Gluon Radiation Studies in $p\bar{p} \rightarrow t\bar{t}+X$

A. Juste (Fermilab)

OUTLINE

- Introduction
- Some studies on the 2→3 ttj process
- First look at the comparison between ME and PS for ttj
- Summary and plans

Introduction

MOTIVATION

- QCD evolution effects in the event (and in particular, hard gluon radiation) represent the single most important contribution to the width of the reconstructed top invariant mass distribution:
  - misassignment of extra-jet to the top
  - increased jet combinatorics
- It constitutes the dominant (physics) systematic uncertainty in the Run I top mass measurement. At D0: ~3.1 GeV (includes 2.5 GeV from W+jets background).
- The availability of ME-based MCs for tt+n jets (e.g. ALPGEN) should allow for a more precise estimate of the systematics associated with extra jet activity in the event, and potentially reduce them.
- On the other hand, the interface between ME calculations and parton shower (PS) raises new questions which, unless properly addressed, can potentially lead to even increased systematics with respect to the fully inclusive approach of PS:
  - ambiguities in scale choices, concern about double-counting or leaving unpopulated regions of phase space,
  - how to make use of different jet multiplicities:
    - cannot straightforwardly use, respectively, tt+0jets and tt+1jet to simulate the signal in e.g. l+4jets and l+5jets events,
    - generation cuts? how to internormalize them?
  - ...
- Really would need a full NLO generator consistently interfaced to PS.

GOAL

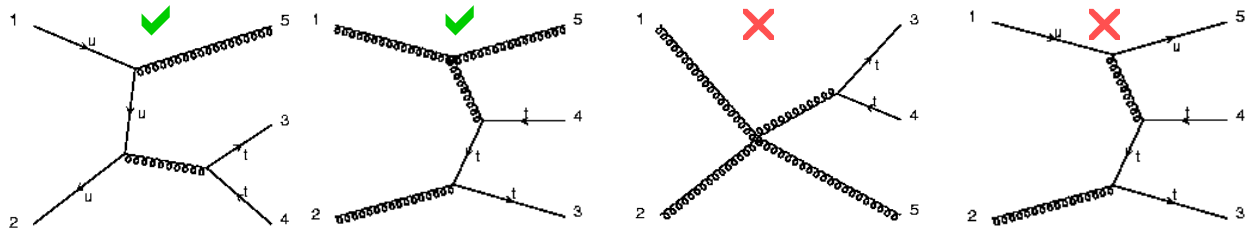
- Rather modest still: first look at ttj in ALPGEN (w/o parton shower) and (naïve) attempt to compare the ME parton level with PYTHIA for some categories of radiation (ISR, etc).

The ttj Process

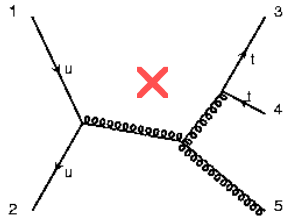
- The 2→3 process, although simple, contains already several classes of gluon radiation which are not present in PYTHIA, plus the interferences (not in PYTHIA either):

Radiation in top production (before the top goes on-shell)

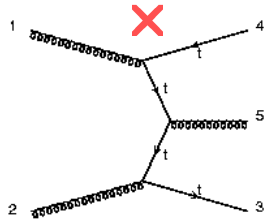
From the initial partons



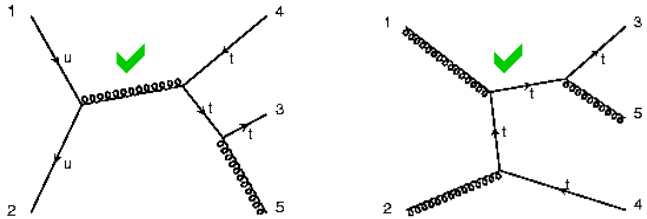
From intermediate gluon



From t-channel top



From s-channel top



Sub-process	# Feynman diagrams in ttj PYTHIA	2→3 ME
$q\bar{q}$	1(LO) + PS ~ “4”	5
gg	3(LO) + PS ~ “12”	18
q(q̄)g	0	5(5)

ttj: ALPGEN vs MADGRAPH

GOAL: Compare tt+0jet and tt+1jet rates and distributions with the results from a home made MC generator based on MADGRAPH matrix elements (HM MADGRAPH).

- Parameters and cuts: $\sqrt{s}$ = 1960 GeV, CTEQ5L
  m_t = 175 GeV
  p_{Tj} > 20 GeV, $|\eta_j|$ < 2.5

Process	Q^2 (renorm+factoriz)	Q^2(extra jet)	σ (pb) HM-MADGRAPH	σ (pb) ALPGEN
tt	$(m_t/2)^2$	same	8.39(2)	8.38(2) (qfac=0.5)
	m_t^2	same	6.22(1)	6.21(2) (qfac=1)
	$(2m_t)^2$	same	5.36(1)	4.46(1) (qfac=2) ← ~20% discrepancy!!
	s	same	4.84(1)	
ttj	m_t^2	same	1.484(4)	1.458(8) (qfac=1)
	$(2m_t)^2$	same	1.279(3)	0.955(6) (qfac=2)
	$4(m_t^2+p_{Tj}^2)$	same	1.245(3)	0.931(5) (qfac=2) ← ~34% discrepancy!!
	s	same	1.002(2)	
	$(2m_t)^2$	p_{Tj}^2	1.895(5)	
	$4(m_t^2+p_{Tj}^2)$	p_{Tj}^2	1.862(5)	
	s	p_{Tj}^2	1.581(4)	

- Of course, observe very large scale dependence on the individual cross-sections. Ratio of σ(ttj)/σ(tt) suggests perturbative calculation and is more stable:

$$\left(\frac{\sigma(ttj)}{\sigma(tt)}\right)_{Q^2=m_t^2} \approx 0.24, \quad \left(\frac{\sigma(ttj)}{\sigma(tt)}\right)_{Q^2=2m_t^2} \approx 0.21, \quad \left(\frac{\sigma(ttj)}{\sigma(tt)}\right)_{Q^2=\hat{s}} \approx 0.21$$

ttj: ALPGEN vs MADGRAPH (cont'd)

- For a given scale choice, compare cross-section for different subprocesses:

$\sqrt{s}$ = 1960 GeV, CTEQ5L
Q^2 (renorm+factoriz) = Q^2(extra jet) = $(2m_t)^2$
m_t = 175 GeV
p_{Tj} > 20 GeV, $|\eta_j|$ < 2.5

Subprocess	σ (fb) HM MADGRAPH	ALPGEN
$q\bar{q}\to ttj$	1071(3)	800(8)
$gg \to ttj$	91.4(2) (~7.2%)	69(2) (~7.2%)
(*) $qg \to ttj$	116.3(3) (~9.1%)	82(1) (~8.6%)
Total	1279(3)	955(6)

(*) Includes charge conjugate

- Relative contribution of subdominant processes (gg, qg) relatively stable vs scale changes and at the level of 7-9%. This fraction may change for different PDF sets depending on the gluon PDF (significantly affects spin correlation coefficient).
- Note that qg is as important as gg and is not included in PYTHIA.

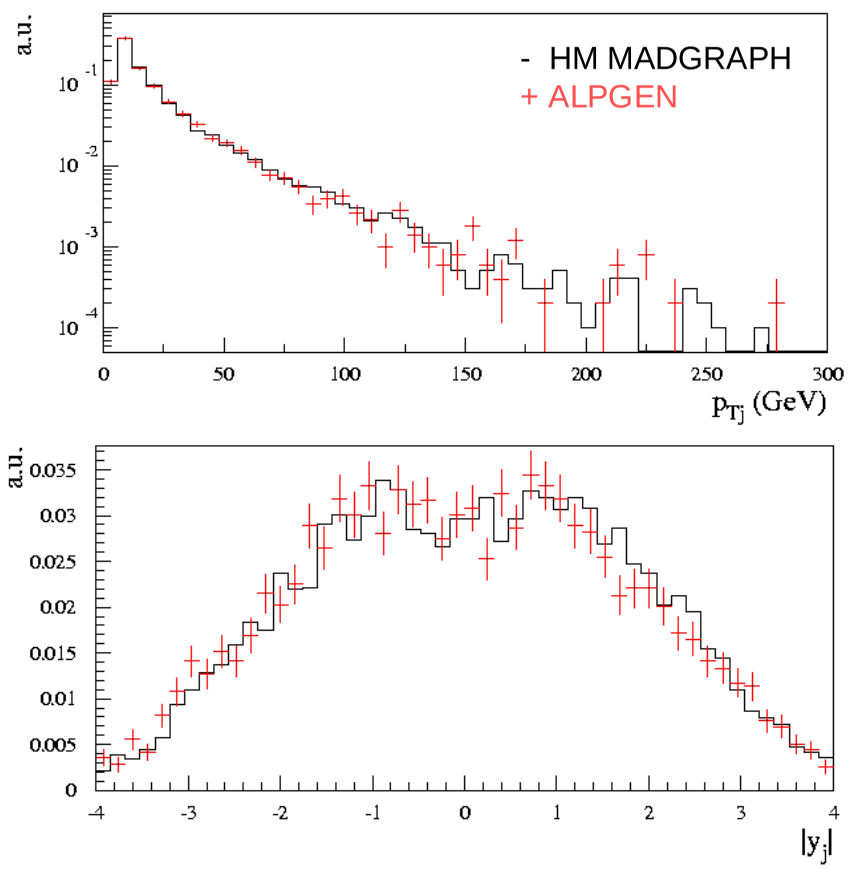
ttj: ALPGEN vs MADGRAPH (cont'd)

- Fixed scale to $Q^2 = m^2_t$, same parameters, and compare as a function of kinematic cuts on the extra jet:

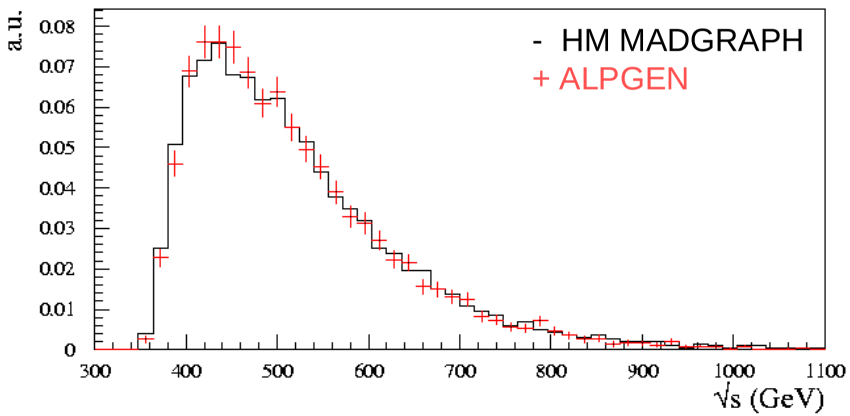
		σ (pb)	
p_{Tj} (GeV)	$\|\eta_j\|$	HM MADGRAPH	ALPGEN
>5	>4.0	5.07(1)	5.04(1)
	>2.5	4.29(1)	4.26(2)
>10	>4.0	3.070(8)	3.03(2)
	>2.5	2.774(7)	2.72(2)
>20	>4.0	1.602(4)	1.58(1)
	>2.5	1.532(4)	1.50(1)
>50	>4.0	0.472(1)	0.468(3)
	>2.5	0.470(1)	0.465(3)

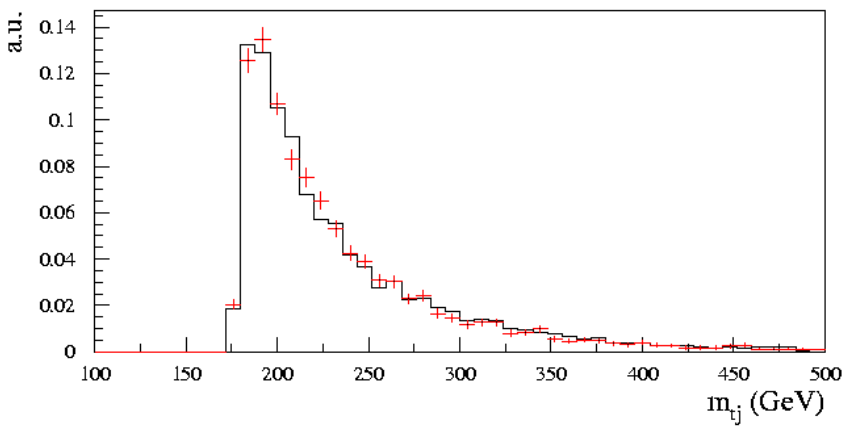
➔ agreement at the 1% level
(for this particular choice of scale!)

- Compare some distributions (at the parton level):



ttj: ALPGEN vs MADGRAPH (cont'd)



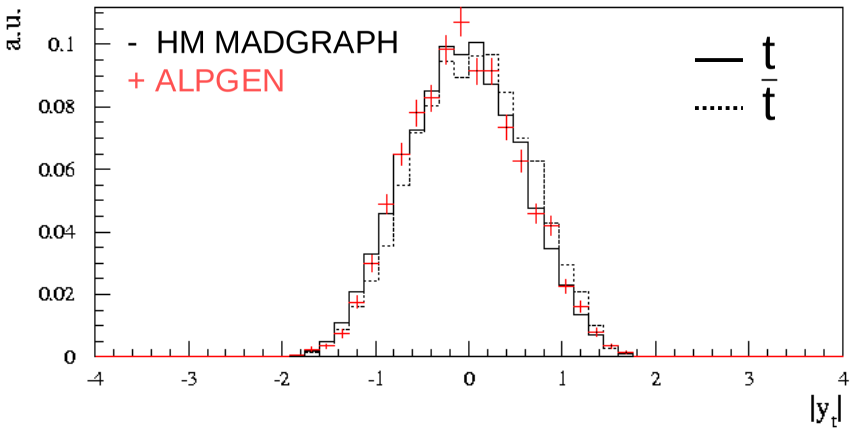


- Interferences can be small in the total cross-sections but visible in differential distributions: e.g. interference between gluon radiated off "initial partons" ("ISR") and off the off-shell top ("top") leads to top charge asymmetry.

$\sqrt{s}$ = 1960 GeV, CTEQ5L
$Q^2 = (2m_t)^2$
m_t = 175 GeV
$p_{Tj} > 5$ GeV, $|\eta_j| < 4$

$$\sigma_{ISR+top} = 4259(11)\text{ fb} \quad \begin{cases} \sigma_{ISR} = 4024(10)\text{ fb} \\ \sigma_{top} = 303.8(5)\text{ fb} \\ \sigma_{interf} = -69(15)\text{ fb} \end{cases}$$

Tiny

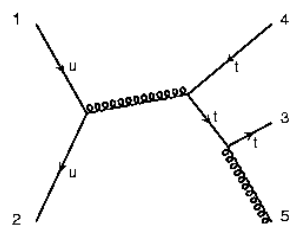


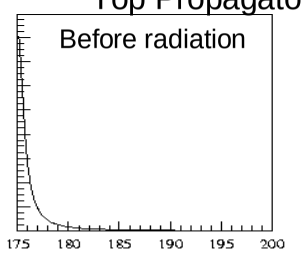
ttj: 2→3 vs 2 → 7 (just a few words)

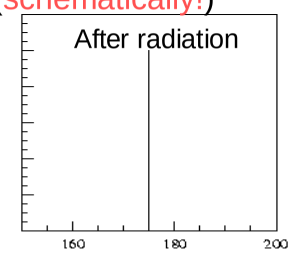
- To be able to freely change parameters, scales and enable/disable diagrams, I decide to use HM-MADGRAPH for more detailed studies (we learn about ALPGEN at the same time, modulo the scale-related discrepancies observed).
- The main limitation of the 2→3 calculation is that the final state top quark is on-shell:
  - is has to be made off-shell (by PYTHIA, HERWIG,...),
  - missing contribution from radiation in top decay (after it goes on-shell) from the top quark,
  - no interferences between radiation in top production and top decay (sensitivity to top quark width),
  - no spin transmission to the final state b and W decay products (can be overcome),
  - ...
- On-shellness of the top underestimates by a factor of 2 the contribution from gluon radiation off the top quark (relevant since it is radiation at large angle).

Top Propagator (schematically!)

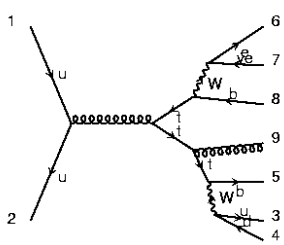
2→3

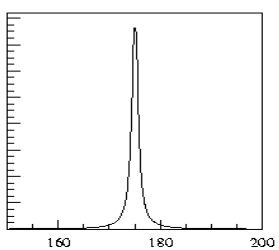


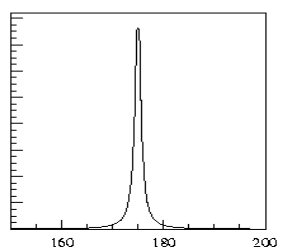




2→7







$\sqrt{s}$ = 1960 GeV, CTEQ5L
$Q^2 = (2m_t)^2$
m_t = 175 GeV
p_{Tj} > 20 GeV, $|\eta_j|$ < 2.5

HM MADGRAPH σ (fb)

Sub-process	2→3 ME	2→7 ME
ISR	1197(3)	1187(15)
Top	121.8(2)	248(2)
ISR+Top	1279(3)	1316(16)

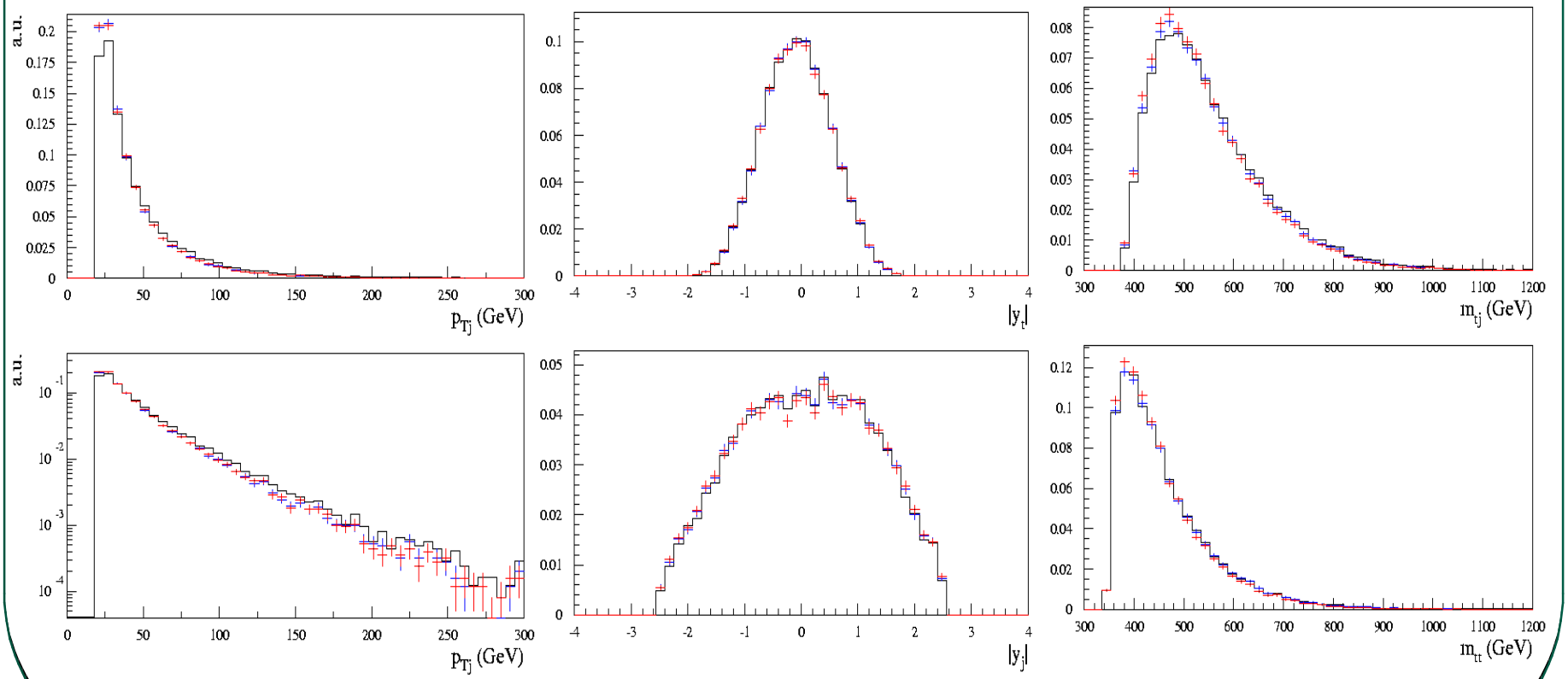
~9.5% ~18.8%

ttj: Effect of scale choice on kinematics

- Comparison of distributions for different scale choices in HM MADGRAPH.

$\sqrt{s}$ = 1960 GeV, CTEQ5L
All diagrams
m_t = 175 GeV
p_{Tj} > 20 GeV, $|\eta_j|$ < 2.5

—	Q^2(fact+renorm) = $(2m_t)^2$,	Q^2(extra jet) = $(2m_t)^2$	"Intuitive"
+	Q^2(fact+renorm) = $(2m_t)^2$,	Q^2(extra jet) = p_{Tj}^2	"Mixed"
+	Q^2(fact+renorm) = $m_t^2 + p_{Tt}^2$,	Q^2(extra jet) = p_{Tj}^2	"PYTHIA-like"



- Choice of Q^2(extra jet) = p_{Tj}^2, leads to softer spectrum for extra jet (and significant increase of total cross-section). Otherwise, no sizeable differences...

Comparison with PYTHIA 6.205: Preliminaries

- PYTHIA generates extra jets from the LO process by parton showering (leading log, accurate in soft+collinear region). The probability for extra gluon emission given the LO process is 1.
- The PS language does not guarantee agreement w/ higher order ME results (in particular real emission at NLO), neither in absolute shape nor in normalization.
- However, in recent versions of PYTHIA (and HERWIG) the standard PS is enhanced with ME corrections to gluon radiation in first branching, including mass effects (relevant for radiation off top and b-quarks).

- Would like to perform a first comparison (at the parton level) of the event kinematics in tt+jet between PYTHIA and the ME calculation: "how good was it?". This is not straightforward:
  - disable subprocesses (i.e. qg) and diagrams not present in PYTHIA
  - arbitrariness in the comparison with fixed order calculation:
    - would like to decouple from systematics associated with the interface between ME and parton shower
    - how to define the "extra-jet" in PYTHIA after QCD evolution?
    - what choice of scales (both renormalization+factorization as well as for QCD evolution)?
    - what region of p_{Tj} spectrum is meaningful to compare? A priori high p_{Tj}…but how high is high p_T?
      - fixed order calculation blows up at low p_{Tj} (➔ violates unitarity)
      - parton showering approach implements exponentiation, which leads to (Sudakov) suppression at low p_{Tj} and conserves the probability.
    - ...

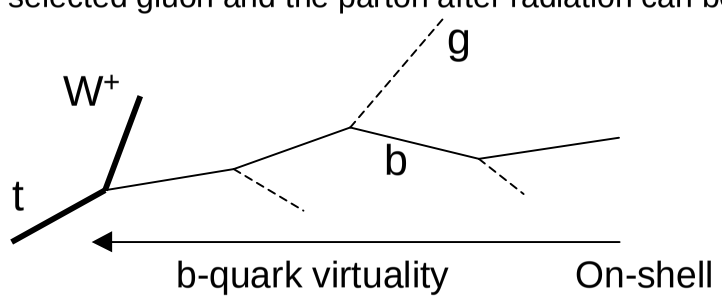
Comparison with PYTHIA: Method

GOAL: compare different categories on gluon radiation in PYTHIA (ISR, radiation off top quark, b-quark and light quarks) w/ ME ➔ consider only relevant diagrams .

- ME calculation is not interfaced to PS
- Scale choice:

  Factorization and renormalization:
  - PYTHIA: few choices available. Default is $Q^2 = p_{Tt}^2 + m_t^2$. An "intuitive one": $Q^2 = s_{tt}$.
  - ME: same as in PYTHIA.

  Scale for extra jet:
  - PYTHIA: cannot be easily changed. Typically $Q^2 = p_{Tj}^2$ or $Q^2 = m_R^2$ (R: resonance)
  - ME: compare two "extreme cases" a) Q^2 (extra jet) = Q^2 (renorm+factor)
    b) Q^2 (extra jet) = p_{Tj}^2
- The extra jet in PYTHIA is defined as the highest p_T gluon in the event after parton shower.All other gluons are ignored. This introduces additional complications:
  - Potential problems of energy-momentum conservation.
  - The partons which are not flagged as parent of the gluon are assigned the 4-momenta before parton shower.
  - The parton immediately after radiation is selected, and its 4-momentum corrected for any gluon radiated prior to the hardest gluon (small effect).
  - Both the selected gluon and the parton after radiation can be off-shell.

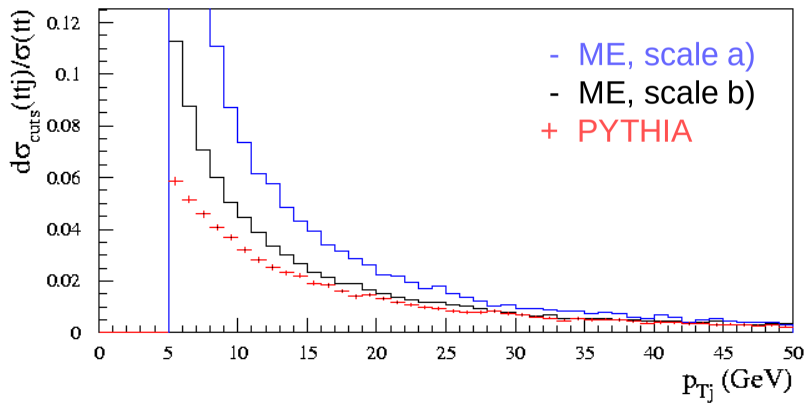


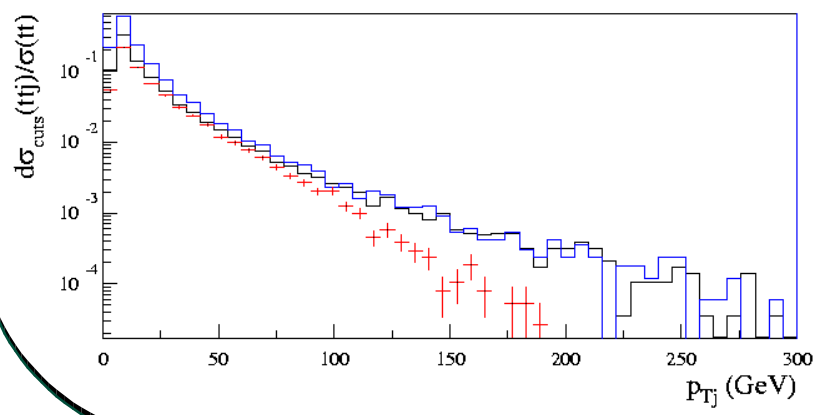
Hope all these complications are "higher order effects" and not very relevant for a comparison to 1st order ME.

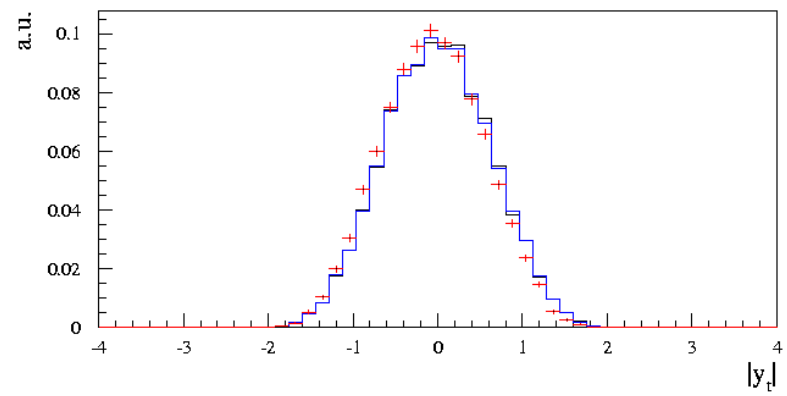
Comparison with PYTHIA: ISR

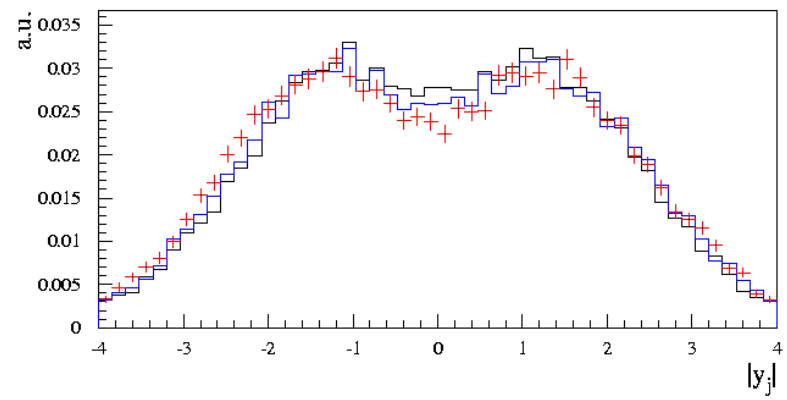
- Comparing ISR between 2→3 HM MADGRAPH (switched off appropriate diagrams) and PYTHIA.

$\sqrt{s}$ = 1960 GeV, CTEQ5L
Q^2 (fact+renorm) = $m_t^2 + p_{Tt}^2$ (PYTHIA default, MSTP(32)=8)
m_t = 175 GeV
$p_{Tg} > 5$ GeV, $|\eta_g| < 4$





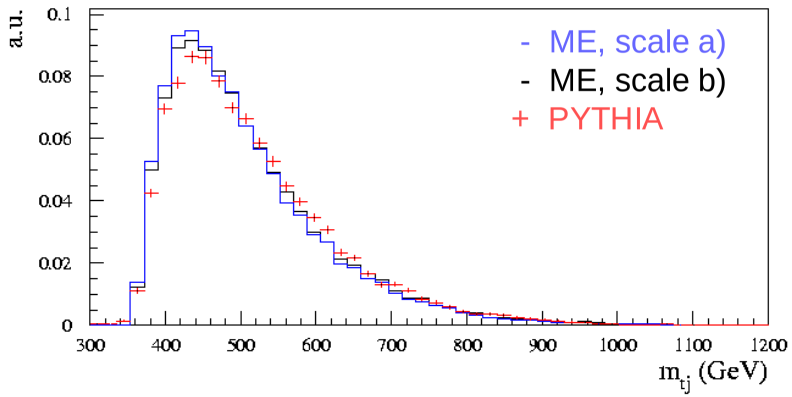


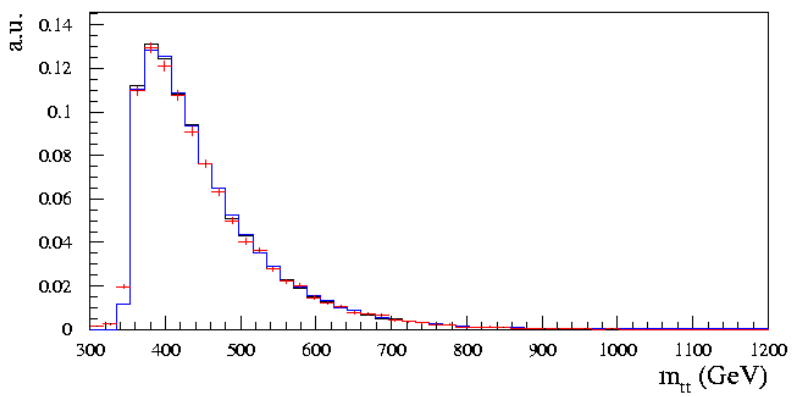


- PYTHIA and ME scale a) predict similar ISR rate of in the intermediate p_{Tg} region ($20 < p_{Tg} < 50$ GeV)
- PYTHIA underpopulates the high p_{Tg} region.

Comparison with PYTHIA: ISR (cont'd)

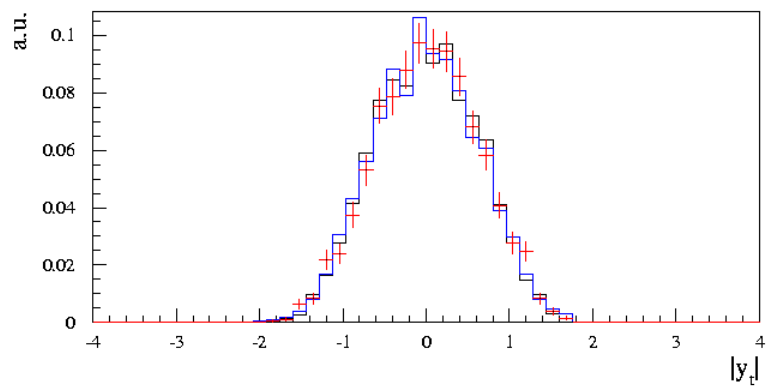
- Relevant invariant mass distributions:

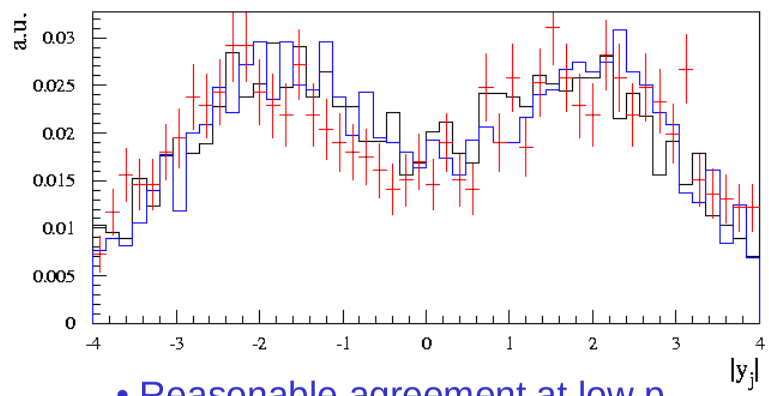




- Looking at different p_T regions:

p_{Tg} ~ 5.5 GeV



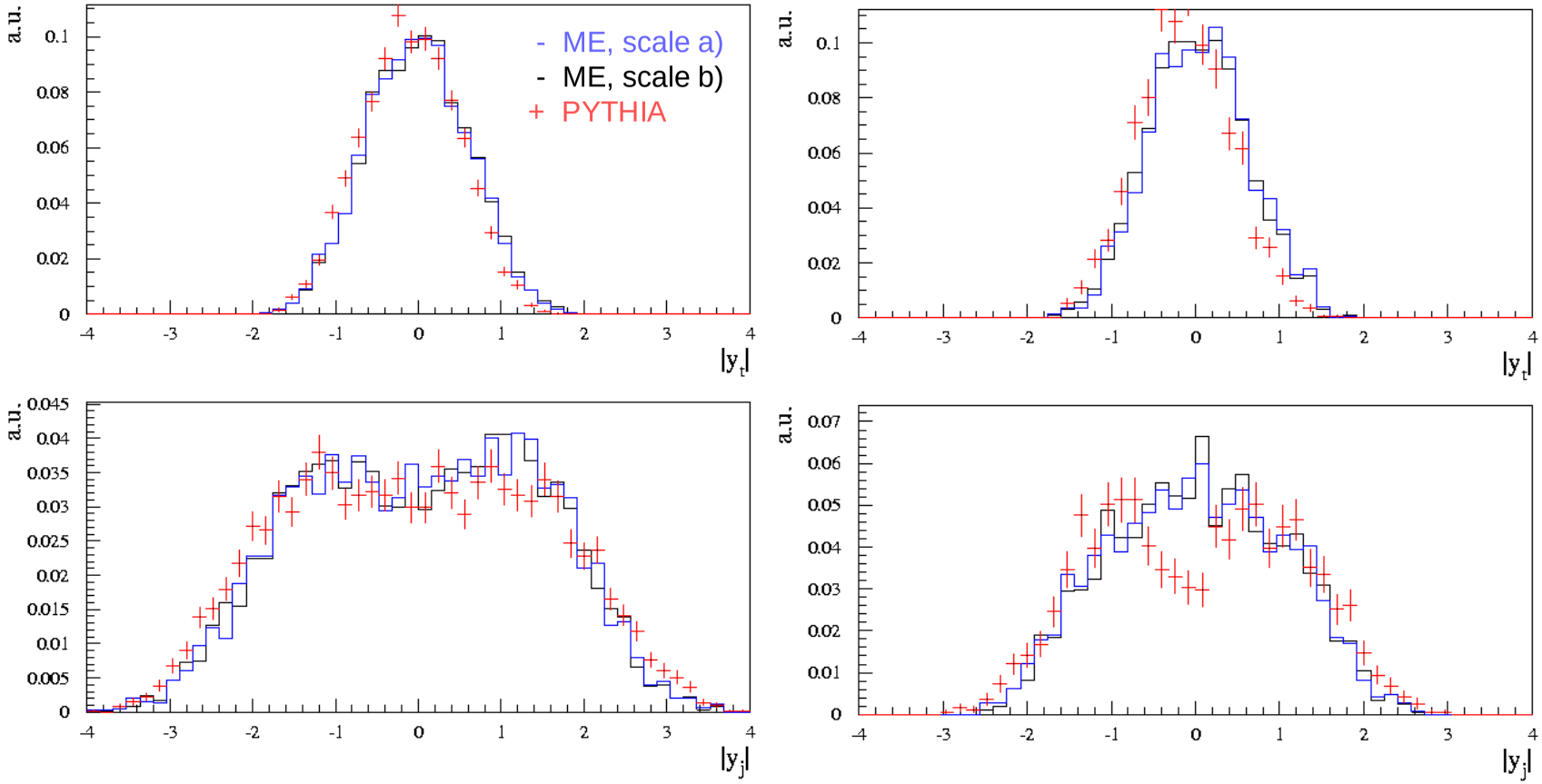


• Reasonable agreement at low p_{Tg}

Comparison with PYTHIA: ISR (cont'd)

20 GeV < p_{Tg} < 50 GeV

p_{Tg} > 50 GeV



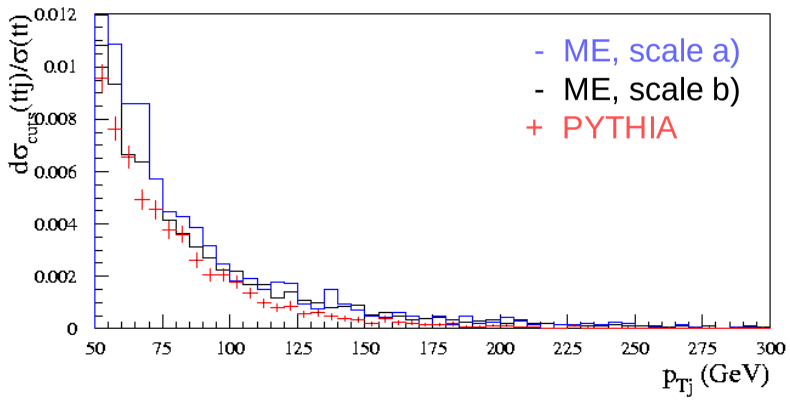
• Not only rate is underestimated, but gluons are more forward in PYTHIA.

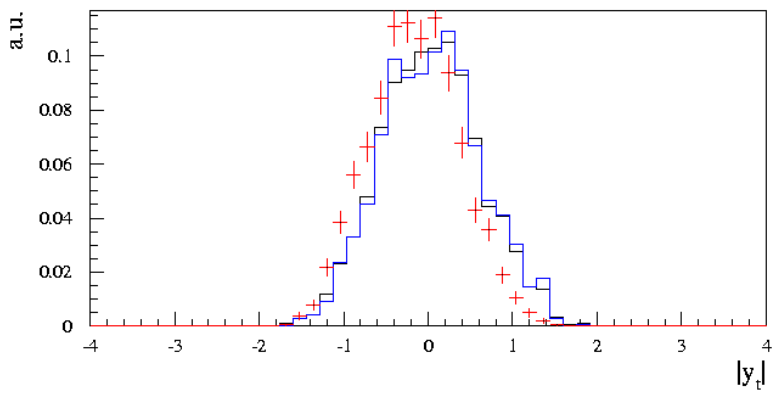
Comparisons with PYTHIA 6.205: ISR (cont'd)

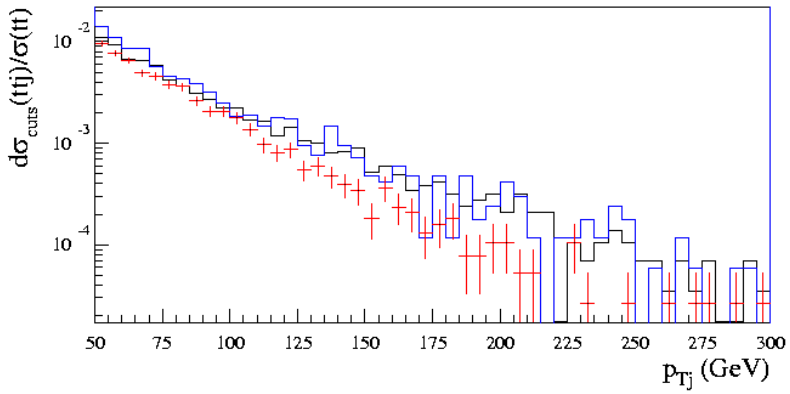
- Try a different choice of renorm+factor scale (didn't observe significant differences for ME).

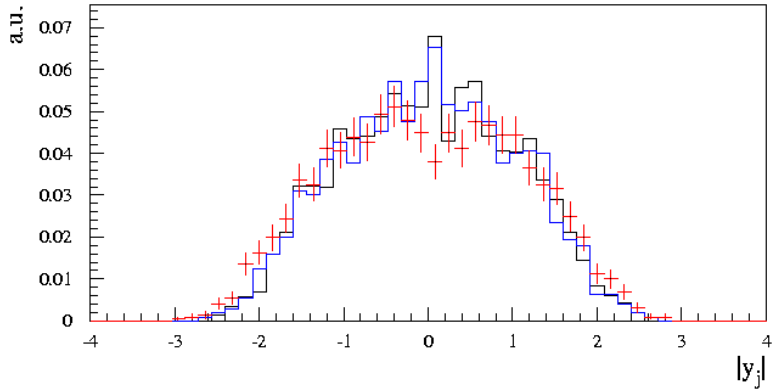
$\sqrt{s}$ = 1960 GeV, CTEQ5L
Q^2 (fact+renorm) = s_{tt} (PYTHIA: MSTP(32)=4)
m_t = 175 GeV
p_{Tg} > 5 GeV, $|\eta_g|$ < 4

p_{Tg} > 50 GeV









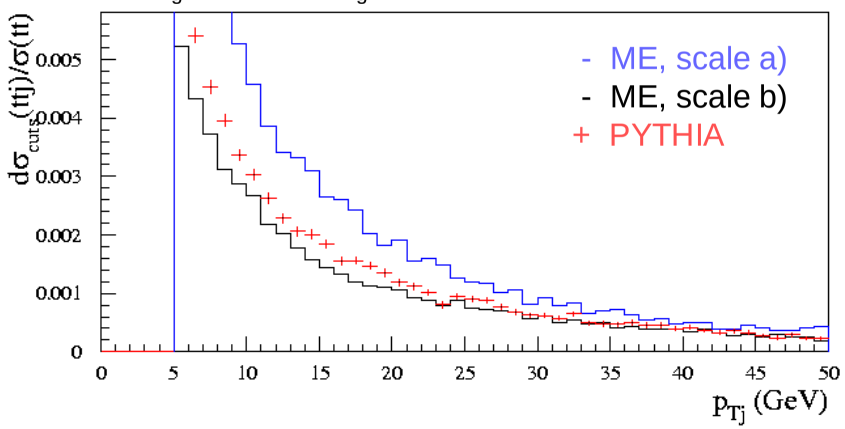
- Improved agreement in the high p_{Tg} region.

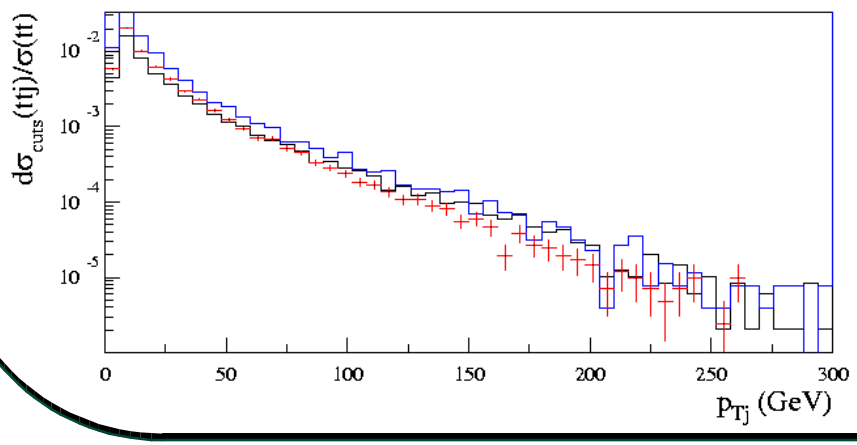
- Improved agreement in the gluon rapidity distribution wrt default PYTHIA scale choice.

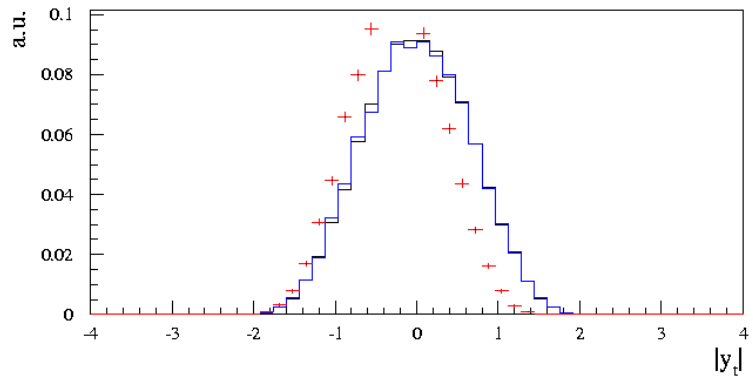
Comparison with PYTHIA: radiation off top-quark

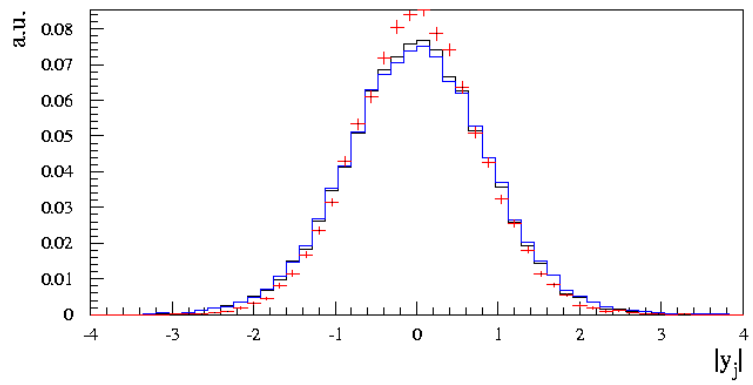
- Comparing radiation off top quark between 2→3 HM MADGRAPH (switched off appropriate diagrams) and PYTHIA.

$\sqrt{s}$ = 1960 GeV, CTEQ5L
Q^2 (fact+renorm) = s_{tt} (PYTHIA: MSTP(32)=4)
m_t = 175 GeV
p_{Tg} > 5 GeV, $|\eta_g|$ < 4







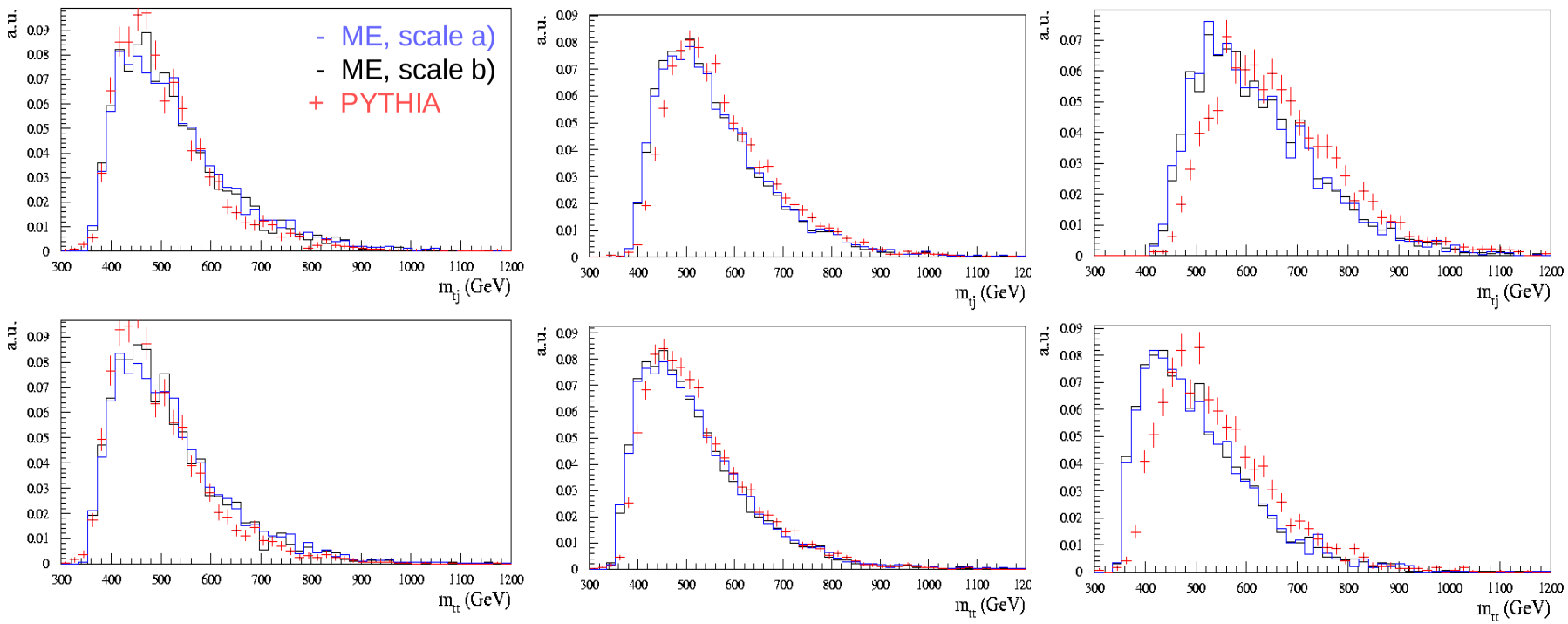


- Similar p_{Tg} spectrum between ME b) and PYTHIA. PYTHIA predicts larger rate for p_{Tg}<25 GeV.
- Strange asymmetry in the top rapidity distribution predicted by PYTHIA.

Comparison with PYTHIA: radiation off top-quark (cont'd)

- Compare invariant mass distributions in different regions of p_{Tg} (disagreement in η_t does not change significantly)

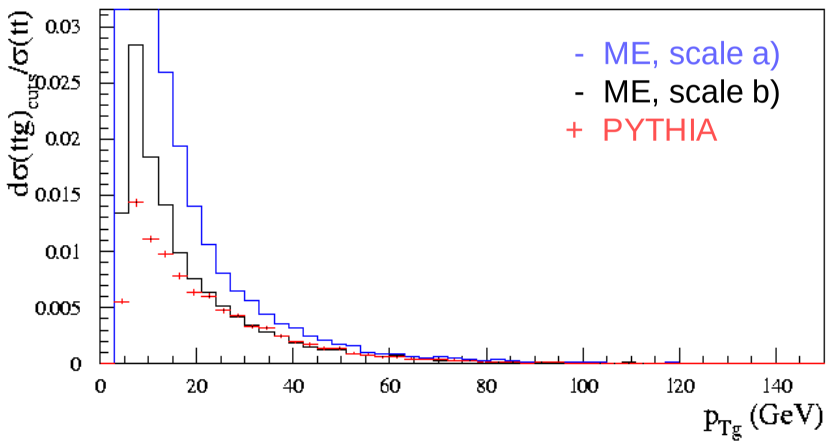
p_{Tg} ~ 5.5 GeV | $20 < p_{Tg} < 50$ GeV | $p_{Tg} > 50$ GeV

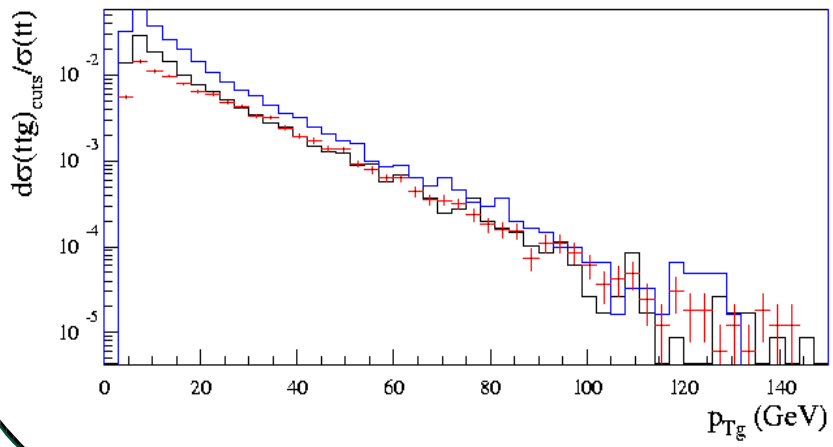


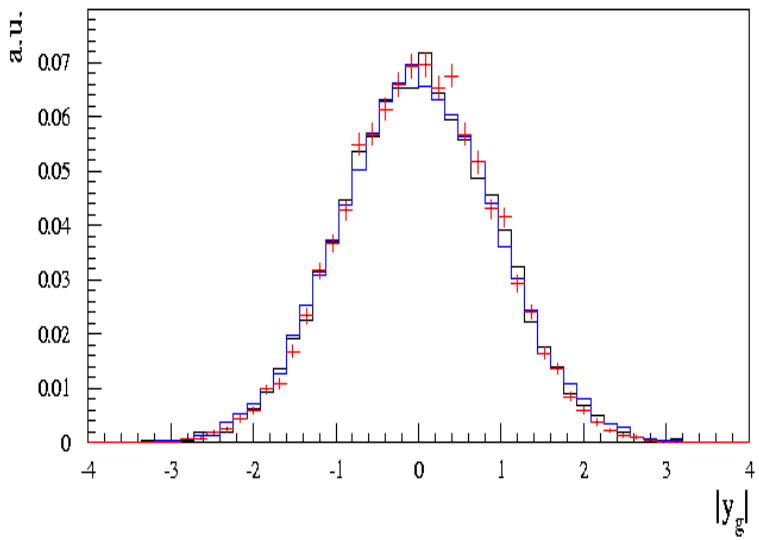
Comparison with PYTHIA: radiation off b-quark

- Comparing radiation from b/$\bar{b}$-quarks between 2→7 HM MADGRAPH (switched off appropriate diagrams) and PYTHIA.

$\sqrt{s}$ = 1960 GeV, CTEQ5L
Q^2 (fact+renorm) = s_{tt} (PYTHIA: MSTP(32)=4)
m_t = 175 GeV
p_{Tg} > 5 GeV, $|\eta_g|$ < 4
p_{Ti} > 20 GeV, $|\eta_i|$ < 2.5, i=u,$\bar{d}$,b,e,ν,$\bar{b}$
ΔR_{ij} > 0.5



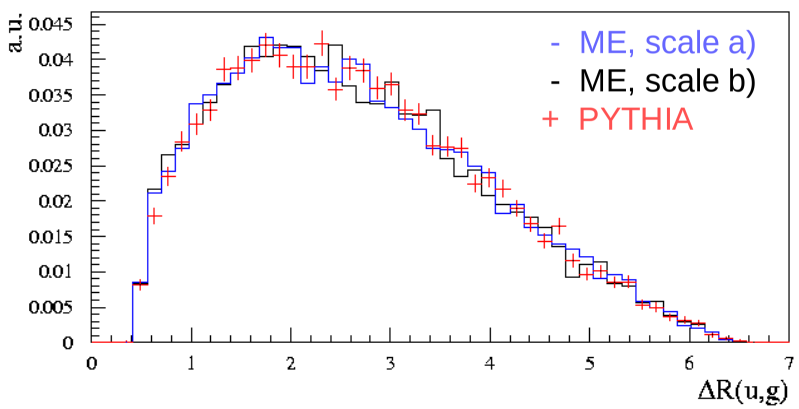


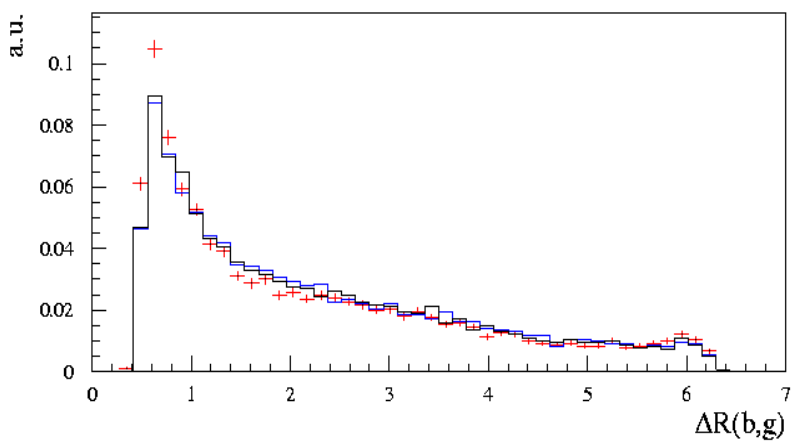


- Similar p_{Tg} spectrum and rate between ME b) and PYTHIA for p_{Tg}>20 GeV.
- Good agreement in gluon rapidity distribution.

Comparison with PYTHIA: radiation off b-quark (cont'd)

- Distance in (y,ϕ)-space between gluon and u-quark (from W), and between gluon and b-quark.

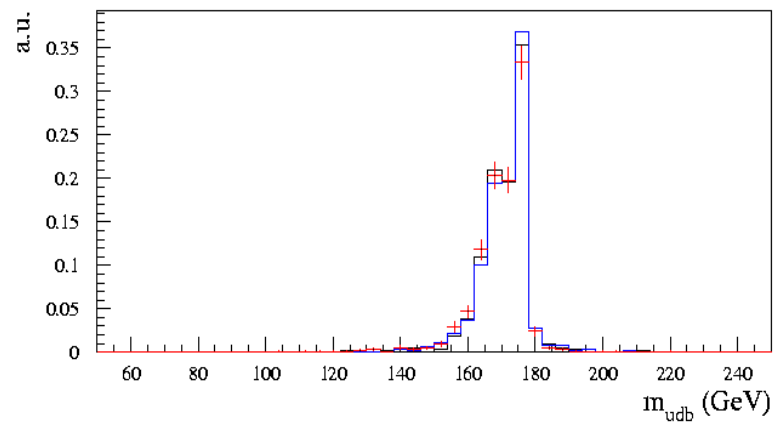


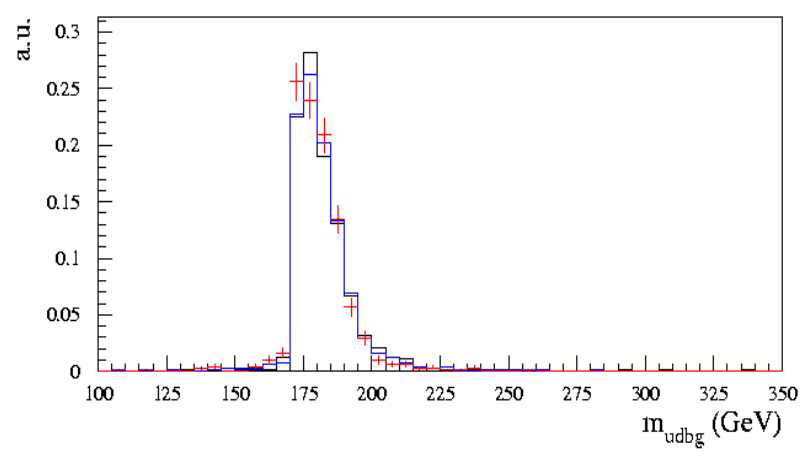


- Separation between gluon and b-quark is smaller in PYTHIA.

- t and tg invariant mass distributions:

p_{Tg} ~ 5.5 GeV

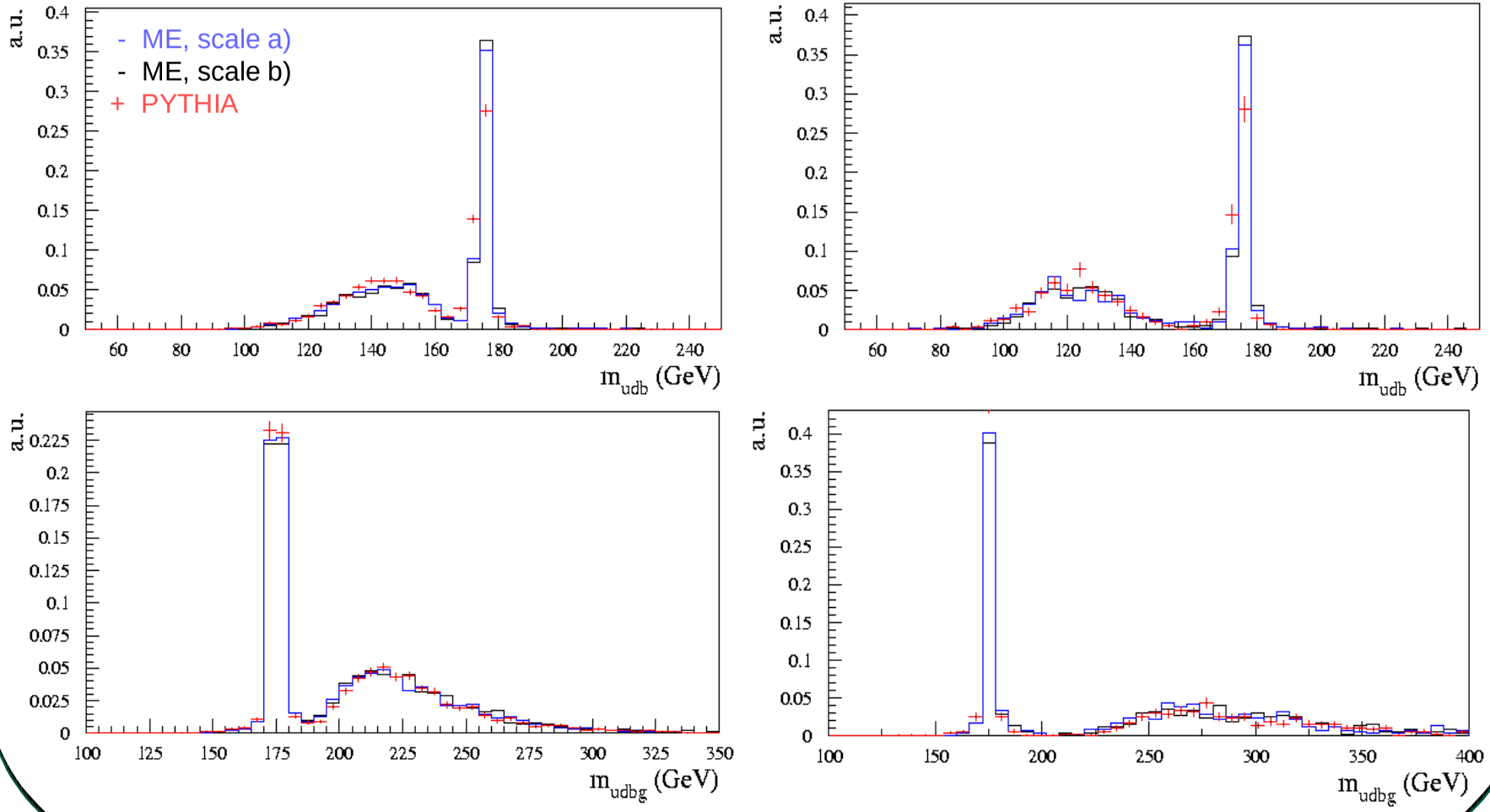




Comparison with PYTHIA: radiation off b-quark (cont'd)

$20 < p_{Tg} < 50$ GeV

$p_{Tg} > 50$ GeV



Summary and plans

- Very good agreement for tt and ttj process between ALPGEN and MADGRAPH (both in cross-section and distributions) for some scale choices. Need to resolve discrepancies.
- Performed first (ad-hoc) comparison between ME and PYTHIA at the parton level. The overall agreement for many distributions suggest the approximations made might be of “higher order”. Finish comparison:
  - look at radiation from W decay products
  - compare with full ME (all diagrams w/ interference)
- Start detailed comparisons between $2 \rightarrow 3$, $2 \rightarrow 7$ ME+PS and PYTHIA.