Introduction to Event Generators

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Topics of the lectures

1. Lecture 1: *The Monte Carlo Principle*
2. Lecture 2: *Parton level event generation*
3. Lecture 3: *Dressing the Partons*
4. Lecture 4: *Modelling beyond Perturbation Theory & Improving the showers*

Thanks to

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- the other Sherpas: J.Archibald, T.Gleisberg, S.Höche, S.Schumann, F.Siegert, M.Schönherr, and J.Winter.

Menu of lecture 4

- Hadronisation models
- Beyond factorisation: Underlying event
- Improving parton showers with exact matrix elements

Prelude: Orientation

Event generator paradigm

Divide event into stages, separated by different scales.

- Signal/background:

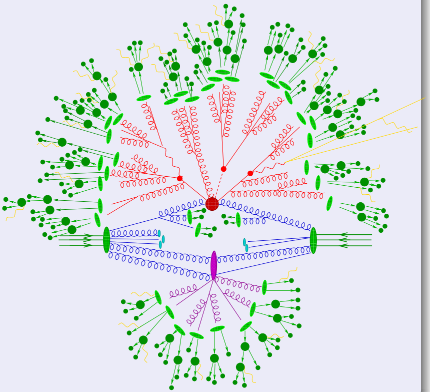
  Exact matrix elements.
- QCD-Bremsstrahlung:

  Parton showers (also in initial state).
- Multiple interactions:

  Beyond factorisation: Modelling.
- Hadronisation:

  Non-perturbative QCD: Modelling.

Sketch of an event

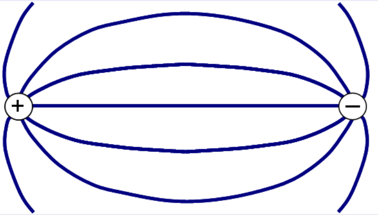


Hadronisation

Confinement

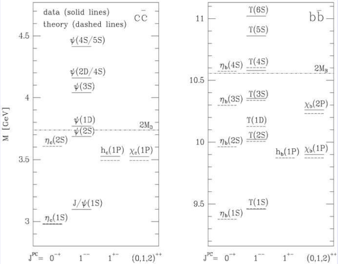
- Consider dipoles in QED and QCD

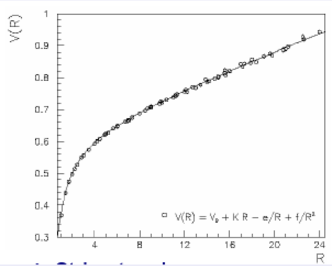
QED:



QCD:

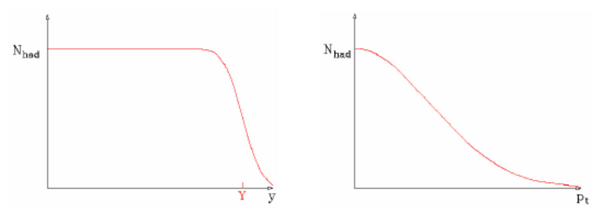
Linear QCD potential in Quarkonia





Some experimental facts → naive parameterisations

- In $e^+e^- \to$ hadrons: Limits $p_\perp$, flat plateau in y.



- Try "smearing": $\rho(p_\perp^2) \sim \exp(-p_\perp^2/\sigma^2)$

Effect of naive parameterisations

- Use parameterisation to "guesstimate" hadronisation effects:

$$\begin{aligned} E &= \int_0^Y \mathrm{d}y\mathrm{d}p_\perp^2\,\rho(p_\perp^2)p_\perp\,\cosh y = \lambda\sinh Y \\ P &= \int_0^Y \mathrm{d}y\mathrm{d}p_\perp^2\,\rho(p_\perp^2)p_\perp\,\sinh y = \lambda(\cosh Y - 1) \approx E - \lambda \\ \lambda &= \int \mathrm{d}p_\perp^2\,\rho(p_\perp^2)p_\perp = \langle p_\perp\rangle\,. \end{aligned}$$

- Estimate $\lambda \sim 1/R_{\rm had} \approx m_{\rm had}$, with $m_{\rm had}$ 0.1-1 GeV.
- Effect: Jet acquire non-perturbative mass $\sim 2\lambda E$ ($\mathcal{O}(10\mathrm{GeV})$ for jets with energy $\mathcal{O}(100\mathrm{GeV})$).

Implementation of naive parameterisations

- Feynman-Field independent fragmentation.

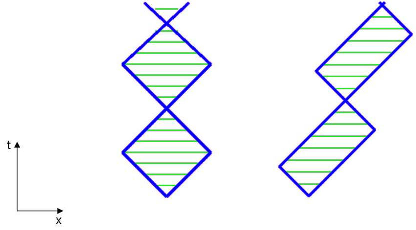
  R.D.Field and R.P.Feynman, Nucl. Phys. B **136** (1978) 1

- Recursively fragment $q \to q' +$ had, where
  - Transverse momentum from (fitted) Gaussian;
  - longitudinal momentum arbitrary (hence from measurements);
  - flavour from symmetry arguments + measurements.
- Problems: frame dependent, "last quark", infrared safety, no direct link to perturbation theory, ...

Yoyo-strings as model of mesons

B.Andersson, G.Gustafson, G.Ingelman and T.Sjostrand, Phys. Rept. **97** (1983) 31.

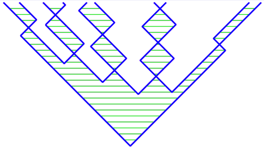
- Light quarks connected by string: area law $m^2 \propto$area.
- L=0 mesons only have 'yo-yo' modes:



Dynamical strings in $e^+e^- \to q\bar{q}$

B.Andersson, G.Gustafson, G.Ingelman and T.Sjostrand, Phys. Rept. **97** (1983) 31.

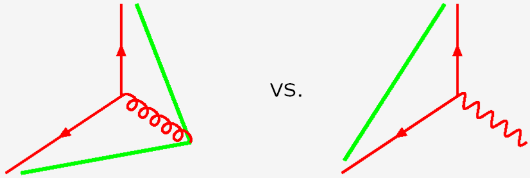
- Ignoring gluon radiation: Point-like source of string.
- Intense chromomagnetic field within string:
  More $q\bar{q}$ pairs created by tunnelling.
- Analogy with QED (Schwinger mechanism):
  $\mathrm{d}\mathcal{P} \sim \mathrm{d}x\mathrm{d}t \exp\left(-\pi m_q^2/\kappa\right)$, $\kappa =$ "string tension".



Gluons in strings = kinks

B.Andersson, G.Gustafson, G.Ingelman and T.Sjostrand, Phys. Rept. **97** (1983) 31.

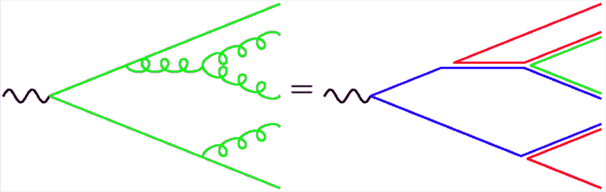
- String model = well motivated model, constraints on fragmentation (Lorentz-invariance, left-right symmetry, . . .)
- Gluon = kinks on string? Check by "string-effect"



- Infrared-safe, advantage: smooth matching with PS.

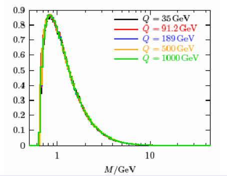
Preconfinement

- Underlying: Large N_c-limit (planar graphs).
- Follows evolution of colour in parton showers: at the end of shower colour singlets close in phase space.
- Mass of singlets: peaked at low scales $\approx Q_0^2$.



Primordial cluster mass distribution

- Starting point: Preconfinement;
- split gluons into $q\bar{q}$-pairs;
- adjacent pairs colour connected, form colourless (white) clusters.
- Clusters ("≈ excited hadrons) decay into hadrons



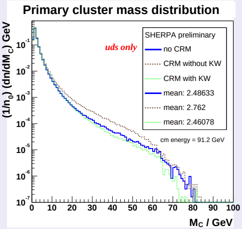
Cluster model

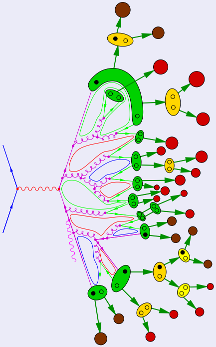
B.R.Webber, Nucl. Phys. B **238** (1984) 492.

- Split gluons into $q\bar{q}$ pairs, form singlet clusters:
  $\Longrightarrow$ continuum of meson resonances.
- Decay heavy clusters into lighter ones;
  (here, many improvements to ensure leading hadron spectrum hard enough, overall effect: cluster model becomes more string-like);
- if light enough, clusters $\rightarrow$ hadrons.
- Naively: spin information washed out, decay determined through phase space only $\rightarrow$ heavy hadrons suppressed (baryon/strangeness suppression).

Colour reconnections in the cluster model

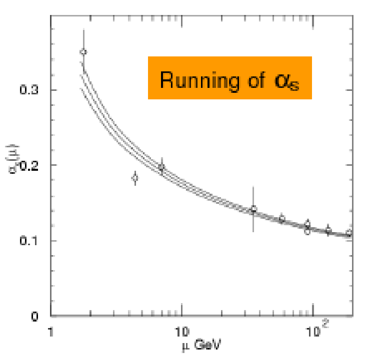
- Maybe toy with phenomenological models of non-perturbative colour reconnection?

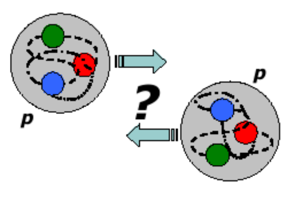




Underlying Event

Multiple parton scattering?



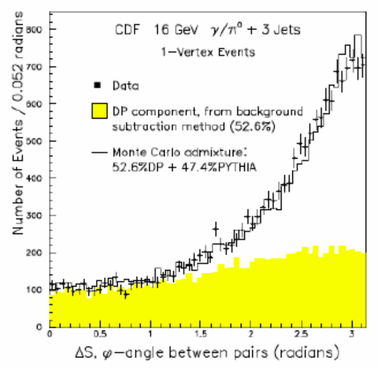


- Hadrons = extended objects!
- No guarantee for one scattering only.
- Running of α_S
  $\Longrightarrow$ preference for soft scattering.

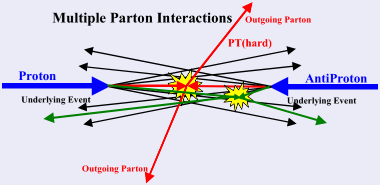
Evidence for multiple parton scattering

- Events with $\gamma + 3$ jets:
  - Cone jets, $R = 0.7$, $E_T > 5$ GeV; $|\eta_j| < 1.3$;
  - "clean sample": two softest jets with $E_T < 7$ GeV;
- $\sigma_{\rm DPS} = \frac{\sigma_{\gamma j}\sigma_{jj}}{\sigma_{\rm eff}}$, $\sigma_{\rm eff} \approx 14 \pm 4$ mb.

CDF collaboration, Phys. Rev. **D56** (1997) 3811.



Definition(s)



1. Everything apart from the hard interaction including IS showers, FS showers, remnant hadronisation.
2. Remnant-remnant interactions, soft and/or hard.
3. Lesson: hard to define

Model: Multiple parton interactions

- To understand the origin of MPS, realism that

$$\sigma_{\rm hard}(p_{\perp,\rm min}) = \int\limits_{p^2_{\perp,\rm min}}^{s/4} {\rm d}p_\perp^2 \, \frac{{\rm d}\sigma(p_\perp^2)}{{\rm d}p_\perp^2} > \sigma_{pp,\rm total}$$

  for low $p_{\perp,\rm min}$. Here: $\frac{{\rm d}\sigma(p_\perp^2)}{{\rm d}p_\perp^2} = \int\limits_0^1 {\rm d}x_1 {\rm d}x_2 {\rm d}\hat{t} f(x_1,\, q^2) f(x_2,\, q^2) \frac{{\rm d}\hat{\sigma}_{2\to 2}}{{\rm d}p_\perp^2} \delta\left(1 - \frac{\hat{t}\hat{u}}{\hat{s}}\right)$

  ($f(x,\, q^2)$ =PDF, $\hat{\sigma}_{2\to 2}$ =parton-parton x-sec)

- $\langle \sigma_{\rm hard}(p_{\perp,\rm min})/\sigma_{pp,\rm total}\rangle \geq 1$
- Depends strongly on cut-off $p_{\perp,\rm min}$ (Energy-dependent)!

Old Pythia model: Algorithm, simplified

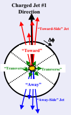
T.Sjostrand and M.van Zijl, Phys. Rev. D **36** (1987) 2019.

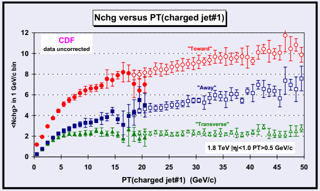
- Start with hard interaction, at scale $Q^2_{\rm hard}$.
- Select a new scale $p_\perp^2$

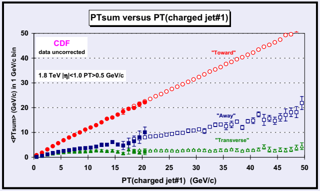
  (according to $f = \frac{d\sigma_{2\to 2}(p_\perp^2)}{dp_\perp^2}$ with $p_\perp^2 \in [p^2_{\perp,\rm min}, Q^2]$)
- Rescale proton momentum ("proton-parton = proton with reduced energy").
- Repeat until below $p^2_{\perp,\rm min}$.
- May add impact-parameter dependence, showers, etc..
- Treat intrinsic $k_\perp$ of partons ($\to$ parameter)
- Model proton remnants ($\to$ parameter)

Observables

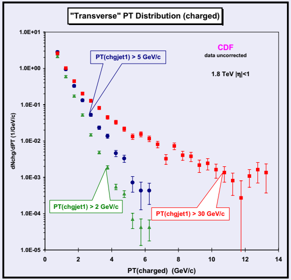
In the following: Data from CDF, PRD 65 (2002) 092002, plots partially from C.Buttar

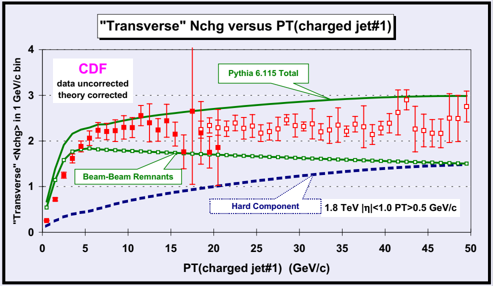






Hard component in transverse region





General facts on current models

- No first-principles approach for underlying event:

  Multiple-parton interactions: beyond factorisation

  Factorisation (simplified) = no process-dependence in use of PDFs.
- Models usually based on xsecs in collinear factorisation: $\mathrm{d}\sigma/\mathrm{d}p_\perp \propto p_\perp^{4-8} \implies$ strong dependence on cut-off $p_\perp^{\min}$.
- "Regularisation": $\mathrm{d}\sigma/\mathrm{d}p_\perp \propto (p_\perp^2 + p_0^2)^{2-4}$, also in α_S.
- Model for scaling behaviour of $p_\perp^{\min}(s) \propto p_\perp^{\min}(s_0)(s/s_0)^\lambda$, $\lambda =$?

  Pythia tunes: $\lambda \in [0.16 0.25]$.
- Herwig model similar to old Pythia and SHERPA
- New Pythia model: Correlate parton interactions with showers, more parameters.

Multijet merging

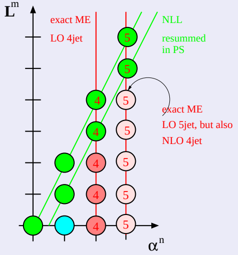
Why multijet merging?

- Parton shower yields approximation to ME
- But: lack of phase space in hadronic collisions typically results in too little QCD activity.

ME vs. PS

- MEs: hard, large-angle emissions; interferences.
- PS: soft, collinear emissions; resummation of large logarithms.
- Combine both, avoid double-counting.
- Right panel: logs in *ee* → jets.

α_s vs. Log



Constructing the algorithm

- Want the best of both - what else?
  - Proper description of soft/collinear and hard emissions
  - Combine QCD matrix elements of different parton multiplicity with showers
- General outline of algorithm:
  - Use LO (tree-level) matrix elements for jet production
    - Could use parton shower kernel $K_{ba}^{ME} \propto |\mathcal{M}_{n+1}|^2/|\mathcal{M}_n|^2$ hampered by low efficiency for $n \to \infty$.
    - Idea effectively used in traditional reweighting for small n.
    - Also in generation of hardest emission in POWHEG./
  - Preserve original parton shower evolution equation

    (N.B.: this guarantees preservation of log accuracy provided by shower)
  - Avoid double-counting (positive or negative)
    Must slice the phase space: Jet production vs. jet evolution
    $\Longrightarrow$ adds a parameter - the jet resolution criterion $Q_{\rm cut}$

    (but inclusive results should better not depend too strongly on this parameter)

Slicing the phase space

- Decompose splitting kernels of parton showers as $K_{ba}(z,\,t) = K_{ba}(z,\,t)\Theta[Q_{\rm cut} - Q_{ba}(z,\,t)] + K_{ba}(z,\,t)\Theta[Q_{ba}(z,\,t) - Q_{\rm cut}]$.
- In hard region, call $K_{ba}\Theta[Q_{ba}(z,\,t) - Q_{\rm cut}] \to K_{ba}^{ME}$,
- Call $K_{ba}\Theta[Q_{\rm cut} - Q_{ba}(z,\,t)] \to K_{ba}^{PS}$ in soft region.
- Sudakov form factor factorises (exponential):

  $$\Delta_a(\mu^2,\,t) = \Delta_a^{PS}(\mu^2,\,t)\Delta_a^{ME}(\mu^2,\,t)$$

  Also, no emission probability can be rewritten:

  $$\mathcal{P}_a^{\rm no}(z,\,t,\,\bar{t}) = \frac{\Delta_a^{PS}(\mu^2,\,\bar{t})}{\Delta_a^{PS}(\mu^2,\,t)}\,\frac{\Delta_a^{ME}(\mu^2,\,\bar{t})}{\Delta_a^{ME}(\mu^2,\,t)}\,\frac{g_a(z,\,t)}{g_a(z,\,\bar{t})}$$
- In shower, need to veto emissions with $Q_{ba} > Q_{\rm cut}$.
  But: maybe emissions at $Q < Q_{\rm cut}$ but t larger than those in ME: must cure "mismatch" of shower and jet measure
  $\longrightarrow$ truncated showers

Defining PS histories

- Identify most likely splitting acc. to PS branching probability
- Combine partons into mother parton acc. to inverse PS kinematics
- Continue until $2 \to 2$ core process

$\rightsquigarrow$ shower specific cluster algorithm

$\rightsquigarrow$ predetermined shower emissions

PS starts at core process

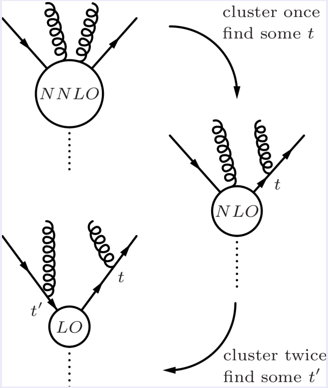
can radiate "between" ME emissions

ME branchings must be respected

evolution-, splitting- & angular variable preserved

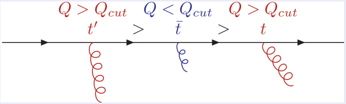
$\rightsquigarrow$ truncated shower

Example branching history



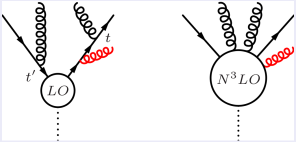
Truncated shower

Shower emission below Q_{cut}:



- $\rightsquigarrow$ emission accepted
- $\rightsquigarrow$ large-angle soft emissions
- $\rightsquigarrow$ soft color coherence
- $\rightsquigarrow$ approx. in CKKW only

Shower emission above Q_{cut}:



- $\rightsquigarrow$ entire event is rejected
- $\rightsquigarrow$ Sudakov suppression $\mathcal{P}^{\mathrm{ME}}_{\mathrm{no},\,a}(t,t')$
- $\rightsquigarrow$ to be described by ME instead
- $\rightsquigarrow$ σ_{tot} preserved at LO

Implementations

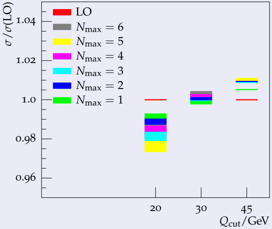
- Available implementations of this method in SHERPA & HERWIG++.
- MLM method for ALPGEN, MADGRAPH etc. (misses some terms)

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)



- improved "merging systematics" of $\boldsymbol{\sigma_{\rm tot}} < \pm\mathbf{3\%}$

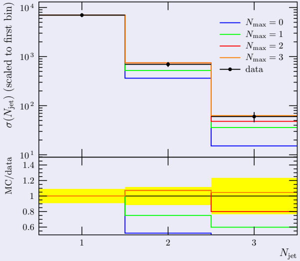
Z^0+jets at Tevatron: jet multiplicities

Jet rates and -spectra improved compared to pure PS simulation

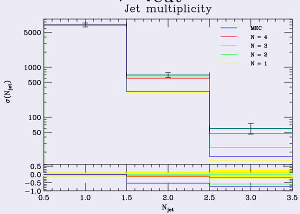
- Example: DY-pair production $\sigma_{\mathrm{e^+e^-+N_{jet}}}$

CDF Data: PRL **100** (2008) 102001

SHERPA, $Q_{\rm cut} = 30$ GeV



HERWIG++, $Q_{\rm cut} = 30$ GeV

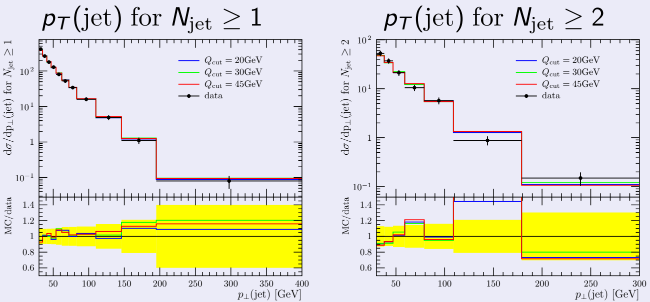


Z^0+jets at Tevatron: jet spectra

- Example: All-jets p_T's in DY-pair production

CDF Data: PRL **100** (2008) 102001

- Compare with results from SHERPA



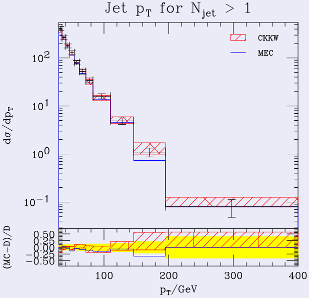
Z^0+jets at Tevatron: jet spectra

- Example: All-jets p_T's in DY-pair production

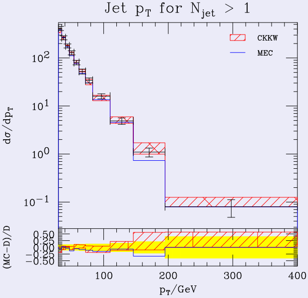
CDF Data: PRL **100** (2008) 102001

- Compare with results from HERWIG++

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



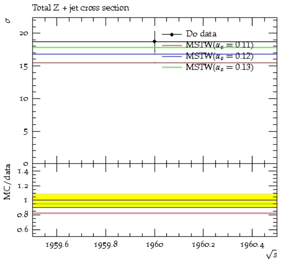
p_T(jet) for $N_{\text{jet}} \geq 2$

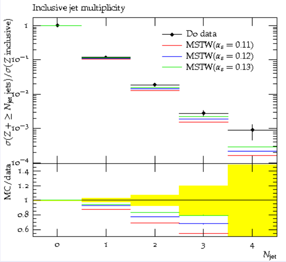


Z^0+jets at Tevatron: cross sections

CDF data from PRL 100 (2008) 102001 and D0/, arXiv:0808:1296

Impact of α_S - global in SHERPA

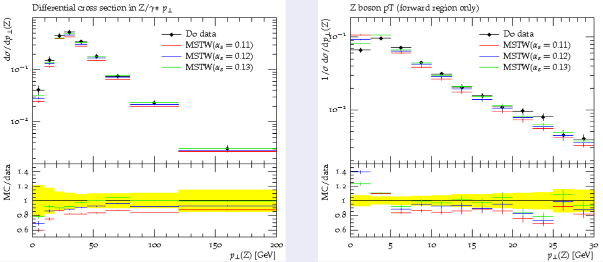




Z^0+jets at Tevatron: Z/γ^* transverse momentum

DØ data: PRL 100 (2008) 102002

Impact of α_S - global in SHERPA



A new Monte Carlo approach for Prompt-Photon Production

(S.Höche, S.Schumann, F.Siegert PRD **81** (2010) 034026)

- treat photons and QCD partons fully democratically

(Glover, Morgan Z. Phys. C **62** (1994) 311)

- combine matrix elements of different parton/photon multiplicity with
- QCD⊕QED evolution and hadronisation $\rightsquigarrow$ models $D^{\gamma}_{q,g}(z, Q^2)$

Generalised merging formalism

- Emission probabilities factorise trivially as before

$$\Delta_a(Q_0^2, Q^2) = \Delta_a^{\rm (QCD)}(Q_0^2, Q^2)\Delta_a^{\rm (QED)}(Q_0^2, Q^2)$$

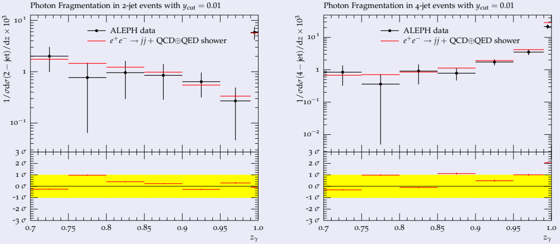
- Implemented by adding splitting functions $q \to q\gamma$
- Different then large-N_C QCD: spectators *all* particles with opposite charge
- Neglect (negative) interference with same-sign charges

(S.Dittmaier, Nucl. Phys. B **565** (2000) 69)

Results: photon fragmentation function in $e^+e^- \to$ Hadrons

(Aleph data from Z. Phys. C **69** (1996) 365)

- Validation of the shower/hadronisation component
- Perform jet finding including final-state photons
- Study photon-energy fraction wrt its containing jet: $z_\gamma \equiv E_\gamma/E_{\rm jet}$



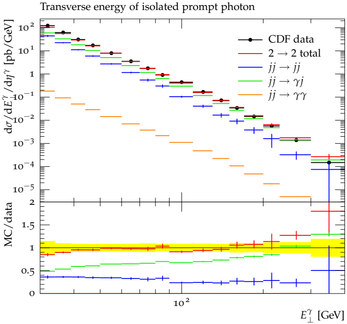
Isolated prompt-photon production at Tevatron

(Data from CDF, Phys. Rev. D **80** (2009) 111106)

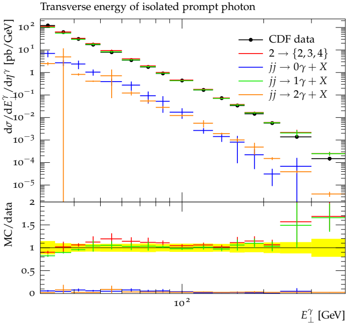
cuts: $30 < E_T^\gamma < 400$ GeV, $|\eta^\gamma| < 1$, isolation: $E_T^{R=0.4} - E_T^\gamma < 2$ GeV

- Sherpa: pure shower vs. ME⊕TS

E_T^γ – pure shower



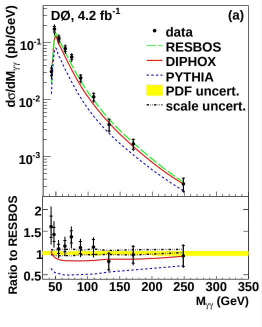
E_T^γ – ME⊕TS

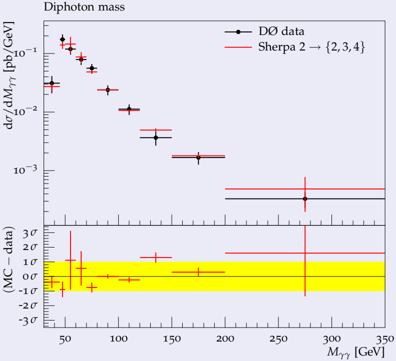


$\gamma\gamma$ production at Tevatron: Invariant mass

(D0/ data, arXiv:1002.4917)

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

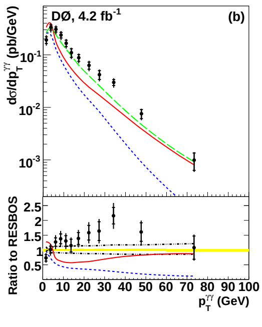


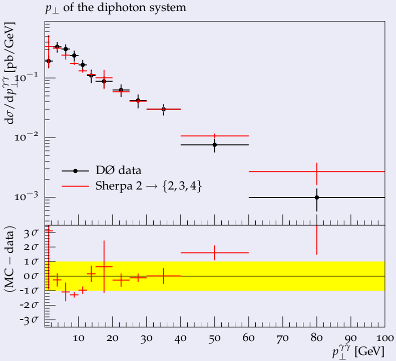


$\gamma\gamma$ production at Tevatron: Transverse momentum of pair

(D0/ data, arXiv:1002.4917)

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

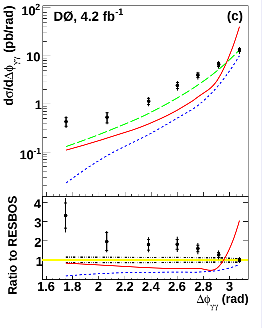


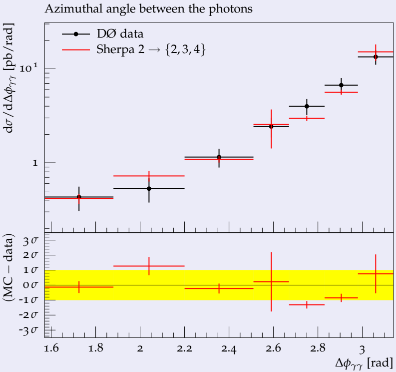


$\gamma\gamma$ production at Tevatron: Azimuthal decorrelation

(D0/ data, arXiv:1002.4917)

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





The POWHEG method

Basic idea

- Want total cross section and first emission correct at $\mathcal{O}(\alpha_S)$
- Master formula:

$$d\sigma_{\rm NLO} = d\Phi_{\mathcal{B}}\bar{\mathcal{B}}(\Phi_{\mathcal{B}})) \left[\bar{\Delta}(p_{\perp,\,\rm min}) + \int\limits_{p_{\perp,\,\rm min}} d\Phi_{\mathcal{R}|\mathcal{B}} \frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{R}})} \bar{\Delta}(p_\perp)\right].$$

- $\mathcal{B}$, $\mathcal{R}$ denote Born and real emission ME, with phase space $\Phi_{\mathcal{B},\mathcal{R}}$.
- $\Phi_{\mathcal{R}|\mathcal{B}}$ is the phase space for one particle splitting connecting both.
- Since Sudakov form factor $\bar{\Delta}$ reads:

$$\bar{\Delta}(p_\perp) = \exp\left[-\int d\Phi_{\mathcal{R}|\mathcal{B}}\Theta[k_\perp(\Phi_R) - p_\perp]\frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{R}})}\right],$$

  the expression in square bracket above $= 1$ (unitarity).
- $\bar{\mathcal{B}}(\Phi_{\mathcal{B}})$ denotes the NLO-weighted differential xsec for Born config..

Algorithm

- Generate a starting Born-type parton configuration distributed according to

$$\mathrm{d}\Phi_{\mathcal{B}}\bar{\mathcal{B}}(\Phi_{\mathcal{B}}) = \mathrm{d}\Phi_{\mathcal{B}}\left[\mathcal{B}(\Phi_{\mathcal{B}}) + \mathcal{V}(\Phi_{\mathcal{B}}) + \int \mathrm{d}\Phi_{\mathcal{R}|\mathcal{B}}\mathcal{R}(\Phi_{\mathcal{R}})\right]$$

  with $\mathcal{B}$ the Born, $\mathcal{V}$ the virtual, and $\mathcal{R}$ the real emission contribution.
- Generate the hardest emission according to $\bar{\Delta}$, where the usual splitting kernel $\mathcal{K}(t, z)$ is replaced by the ratio $\mathcal{R}(\Phi_{\mathcal{R}})/\mathcal{B}((\Phi_{\mathcal{B}})$:

$$\frac{\mathrm{d}t}{t}\mathrm{d}z\,\mathcal{K}(t, z) \to \mathrm{d}\Phi_{\mathcal{R}|\mathcal{B}}(t, z)\frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{B}})}$$

- Perform truncated shower on resulting parton configuration.
- Three publicly available implementations:
  HERWIG++, POWHEGBOX, and SHERPA
- The POWHEGBOX implementation “sits” on top of arbitrary parton shower through LHE-Interface, harms truncating the shower.

Available processes/implementations in SM

Process	POWHEGBOX	HERWIG++	SHERPA
$e^+e^- \to jj$	✗	✓	✓
DIS	✗	in prep.	✓
$pp \to W/Z$	✓	✓	✓
$pp \to H$ (gluon fusion)	✓	✓	✓
$pp \to V+H$	✗	✓	✓
$pp \to VV$	✗	✓	✓
VBF	✓	in prep.	in prep.
$pp \to Q\bar{Q}$	✓	✗	✗
$pp \to Q\bar{Q}+j$	in prep.	✗	✗
single-top	✓	✗	✗
$pp \to V+j$	✓	✗	in prep.
$pp \to V+jj$	in prep.	✗	in prep.
$pp \to H+j$ (gluon fusion)	✗	✗	in prep.
$pp \to H+jj$ (gluon fusion)	✗	✗	in prep.
$pp \to V+b\bar{b}$	in prep.	✗	in prep.
dijets	✓	✗	in prep.
$pp \to W^+W^+jj$	✓	✗	✗

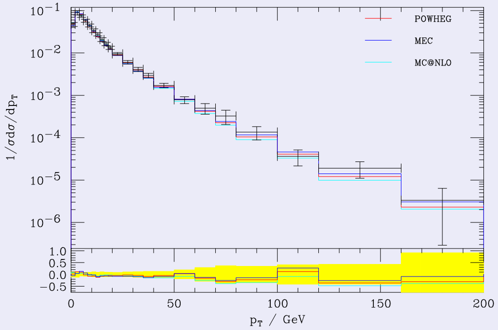
(SHERPA benefits from ME-generator plus subtraction terms - makes implementations fairly automatic . . . .)

W+jets at Tevatron: $p_\perp^W$-spectra

- POWHEG method as implemented in HERWIG++ vs. MC@NLO and HERWIG++.

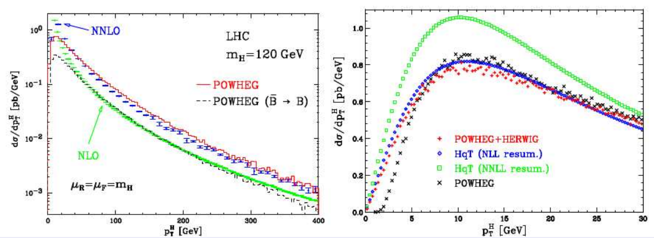
(Note: when only shape considered, do not expect difference to native HERWIG++ with ME corrections included

$\Longrightarrow$ simple check of implementation.)



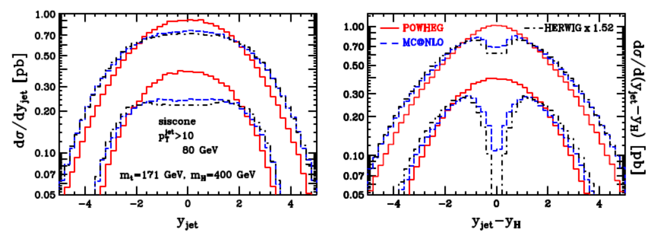
H+jets at LHC: Implicit higher orders in POWHEG

- Can replace $\bar{\mathcal{B}} \to \mathcal{B}$ in $\mathrm{d}\sigma$ to check if huge K-factor of $\mathcal{O}(2)$ is just due to proper NLO correction (left panel): expect only a vertical shift.
- Can also check for shape w.r.t. higher-order code and switch on/off shower & hadronisation effects (right panel)



H+jets at LHC: Implicit higher orders in POWHEG

- Cross check with MC@NLO (similar goal, different algorithm).
- Problem in MC@NLO becomes apparent: resides on HERWIG-shower, which does not have full phase space coverage - interplay of positive and negative weights with this partial phase space filling produces dips.
- That's why I like POWHEG better - and it's easier to implement.



The MENLOPS method

Basic idea

- At present:
    - can merge "arbitrary" tree-level MEs with PS
    - Several automated codes on the market
    - Automation of 1-loop QCD corrections seems feasible (automated codes now emerging)
- We should make use of both and automate ME$\otimes$PS at 1-loop
- Strategy: Use whatever is available
    - Process NLO parton-level events with PS at low multiplicities (through MC@NLO or, preferably, POWHEG method)
    - Combine NLO simulation with higher-order tree-level using standard ME$\otimes$PS technique for high multiplicities
- First step: POWHEG for lowest multiplicity only.

Some theoretical considerations

- Compare $\sigma_{(\mathrm{NLO})}$ for POWHEG and ME⊗PS:

$$\mathrm{d}\sigma^{(\mathrm{POW})}_{\mathrm{NLO}} =$$

$$\mathrm{d}\Phi_{\mathcal{B}}\bar{\mathcal{B}}(\Phi_{\mathcal{B}})) \left[\bar{\Delta}(p_{\perp,\,\mathrm{min}}) + \int\limits_{p_{\perp,\,\mathrm{min}}} \mathrm{d}\Phi_{\mathcal{R}|\mathcal{B}} \frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{R}})} \bar{\Delta}(p_{\perp})\right] ;$$

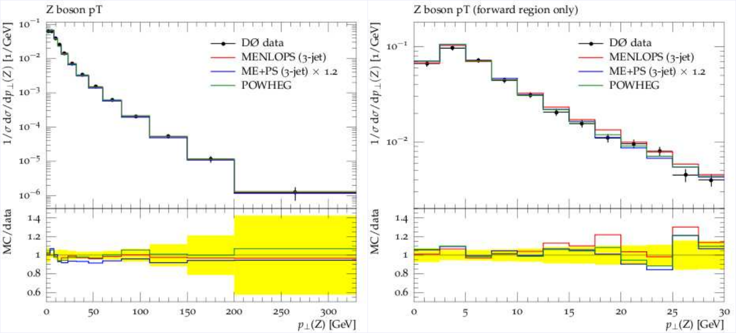
$$\mathrm{d}\sigma^{(\mathrm{MEPS})}_{\mathrm{NLO}} =$$

$$\mathrm{d}\Phi_{\mathcal{B}}\mathcal{B}(\Phi_{\mathcal{B}})) \left[\Delta(p_{\perp,\,\mathrm{min}}) + \int\limits_{p_{\perp,\,\mathrm{min}}} \mathrm{d}\tilde{\Phi}_{\mathcal{R}|\mathcal{B}} \frac{\mathcal{R}(\Phi_{\mathcal{R}})}{\mathcal{B}(\Phi_{\mathcal{R}})} \Delta(p_{\perp})\right] .$$

- Nearly the same. Most notably: NLO vs. LO normalisation.
  Boils down to a local K factor $= \bar{\mathcal{B}}\,/\mathcal{B}$
- Also note: different Sudakovs, in ME⊗PS [...] does not integrate to one.
  Reason: Kernel in Sudakov Δ differs from $\mathcal{R}/\mathcal{B}$.

Drell-Yan production at Tevatron

Data from D0, comparison in S.Hoeche et al., arXiv:1009.1127



Drell-Yan production at Tevatron

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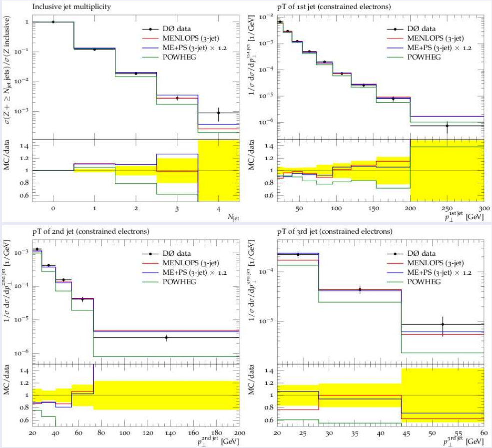

Summary of lecture 4

- Hadronisation
  - Various phenomenological models;
  - tuned to LEP data, overall agreement satisfying;
  - validity for hadron data not quite clear.

(beam remnant fragmentation not in LEP.)

- Underlying event
  - Theoretically not understood;
  - models typically based on collinear factorisation and semi-independent multi-parton scattering;
  - models highly parameter-dependent, leading to large differences in predictions;
  - even unclear: good observables to distinguish models.