^5)\\ +\alpha_s^3(L^2+L^3)\\ +\alpha_s^3(1+L)\end{matrix}} + \ldots\}$$

$$\frac{d\sigma}{dQ_T^2} = Q_T^{-2}\{\boxed{\alpha_s(1+L)+\alpha_s^2(L^2+L^3)+\alpha_s^3(L^4+L^5)} + \boxed{\alpha_s^2(1+L)+\alpha_s^3(L^2+L^3)} + \boxed{\alpha_s^3(1+L)} + \ldots\}$$

NLO + soft gluon emission example: $t\bar{t}$

Here we can see the top-pair spectrum in p-p collision at the LHC.



- ✓ **NLO:**
  If we only consider the NLO contribution in calculating cross section, the distribution is good for total x-section and high-p_T, but it is bad at low-p_T ($t\bar{t}$ often produced at rest which is not the case in reality). NLO calculation fails in low-p_T because large logarithms are not properly resumed. But if we are interested in high-p_T NlO calculations are reliable. (**blue curve**)

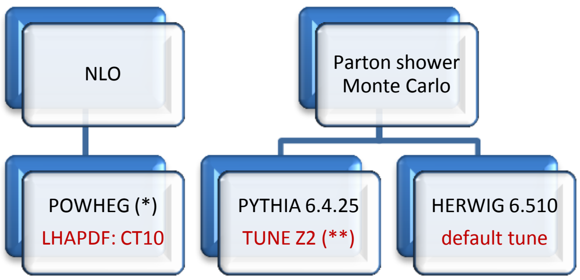
- ✓ **Parton-shower MC (LO):**
  Parton Shower models, simulate gluon radiation in initial and final states. Their algorithms are based on resummation of the leading soft and collinear logarithms. Parton showers exellently describe phase space regions dominated by soft and collinear gluon emission, but ignore large energy, wide

angle gluon emmision. So the SMC distribution is good for low-p_T but it misses total x-section (only considers LO order) and high-p_T. (**red curve**)

✓ **NLO + parton-shower**:
A combination of Parton showers and matrix element calculations that makes best use of each method's strengths, is thus desirable and it is good everywhere. (**black curve**)

Goals of study and theoretical tools:

Goal: Study low part of p_T distributions for various heavy-particles: DY,W, Z, H and $t\bar{t}$.
How: Studying the evolution of the peak of $d\sigma / dp_T$ (whose position is dominated by soft-gluon resummation effects) as a function of the mass of the particle and $\sqrt{s}$.
Tools:



* POsitive Weight Hardest Emission Generator (Avoids double-counting of parton-shower contributions based on p_T of parton)
** Tune: models semi-hard and non-perturbative part of collision: MPI, UE, hadronization, ...

Monte Carlo production for DY, W, Z, H, and $t\bar{t}$

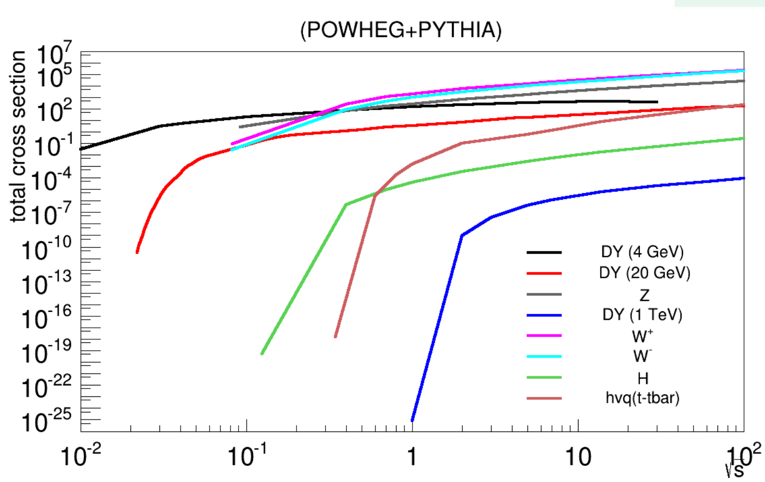
- We run **POWHEG+PYTHIA** and **POWHEG+HERWIG** for energies between threshold (4 GeV for DY lowest) to $\sqrt{s} = 100 \quad \text{TeV}$

- We obtain the differential $d\sigma / dp_T$ at each $\sqrt{s}$ and we determine the peak of the distribution.

Total MC production:

8 systems × 10 energies × 2 parton-showers = 160 files

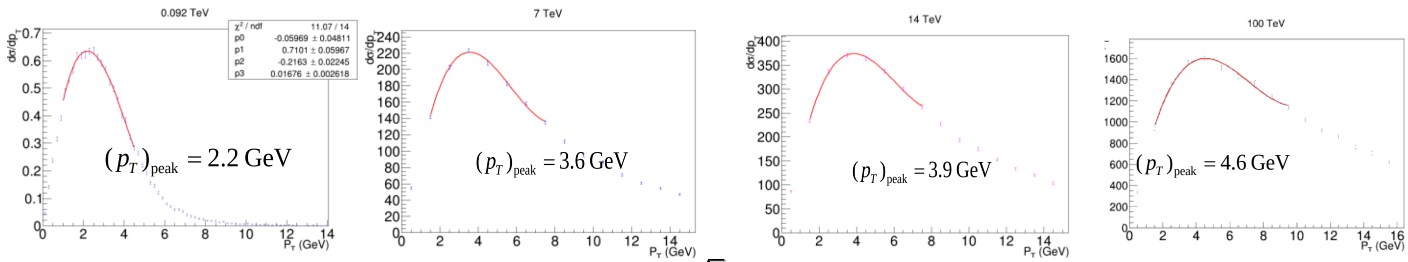
SYSTEMS STUDIED
DY (4 GeV)
DY (20 GeV)
W^+
W^-
Z
H
t-tbar
DY (1 TeV)



Total cross section versus $\sqrt{s}$ for different systems

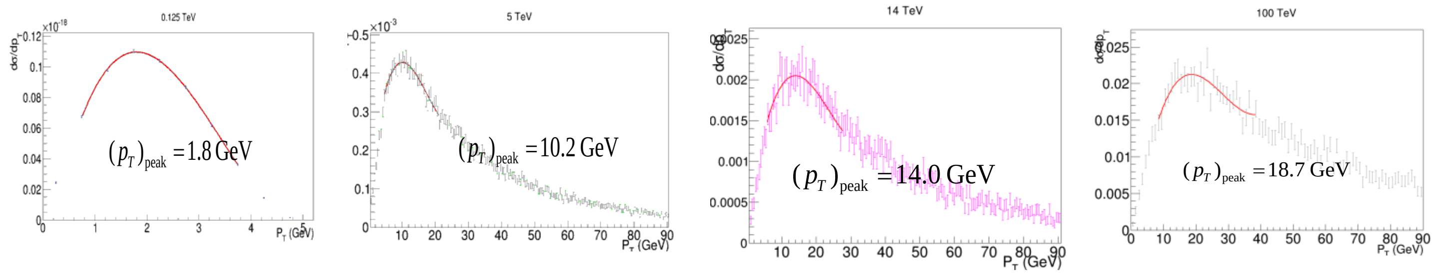
$d\sigma / dp_T$ for Z:

Local fit (e.g. polynomial 3) for finding peak of p_T distribution :



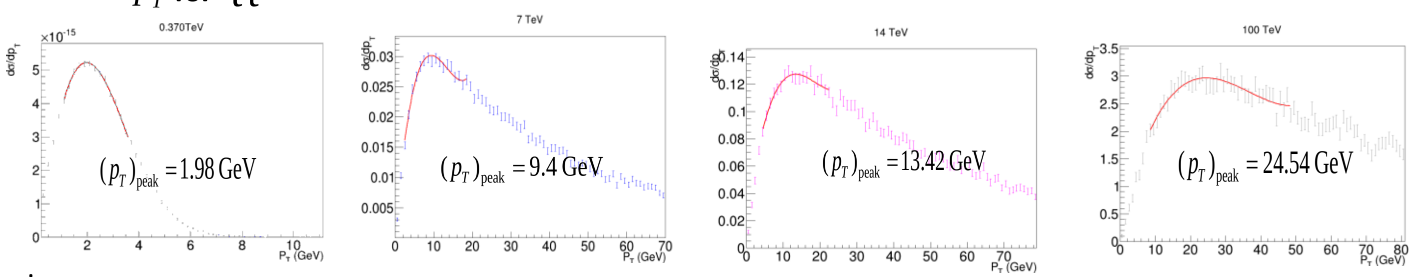
- ✓ The p_T -distribution gets harder with increasing $\sqrt{s}$.
- ✓ The peak position increases slowly (logarithmically) with energy.
- ✓ Similar generic behaviour found for W and DY.

$d\sigma / dp_T$ for gg ⟶ Higgs (125 GeV)



- ✓ The p_T -distribution gets harder with increasing $\sqrt{s}$.
- ✓ The peak position increases logarithmically with energy, but (much) faster than for Z: Gluons ($gg \to H$) radiate more than quarks ($q,\bar{q} \to Z$).

$d\sigma / dp_T$ for $t\bar{t}$



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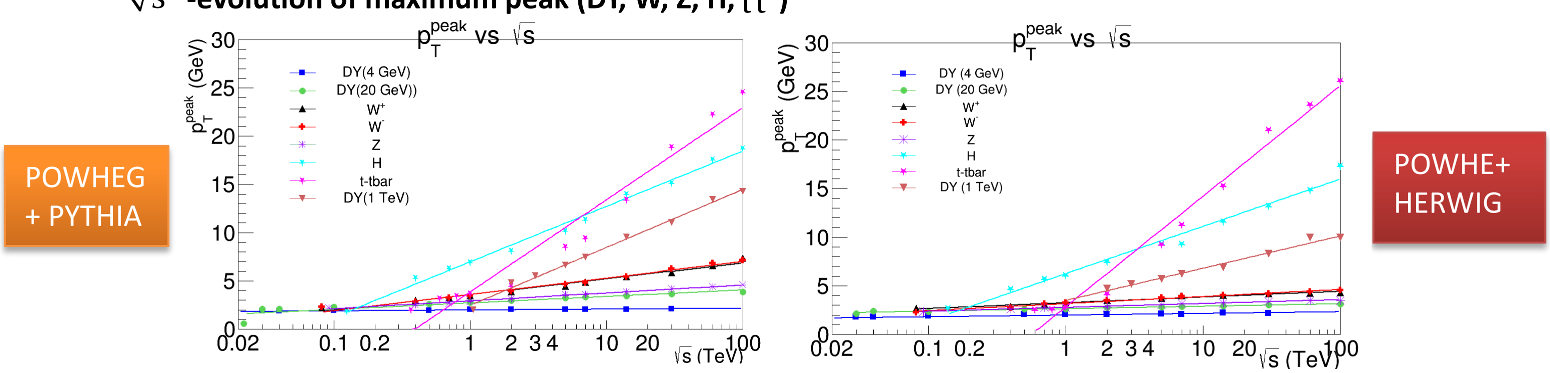
- ✓ The p_T -distribution gets harder with increasing $\sqrt{s}$
- ✓ The peak position increases faster than for H or Z: $t\bar{t}$ is heavier than Higgs and it's mostly produced by gluons (which radiate more than $q,\bar{q} \to Z$).

$\sqrt{s}$ -evolution of maximum peak (DY, W, Z, H, $t\bar{t}$)

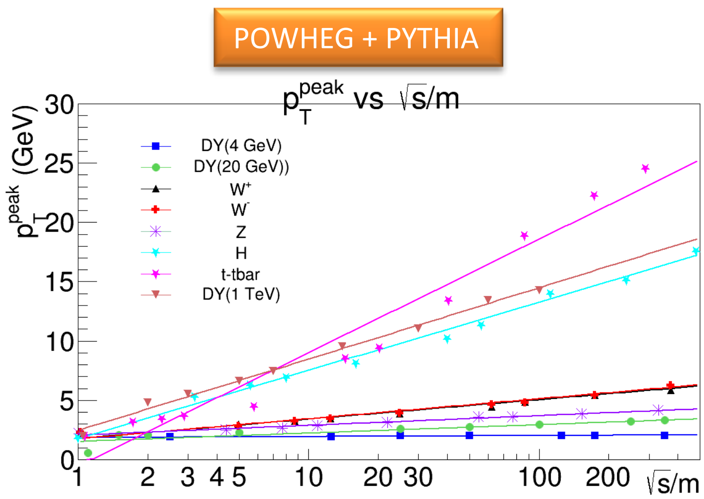


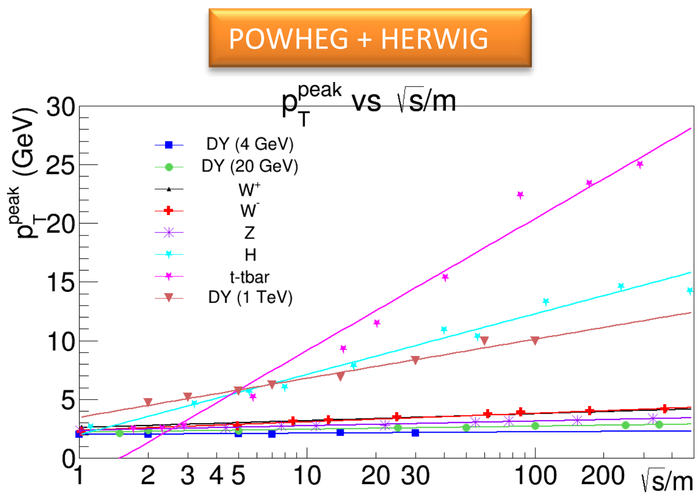
- ❑ HERWIG tends to predict smaller p_T (peak) than PYTHIA.
- ❑ **Fit to** $A\log(B\sqrt{s})$

1) At threshold, minimum $p_T^{\text{peak}} = 2\,\text{GeV}$ (intrinsic parton k_T).
2) Slope B increases as $\log(\sqrt{s})$ for DY, W, Z, H but faster, as a power law (s^n), for $t\bar{t}$.
3) The slope is higher for heavier particles (higher virtuality to radiate) and for gluon-induced processes (compared to quark).

$\sqrt{s}/m_X$ -evolution of maximum peak (DY, W, Z, H,$t\bar{t}$)

Evolution versus normalized $\sqrt{s}/m_X$ factorizes out effects due to different masses:





- ❑ The same results as the previous one.

Summary:

- ✓ The peak of $d\sigma/dp_T$ distribution of a heavy particle produced in p-p collisions is mostly determined by soft-gluon emission of the colliding partons.
- ✓ We study the evolution of the peak of $d\sigma/dp_T$ as a function of the mass of the particle and $\sqrt{s}$ using NLO+"NLL" soft-gluon resummation tools (POWHEG + parton-shower: PYTHIA or HERWIG) for the following systems: DY, W, Z, H, $t\bar{t}$ in the range $\sqrt{s} \sim$ threshold –100 TeV
- ✓ The p_T-distribution for all particles gets harder with increasing $\sqrt{s}$.
- ✓ HERWIG tends to predict smaller p_T (peak) than PYTHIA.
- ✓ The peak position increases logarithmically with energy and with the mass of the system.
- ✓ The speed of increase of p_T (peak) is faster for gluon-dominated processes (Higgs, $t\bar{t}$) than for quark-induced ones (DY, W, Z) as expected: gluons radiate 2.25 times more than quarks.

Outlook:

- ❑ We want to cross-check the POWHEG + parton-shower results with those obtained from analytical NNLO+NNLL calculations (e.g. RESBOS and DYRES for Z boson).
- ❑ We'll try to determine the quantitative scaling-law governing the increase of p_T (peak) with $\sqrt{s}$ and m_X .