LUND UNIVERSITY

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Monte Carlo Event Generators

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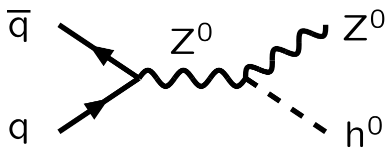
1. (yesterday) Introduction and Overview; Monte Carlo Techniques
2. (yesterday) Matrix Elements; Parton Showers I
3. **(today) Parton Showers II; Matching Issues**
4. (today) Multiple Interactions and Beam Remnants
5. (tomorrow) Hadronization and Decays; Summary and Outlook

Event Physics Overview

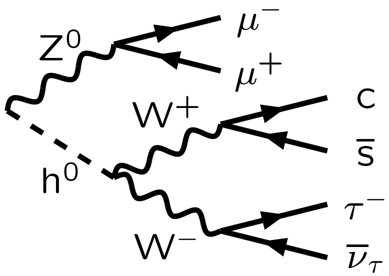
Repetition: from the “simple” to the “complex”,
or from “calculable” at large virtualities to “modelled” at small

Matrix elements (ME):

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

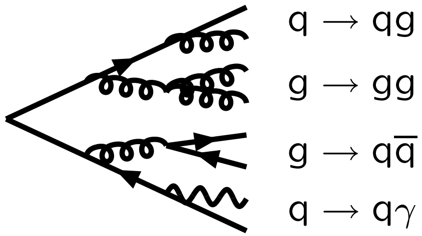


2) Resonance decays:
includes correlations.

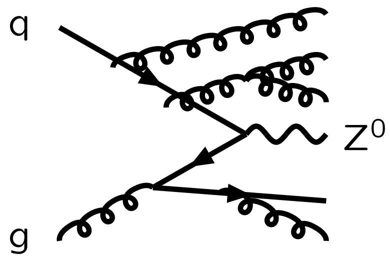


Parton Showers (PS):

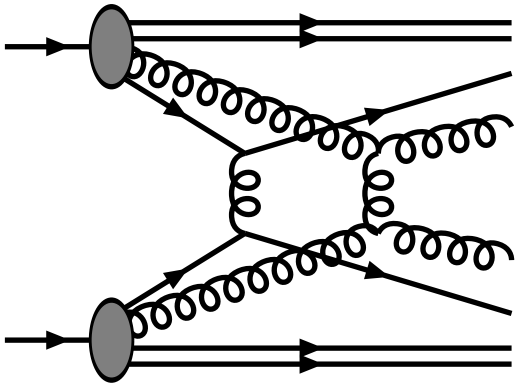
3) Final-state parton showers.



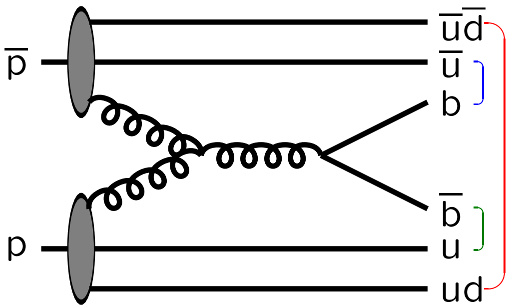
4) Initial-state parton showers.



5) Multiple parton–parton interactions.

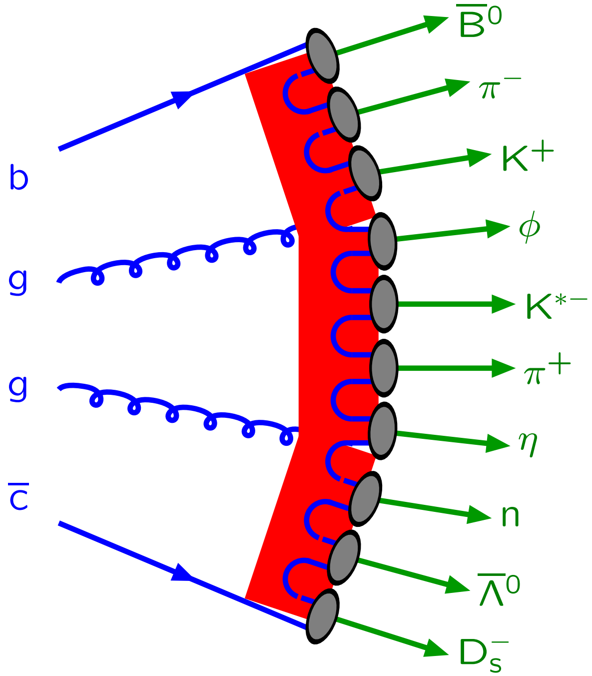


6) Beam remnants, with colour connections.

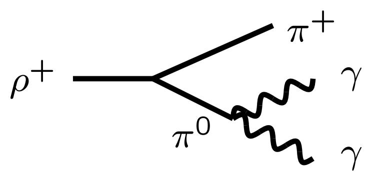


5) + 6) = Underlying Event

7) Hadronization

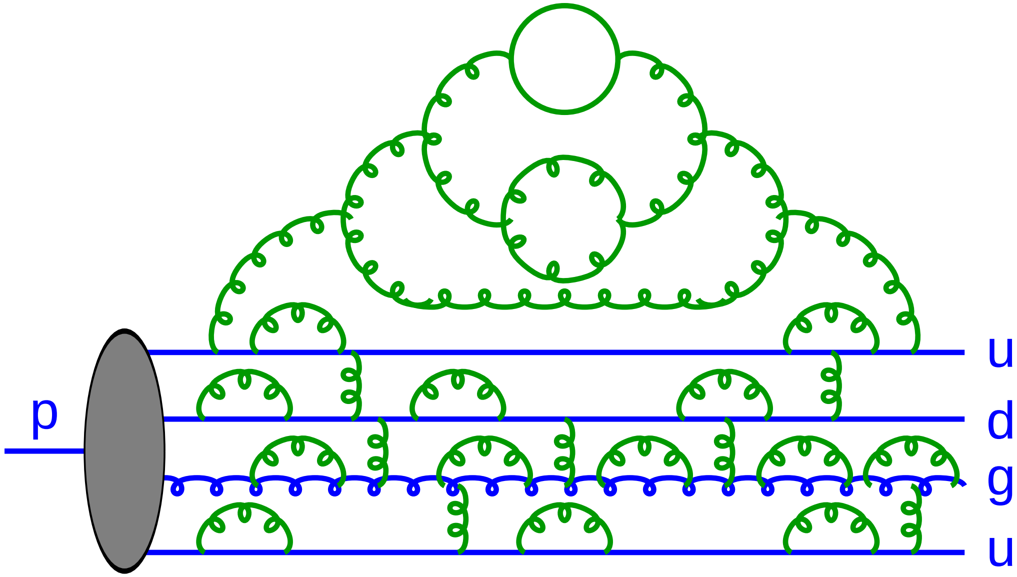


8) Ordinary decays: hadronic, τ, charm, . . .



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):

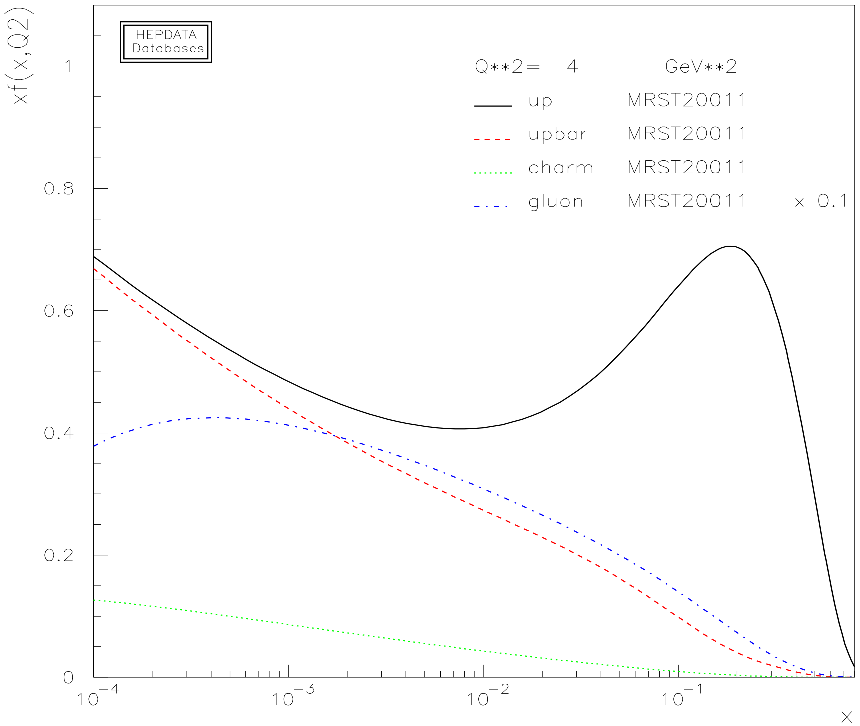
$$F_2(x, Q^2) \;=\; \sum_i e_i^2 \, x f_i(x, Q^2)$$

structure function   parton distributions

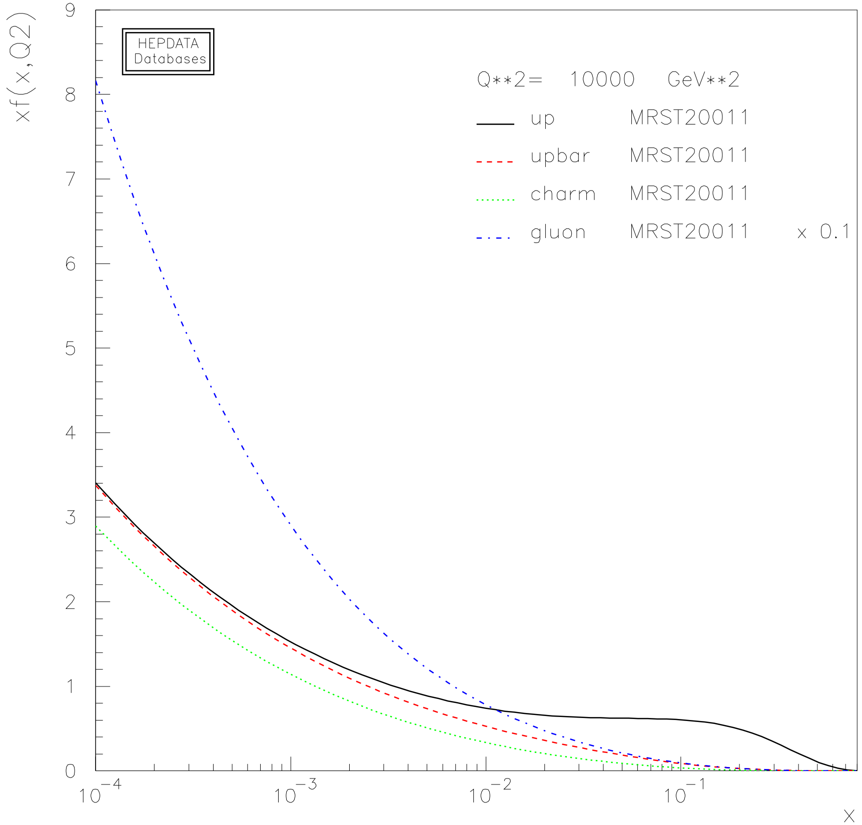
Absolute normalization at small Q_0^2 unknown.
Resolution dependence by DGLAP:

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

$Q^2 = 4\ \mathrm{GeV}^2$

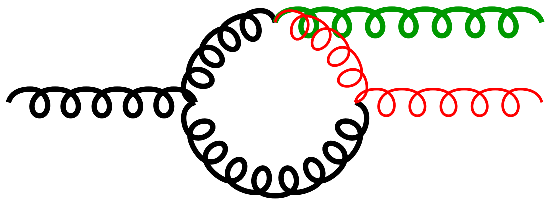


$Q^2 = 10000\ \mathrm{GeV}^2$

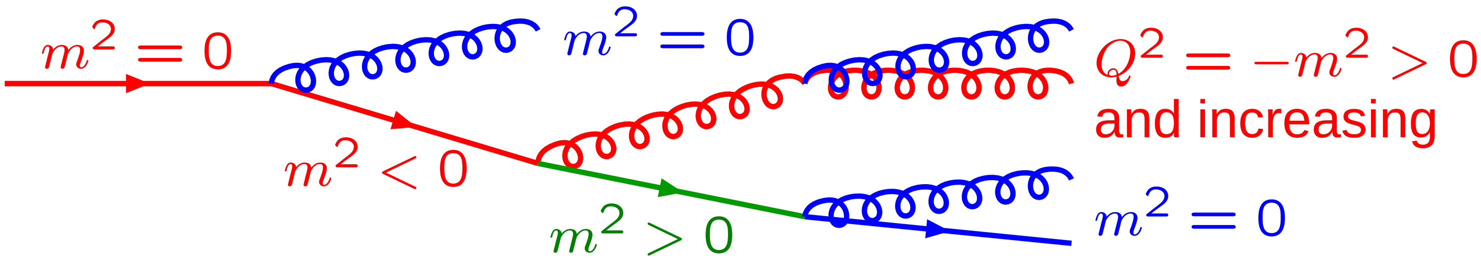


Initial-State Shower Basics

- 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.



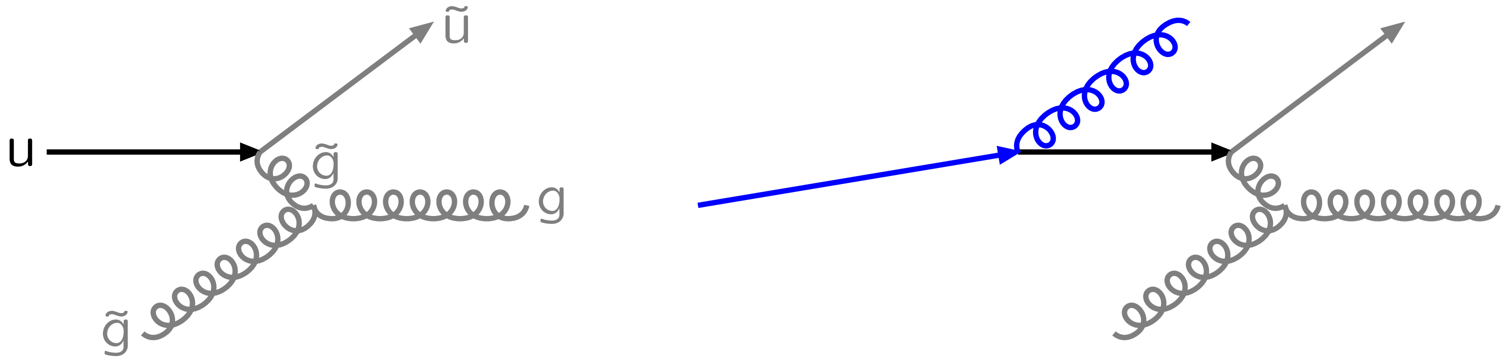
- Convenient reinterpretation:



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 ~equivalent alternative:
start at hard interaction and trace what happened "before"



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

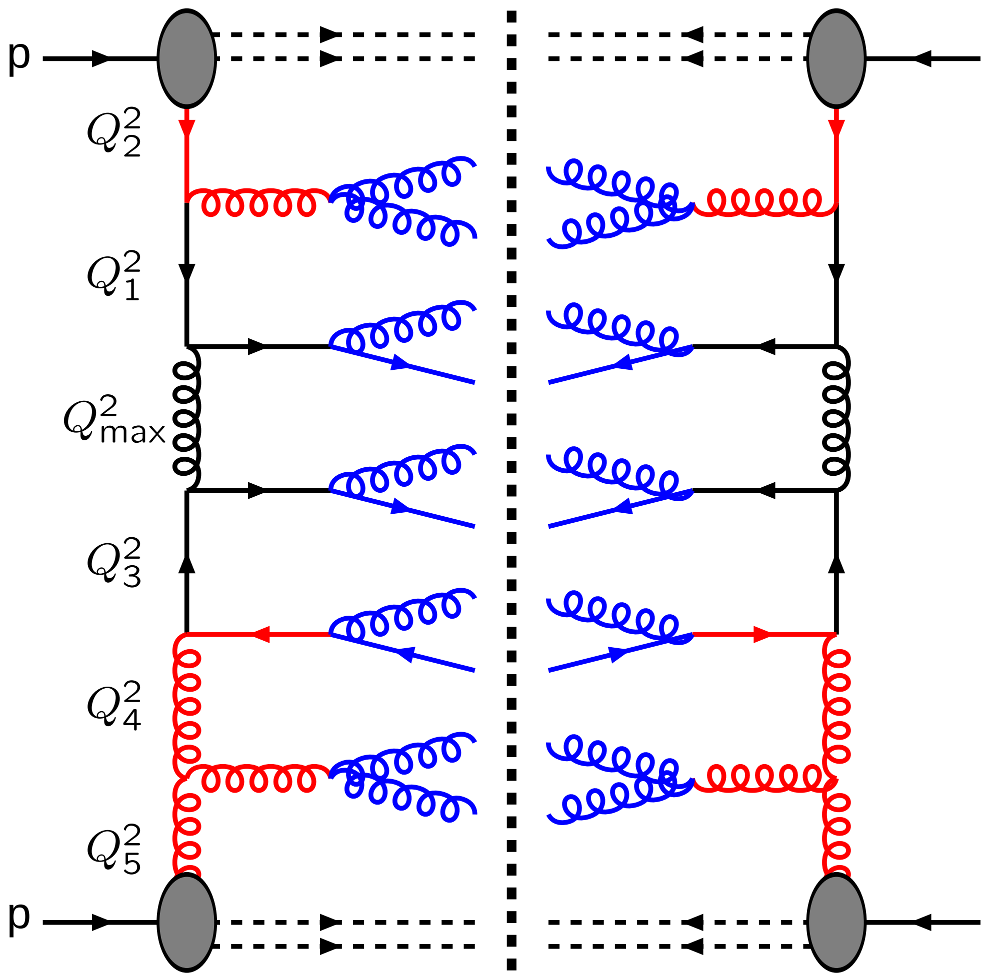
$$\frac{\mathrm{d}f_b(x,Q^2)}{\mathrm{d}t} = \sum_a \int_x^1 \frac{\mathrm{d}z}{z} f_a(x',Q^2) \frac{\alpha_s}{2\pi} P_{a\to bc}(z)$$

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

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

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

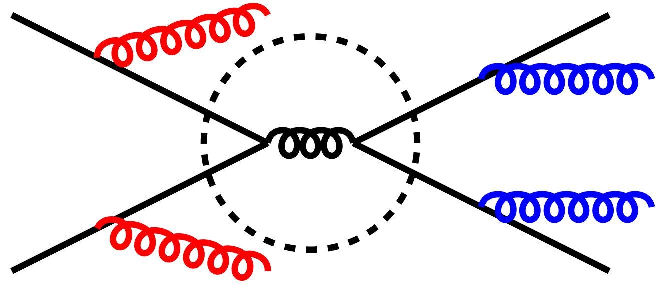
Ladder representation combines whole event:



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:

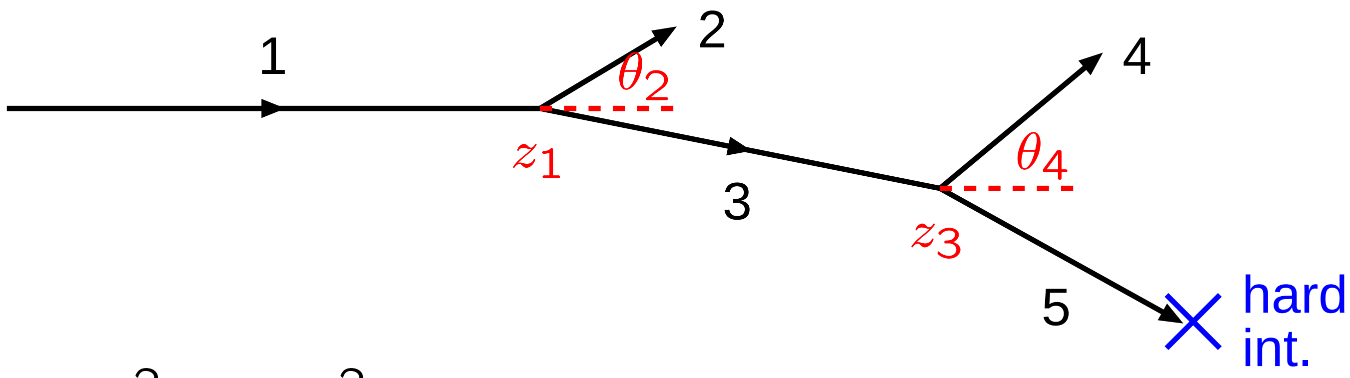
1) Hard scattering

2) Initial-state shower

from center outwards

3) Final-state showers

Coherence in spacelike showers



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

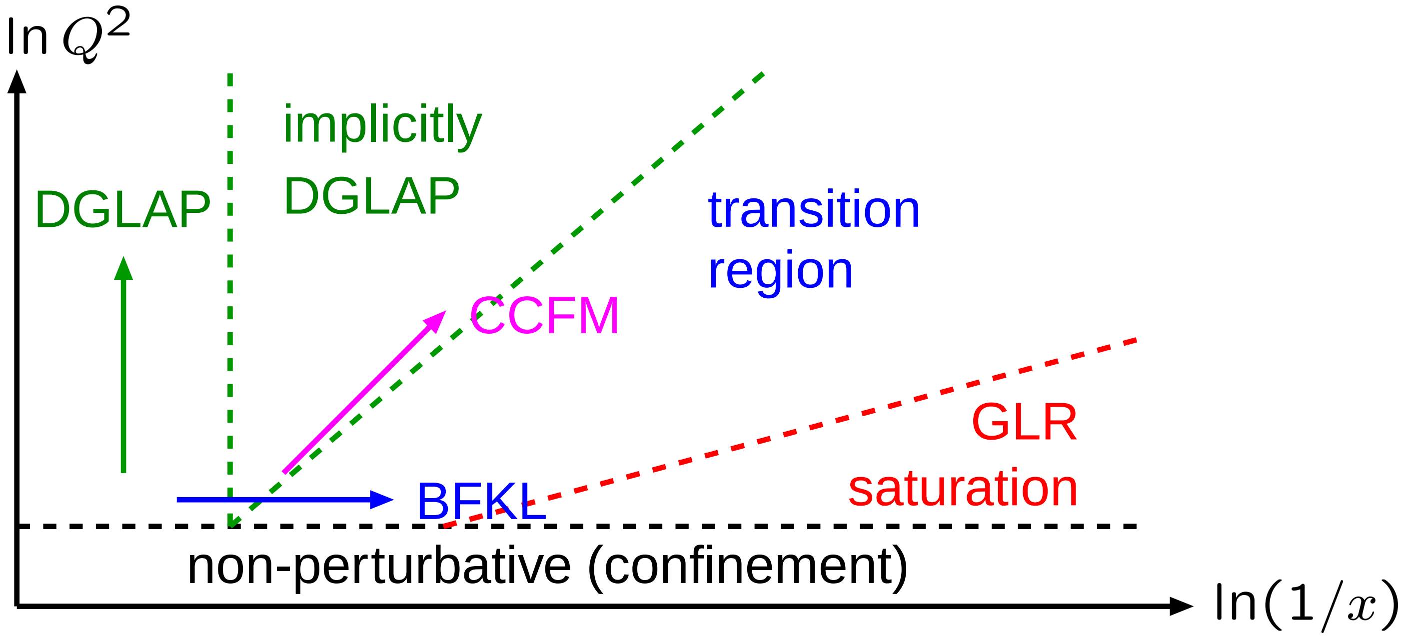
with $Q^2 = -m^2 =$ spacelike virtuality

- 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:

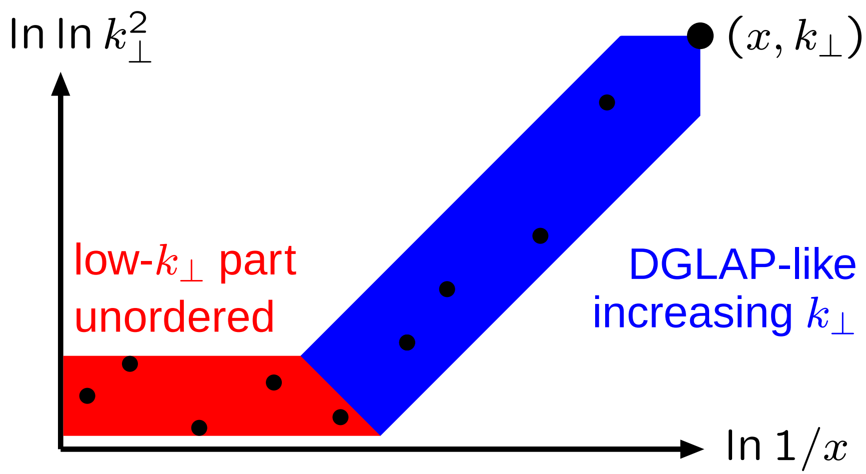
(SMALLX (Marchesini, Webber))

CASCADE (Jung, Salam)

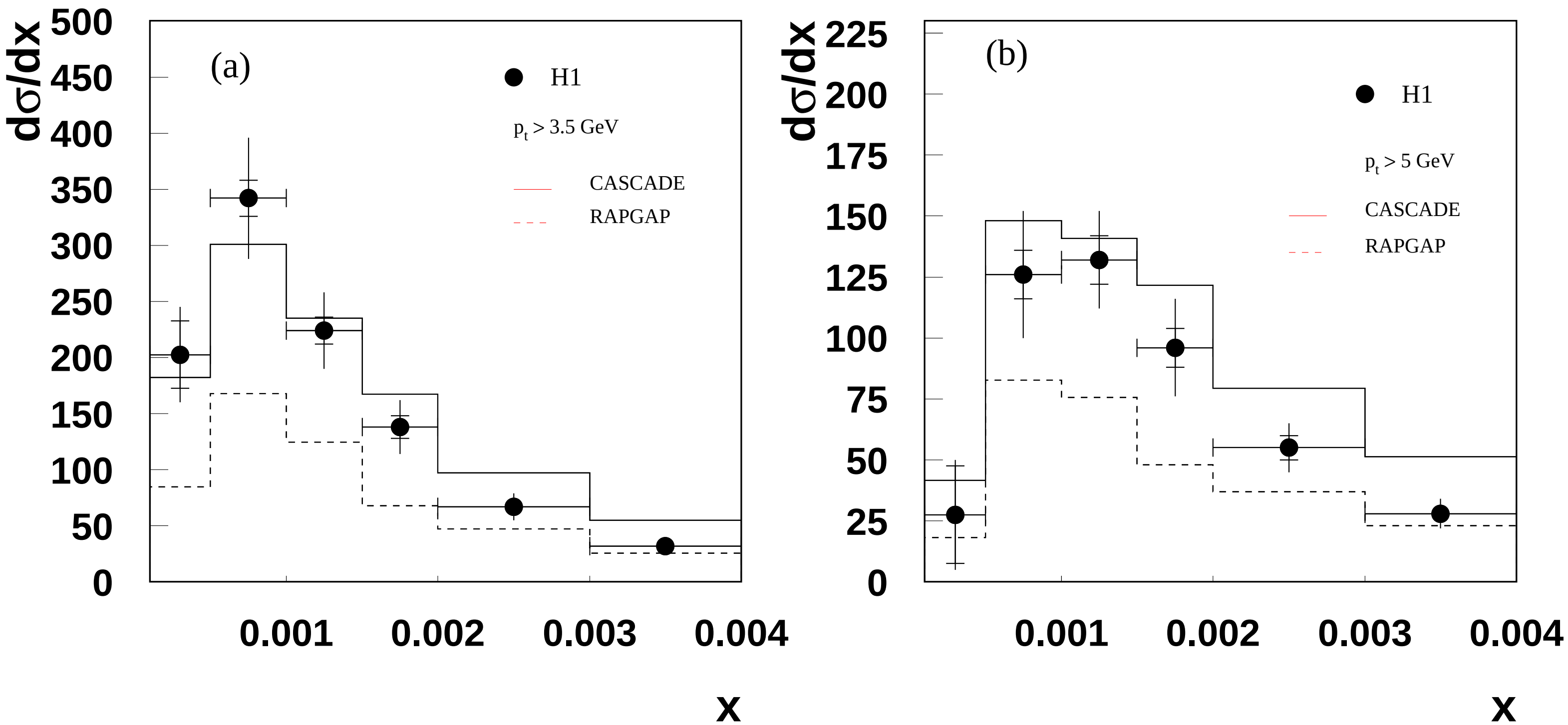
LDC (Gustafson, Lönnblad):

reformulated initial/final rad.

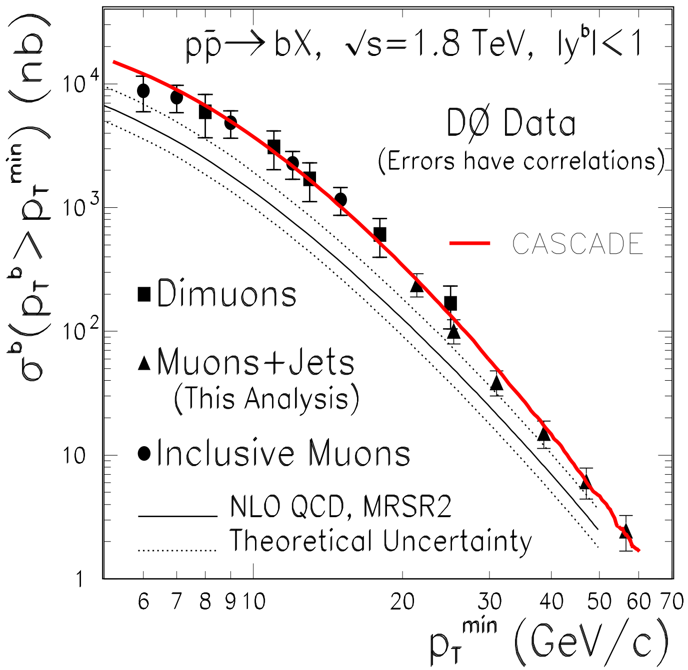
$\Longrightarrow$ eliminate non-Sudakov

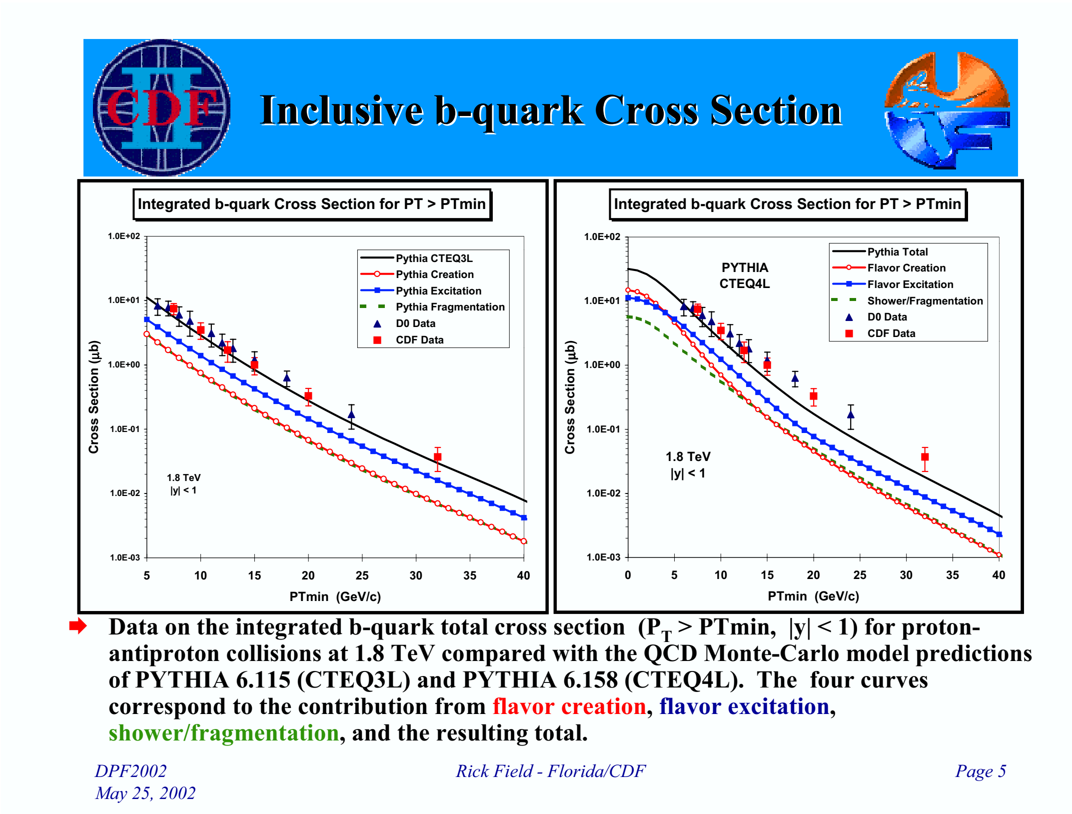


Test 1) forward (= p direction) jet activity at HERA



2) Heavy flavour production





but also explained by DGLAP with leading order pair creation
+ flavour excitation ($\approx$ 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

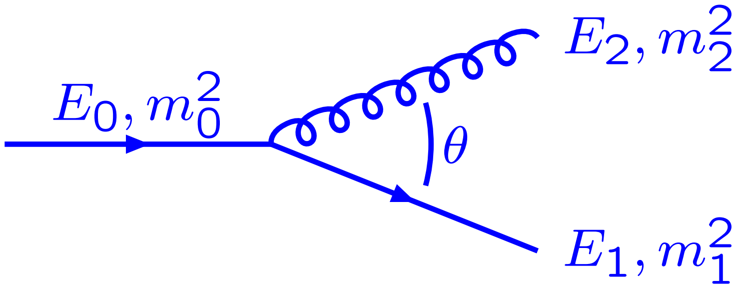
Initial- vs. final-state showers

Both controlled by same evolution equations

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

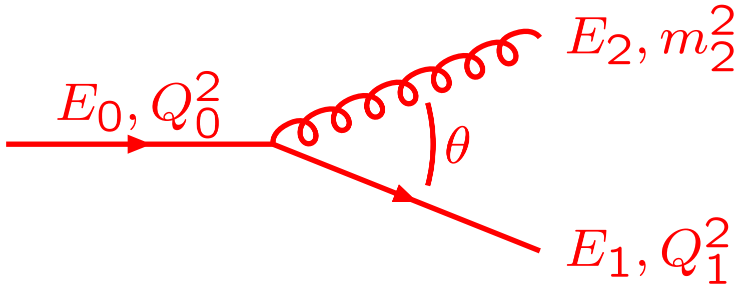
but

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 ($\approx -m^2$)

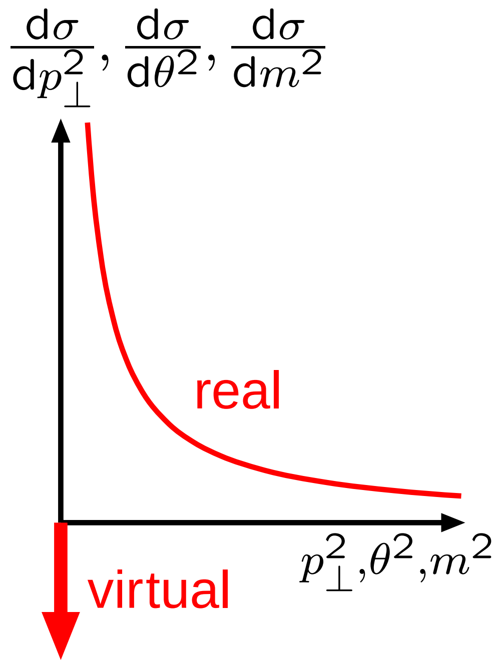


decreasing E, increasing Q^2, θ
one daughter $m^2 \geq 0$, one $m^2 < 0$
physics more complicated
$\Rightarrow$ more formalisms:
DGLAP, BFKL, CCFM, GLR, . . .

Matrix Elements vs. Parton Showers

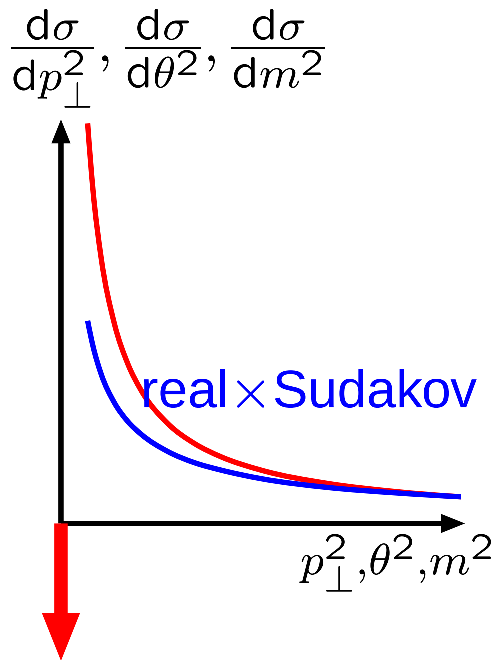
ME : Matrix Elements

- $+$ 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*



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

Merging

= cover full phase space with smooth transition ME/PS

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

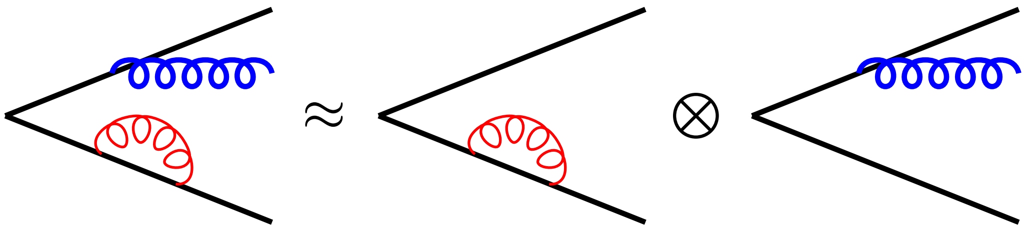
by shower generation + correction procedure

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

- 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 $\mathcal{O}(\alpha_{\mathrm{s}}^2)$ either way)



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

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

Final-State Shower Merging

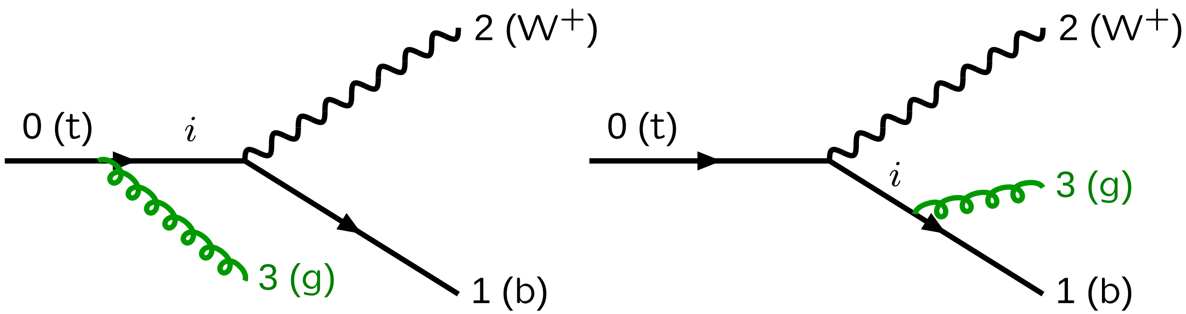
Merging with $\gamma^*/\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}\mathrm{g}$ for $m_{\mathrm{q}} = 0$ since long

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

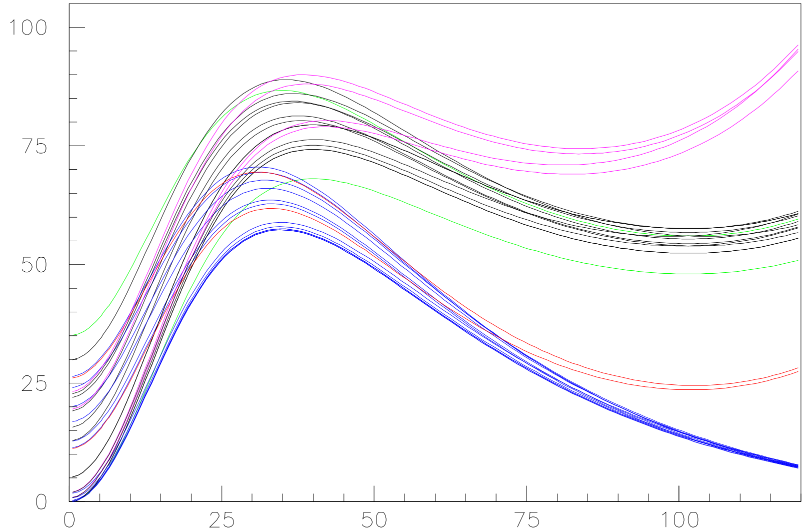
$\Rightarrow$ can merge PS with generic $a \to bc\mathrm{g}$ ME

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

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

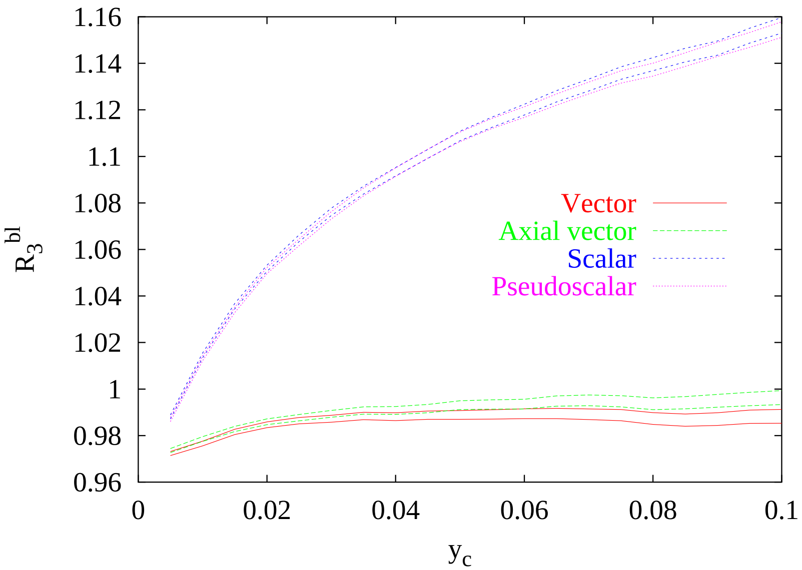
PYTHIA performs merging with generic FSR $a \to bc$g ME,
in SM: $\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm \to \mathrm{q\overline{q}}$, $\mathrm{t} \to \mathrm{bW}^+$, $\mathrm{H}^0 \to \mathrm{q\overline{q}}$,
and MSSM: $\mathrm{t} \to \mathrm{bH}^+$, $\mathrm{Z}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{W}^+$, $\mathrm{H}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{H}^+$,
$\chi \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\chi \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\chi$, $\mathrm{t} \to \tilde{\mathrm{t}}\chi$, $\tilde{\mathrm{g}} \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$, $\tilde{\mathrm{q}} \to \mathrm{q}\tilde{\mathrm{g}}$, $\mathrm{t} \to \tilde{\mathrm{t}}\tilde{\mathrm{g}}$

g emission for different colour, spin and parity:

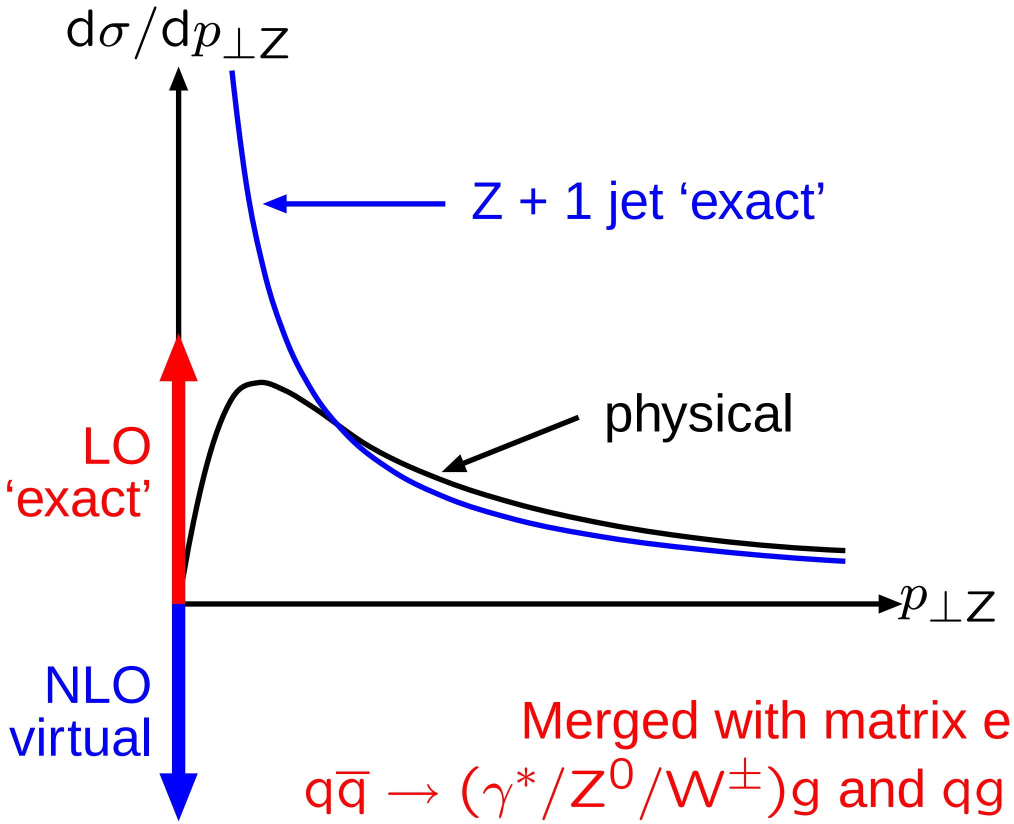


angle (degrees)

$R_3^{\mathrm{bl}}(y_c)$: 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
$q\bar{q} \to (\gamma^*/Z^0/W^{\pm})g$ and $qg \to (\gamma^*/Z^0/W^{\pm})q'$:
(G. Miu & TS, PLB449 (1999) 313)

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

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

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

Merging in HERWIG

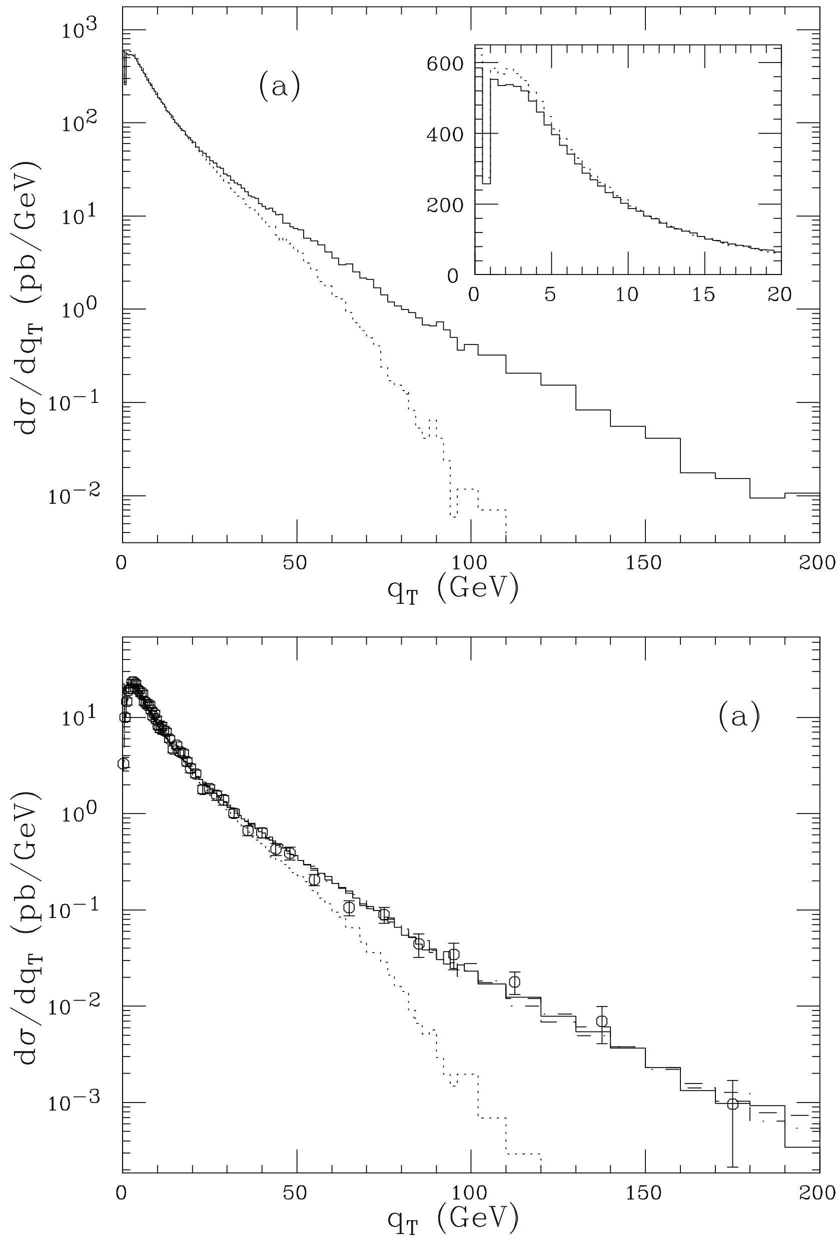
HERWIG also contains merging, for

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

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, in preparation

Generic method to combine ME's of several different orders to NLL accuracy; will be a 'standard tool' in the future

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:

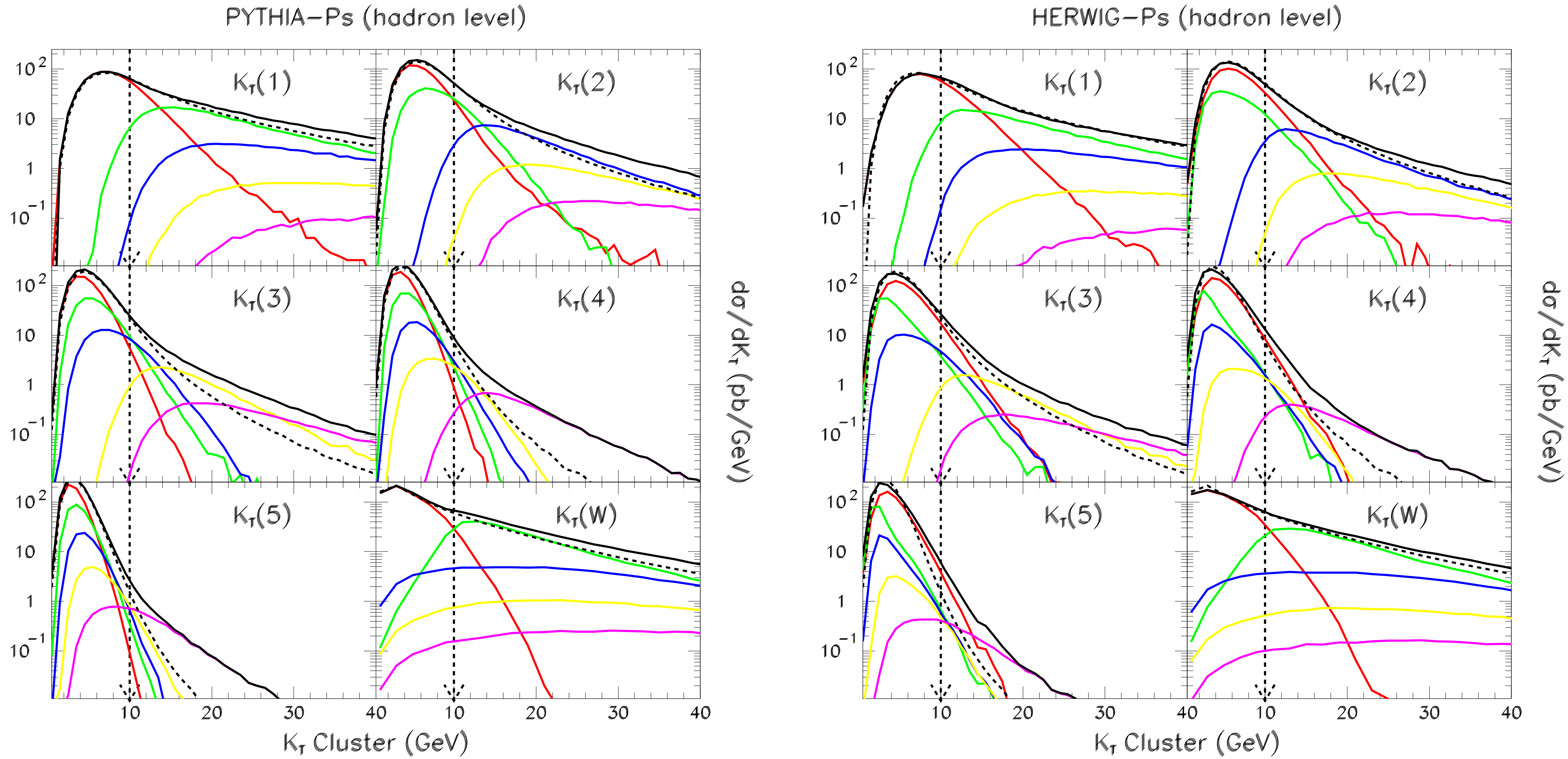
4) do parton showers

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

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



(S.Mrenna, P. Richardson)

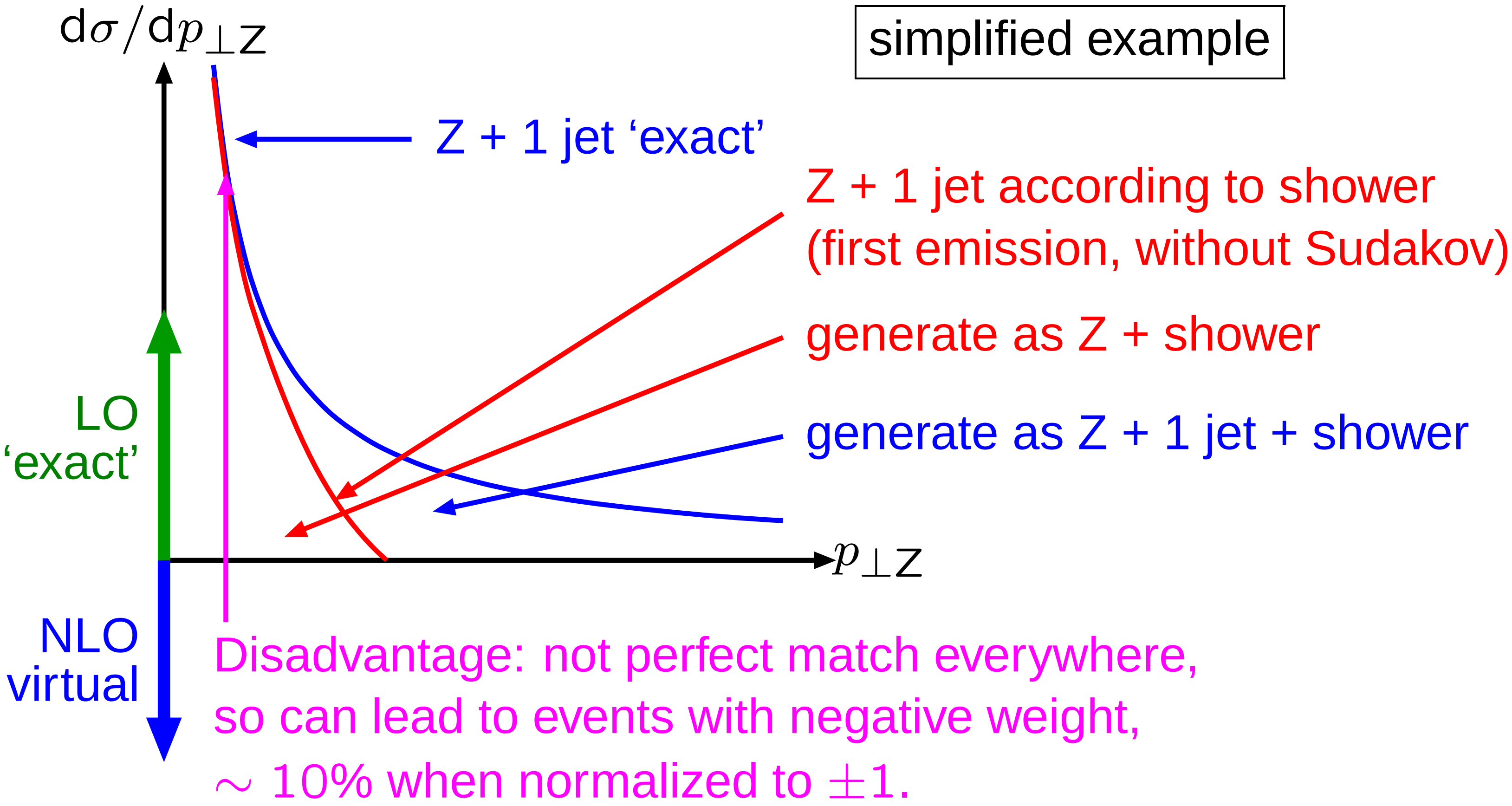
MC@NLO

Objectives:

- Total rate should be accurate to NLO.
- NLO results are obtained for all observables when (formally) expanded in powers of α_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 σ_NLO as n-body.
4) Add showers to both kinds of events.



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.

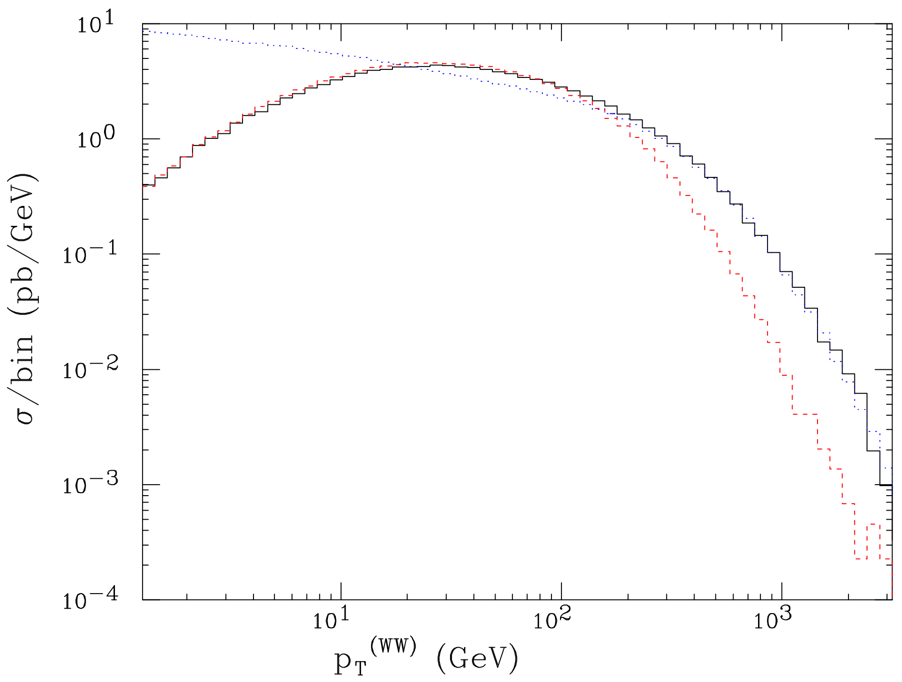
MC@NLO 2.31 [hep-ph/0402116]

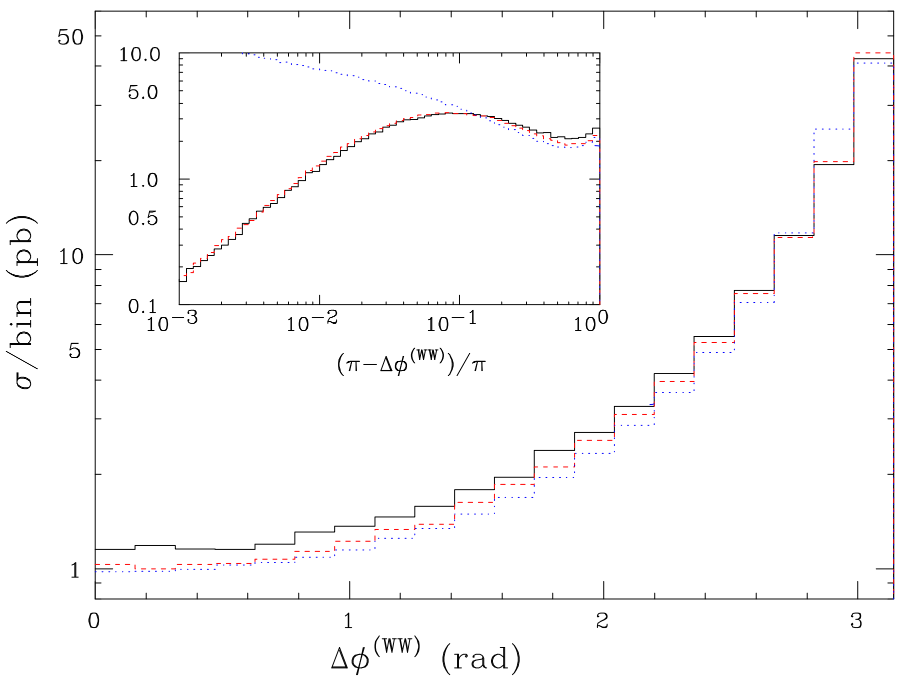
IPROC	Process
–1350–IL	$H_1H_2 \to (Z/\gamma^* \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
–1360–IL	$H_1H_2 \to (Z \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
–1370–IL	$H_1H_2 \to (\gamma^* \to)l_{\rm IL}\bar{l}_{\rm IL} + X$
–1460–IL	$H_1H_2 \to (W^+ \to)l^+_{\rm IL}\nu_{\rm IL} + X$
–1470–IL	$H_1H_2 \to (W^- \to)l^-_{\rm IL}\bar{\nu}_{\rm IL} + X$
–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	$H_1H_2 \to W^-Z^0 + X$

(Frixione, Webber)

- 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

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

PYTHIA shower improvements

Objective:
Incorporate several of the good points of the dipole formalism (like ARIADNE) within the shower approach ($\Rightarrow$ hybrid)

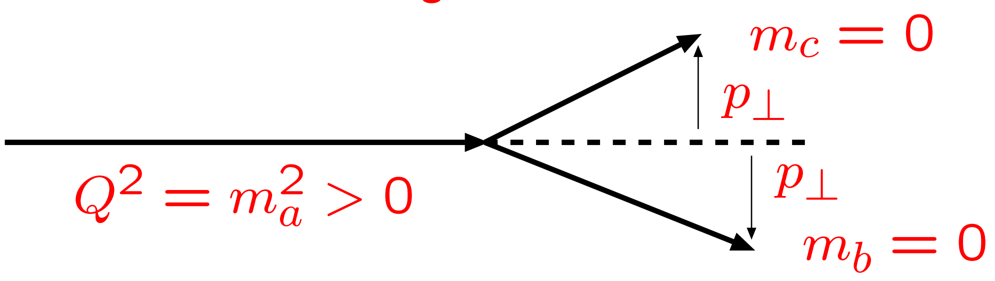
$\pm$ explore alternative $p_\perp$ definitions
$+$ $p_\perp$ ordering $\Rightarrow$ coherence inherent
$+$ ME merging works as before (unique $p_\perp^2 \leftrightarrow Q^2$ mapping; same z)
$+$ g $\to$ q$\overline{\text{q}}$ natural
$+$ kinematics constructed after each branching
(partons explicitly on-shell until they branch)
$+$ showers can be stopped and restarted at given $p_\perp$ scale
(not yet worked-out for ISR+FSR)
$+$ $\Rightarrow$ well suited for ME/PS matching (L-CKKW, real+fictitious showers)
$+$ $\Rightarrow$ well suited for simple match with $2 \to 2$ hard processes
$++$ well suited for *interleaved multiple interactions*

Simple kinematics

Consider branching $a \to bc$ in lightcone coordinates $p^\pm = E \pm p_z$

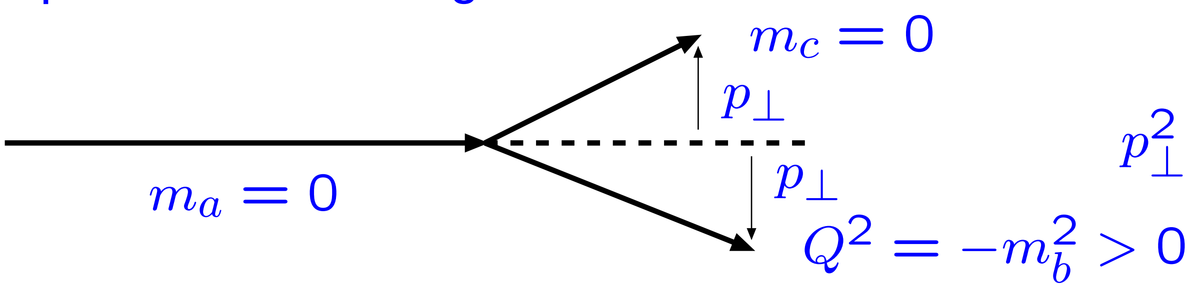
$$\left.\begin{array}{l} p_b^+ = z p_a^+ \\ p_c^+ = (1-z) p_a^+ \\ p^- \text{ conservation} \end{array}\right\} \Longrightarrow m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:



$$p_\perp^2 = z(1-z)Q^2$$

Spacelike branching:



$$p_\perp^2 = (1-z)Q^2$$

Guideline, not final $p_\perp$!

Transverse-momentum-ordered showers

1) *Define* $\mathrm{p}^2_{\perp\mathrm{evol}} = z(1-z)Q^2 = z(1-z)M^2$ for FSR
$\mathrm{p}^2_{\perp\mathrm{evol}} = (1-z)Q^2 = (1-z)(-M^2)$ for ISR

2) *Evolve* all partons *downwards* in $\mathrm{p}_{\perp\mathrm{evol}}$ from common $p_{\perp\mathrm{max}}$

$$\mathrm{d}\mathcal{P}_a = \frac{\mathrm{dp}^2_{\perp\mathrm{evol}}}{\mathrm{p}^2_{\perp\mathrm{evol}}} \frac{\alpha_{\mathrm{s}}(\mathrm{p}^2_{\perp\mathrm{evol}})}{2\pi} P_{a\to bc}(z)\,\mathrm{d}z\, \exp\left(-\int_{\mathrm{p}^2_{\perp\mathrm{evol}}}^{p^2_{\perp\mathrm{max}}} \cdots\right)$$

$$\mathrm{d}\mathcal{P}_b = \frac{\mathrm{dp}^2_{\perp\mathrm{evol}}}{\mathrm{p}^2_{\perp\mathrm{evol}}} \frac{\alpha_{\mathrm{s}}(\mathrm{p}^2_{\perp\mathrm{evol}})}{2\pi} \frac{x' f_a(x', \mathrm{p}^2_{\perp\mathrm{evol}})}{x f_b(x, \mathrm{p}^2_{\perp\mathrm{evol}})} P_{a\to bc}(z)\,\mathrm{d}z\, \exp\left(-\cdots\right)$$

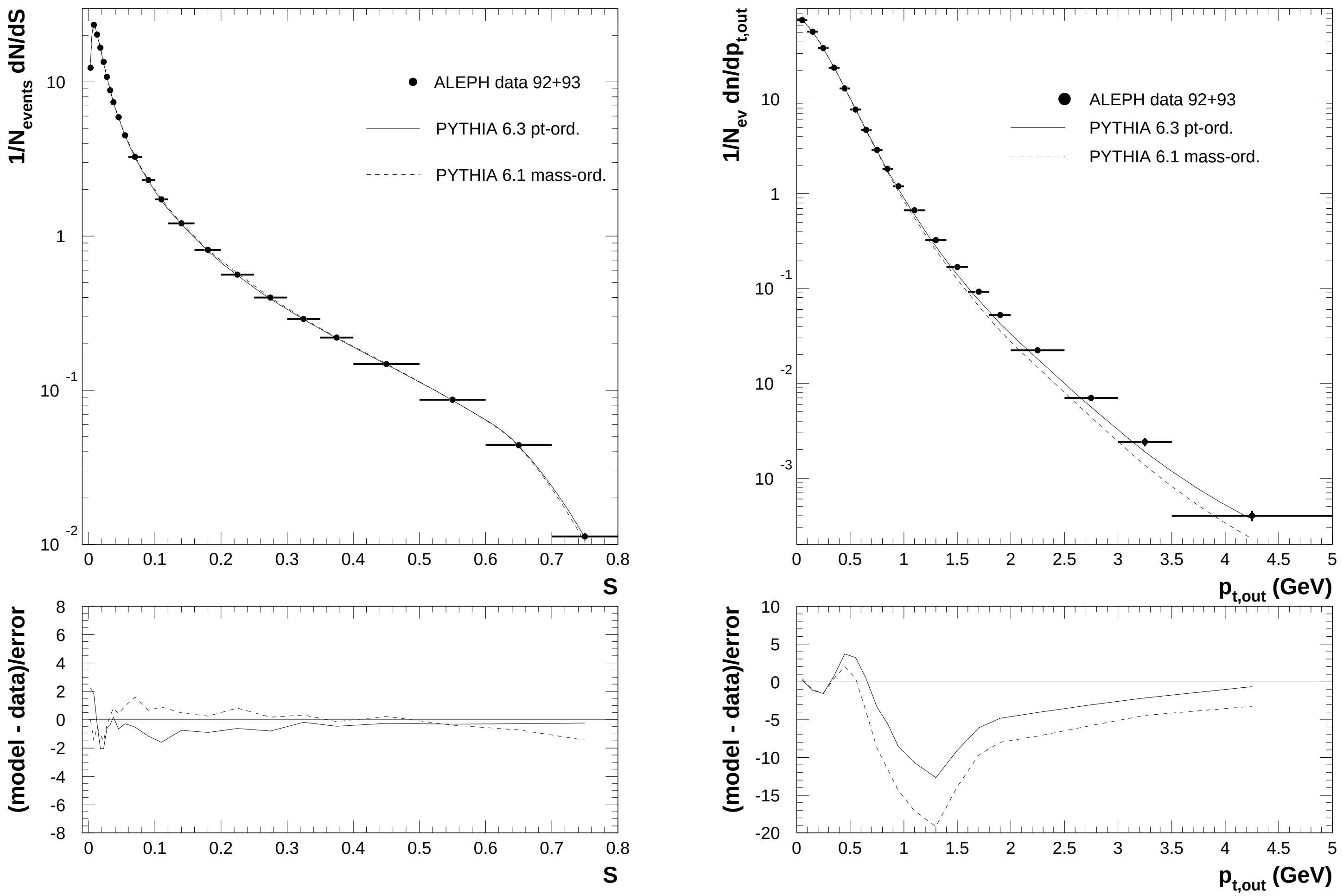
Pick the one with *largest* $\mathrm{p}_{\perp\mathrm{evol}}$ to undergo branching; also gives z.

3) Kinematics: *Derive* $Q^2 = \pm M^2$ by inversion of 1), but then interpret z as *energy fraction* (not lightcone) in "dipole" rest frame, so that *Lorentz invariant* and matched to matrix elements.
Assume yet unbranched partons on-shell and shuffle $(E, \mathbf{p})$ inside dipole.

4) *Iterate* $\Rightarrow$ combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$.

Testing the FSR algorithm

Tune performed by Gerald Rudolph (Innsbruck)
based on ALEPH 1992+93 data:



Quality of fit

Distribution of	nb.of interv.	$\sum \chi^2$ of model PY6.3 $p_\perp$-ord.	PY6.1 mass-ord.
Sphericity	23	25	16
Aplanarity	16	23	168
1$-$Thrust	21	60	8
Thrust$_{\text{minor}}$	18	26	139
jet res. y_3(D)	20	10	22
$x = 2p/E_{\text{cm}}$	46	207	151
$p_{\perp\text{in}}$	25	99	170
$p_{\perp\text{out}} < 0.7$ GeV	7	29	24
$p_{\perp\text{out}}$	(19)	(590)	(1560)
x(B)	19	20	68
sum $N_{\text{dof}} =$	190	497	765

Generator is not assumed to be perfect, so

add fraction p of value in quadrature to the definition of the error:

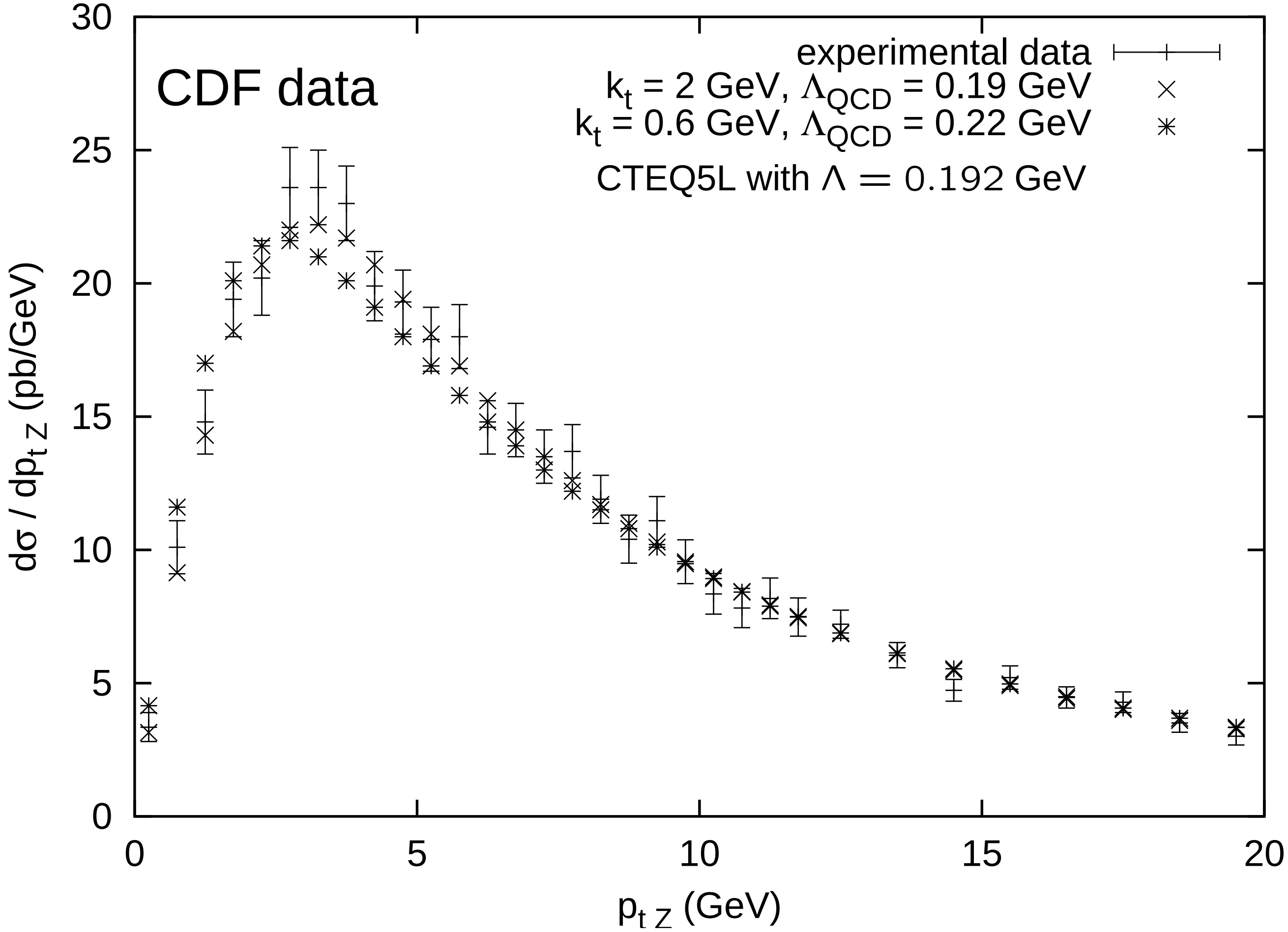
p	0%	0.5%	1%
$\sum \chi^2$	523	364	234

for $N_{\text{dof}} = 196 \Rightarrow$ generator is 'correct' to $\sim$1%

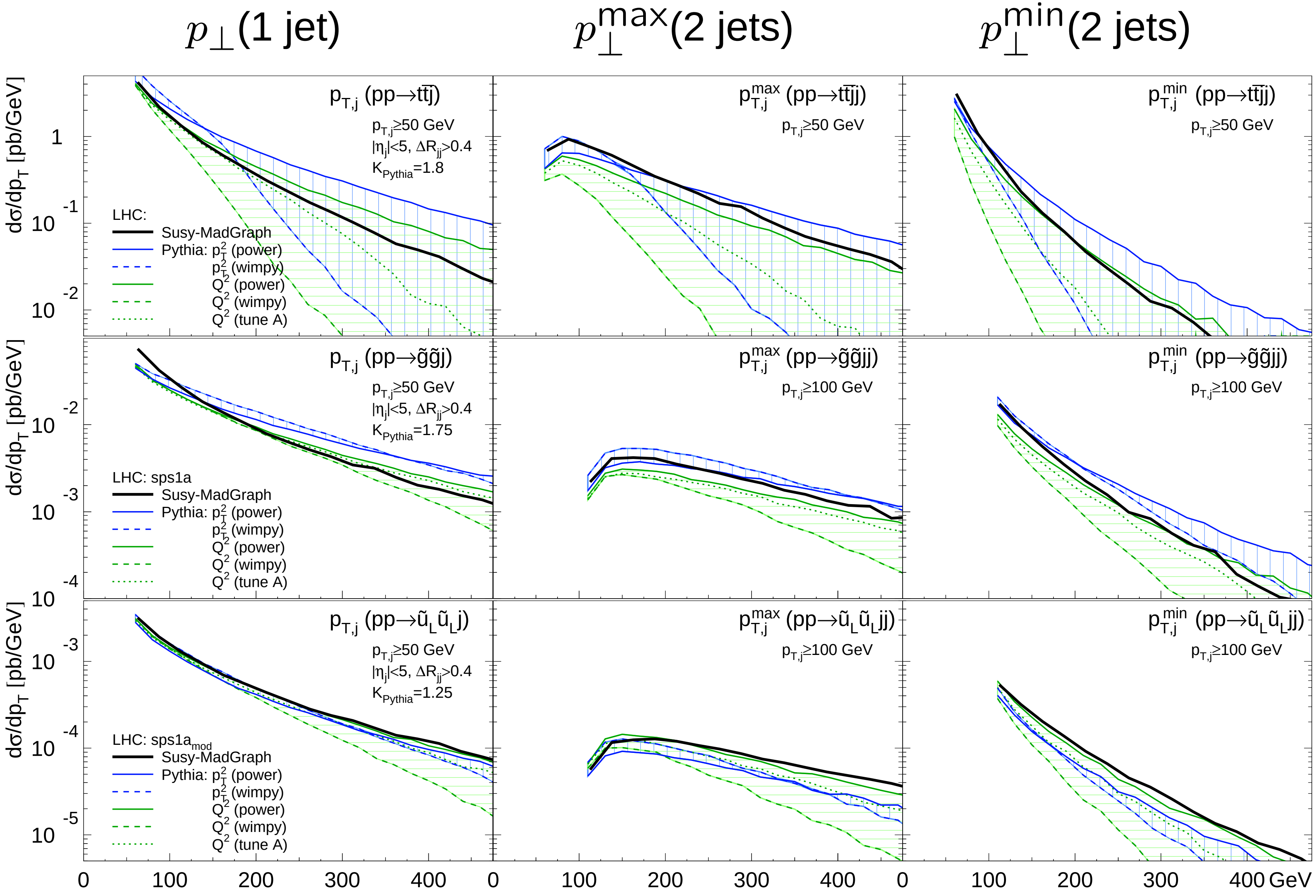
except $p_{\perp\text{out}} > 0.7$ GeV (10%–20% error)

Testing the ISR algorithm

Still only begun. . .



. . . but so far no showstoppers



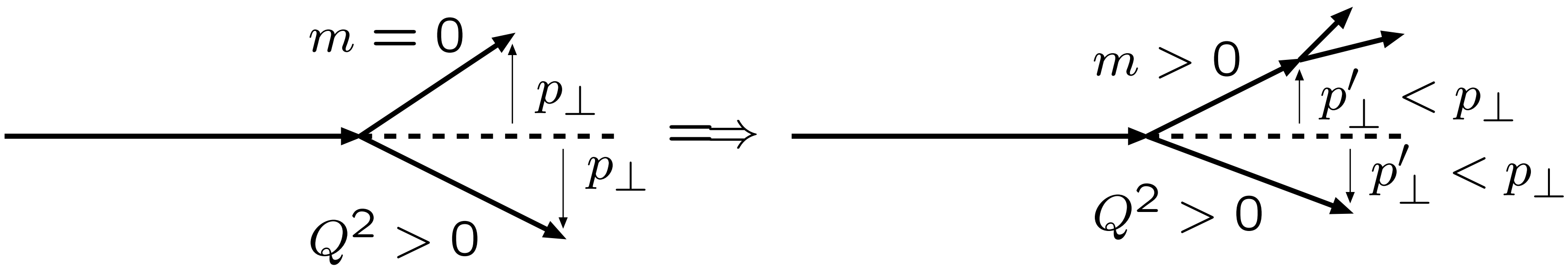
power: $Q^2_{\mathrm{max}} = s$; wimpy: $Q^2_{\mathrm{max}} = m_\perp^2$; tune A: $Q^2_{\mathrm{max}} = 4m_\perp^2$

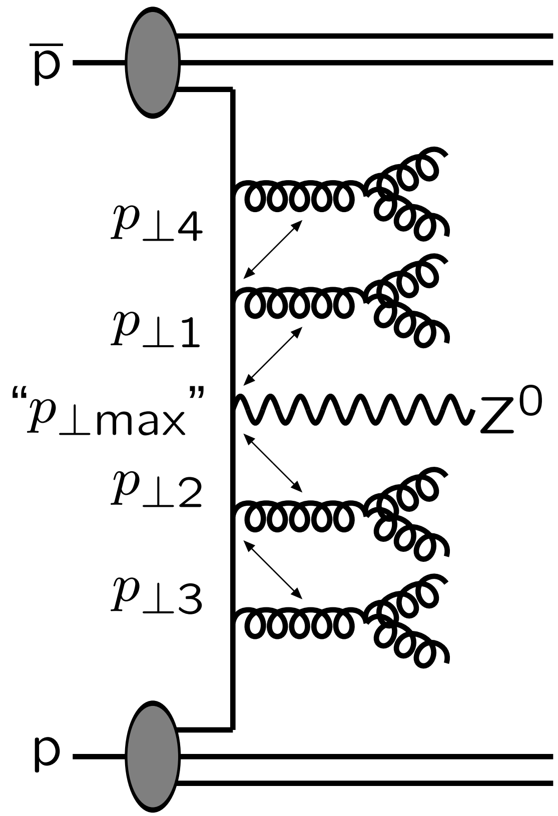
$m_{\mathrm{t}} = 175$ GeV, $m_{\tilde{\mathrm{g}}} = 608$ GeV, $m_{\tilde{\mathrm{u}}_L} = 567$ GeV

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

Combining FSR with ISR

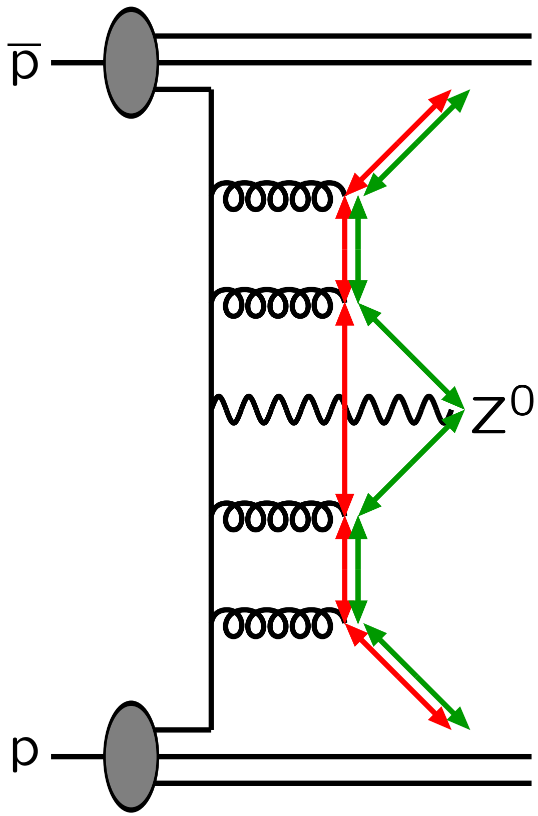
Evolution of timelike sidebranch cascades can reduce $p_\perp$:





Old:

Z^0 takes recoil



New:

Z^0 takes recoil

or

Z^0 unaffected by FSR (latter later)

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, NLL, small-x, $k_\perp$ factorization, BFKL/CCFM, ... $\star$

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

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