# 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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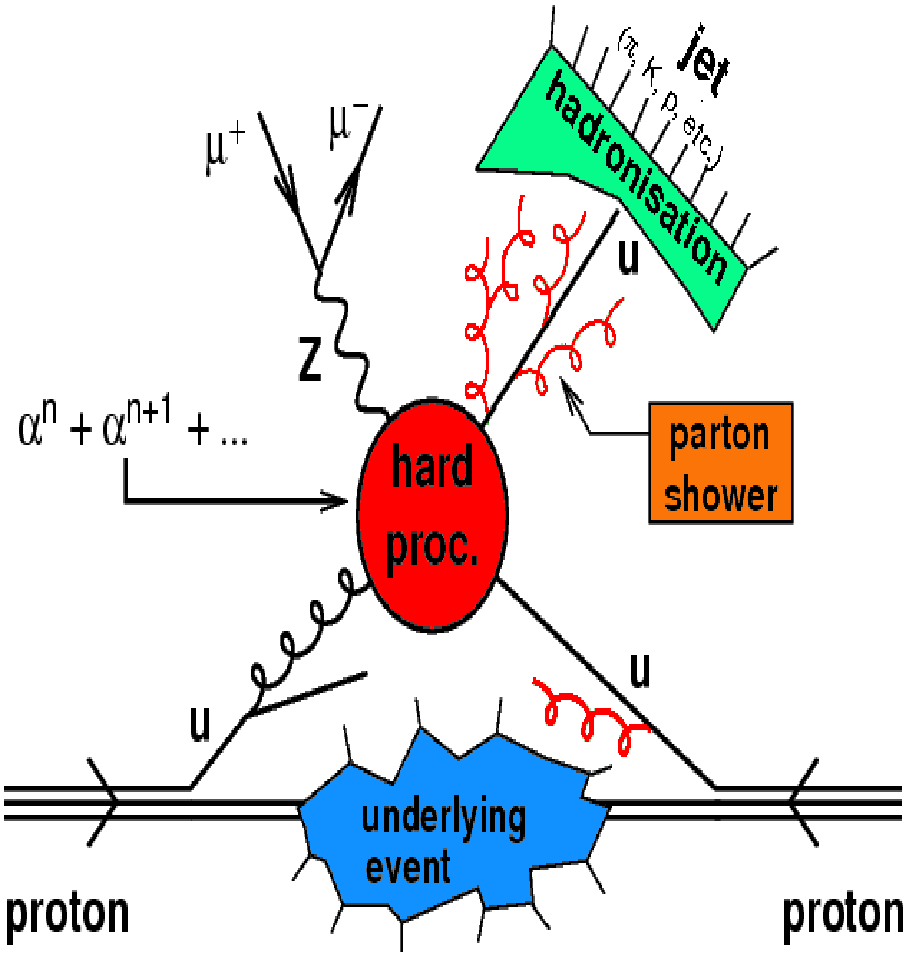
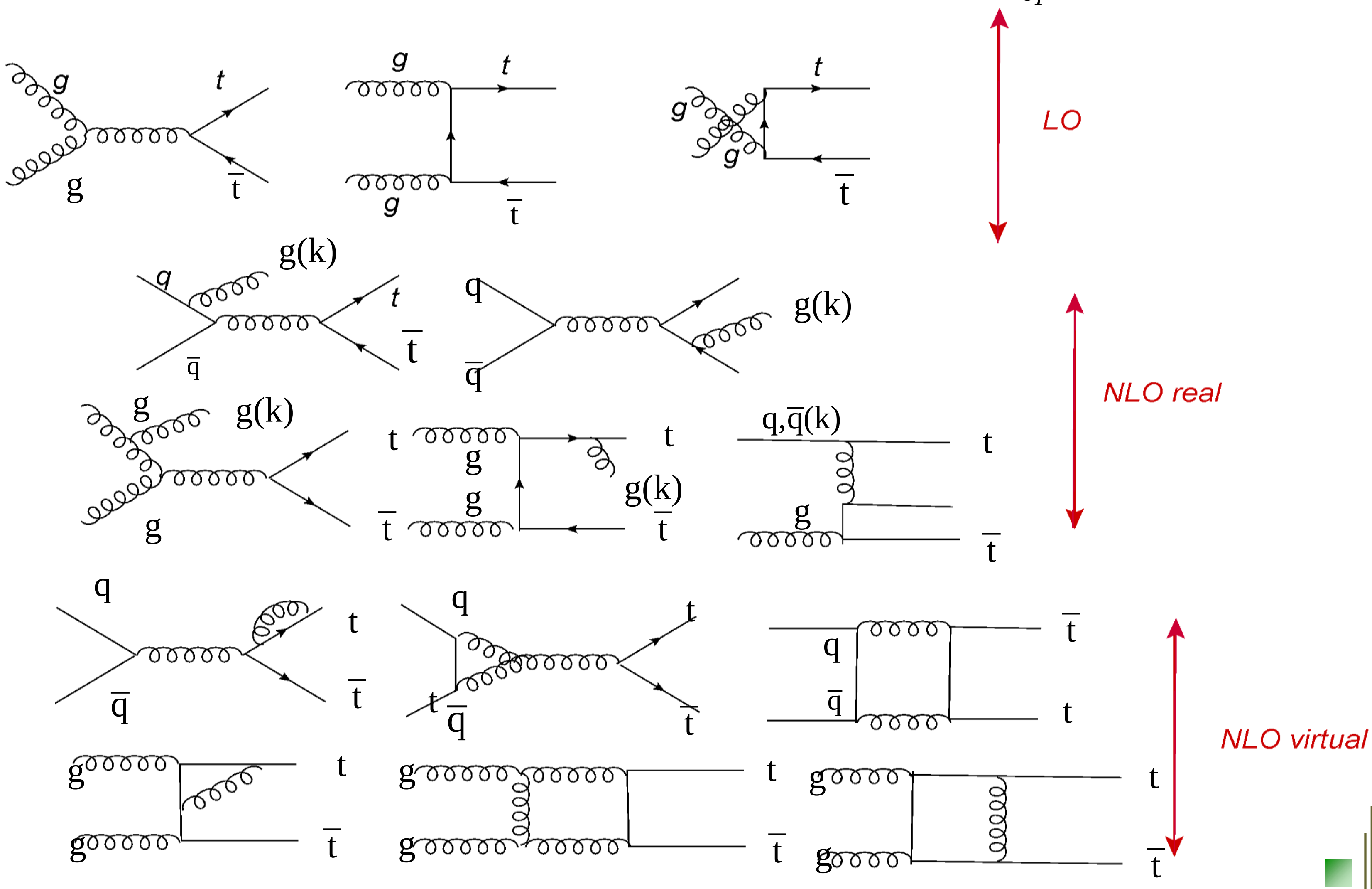
# Typical proton-proton collision

1. Incoming hadron
   ➡ Parton distribution function (fitted to data)
2. Initial-state radiation (ISR)
   ➡ DGLAP parton evolution
3. Hard scattering:
   ➡ Matrix element calculation at LO, NLO, ... level
4. Final state radiation
   ➡ DGLAP parton evolution
5. Underlying event
   ➡ Multiple softer parton interactions
6. Hadronization
   ➡ Parton fragmentation functions (fitted to data)



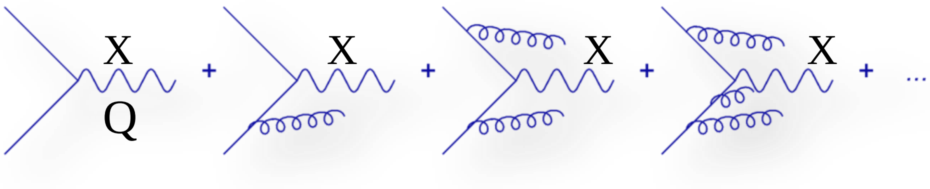
# Hard scattering example: top pair production (NLO)

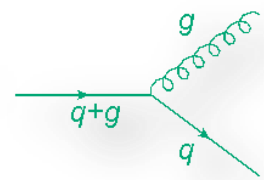
The (differential) cross section can be expressed as: $\frac{d\sigma}{dQ_T^2} \sim \alpha_s + \alpha_s{}^2 + \alpha_s{}^3 + \ldots$



# Soft gluon radiation

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




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

soft divergence if $E_g \to 0$

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

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.

Thus, 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:

**fixed-order calculation**

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

**Log resummation**

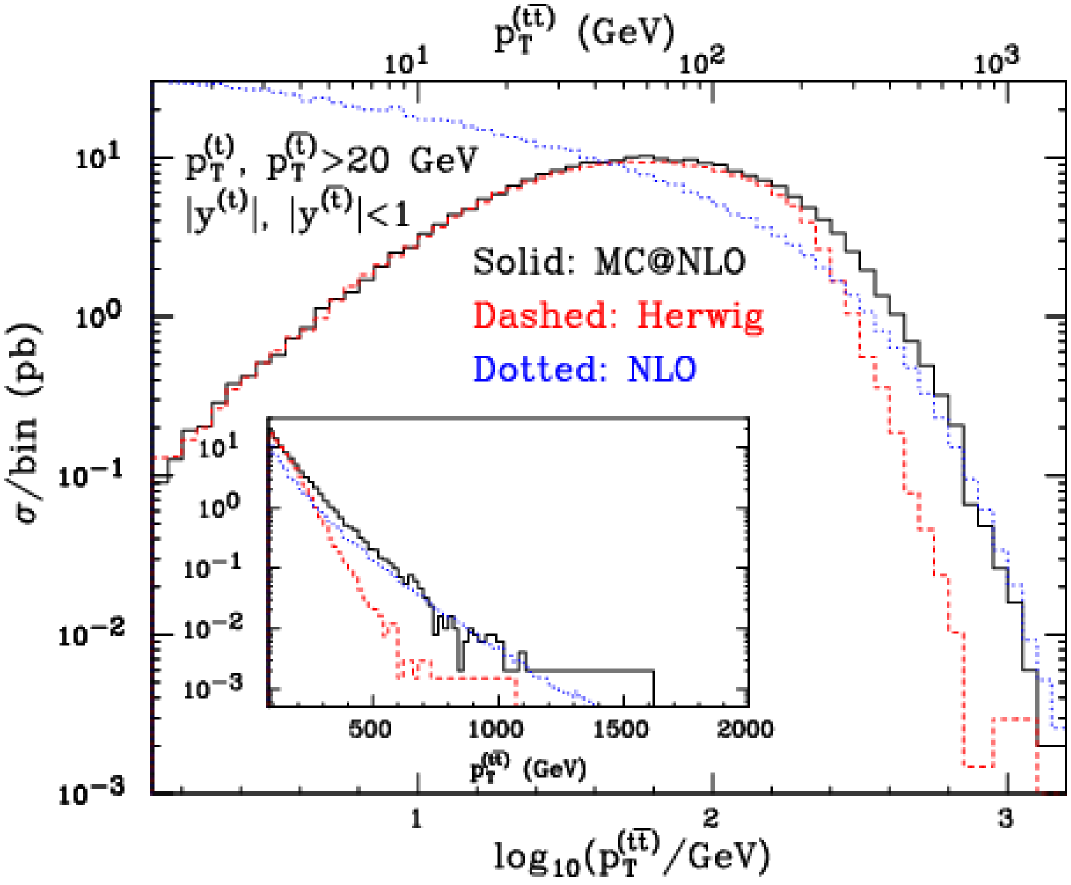
$$\frac{d\sigma}{dQ_T^2} = Q_T^{-2}\{\alpha_s(1+L) + \alpha_s^2(L^2+L^3) + \alpha_s^3(L^4+L^5)$$
$$+\alpha_s^2(1+L) + \alpha_s^3(L^2+L^3)$$
$$+\alpha_s^3(1+L) + \ldots\}$$

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

1) Parton-shower (LO):
Soft & collinear gluon emission via Monte Carlo
**Good:** low-$p_T$ distribution
**Bad:** it misses total x-section and high-$p_T$

2) NLO:
**Good:** total x-section & high-$p_T$
**Bad:** Artificially large distribution at low-$p_T$ ( $t\bar{t}$ often produced at ~rest)

3) NLO+parton-shower:
**Good:** everywhere…



# 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**:

**NLO** + **Parton shower Monte Carlo**

POWHEG
**LHAPDF:**
CT10 & MSTW2008nlo & NNPDF23_nlo
**Factorization and renormalization scales:**
$m_X$ & 0.5 $m_X$ & 2 $m_X$

**PYTHIA 6.4.25**
**TUNE Z2(*)**

**HERWIG 6.510**
**default TUNE**

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, ...

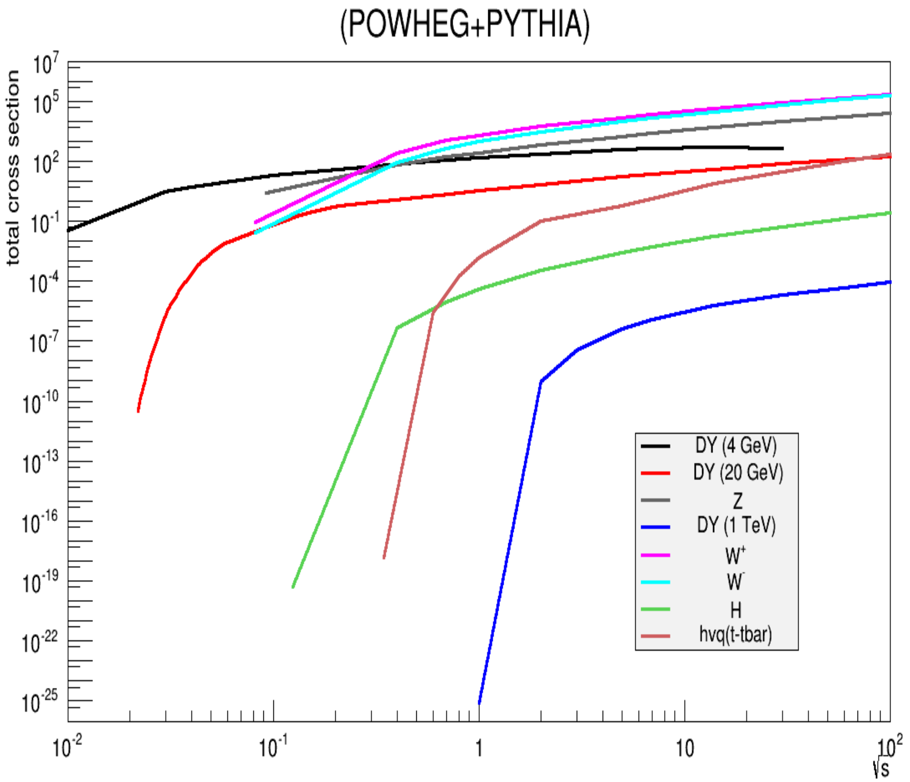
# Monte Carlo production for DY, W, Z, H, and $t\bar{t}$

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

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

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

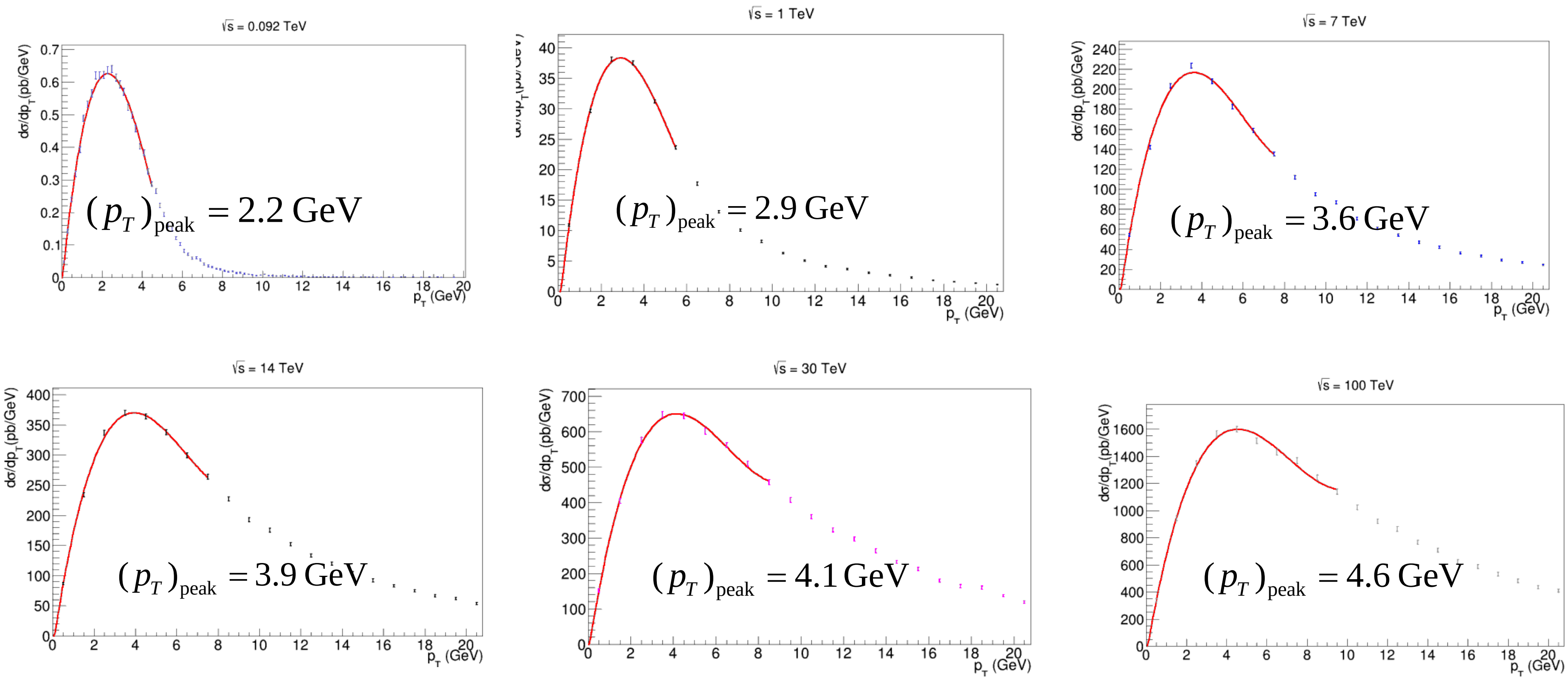
**Total cross sections versus $\sqrt{s}$**




Total MC production: 3 PDF sets × 2 renormalization scales × 8 systems × 10 energies × 2 parton-showers = 960 files

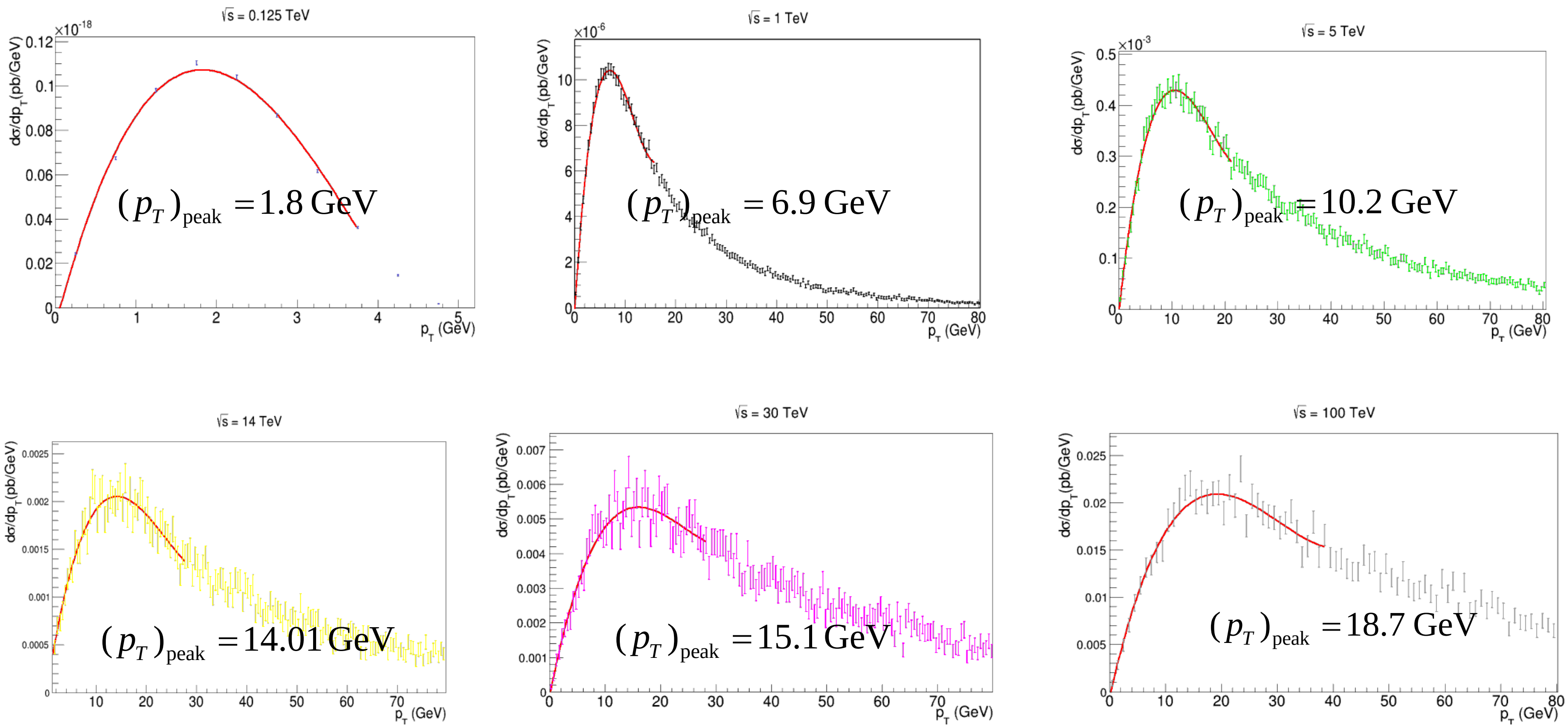
# $d\sigma / dp_T$ for Z, PDF set: CT10nlo & $(\mu_f, \mu_R) = (m_X, m_X)$

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



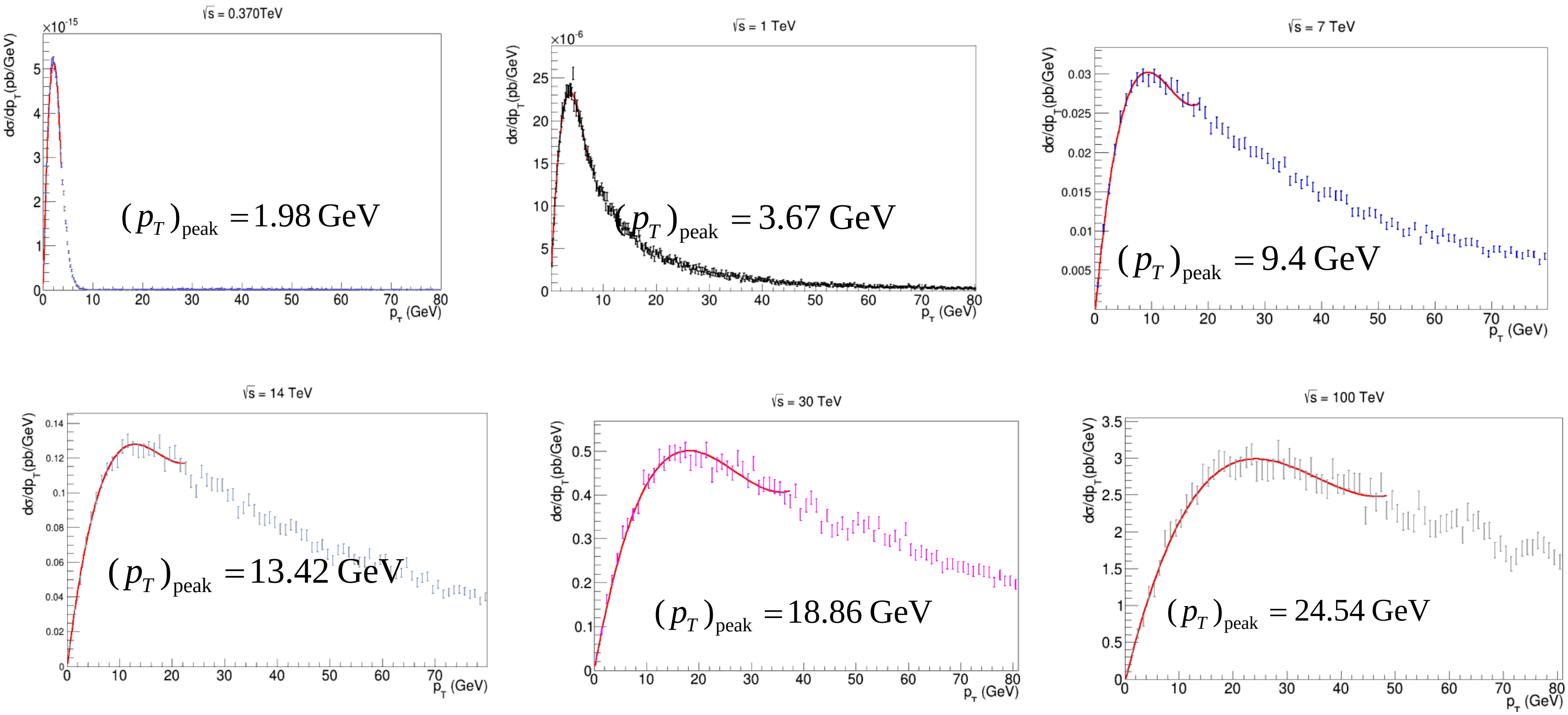

- ✓ The $p_T$ -distribution gets harder with increasing $\sqrt{s}$ .
- ✓ The peak position increases slowly (logarithmically) with energy.
- ✓ Similar generic behaviour found for W and DY.

# $d\sigma / dp_T$ for $gg \longrightarrow$ Higgs(125 GeV) , PDF set: CT10nlo &$(\mu_f, \mu_R) = (m_X, m_X)$




- ✓ 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 $t\bar{t}$, PDF set: CT10nlo & $(\mu_f, \mu_R) = (m_X, m_X)$

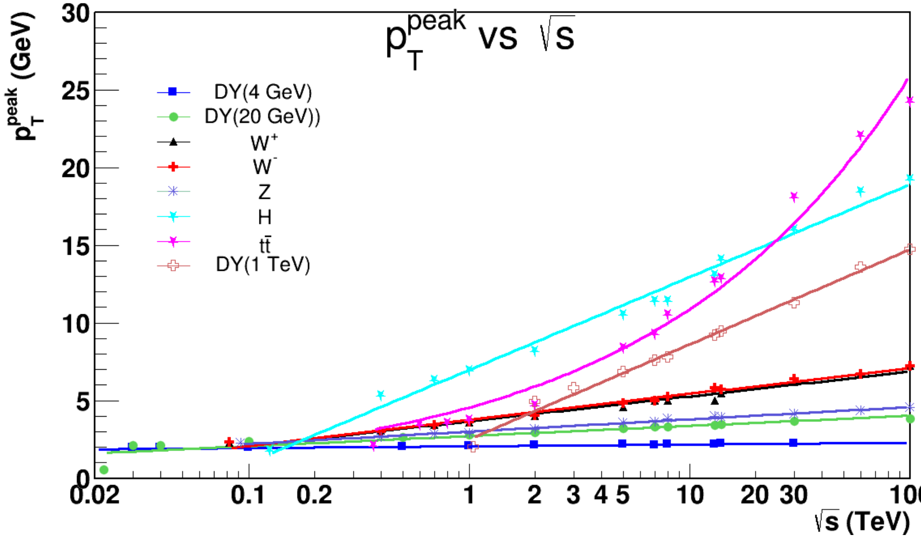



- ✓ The $p_T$-distribution gets harder with increasing $\sqrt{s}$.
- ✓ The peak position increases faster than for H or Z: $t\bar{t}$ is heavier than Higgs and it's mostly produced by gluons (which radiate more than $q,\bar{q} \rightarrow Z$).

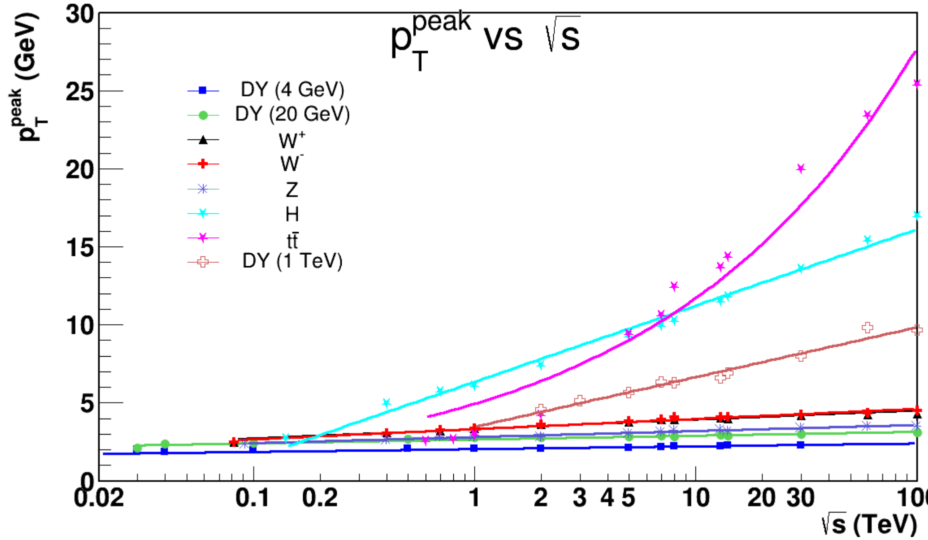
# $\sqrt{s}$ - evolution of maximum peak (DY, W, Z, H, $t\bar{t}$ )



POWHEG + PYTHIA




POWHEG + HERWIG

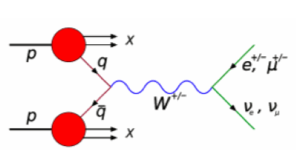


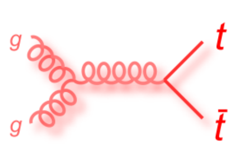

- ❑ HERWIG tends to predict smaller $p_T$ (peak) than PYTHIA.
- ❑ Logarithmic and power-law fits

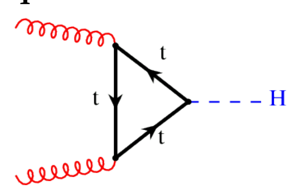
I. At threshold, minimum $p_T^{\text{peak}} = 2\,\text{GeV}$ (intrinsic parton $k_T$ ).

II. The Slope increases as $\log(\sqrt{s})$ for DY, W, Z, H but faster, as a power law ($s^n$), for $t\bar{t}$ .

III. The slope is higher for heavier particles (higher virtuality to radiate) and for gluon-induced processes (compared to quark- induced)



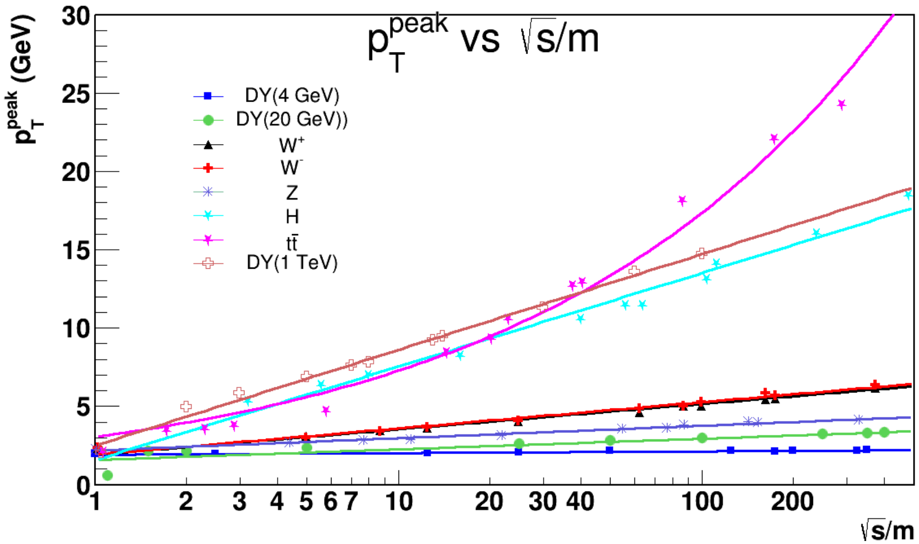

Soft gluon radiation is larger for gluons (two colours) than for quarks (1 colour) by a factor:

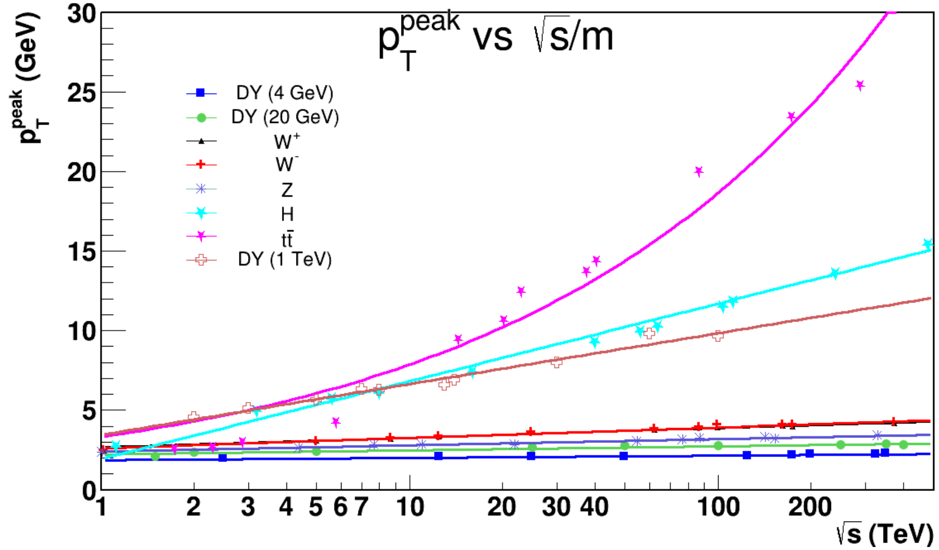
$$2N_c^2 / N_c^2 - 1 = 2.25$$

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

Evolution as a function of normalized $\sqrt{s}/m_X$ factorizes out the effects due to different masses of the produced systems:

**POWHEG + PYTHIA** | **POWHEG + HERWIG**




Logarithmic and power-law fits

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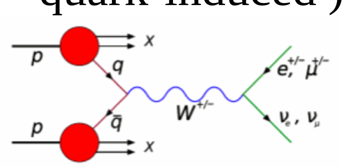
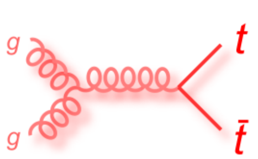
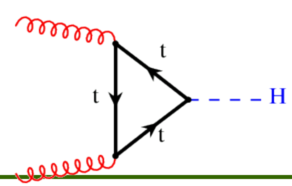
II. The slope increases as $\log(\sqrt{s})$ for DY, W, Z, H but faster, as a power law ($s^n$), for $t\bar{t}$ .

III. The slope is higher for heavier particles and for gluon-induced processes (compared to quark-induced ).



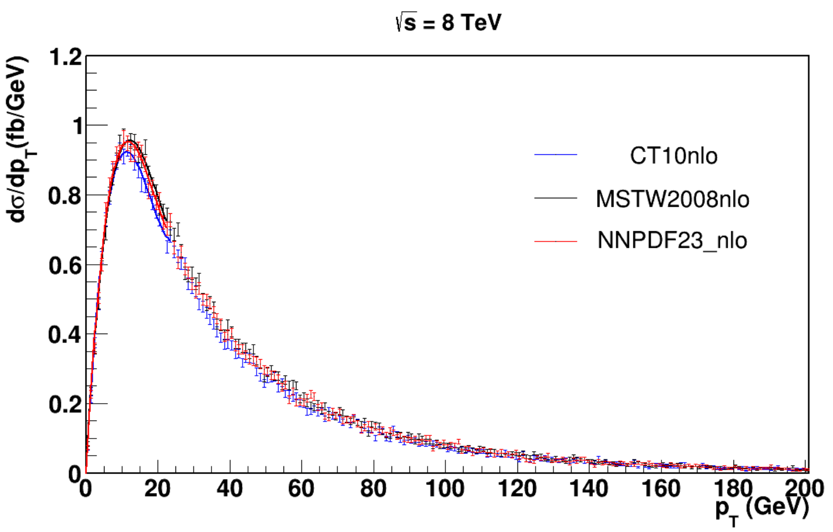



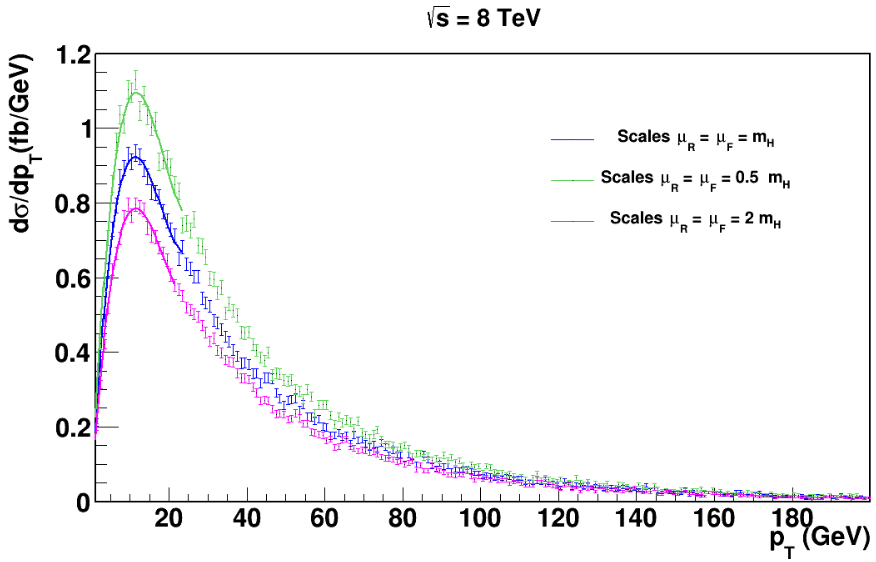




Soft gluon radiation is larger for gluons(two colours) than for quarks (1 colour) by a factor:

$$2N_c^2 / N_c^2 - 1 = 2.25$$

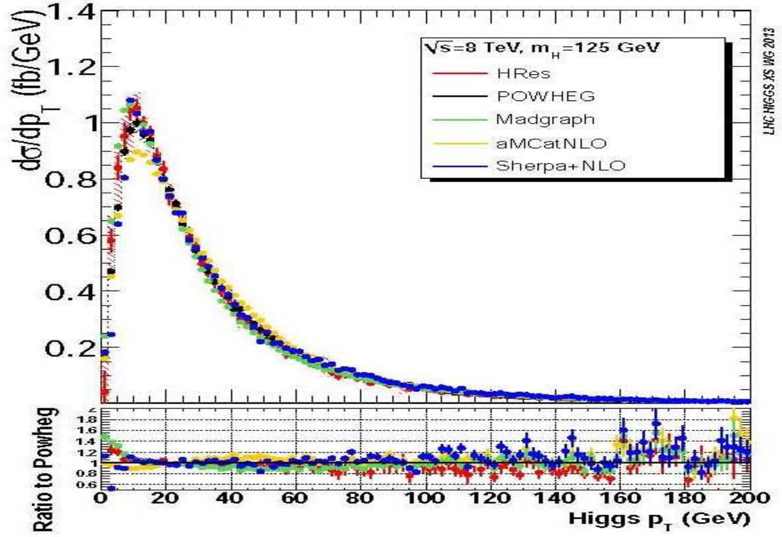
# $d\sigma / dp_T$ for gg $\longrightarrow$ Higgs(125 GeV) for $\sqrt{s} = 8$ TeV for different PDF sets and scales



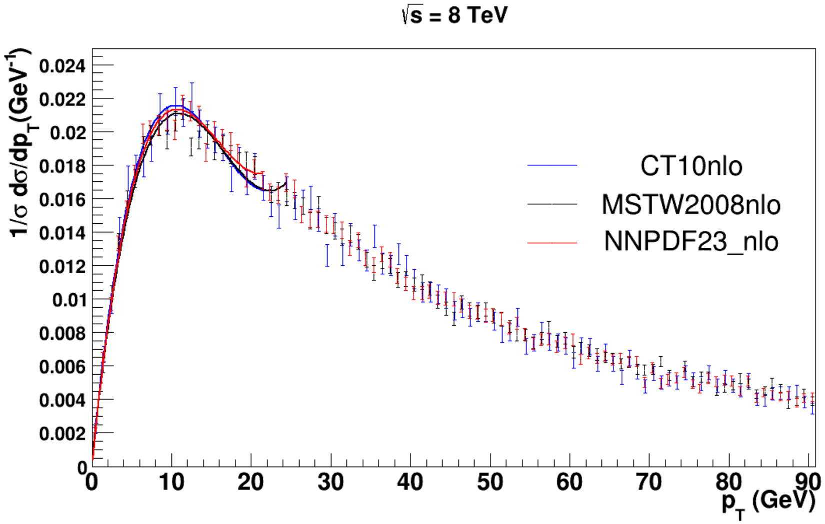



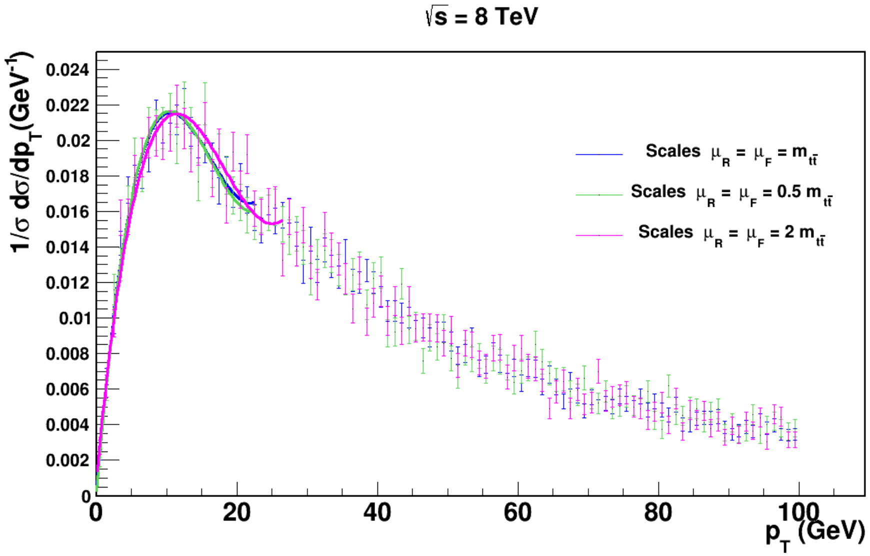

Higgs peak position robust wrt. changes of scales.

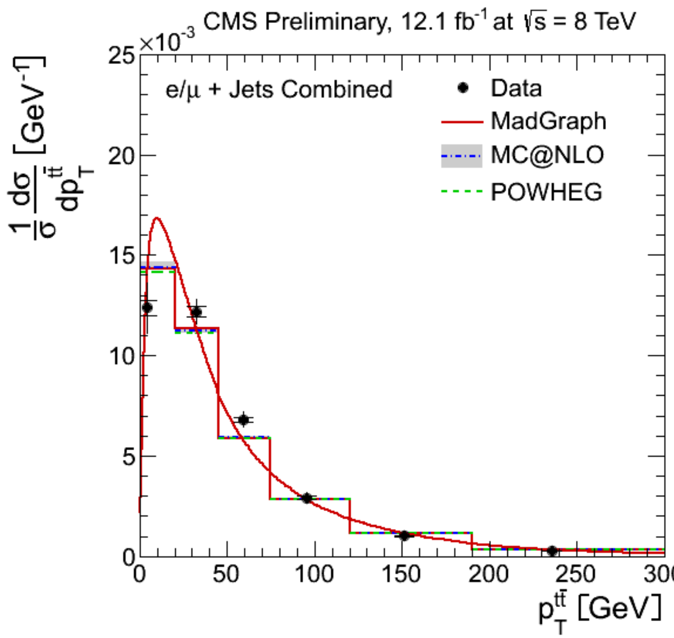
Higgs peak position is a robust observable, consistent with other calculations (HRes, MadGraph, aMCatNLO and SHERPA+NLO, arXiv:1307.1347 [hep-ph]).



# $d\sigma / dp_T$ for $t\bar{t}$ for $\sqrt{s} = 8$ TeV for different PDF sets and scales



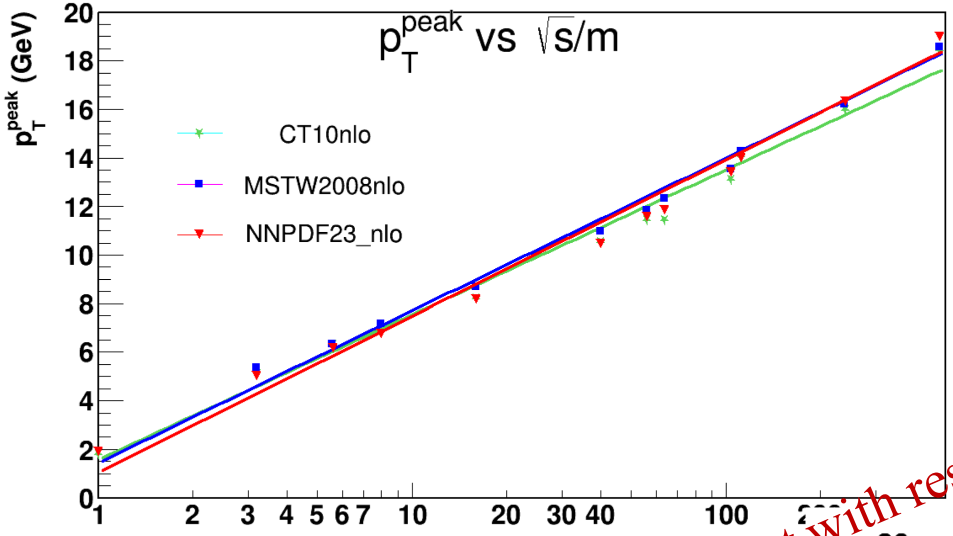



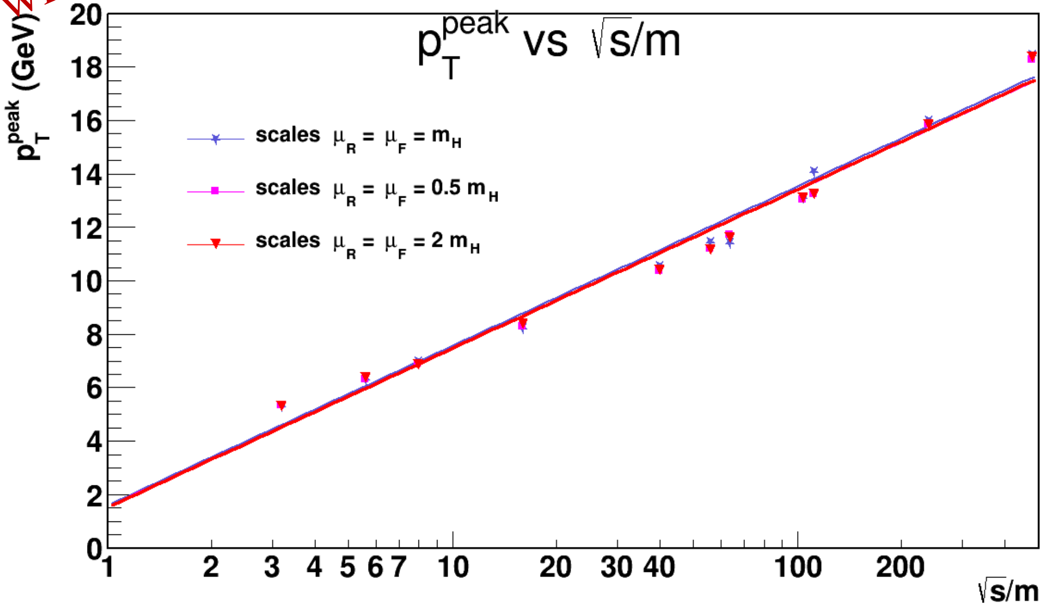




$t\bar{t}$ Peak position robust wrt. changes of scales.

Experimental spectrum should be binned more finely to study low $p_T$ peak position.

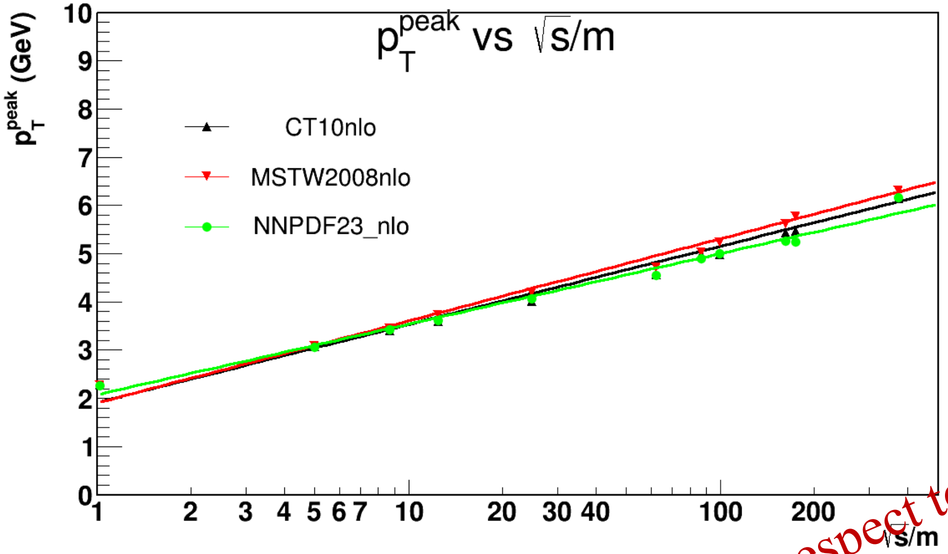
# $\sqrt{s} / m_X$- evolution of maximum peak of H for different PDF sets and scales



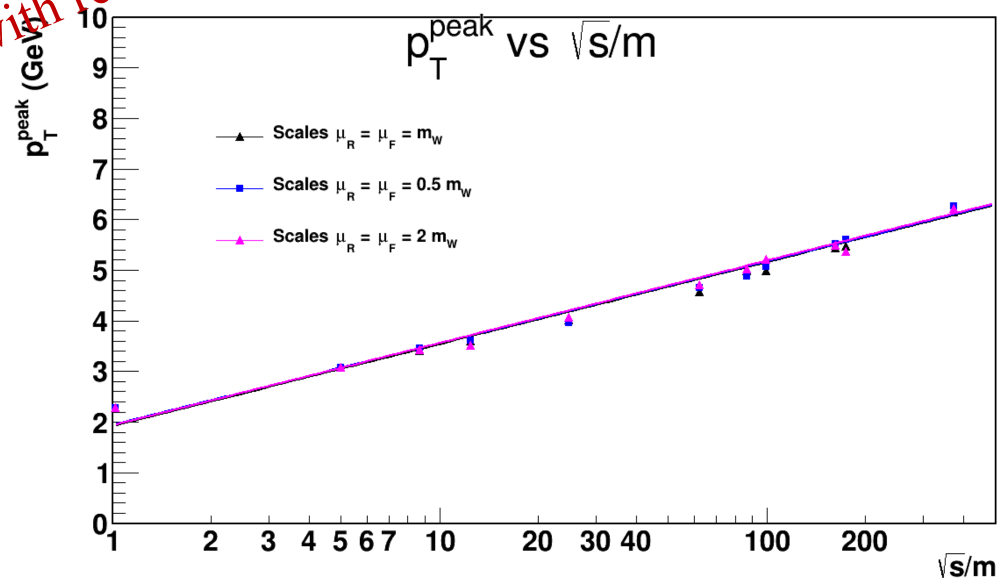




Position of the peak is robust with respect to scale & PDF uncertainties.

# $\sqrt{s} / m_X$- evolution of maximum peak of W for different PDF sets and scales




Position of the peak is robust with respect to scale & PDF uncertainties.



# 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 $\sqrt{s}$ ~ 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.
- ✓ Position of the peak is robust with respect to scale & PDF uncertainties.

# 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 $m_X$.

THANKS

# Backup slides

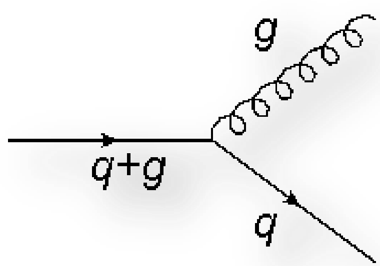
| Analytical $Q_T$ resummation | Parton showering programs (Pythia, MC@NLO, Sherpa...) |
| --- | --- |
| evaluate(s) effects of multiple parton radiation in hadronic scattering | |
| applies to a restricted class of processes and observables (e.g., lepton distributions in Drell-Yan-like processes); inclusive with respect to hadronic radiation | apply to a wide range of observables; exclusive with respect to hadronic radiation |
| is proved to all orders in the QCD coupling by special factorization theorems devised for each qualified observable | no factorization proofs for individual observables |
| streamlined computation of higher-order corrections and high-$p_T$ contributions | beyond the leading order, radiative contributions and high-$p_T$ tails may be difficult to implement |
| resummation of all logarithms $\ln Q_T^2/Q^2$ | resummation of leading logarithms $\ln Q_T^2/Q^2$ |
| nonperturbative contributions are constrained by invoking their universality in the considered class of processes | nonperturbative scattering is evaluated in one of several available models |
| more strict and precise; relies on first principles of perturbative QCD | more flexible; more parameters to tune to describe various hadronic scattering effects |

# POsitive Weight Hardest Emission Generator

- It's a method to generate the hardest emission first, with NLO accuracy, independently from the subsequent shower.
- It generates events with positive weights only. No negative weights to handle.
- It can be interfaced with any SMC program (HERWIG,PYTHIA,SHERPA,...) which comply with the Les Houches User Process Interface and has the capability to veto emissions harder than the first (SCALUP). It is thus possible to compare different outputs.
- Can use existing NLO calculations with little effort. No need to be a SMC expert to implement them.

# Shower Monte Carlo

- 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 $m_q = 0$)

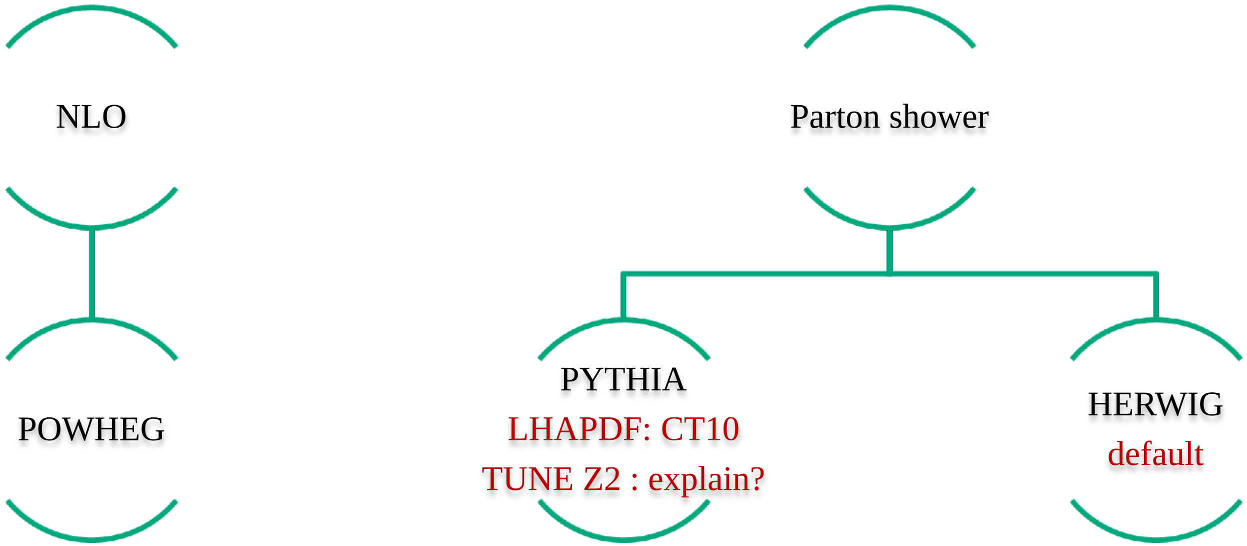
- Shower algorithms evaluate all these enhanced contributions at all orders
- They give a description of hard collisions up to a distance scale of the order $1/\Lambda_{QCD}$ .
- At larger distance perturbation theory breaks down and we need to rely on non perturbative methods (i.e. lattice).

# Shower Monte Carlo

- SMC's contain a large library of hard SM and BSM cross sections.
- They dress the hard event with QCD radiation that enhances the cross section in the soft or collinear limit. From this the name shower.
- They contain models for hadron formation.
- They handle unstable particle decays.

Thanks to factorization theorem we can separate "hard" physics from "soft" one. Parton shower is the link between the two.

Moreover, theoretical basis of the shower are process and energy independent. In principle, once tuned at a certain energy, SMC's have predictive power to all other energies.


NLO
POWHEG
Parton shower
PYTHIA
LHAPDF: CT10
TUNE Z2 : explain?
HERWIG
default

## Differences between HERWIG and PYTHIA

They share many common features but

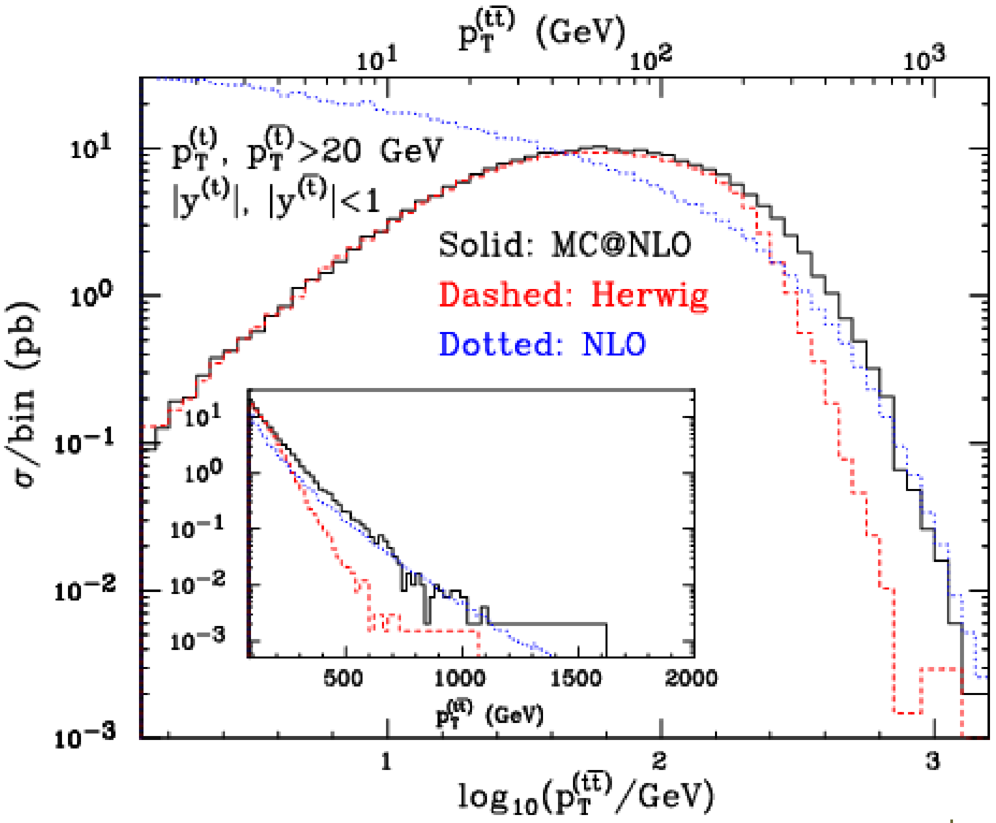
- Their difference is in particular in the treatment of the non-perturbative processes. The PYTHIA philosophy, in fact, is to describe also the hadronisation processes in as much detail as possible.
- They are slightly different also in the description of the hard sub-process.
- Another difference is the scale of the hard scattering, $\mu^2$ ; PYTHIA sets it to the transverse mass of the two outgoing partons, whereas the scale used by HERWIG is given by the Formula:

$$\mu^2 = \frac{2\,\hat{s}\,\hat{t}\,\hat{u}}{\hat{s}^2 + \hat{t}^{\,2} + \hat{u}^2}$$

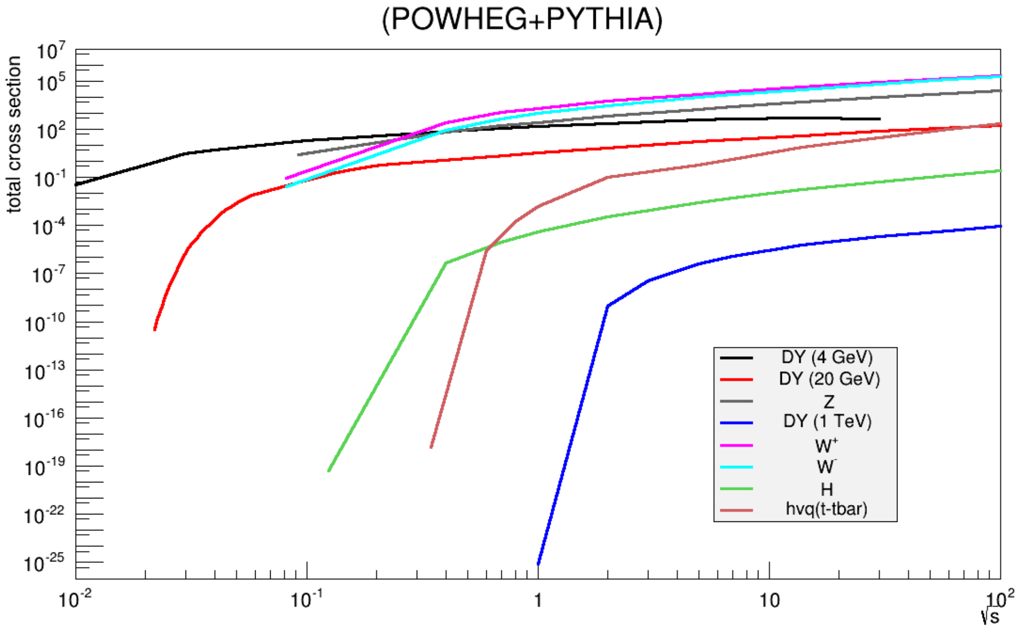
- I will complete this slide when I understand well.

we should include full NLO calculation in SMC's, avoiding double-counting of radiation. This would merge benefits of both approaches:

- Observables integrated over singular regions are reasonably described by both approaches.
- At low $p_T$ , exclusive observables, sensitive to IR singularities, are well described by SMC's). NLO calculation fails in this region because large logarithms are not properly resummed.
- If interested in high pT (LHC, Tevatron) NLO calculation is more reliable.



# Results


(POWHEG+PYTHIA)
total cross section
√s
DY (4 GeV)
DY (20 GeV)
Z
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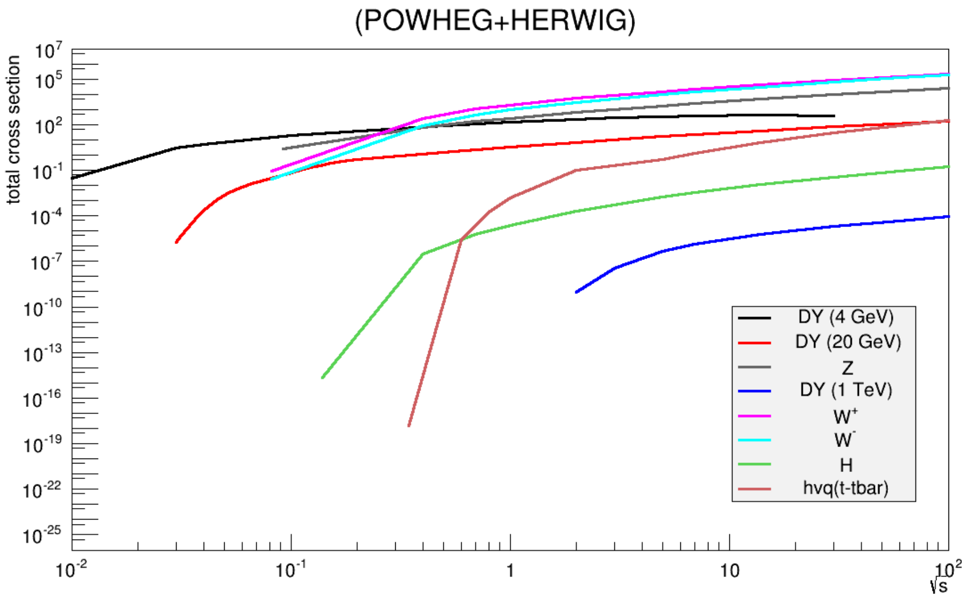
W+
W-
H
hvq(t-tbar)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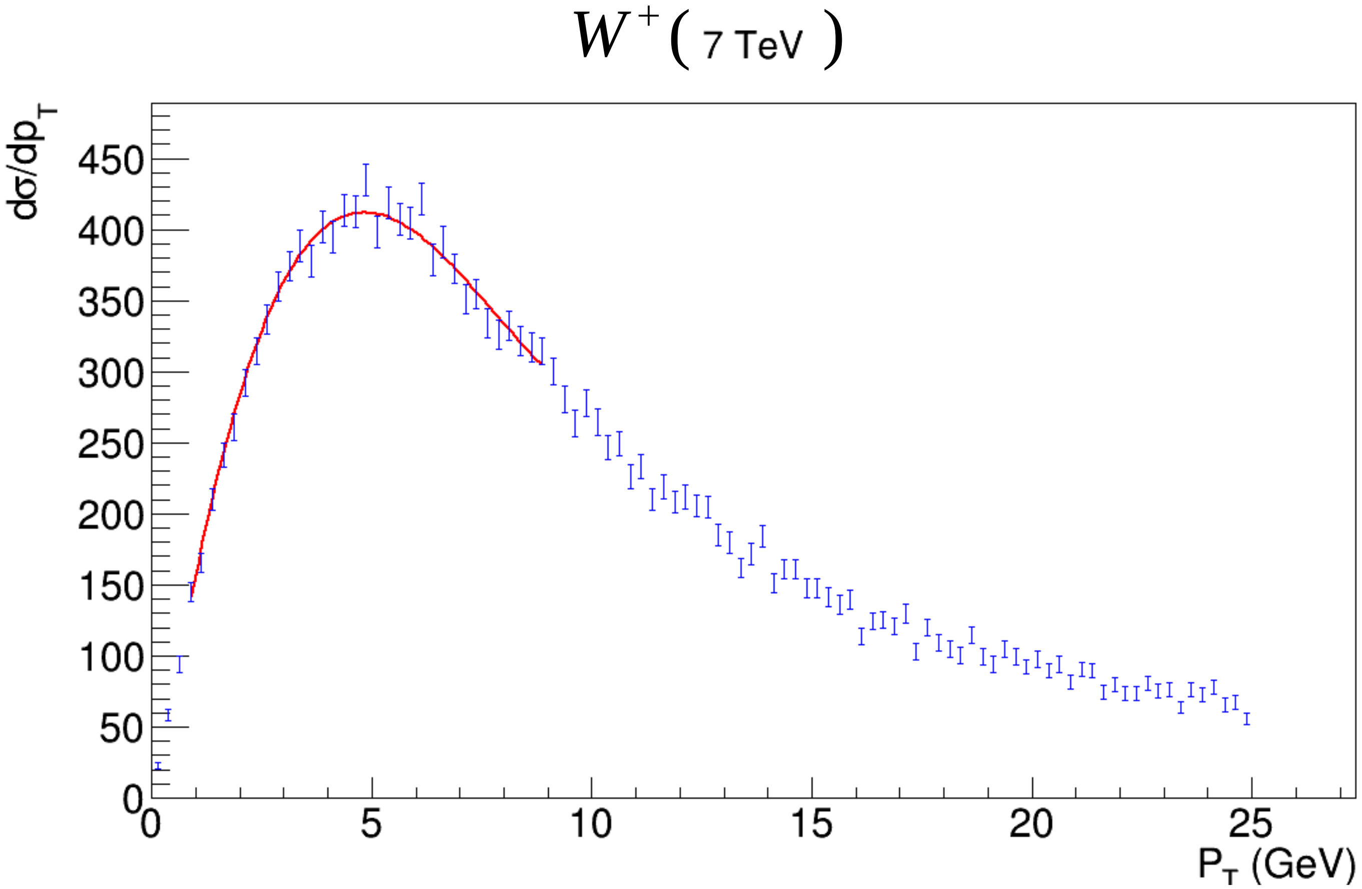
# Results

Local fit for finding peak: Polynomial 3



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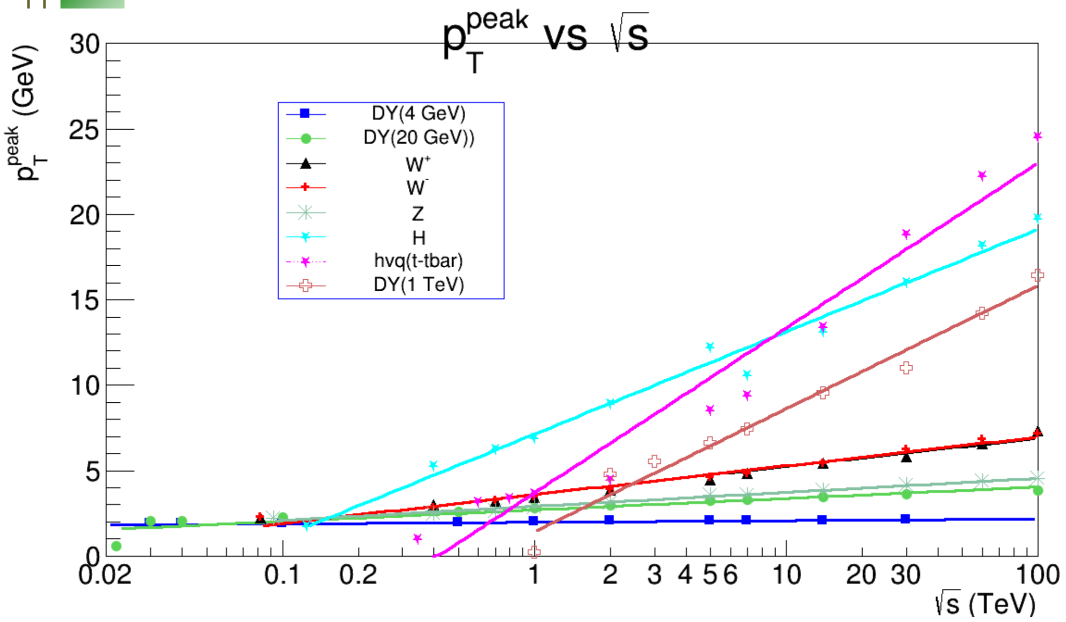
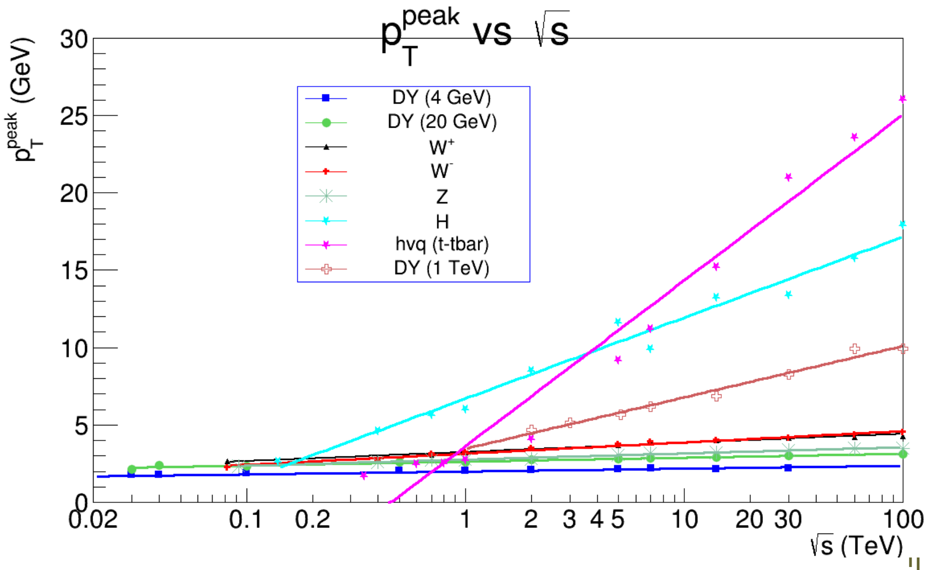
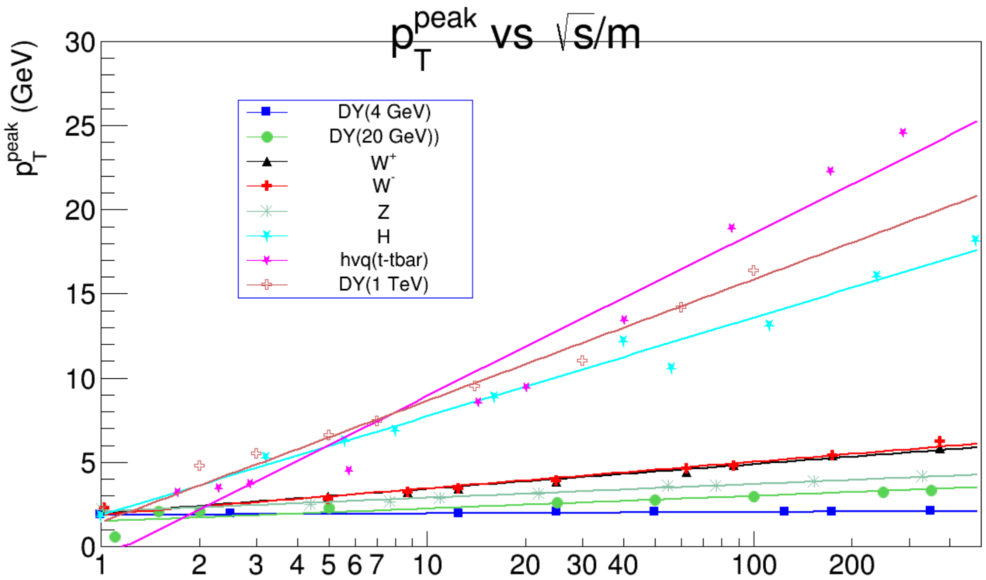



POWHEG + PYTHIA

POWHEG + HERWIG

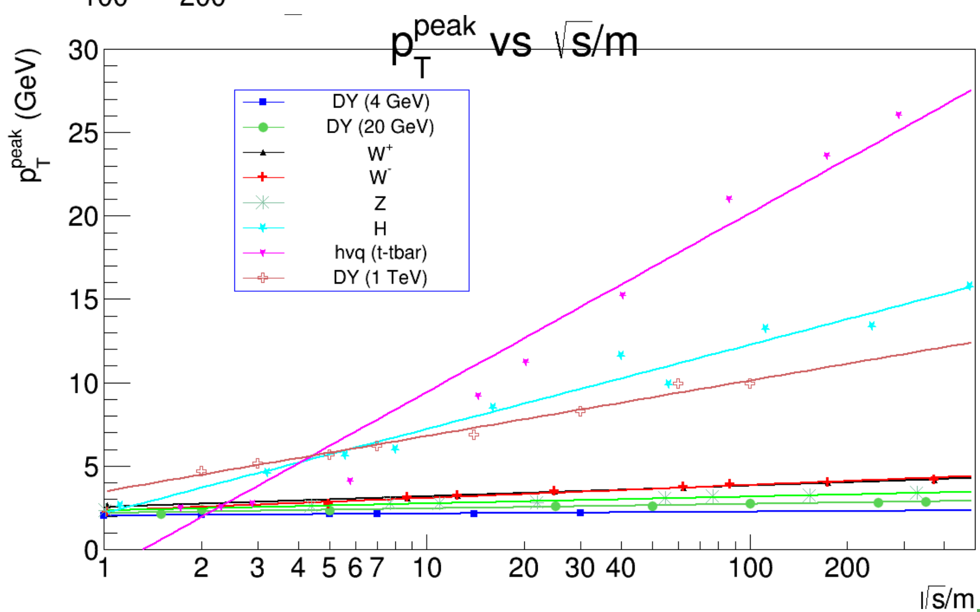


# Results




POWHEG + PYTHIA

POWHEG + HERWIG



# Conclusions

- All of them start at 2 GeV. Except hvq. Why?
- As the particles become heavier, the slope becomes greater. It is not the case for W+/- and Z. Why?
- Gluon processes have higher peaks than quark processes.