The Physics of Herwig++

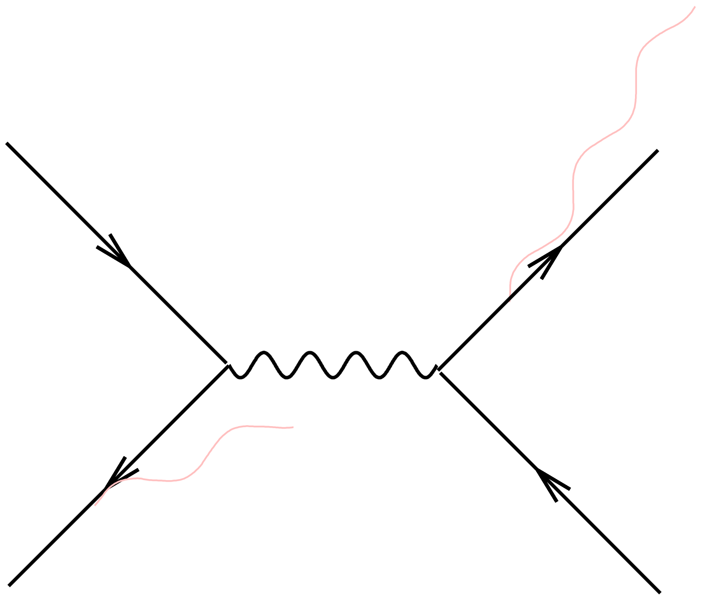
Stefan Gieseke

University of Cambridge
Cavendish Laboratory

work with A Ribon, MH Seymour, P Stephens, BR Webber (Cambridge, Manchester, CERN)

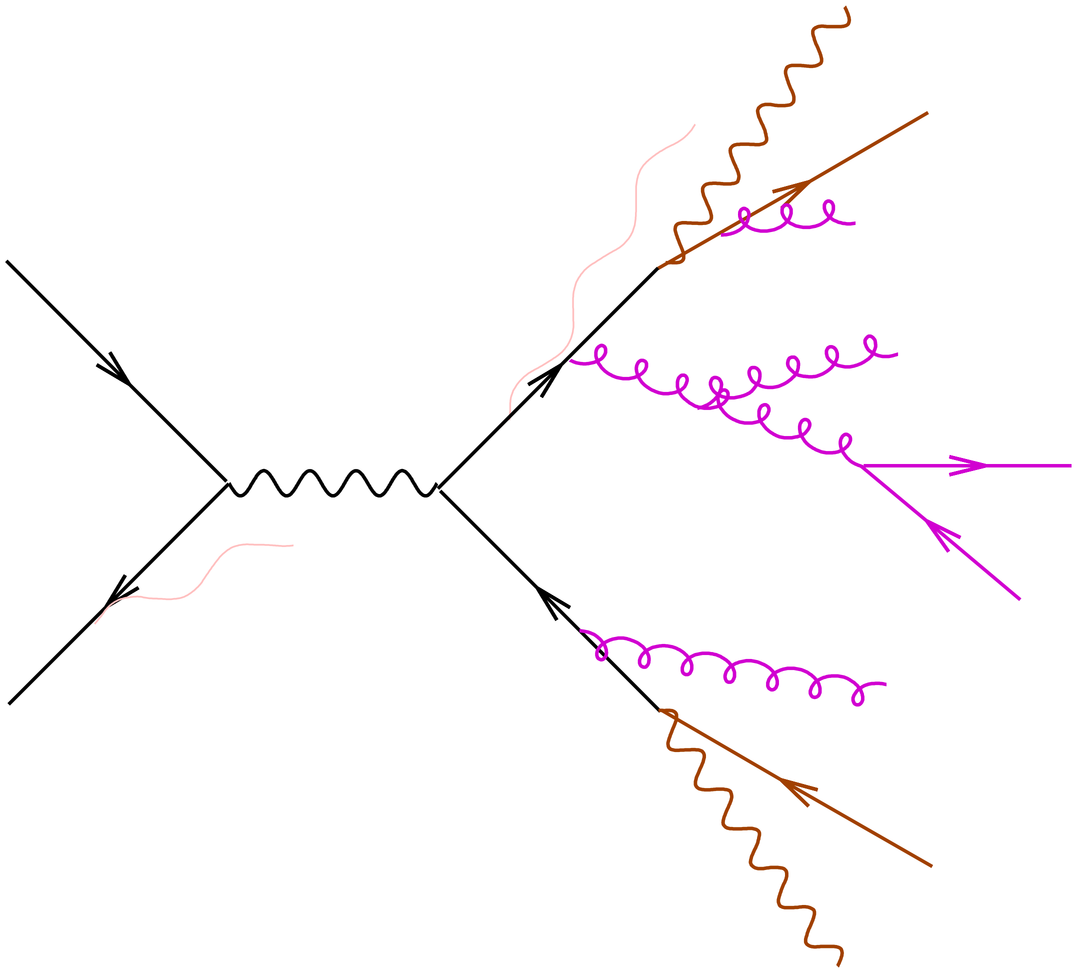
- Introduction
- Tour of Herwig++
- Outlook

e^+e^- Event Generator



- hard scattering
- (QED) initial/final state radiation

e^+e^- Event Generator



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- parton shower evolution

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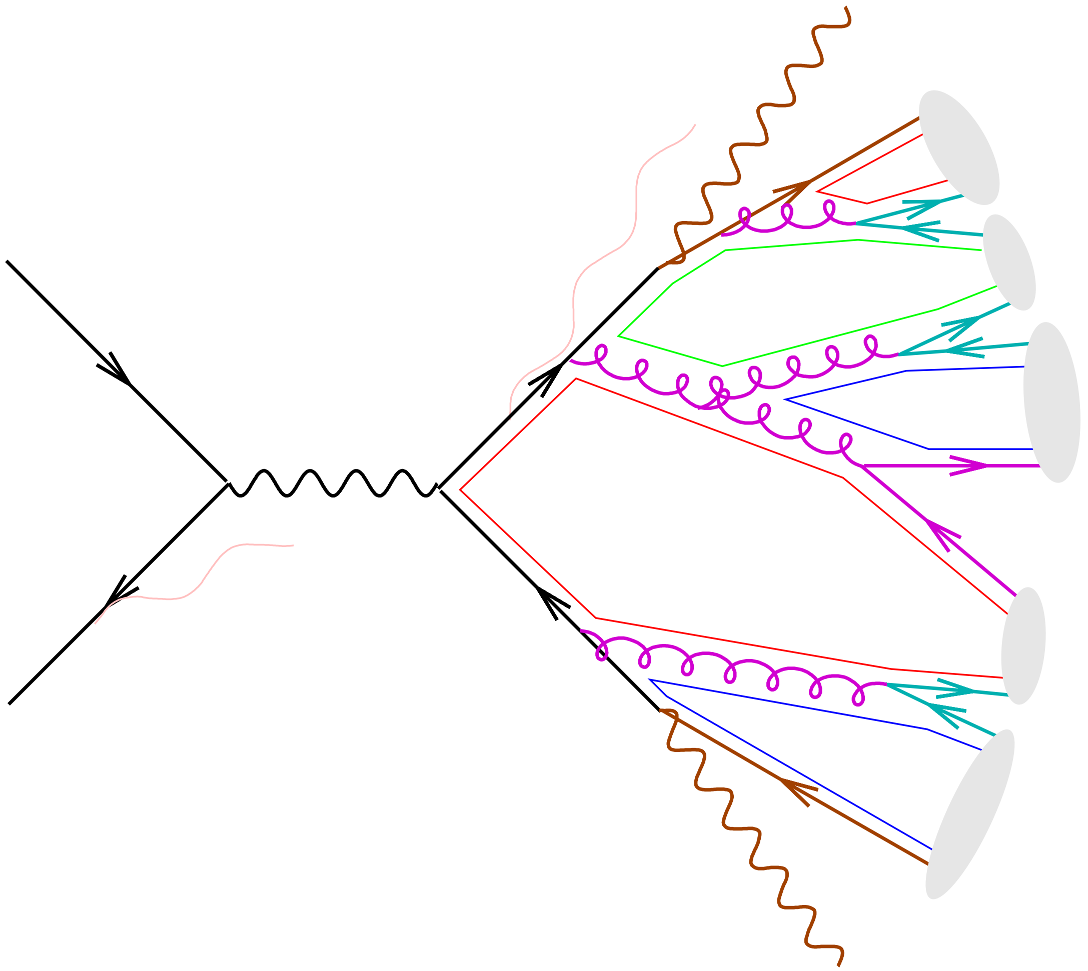

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- nonperturbative gluon splitting
- colour singlets
- colourless clusters

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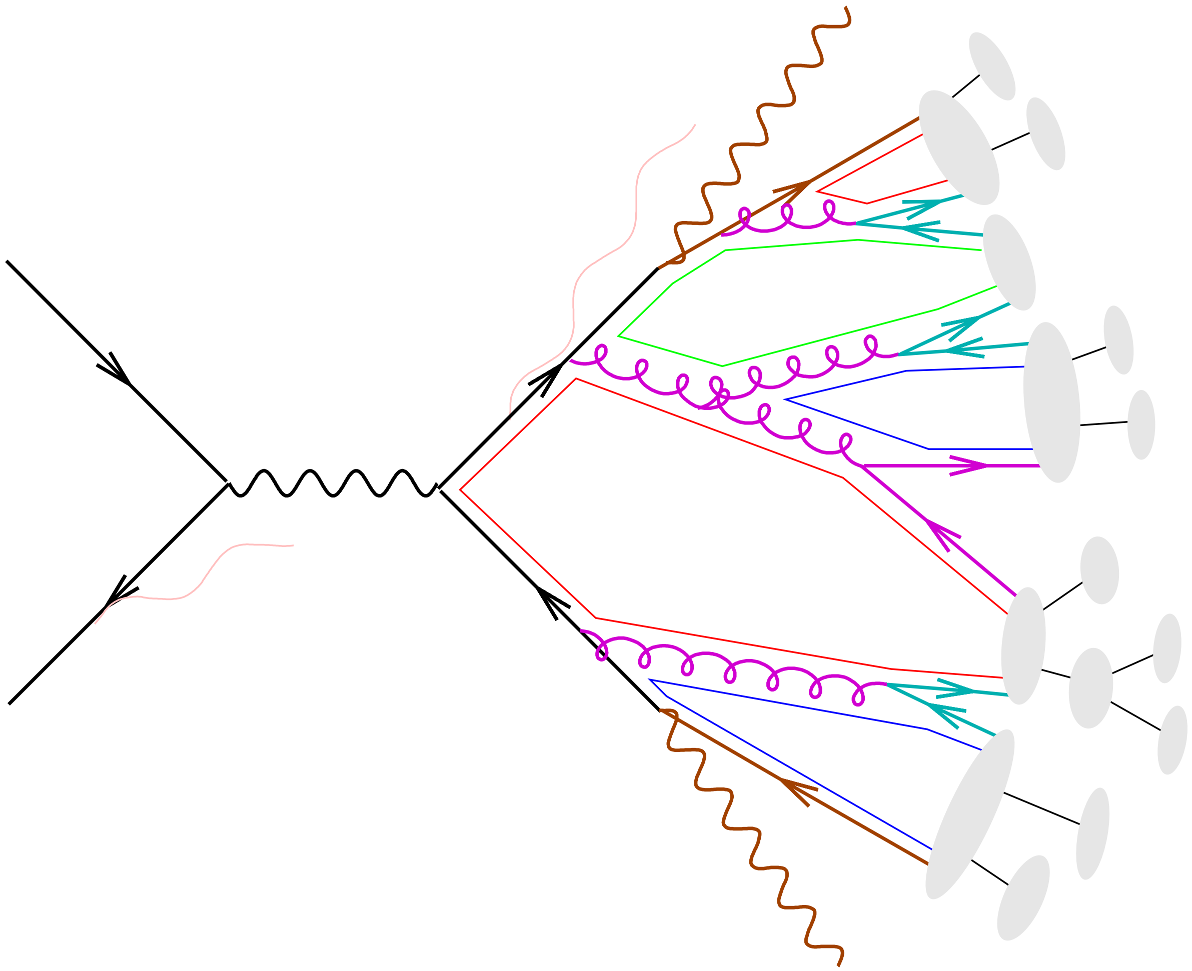

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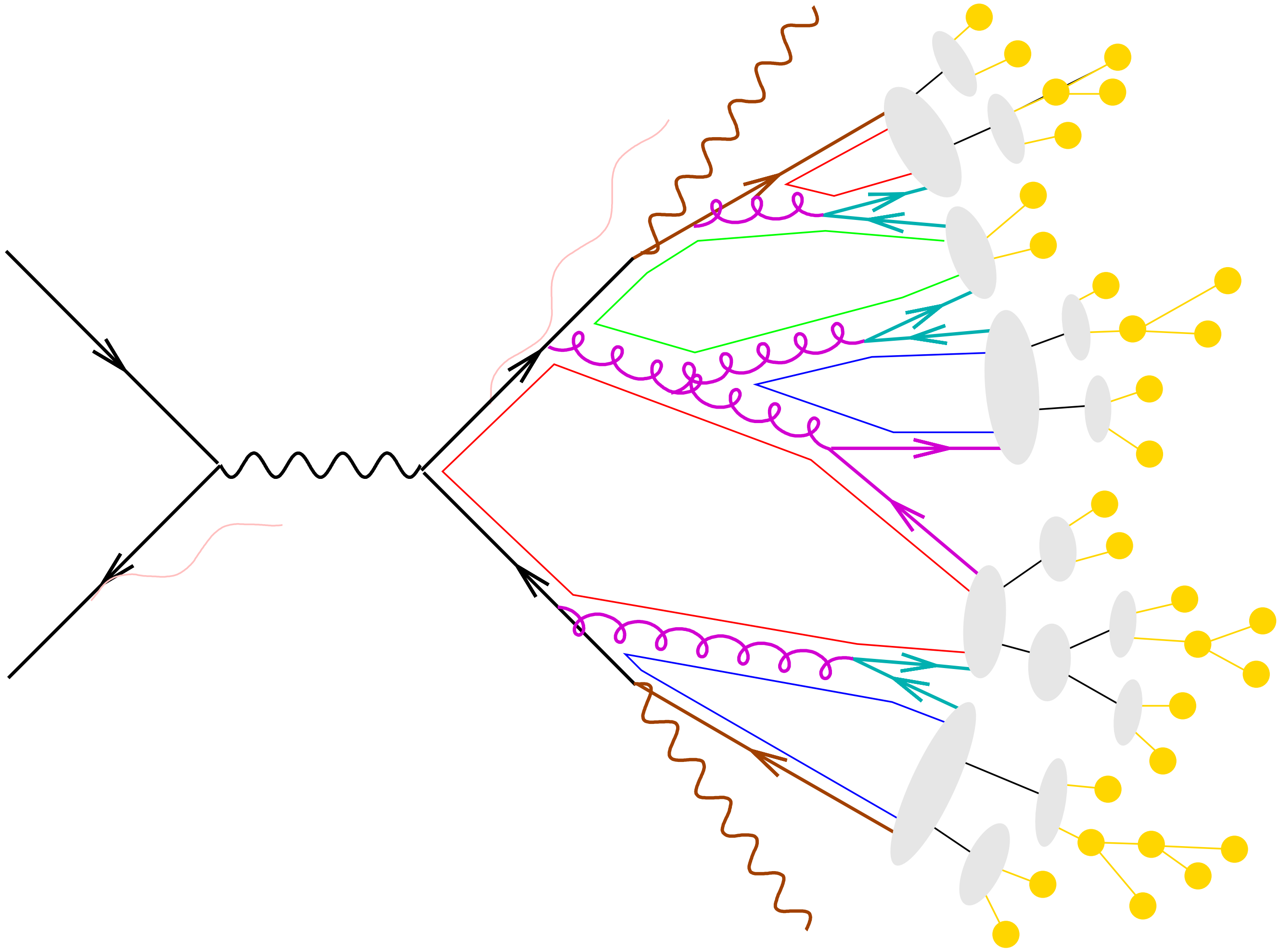

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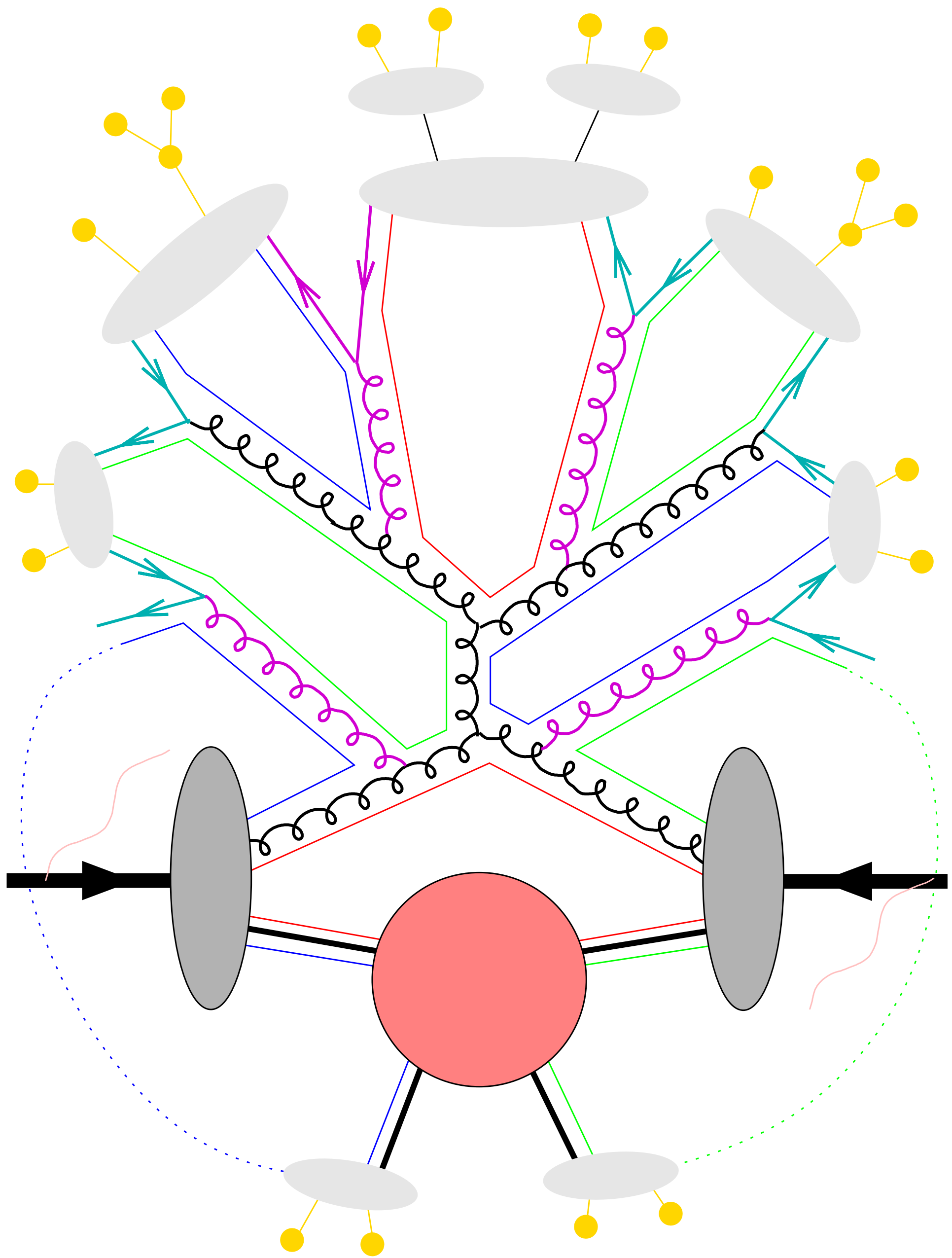
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays

Additional Complications in pp

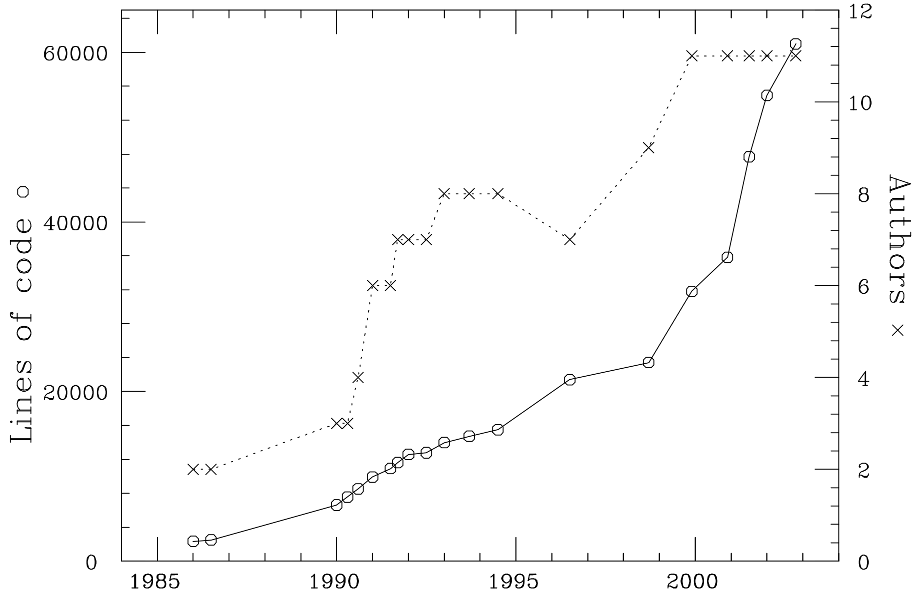


+ backward parton evolution
+ soft underlying event

The new generator Herwig++

Complete rewrite of `HERWIG` *in C++*

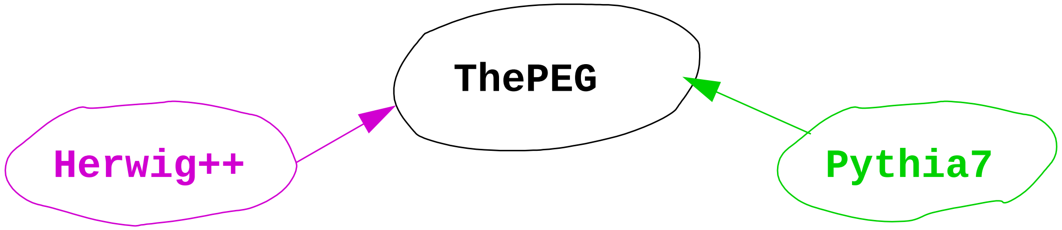
- aiming at full multi–purpose generator for LHC and future colliders.
- Preserve main features of `HERWIG` such as
  - angular ordered parton shower
  - Cluster Hadronization
- New features and improvements
  - correct parton shower evolution for heavy quarks
  - consistent radiation from unstable particles



`HERWIG`'s growth. . .

Use of ThePEG in Herwig++

ThePEG = Toolkit for high energy Physics Event Generation



Won't re-invent the wheel

Share administrative overhead, common to event generators with Pythia7

Independent *physics* implementation

Large but very flexible implementation

Common basis for Pythia7/Herwig++:

- ✗ Lack of independence.
- ✗ Miss the possiblity to test codes against each other.
- ✓ Physics, however, is still independent.
- ✓ Beneficial for the user to have the same framework.
- ✓ Running Herwig++ with the Lund String Fragmentation from Pythia7 is very simple!

Hard interactions

- Basic ME's included in ThePEG, such as:

$$e^+e^- \to q\bar{q}, \text{ partonic } 2 \to 2,$$

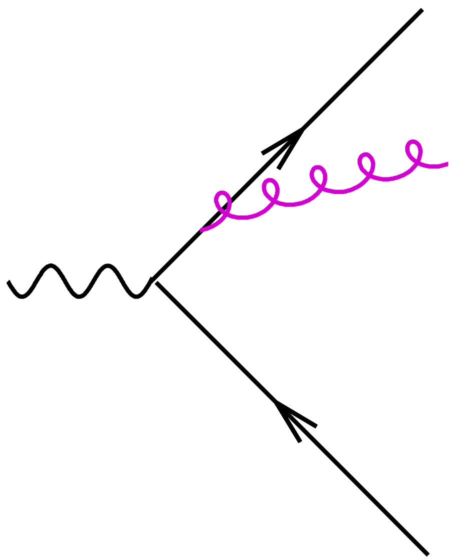
  we use them.
- Will check them/provide our own extended set.
- AMEGIC++ will provide arbitrary ME's for multiparton final states via AMEGICInterface.
- ME corrections as a simple option.
- CKKW ME+PS foreseen.
- Other authors can easily include their own matrix elements ($\to$ *safety* of OO code)

Collinear Enhancement

ME for $e^+e^- \to q\bar{q}g$ strongly enhanced whenever emitted gluon is collinear to one of the quarks. Propagator factor

$$\frac{1}{(p_q + p_g)^2} \approx \frac{1}{2E_qE_g(1 - \cos\theta_{qg})}$$

- soft+collinear divergences.
- dominant contribution to the ME.
- still strong enhancement for massive particles.



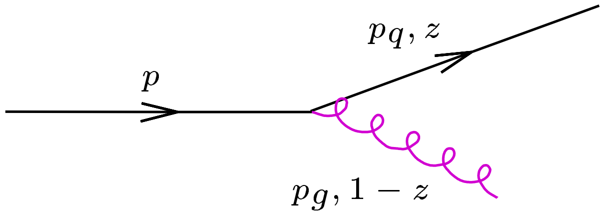
Collinear factorization

$$|M_{p+1}|^2 d\Phi_{p+1} \approx |M_p|^2 d\Phi_p \frac{dt}{t}\frac{C\alpha_s}{2\pi}P(z)dz$$

$\longrightarrow$ Parton shower MC.

Parton shower resums leading logarithmic contributions.

Quasi–Collinear Limit (Heavy Quarks)



Sudakov-basis p, n with $p^2 = M^2$ ('forward'), $n^2 = 0$ ('backward'),

$$\begin{aligned} p_q &= zp + \beta_q n - q_\perp \\ p_g &= (1-z)p + \beta_g n + q_\perp \end{aligned}$$

Collinear limit for radiation off heavy quark,

$$\begin{aligned} P_{gq}(z, \boldsymbol{q}^2, m^2) &= C_F \left[\frac{1+z^2}{1-z} - \frac{2z(1-z)m^2}{\boldsymbol{q}^2 + (1-z)^2 m^2} \right] \\ &= \frac{C_F}{1-z} \left[1 + z^2 - \frac{2m^2}{z\tilde{q}^2} \right] \end{aligned}$$

$\longrightarrow$ $\tilde{q}^2 \sim \boldsymbol{q}^2$ may be used as evolution variable.

New evolution variables

Kinematics to allow better treatment of heavy particles, avoiding overlapping regions in phase space, in particular for soft emissions

We choose $\tilde{q}^2$ as new evolution variable,

$$\tilde{q}^2 = \frac{\boldsymbol{q}^2}{z^2(1-z)^2} + \frac{m^2}{z^2} \quad \text{for} \quad q \to qg$$

and with the argument of running α_S chosen according to

$$\alpha_S(z^2(1-z)^2\tilde{q}^2)$$

angular ordering

$$\tilde{q}_{i+1} < z_i \tilde{q}_i \qquad \tilde{k}_{i+1} < (1-z_i)\tilde{q}_i$$

Technically: *reinterpretation* of known evolution variables, i.e. the branching probability for $a \to bc$ still is

$$dP(a \to bc) = \frac{d\tilde{q}^2}{\tilde{q}^2}\frac{C_i \alpha_S}{2\pi} P_{bc}(z, \tilde{q})\, dz$$

$\longrightarrow$ Sudakov's etc. technically remain the same!

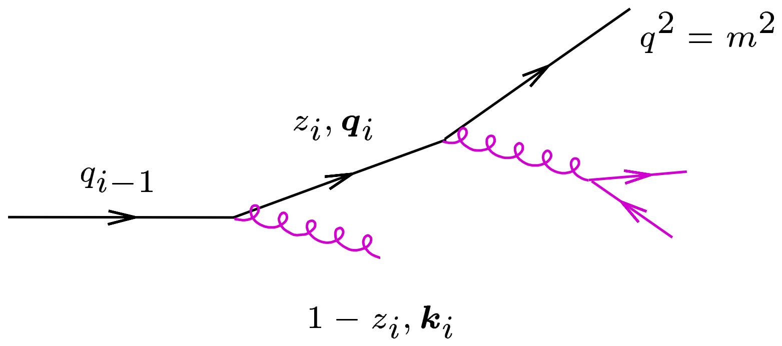
Kinematics

Sudakov basis p, n with $p^2 = m^2$, $n^2 = 0$,

$$q_i = \alpha_i p + \beta_i n + \boldsymbol{q}_i$$

Longitudinal splitting

$$\alpha_i = z_i \alpha_{i-1}$$



transverse momenta reconstructed from $\boldsymbol{p}_i$,

$$\boldsymbol{q}_i = \boldsymbol{p}_i + z_i \boldsymbol{q}_{i-1} \qquad \boldsymbol{k}_i = -\boldsymbol{p}_i + (1 - z_i)\boldsymbol{q}_{i-1}$$

Azimuthal angle φ still chosen randomly or as a result of *azimuthal spin correlations* (planned) β_i from virtuality q_i

$$\beta_i = \frac{\boldsymbol{q}_i^2 + q_i^2 - \alpha_i^2 m^2}{2p \cdot n \alpha_i}$$

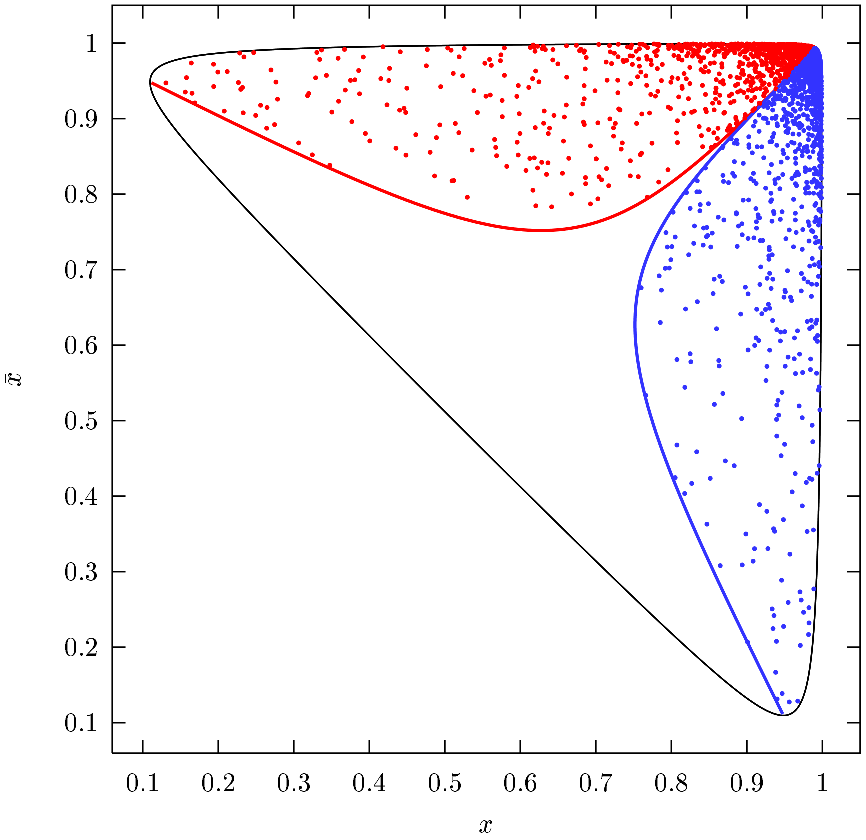
with recursive reconstruction of virtualities from

$$q_{i-1}^2 = \frac{q_i^2}{z_i} + \frac{k_i^2}{1 - z_i} + \frac{\boldsymbol{p}_i^2}{z_i(1 - z_i)}$$

Phase Space Coverage

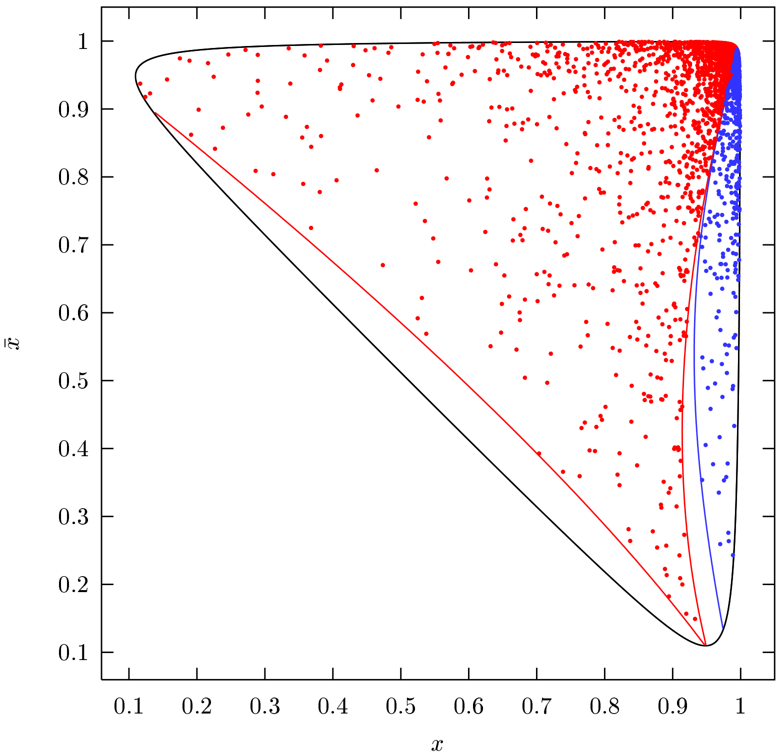
Consider $e^+e^- \to q\bar{q}g$ phase space (here: $b\bar{b}$ at LEP)
Only one gluon emitted, dots from Herwig++ parton shower with new variables.

- smooth coverage of the soft region is achieved by choosing appropriate initial conditions for the parton shower
- soft ME correction can be applied without double counting

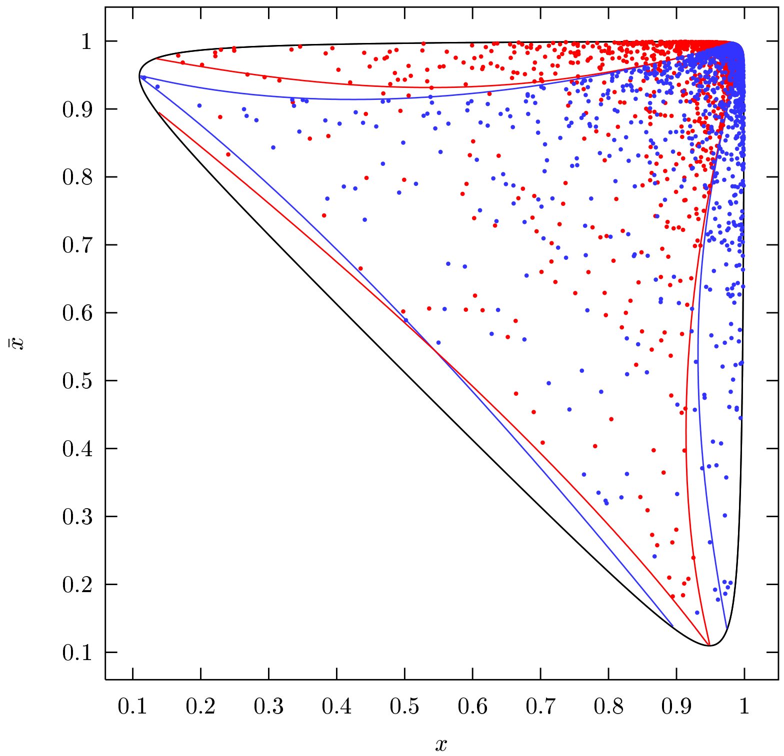


More Phase Space Coverage

Choose most asymmetric initial conditions. . .



. . . and symmetrize the phase space randomly



Branching Probability

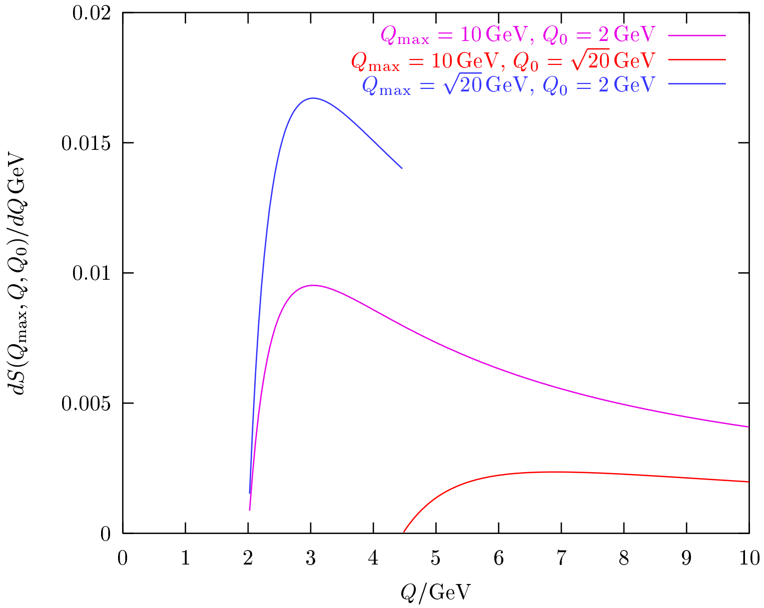
(timelike) Sudakov Form Factor: parton i at scale t_1 remains unresolved down to t when a minimum scale of t_0 is being resolved:

$$S_i(t, t_1; t_0) = \frac{\Delta_i(t_0, t)}{\Delta_i(t_0, t_1)}$$

with

$$\log \Delta_i(t_a, t_b) = -\int_{t_a}^{t_b} \frac{dt}{t} \sum_j \int_{z_0(t)}^{z_1(t)} dz \frac{\alpha_s(z, t)}{4\pi} P_{ji}(z, t)$$

$$\Rightarrow P(\text{“next branching at } t\text{”}) = \frac{dS(t, t_1; t_0)}{dt}$$



Sampled with 'veto algorithm' $\longrightarrow$ generates pair $(\tilde{q}, z)$ for the next branching.

Parton Shower Phase–Space

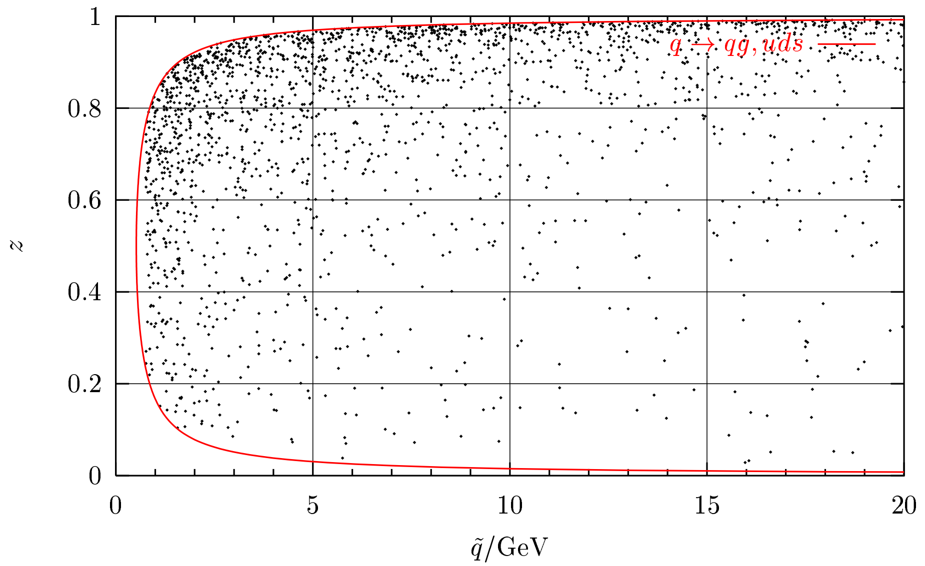
Introduce a kinematical cutoff Q_g in order to avoid the soft gluon singularity (usually $z \to 1$).

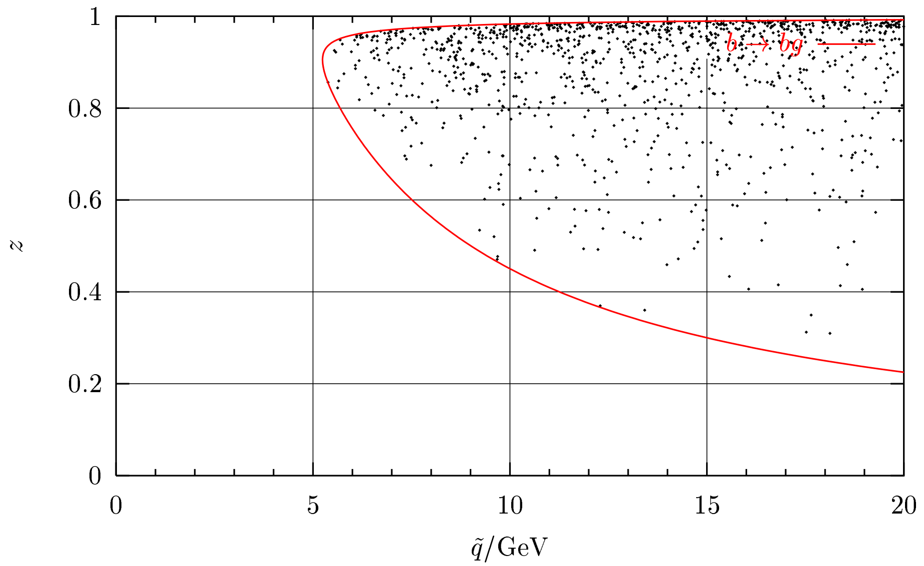
Reconstruct transverse momentum $\boldsymbol{q}$ from our *definition* of $\tilde{q}$ for $q \to qg$ splitting,

$$z(1-z)\tilde{q}^2 = \frac{\boldsymbol{q}^2}{z(1-z)} + \frac{Q_g^2}{1-z} + \frac{1-z}{z}m^2$$

Allowed phase space, where $\boldsymbol{q}$ real. For large $\tilde{q}$

$$\frac{m}{\tilde{q}} < z < 1 - \frac{Q_g}{\tilde{q}}.$$





Parton Shower Phase–Space (ctd')

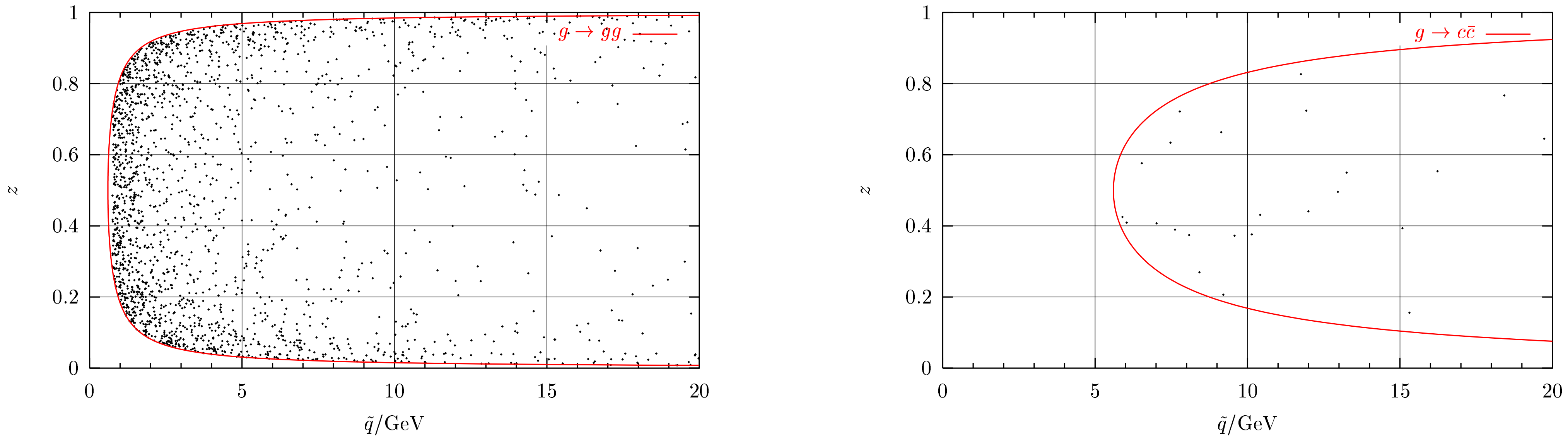
definition of $\tilde{q}$ for $g \to q\bar{q}, g \to gg$ splitting (also motivated by collinear limits),

$$\tilde{q}^2 = \frac{\boldsymbol{q}^2 + \mu^2}{z^2(1-z)^2},$$

where $\mu = m_q, Q_g$ for $g \to q\bar{q}, g \to gg$, respectively. Again, allowed phase space, where $\boldsymbol{q}$ real, now explicitly

$$\frac{1}{2}\left(1 - \sqrt{1 - \frac{4m}{\tilde{q}}}\right) < z < \frac{1}{2}\left(1 + \sqrt{1 - \frac{4m}{\tilde{q}}}\right),$$

hence, $\tilde{q} > 4\mu$.



Parton Shower Cutoffs

We supersede small quark masses with previously introduced Q_g, i.e. we use a kinematical cutoff

$$Q_0 = \max(m_q, Q_g)$$

rather than quark masses.

Furthermore we impose an overall cutoff

$$\tilde{q} > \max(Q_0, Q_{\min})$$

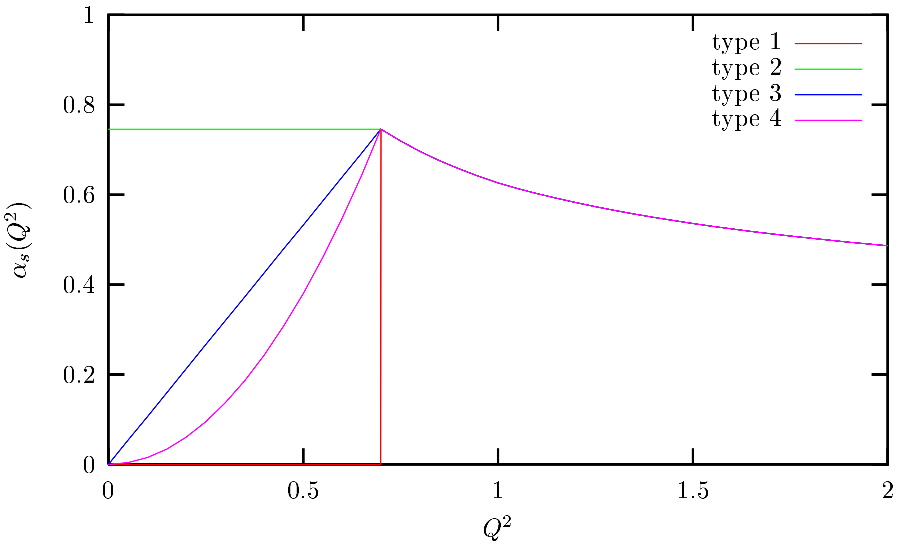
with $Q_{\min} \sim m_g$ in case we had chosen a very small value Q_g. However, typically we keep

$$Q_g \sim Q_{\min} \sim m_g \sim 750\,\mathrm{GeV}$$

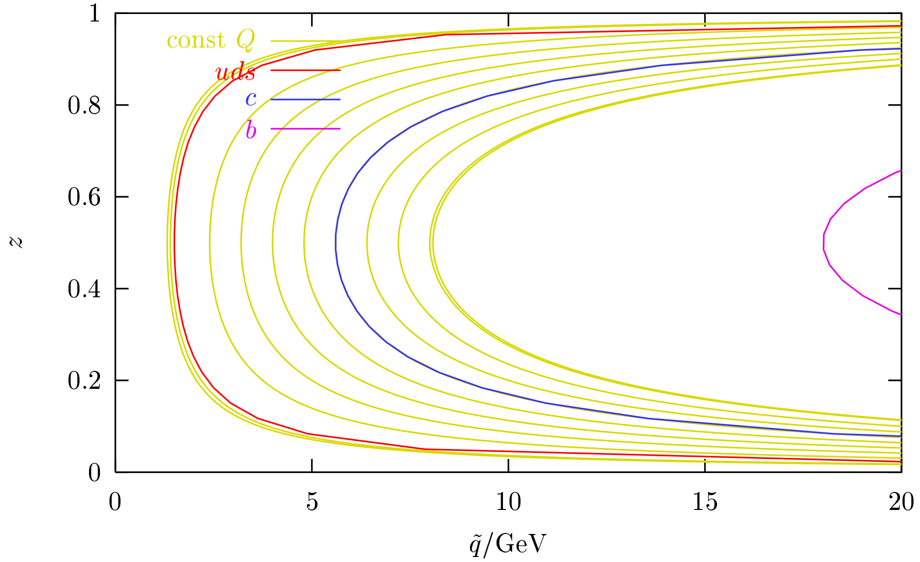
α_s in Parton Shower Phase Space

Different parametrizations below $Q_{\min}$

1. cut off at $Q_{\min}$
2. frozen
3. linear
4. quadratic



Contours of α_s in parton shower phase space (with phase space boundaries for $g \to q\bar{q}$ splittings)



Reconstruction of Kinematics

After shower termination: original partons acquire virtualities q_i^2

$\longrightarrow$ boost/rescale jets:

Started with

$$\sqrt{s} = \sum_{i=1}^{n} \sqrt{m_i^2 + \boldsymbol{p}_i^2}$$

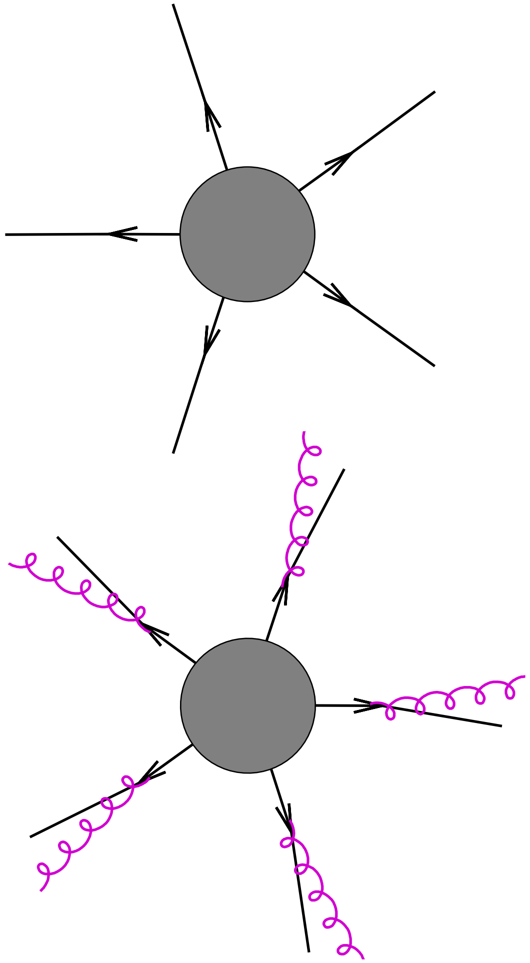
we *rescale* momenta with common factor k,

$$\sqrt{s} = \sum_{i=1}^{n} \sqrt{q_i^2 + k\boldsymbol{p}_i^2}$$

to preserve overall energy/momentum.

[Solution explicit for two jets, numerically obtained for more.]

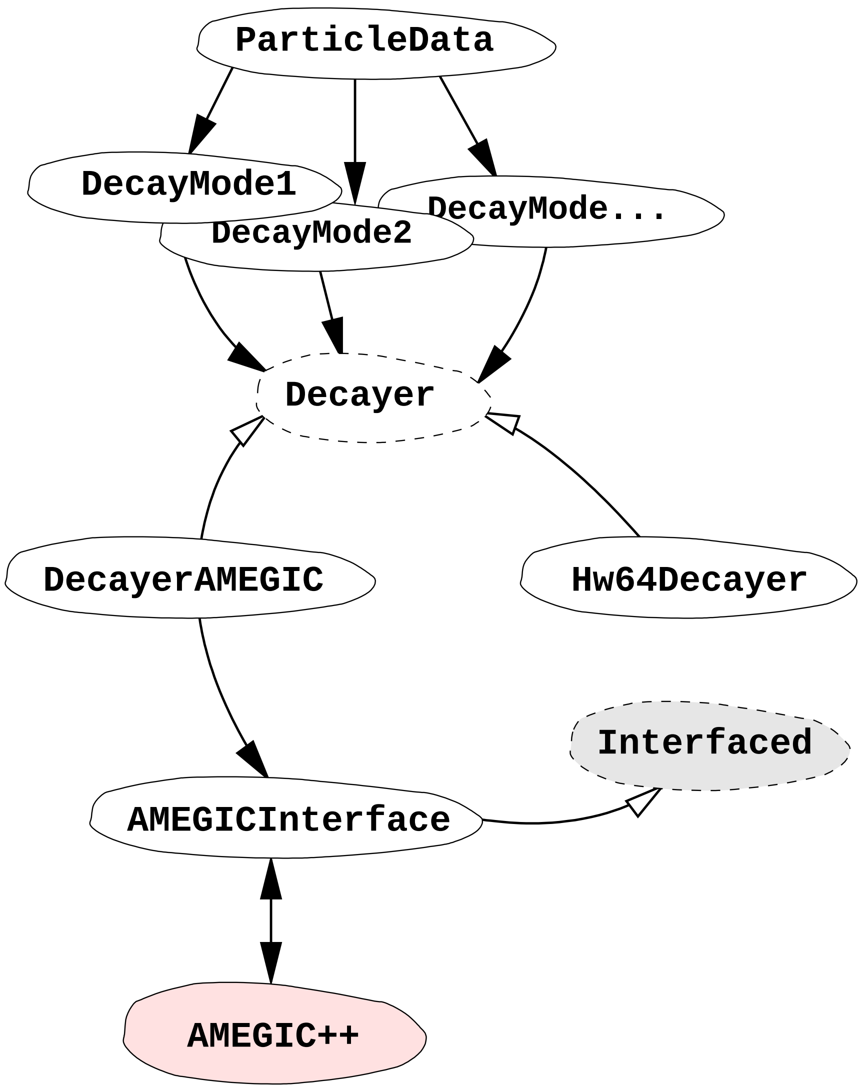
$\longrightarrow$ resulting jets are boosted accordingly.



Cluster Hadronization

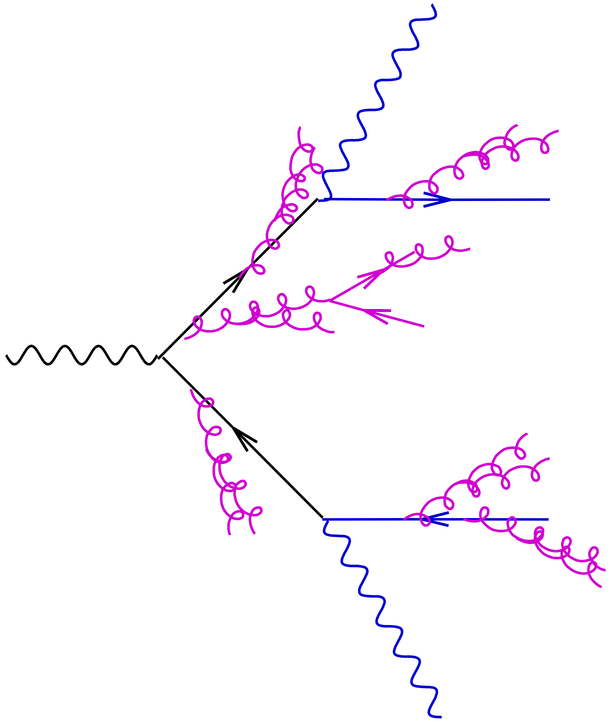
See talk by Philip Stephens

Decays



- FORTRAN HERWIG is reproduced with Hw64Decayer using the same Matrix element codes as before (will be used for hadronic decays right now)
- DecayerAMEGIC gets final states for a decay mode directly from AMEGIC++
- works fine in principle, further tests required

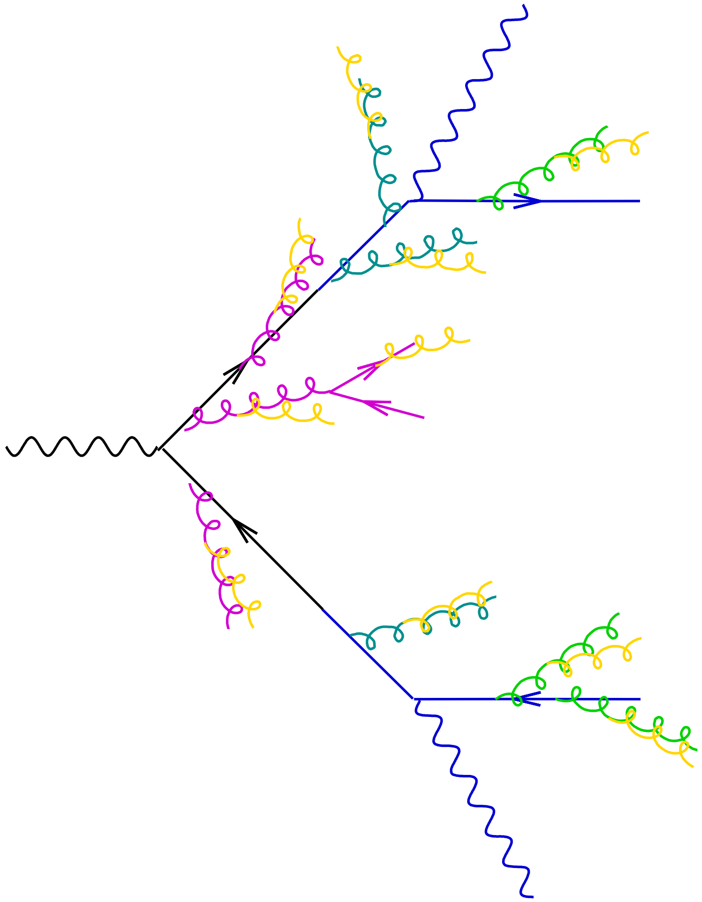
Shower from unstable partons (old)



1. hard process $e^+e^- \to t\bar{t}$
2. radiation from t, $\bar{t}$ $(\hat{s} \to \mu_0)$
3. decay $t \to Wb$, $\bar{t} \to W\bar{b}$,
4. radiation from b, $\bar{b}$ $(m_t \to \mu_0)$

Radiation down to μ_0, ignoring the finite width Γ_t.

Multiscale Shower



1. hard process $e^+e^- \to t\bar{t}$
2. `showerNormally()` ($\hat{s} \to \Gamma_t$) from t, $\bar{t}$
3. decay $t \to Wb$, $\bar{t} \to W\bar{b}$,
4. `showerDecay()` ($m_t \to \Gamma_t$) from t, $\bar{t}$ (DIS-like)
5. `showerDecay()` ($m_t \to \Gamma_t$) from b, $\bar{b}$
6. `showerGlobally()` ($\Gamma_t \to \Gamma_b$) everywhere

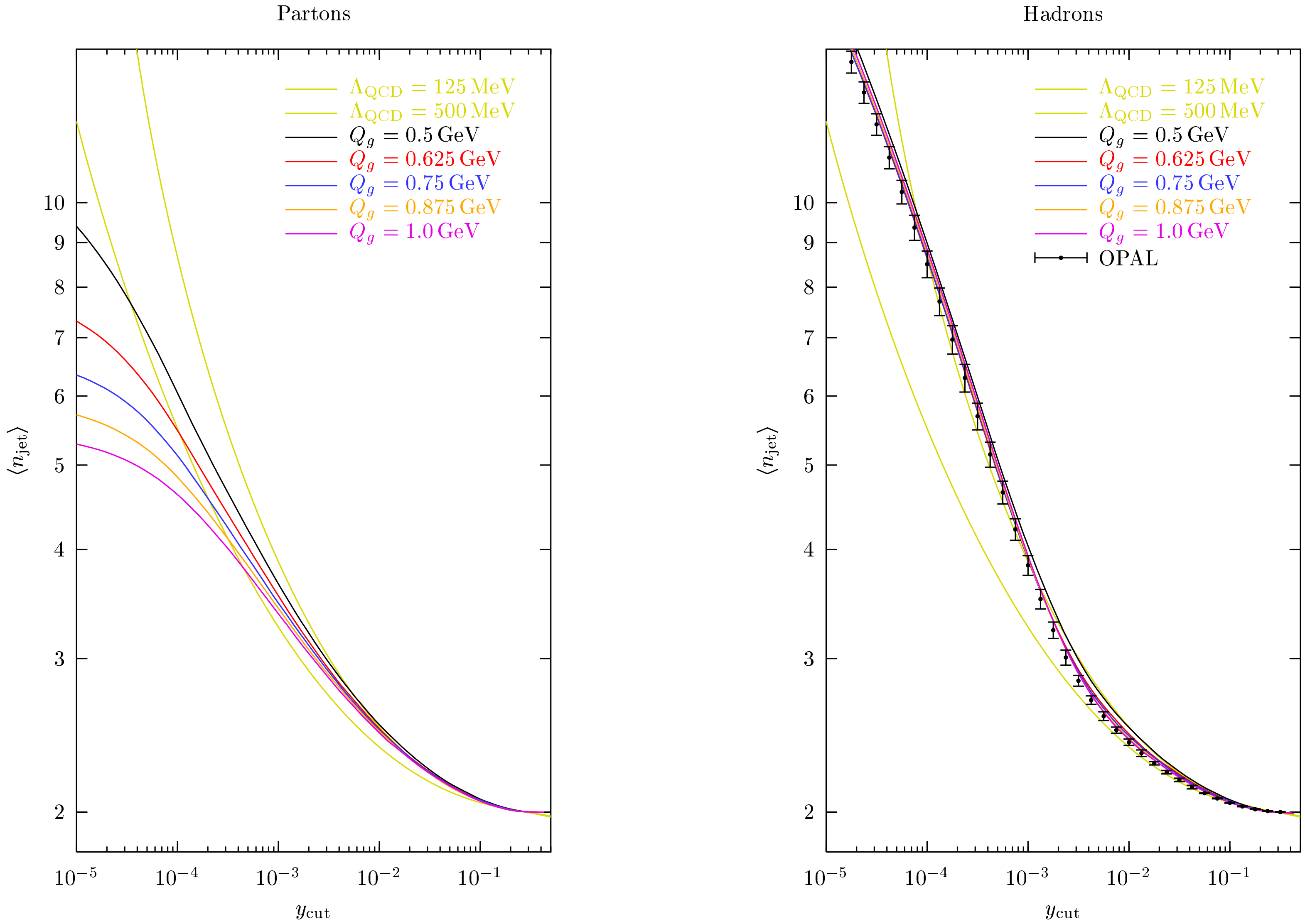
Included in the parton shower design, not fully implemented

First Herwig++ results

- $e^+e^- \to$ jets, mainly at Z^0.
- No ME corrections.
- Soft gluon cutoffs Q_g in the shower.
- Aim: test new parton shower and its interplay with other parts of the program in great detail.

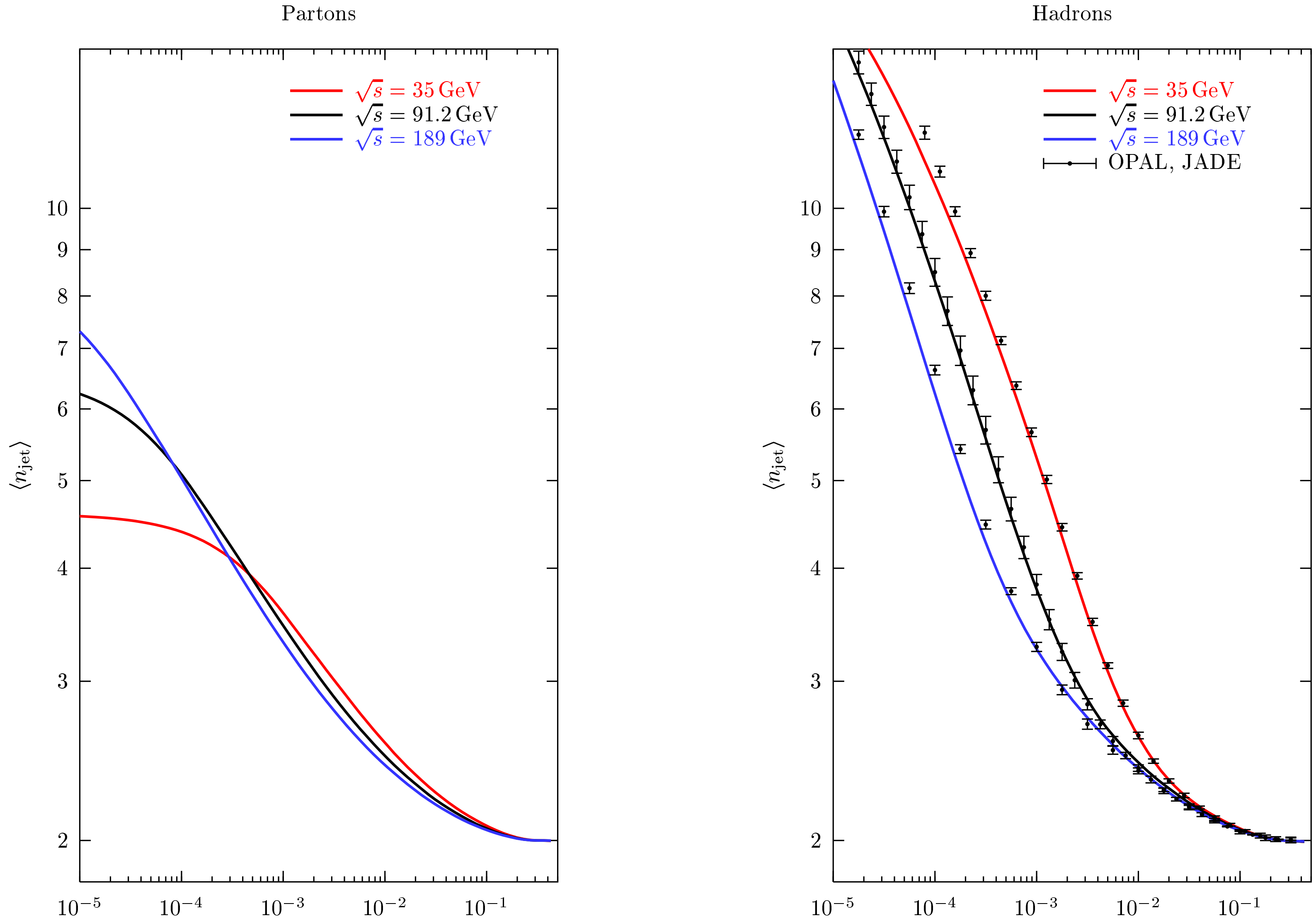
Jet Multiplicity

Durham algorithm. Smooth interplay between shower and hadronization.

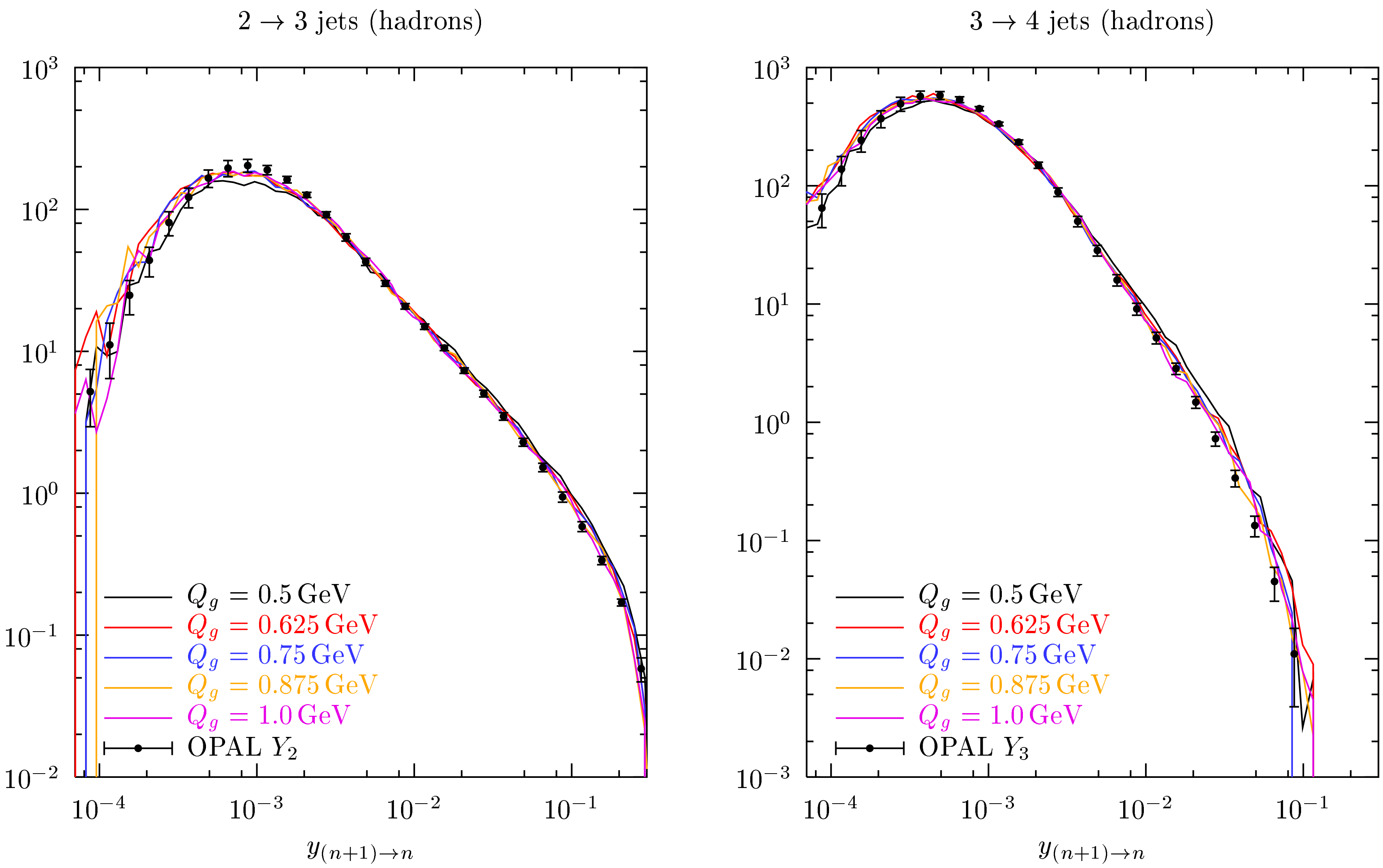


Jet Multiplicity

$\sqrt{s} = \{35, 91.2, 189\}$ GeV

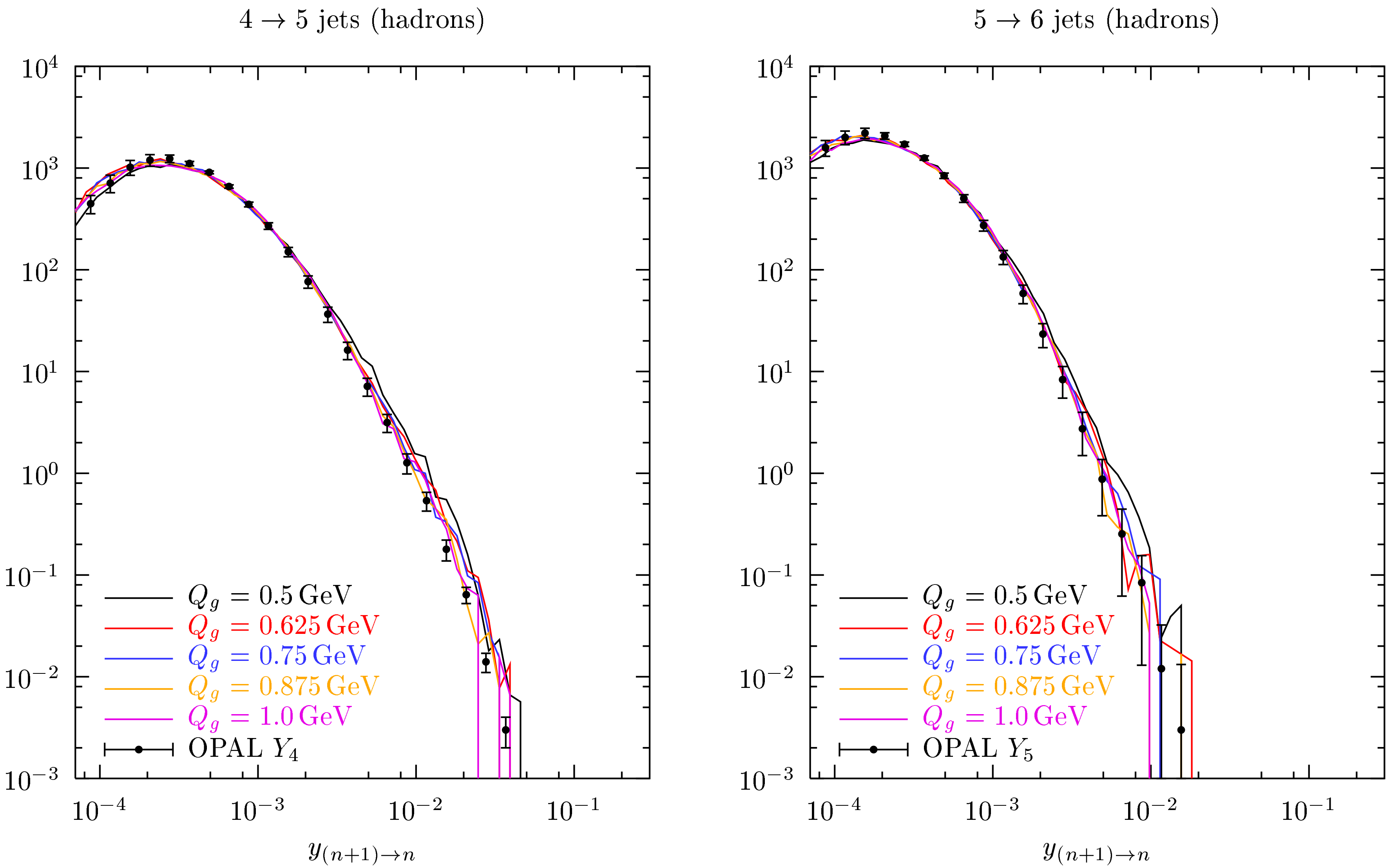


Durham Y_n

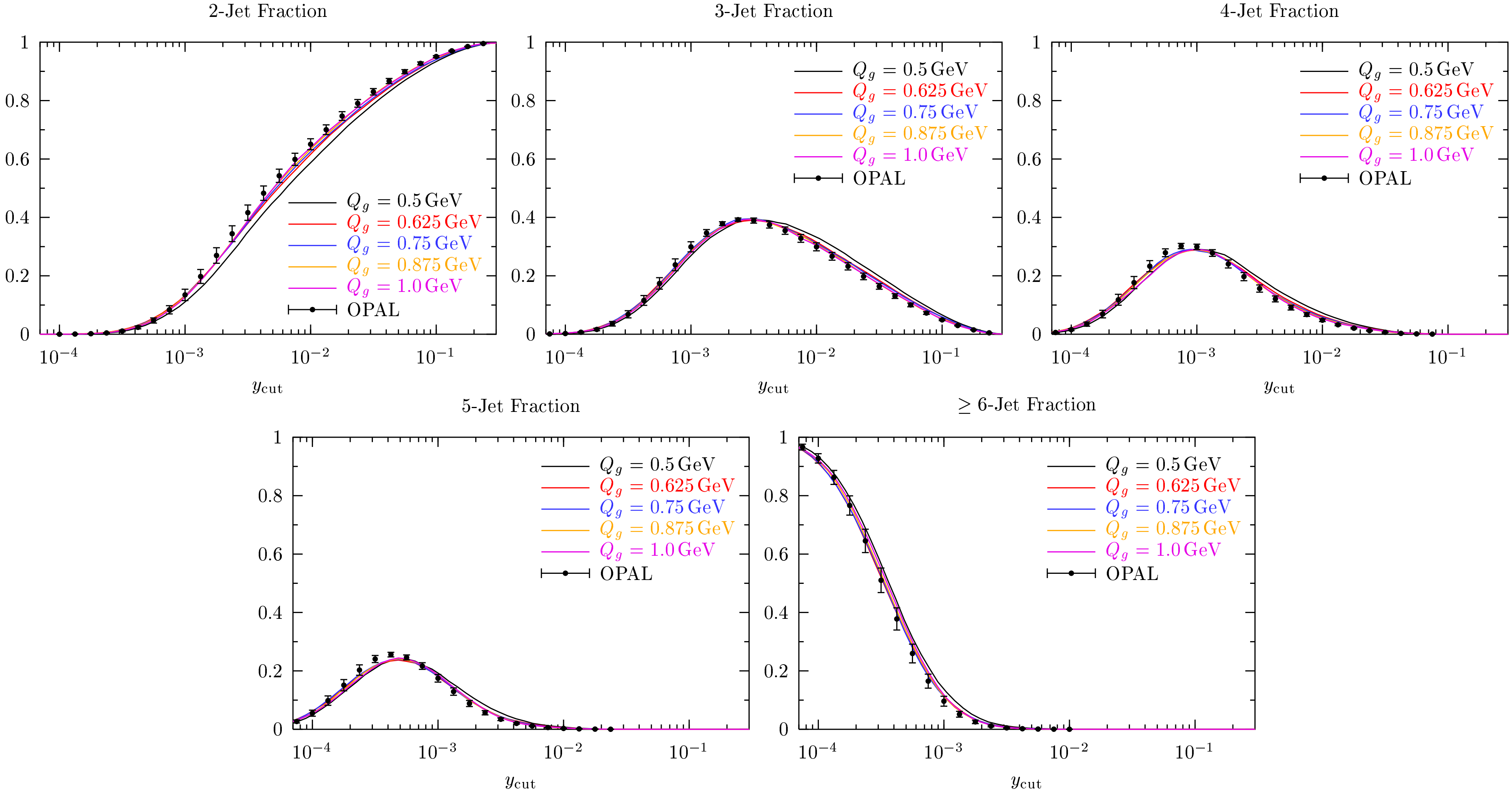


2 → 3 jets (hadrons)
3 → 4 jets (hadrons)
Q_g = 0.5 GeV
Q_g = 0.625 GeV
Q_g = 0.75 GeV
Q_g = 0.875 GeV
Q_g = 1.0 GeV
OPAL Y_2
OPAL Y_3
$y_{(n+1)\to n}$

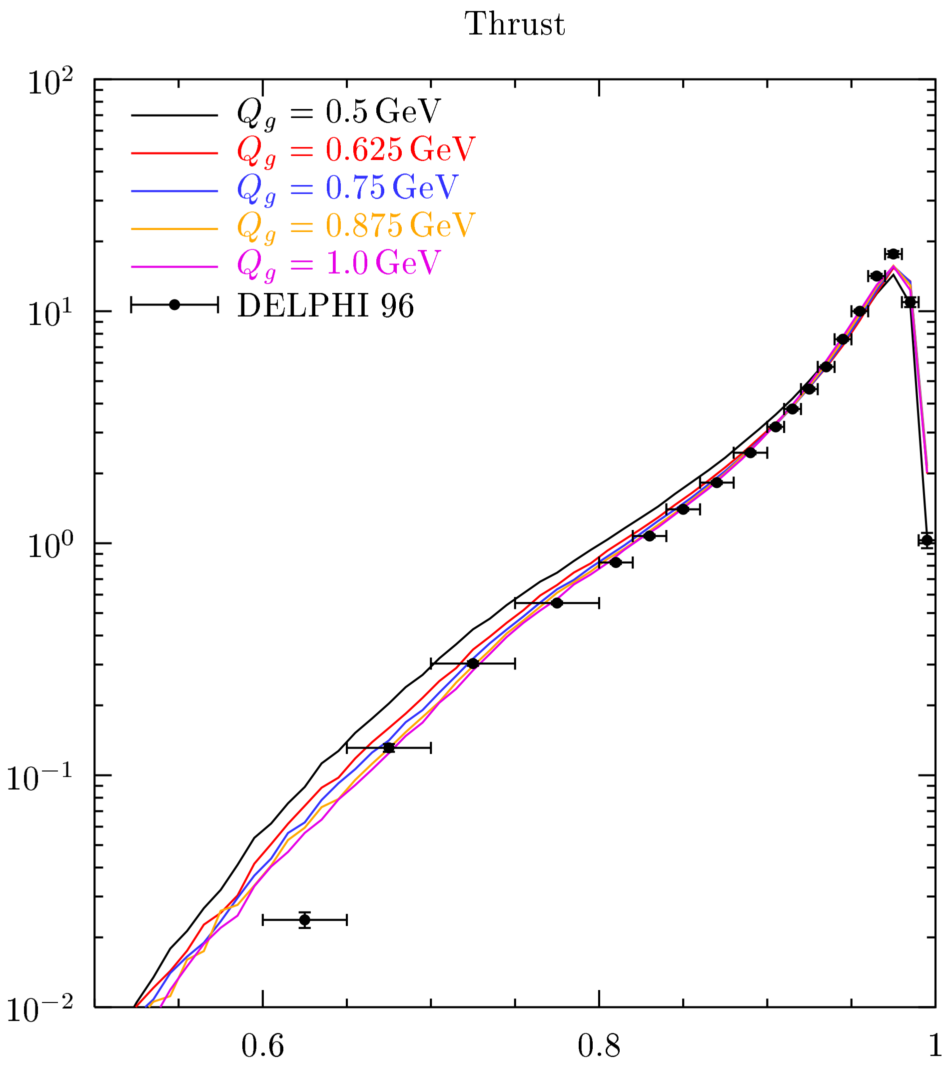
Durham Y_n (ctd')

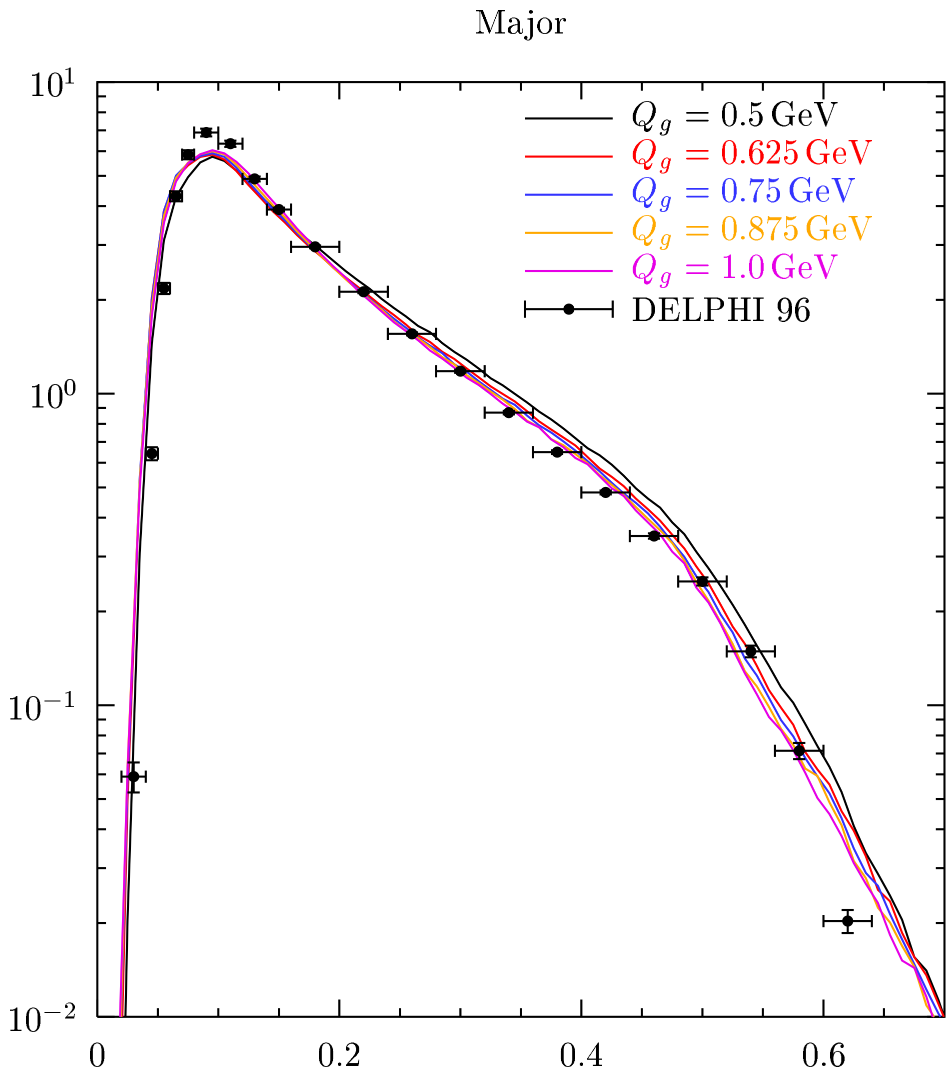


Jet Rates

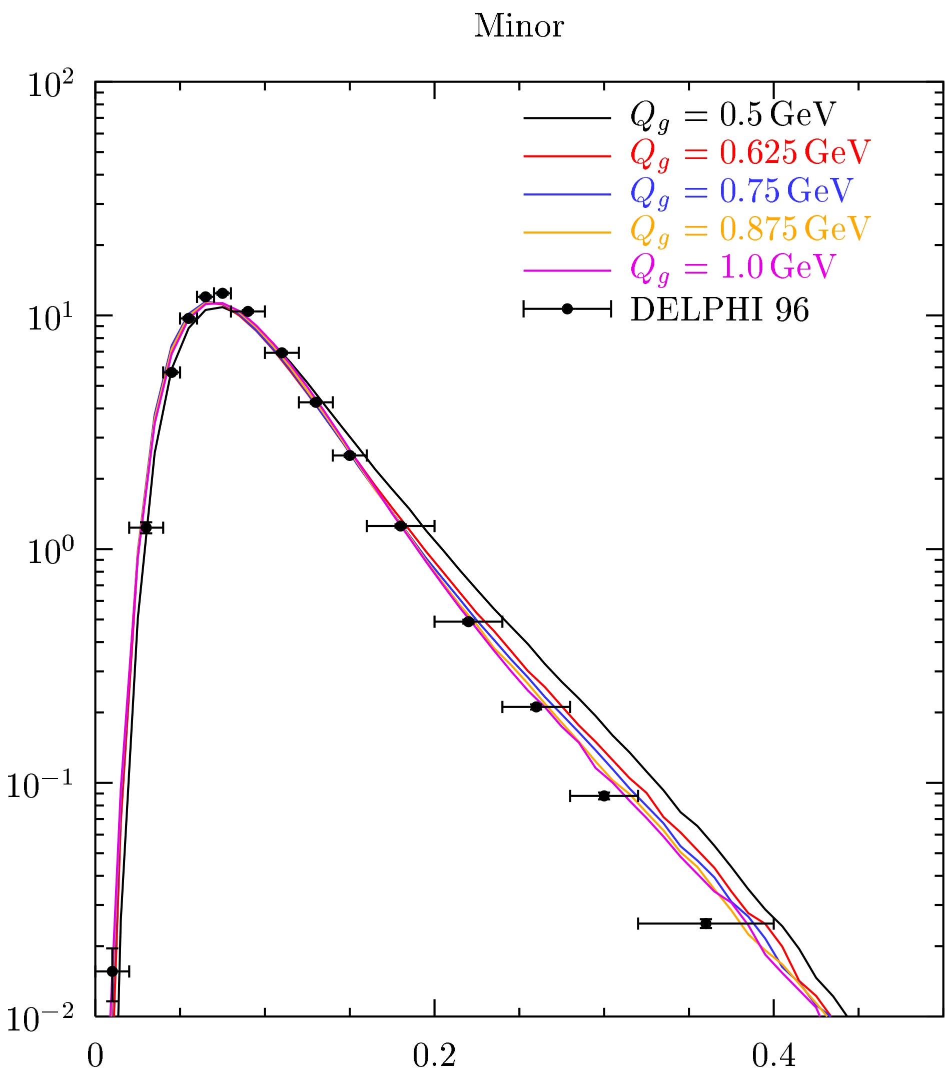

2-Jet Fraction
3-Jet Fraction
4-Jet Fraction
5-Jet Fraction
≥ 6-Jet Fraction
$Q_g = 0.5\,\mathrm{GeV}$
$Q_g = 0.625\,\mathrm{GeV}$
$Q_g = 0.75\,\mathrm{GeV}$
$Q_g = 0.875\,\mathrm{GeV}$
$Q_g = 1.0\,\mathrm{GeV}$
OPAL
y_{cut}
0
0.2
0.4
0.6
0.8
1
10^{-4}
10^{-3}
10^{-2}
10^{-1}

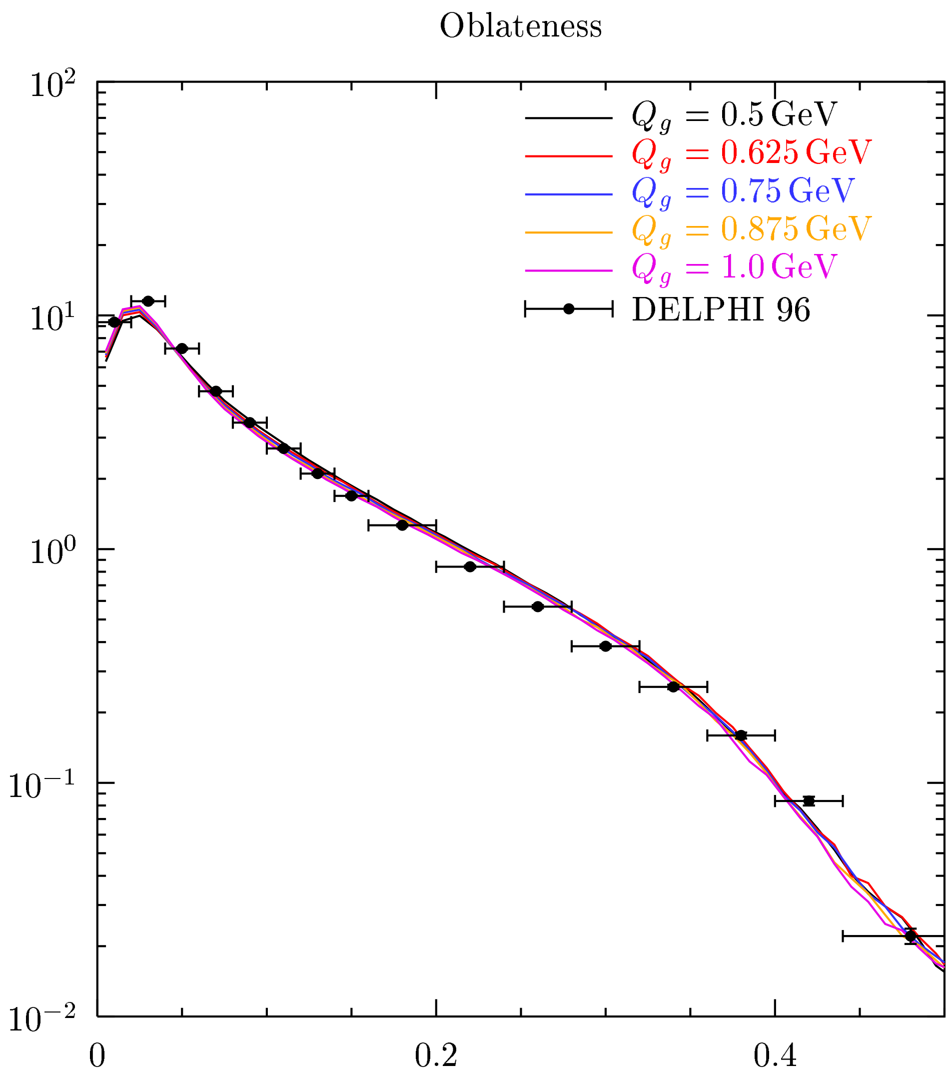
Event Shapes





Event Shapes (ctd')





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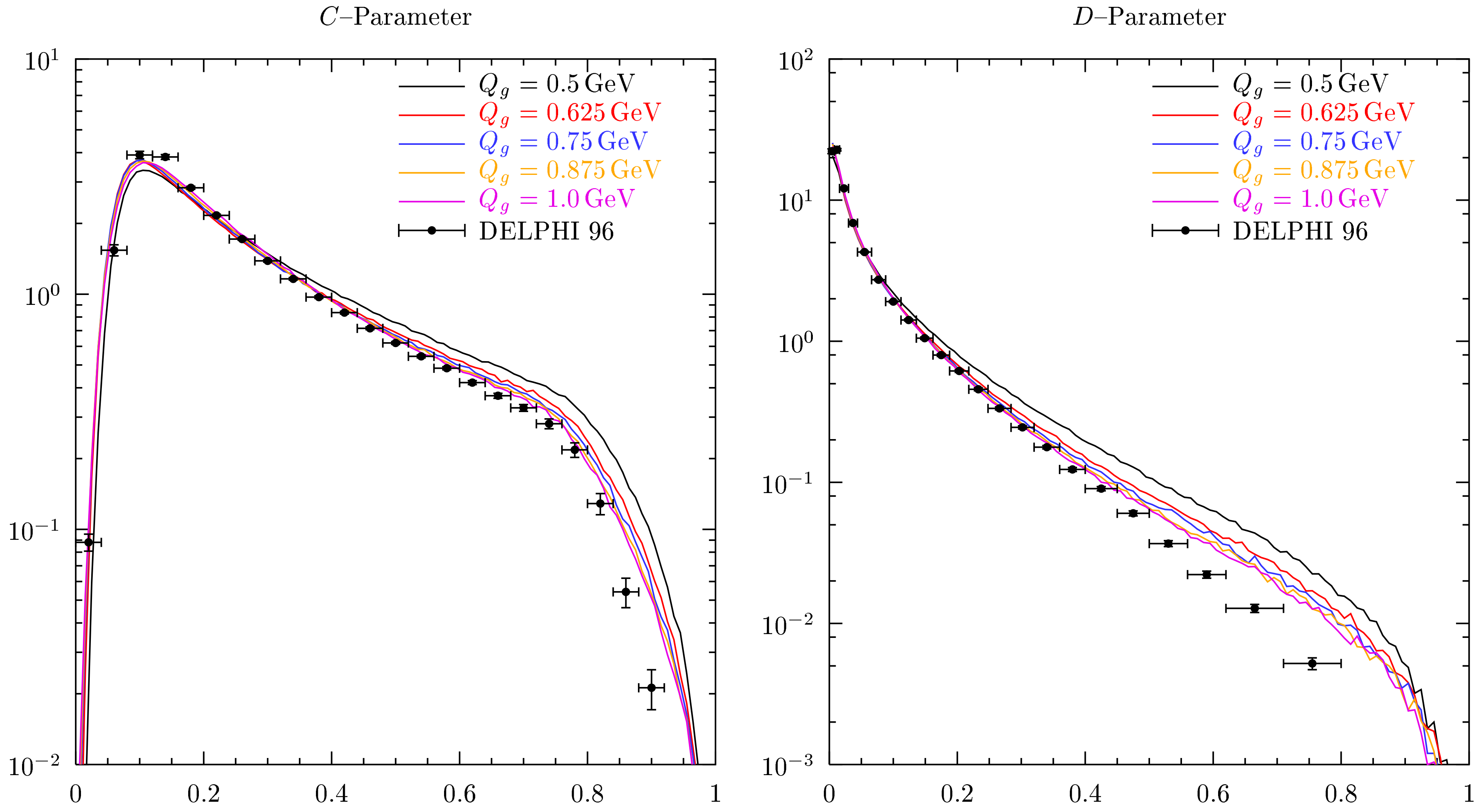
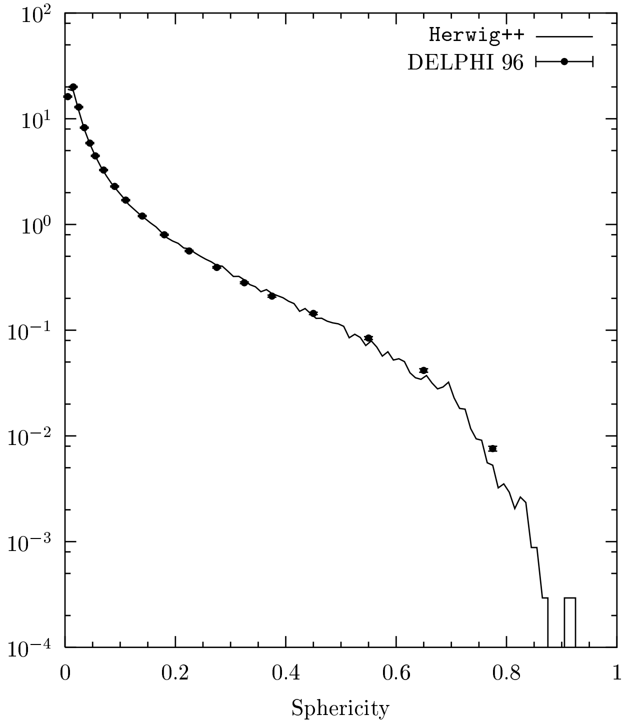
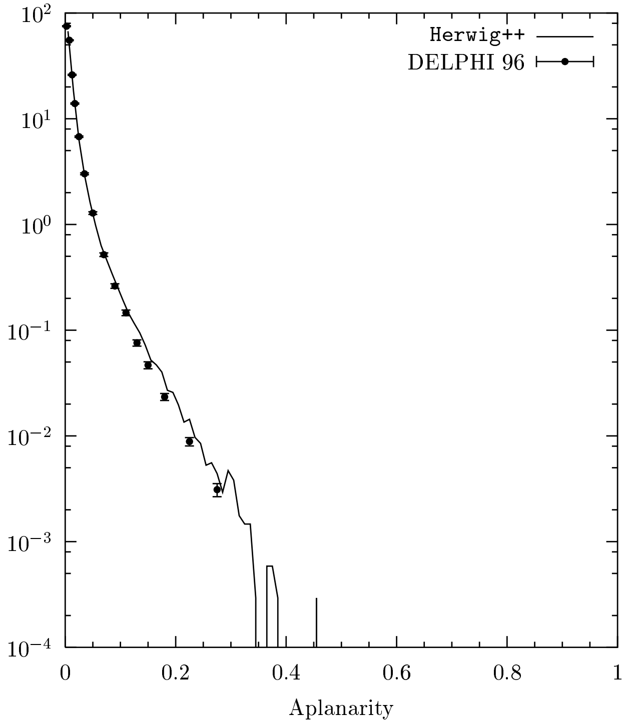
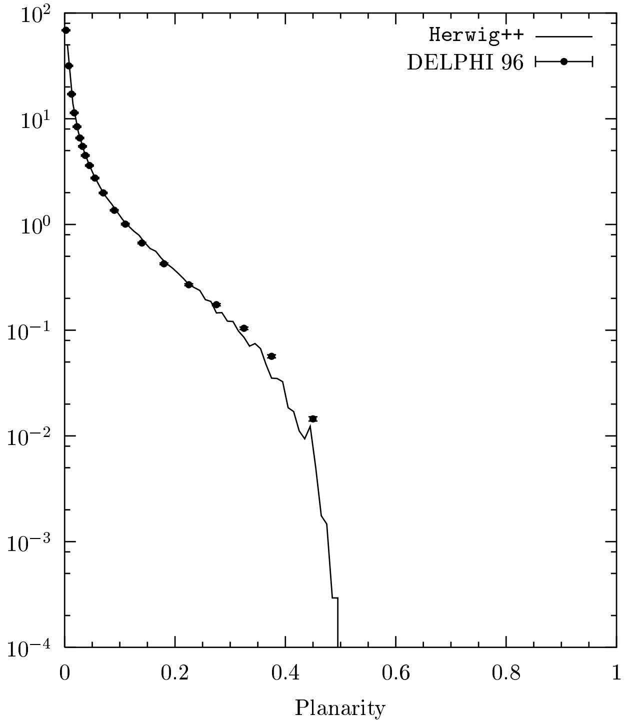


Tend to be too hard! ME corrections?

Event Shapes (ctd')

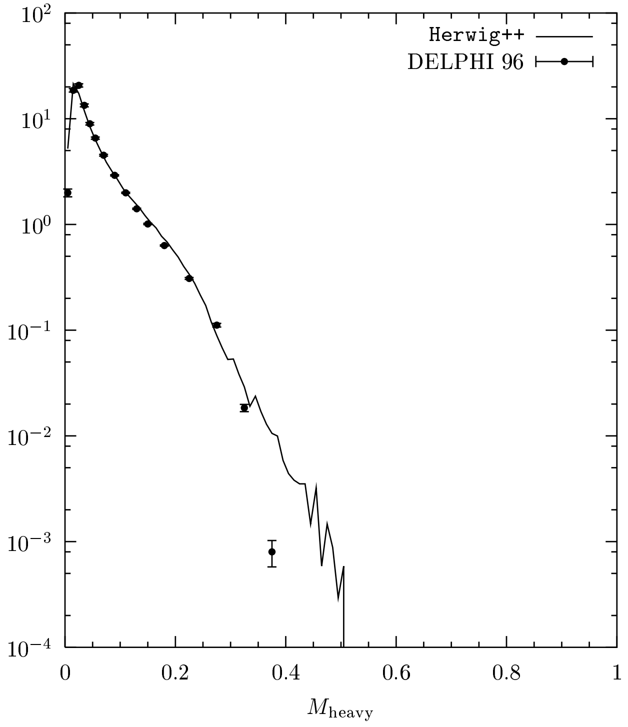


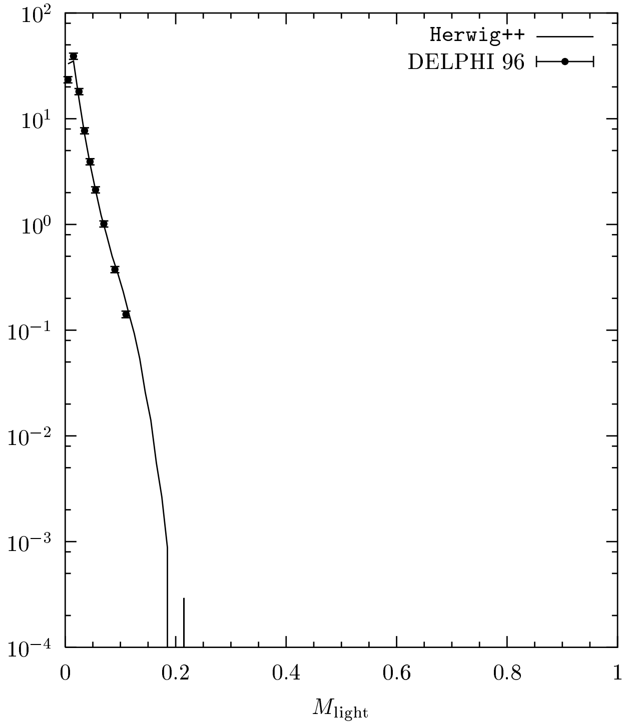


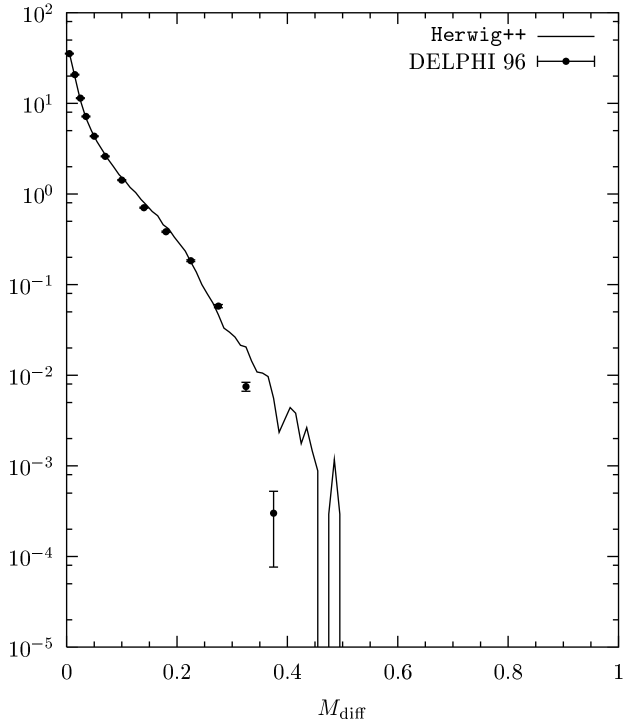


More emphasis on large momenta in quadratic tensor

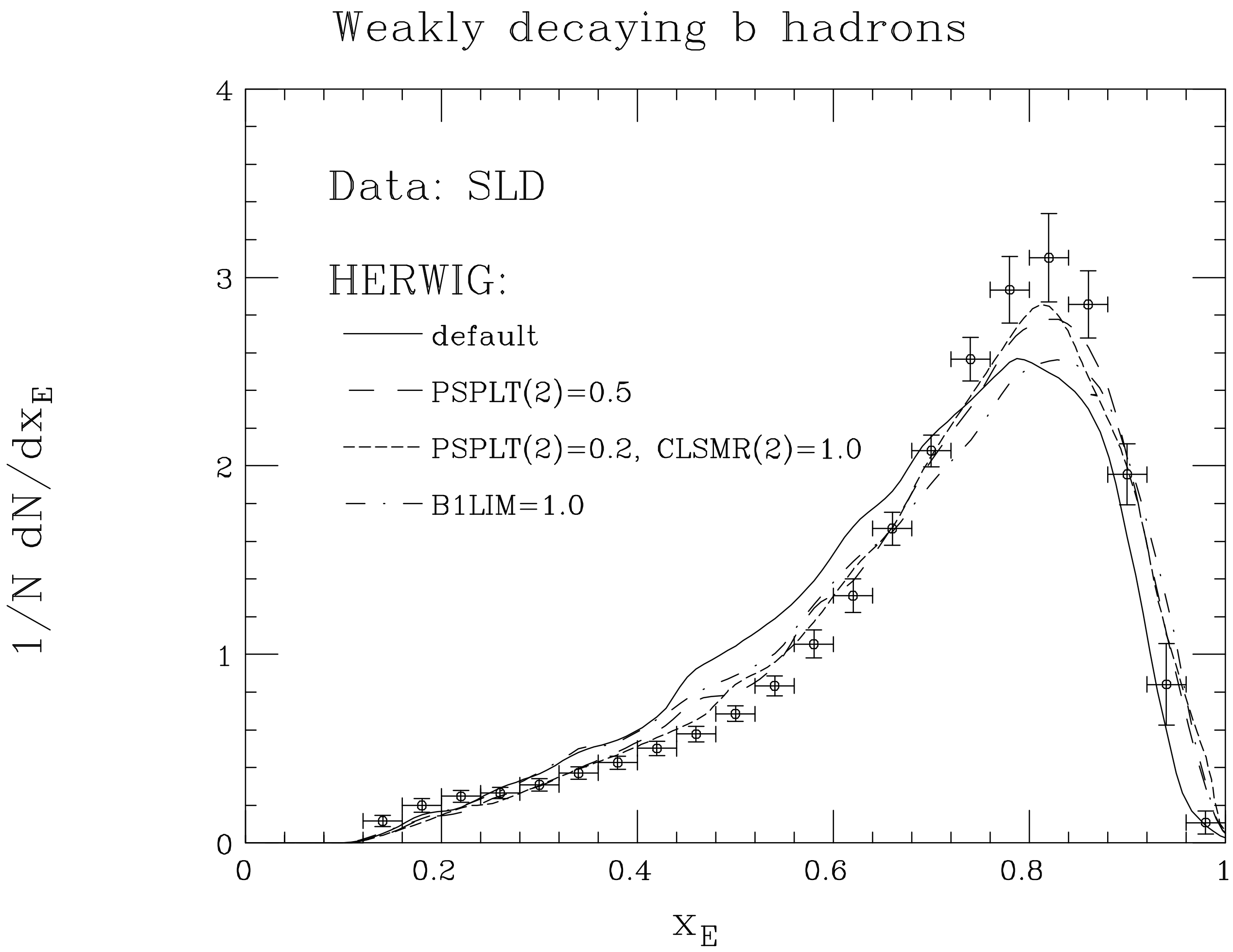
Event Shapes (ctd')





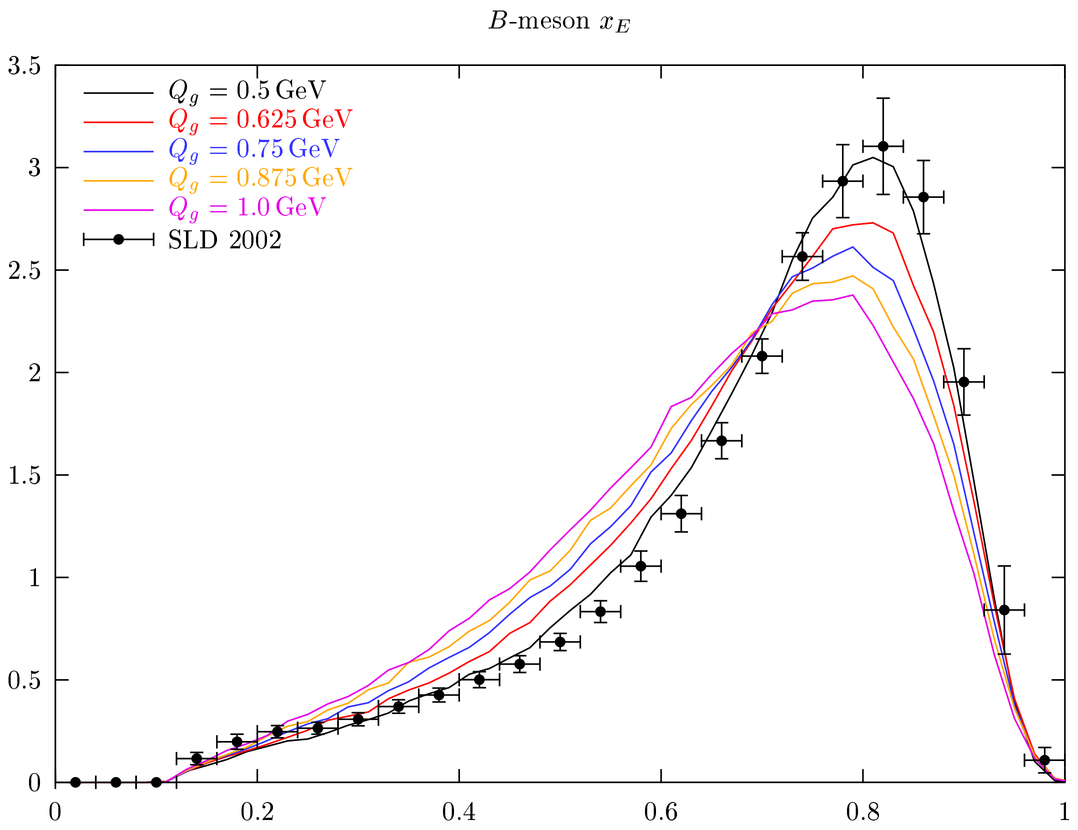


B-fragmentation function



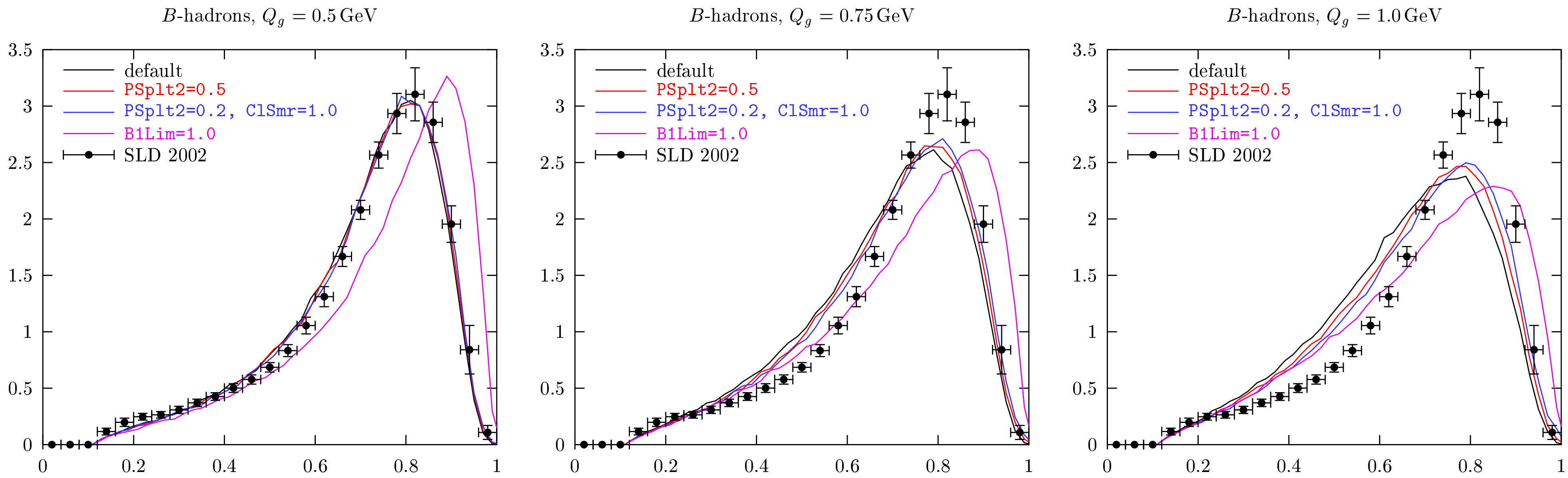
HERWIG 6.4, very sensitive on hadronization!

B-fragmentation function



Herwig++, only parton shower parameters varied!

B-fragmentation function



Same choice of hadronization parameters as in `HERWIG`

Status of Herwig++

S. Gieseke, A. Ribon, M.H. Seymour, P. Stephens, B.R. Webber
(Cambridge, Manchester, CERN)
http://www.hep.phy.cam.ac.uk/~gieseke/Herwig++

Hard Matrix Elements

- ✓ Simple $2 \to 2$ ME so far.
- ✓ We have a working interface to AMEGIC++. For e^+e^- this will do the job for up to 6 jets.
- ★ The ME+PS matching algorithm of Catani, Krauss, Kühn and Webber will be implemented.
- ★ More processes straightforward.
- ★ Users can easily and safely include their own matrix elements.

Parton Shower

- ✓ New parton shower developed.
- ✓ *Multiscale shower* designed for general treatment of instable particles (no physics implementation yet).
- ✓ New evolution variables for better treatment of heavy quarks and smooth coverage of phase space.
- ✗ Extension to spacelike shower for pp and ep ongoing.

Status of Herwig++ (ctnd')

Decays

- ✓ `HERWIG`–decays are reproduced with a class `Hw64Decayer` using the same Matrix element codes as before.
- ✓ `DecayerAMEGIC` gets final states for a decay mode (eg. for t decay, SUSY in the future) directly from `AMEGIC++`
- ✓ works very well, further thorough tests required.
- ★ More to come (`EvtGen`,. . .)?

Hadronization

- ✓ Cluster Hadronization is designed and implemented completely.
- ✓ Works very well, further thorough tests ongoing.
- ★ Aside, the Lund String Fragmentation model is implemented in Pythia7 and will work together with `Herwig++`.
- ✓ Hadronic decays $\rightarrow$ above.

What's next?

Ongoing. . .

- ★ B fragmentation: study the effects of the new shower variables and test the shower in all respects.
- ★ Jet multiplicities/rates: tell us about QCD physics, α_s, angular ordering etc.
- ★ Event Shapes: test of parton shower and its interplay with hadronization.

Near Future. . .

- ★ Initial state shower:
  - Complete implementation and tests.
- ★ Refine e^+e^-:
  - Full CKKW ME+PS matching.
  - Precision tune to LEP data should be possible.
- ★ with IS and FS showers running:
  - we can start to test Drell–Yan and jets in pp collisions.
  - cross check with Tevatron data and finally make predictions for the LHC.
- ★ Underlying Event.
- ★ Hadronic Decays.

Schedule?

- Ready for LHC!

Herwig++ Tutorial

$\longrightarrow$ next Wednesday (from 9am)

Please attend the ThePEG/Pythia7 tutorial on Tuesday as well!

Some aspcets of the use of Herwig++ will already be covered there.