[I] Inclusive $W\gamma$ Production at the LHC
[II] A Study of Monte Carlo Event Generators of Interest

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january, 2009

Outline

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   - What are we interesed in measuring
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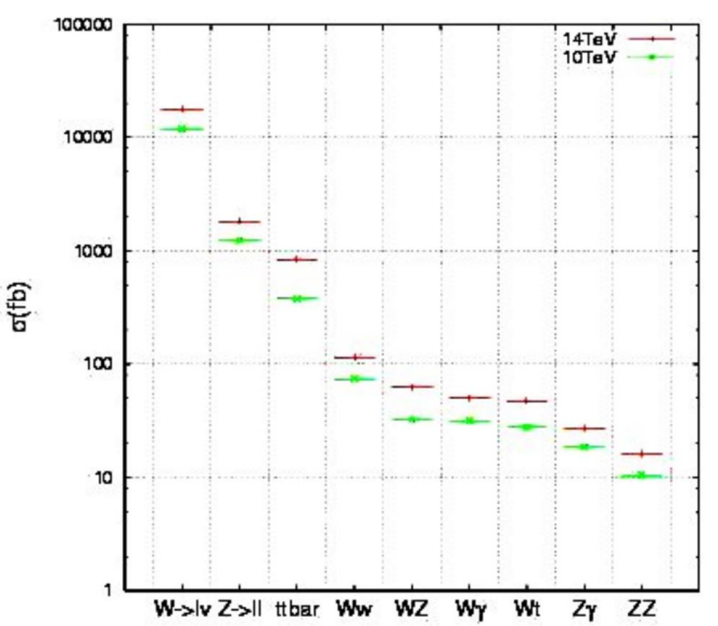
Introduction

- Measurement of triple gauge boson couplings (TGC) $V_1 V_2 V_3$, where $V_{1,2,3} \equiv \gamma$, W or Z, is an important test of the gauge structure of the Standard Model (SM).
- The triple and quartic gauge couplings are among the least studied features of the Standard Model till date.
- The nature of the gauge boson couplings , eg. WWγ, WWZ vertices are may be different in physics beyond the Standard Model. These could be due to compositeness of the W,Z bosons or radiative loop corrections involving new particles.
- Anomalous structure of triple gauge vertices like WWV ($V \equiv \gamma, Z$) were first studied in LEP.
- The di-boson production rate will be reasonably high at the LHC, even under low energy and low luminosity conditions.
- In recent years, CDF and D0 has reported studies of WZ, ZZ, Wγ and Zγ processes. With the advent of LHC data the limits on anomalous couplings are expected to improve by order of magnitude.

Cross-sections of several Standard Model processes at the LHC, including diboson production



- Multiboson production at hadron collider:

$$q\bar{q}' \to W^* \quad \to W\gamma : WW\gamma \text{ vertices}$$
$$q\bar{q}' \to W^* \quad \to WZ : WWZ \text{ vertices}$$
$$q\bar{q} \to Z/\gamma^* \quad \to WW : WW\gamma, WWZ \text{ vertices}$$
$$q\bar{q} \to Z/\gamma^* \quad \to Z\gamma : ZZ\gamma, Z\gamma\gamma \text{ vertices}$$
$$q\bar{q} \to Z/\gamma^* \quad \to ZZ : ZZ\gamma, ZZZ \text{ vertices}$$

- Leptonic (e, μ) decay modes of W and Z provide the cleanest signatures in a hadron collider environment. Experimentally easy to identify and trigger; can be measured with high resolution as well.
- CMS experiment at the LHC has very good capabilities for electron, muon and photon detection.

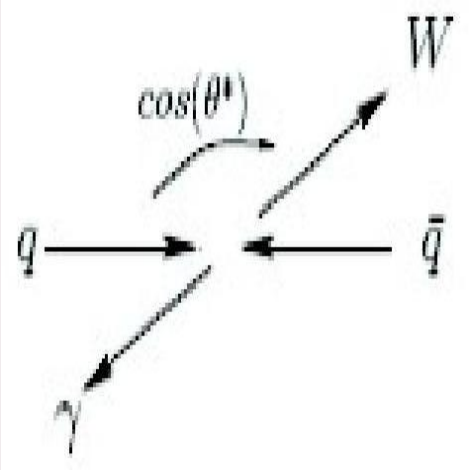
What are we interested in measuring

- Measure the total and differential cross-section for the process

  $pp \rightarrow W\gamma X$ with $W \rightarrow \mu\nu_\mu$
- We need to choose a parameter, the differential cross-section with respect to which is most sensitive to deviaions from the Standard Model. Apriori, the photon transverse momtntum, p_T^γ seems to be a good choice.

- Measure the radiation amplitude zero:

- Zero amplitude at $cos\theta^* = 1/3$ for W^+ and $cos\theta^* = -1/3$ for W^-.



- Measure the triple gauge boson coupling $WW\gamma$ as parametrized by λ and κ which are related to the electric and magnetic dipole moments of the W-boson respectively.

Essence of $W\gamma$ process - I

- TGC Effective Lagrangian

$$\mathcal{L}_{WWV} = -i\epsilon\Big[W^{\dagger}_{\mu\nu}W^{\mu}V^{\nu} - W^{\dagger}_{\mu}V_{\nu}W^{\mu\nu} + \kappa_V W^{\dagger}W_{\mu}V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}\Big]$$

where $V = \gamma, Z$.

- In SM: $\lambda_V = 0$, $\kappa_V = 1$
- Magnetic dipole moment :

$$\mu_W = \frac{e}{2M_W}(1 + \kappa + \lambda)$$

- electric quadrupole moment :

$$Q_W = -\frac{e}{M_W^2}(\kappa - \lambda)$$

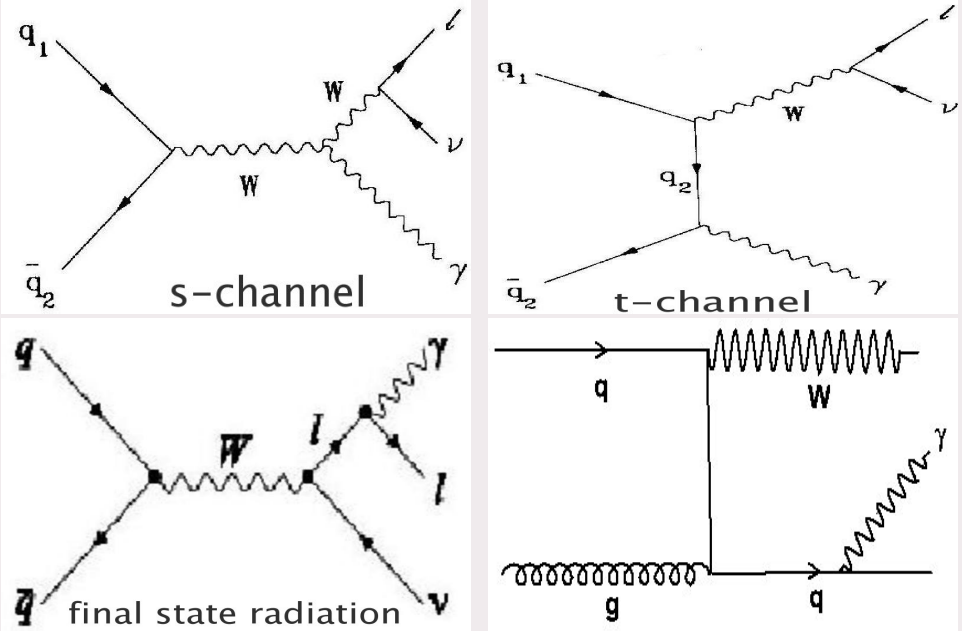
- Dipole moment $\sim 1/r^3$, and quad. mom. $\sim 1/r^4 \rightarrow$ can be probed with high energy.
- Unitarity violation avoided by using form factor:

$$\lambda(\hat{s}) \rightarrow \frac{\lambda(\hat{s})}{(1 + \hat{s}/\Lambda^2)^n}$$

- The Lagrangian contains terms respecting CP invariance only. CP-violating terms lead to additional two parameters $\tilde{\kappa}$ and $\tilde{\lambda}$. These terms are found to be small from measurement of neutron scattering cross-section in nuclear physics and are hence neglected here.

Essence of $W\gamma$ process - II

$W\gamma$ production at tree level and *RAZ*



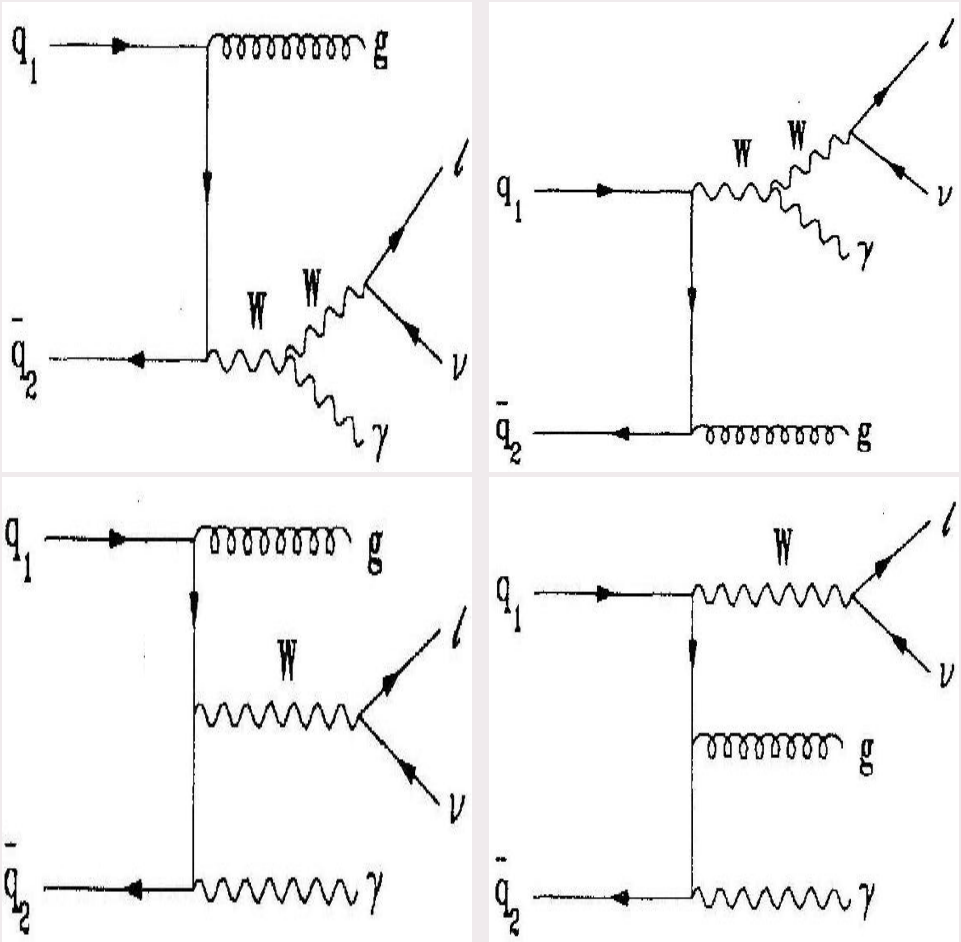
- *RAZ* due to destructive intereference among the processes shown.
- Related to Standard Model gauge structure; will not hold in BSM scenarios.

- Measurement of the cross-section at the LHC energy for $pp \rightarrow W\gamma X$ is one of the confirmatory tests of SM.
- $WW\gamma$ coupling involved only in the s-channel process.
- The last plot on the left shows the quark-gluon fusion diagram for production of a $W\gamma$ final state with a jet from the outgoing quark. Has large probability of occurrence at LHC energy. We use a jet veto on the final state to eliminate diagrams such as these.
- For probing *RAZ*, a promising variable is the charge-signed rapidity difference between the photon and the charged-lepton from W-decay: $Q^l \times |\eta^l - \eta^\gamma|$.

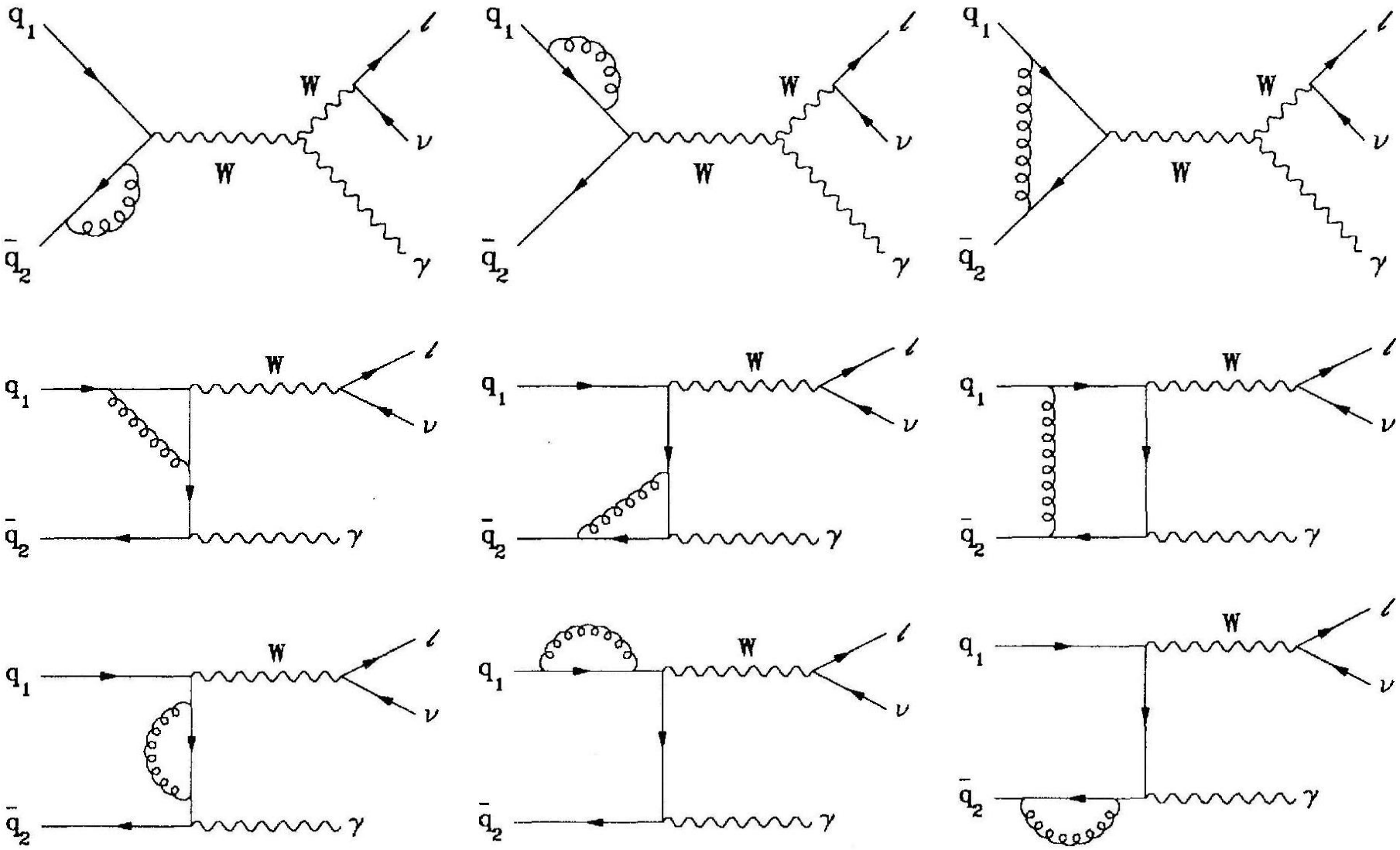
Event Generator – Baur Monte Carlo

- For understanding signal and background from collider data, Monte Carlo generated data have to be used.
- We have chosen Baur's Monte Carlo generator package for $W\gamma$ events for our study due to
  - Matrix element calculation for the hard-scattering part.
  - QCD Corrections available upto next-to-leading order.
  - Anomalous couplings can be incorporated.
- We use *Pythia* for showering and hadronization of Baur's final state particles and for underlying events

Real Gluon Emission Diagrams



NLO QCD Diagrams included in Baur WGAMMA_NLO Monte Carlo

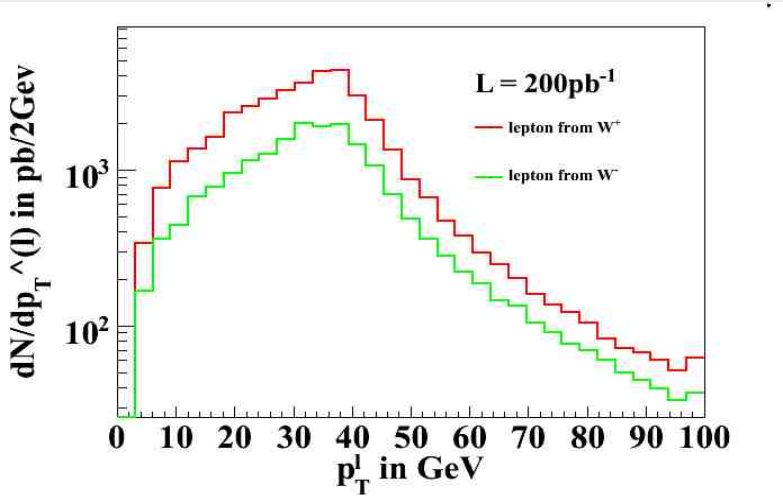


Genertor level cuts on parameters and Plots

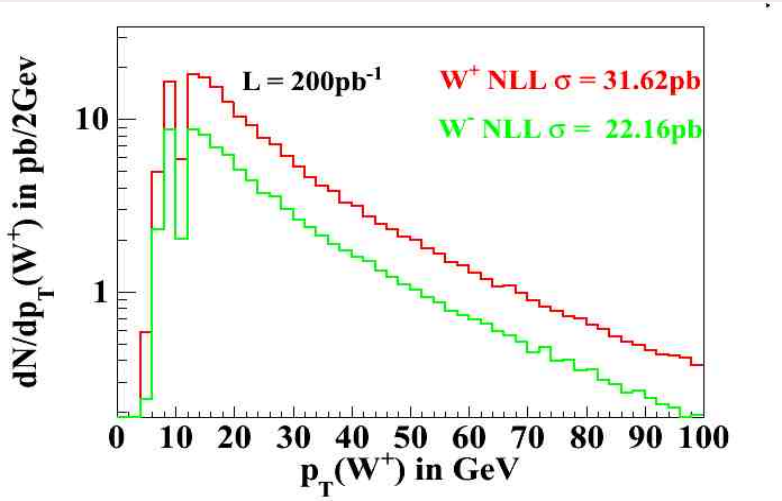
Gen Level Cuts

$p_T(\gamma)$	$> 5GeV$
$\lvert\eta(\gamma)\rvert$	< 10.0
$p_T(l)$	$> 5GeV$
$\lvert\eta(l)\rvert$	< 10.0
$p_T(\nu)$	$> 5GeV$
$p_T(jets)$	$> 5GeV$
$\lvert\eta(jets)\rvert$	< 10.0
$\Delta(R_{l\gamma})$	> 0.05
$M_T(l\nu\gamma)$	$> 10GeV$

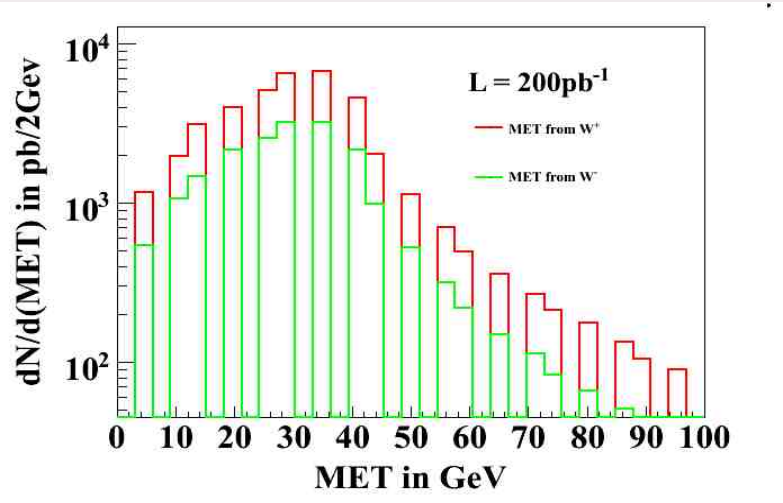
Lepton p_T spectra



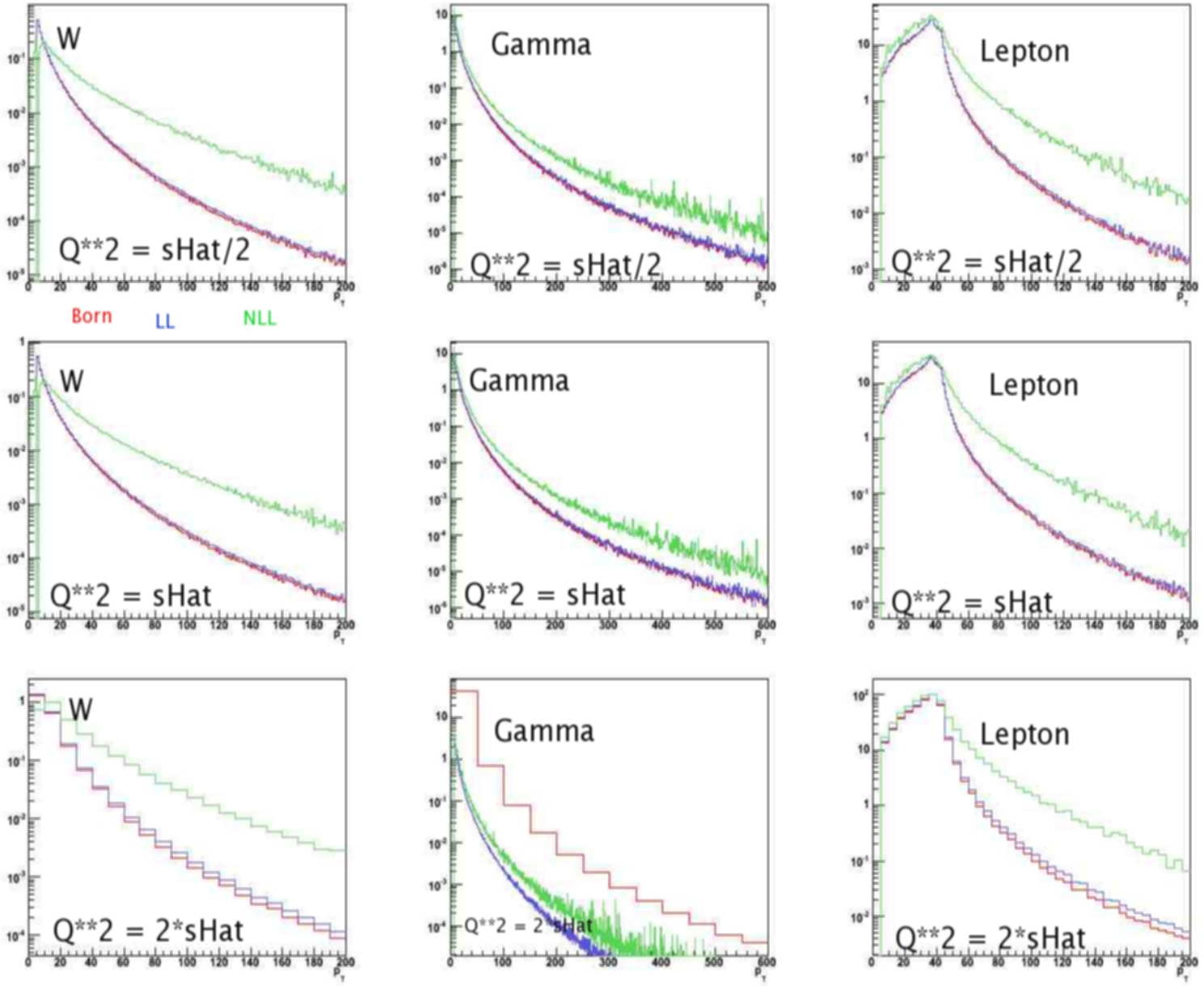
W p_t Spectrum



Neutrino p_T spectra



Baur: Comparison of Factorization Scales



Prospective Studies at Lund – I

- One of the most important parameters in studying inclusive $W\gamma$ production at LHC is the photon p_T spectrum.
- Sources of photon could be the hard scattering process, namely the $W\gamma$ production process, as well as underlying events and other hard scattering in the same event.
- We hope to gain some understanding of the different processes leading to the production of a final-state photon.
- This would also lead us to investigating the interplay between the different sources of photons in a p-on-p collision at LHC energies.

Comparion of Pythia with Baur_NLO matrix element generator

- As a startup, we are comparing the output of Baur's program, which is a matrix element generator, with Pythia, which is a parton shower generator
- Baur contains all QCD corrections to O(α_S)
- We expect that the tree level calculation of Baur to match Pythia's outcome when ISR s switched off
- We compare the effect of gluon radiation in Baur's program with the effect of ISR in Pythia
- We compare the p_T spectrum of the photon and effects of gluon radiation/ ISR on the $W\gamma$ system

Standard Model Parameters and Kinematic Cuts

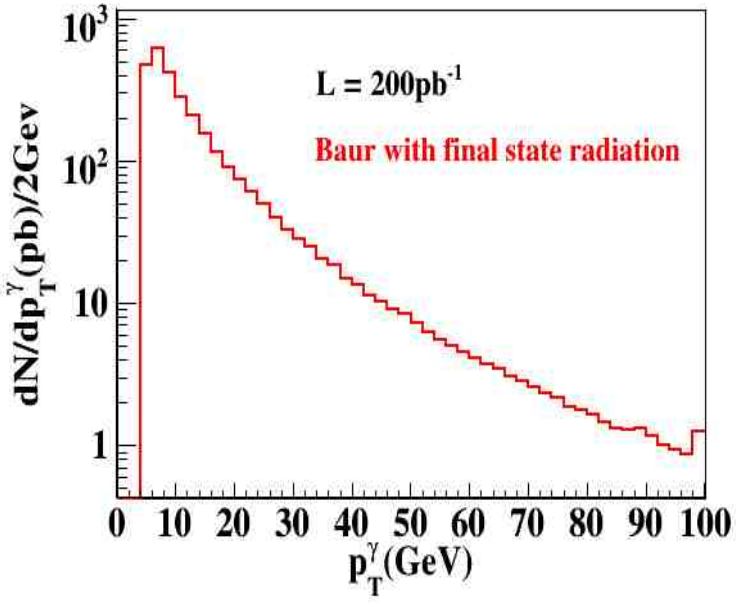
Parameter	Value
PDF	CTEQ5l
Q_f^2	$\hat{s}$
α_s	0.1000
M_W	80.41 GeV
M_Z	91.188 GeV
$sin^2\theta_W$	0.222247
α_{em}	0.007758
M_{top}	172.

Pythia Gen Level Cut: CKIN(3) = 5.0GeV

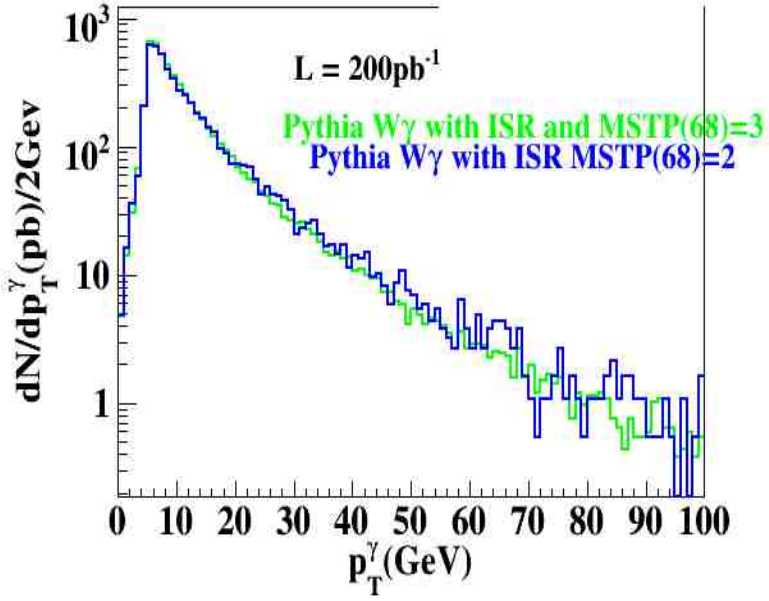
Parameter	Cut
γ p_T	5.0GeV
Charged lepton p_T	5.0 GeV
Photon rapidity	8.0
Charged lepton rapidity	8.0
Jet p_T	5.0GeV
Jet rapidity	8.0
$\Delta R(\gamma, lepton)$	0.05
Cluster(W,γ) transverse mass	10.0 GeV
Fraction of hadronic energy in a cone around the photon	0.15

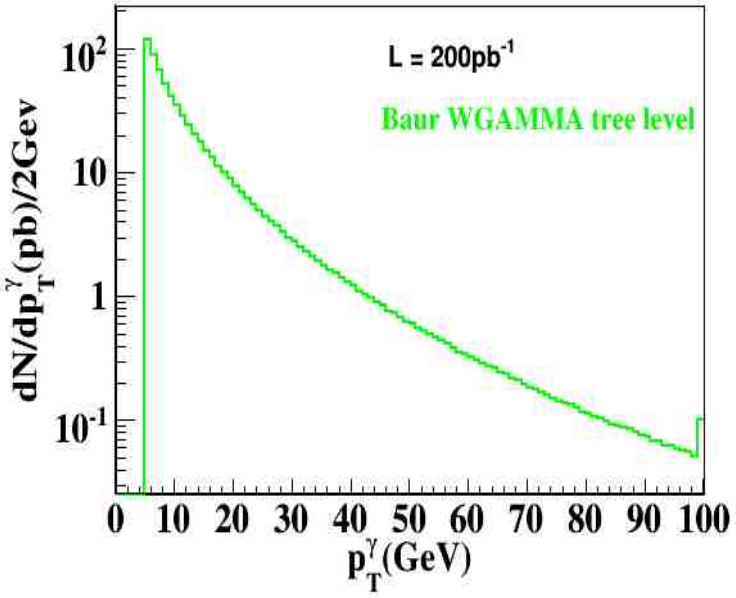
Pythia-Baur Comparison of Photon p_T

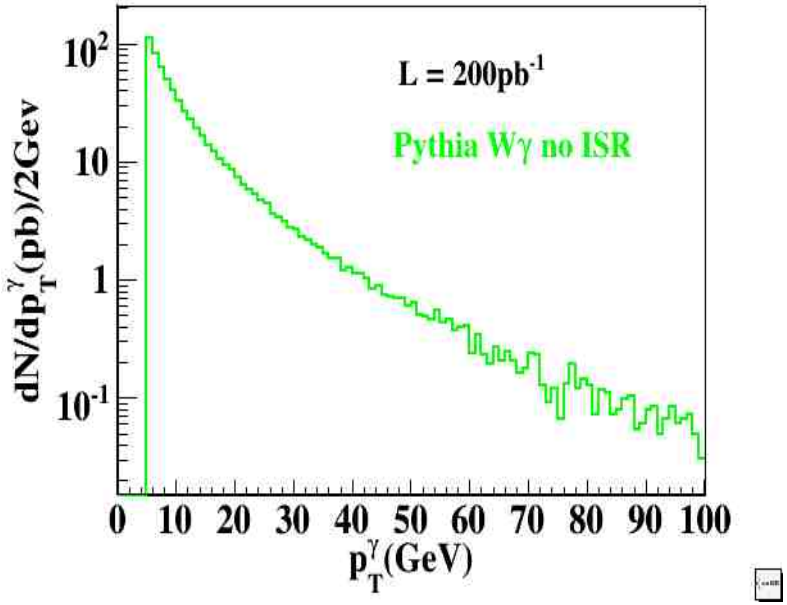
Baur WGAMMA:



Pythia6



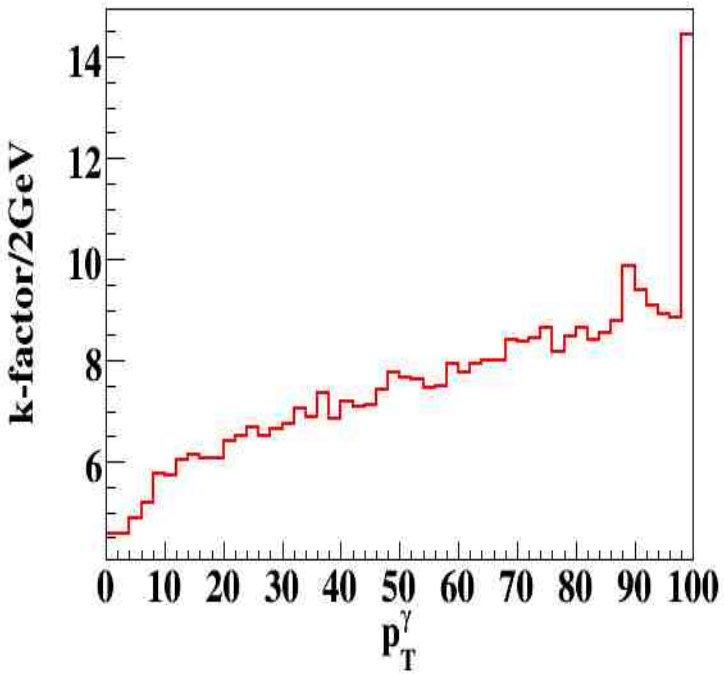


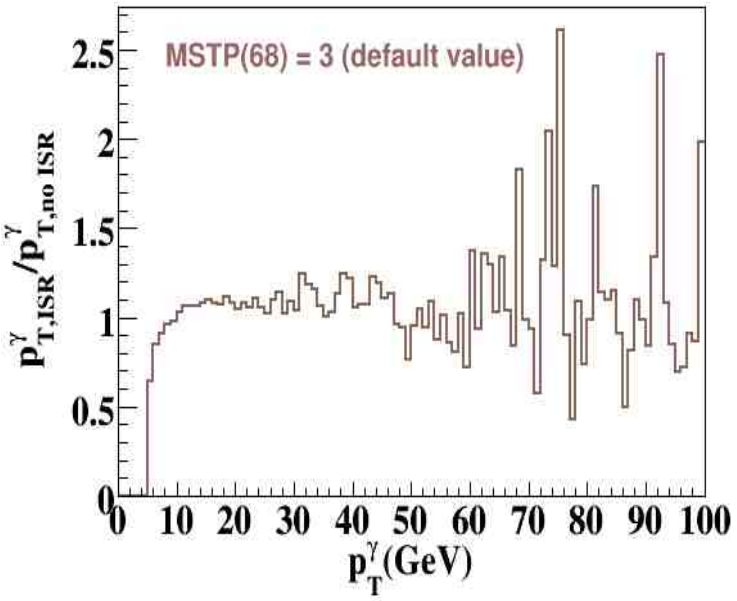


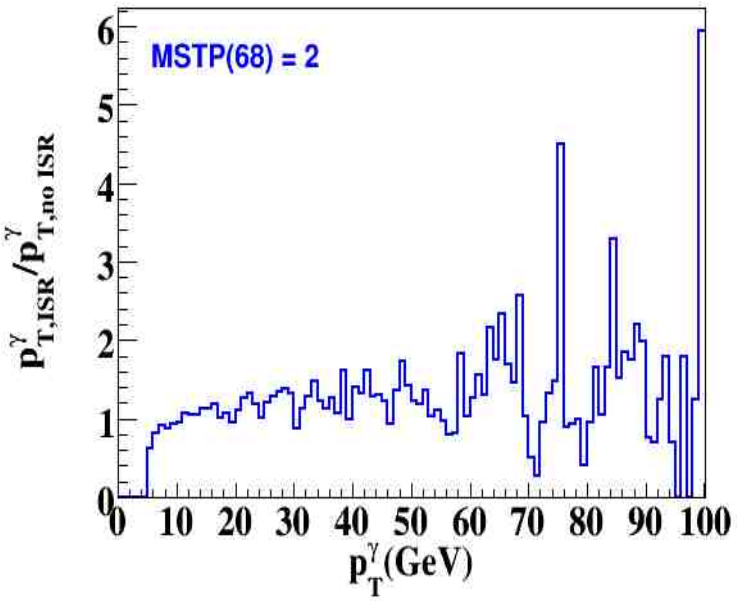
"K-factors" from Baur and Pythia

Pythia6

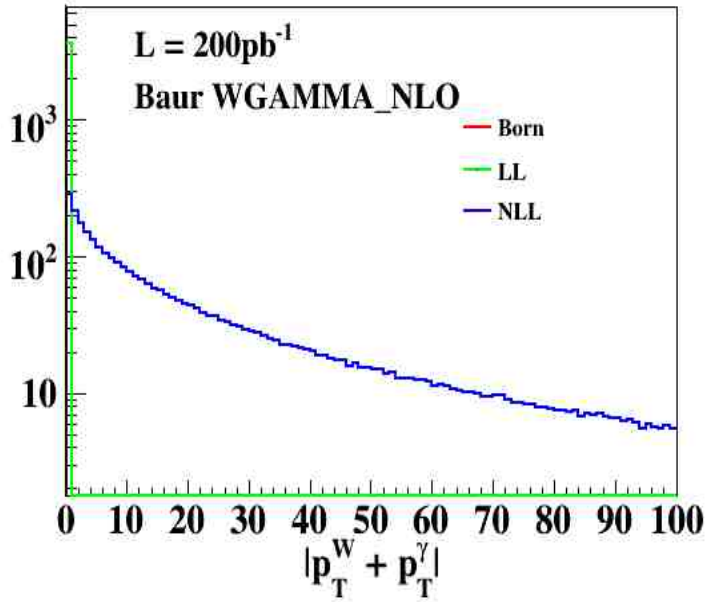
Baur WGAMMA

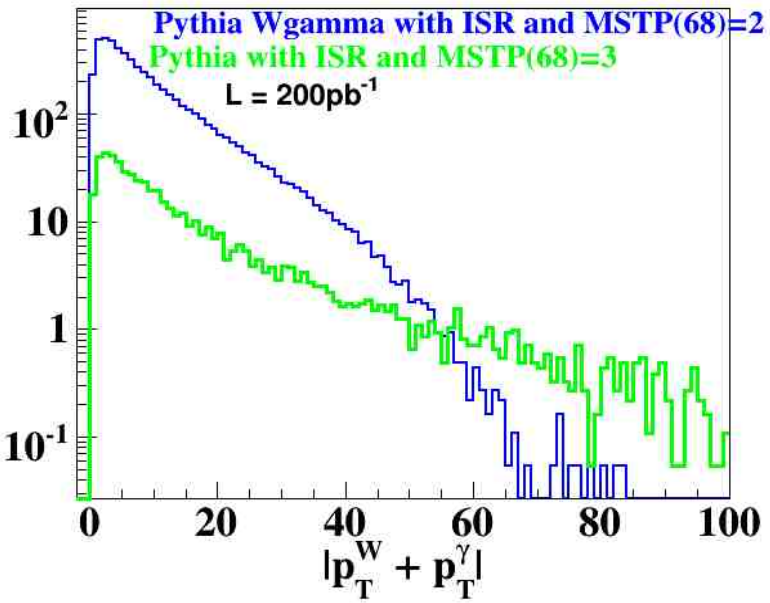






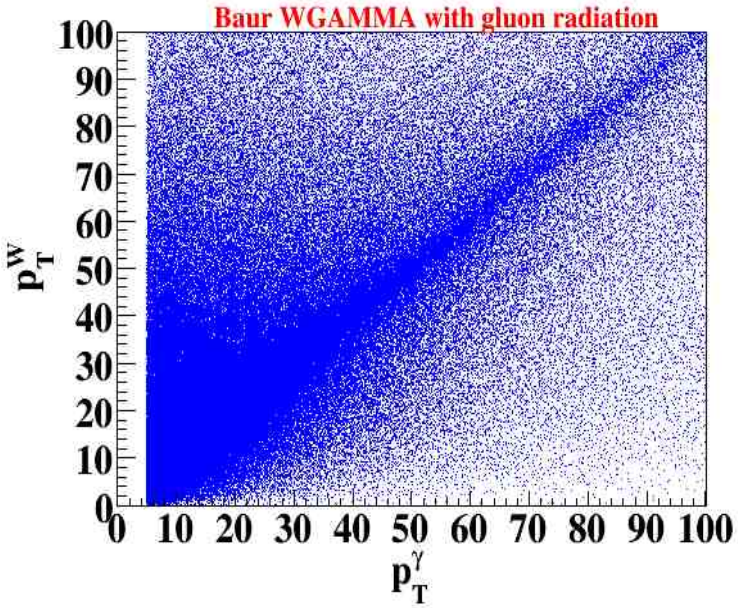
Baur-Pythia Comparison contd....

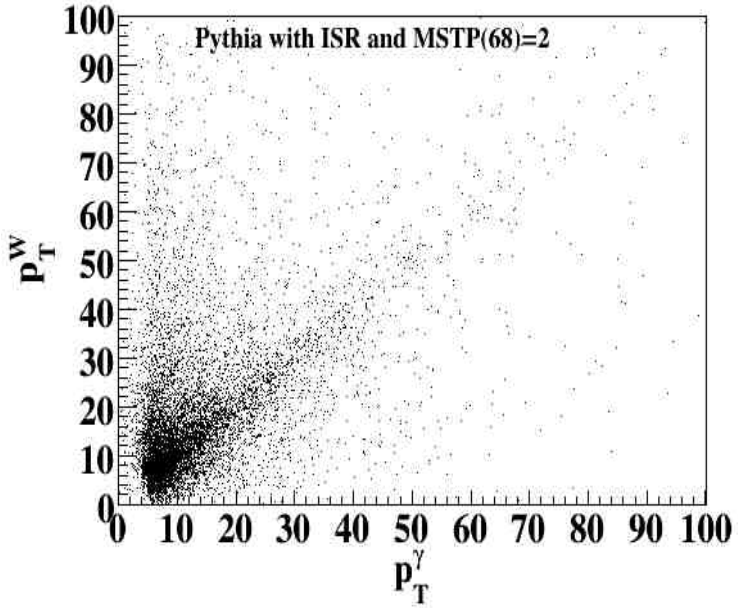




- For process with a jet (gluon) in the final state, p_T of the W and the photon is not back-to-back and $\mathbf{p_T^W} + \mathbf{p_T^\gamma}$ will be opposite to the $\mathbf{p_T}$ of the emitted jet
- On th left are the plots of the sum of the photon and W p_T for both Baur and Pythia
- We see that Baur gives a much harder p_T spectrum for the emitted jet than Pythia, even when Pythia is configured such that the gluon from ISR has no upper limit on its p_T

Baur-Pythia Comparison contd....





- The distributions show the p_T of the photon vs that of the W in the three-body final state: i.e. when we have a gluon jet in the event
- The distribution is asymmetric yet we do not have any apriori reason for this
- Work in progress....

Prospective Studies as MCNEt scholar – contd.

- The other aspect of our study would be to try comparing Pythia6 generator with the new version of Pythia.
- Pythia 8 also provides the opportunity to simulate multiple hard interactions. This should be interesting to study as well.
- Further, we want to gain an understanding of the matching between a matrix element calculator, eg. Baur WGAMMA generator and a parton shower generator,eg. Pythia.