Higgs p_T at LHC: Parton Shower vs Resummation

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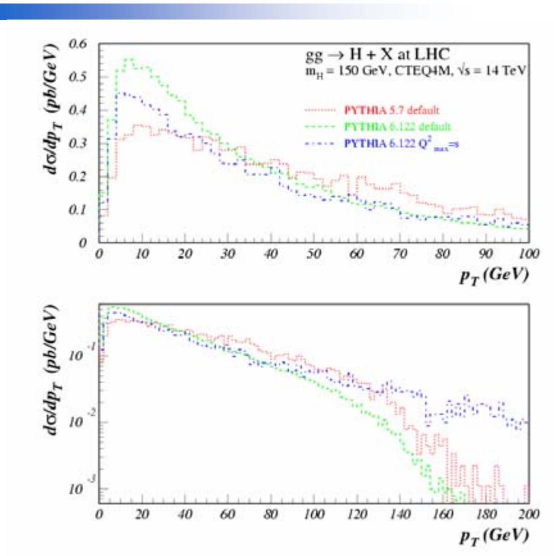
  - **m_H = 500 GeV @ LHC and SLHC**
- **k_T effects in Higgs production**
- **Conclusions**

- **Work done in collaboration with C. Balazs, J. Huston, S. Mrenna and M. Tonnesman (Phys.Rev.D63:014021,2001 hep-ph/0204316, hep-ph/0011122, hep-ph/0005025)**

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→ γγ**
- **Which version is more reasonable?**
  - **Since there is no data, find another p_T distribution prediction to compare.**

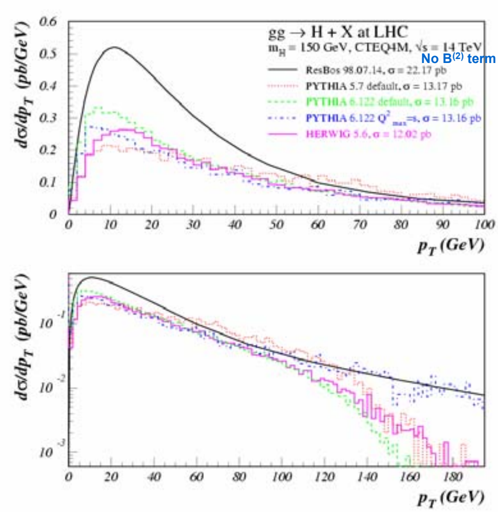
Motivation – K factor

- **Monte Carlo event generators (MCEG) give a LO estimation of σ**
- **From the theory, in this mass region, we know:**

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}} \approx 1.8$$

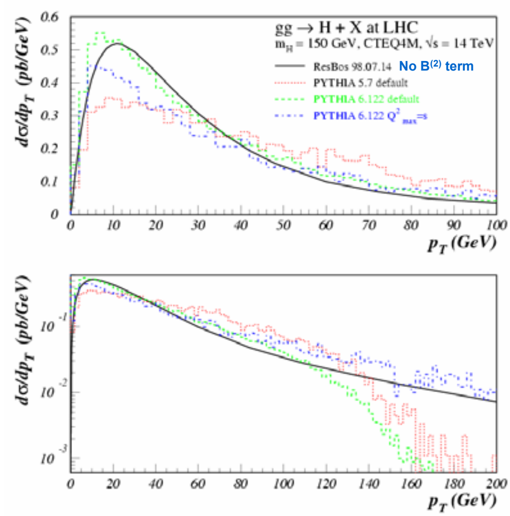
for gg fusion

- **Usually, K factor implemented by scaling**
  - **Good kinematical agreement essential**
  - **Which is here obviously not the case for all MCEG versions**



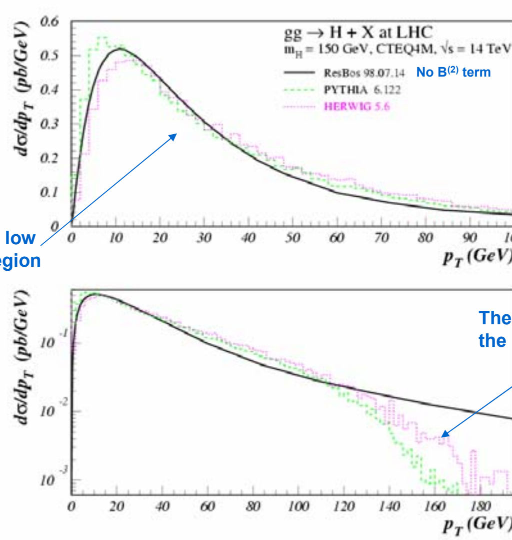
Motivation – K factor (2)

- **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 (f.g. H→ZZ*→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

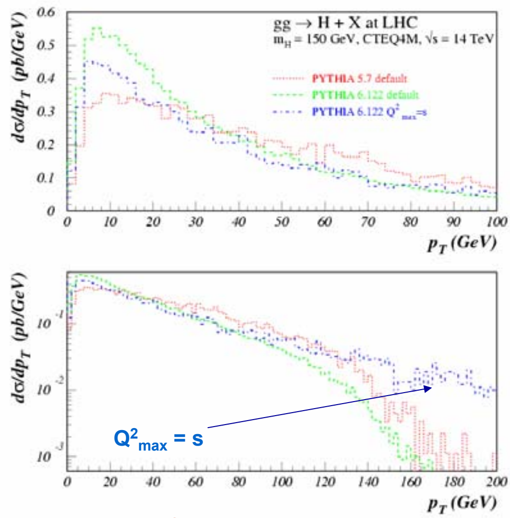
- Monte Carlo event generators (PYTHIA, HERWIG, ISAJET etc.) based on parton showering (PSEG) are essential tools in HEP.
- PSEGs are useful because
  - they accurately describe the emission of multiple soft gluons,
  - allow a direct connection with non-perturbative models of hadronization.
- Energy-momentum 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 then previous emissions.

PYTHIA Evolution: 5.7 → 6.1

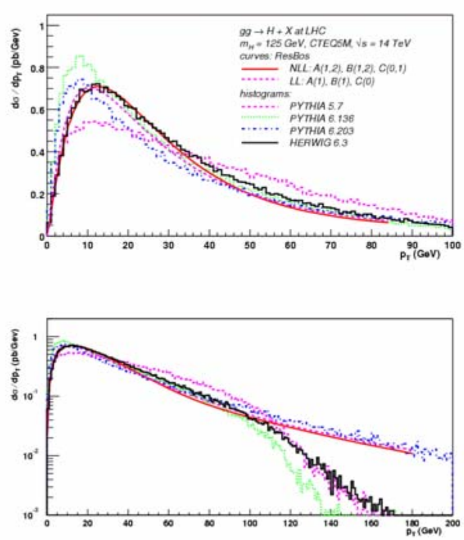
- **Two changes**
  - **A cut has been placed on the combination of z and Q^2 values in a branching: $\hat{u} = Q^2 - \hat{s}(1-z) < 0$ where $\hat{s}$ refers to the subsystem of hard scattering plus shower partons**
    - corner of emissions that do not respect this requirement occurs when Q^2 value 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/γ factor for boost to hard subprocess frame**
    - *result is increase in gluon radiation*
  - First efect 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→ γγ investigated and no significant effect found (K. Lassila)**

PYTHIA Evolution: 6.1 → 6.2

- **An additional hard matrix element correction was applied to the parton shower.**
  - Maximum virtuality of the shower is increased from its nominal value at $Q^2_{max} = m_H^2$ up to the larges kinematically allowed value $Q^2_{max} = s$.
  - 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 pT region.**
  - Herwig still have a cutoff set by m_H.



Resummation - Introduction

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

$$\alpha_s^n(p_T^2)\sum_{m=0}^{2n-1}\ln^m(Q^2/p_T^2) = \alpha_s^n L \equiv V^n$$

- The logarithms arise from the incoplete 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 V^n instead of α^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 (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 α_s

$$\{A,B\} = \sum_{n=1}^{\infty}\left(\frac{\alpha_s(\mu)}{\pi}\right)^n \{A^{(n)}, B^{(n)}\}, \qquad C_{ij} = \sum_{n=0}^{\infty}\left(\frac{\alpha_s(\mu)}{\pi}\right)^n C^{(n)}$$

$ij = gg, gq, qq$

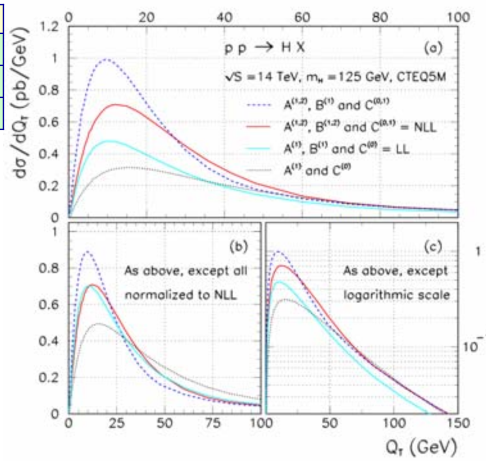
- $A^{(n)}$ coefficients are universal (i.e. process independent)
- $B^{(n)}$ coefficients are process dependant, with the exception of $B^{(1)}$
- $A^{(1)}$, $B^{(1)}$ and (approximately) $A^{(2)}$ are effectively in Monte Carlos
  - Especially HERWIG
- $A^{(1)}$, $A^{(2)}$, $B^{(1)}$ and $B^{(2)}$ 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 clasifications or logarithms:**
  - **According to their appearance in the *Sudakov* exponent**
  - **Organize logs in the expanded perturbative *series***

	Sudakov	***Series***
LL	$A^{(1)}, C^{(0)}$	$A^{(1)}, B^{(1)}, C^{(0)}$
NLL	$A^{(1,2)}, B^{(1)}, C^{(0)}$	$A^{(1,2)}, B^{(1,2)}, C^{(0,1)}$
NNLL	$A^{(1,2,3)}, B^{(1,2)}, C^{(0,1)}$	$A^{(1,2,3)}, B^{(1,2,3)}, C^{(0,1,2)}$

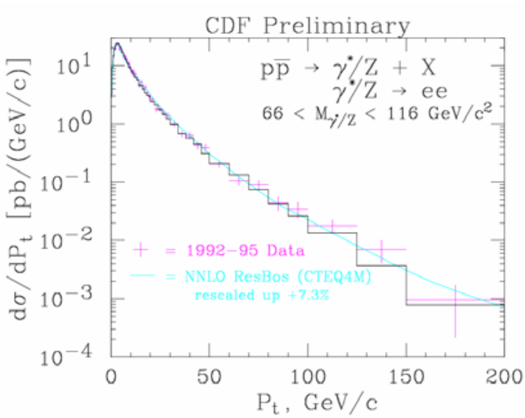
- **Here we choose clasification according to the perturbative expansion (*series*)**
- **The change from LL to NLL results in a**
  - **Increase of the cross section**
  - **Slight shift of the peak toward higher Q_T**
  - **But when normalizing to the same cross section, the shapes look very similar**
- **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

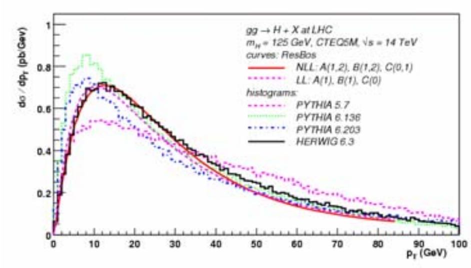
Z boson production at Tevatron

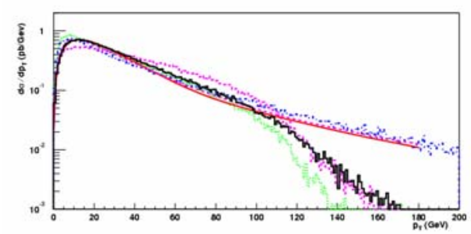
- **One of the highest precision testing grounds for the effects of multiple soft-gluon emission**
  - **Fully differential fixed order cross section has been calculated up to $O(\alpha_s^2)$**
  - **$A^{(1,2)}, B^{(1,2)}, C^{(0,1)}$ coefficients are known and have been numerically implemented**



- **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

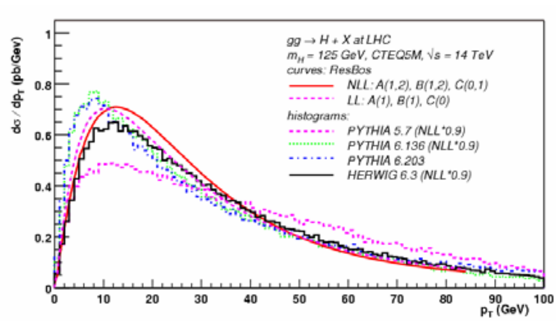




- **All distributions are normalized to the ResBos NLL cross section**
  - **Without this the MC curves would be about a factor 2 lower then ResBos**
- **ResBos curves appear close to the HERWIG predictions, and somewhat less close to the predictions of PYTHIA**
- **In the high p_T region**
  - **Correct 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**

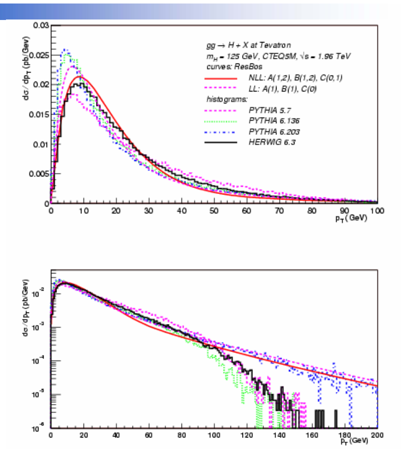
Comparison – 125 GeV Higgs at LHC (2)

- **Normalizing the cross sections in the low p_T region alone**



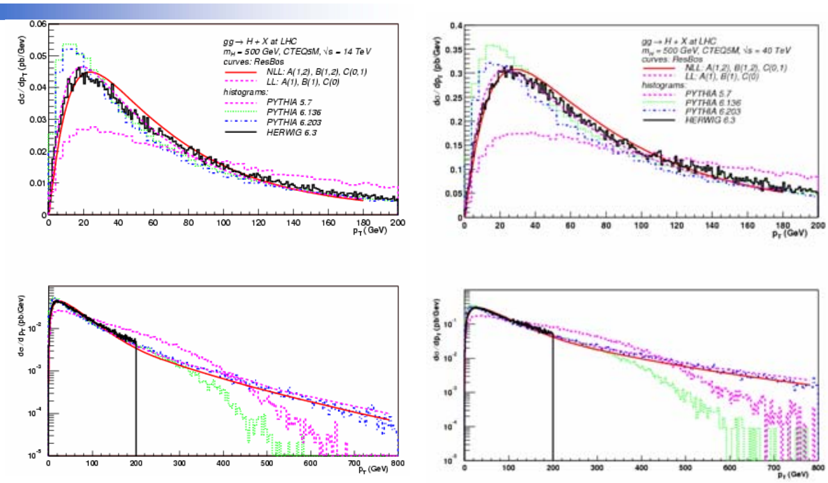
- **HERWIG in very good agreement with ResBos**
- **PYTHIA 6.x prediction peak at lower p_T values then HERWIG and ResBos**

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-PYTHIA6.2 only**

Comparison – 500 GeV Higgs at LHC and SLHC

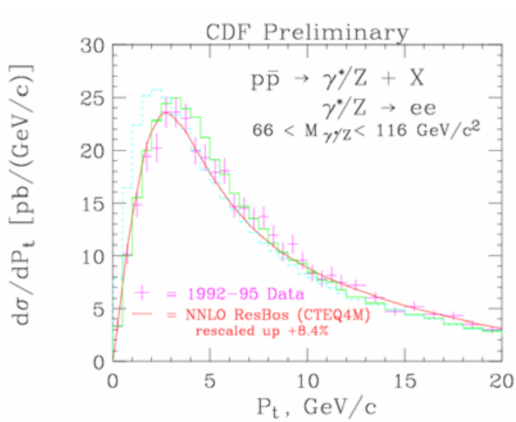


- **Average pT is noticably larger than that for a 125 GeV Higgs, since the hard scale for the process is mH**
- **Conclusions for comparisons ResBos-HERWIG-PYTHIA still hold**

k_T Effects - Motivations

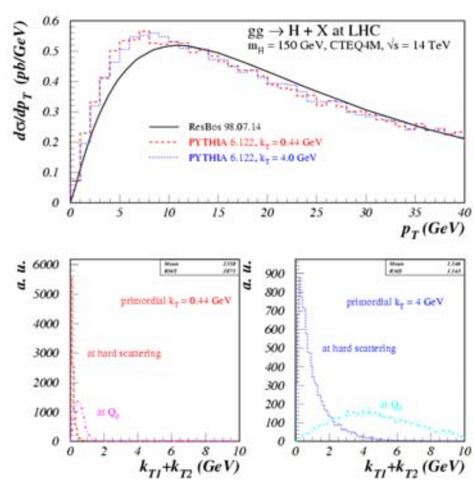
- At a point in it evolution (typically corresponding to the virtuality of a few GeV) the parton shower is cut off and the effects on gluon emission at softer scales must be parametrized and inserted by hand
- The parametrisation is typically expressed in a Gaussian form, in terms of non-perturbative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

- Testing ground:
  Z production at Tevatron
- PYTHIA predictions:
  - k_T^{rms} = 0.44 GeV (default), dashed hist.
  - k_T^{rms} = 2.15 GeV, solid histogram
  - Latter value was found to give the best agreement with data
- All the difference for these two k_Ts 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?



k_T Effects – Results

- Answer: (surprisingly), ***no difference is observed between the predictions with the different values of k_T***
- 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→ $\gamma\gamma$**
- **Non-perturbative k_T effects are small in case of Higgs production**