V+jets with Sherpa

Validating ME+PS merging against Tevatron data

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MC4LHC readiness

CERN 01/04/10

- The Sherpa approach ($\geq$ v1.2.0)
  - tree-level matrix elements and truncated showers
  - inherent systematics
- Validation/Application for DY & prompt-photons at Tevatron

Simulating Hadron–Hadron Collisions

The Monte Carlo approach

- **Hard interaction**

  exact matrix elements $|\mathcal{M}|^2$

- **QCD bremsstrahlung**

  parton showers in the initial and final state

- **Multiple Interactions**

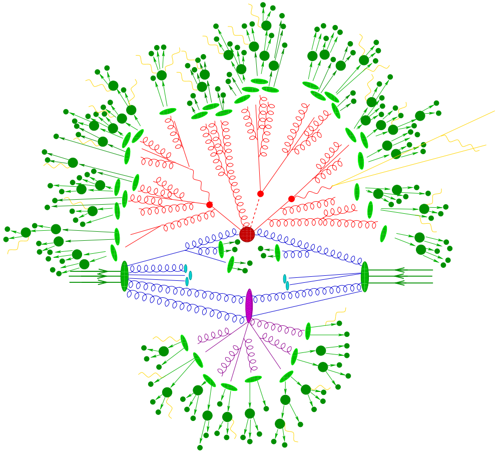
  beyond factorisation: modelling

- **Hadronisation**

  non perturbative QCD: modelling

- **Hadron Decays**

  phase space or effective theories



$\Rightarrow$ **fully exclusive hadronic final states**

$\Rightarrow$ **direct comparison with experimental data**

modulo detector simulation

Herwig, Pythia, Sherpa

Catani–Seymour dipole factorisation based Shower

Catani–Seymour local subtraction term

$$\int_{m+1} \mathrm{d}\sigma^{\mathrm{A}} = \sum_{\mathrm{dipoles}} \int_m \mathrm{d}\sigma^{\mathrm{B}} \otimes \int_1 \mathrm{d}V_{\mathrm{dipole}}$$

spin- & color correlation ⟵ ⟶ universal dipole term

[Catani, Seymour Nucl. Phys. B **485** (1997) 291]

[Catani, Dittmaier, Seymour, Trocsanyi Nucl. Phys. B **627** (2002) 189]

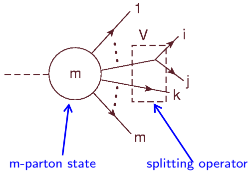
Ansatz: complete factorisation through

- projection onto leading term in $1/N_c$
- spin averaged dipole terms $V_{\mathrm{dipole}} \longrightarrow \langle V_{\mathrm{dipole}} \rangle$

Shower Algorithm [Krauss, S. JHEP **0803** (2008) 038]

- color connected emitter–spectator 'dipoles'
- subsequent branchings of type II, IF, FI, FF
- exact momentum mappings invertable
- emissions ordered in $k_\perp^2$

$$\mathcal{K}^{\mathrm{QCD}}_{(ij)i}(z, \mathrm{k}_\perp^2) \sim \frac{\alpha_s(\mathrm{k}_\perp^2)}{2\pi} \sum_k \langle \mathrm{V}^{\mathrm{QCD}}_{(ij)i,k}(\mathrm{k}_\perp^2, z) \rangle$$



Matrix Elements and Truncated Showers: ME⊕TS

Describe few hardest emissions through ME

- emission phase space sliced IR sensible measure Q
  - Soft/collinear emissions from shower $Q < Q_{\rm cut}$
  - Hard emissions from matrix element $Q > Q_{\rm cut}$

⇝ Sudakov form factor factorises

$$\Delta_a(\mu^2, k_\perp^2) = \Delta_a^{\rm PS}(\mu^2, k_\perp^2)\, \Delta_a^{\rm ME}(\mu^2, k_\perp^2)$$

⇝ $$\mathcal{K}_{ba}^{\rm ME}(z, k_\perp^2) \rightarrow \frac{1}{{\rm d}\hat{\sigma}_a^{(N)}(\Phi_N)} \frac{{\rm d}\hat{\sigma}_b^{(N+1)}(z, k_\perp^2; \Phi_N)}{{\rm d}\log(k_\perp^2/\mu^2)\,{\rm d}z}$$

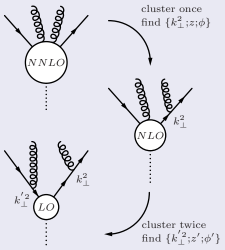
A new merging algorithm [Höche, Krauss, S., Siegert JHEP **0905** (2009) 053]

→ **pseudo shower history for MEs**
cluster algorithm inverse to the shower

→ **Truncated Shower**
PS starts at $2 \rightarrow 2$ core and can radiate partons off intermediate lines i.e. "between" ME partons

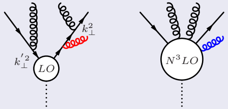
ME branchings must be respected
evolution-, splitting- & angular variables $\{k_\perp^2, z, \phi\}$ preserved

Pseudo shower history



Truncated shower

$Q < Q_{\rm cut}$ $Q > Q_{\rm cut}$



Matrix Elements and Truncated Showers: ME⊕TS

The proposed measure: final-state splitting $(ij) \to ij$

$$Q_{ij}^2 \;=\; 2\,p_i p_j \,\min_{k\neq i,j} \frac{2}{C_{i,j}^k + C_{j,i}^k}\,; \qquad C_{i,j}^k \;=\; \begin{cases} \dfrac{p_i p_k}{(p_i+p_k)p_j} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j=g \\ 1 & \text{else} \end{cases}$$

↪ minimize over color partners k

The proposed measure: initial-state splitting $a \to (aj)j$

$$Q_{aj}^2 \;=\; 2\,p_a p_j \,\min_{k\neq a,j} \frac{2}{C_{(aj),j}^k + C_{j,(aj)}^k}\,; \qquad C_{(aj),j}^k \;=\; \begin{cases} \dfrac{p_{aj} p_k}{(p_{aj}+p_k)p_j} & \text{if } j=g \\ 1 & \text{else} \end{cases}$$

↪ minimize over color partners k

- measure correctly identifies IR enhanced phase-space regions
- regulator for matrix elements & veto measure for the shower
- no additional free parameter is introduced as e.g. D for the Run II k_T algorithm

Systematics

Sources of Systematics

merging related we try hard to minimize that

- value of phase-space separation cut, Q_{cut} [cancels to the log-accuracy of the shower]
- maximum number of jets from hard ME's, N_{max}
- choice of internal separation measure

pQCD related dynamical scale choice inherent

- scale uncertainties from ME's [e.g. μ_R of the $2 \to 2$ core]
- scale uncertainties from PS's [e.g. rescaled factorisation/start scale]

pQCD/npQCD transition

- parton-shower IR cut-off / intrinsic transverse momentum [tuned at LEP & low-p_T DY]
- PDF $+$ α_S from the fit [enter in ME and PS]

npQCD related need to be tuned

- hadronisation parameters [Professor tune to LEP data]
- Underlying Event parameters [so far hand-tuned only]

Drell-Yan

Z^0+jets at Tevatron: Total cross sections

Q_{cut} and/or N_{max} variation should affect σ_{tot} only beyond (N)LL

Example: DY-pair production $\sigma_{\rm tot}$ @ Tevatron

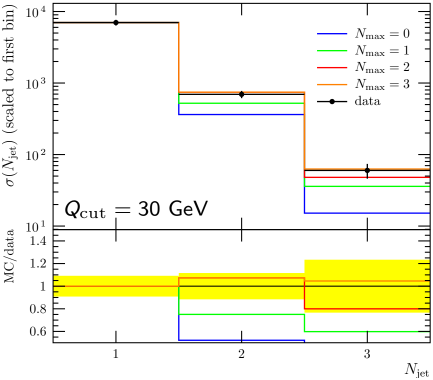
		$N_{\rm max}$						
		0	1	2	3	4	5	6
$Q_{\rm cut}$	20 GeV	192.6(1)	191.0(3)	190.5(4)	189.0(5)	189.4(7)	188.2(8)	189.9(10)
	30 GeV		192.3(2)	192.7(2)	192.6(3)	192.9(3)	192.7(3)	193.2(3)
	45 GeV		193.6(1)	194.4(1)	194.3(1)	194.4(1)	194.6(2)	194.4(1)

$\rightsquigarrow$ **"merging systematics" of $\sigma_{\rm tot} < \pm 3\%$**

Z^0+jets at Tevatron: jet multiplicities

Jet rates and -spectra improved compared to pure PS simulation
due to exact real emission ME's

Example: DY-pair production $\sigma_{e^+e^-+N_{jet}}$ CDF Data: PRL **100** (2008) 102001
[Sherpa normalized to $\sigma_{e^+e^-+1_{jet}}$]



Z^0+jets at Tevatron: jet spectra

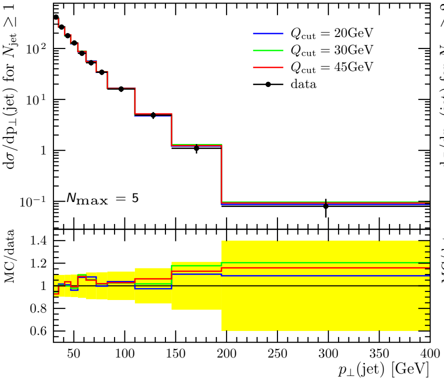
Variation of Q_{cut} should affect distributions only beyond (N)LL

But Q_{cut} must be in range where PS approximation is valid!

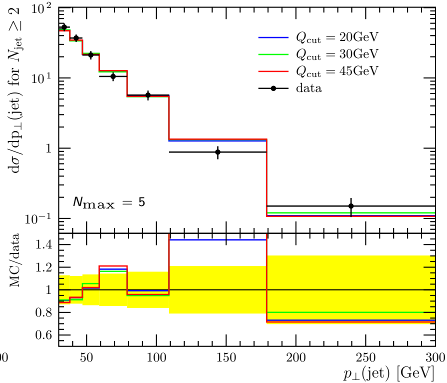
Example: All-jets p_T's in DY-pair production CDF Data: PRL **100** (2008) 102001

[Sherpa normalized to $\sigma_{e^+e^-+1_{jet}}$]

p_T(jet) for $N_{jet} \geq 1$



p_T(jet) for $N_{jet} \geq 2$



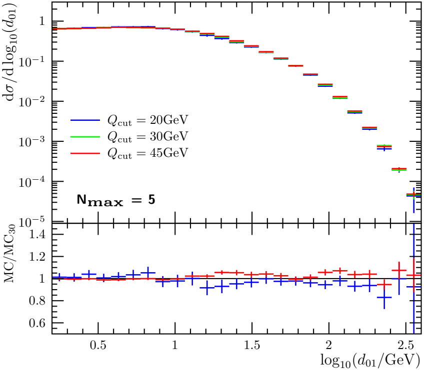
Z^0+jets at Tevatron: jet spectra

Variation of Q_{cut} should affect distributions only beyond (N)LL

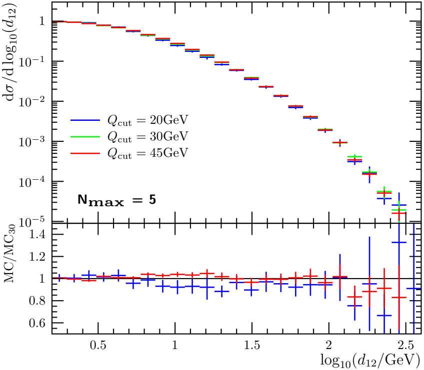
But Q_{cut} must be in range where PS approximation is valid!

Example: Differential $\mathbf{k_T}$ jet rates

1 ⟶ 0



2 ⟶ 1



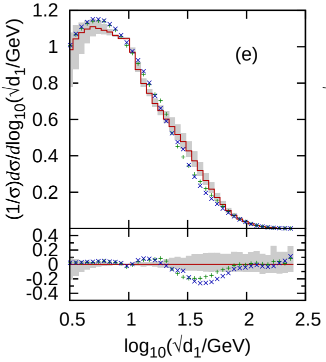
⇝ **Q_{cut} variations within $\pm 10\%$**

Z^0+jets at Tevatron: jet spectra

Variation of Q_{cut} should affect distributions only beyond (N)LL
But Q_{cut} must be in range where PS approximation is valid!

Example: Differential $\mathbf{k_T}$ jet rates

$\Rightarrow$ 'old' Sherpa CKKW for W+jets [Alwall et. al Eur. Phys. J. C **53** (2008) 473]

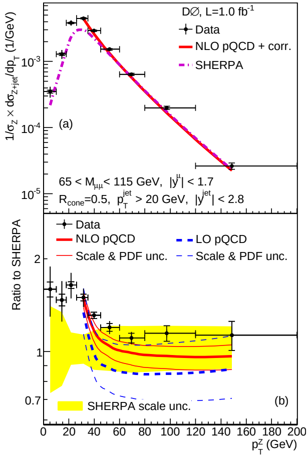


Z^0+jets at Tevatron: Z/γ^* transverse momentum

Comparison to Sherpa's CKKW implementation in v1.1.3

Example: DY-p_T in Z/γ^*+jet events DØ Data: Phys. Lett. B **669** (2008) 278

Sherpa v1.1.3



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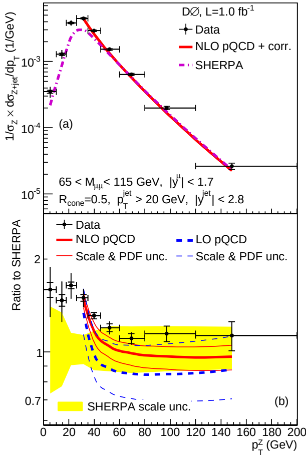
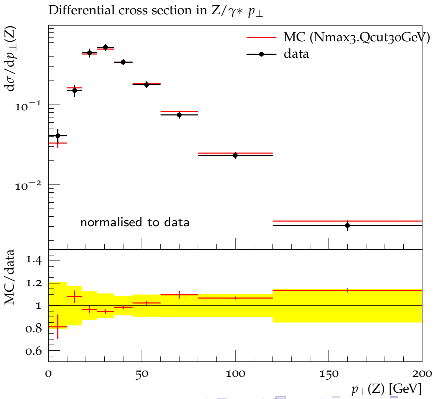


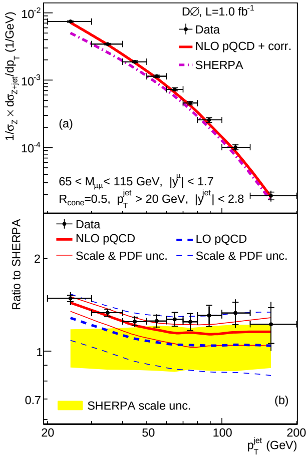
Sherpa v1.2



Comparison to Sherpa's CKKW implementation in v1.1.3

Example: 1st jet-p_T in Z/γ^*+jet events DØ Data: Phys. Lett. B **669** (2008) 278

Sherpa v1.1.3



Z^0+jets at Tevatron: jet spectra

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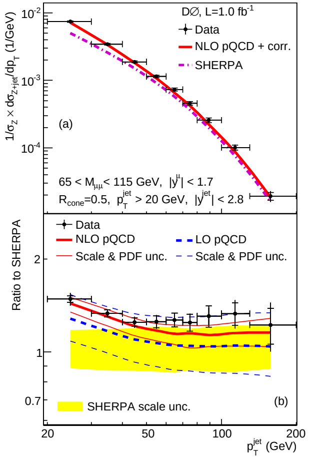
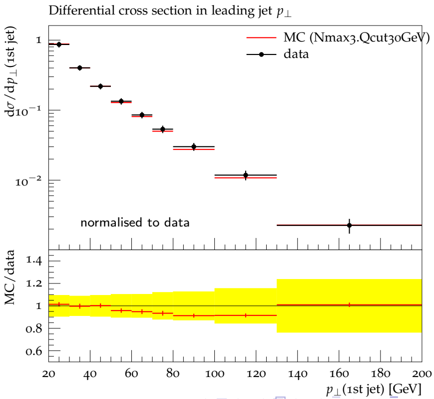
Sherpa v1.1.3



Sherpa v1.2

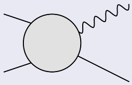


Prompt-Photons

Prompt-Photon Production at Hadron Colliders

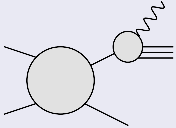
The perturbative QCD approach

Direct production



- fixed-order calculations
  - γ+jet @ NLO (JetPhox) [Catani et. al]
  - $\gamma\gamma$ @ NLO (DiPhox) [Binoth et. al]
  - $\gamma\gamma$+jet @ NLO [Del Duca et. al]
  - $gg \to \gamma\gamma g$ [de Florian et. al]

Fragmentation component



- QED $\gamma - q$ collinear singularity
- resummation to all orders α_s
- fragmentation function $D^{\gamma}_{q,g}$

[Llewellyn Smith Phys. Lett. B **79** (1978) 83]

Pre-requisits

- IR safe cross-section definition based on photon-isolation criterium

  [cone, smooth isolation, democratic approach]
- input for the non-perturbative component of $D^{\gamma}_{q,g}(z, Q^2)$
- non-prompt component, e.g. $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, experimentally separable

Prompt-Photon Production at Hadron Colliders

A new Monte Carlo model [Höche, S., Siegert PRD **81** (2010) 034026]

Democratic Monte Carlo model

- treat photons and QCD partons fully democratically [Glover, Morgan Z. Phys. C **62** (1994) 311]
- combine matrix elements of different parton/photon multiplicity with
- interleaved QCD$\oplus$QED evolution and hadronization $\rightsquigarrow$ models $D^{\gamma}_{q,g}(z, Q^2)$

Generalized merging formalism

- emission probabilities factorise trivially

$$\Delta_a(\mu^2, k_\perp^2) = \Delta_a^{\mathrm{QCD}}(\mu^2, k_\perp^2)\Delta_a^{\mathrm{QED}}(\mu^2, k_\perp^2)$$

- implemented by adding splitting functions $q \to q\gamma$

$$\mathcal{K}^{\mathrm{QED}}_{(ij)i}(z, \mathrm{k}_\perp^2) \sim \frac{\alpha(\mathrm{k}_\perp^2)}{2\pi} \sum_k \langle \mathrm{V}^{\mathrm{QED}}_{(ij)i,k}(\mathrm{k}_\perp^2, z)\rangle$$

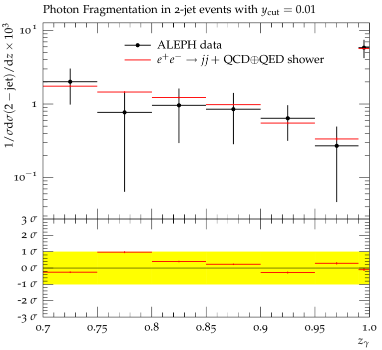
  - different than large-N_C QCD: spectators *all* particles with opposite charge
  - neglect (negative) interference with same-sign charges [Dittmaier Nucl. Phys. B **565** (2000) 69]

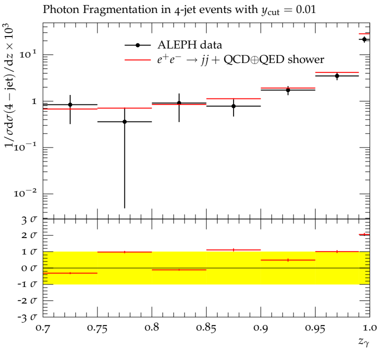
Prompt-Photon Production at Hadron Colliders

Measuring the photon fragmentation function in $e^+e^- \to$ Hadrons

- validation of the shower/hadronization component
- perform jet finding including final-state photons
- study photon-energy fraction wrt its containing jet: $z_\gamma \equiv E_\gamma / E_{\rm jet}$
- measured by ALEPH for 2-jet, 3-jet, ≥4-jet events at varying $y_{\rm cut}^{\rm Durham}$

[Z. Phys. C **69** (1996) 365]





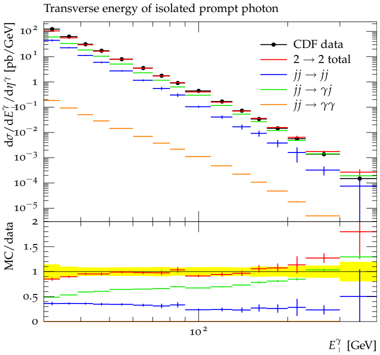
Prompt-Photon Production at Hadron Colliders

Isolated prompt-photon production at Tevatron

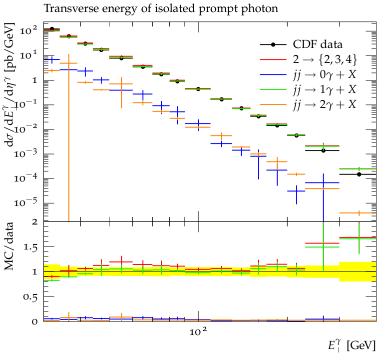
- CDF data [Phys. Rev. D **80** (2009) 111106]

  cuts: $30 < E_T^\gamma < 400$ GeV, $|\eta^\gamma| < 1$, isolation: $E_T^{R=0.4} - E_T^\gamma < 2$ GeV
- Sherpa: $jj \to jj/\gamma j/\gamma\gamma$ + shower vs. ME⊕TS with $N_{\rm max} = 2$

E_T^γ – pure shower



E_T^γ – ME⊕TS



Prompt-Photon Production at Hadron Colliders

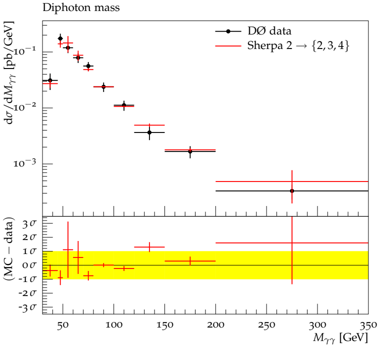
Di-Photon production at Tevatron

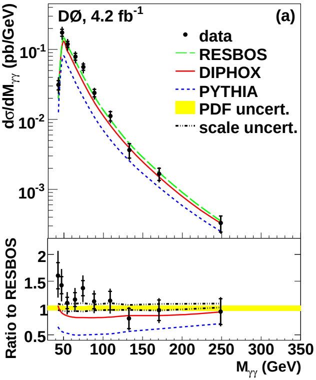
- DØ data [arXiv:1002.4917]

  cuts: $E_T^{\gamma_1} > 21$ GeV, $E_T^{\gamma_2} > 20$ GeV, $|\eta^{\gamma_{1,2}}| < 0.9$ isolation: $E_T^{R=0.4} - E_T^{\gamma} < 2.5$ GeV

  ResBos, DiPhox, Pythia
- Sherpa: merged $2 \to \{2, 3, 4\}$ plus $gg \to \gamma\gamma$ box

Di-Photon invariant mass





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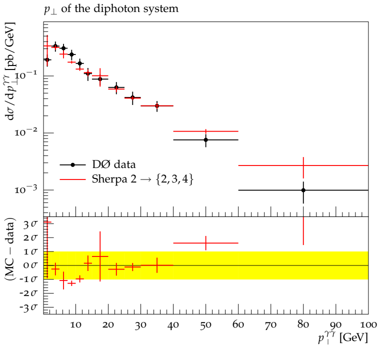
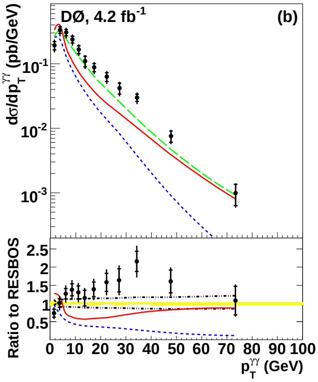
Di-Photon transverse momentum





Prompt-Photon Production at Hadron Colliders

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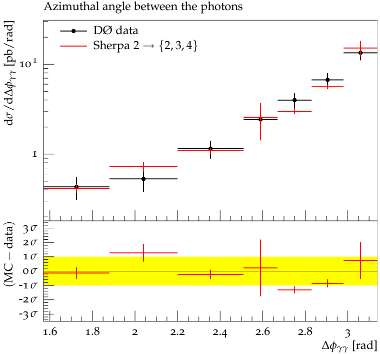
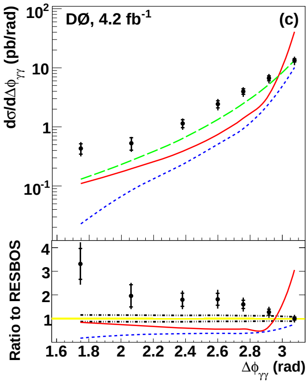
Di-Photon azimuthal de-correlation





Summary/Outlook

Summary

- Multijet ME-PS merging sustainable approach to describe multijet events
- Virtues of two complementary approaches combined
  - hard emissions through exact tree-level matrix elements
  - (intra) jet evolution through truncated QCD parton showers
- New formalism available within Sherpa-1.2 [Höche, Krauss, S., Siegert JHEP **0905** (2009) 053]
  - MEs from Comix [Gleisberg, Höche JHEP **0812** (2008) 039]
  - dipole subtraction based shower [S., Krauss JHEP **0803** (2008) 038]
  - interleaved QCD$\oplus$QED evolution [Höche, S., Siegert PRD **81** (2010) 034026]
  - Deep Inelastic Scattering [Carli, Gehrmann, Höche arXiv:0912:3715]

Validation

- improved/reduced systematics wrt 'old' CKKW implementation
- good agreement with Tevatron data & pQCD NLO calculations
- Tevatron data extremely useful to develop/validate our MC models
- Rivet proves to be the perfect tool for direct comparison