Higgs $p_T$ at LHC: Parton Shower vs Resummation

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Motivation – Change in PYTHIA

- Large discrepancy in Higgs $p_T$ distribution from PYTHIA 5.7 to 6.1
  - Especially in low $p_T$ region (dominated by soft gluons radiations)
  - Both default versions sharply fall to 0 for $p_T = m_H$ * not very natural
  - Version 6.1 can be tuned for better behavior at large $p_T$
  - Pythia 6.1 considerably softer, possible concerns for $H \rightarrow \gamma\gamma$
- Which version is more reasonable?
  - Since there is no data, find another $p_T$ distribution prediction to compare.

Motivation – K factor

- Monte Carlo event generators (MCEG) give a LO estimation of $\sigma$
- From the theory, in this mass region, we know:
  \[ K = \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}} \approx 1.8 \]  
  for gg fusion
- Usually, K factor implemented by scaling
  - Good kinematical agreement essential
  - Which is here obviously not the case for all MCEG versions
Motivation – K factor (2)

- As a theoretical tool we take a resummation technique
  - implemented in ResBos
  - more about it later
- K factor implemented by scaling
  - i.e. all cross sections are the same (that of ResBos)
- For inclusive studies (e.g. $H \rightarrow ZZ^* \rightarrow 4l$) agreement between Pythia 6.1 and ResBos good enough
- For exclusive studies one should be careful

Comparison with HERWIG

- Not so trivial, since all MCs are not equal

Agreement good in low and intermediate region

The same as PYTHIA in the high $p_T$ region
Parton Showers

- Monte Carlo event generators (PYTHIA, HERWIG, ISAJET etc.) based on parton showering (PSEG) are essential tools in HEP.
- PSEGs are useful because
  - they accurately describe the emission of multiple soft gluons,
  - allow a direct connection with non-perturbative models of hadronization.
- Energy-momentum is conserved at every step
  - Realistic predictions can be made for arbitrary physical quantities.
- However, the prediction of the total cross section is only accurate to LO.
- PSEGs do not accurately describe kinematical configurations with hard partons emitted at a large angle.
- Higgs $p_T$ depends primarily on the details of the soft gluon emission from the initial state partons.
- For technical reasons, the initial state parton shower proceeds by a backward evolution.
  - Starting at the large (negative) $Q^2$ scale of the hard scattering.
  - And then considering emissions at lower and lower (negative) virtualities, corresponding to earlier points on the cascade, until the factorization scale is reached.
  - The transverse momentum of the initial state is build up from the whole series of splittings and boosts.

Parton Showers (2)

- The showering process is fairly independent of the hard scattering process being considered.
- Depends only on the initial state partons and the hard scale of the process.
- Parton showers in PYTHIA
  - Obey a strict ordering in virtuality: a parton that initiates a hard scattering has a larger virtuality than any other parton in the shower.
- Parton showers in HERWIG
  - Proceed via a coherent branching process in which a strict angular ordering is imposed on sequential gluon emissions.
- Because of the demonstrated importance of coherence effects, PYTHIA includes an additional veto on showers which are not also angular-ordered
  - But this does not make two schemes equivalent – some late emissions in a HERWIG shower can have virtuality larger than previous emissions.
Two changes

- A cut has been placed on the combination of $z$ and $Q^2$ values in a branching: $\delta = Q^2 - z(1-z) < 0$ where $\delta$ refers to the subsystem of hard scattering plus shower partons
  - corner of emissions that do not respect this requirement occurs when $Q^2$ value of space-like emitting parton is little changed and $z$ value of branching is close to unity
  - necessary if matrix element corrections are to be made to process
  - net result is substantial reduction in amount of gluon radiation
  - in principle affects all processes; in practice only gg initial states
- Parameter for minimum gluon energy emitted in space-like showers is modified by extra factor corresponding to 1/$\gamma$ factor for boost to hard subprocess frame
  - result is increase in gluon radiation
  - first effect is dominant, resulting in reduction of radiation and therefore softer $p_T$ spectrum

The above are choices, not bugs; which version is more correct?

- Compare to ResBos
- Possible implication for $H \rightarrow \gamma\gamma$ investigated and no significant effect found (K. Lassila)

An additional hard matrix element correction was applied to the parton shower.

- Maximum virtuality of the shower is increased from its nominal value at $Q^2_{\text{max}} = m_H^2$ up to the largest kinematically allowed value $Q^2_{\text{max}} = s$.
- Each parton emission is corrected by ratio of the exact matrix element squared at NLO to the approximate matrix element squared given by the parton shower approximation.

Showers generated by PYTHIA 6.2 have better shape in the high $p_T$ region.

- Herwig still have a cutoff set by $m_T$.
Resummation - Introduction

- At hadron colliders, the partonic cross section for heavy boson production can receive substantial corrections at higher orders in $\alpha_s$.
  - This affects not only the total production rate, but also the kinematics of the heavy boson.
- At LO, the heavy boson has a $\delta(p_T^2)$ distribution in $p_T^2$.
- At NLO
  - Real emission of a single gluon generates a contribution to $d\sigma/dp_T^2$ that behaves as $\alpha_s(p_T^2)/p_T^2$ and $a_{\Delta}(p_T^2)\log(Q^2/p_T^2)/p_T$.
  - Soft and virtual corrections are proportional to $-\delta(p_T^2)$.
- At higher orders, the most singular terms follow the pattern

$$a^n_s(p_T^2)\sum_{n=0}^{\infty} \frac{\log(n)}{p_T^2} = a^n_s L + V^n$$

- The logarithms arise from the incomplete cancellation of the virtual and real QCD corrections.
- This cancellation becomes complete for the integrated spectrum, where the real gluon can become arbitrarily soft and/or collinear to other partons.
- The pattern of singular terms suggest that perturbation theory should be performed in powers of $1^n$ instead of $a^n_s$.
- This reorganisation of perturbative series is called resummation.

Resummation - ResBos

- Here we use so called Collins-Soper-Sterman (CSS) formalism for $p_T$ resummation.
  - Implemented in the ResBos program: [Link](http://www.pa.msu.edu/~balazs/ResBos/)
- CSS resums all of the important logarithms.
  - This is achieved after a Fourier transformation with respect to $p_T$ in the transverse coordinate $b$, so that the series involving the delta function and terms $V_n$ simplifies to the form of an exponential.
- The most important factors are $A$, $B$ and $C$ coefficients, which are free of large logarithmic corrections and safely calculable perturbatively as expansions in the strong coupling $\alpha_s$.

$$\{A, B\} = \sum_{n=1}^{\infty} \left[ \frac{\alpha_s(\mu)}{\pi} \right]^n A^{(n)} B^{(n)}$$

$$C^0 = \sum_{n=1}^{\infty} \left[ \frac{\alpha_s(\mu)}{\pi} \right]^n C^{(n)}$$

- $A^{(n)}$ coefficients are universal (i.e. process independent).
- $B^{(n)}$ coefficients are process dependant, with the exception of $B^{(1)}$.
- $A^{(1)}$, $B^{(1)}$ and (approximately) $A^{(2)}$ are effectively in Monte Carlos.
  - Especially HERWIG
- $A^{(1)}$, $A^{(2)}$, $B^{(1)}$, and $B^{(2)}$ for Higgs production are in current version of ResBos.
  - As are $C^{(0)}$ and $C^{(1)}$ which control the NLO normalization.
Resummation – LL, NLL, ...

- Two possible classifications or logarithms:
  - According to their appearance in the Sudakov exponent
  - Organize logs in the expanded perturbative series

<table>
<thead>
<tr>
<th></th>
<th>Sudakov</th>
<th>Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL</td>
<td>A(1), C(1)</td>
<td>A(1), B(1), C(1)</td>
</tr>
<tr>
<td>NLL</td>
<td>A(1,2), B(1,2), C(1,2)</td>
<td>A(1,2,3), B(1,2,3), C(1,2,3)</td>
</tr>
<tr>
<td>NNLL</td>
<td>A(1,2,3), B(1,2,3), C(1,2,3)</td>
<td>A(1,2,3), B(1,2,3), C(1,2,3)</td>
</tr>
</tbody>
</table>

- Here we choose classification according to the perturbative expansion
  (series)
- The change from LL to NLL results in a
  - Increase of the cross section
  - Slight shift of the peak toward higher Q_t
  - But when normalizing to the same cross section, the shapes look very similar
- Effect of B(2) is surprisingly large
  - F.g. it is small for Drell-Yan production
- ResBos switches to NLO Higgs+jet matrix element at high P_T

Comparison with Experiment

Z boson production at Tevatron

- One of the highest precision testing grounds for the effects of multiple soft-gluon emission
  - Fully differential fixed order cross section has been calculated up to O(\alpha_s^4)
  - A(1,2), B(1,2), C(1,2) coefficients are known and have been numerically implemented

- Comparison involves
  (only shapes are compared)
  - Z p_T distribution from CDF for Run 1
  - Prediction from ResBos (rescaled upwards by 8.4%)
  - Prediction from PYTHIA 6.125 (rescaled upwards by 40%)
  - PYTHIA and ResBos both describes the data well
    - Agreement of PYTHIA in the high p_T region is made possible by explicit matrix element corrections
  - Low p_T region in more details later
Comparison – 125 GeV Higgs at LHC

- All distributions are normalized to the ResBos NLL cross section
  - Without this the MC curves would be about a factor 2 lower than ResBos
- ResBos curves appear close to the HERWIG predictions, and somewhat less close to the predictions of PYTHIA
  - In the high $p_T$ region
    - Correct description by PYTHIA 6.2 and ResBos, because both use the exact matrix element for Higgs + jet
    - Pure parton showering description (HERWIG and old PYTHIAs) is inadequate

Comparison – 125 GeV Higgs at LHC (2)

- Normalizing the cross sections in the low $p_T$ region alone
  - HERWIG in very good agreement with ResBos
  - PYTHIA 6.x prediction peak at lower $p_T$ values than HERWIG and ResBos
Comparison – 125 GeV Higgs at Tevatron and SLHC

- Average Higgs $p_T$ increases with increasing CMS energy
  - due to the increasing phase space available for gluon emission
- The same conclusion still valid:
  - for low $p_T$, good agreement ResBos-HERWIG and to less extent ResBos-PYTHIA 6.x,
  - for high $p_T$, good agreement ResBos-PYTHIA 6.2 only

Comparison – 500 GeV Higgs at LHC and SLHC

- Average $p_T$ is noticeably larger than that for a 125 GeV Higgs, since the hard scale for the process is $m_H$
- Conclusions for comparisons ResBos-HERWIG-PYTHIA still hold
**k_T Effects - Motivations**

- At a point in its evolution (typically corresponding to the virtuality of a few GeV) the parton shower is cut off and the effects on gluon emission at softer scales must be parametrized and inserted by hand.
- The parametrization is typically expressed in a Gaussian form, in terms of non-perturbative $<k_T>$ depending on the particular kinematics and initial state being investigated.

**Testing ground:**
- $Z$ production at Tevatron

**PYTHIA predictions:**
- $k_T^{\text{rms}} = 0.44$ GeV (default), dashed hist.
- $k_T^{\text{rms}} = 2.15$ GeV, solid histogram
- Latter value was found to give the best agreement with data.

- All the difference for these two $k_T$ are in the low $p_T$ region.
- High $p_T$ region is unaffected due to the number of gluon branches before collision, that carry off a sizable fraction of the original non-pert. $k_T$.
- Equivalent $k_T$ in ResBos is about 2.5 GeV.

**What are $k_T$ effects in Higgs production?**

**Answer:** (surprisingly), no difference is observed between the predictions with the different values of $k_T$.

**k_T Effects – Results**

- Lower plots show the sum of the non-perturbative partonic initial state $k_T$'s at $Q_0$ and at the hard scatter scale $Q$.
- Most of the $k_T$ is radiated away with the effects being larger at the LHC.
- The large gluon radiation probability from a $gg$ initial state and the greater phase space available at the LHC lead to a stronger degradation of the non-perturbative $k_T$ than was observed with $Z$ production at the Tevatron.
Conclusions

- Comparing the recent versions of MC event generators using the parton showers (HERWIG and PYTHIA) with the resummation calculations implemented in ResBos we come to following conclusions:
  - PSEG and ResBos agree well in the low and intermediate $p_T$ region
    - With slightly better agreement with HERWIG than with PYTHIA
  - The agreement is better with increasing mass and cms energy
  - In high $p_T$ region matrix element corrections are necessary for PSEGs (as implemented in recent PYTHIA)
- $p_T$ spectrum softening observed from PYTHIA 5.7 → 6.1 does not significantly affect event vertex finding in $H\rightarrow \gamma\gamma$
- Non-perturbative $k_T$ effects are small in case of Higgs production