LUND UNIVERSITY

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Introduction to Monte Carlo Event Generators

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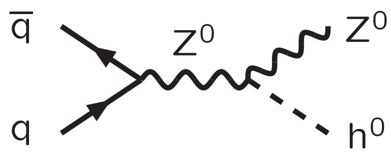
1. (yesterday) Introduction and Overview; Monte Carlo Techniques
2. (yesterday) Matrix Elements; Parton Showers I
3. **(today) Parton Showers II; Matching Issues**
4. (today) Multiple Parton–Parton Interactions
5. (tomorrow) Hadronization and Decays; Generator Status

Event Physics Overview

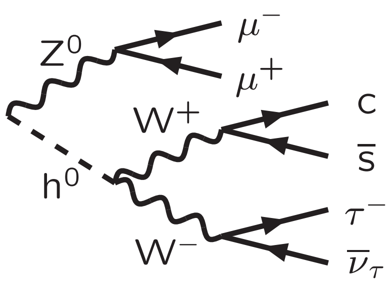
Repetition: from the “simple” to the “complex”,
or from “calculable” at large virtualities to “modelled” at small

Matrix elements (ME):

1) Hard subprocess:
$|\mathcal{M}|^2$, Breit-Wigners,
parton densities.

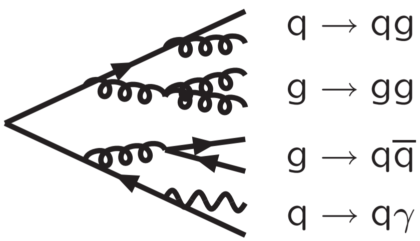


2) Resonance decays:
includes correlations.

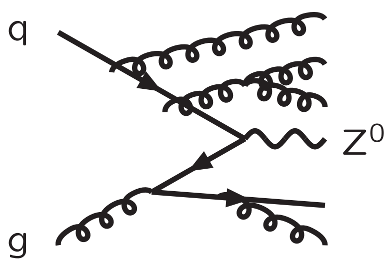


Parton Showers (PS):

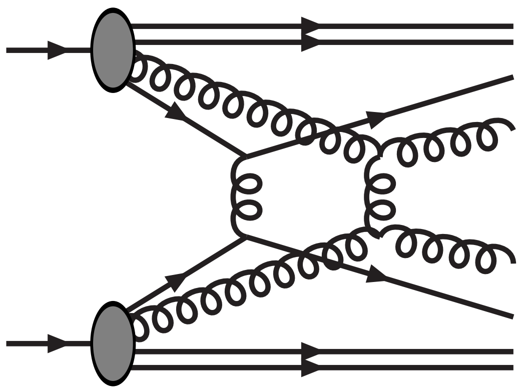
3) Final-state parton showers.



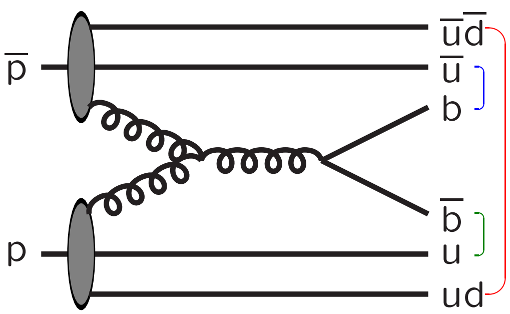
4) Initial-state parton showers.



5) Multiple parton–parton interactions.

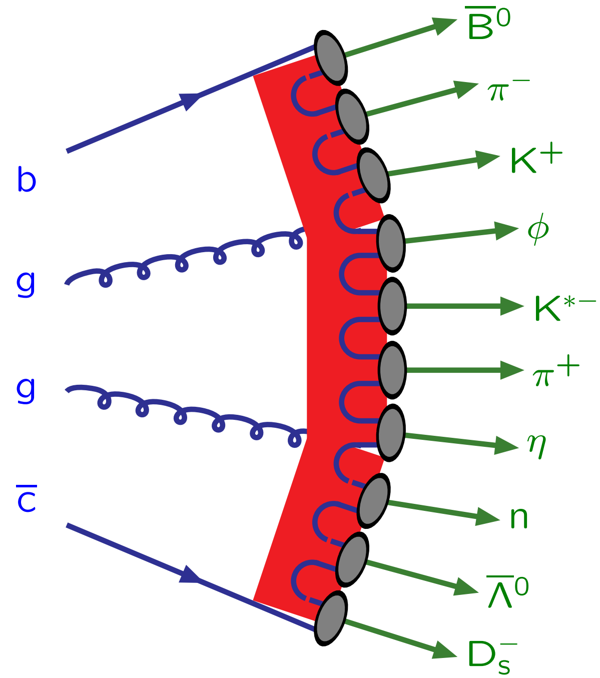


6) Beam remnants, with colour connections.

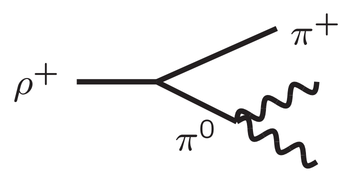


5) + 6) = Underlying Event

7) Hadronization

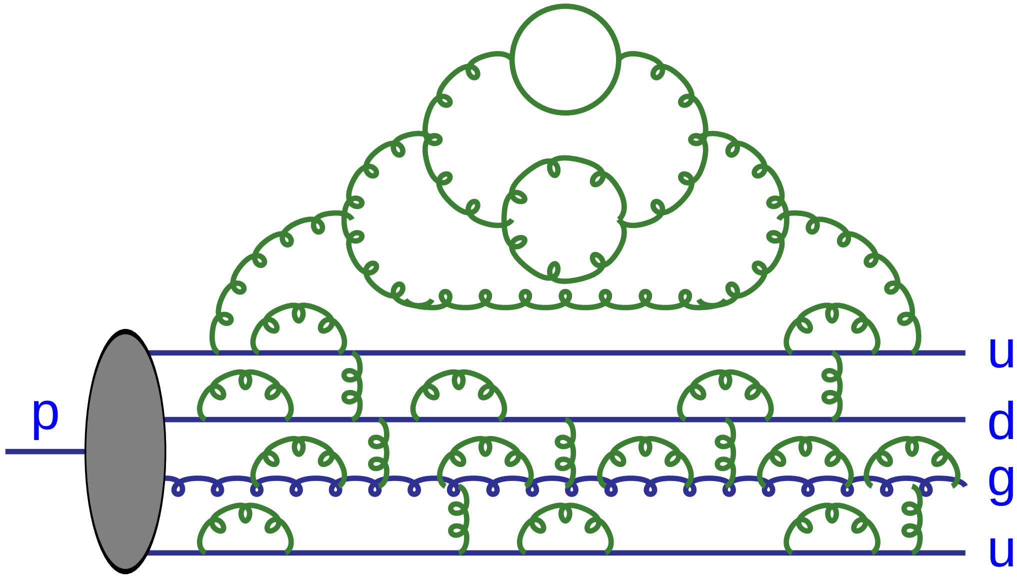


8) Ordinary decays: hadronic, τ, charm, ...



Parton Distribution Functions

Hadrons are composite, with time-dependent structure:



$f_i(x, Q^2) =$ number density of partons i
at momentum fraction x and probing scale Q^2.

Linguistics (example):

$$F_2(x, Q^2) \;=\; \sum_i e_i^2 \, x f_i(x, Q^2)$$

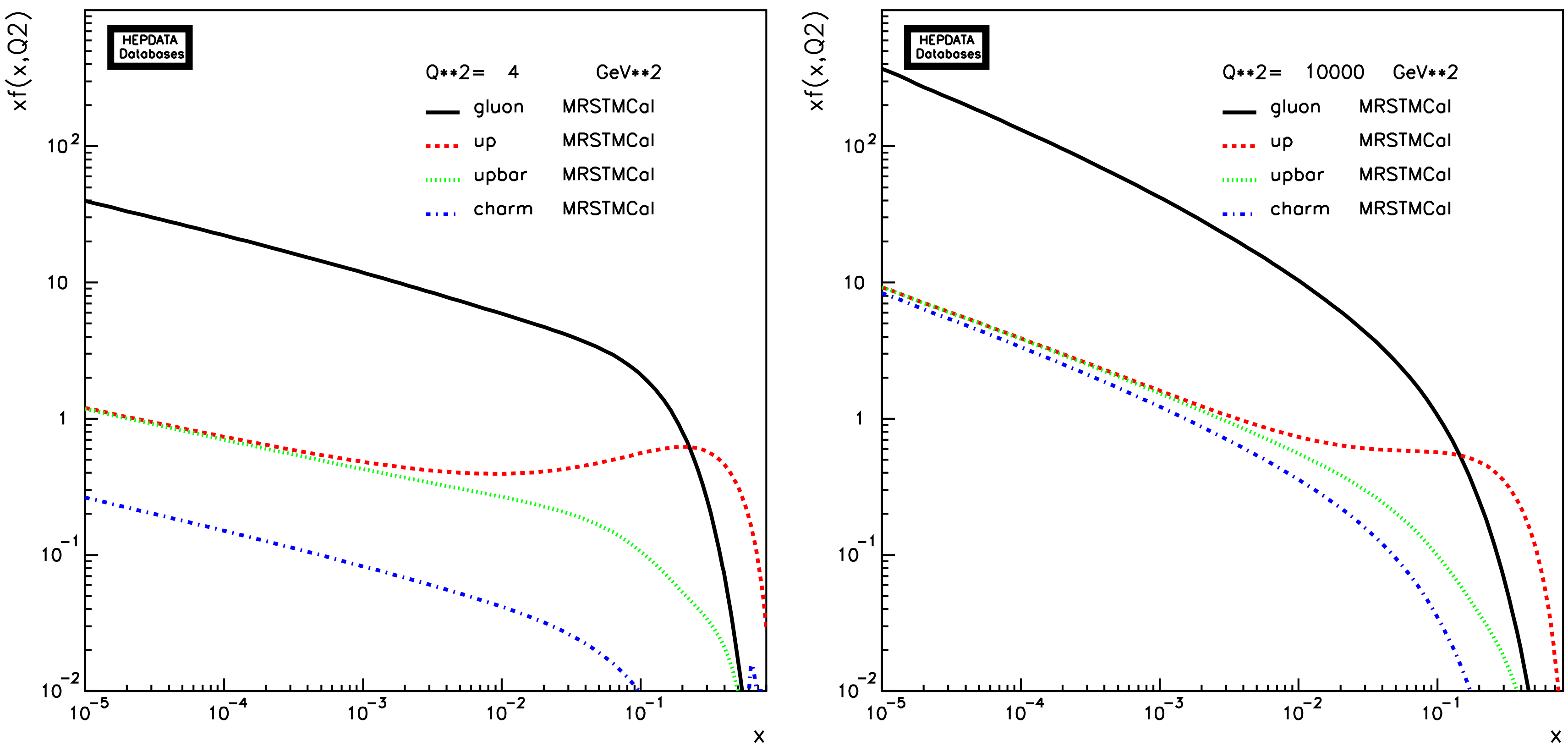
structure function parton distributions

Absolute normalization at small Q_0^2 unknown.

Resolution dependence by DGLAP:

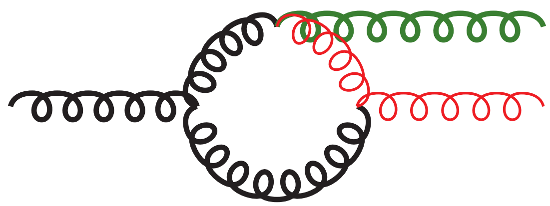
$$\frac{\mathrm{d}\, f_b(x, Q^2)}{\mathrm{d}(\ln Q^2)} = \sum_a \int_x^1 \frac{\mathrm{d}z}{z}\, f_a(x', Q^2)\, \frac{\alpha_s}{2\pi}\, P_{a\to bc}\left(z = \frac{x}{x'}\right)$$

$Q^2 = 4$ GeV^2 MRST LO** $Q^2 = 10000$ GeV^2

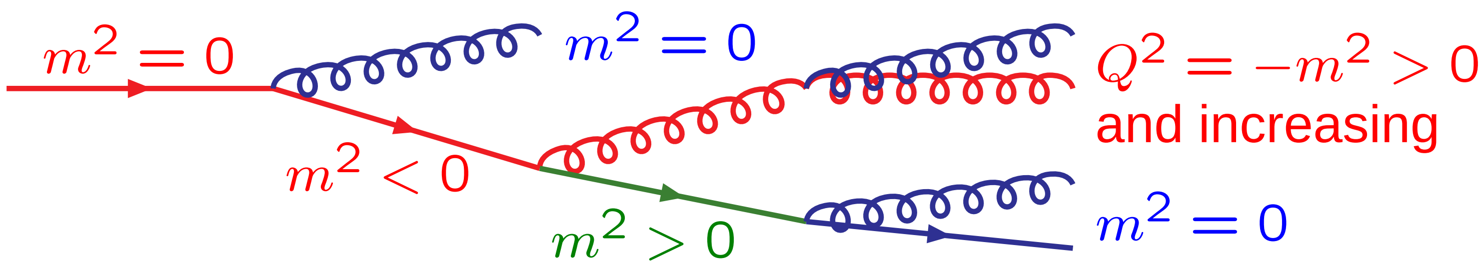


Initial-State Shower Basics

- Parton cascades in p are continuously born and recombined.
- Structure at Q is resolved at a time $t \sim 1/Q$ *before* collision.
- A hard scattering at Q^2 probes fluctuations up to that scale.
- A hard scattering inhibits full recombination of the cascade.



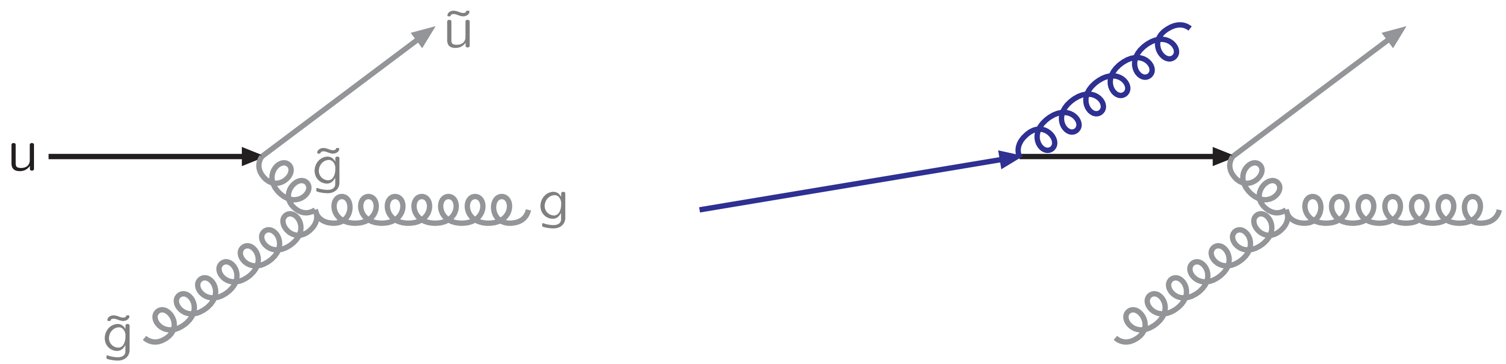
- Convenient reinterpretation:



Event generation could be addressed by **forwards evolution**:
pick a complete partonic set at low Q_0 and evolve, see what happens.
Inefficient:
1) have to evolve and check for *all* potential collisions, but 99.9... % inert
2) impossible to steer the production e.g. of a narrow resonance (Higgs)

Backwards evolution

Backwards evolution is viable and $\sim$equivalent alternative:
start at hard interaction and trace what happened "before"



Monte Carlo approach, based on *conditional probability*: recast

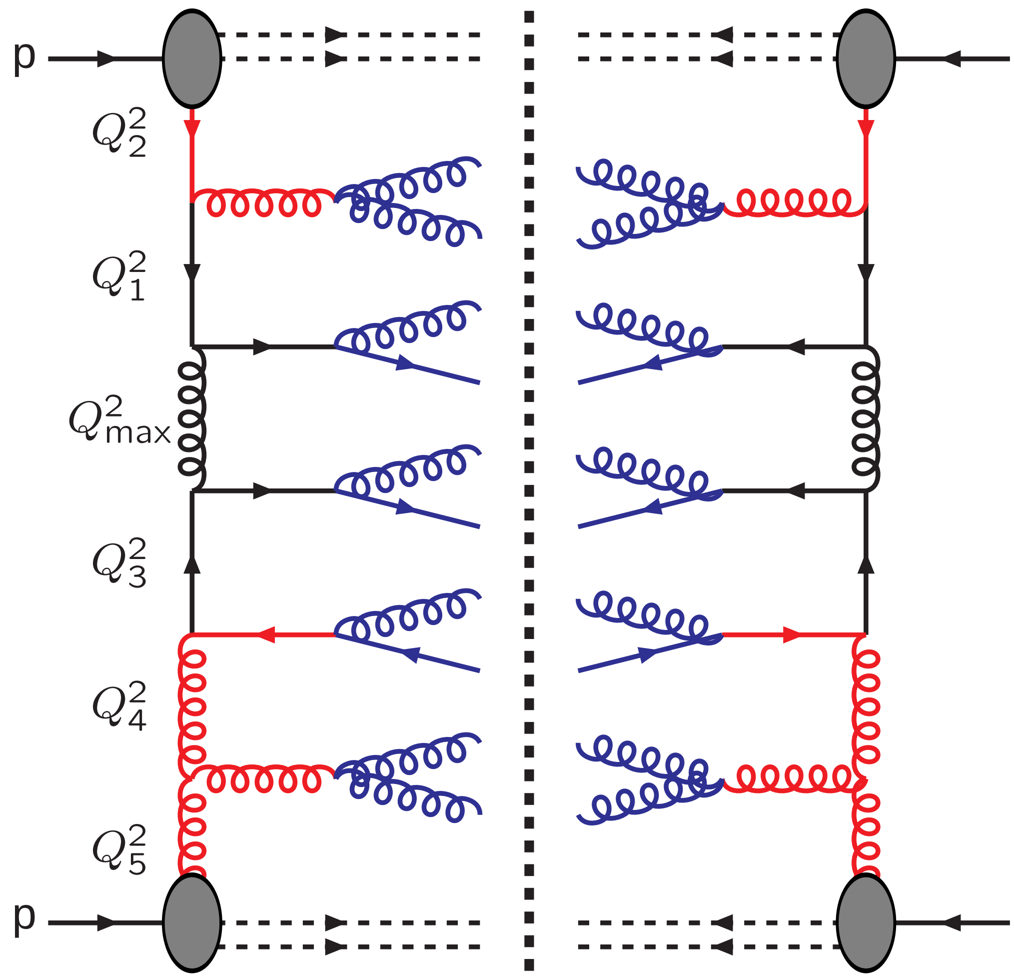
$$\frac{\mathrm{d}f_b(x,Q^2)}{\mathrm{d}t} = \sum_a \int_x^1 \frac{\mathrm{d}z}{z}\, f_a(x',Q^2)\,\frac{\alpha_\mathrm{s}}{2\pi}\,P_{a\to bc}(z)$$

with $t = \ln(Q^2/\Lambda^2)$ and $z = x/x'$ to

$$\mathrm{d}\mathcal{P}_b = \frac{\mathrm{d}f_b}{f_b} = |\mathrm{d}t| \sum_a \int \mathrm{d}z\, \frac{x' f_a(x',t)}{x f_b(x,t)}\,\frac{\alpha_\mathrm{s}}{2\pi}\,P_{a\to bc}(z)$$

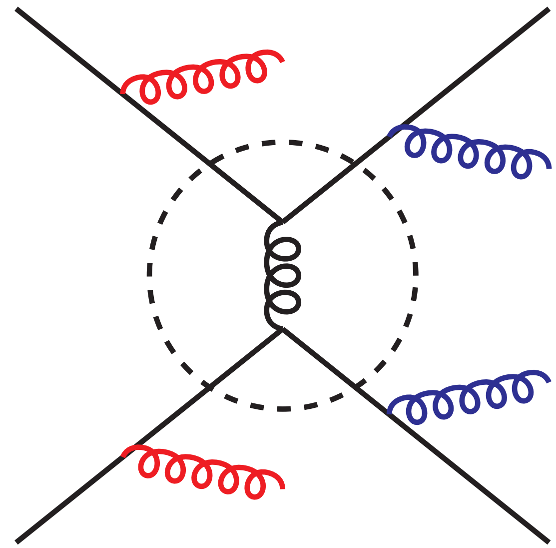
then solve for *de*creasing t, i.e. backwards in time,
starting at high Q^2 and moving towards lower,
with Sudakov form factor $\exp(-\int \mathrm{d}\mathcal{P}_b)$

Ladder representation combines whole event:



DGLAP: $Q^2_{\mathrm{max}} > Q_1^2 > Q_2^2 \sim Q_0^2$
$Q^2_{\mathrm{max}} > Q_3^2 > Q_4^2 > Q_5^2 \sim Q_0^2$

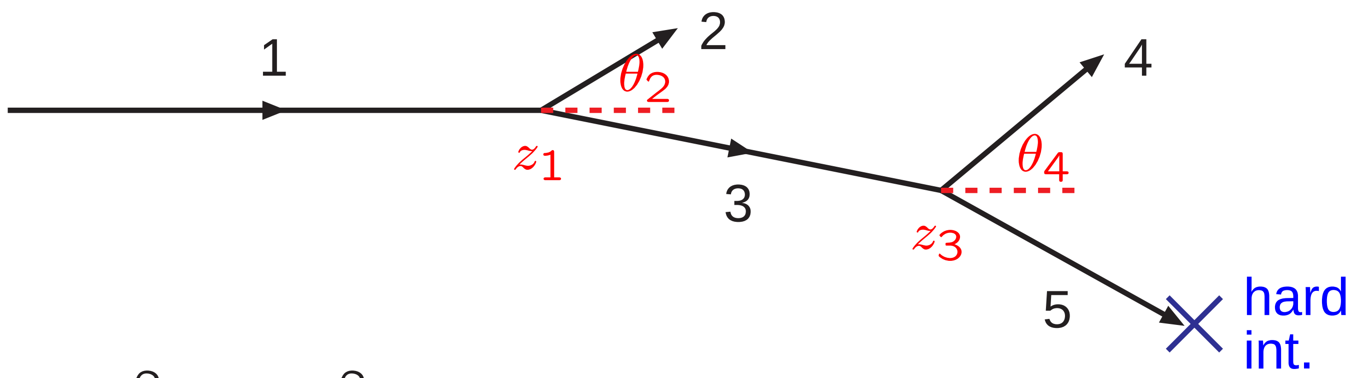
cf. previously:



One possible
Monte Carlo order:

1) Hard scattering
2) Initial-state shower
   from center outwards
3) Final-state showers

Coherence in spacelike showers



$z_1 = E_3/E_1$
$z_3 = E_5/E_3$
$\theta_2 = \theta_{12}$
$\theta_4 = \theta_{14}$!!

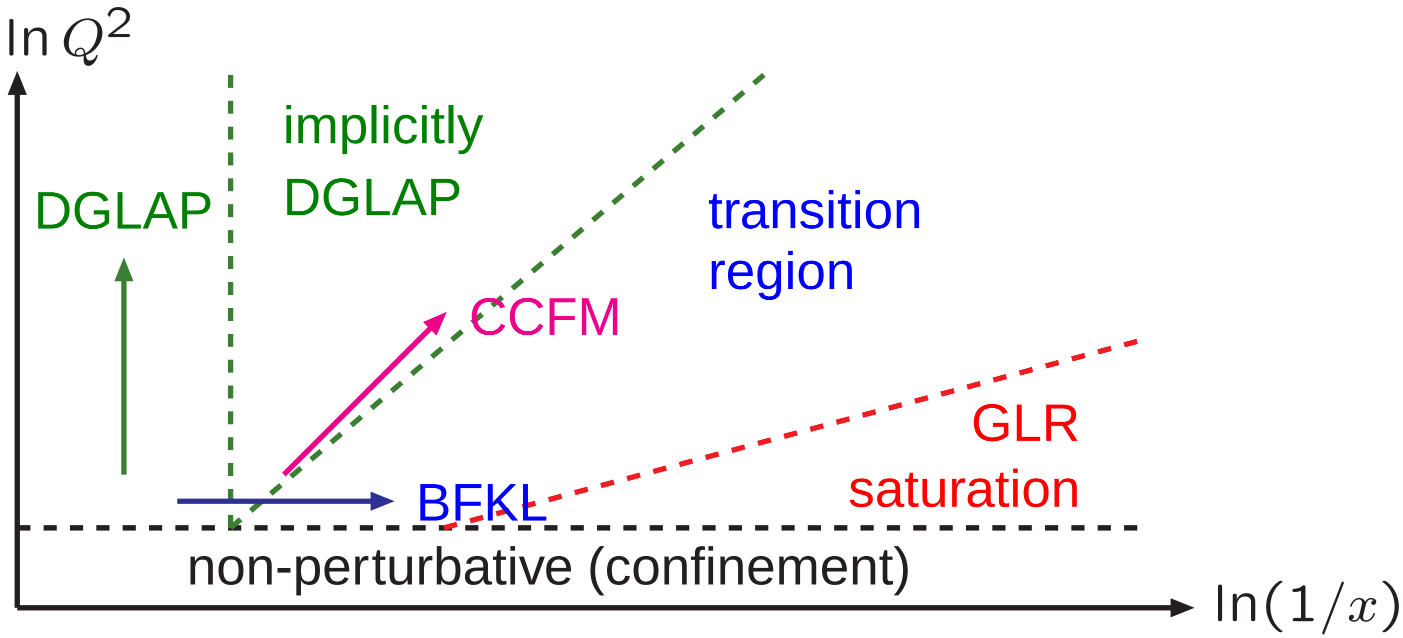
with $Q^2 = -m^2 =$ spacelike virtuality

- kinematics only:
  $Q_3^2 > z_1 Q_1^2$, $Q_5^2 > z_3 Q_3^2$, $\ldots$
  i.e. Q_i^2 need not even be ordered

- coherence of leading collinear singularities:
  $Q_5^2 > Q_3^2 > Q_1^2$, i.e. Q^2 ordered

- coherence of leading soft singularities (more messy):
  $E_3\theta_4 > E_1\theta_2$, i.e. $z_1\theta_4 > \theta_2$
  $z \ll 1$: $E_1\theta_2 \approx p_{\perp 2}^2 \approx Q_3^2$, $E_3\theta_4 \approx p_{\perp 4}^2 \approx Q_5^2$
  i.e. reduces to Q^2 ordering as above
  $z \approx 1$: $\theta_4 > \theta_2$, i.e. angular ordering of soft gluons
  $\Longrightarrow$ reduced phase space

Evolution procedures



DGLAP: Dokshitzer–Gribov–Lipatov–Altarelli–Parisi
evolution towards larger Q^2 and (implicitly) towards smaller x

BFKL: Balitsky–Fadin–Kuraev–Lipatov
evolution towards smaller x (with small, unordered Q^2)

CCFM: Ciafaloni–Catani–Fiorani–Marchesini
interpolation of DGLAP and BFKL

GLR: Gribov–Levin–Ryskin
nonlinear equation in dense-packing (saturation) region,
where partons recombine, not only branch

Initial-State Shower Comparison

Two(?) CCFM Generators:

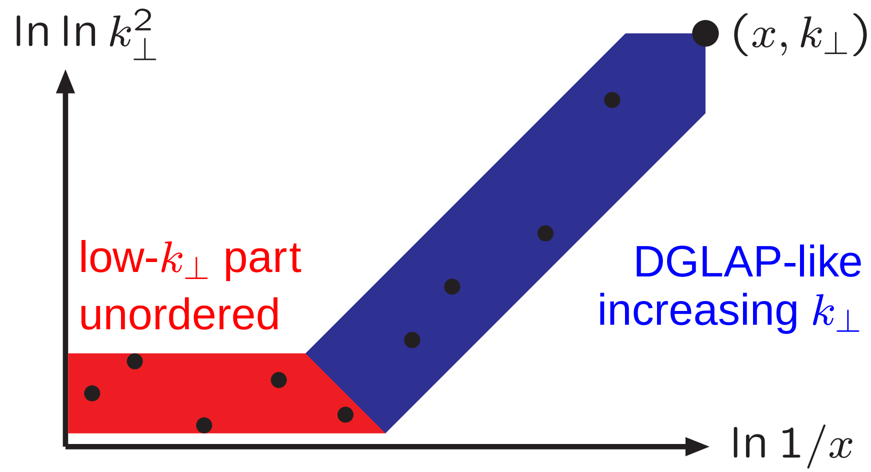
(SMALLX (Marchesini, Webber))

CASCADE (Jung, Salam)

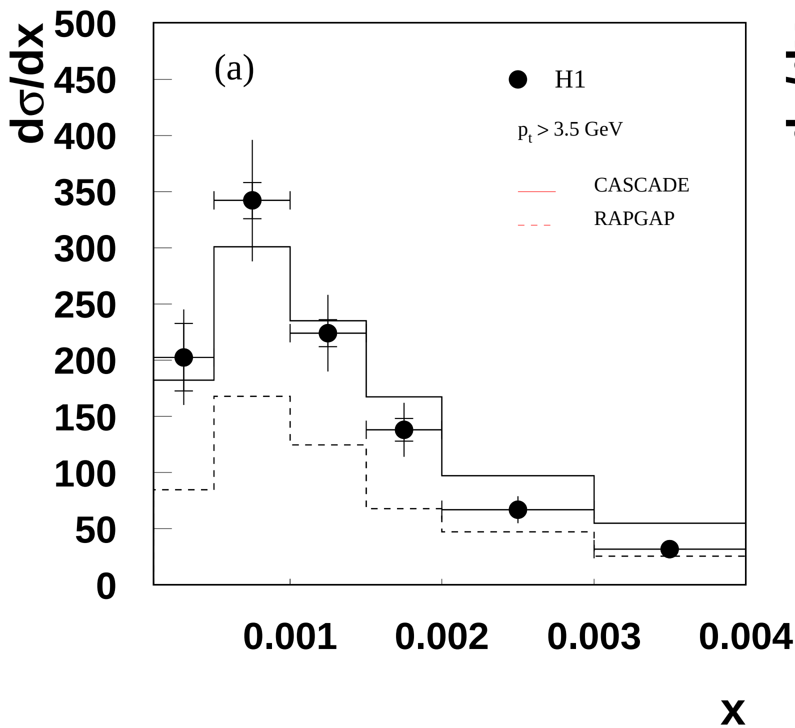
LDC (Gustafson, Lönnblad):

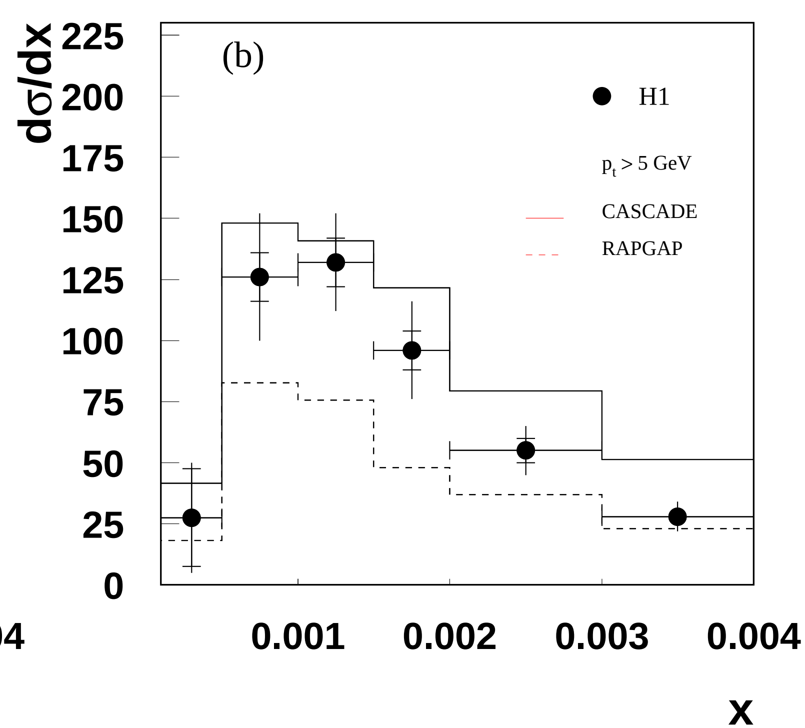
reformulated initial/final rad.

$\Longrightarrow$ eliminate non-Sudakov

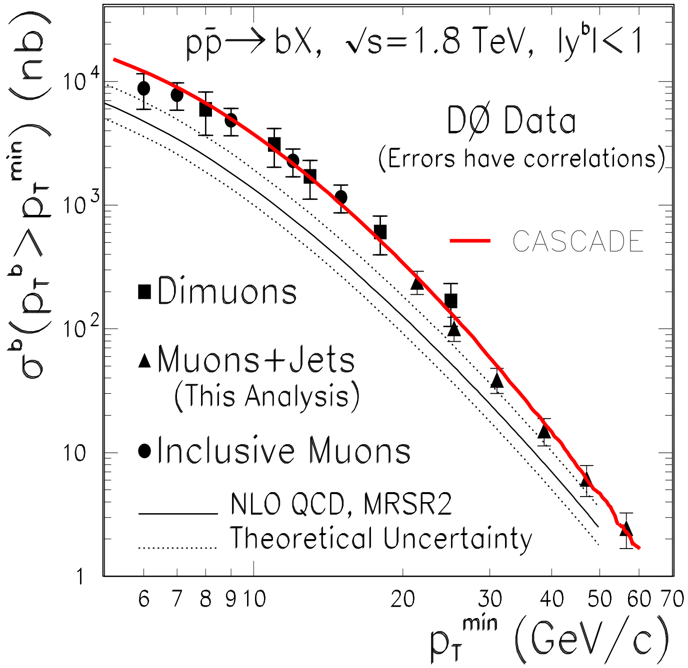


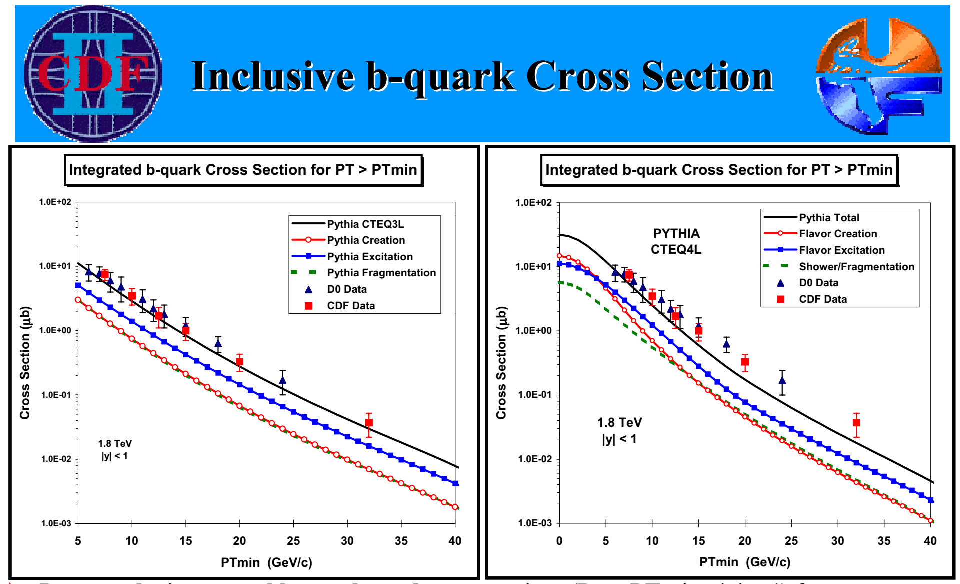
Test 1) forward (= p direction) jet activity at HERA





2) Heavy flavour production





➡ **Data on the integrated b-quark total cross section (P_T > PTmin, |y| < 1) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of PYTHIA 6.115 (CTEQ3L) and PYTHIA 6.158 (CTEQ4L). The four curves correspond to the contribution from flavor creation, flavor excitation, shower/fragmentation, and the resulting total.**

DPF2002 May 25, 2002 — *Rick Field - Florida/CDF* — *Page 5*

but also explained by DGLAP with leading order pair creation
+ flavour excitation (≈ unordered chains)
+ gluon splitting (final-state radiation)

CCFM requires off-shell ME's + unintegrated parton densities

$$F(x,Q^2) = \int^{Q^2} \frac{\mathrm{d}k_\perp^2}{k_\perp^2}\mathcal{F}(x,k_\perp^2) + (\text{suppressed with } k_\perp^2 > Q^2)$$

so not ready for prime time in pp

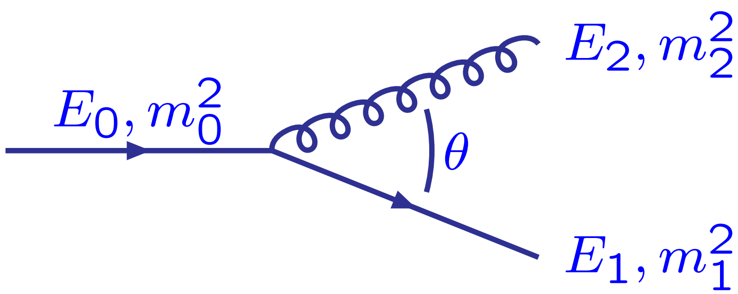
Initial- vs. final-state showers

Both controlled by same evolution equations

$$\mathrm{d}\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}Q^2}{Q^2} P_{a\to bc}(z)\,\mathrm{d}z \cdot (\text{Sudakov})$$

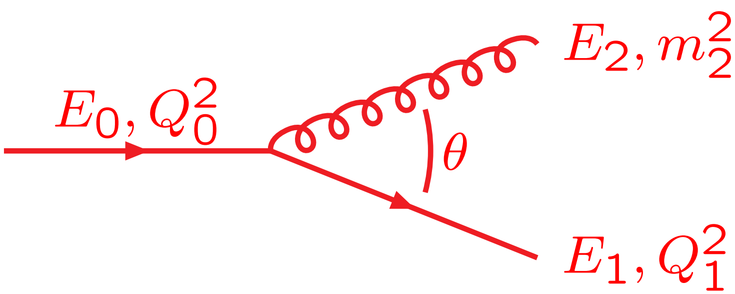
but

Final-state showers:
Q^2 timelike ($\sim m^2$)



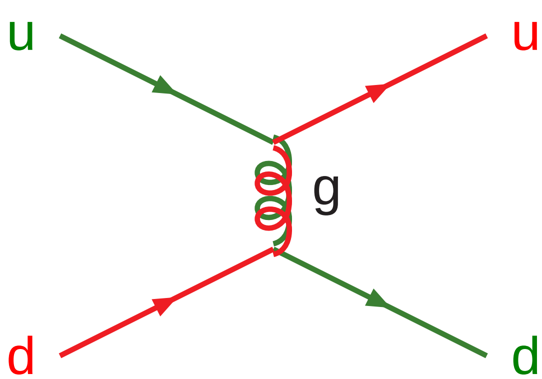
decreasing E, m^2, θ
both daughters $m^2 \geq 0$
physics relatively simple
$\Rightarrow$ "minor" variations:
Q^2, shower vs. dipole, ...

Initial-state showers:
Q^2 spacelike ($\approx -m^2$)

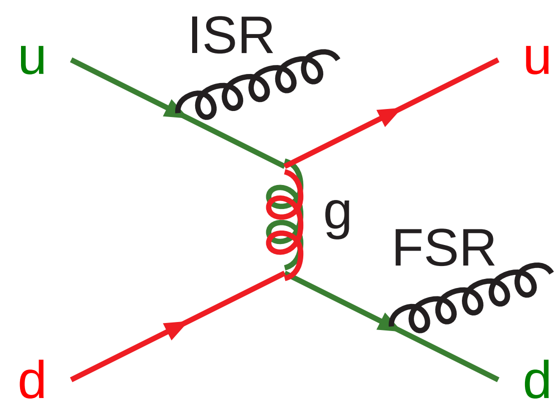


decreasing E, increasing Q^2, θ
one daughter $m^2 \geq 0$, one $m^2 < 0$
physics more complicated
$\Rightarrow$ more formalisms:
DGLAP, BFKL, CCFM, GLR, ...

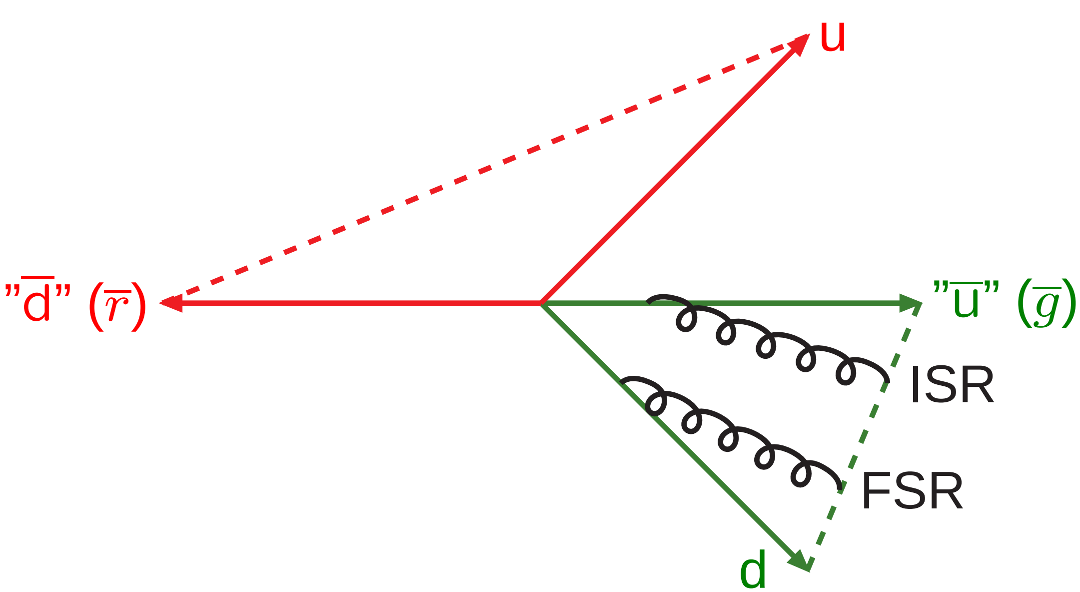
Combining FSR with ISR



dress
with
radiation



Separate processing of ISR and FSR misses interference ($\sim$ colour dipoles)



ISR+FSR add coherently
in regions of colour flow

in "normal" shower by
azimuthal anisotropies

automatic in dipole
(by proper boosts)

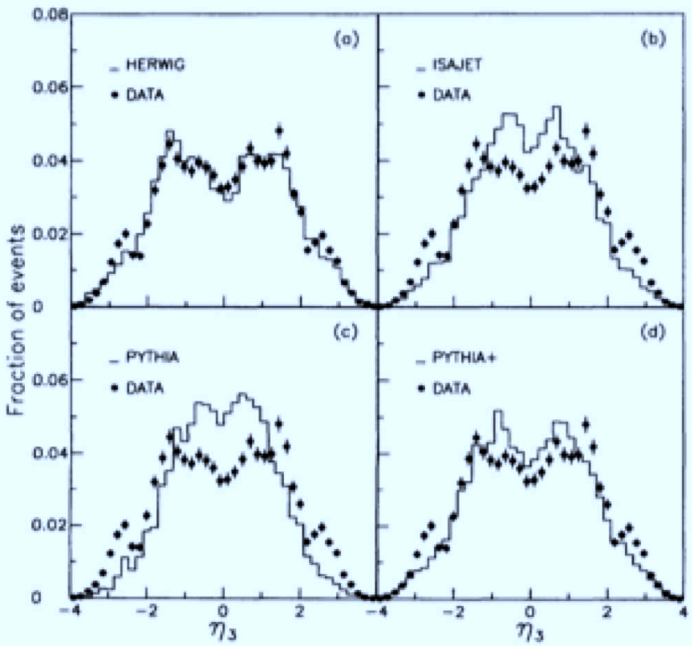


FIG. 13. Observed η_3 distribution compared to the predictions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

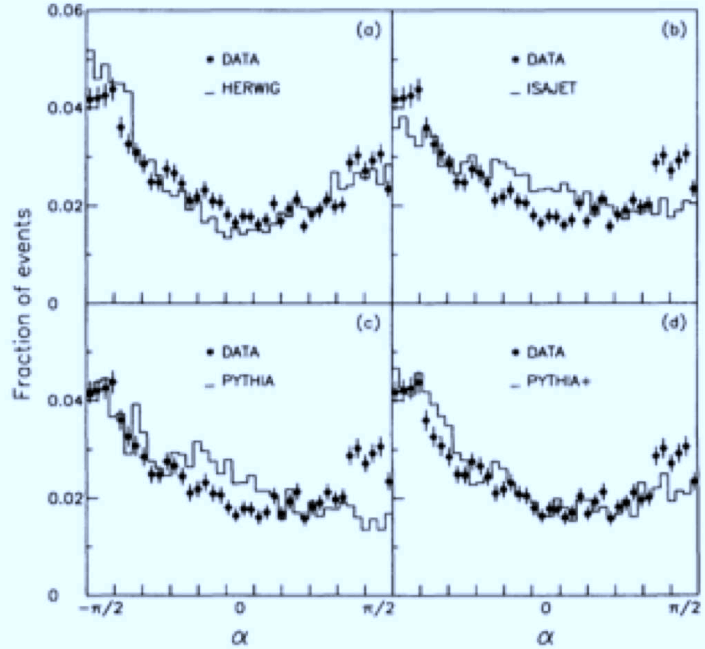
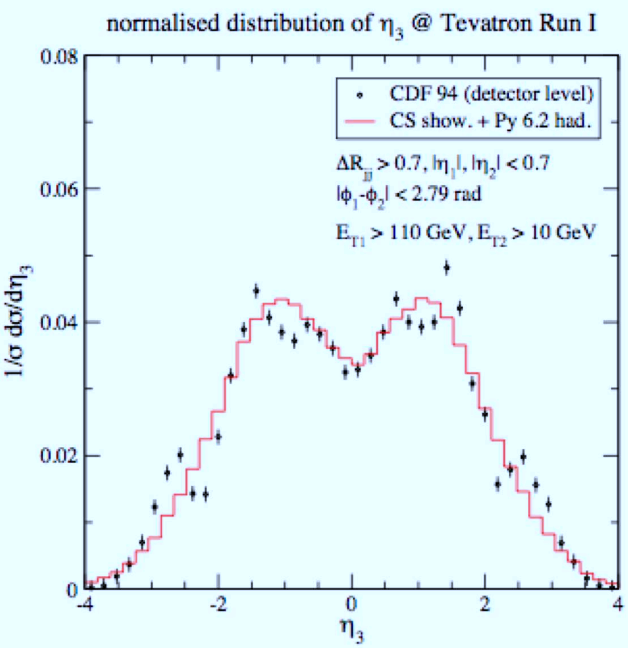
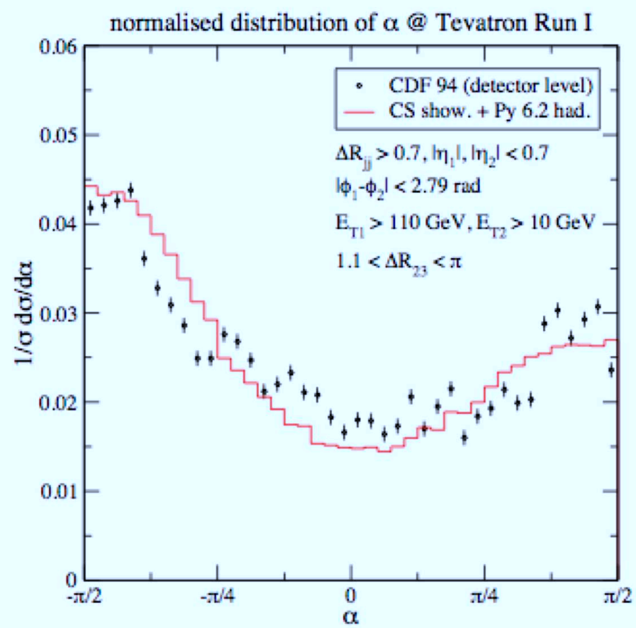


FIG. 15. Observed α distribution compared to the predictions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

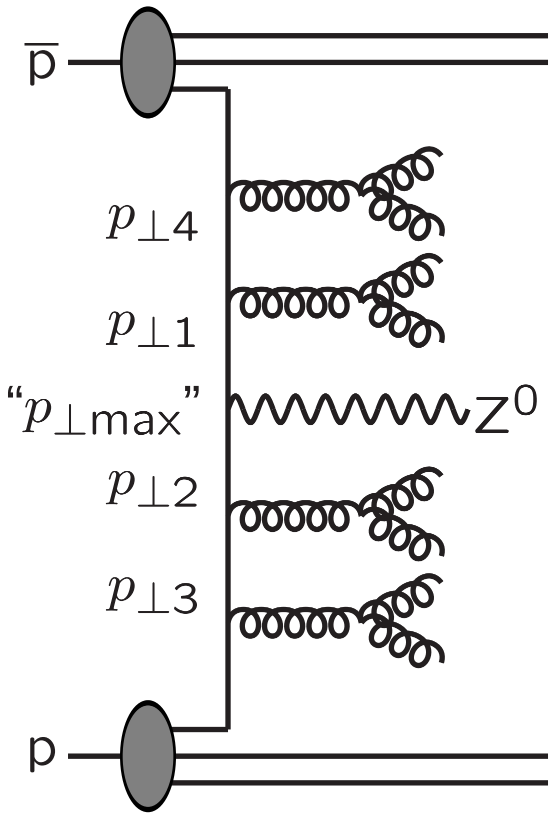
normal showers w/wo φ weight



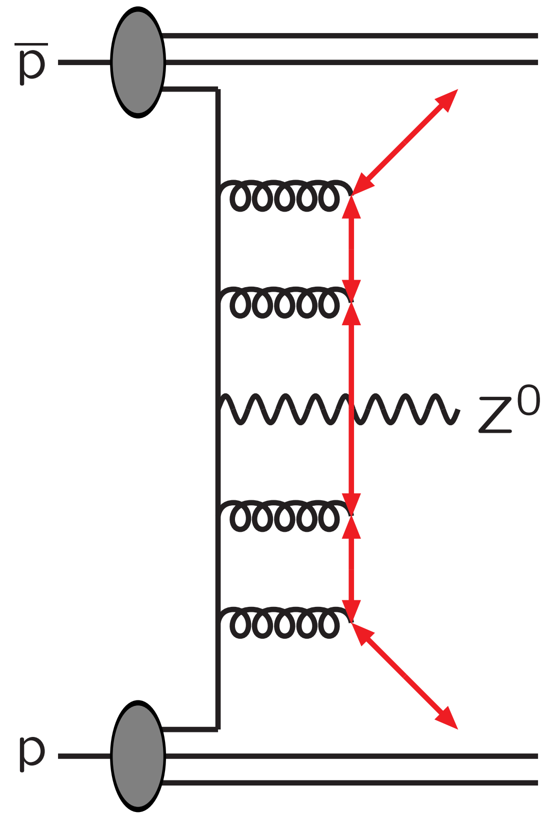


Sherpa dipoles

CDF data

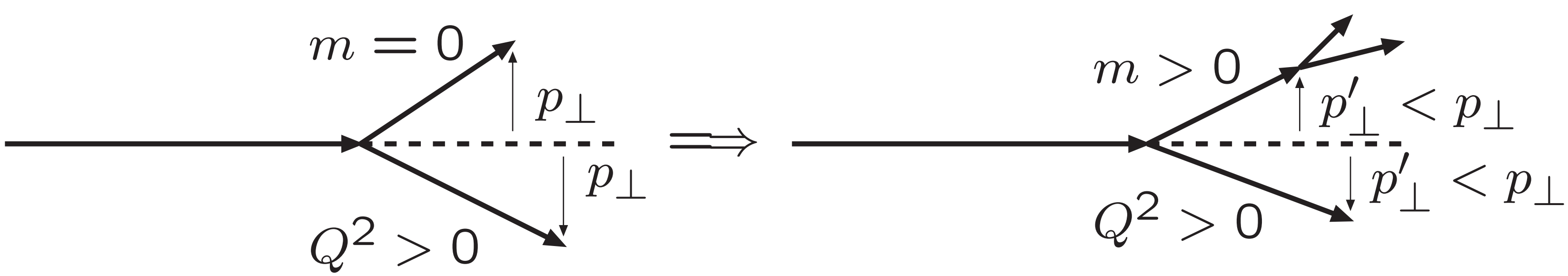


Feynman diagrams: Z^0 takes combined recoil



Dipole approach: Z^0 only affected by first ISR, not at all by FSR

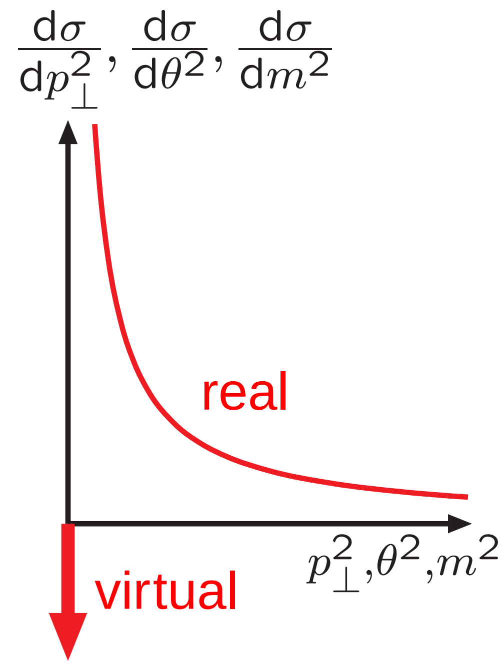
Evolution of timelike sidebranch cascades can reduce $p_\perp$:



Matrix Elements vs. Parton Showers

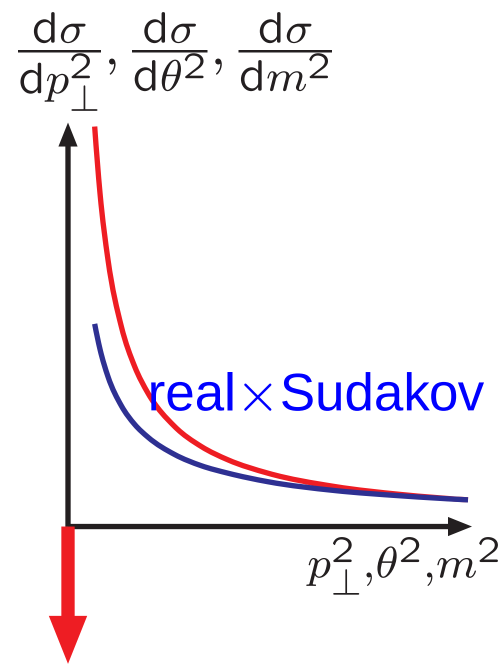
ME : Matrix Elements

+ systematic expansion in α_{s} (‘*exact*’)
+ powerful for multiparton Born level
+ flexible phase space cuts
− loop calculations very tough
− negative cross section in collinear regions
  $\Rightarrow$ unpredictive jet/event structure
− *no easy match to hadronization*

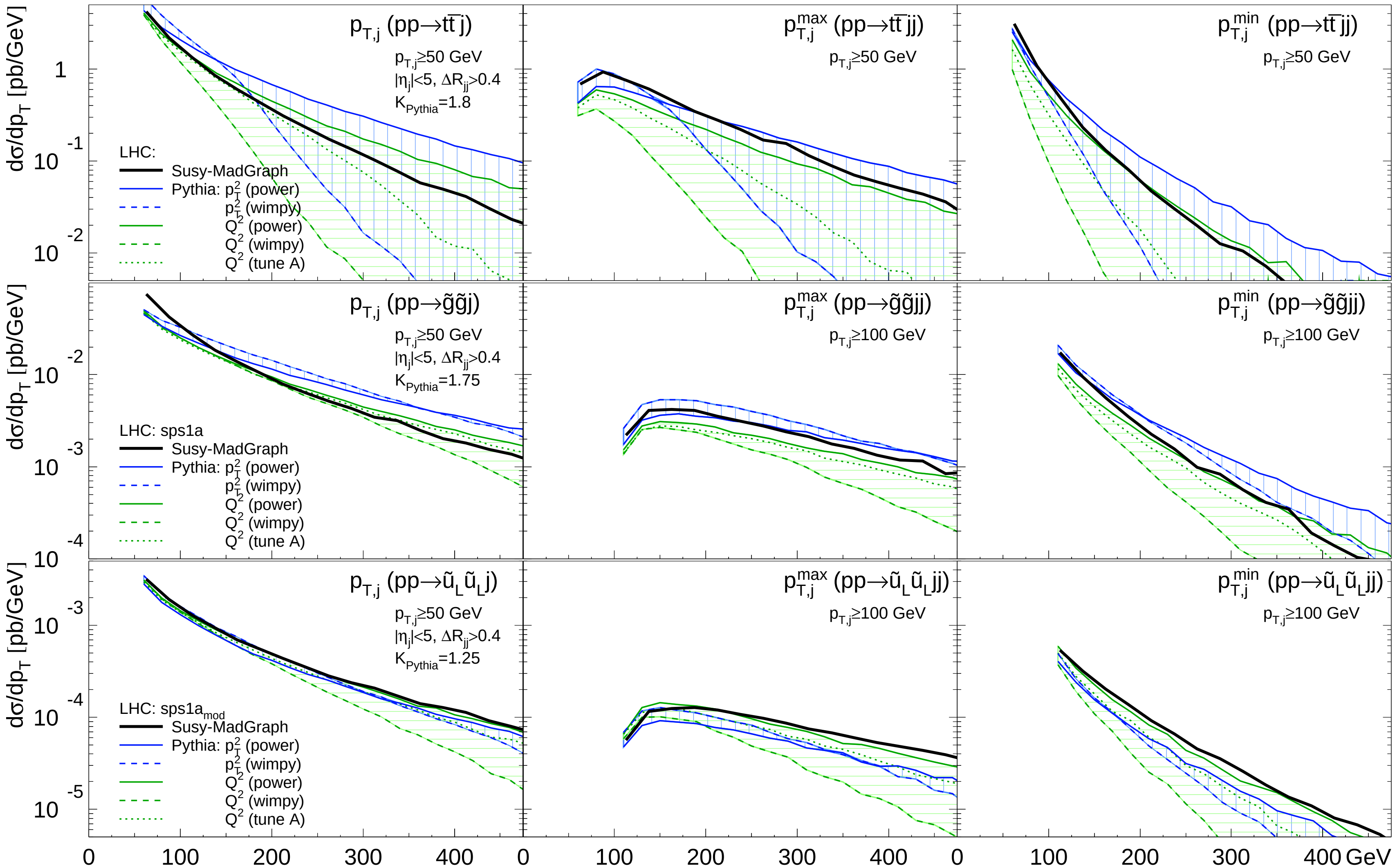


PS : Parton Showers

− approximate, to LL (or NLL)
− main topology not predetermined
  $\Rightarrow$ inefficient for exclusive states
+ process-generic $\Rightarrow$ simple multiparton
+ Sudakov form factors/resummation
  $\Rightarrow$ sensible jet/event structure
+ *easy to match to hadronization*



$p_\perp$(1 jet) $\quad$ $p_\perp^{\max}$(2 jets) $\quad$ $p_\perp^{\min}$(2 jets)



power: $Q^2_{\max} = s$; $\quad$ wimpy: $Q^2_{\max} = m_\perp^2$; $\quad$ tune A: $Q^2_{\max} = 4m_\perp^2$

$m_{\rm t} = 175$ GeV, $\quad m_{\tilde{\rm g}} = 608$ GeV, $\quad m_{\tilde{\rm u}_L} = 567$ GeV

(T. Plehn, D. Rainwater, P. Skands)

Matrix Elements and Parton Showers

Recall complementary strengths:

- ME's good for well separated jets
- PS's good for structure inside jets

Marriage desirable! But how?

Problems:
- gaps in coverage?
- doublecounting of radiation?
- Sudakov?
- NLO consistency?

Much work ongoing $\Longrightarrow$ no established orthodoxy

Three main areas, in ascending order of complication:

1) Match to lowest-order nontrivial process — merging

2) Combine leading-order multiparton process — vetoed parton showers

3) Match to next-to-leading order process — MC@NLO, POWHEG

Merging

= cover full phase space with smooth transition ME/PS

Want to reproduce $$W^{\mathrm{ME}} = \frac{1}{\sigma(\mathrm{LO})} \frac{\mathrm{d}\sigma(\mathrm{LO}+\mathrm{g})}{\mathrm{d(phasespace)}}$$

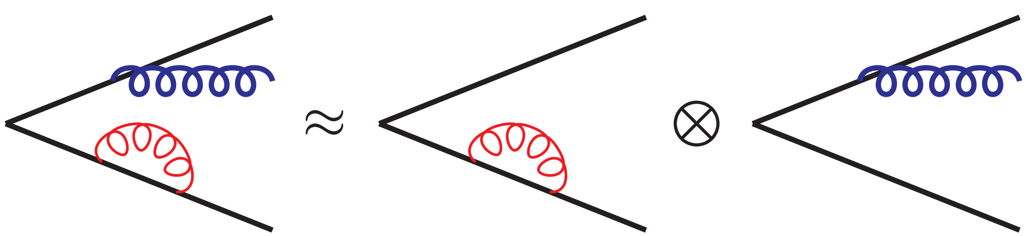
by shower generation + correction procedure

$$\underbrace{W^{\mathrm{ME}}}_{\text{wanted}} = \underbrace{W^{\mathrm{PS}}}_{\text{generated}} \overbrace{\frac{W^{\mathrm{ME}}}{W^{\mathrm{PS}}}}^{\text{correction}}$$

- Exponentiate ME correction by shower Sudakov form factor:

$$W^{\mathrm{PS}}_{\mathrm{actual}}(Q^2) = W^{\mathrm{ME}}(Q^2) \exp\left(-\int_{Q^2}^{Q^2_{\mathrm{max}}} W^{\mathrm{ME}}(Q'^2)\,\mathrm{d}Q'^2\right)$$

- Do not normalize W^{ME} to $\sigma(\mathrm{NLO})$ (error $\mathcal{O}(\alpha_s^2)$ either way)



$$\begin{array}{ccccc} & & 1+\mathcal{O}(\alpha_s) & & \int = 1 \\ & & \downarrow & & \downarrow \\ \mathrm{d}\sigma & = & K & \sigma_0 & \mathrm{d}W^{\mathrm{PS}} \end{array}$$

- Normally several shower histories $\Rightarrow$ $\sim$equivalent approaches

Final-State Shower Merging

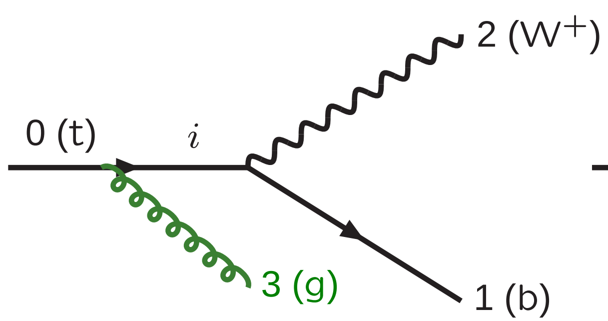
Merging with $\gamma^*/\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}\mathrm{g}$ for $m_\mathrm{q} = 0$ since long

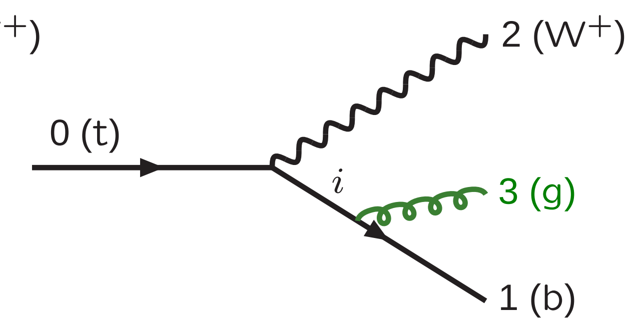
(M. Bengtsson & TS, PLB185 (1987) 435, NPB289 (1987) 810)

For $m_\mathrm{q} > 0$ pick $Q_i^2 = m_i^2 - m_{i,\mathrm{onshell}}^2$ as evolution variable since

$$W^{\mathrm{ME}} = \frac{(\ldots)}{Q_1^2 Q_2^2} - \frac{(\ldots)}{Q_1^4} - \frac{(\ldots)}{Q_2^4}$$

Coloured decaying particle also radiates:





ME $\frac{1}{Q_0^2 Q_1^2}$

matches

PS $\mathrm{b} \to \mathrm{bg}$

$\boxed{\Rightarrow \text{can merge PS with generic } a \to bc\mathrm{g} \text{ ME}}$

(E. Norrbin & TS, NPB603 (2001) 297)

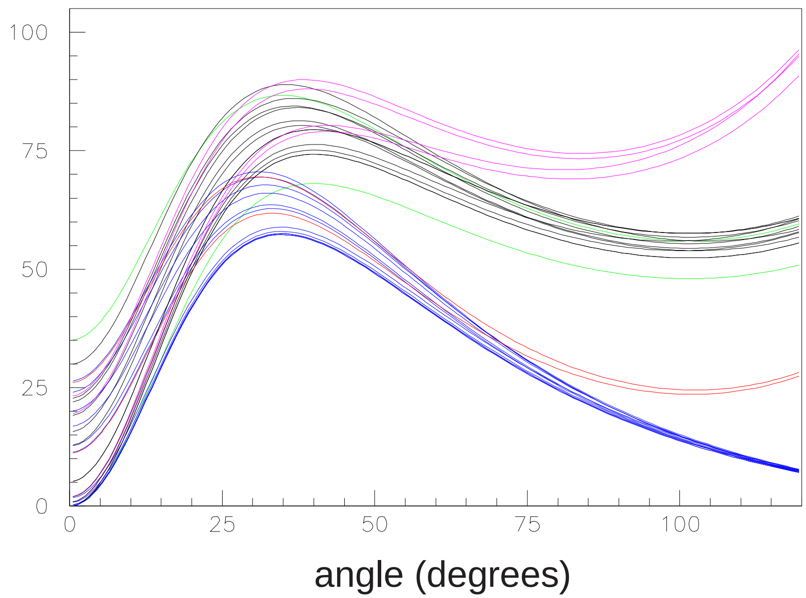
Subsequent branchings $\mathrm{q} \to \mathrm{qg}$: also matched to ME, with reduced energy of system

PYTHIA performs merging with generic FSR $a \to bc$g ME,

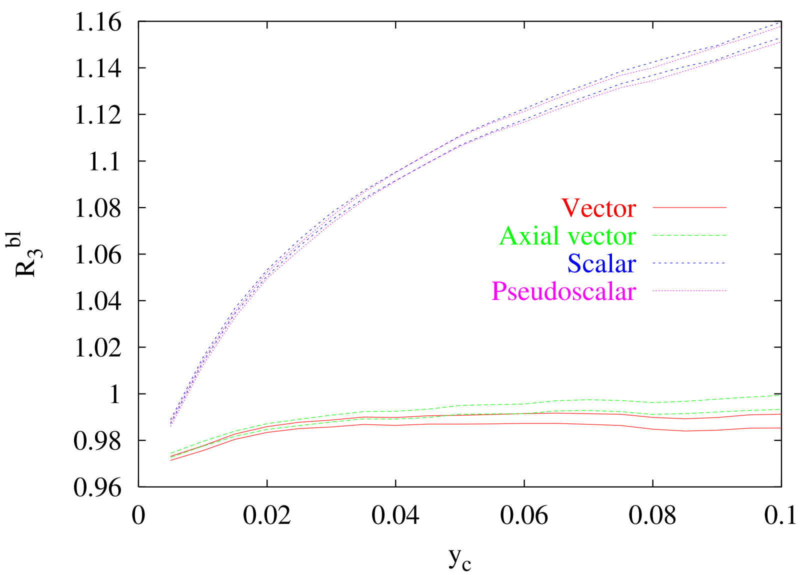
in SM: $\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm \to \mathrm{q\overline{q}}$, $\mathrm{t} \to \mathrm{bW}^+$, $\mathrm{H}^0 \to \mathrm{q\overline{q}}$,

and MSSM: $\mathrm{t} \to \mathrm{bH}^+$, $\mathrm{Z}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{W}^+$, $\mathrm{H}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{H}^+$,
$\chi \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\chi \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\chi$, $\mathrm{t} \to \tilde{\mathrm{t}}\chi$, $\tilde{\mathrm{g}} \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\tilde{\mathrm{g}}$, $\mathrm{t} \to \tilde{\mathrm{t}}\tilde{\mathrm{g}}$

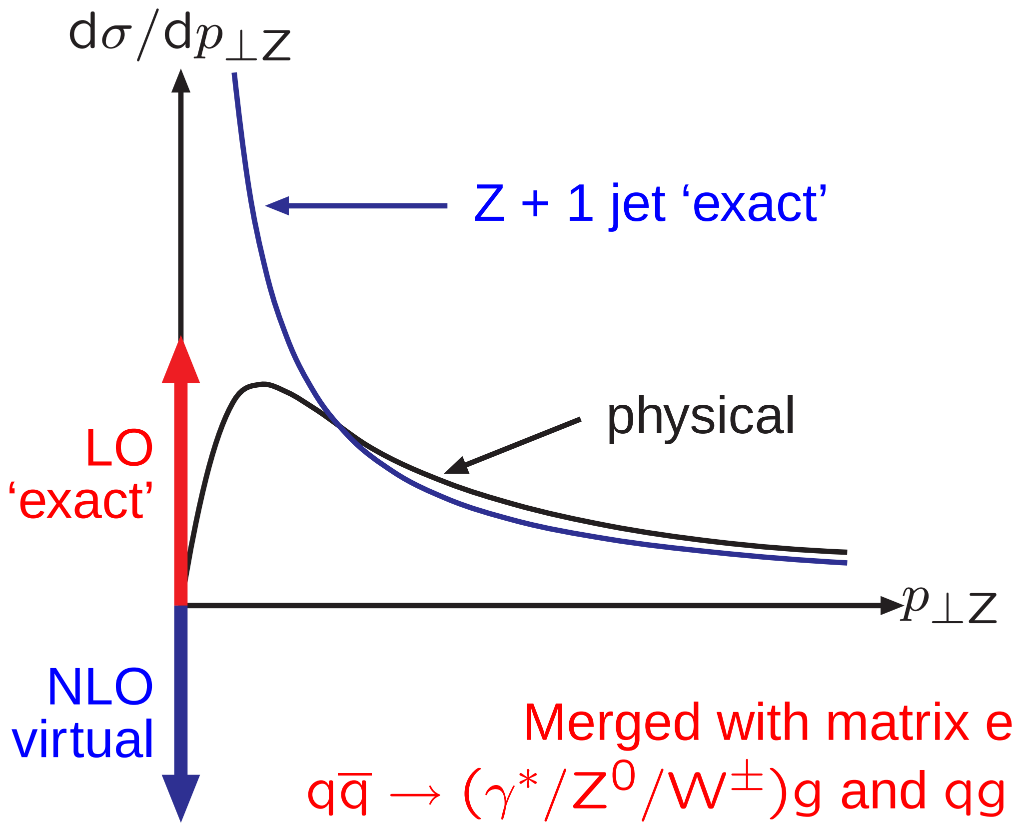
g emission for different colour, spin and parity:



$R_3^{\mathrm{bl}}(y_c)$: mass effects in Higgs decay:



Initial-State Shower Merging



resummation:
physical $p_{\perp Z}$ spectrum

shower: ditto
+ accompanying
jets (exclusive)

Merged with matrix elements for
$q\overline{q} \to (\gamma^*/Z^0/W^\pm)g$ and $qg \to (\gamma^*/Z^0/W^\pm)q'$:
(G. Miu & TS, PLB449 (1999) 313)

$$\left(\frac{W^{\mathrm{ME}}}{W^{\mathrm{PS}}}\right)_{q\overline{q}'\to gW} = \frac{\hat{t}^2 + \hat{u}^2 + 2m_W^2\hat{s}}{\hat{s}^2 + m_W^4} \leq 1$$

$$\left(\frac{W^{\mathrm{ME}}}{W^{\mathrm{PS}}}\right)_{qg\to q'W} = \frac{\hat{s}^2 + \hat{u}^2 + 2m_W^2\hat{t}}{(\hat{s} - m_W^2)^2 + m_W^4} < 3$$

with $Q^2 = -m^2$
and $z = m_W^2/\hat{s}$

Merging in HERWIG

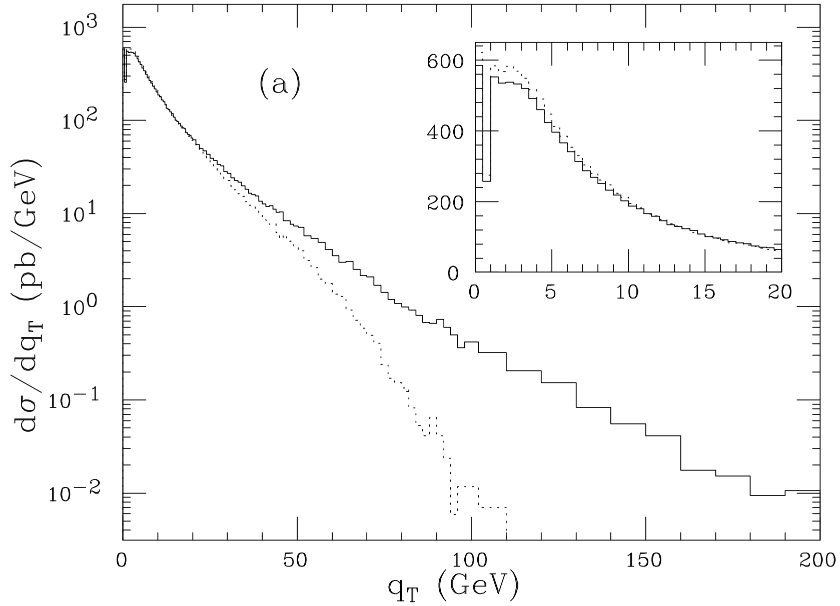
HERWIG also contains merging, for

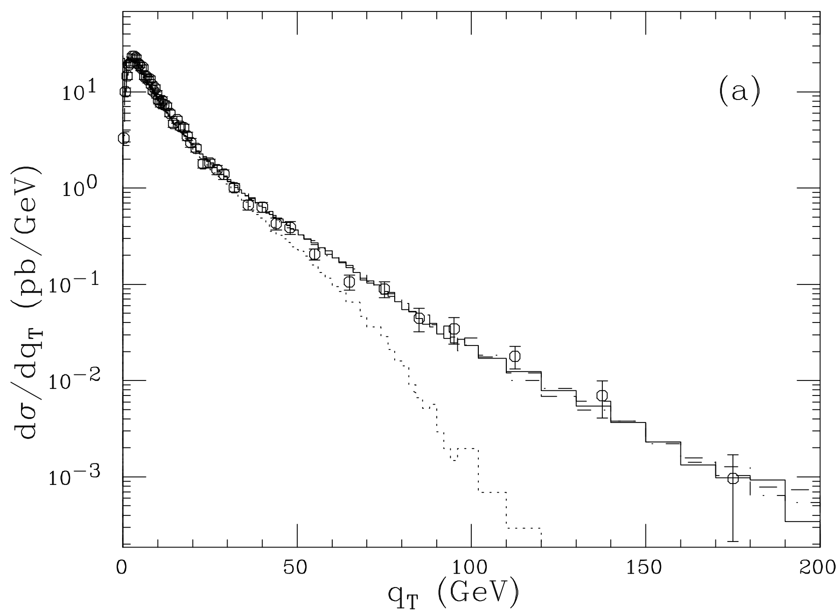
- $Z^0 \to q\overline{q}$
- $t \to bW^+$
- $q\overline{q} \to Z^0$

and some more

Special problem:
angular ordering does not cover full phase space; so
(1) fill in “dead zone” with ME
(2) apply ME correction
in allowed region

Important for agreement with data:





Vetoed Parton Showers

S. Catani, F. Krauss, R. Kuhn, B.R. Webber, JHEP 0111 (2001) 063; L. Lönnblad, JHEP0205 (2002) 046;

F. Krauss, JHEP 0208 (2002) 015; S. Mrenna, P. Richardson, JHEP0405 (2004) 040;

M.L. Mangano et al., JHEP0701 (2007) 013

Generic method to combine ME's of several different orders
to NLL accuracy; has become a standard tool for many studies

Basic idea:

- consider (differential) cross sections $\sigma_0, \sigma_1, \sigma_2, \sigma_3, \ldots$, corresponding to a lowest-order process (e.g. W or H production), with more jets added to describe more complicated topologies, in each case to the respective leading order
- σ_i, $i \geq 1$, are divergent in soft/collinear limits
- absent virtual corrections would have ensured "detailed balance", i.e. an emission that adds to σ_{i+1} subtracts from σ_i
- such virtual corrections correspond (approximately) to the Sudakov form factors of parton showers
- so use shower routines to provide missing virtual corrections $\Rightarrow$ rejection of events (especially) in soft/collinear regions

Veto scheme:

1) Pick hard process, mixing according to $\sigma_0 : \sigma_1 : \sigma_2 : \ldots$,
above some ME cutoff (e.g. all $p_{\perp i} > p_{\perp 0}$, all $R_{ij} > R_0$),
with large fixed α_{s0}

2) Reconstruct imagined shower history (in different ways)

3) Weight $W_\alpha = \prod_{\text{branchings}} (\alpha_s(k_{\perp i}^2)/\alpha_{s0}) \Rightarrow$ accept/reject

CKKW-L:

4) Sudakov factor for non-emission
on all lines above ME cutoff
$W_{\text{Sud}} = \prod_{\text{“propagators”}}$
$\text{Sudakov}(k_{\perp\text{beg}}^2, k_{\perp\text{end}}^2)$

4a) CKKW : use NLL Sudakovs

4b) L: use trial showers

5) $W_{\text{Sud}} \Rightarrow$ accept/reject

6) do shower,
vetoing emissions above cutoff

MLM:

4) do parton showers

5) (cone-)cluster
showered event

6) match partons and jets

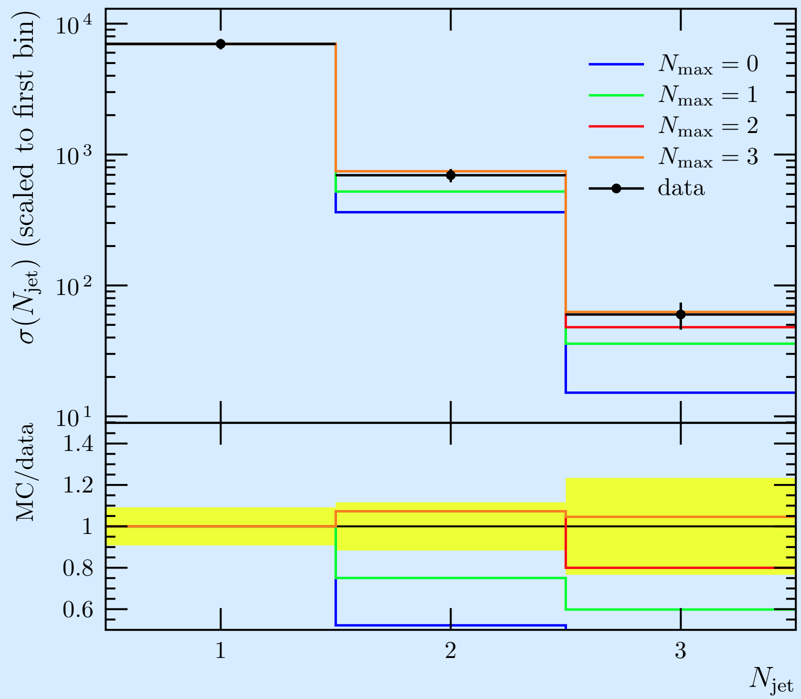
7) if all partons are matched,
and $n_{\text{jet}} = n_{\text{parton}}$,
keep the event,
else discard it

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

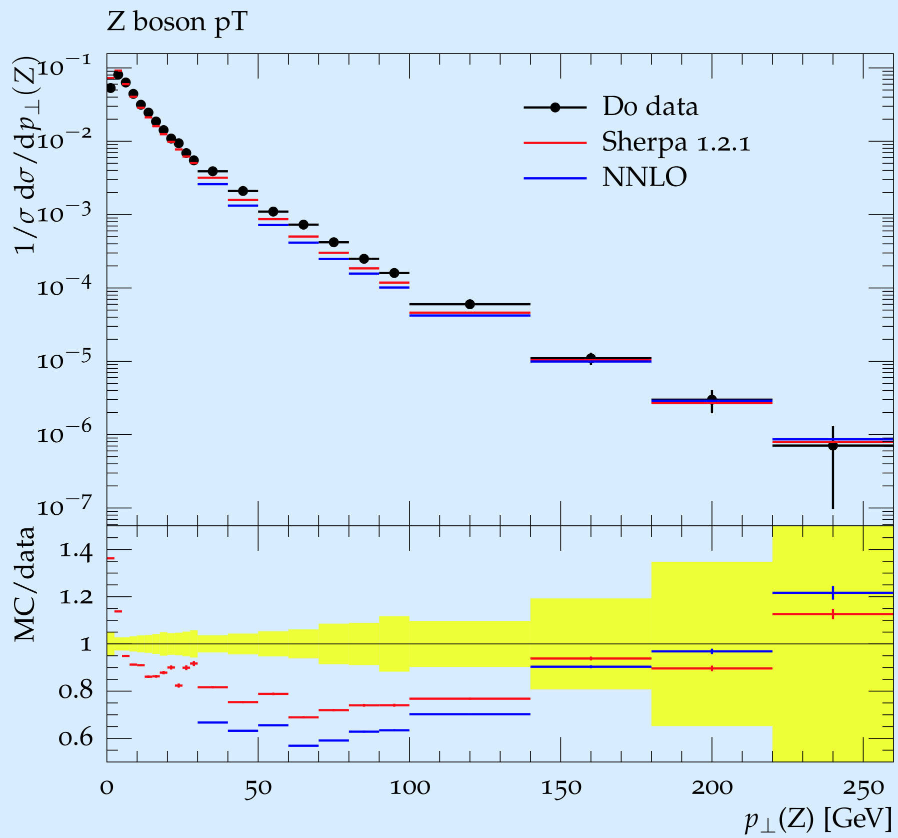


$Q_{\rm cut} = 30$ GeV

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

DØ data: Phys. Lett. B **669** (2008) 278

Comparison between SHERPA 1.2.1 and NNLO Z production



Z^0+jets at Tevatron: jet spectra

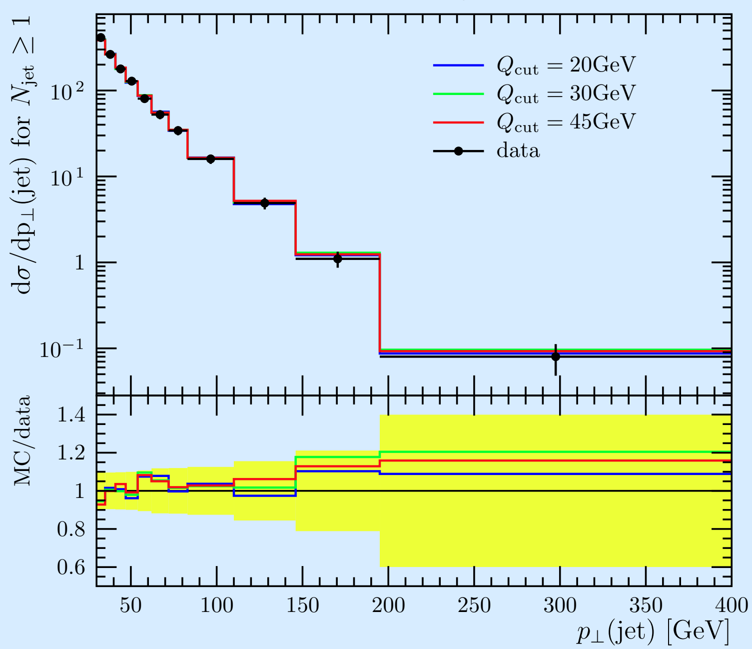
Variation of Q_{cut} should affect distributions only beyond (N)LL

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

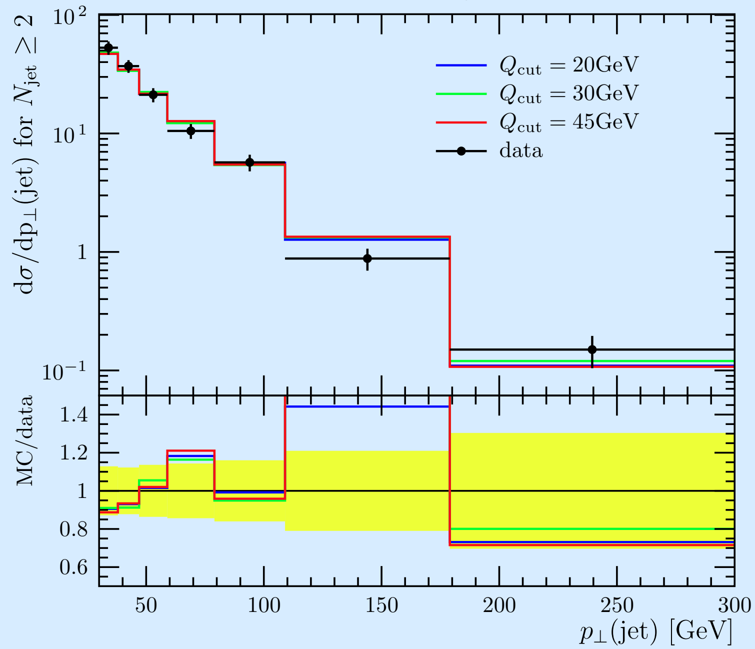
- Example: All-jets p_T's in DY-pair production

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

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



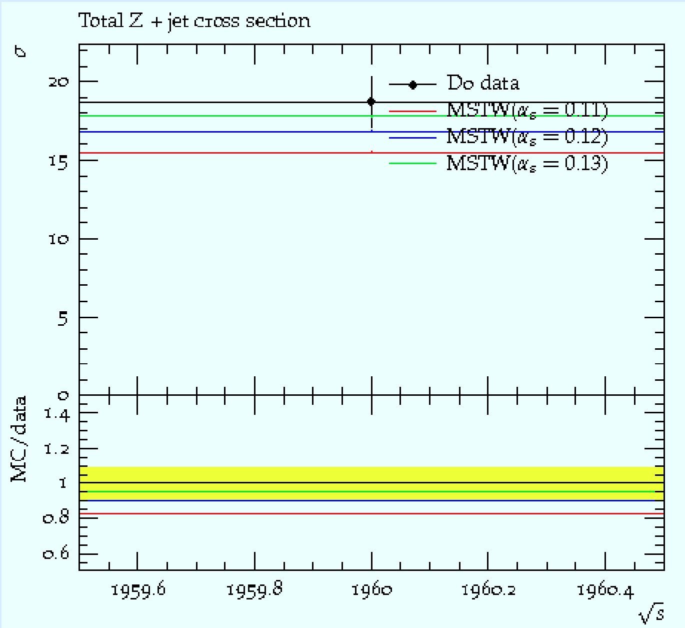
p_T(jet) for $N_{\text{jet}} \geq 2$

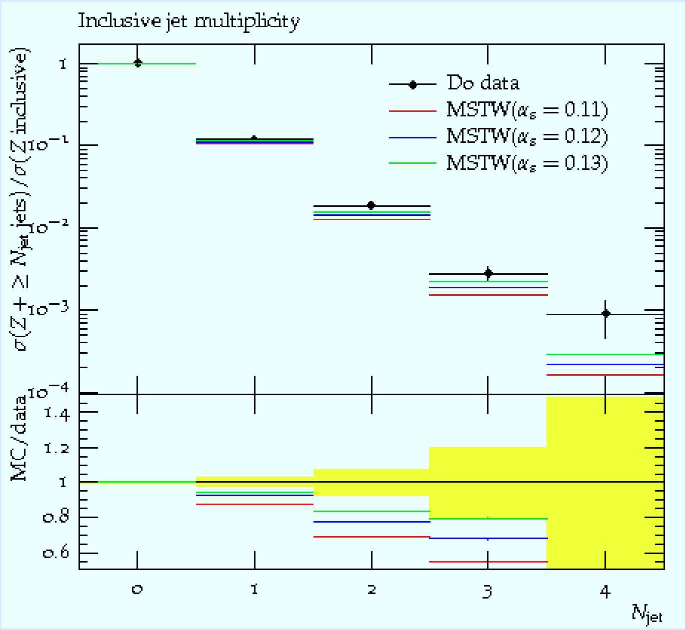


Z^0+jets at Tevatron: cross sections

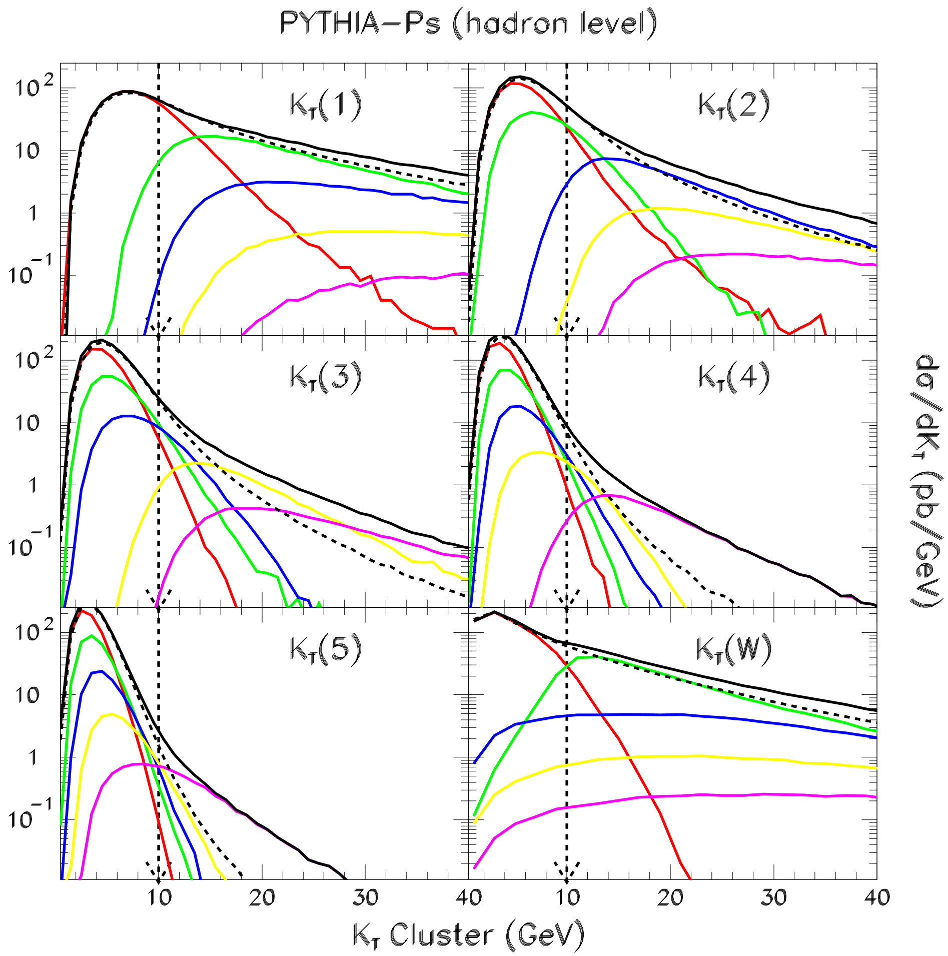
CDF data from PRL 100 (2008) 102001 and D0/, arXiv:0808:1296

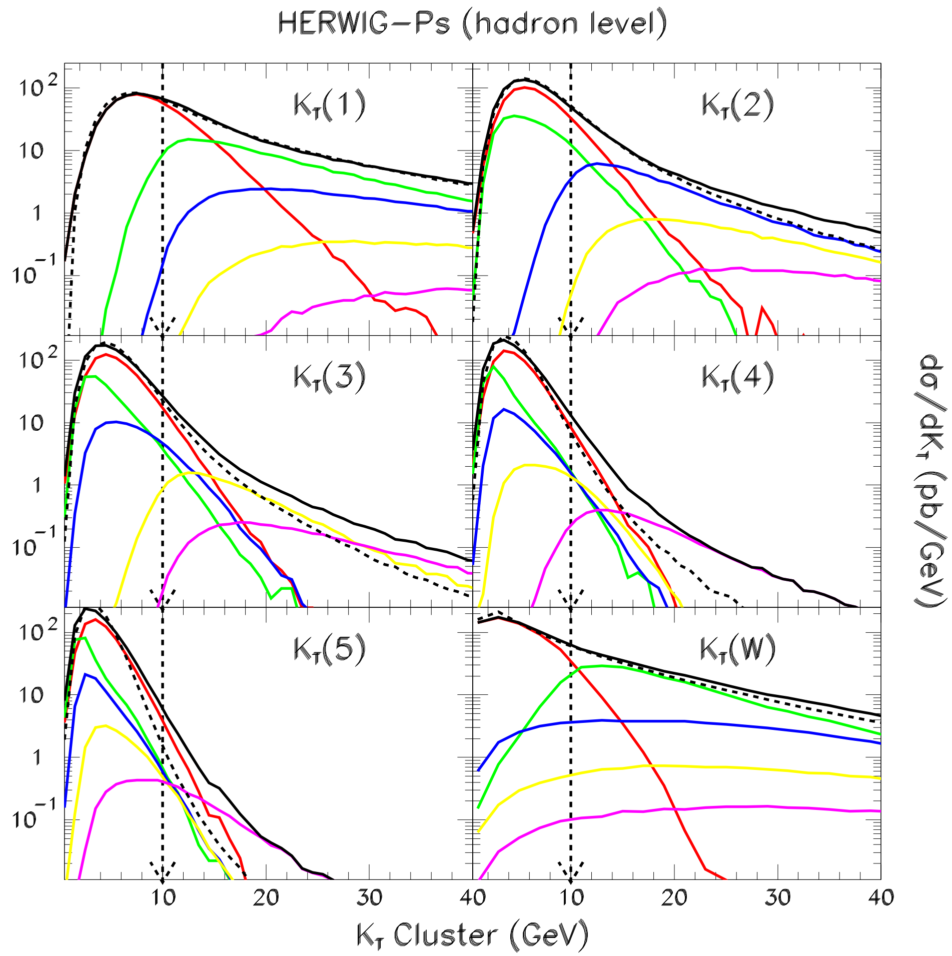
Impact of α_S - global in SHERPA



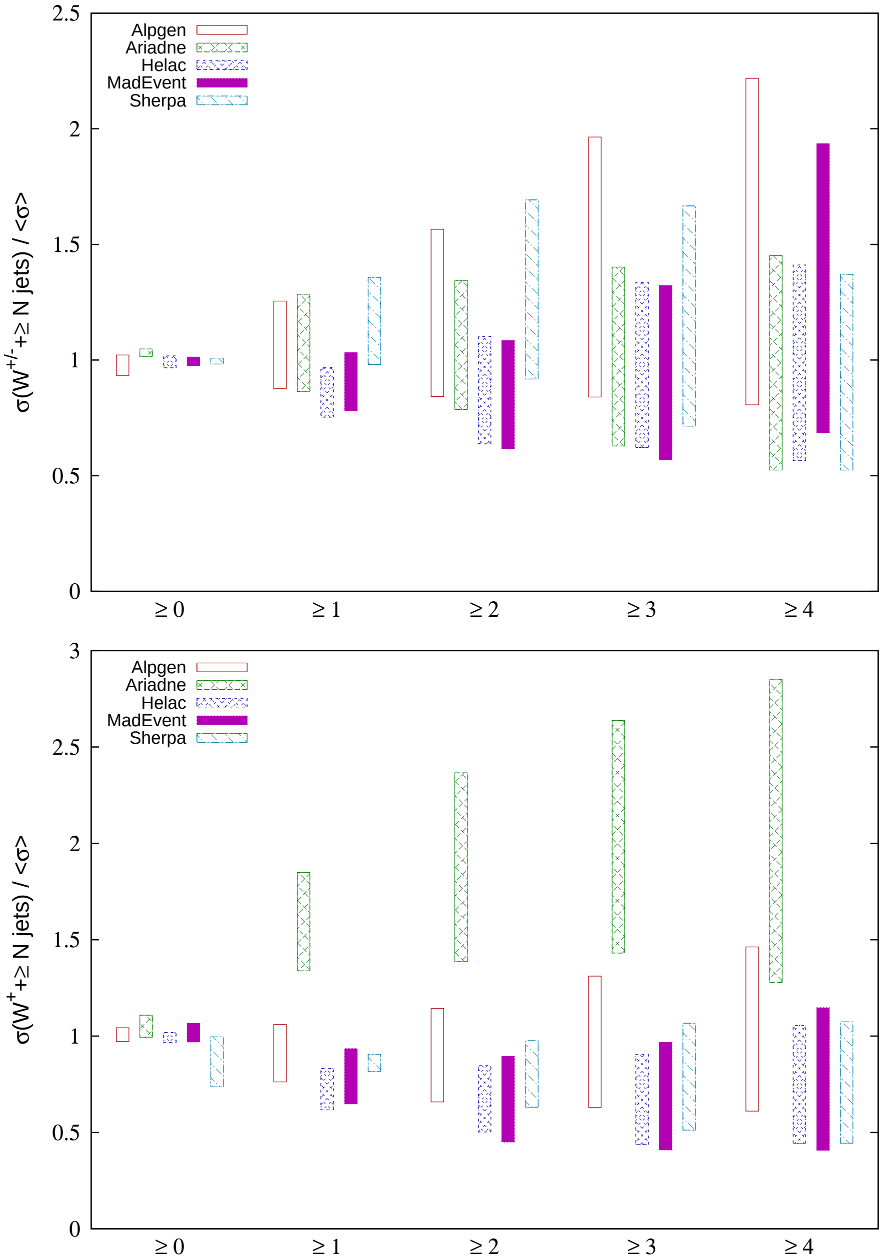


CKKW mix of W + (0, 1, 2, 3, 4) partons, hadronized and clustered to jets:





(S.Mrenna, P. Richardson)



Spread of W + jets rate for different matching schemes + showers,
top: Tevatron,
bottom: LHC.

ALPGEN: MLM + HERWIG

ARIADNE: CKKW-L + ARIADNE

HELAC: MLM + PYTHIA

MADEVENT: MLM/CKKW + PYTHIA

SHERPA: CKKW + SHERPA

model varation: α_S, cuts, . . .

(Alwall, Krauss, Lavesson, Lönnblad, Mangano, Worek, . . .)

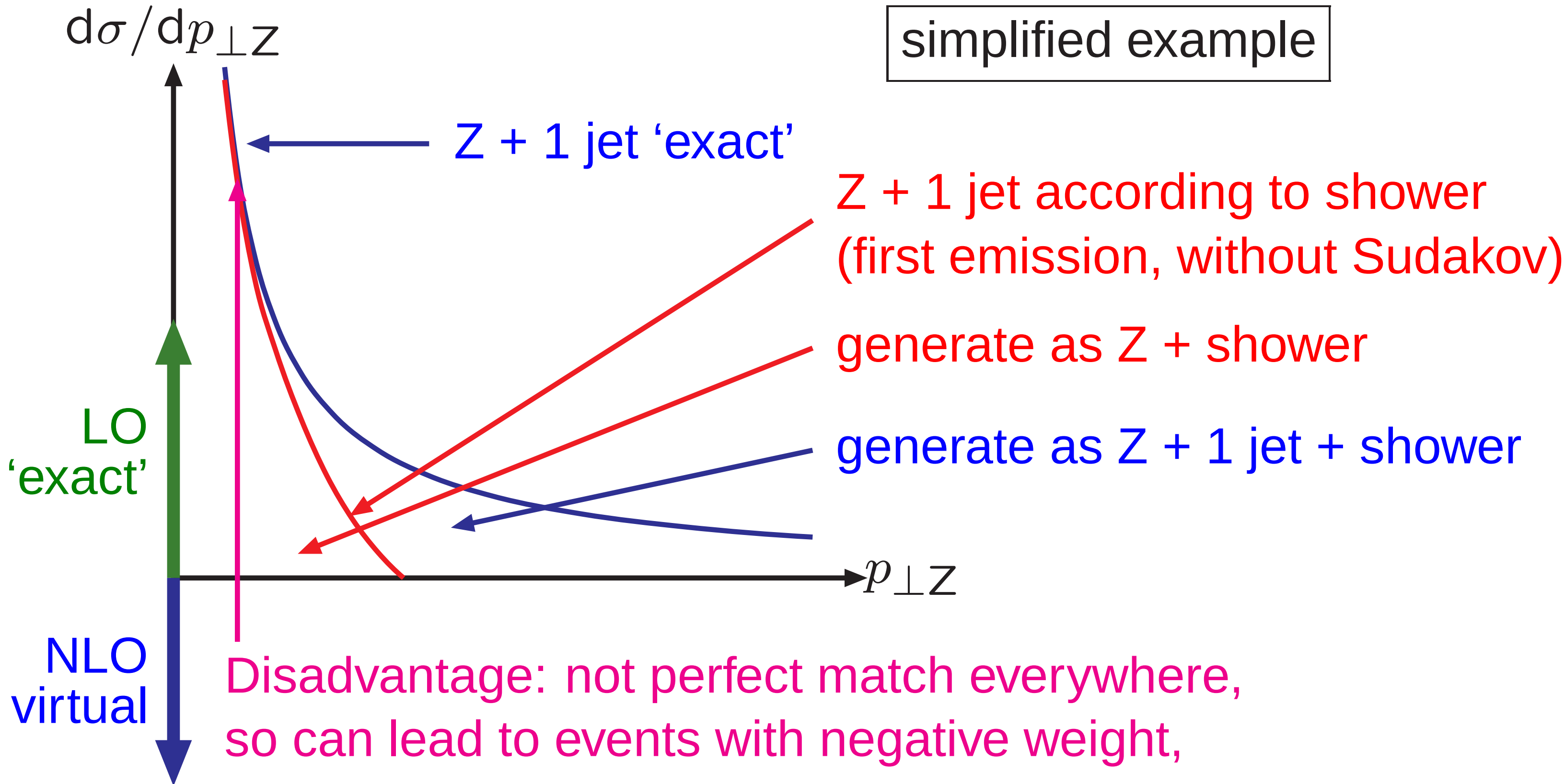
MC@NLO

Objectives:

- Total rate should be accurate to NLO.
- NLO results are obtained for all observables when (formally) expanded in powers of $\alpha_{\rm S}$.
- Hard emissions are treated as in the NLO computations.
- Soft/collinear emissions are treated as in shower MC.
- The matching between hard and soft emissions is smooth.
- The outcome is a set of “normal” events, that can be processed further.

Basic scheme (simplified!):

1) Calculate the NLO matrix element corrections to an n-body process (using the subtraction approach).
2) Calculate analytically (no Sudakov!) how the first shower emission off an n-body topology populates $(n+1)$-body phase space.
3) Subtract the shower expression from the $(n+1)$ ME to get the “true” $(n+1)$ events, and consider the rest of $\sigma_{\rm NLO}$ as n-body.
4) Add showers to both kinds of events.



Disadvantage: not perfect match everywhere,
so can lead to events with negative weight,
$\sim$ 10% when normalized to ± 1.

MC@NLO in comparison:

- Superior with respect to "total" cross sections.
- Equivalent to merging for event shapes (differences higher order).
- Inferior to CKKW–L for multijet topologies.

$\Rightarrow$ pick according to current task and availability.

MC@NLO 2.31 [hep-ph/0402116]

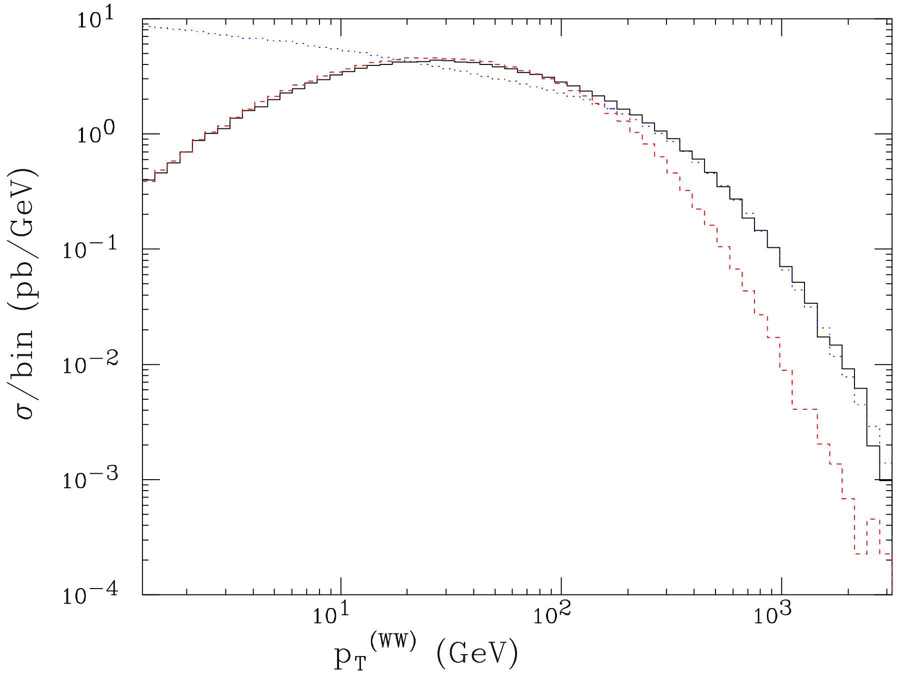
(Frixione, Webber)

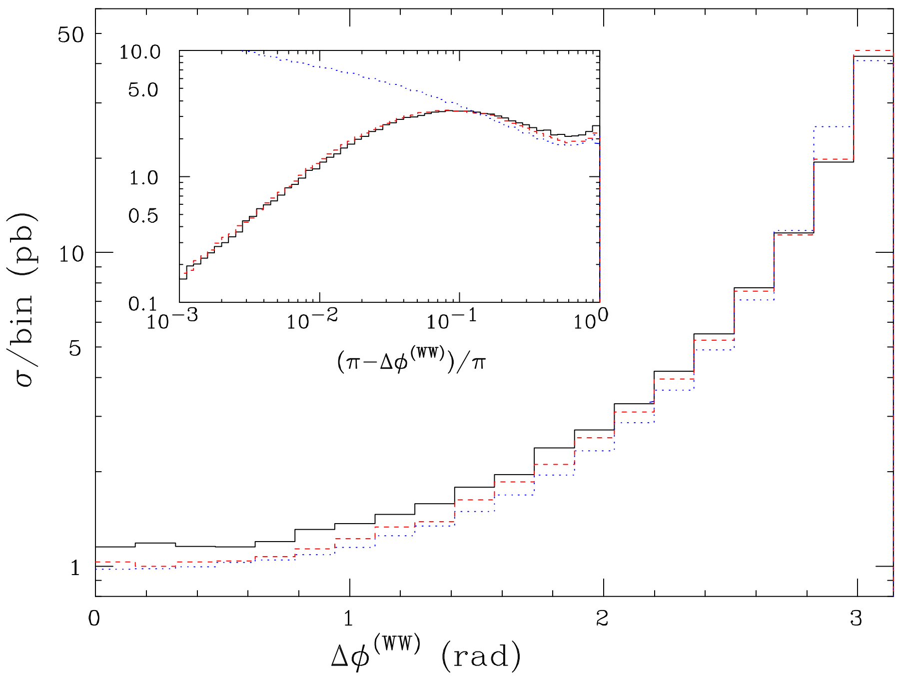
IPROC	Process
–1350–IL	$H_1H_2 \to (Z/\gamma^* \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
–1360–IL	$H_1H_2 \to (Z \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
–1370–IL	$H_1H_2 \to (\gamma^* \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
–1460–IL	$H_1H_2 \to (W^+ \to)l^+_{\rm IL}\nu_{\rm IL} + X$
–1470–IL	$H_1H_2 \to (W^- \to)l^-_{\rm IL}\bar{\nu}_{\rm IL} + X$
–1396	$H_1H_2 \to \gamma^*(\to \sum_i f_i\bar{f}_i) + X$
–1397	$H_1H_2 \to Z^0 + X$
–1497	$H_1H_2 \to W^+ + X$
–1498	$H_1H_2 \to W^- + X$
–1600–ID	$H_1H_2 \to H^0 + X$
–1705	$H_1H_2 \to b\bar{b} + X$
–1706	$H_1H_2 \to t\bar{t} + X$
–2850	$H_1H_2 \to W^+W^- + X$
–2860	$H_1H_2 \to Z^0Z^0 + X$
–2870	$H_1H_2 \to W^+Z^0 + X$
–2880	$H_1H_2 \to W^-Z^0 + X$

- Works identically to HERWIG: the very same analysis routines can be used
- Reads shower initial conditions from an event file (as in ME corrections)
- Exploits Les Houches accord for process information and common blocks
- Features a self contained library of PDFs with old and new sets alike
- LHAPDF will also be implemented

Later additions: single top, $H^0W^\pm$, H^0Z^0, tW, ...

W^+W^- Observables





These correlations are problematic: the soft and hard emissions are both relevant. MC@NLO does well, resumming large logarithms, and yet handling the large-scale physics correctly

Solid: MC@NLO

Dashed: HERWIG$\times\frac{\sigma_{NLO}}{\sigma_{LO}}$

Dotted: NLO

POWHEG

Nason; Frixione, Oleari, Ridolfi (e.g. JHEP **0711** (2007) 070)
Better (?) alternative to MC@NLO:

$$\mathrm{d}\sigma = \bar{B}(v)\mathrm{d}\Phi_v \left[\frac{R(v,r)}{B(v)} \exp\left(- \int_{p_\perp} \frac{R(v,r')}{B(v)} \mathrm{d}\Phi'_r \right) \mathrm{d}\Phi_r \right]$$

where

$$\bar{B}(v) = B(v) + V(v) + \int \mathrm{d}\Phi_r [R(v,r) - C(v,r)] \, .$$

and
v, $\mathrm{d}\Phi_v$ Born-level n-body variables and differential phase space
r, $\mathrm{d}\Phi_r$ extra $n+1$-body variables and differential phase space
$B(v)$ Born-level cross section
$V(v)$ Virtual corrections
$R(v,r)$ Real-emission cross section
$C(v,r)$ Conterterms for collinear factorization of parton densities.

Basic idea:

- Pick the real emission with largest $p_\perp$ according to complete ME's, with NLO normalization.
- Let showers do subsequent evolution downwards from this $p_\perp$ scale.

Relative to MC@NLO:

$+$ no negative weights (except in regions with extreme virtual corrections)

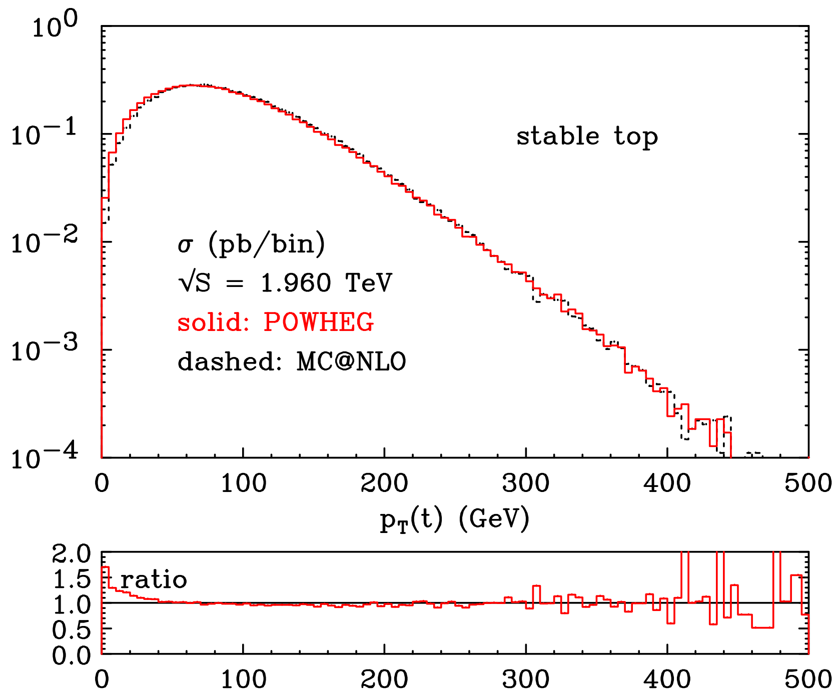
$+$ clean separation to shower stage

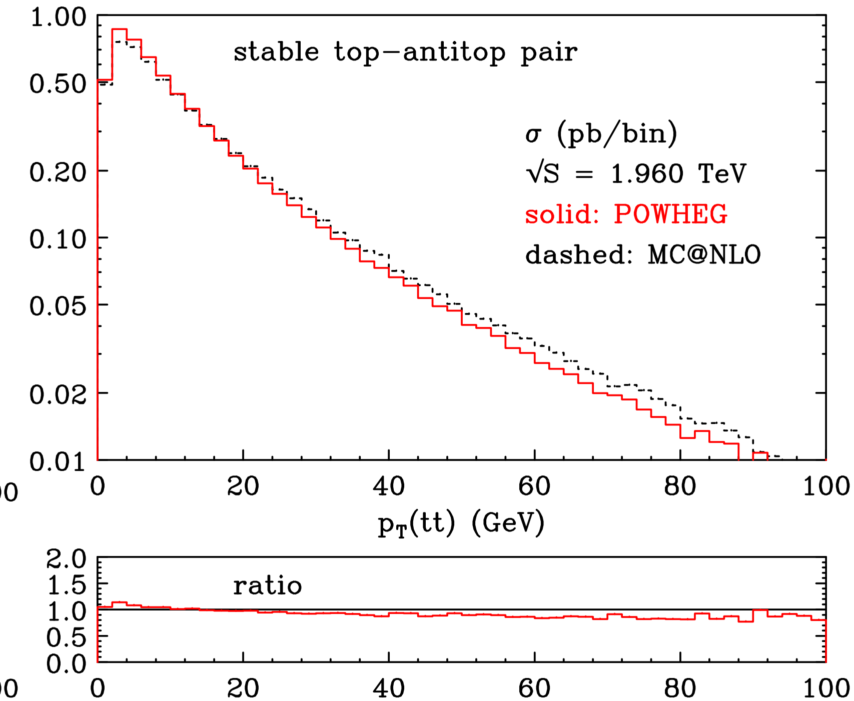
$\pm$ optimal for $p_\perp$-ordered showers, messy but manageable for others

$\pm$ different higher-order terms

$-$ as of yet fewer processes than MC@NLO

$p_\perp$ spectrum of individual t quark and of $t\bar{t}$ pair:





Status of POWHEG

Up to now, the following processes have been implemented in POWHEG:

- $hh \to ZZ$ (Ridolfi, P.N., 2006)
- $e^+e^- \to \mathrm{hadrons}$, (Latunde-Dada,Gieseke,Webber, 2006),
  $e^+e^- \to t\bar{t}$, including top decays at NLO (Latunde-Dada,2008),
- $hh \to Q\bar{Q}$ (Frixione, Ridolfi, P.N., 2007)
- $hh \to Z/W$ (Alioli, Oleari, Re, P.N., 2008;)
  (Hamilton,Richardson,Tully, 2008;)
- $hh \to H$ (gluon fusion) (Alioli, Oleari, Re, P.N., 2008; Herwig++)
- $hh \to H$, $hh \to HZ/W$ (Hamilton,Richardson,Tully, 2009;)
- $hh \to t + X$ (single top) NEW (Alioli, Oleari, Re, P.N., 2009)
- $hh \to Z + \mathrm{jet}$, Very preliminary (Alioli, Oleari, Re, P.N., 2009)
- The POWHEG BOX, Very preliminary, (Alioli, Oleari, Re, P.N., 2009)

Summary Lecture 3

• Showers bring us *from* few-parton "pencil-jet" topologies
to multi-broad-jet states. •

• Necessary complement to matrix elements: •
$\star$ Do not trust off-the-shelf ME for $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \lesssim 1$ $\star$
$\star$ Do not trust unmatched PS for $R \gtrsim 1$ $\star$

• Two main lines of evolution: •

$\star$ (1) Improve algorithm as such: evolution variables, kinematics,
dipoles, NLL, small-x, $k_\perp$ factorization, BFKL/CCFM, ... $\star$

$\star$ (2) Improve matching ME-PS: merging,
vetoed parton showers, MC@NLO, POWHEG $\star$

$\star$ $\Rightarrow$ active area of development; high profile $\star$