Comparison of Event Generators

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Why do we need simulations?

Collisions of elementary particles and hadrons at high energies show large multiplicities and complicated event structures.
How do we extract relevant information about fundamental interactions and hadronic structure?

> Simulations provide a link between pQCD description of hard partonic scattering and measured events!

Experimentalists use simulations to

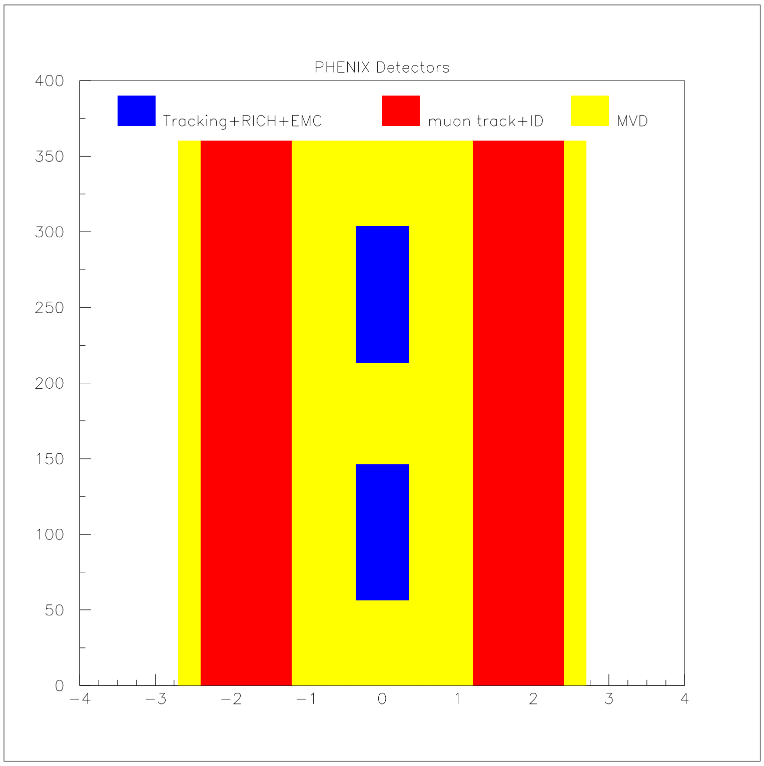
- estimate rates, asymmetries, sensitivity to different scenarios;
- study the background (esp. hadronic background, decays);
- test the reliability of reconstruction of partonic kinematics from the final state;
- estimate detector acceptances;
- ...

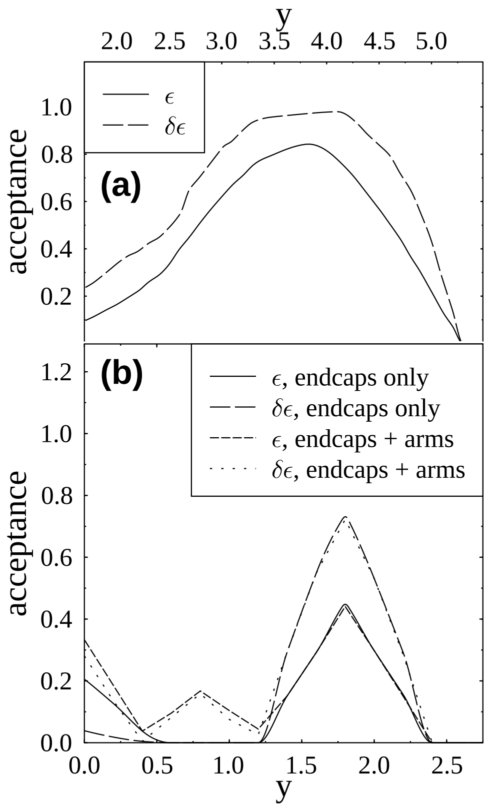
For polarized scattering we need polarized simulations!

Influence of Detector Acceptance on Asymmetries

Example: $\mu^+\mu^-$-production as signal for the transversity distribution at PHENIX

Acceptance: $$(\delta)\epsilon = \frac{\mathrm{d}(\delta)\sigma\ (\text{with PHENIX})}{\mathrm{d}(\delta)\sigma\ (\text{with perfect } 4\pi \text{ detector})}$$





$$A_{TT}^{exp} = \frac{N^{\uparrow\uparrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\uparrow\downarrow}} = \mathcal{P}_A \mathcal{P}_B \frac{\int_{\text{bin}} \delta\epsilon \, \mathrm{d}\delta\sigma}{\int_{\text{bin}} \epsilon \, \mathrm{d}\sigma} = \mathcal{P}_A \mathcal{P}_B A_{TT}^{theory} \cdot R_\epsilon$$

$$R_\epsilon = \frac{\left[\int \delta\epsilon \, \mathrm{d}\delta\sigma\right] / \left[\int \mathrm{d}\delta\sigma\right]}{\left[\int \epsilon \, \mathrm{d}\sigma\right] / \left[\int \mathrm{d}\sigma\right]}$$

Requirements for Simulations

- provide complete events which are as detailed as events that could be observed with a perfect detector;
- the generated events should fluctuate with the same deviations about the same mean values as real events.

$\Rightarrow$ Event Generator (EG)

How to construct such a program?

- seperate perturbative from nonperturbative physics (pdf, hadronization);
- try to calculate perturbative cross section as precisely as possible; presently limited to (N)NLO QCD.

$\Rightarrow$ Two problems arise:

- How are the few final-state partons of pQCD related to the large number of observed final-state hadrons?
- The perturbative result receives divergent contributions from configurations with different numbers of partons in the final state which do not cancel for fully exclusive cross sections.

Presently, no complete solution is available.

But:
For certain classes of infrared observables (jet observables, inclusive prompt photon production, ...) some of the experimental cuts can be implemented into a numeric integration of the cross section.

Example (subtraction method):

$$\begin{aligned} I &= \int_0^A \mathrm{d}x x^\epsilon \frac{1}{x} f(x) \\ &= \left[\int_0^A \mathrm{d}x\, x^\epsilon \frac{1}{x} (f(x) - f(0))\right] + \left[\int_0^A \mathrm{d}x\, x^\epsilon \frac{1}{x} f(0)\right] \\ &= \frac{1}{\epsilon} f(0) + f(0) \ln A + \int_0^A \mathrm{d}x\, \frac{1}{x} (f(x) - f(0)) + \mathcal{O}(\epsilon) \end{aligned}$$

$\Rightarrow$ Parton Generator (PG).

Codes for $\vec{p}\vec{p}$-collisions at RHIC:

γ, γJ:	L.E. Gordon, Nucl. Phys. B501, 197-206 (1997);
	S. Frixione, W. Vogelsang, hep-ph/9908387.
J, JJ:	D. de Florian et al., Nucl. Phys. B539, 455-476 (1999).
$c\bar{c}$:	I. Bojak, M. Stratman et al., hep-ph/00????? (?).

(Dis)Advantages:

+ minimal number of parameters ($\Lambda_{QCD}, \mu_R, \mu_F,\ m_c$);

+ relatively small dependence on unphysical scales;

− not all experimental cuts can be implemented.

Event Generators

- Restrict to LO QCD → cross section is positive and finite and MC probability methods can be used.

- Incorporate universal radiative corrections through iterative parton showers.

- Correct treatment of polarization of partons in hard interaction and parton showers is straight forward (⇒ Sphinx, S. Güllenstern et al., Comp. Phys. Com. 87, 416-431 (1995)).

(Dis)Advantages:

+ Showers yield large number of partons with low virtuality which can be fed into hadronization procedure → fully exclusive events are generated!

− Large scale dependence makes absolute predictions nearly impossible.

− Several new parameters must be introduced for the parton shower description.

− Hard parton emission is underestimated. Correlations between final-state partons are not fully/correctly incorporated.

− The precise calculation of typical asymmetries requires an infinite amount of CPU time.

How to safe time generating polarized events

(Used so far for most studies related to the RHIC Spin Program.)

Method of Weighted Asymmetries (MWA):

- Generate unpolarized events with Pythia. Extract x_A, x_B, $\hat{s}$, $\hat{t}$, $\hat{u}$, μ and parton flavours.

- Calculate

$$A_{LL} = \frac{\Delta f_a^A(x_A,\mu^2)\Delta f_b^B(x_B,\mu^2)}{f_a^A(x_A,\mu^2) f_b^B(x_B,\mu^2)} \frac{\Delta\hat{\sigma}_{ab}(\hat{s},\hat{t},\hat{u},\mu)}{\hat{\sigma}_{ab}(\hat{s},\hat{t},\hat{u},\mu)} .$$

  Fill histogram with weight equal to A_{LL}.

- Finally, divide each bin by number of entries.

(Dis)Advantages:

+ FAST! Direct calculation. Asymmetries for different sets of polarized pdf can be computed simultaneously.

− Polarization of partons cannot be treated correctly in parton showers.
  $\Rightarrow$ Any visible deviations from 'correct' method?

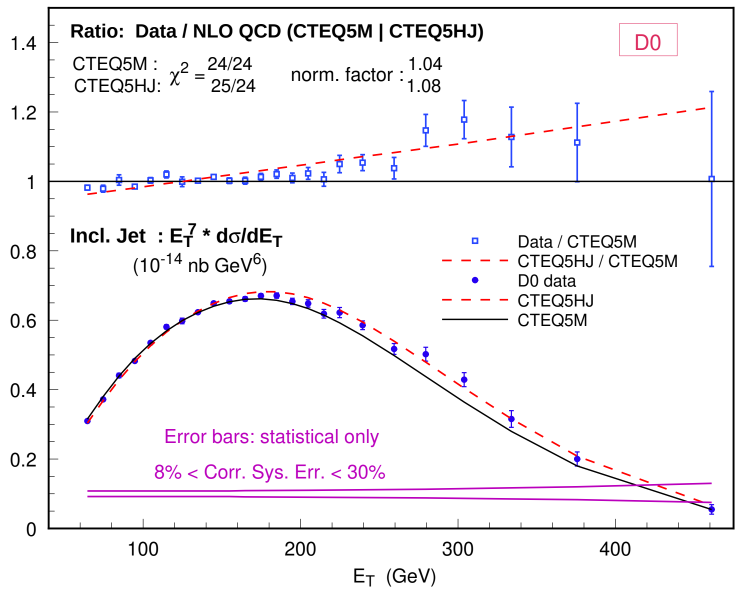
− Since we do not generate events for different hadronic spin configurations, they cannot be used as input for 'real' analysis software.

Comparison of the three methods

Since the experimental analysis partly relies on results from event generators we better make sure that they give a good description of nature.
Difficult: no $\vec{p}\vec{p}$-data available yet, large number of cuts for available unpolarized observables, ...

Comparison of PG with EG/MWA interesting in its own right:

- NLO QCD gives a good description of unpolarized $p\bar{p}$ jet data (CTEQ Collab., Eur. Phys. J. C12, 375-392 (2000)).
  Not the case for prompt photon production, but NLO QCD will be important ingredient for final solution.



- Do both approximations to the full perturbative series give similar results?

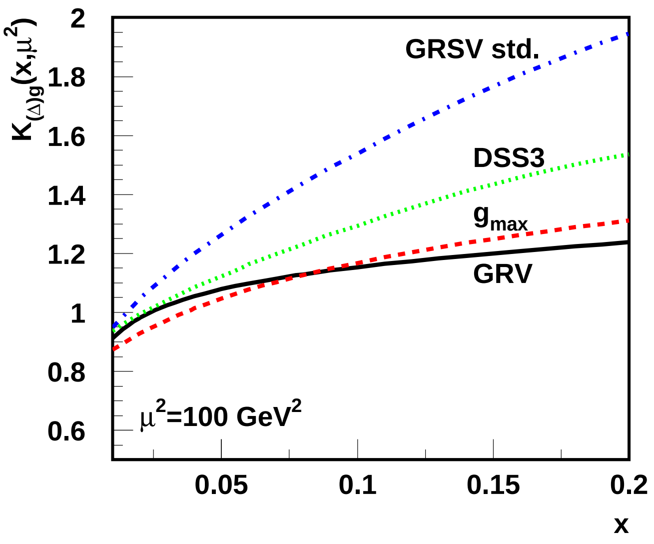
- Does the correct treatment of polarization in the parton showers have any observable effect?

Preliminaries

NLO α_s and NLO pdf used throughout:
GRV95, GRSV std. and g_{max}, DSS3.

$$K_{(\Delta)g}(x,\mu^2) = \frac{(\Delta)g^{NLO}(x,\mu^2)}{(\Delta)g^{LO}(x,\mu^2)}$$

Start from pure Born xsec and regard NLO / parton shower effects as 'small' corrections.
ES jet algorithm with $R = 1$.



1- and 2-Jet Observables

(inspired by D. de Florian et al., Nucl. Phys. B539, 455-476 (1999).)

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}E_T}, \quad 14\ \text{GeV} < E_T < 50\ \text{GeV}, \quad |\eta| < 1$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}\eta}, \quad 0 < \eta < 2, \quad E_T > 15\ \text{GeV}$$

Requirements for 2-jet events:

$$E_{T,J_1} > 15\ \text{GeV}, \quad E_{T,J_2} > 10\ \text{GeV}, \quad |\eta_{J_1}| < 1, \quad |\eta_{J_2}| < 1.$$

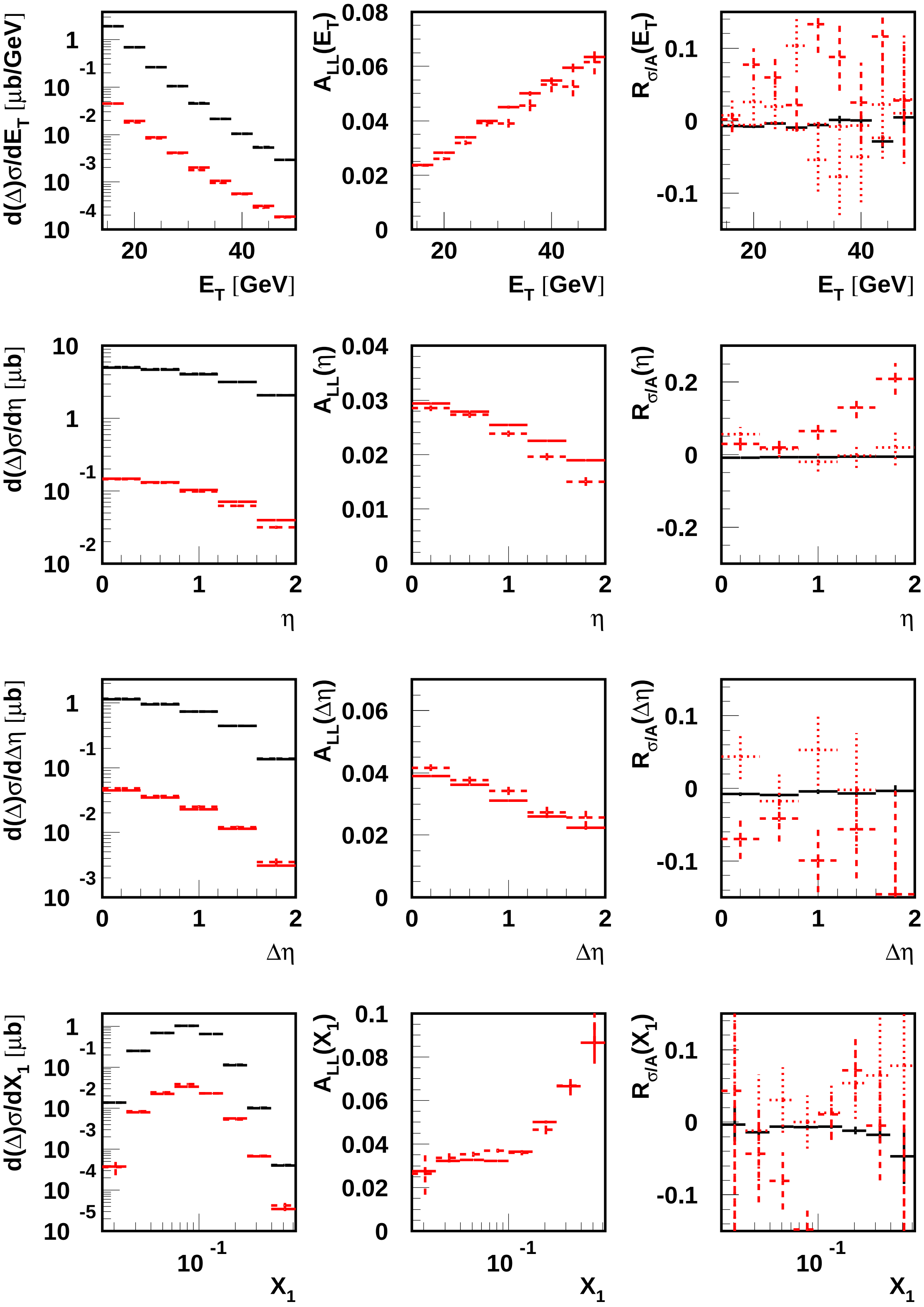
$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}\Delta\eta}, \quad 0 < \Delta\eta < 2, \quad \Delta\eta \equiv \eta_{J_1} - \eta_{J_2}$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}X_1}, \quad X_1 \equiv \frac{E_{T,J_1}e^{\eta_{J_1}} + E_{T,J_2}e^{\eta_{J_2}}}{\sqrt{S}}$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}M_{JJ}}, \quad M_{JJ} < 100\ \text{GeV}, \quad M_{JJ}^2 \equiv (p_{J_1} + p_{J_2})^2$$

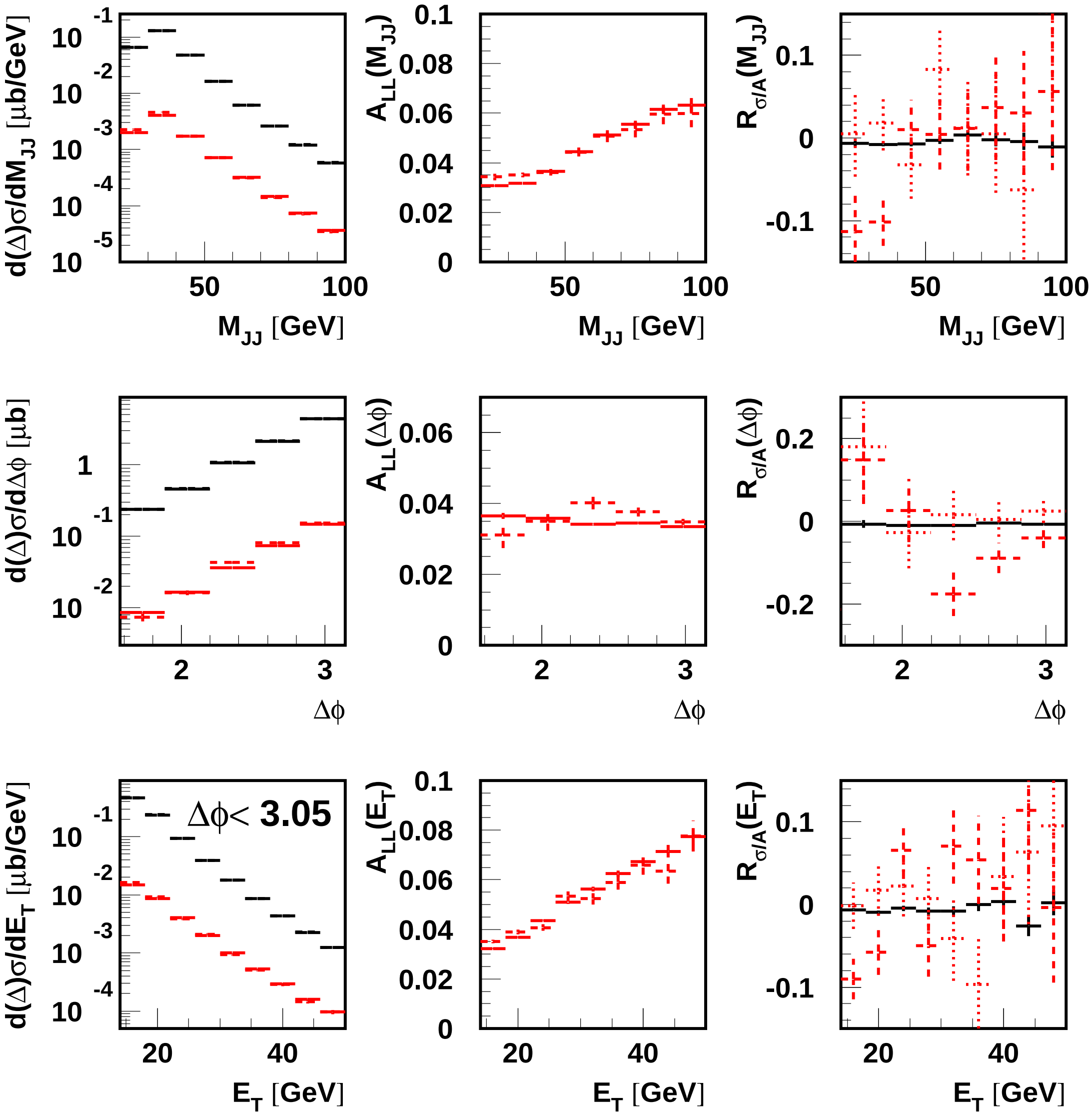
$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}\Delta\phi}, \quad 1.6 < \Delta\phi \leq \pi, \quad \Delta\phi \equiv \phi_{J_1} - \phi_{J_2},$$

Jets - SPHINX vs. MWA



$$R_\sigma \equiv \frac{\mathrm{d}\sigma_{\mathrm{MWA}} - \mathrm{d}\sigma_{\mathrm{SPHINX}}}{\mathrm{d}\sigma_{\mathrm{MWA}}}\,, \qquad R_A \equiv \frac{A_{LL,\mathrm{MWA}} - A_{LL,\mathrm{SPHINX}}}{A_{LL,\mathrm{MWA}}}$$

Jets - SPHINX vs. MWA

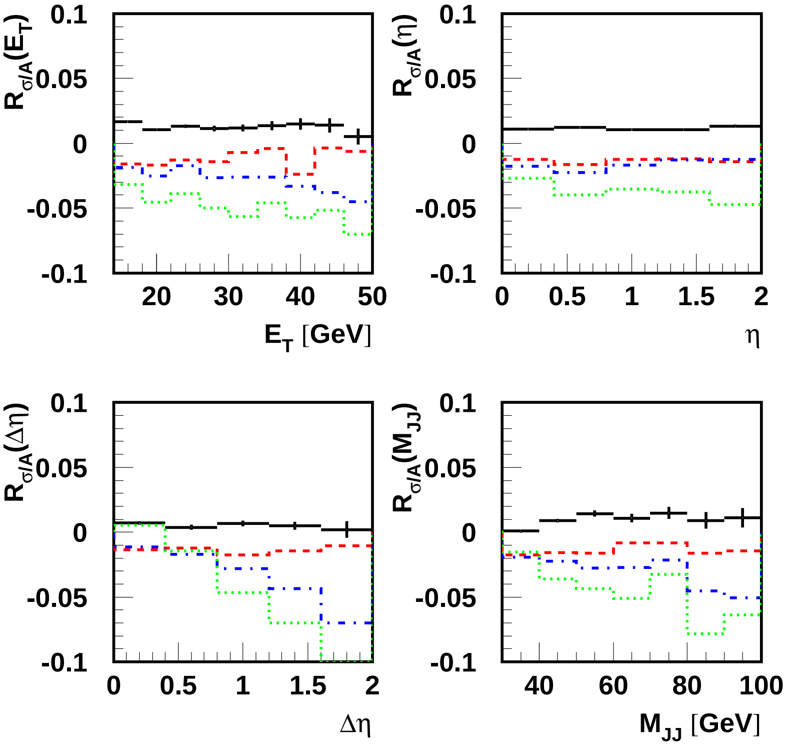


$$R_\sigma \equiv \frac{\mathrm{d}\sigma_{\mathrm{MWA}} - \mathrm{d}\sigma_{\mathrm{SPHINX}}}{\mathrm{d}\sigma_{\mathrm{MWA}}}, \qquad R_A \equiv \frac{A_{LL,\mathrm{MWA}} - A_{LL,\mathrm{SPHINX}}}{A_{LL,\mathrm{MWA}}}$$

$\Rightarrow$ Polarization in the initial state shower is important for some observables!

- What about other scenarios for $\Delta g(x, \mu^2)$?

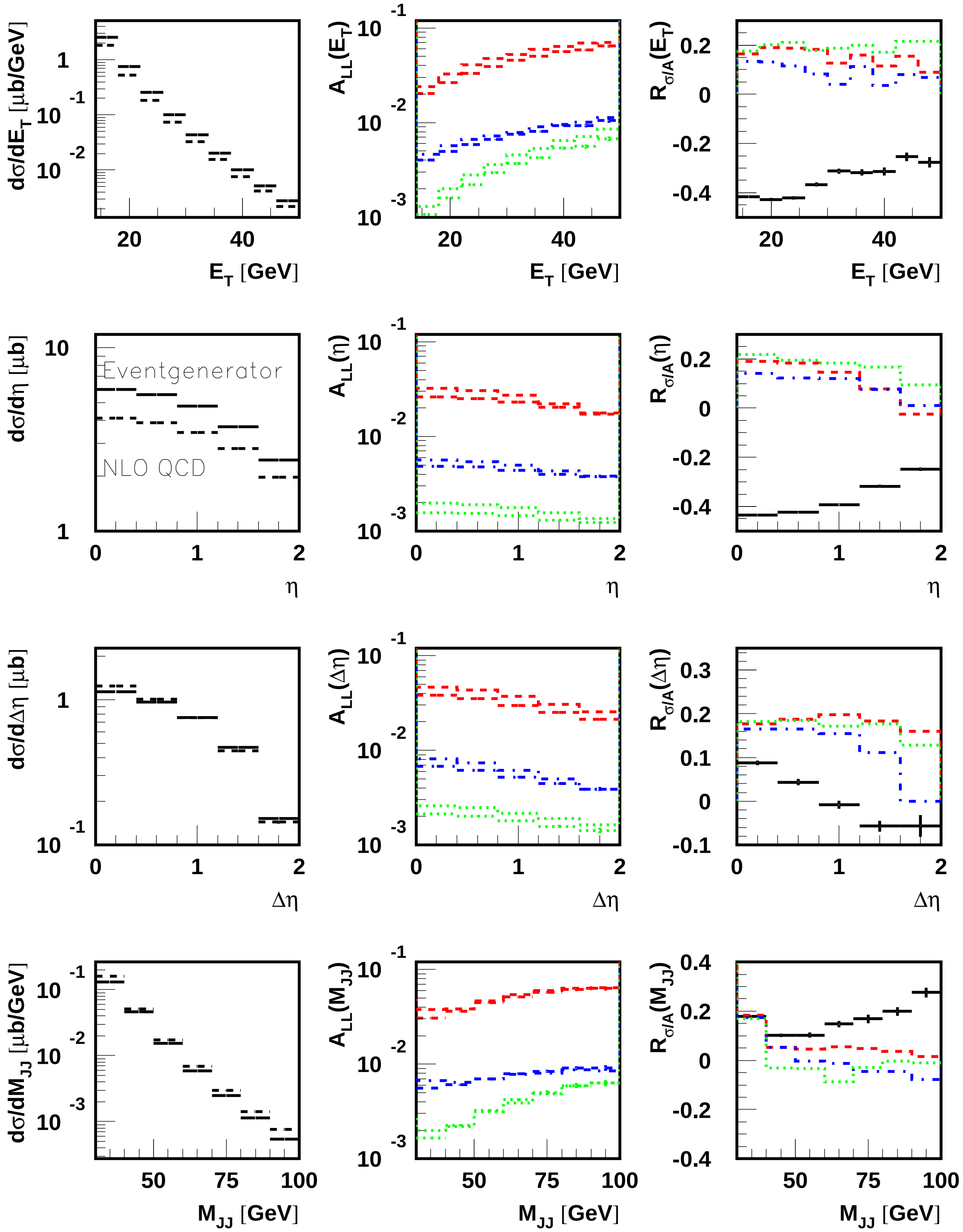
Jets - LO QCD vs. MWA



$$R_\sigma \equiv \frac{d\sigma_{\text{LO QCD}} - d\sigma_{\text{MWA}}}{d\sigma_{\text{LO QCD}}}, \qquad R_A \equiv \frac{A_{LL,\text{LO QCD}} - A_{LL,\text{MWA}}}{A_{LL,\text{LO QCD}}}$$

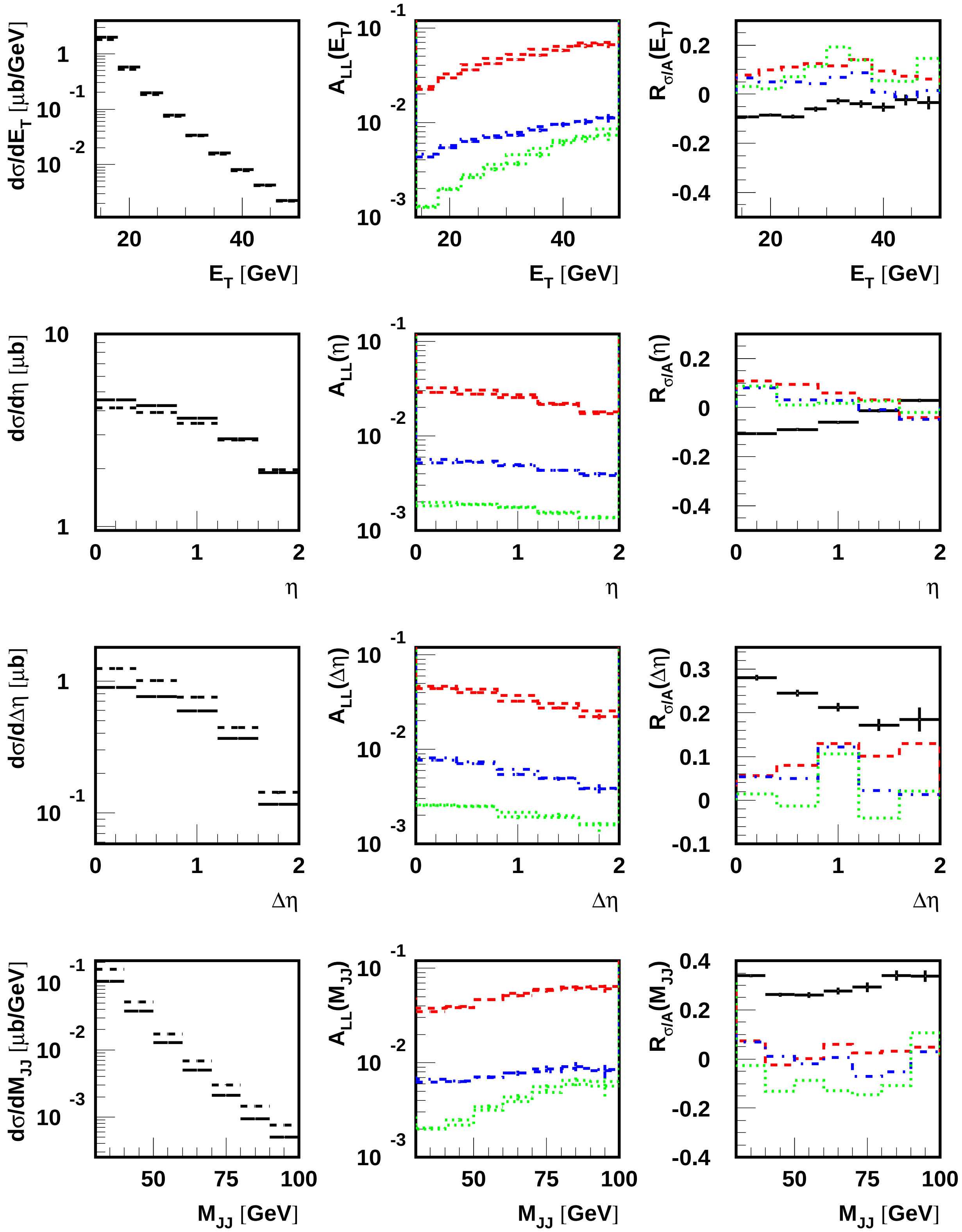
Differences of up to 5%.
Origin?
Different treatment of color interference terms?

Jets - NLO QCD vs. MWA



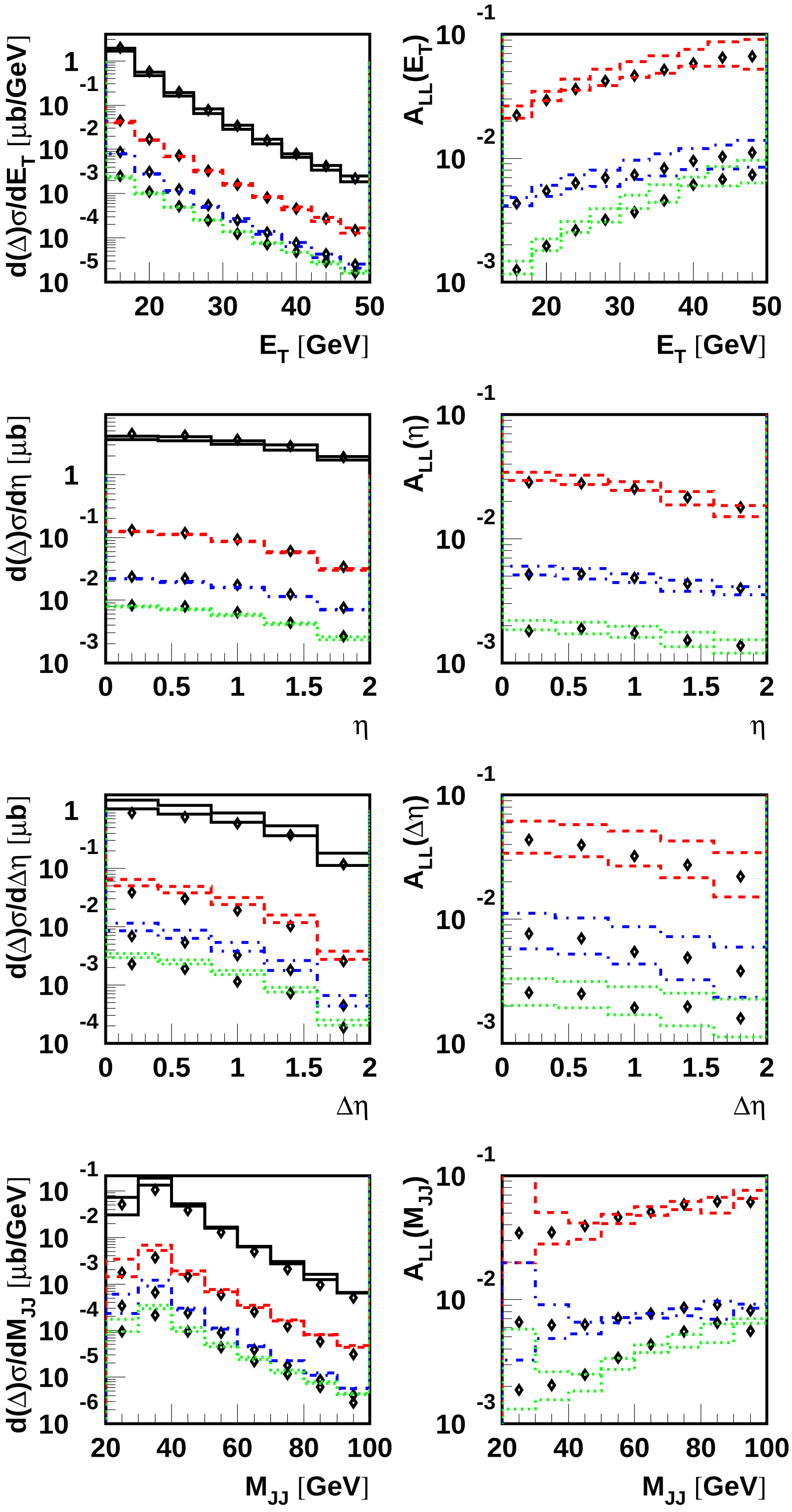
$$R_\sigma \equiv \frac{d\sigma_{\mathrm{NLO\,QCD}} - d\sigma_{\mathrm{MWA}}}{d\sigma_{\mathrm{NLO\,QCD}}}, \qquad R_A \equiv \frac{A_{LL,\mathrm{NLO\,QCD}} - A_{LL,\mathrm{MWA}}}{A_{LL,\mathrm{NLO\,QCD}}}$$

Jets - NLO QCD vs. MWA (tuned)



$$R_\sigma \equiv \frac{d\sigma_{\text{NLO QCD}} - d\sigma_{\text{MWA}}}{d\sigma_{\text{NLO QCD}}}, \qquad R_A \equiv \frac{A_{LL,\text{NLO QCD}} - A_{LL,\text{MWA}}}{A_{LL,\text{NLO QCD}}}$$

Jets - scale dep. of NLO QCD vs. MWA (tuned)



NLO QCD: $\mu_R = \mu_F = 2\overline{|k_T|}, \frac{1}{2}\overline{|k_T|}$

MWA: $\mu_R = \mu_F = \overline{|k_T|}$

γ- and γJ-Observables

(inspired by S. Frixione, W. Vogelsang, hep-ph/9908387)

- Photon isolation according to S. Frixione, Phys. Lett. B429, 369-374 (1998) with $\delta_0 = 0.7$
  $\Rightarrow$ no fragmentation contribution.

- $\sqrt{S} = 200$ GeV yields larger asymmetries.

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}p_{T,\gamma}}\,, \quad 10 \text{ GeV} < p_{T,\gamma} < 50 \text{ GeV}\,, \quad |\eta_\gamma| < 0.5$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}\eta_\gamma}\,, \quad 0 < \eta_\gamma < 2\,, \quad p_{T,\gamma} > 10 \text{ GeV}$$

Requirements for γJ-events:

$$E_{T,J} > 11 \text{ GeV}\,, \quad -1 < \eta_{J,\gamma} < 2\,, \quad |\Delta\phi| \equiv |\phi_J - \phi_\gamma| > \frac{\pi}{2}$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}\Delta\eta}\,, \quad 0 < \Delta\eta < 2.4\,, \quad \Delta\eta \equiv \eta_J - \eta_\gamma$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}M_{\gamma J}}\,, \quad M_{\gamma J} < 100 \text{ GeV}\,, \quad M_{\gamma J}^2 \equiv (p_\gamma + p_J)^2$$

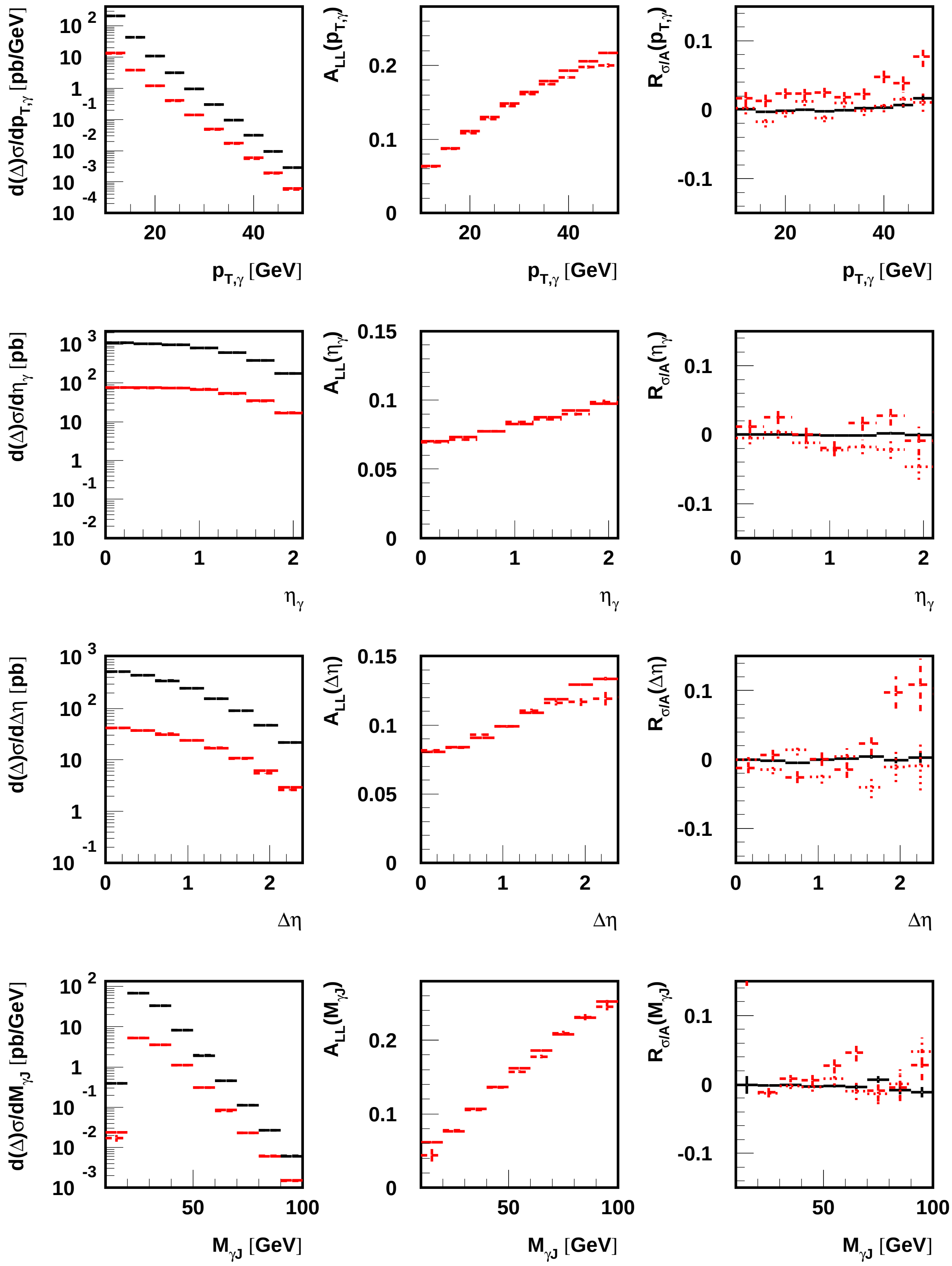
$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}X_{\text{min}}}\,, \frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}X_{\text{max}}}\,, \quad 0.01 < X_{\text{min}}, X_{\text{max}} < 1\,,$$

$$X_{\text{min/max}} \equiv \text{min / max}\left(\frac{p_{T,\gamma}e^{\eta_\gamma} + E_{T,J}e^{\eta_J}}{\sqrt{S}}, \frac{p_{T,\gamma}e^{-\eta_\gamma} + E_{T,J}e^{-\eta_J}}{\sqrt{S}}\right)$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}R_{\gamma J}}\,, \quad R_{\gamma J} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

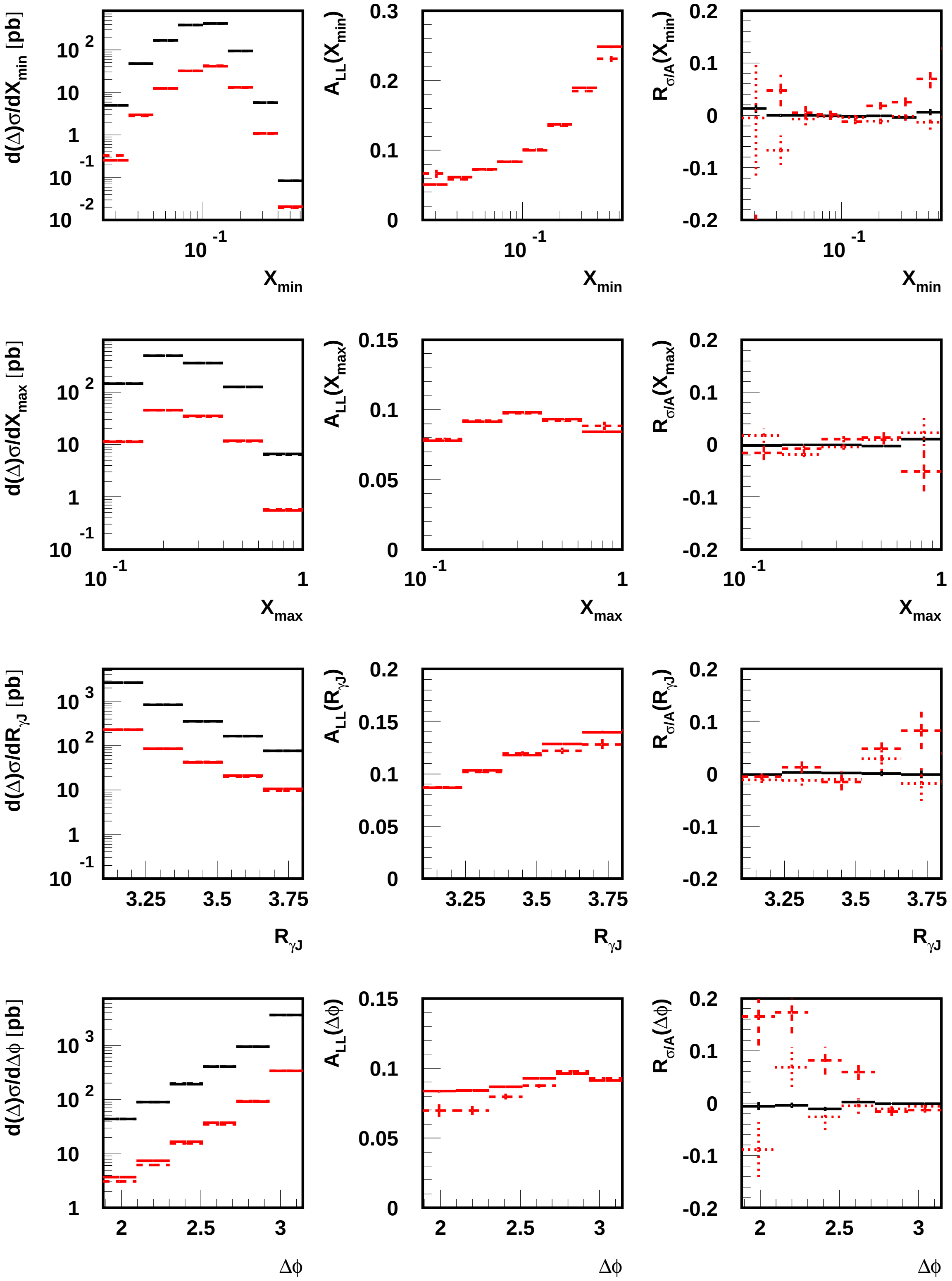
$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}\Delta\phi}\,, \quad \frac{\pi}{2} < \Delta\phi < \pi$$

Photons - SPHINX vs. MWA (no Bremsstrahlung-γ)



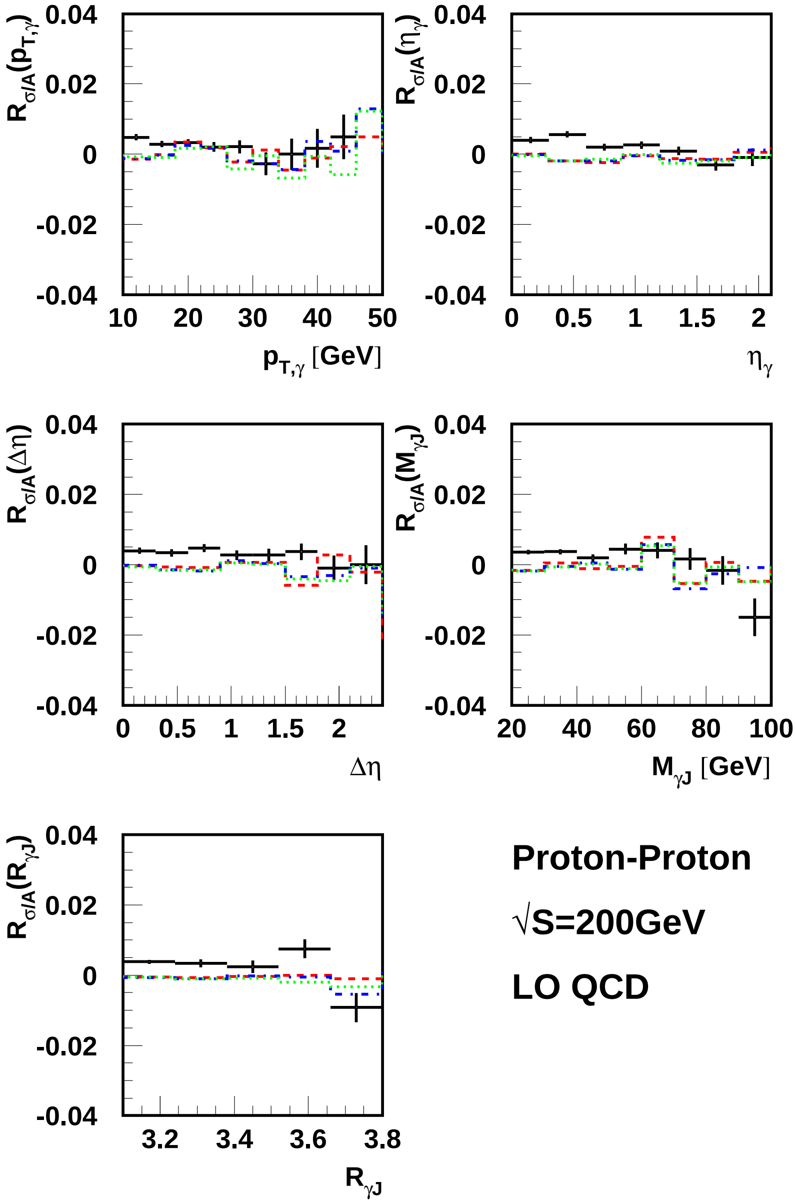
$$R_\sigma \equiv \frac{\mathrm{d}\sigma_{\mathrm{MWA}} - \mathrm{d}\sigma_{\mathrm{SPHINX}}}{\mathrm{d}\sigma_{\mathrm{MWA}}}, \qquad R_A \equiv \frac{A_{LL,\mathrm{MWA}} - A_{LL,\mathrm{SPHINX}}}{A_{LL,\mathrm{MWA}}}$$

Photons - SPHINX vs. MWA (no Bremsstrahlung-γ)



$$R_\sigma \equiv \frac{d\sigma_{\text{MWA}} - d\sigma_{\text{SPHINX}}}{d\sigma_{\text{MWA}}}, \qquad R_A \equiv \frac{A_{LL,\text{MWA}} - A_{LL,\text{SPHINX}}}{A_{LL,\text{MWA}}}$$

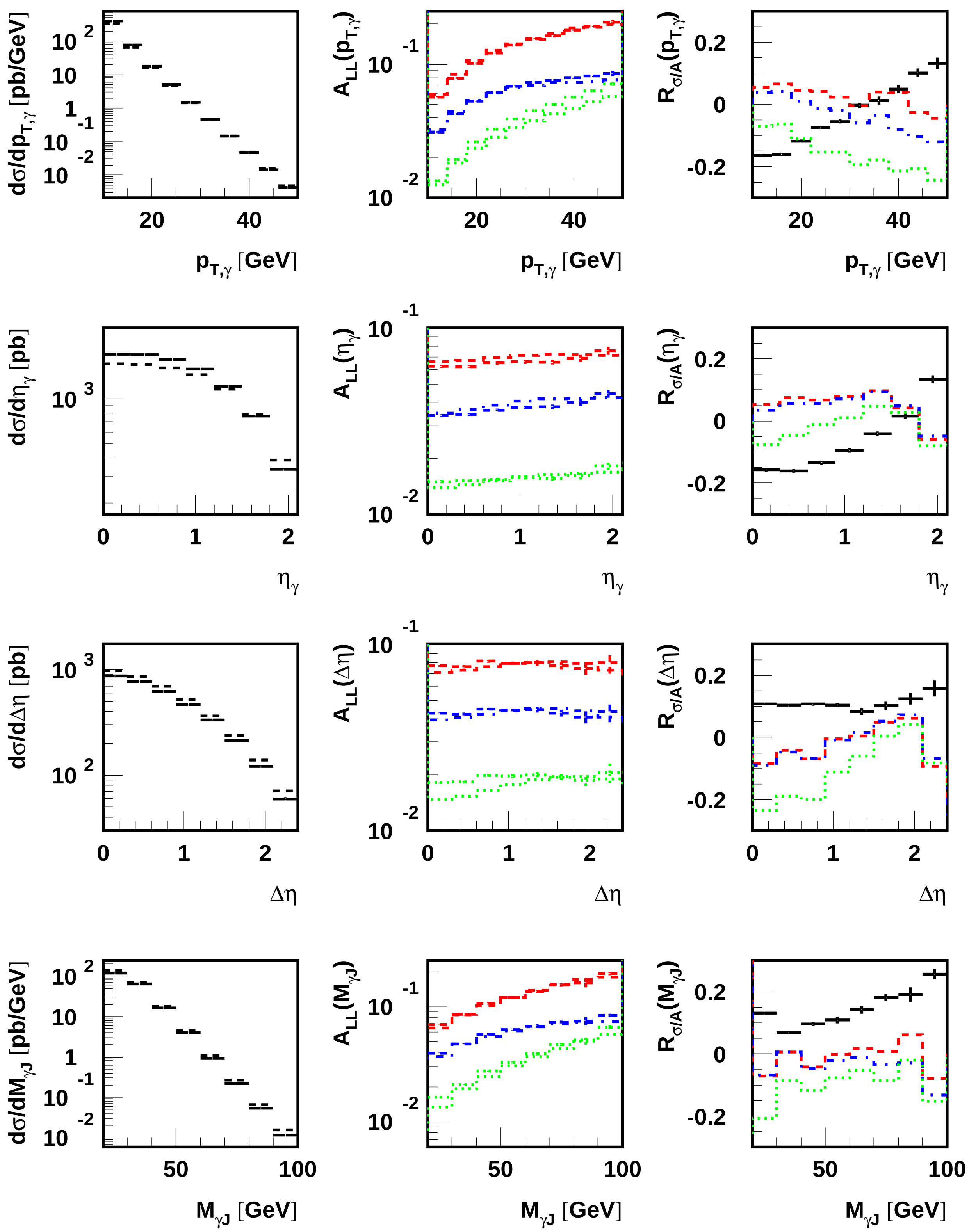
Photons - LO QCD vs. MWA



$$R_\sigma \equiv \frac{d\sigma_{\text{LO QCD}} - d\sigma_{\text{MWA}}}{d\sigma_{\text{LO QCD}}}\,, \qquad R_A \equiv \frac{A_{LL,\text{LO QCD}} - A_{LL,\text{MWA}}}{A_{LL,\text{LO QCD}}}$$

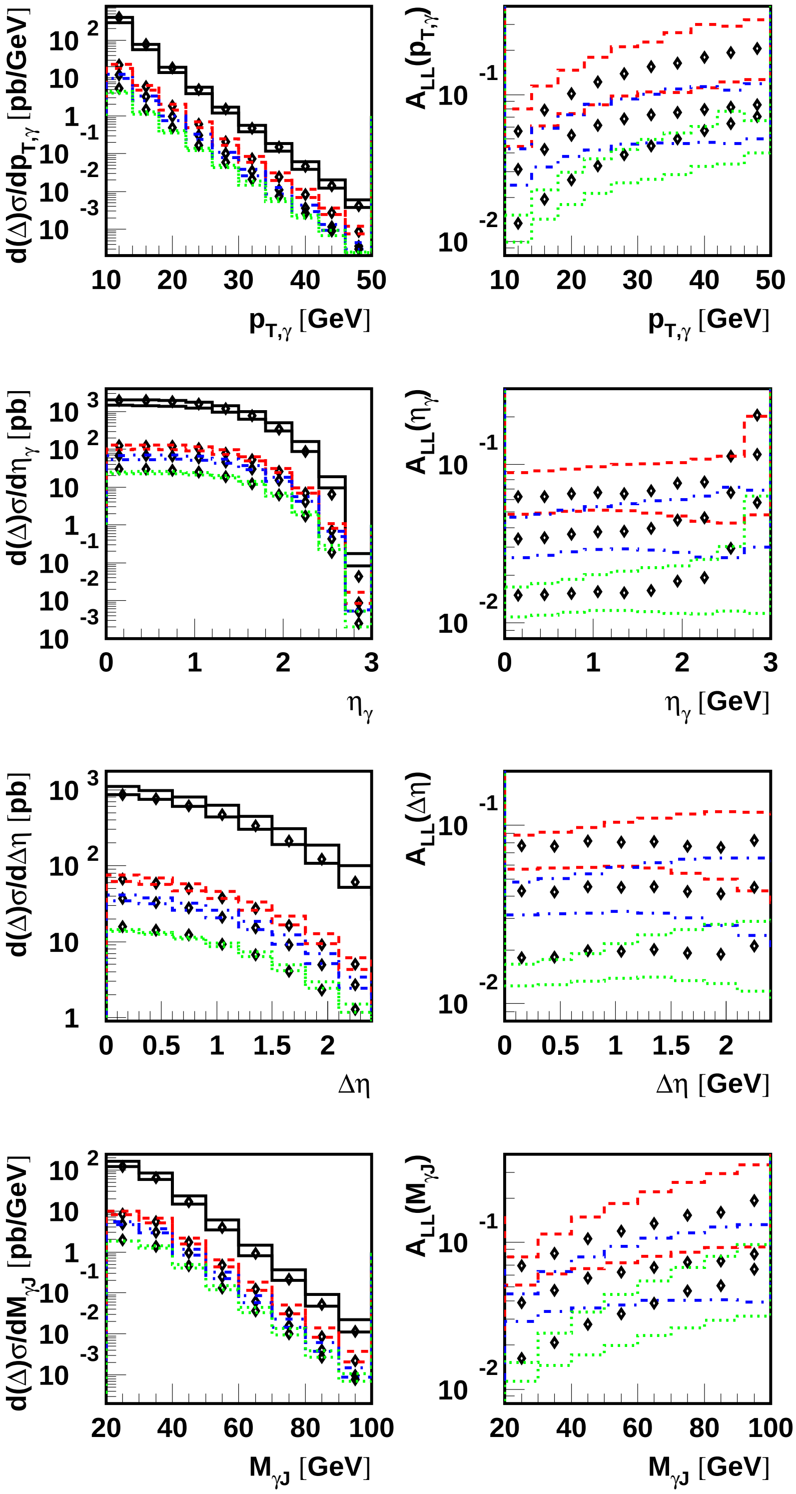
OK.

Photons - NLO QCD vs. MWA



$$R_\sigma \equiv \frac{d\sigma_{\text{NLO QCD}} - d\sigma_{\text{MWA}}}{d\sigma_{\text{NLO QCD}}}, \qquad R_A \equiv \frac{A_{LL,\text{NLO QCD}} - A_{LL,\text{MWA}}}{A_{LL,\text{NLO QCD}}}$$

Photons - scale dep. of NLO QCD vs. MWA



$$R_\sigma \equiv \frac{d\sigma_{\text{NLO QCD}} - d\sigma_{\text{MWA}}}{d\sigma_{\text{NLO QCD}}}\,, \qquad R_A \equiv \frac{A_{LL,\text{NLO QCD}} - A_{LL,\text{MWA}}}{A_{LL,\text{NLO QCD}}}$$

Conclusions from the comparisons

- Within the limited statistics gathered, the effect of the correct treatment of polarization in the initial state shower is clearly significant.

- Relative deviations of the asymmtry of up to 20% were found.
  ⇒ Sphinx should be used instead of MWA for production runs (if computing power is available).

- We encountered substantial differences between absolute cross sections calculated with Pythia+MWA and NLO QCD, which cannot be resolved by tuning the parton showers.

- However, the relative deviations of the asymmetries never exceed 20% and are in many cases smaller than 10% (tuning).

- Situation is not satisfying yet. Improvement through merging NLO QCD with parton showers?