Jetty Investigations

Bryan Webber

Yuri Fest 18 Nov 2016

Outline

- Early days
- Jet algorithms
- Power corrections
- Quark-gluon jet discrimination
- Electroweak DGLAP

DDT < 1980

ELSEVIER

Physics Reports

Volume 58, Issue 5, February 1980, Pages 269-395

Hard processes in quantum chromodynamics

Yu.L. Dokshitzer, D.I. Dyakonov, S.I. Troyan

Abstract

The use of Quantum Chromodynamics (QCD) in treating the hadronic world has become an overwhelming trend in particle physics. Owing to the asymptotic freedom of QCD, one can use perturbative methods to describe hard hadronic processes, i.e. those in which small distances as compared to hadron size are important. This paper is devoted to an improved perturbative QCD analysis of a wide class of hard processes. We start with the deep inelastic lepton-hadron scattering and the inclusive e^+e^- annihilation to hadrons, and show how and to what extent QCD imitates the parton model. We move further to hard semi-inclusive processes, and demonstrate that in this case the QCD predictions differ drastically from those of the parton model. The approach outlined in the paper paves the way for a detailed quantitative description of hard processes (provided QCD is the right theory).

Special attention is given to the underlying physics. In particular, a possible influence of the hitherto unknown confinement mechanism on perturbative QCD analysis is discussed.

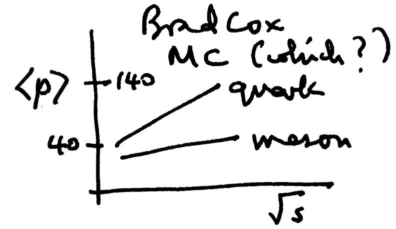
Gatchina 1989

Gatchina 1989

Gatchina 1989

Leningrad QCD Workshop — 16 Oct 89

Vorobyov — Important questions for B physics:

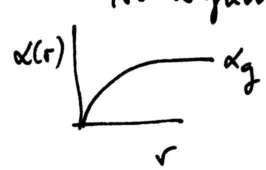


Correlations between b & $\bar{b}$
Ang. distn of b — forward?
b hadronisation: $\langle p \rangle_b$ vs $\langle p \rangle_B$?

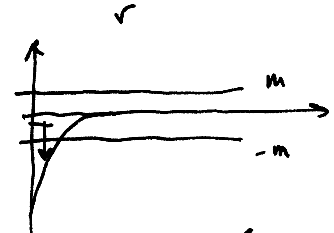
[Possible topics: Small x (spacelike) ✓
Heavy quarks
Pedestals
QCD at LEP: IR safe
Multiplicity distn ✓
Small x (timelike) ✓
Coherence in QCD Cascade and MC Simulation]

Gribov — Confinement

Infrared instability — colour spins try to align
$\Rightarrow$ either ferromag. vacuum or formation of domains of size $\sim R_\lambda \sim 1/\lambda$
Suppose there are only heavy quarks $m_q \gg \lambda$
No arguments for confinement. Suppose $\alpha(r) \to \alpha_g$ const.



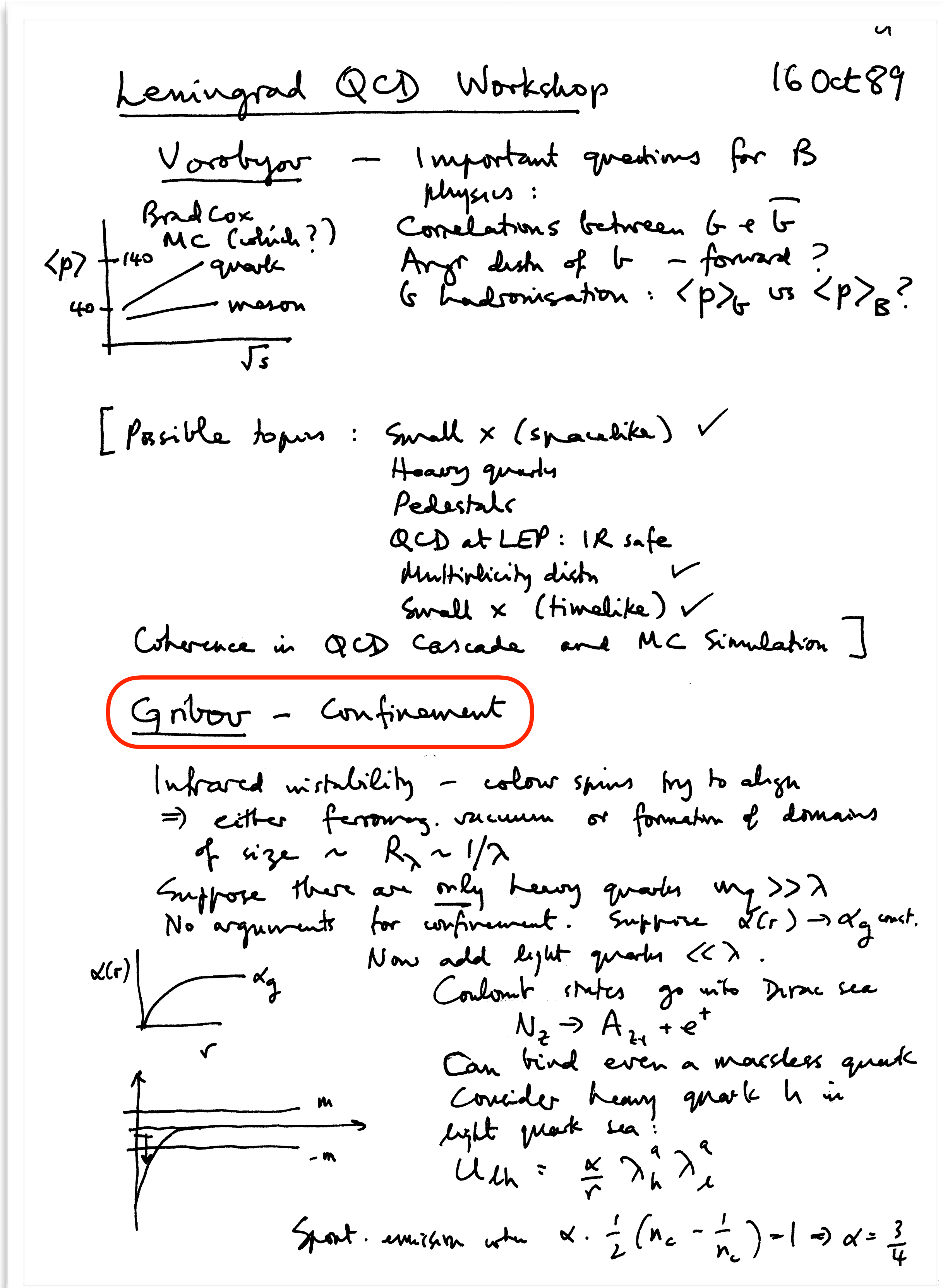
Now add light quarks $\ll \lambda$.
Coulomb states go into Dirac sea
$N_Z \to A_{Z+1} + e^+$
Can bind even a massless quark



Consider heavy quark h in light quark sea:
$U_{\ell h} = \frac{\alpha}{r} \lambda^a_h \lambda^a_\ell$

Spont. emission when $\alpha \cdot \frac{1}{2}\left(n_c - \frac{1}{n_c}\right) = 1 \Rightarrow \alpha = \frac{3}{4}$

Gatchina 1989



Leningrad QCD Workshop 16 Oct 89

Vorobyov – Important questions for B physics:

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Infrared instability – colour spins try to align
⇒ either ferromag. vacuum or formation of domains
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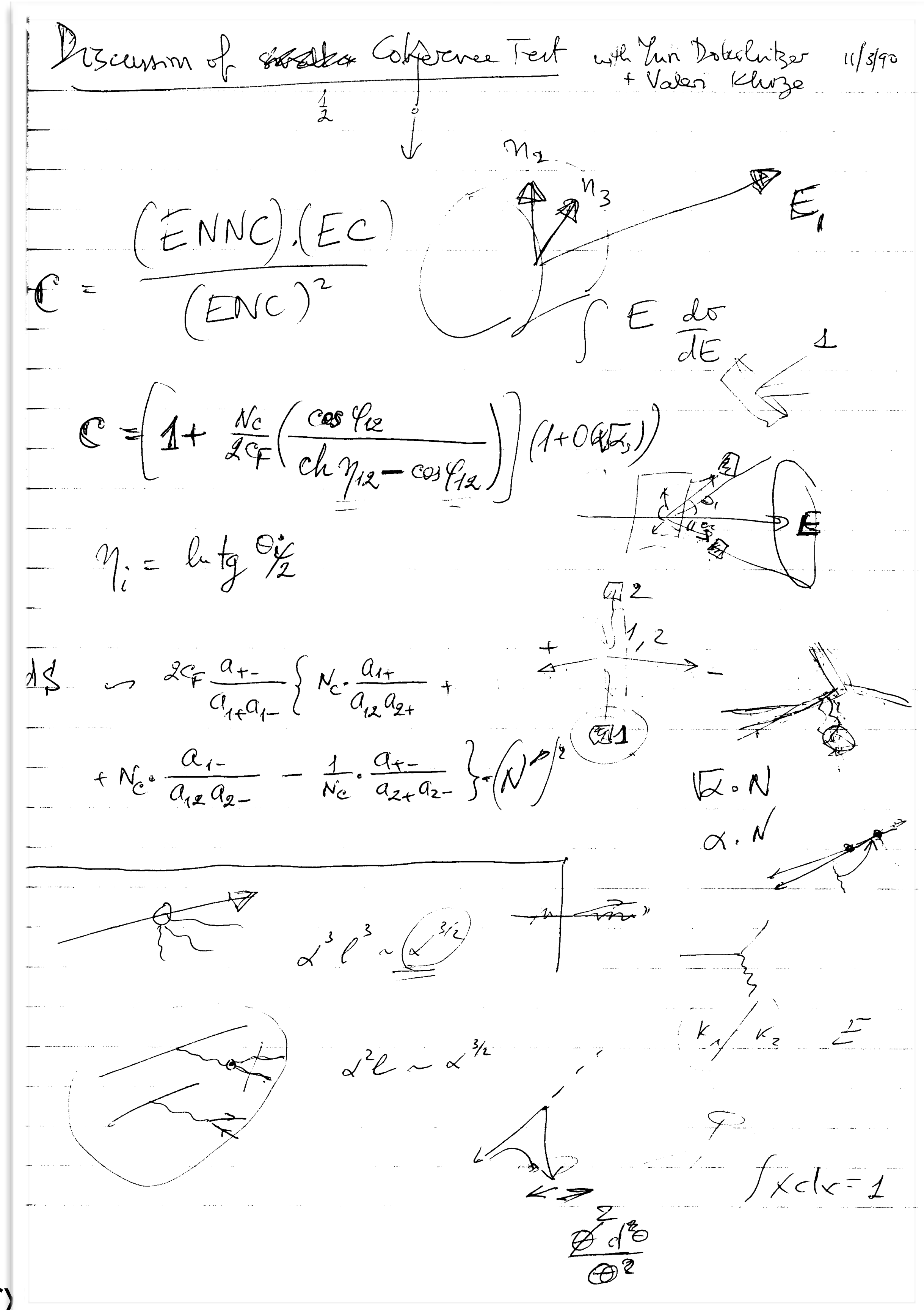
Leningrad 1989

First collaboration 1990



← Moriond 1990

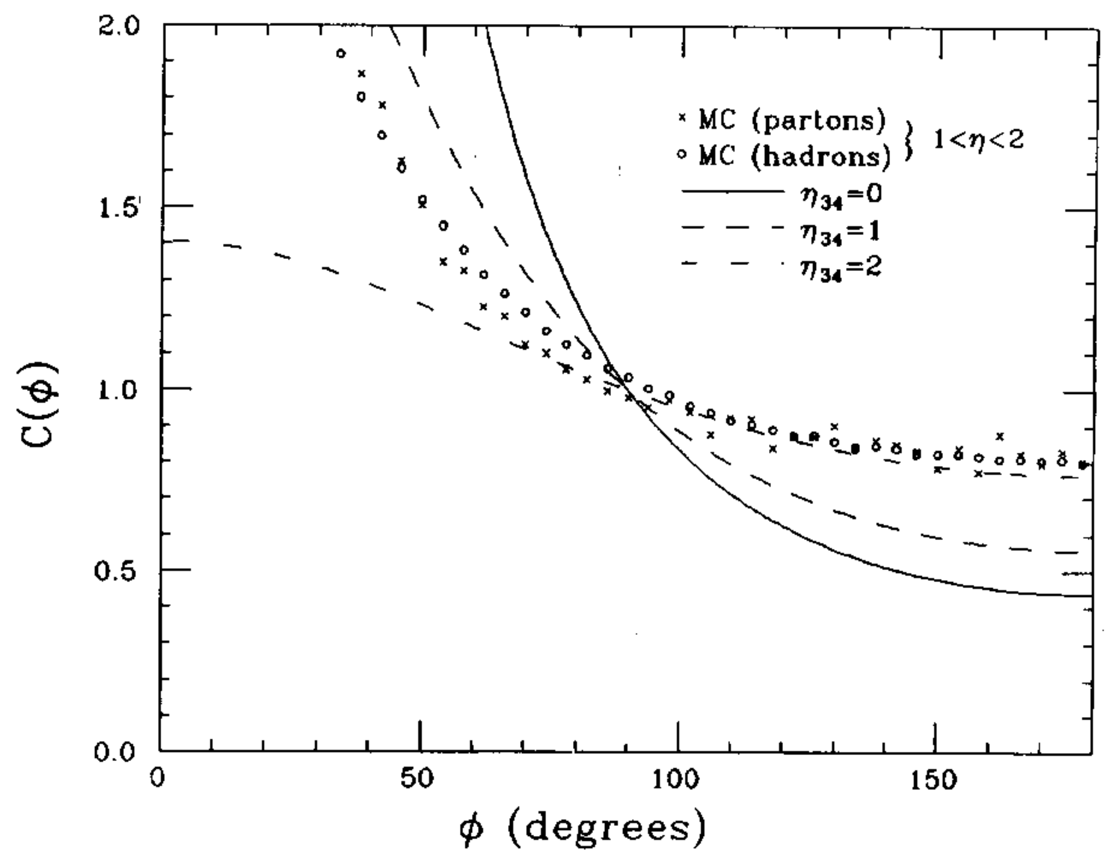
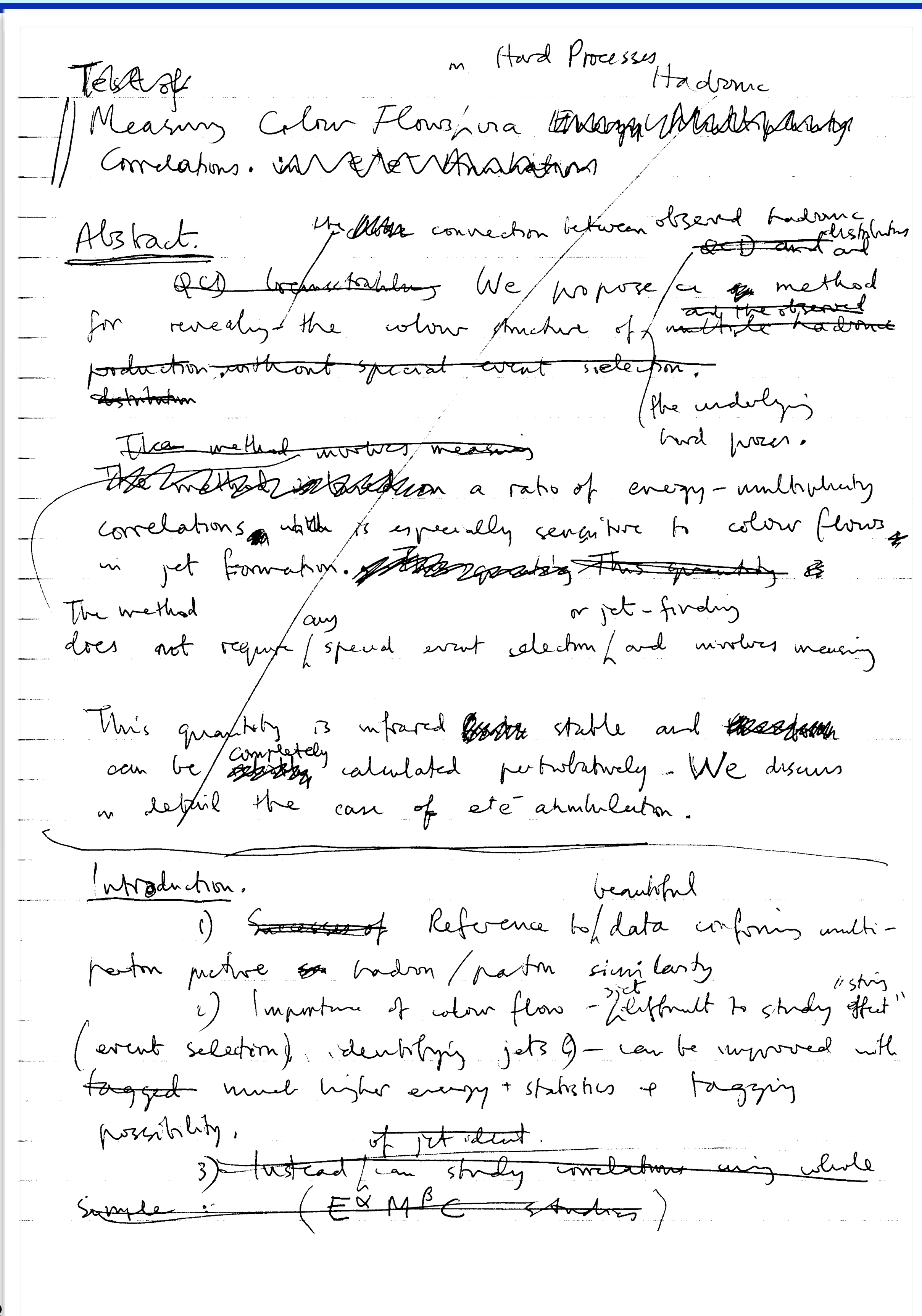


Fig. 1. Hadronic flow correlation defined by eq. (11) as a function of the azimuthal angle ϕ for a rapidity interval $1<\eta_{j,k}<2$. The points are Monte Carlo predictions from the program HERWIG [8] at the parton and hadron levels, for e^+e^- annihilation at $E_{CM}=91$ GeV. The curves show the leading-order prediction (6) for various rapidity differences η_{34}.

First collaboration 1990


Measuring Colour Flows in Hard Processes via Hadronic Correlations.

Abstract. We propose a method for revealing the connection between observed hadronic distributions and the colour structure of the underlying hard process. ... a ratio of energy-multiplicity correlations which is especially sensitive to colour flows in jet formation. The method does not require any special event selection or jet-finding and involves measuring ... This quantity is infrared stable and can be completely calculated perturbatively. We discuss in detail the case of e+e− annihilation.

Introduction.
1) Reference to beautiful data conforming multi-parton picture + hadron/parton similarity
2) Importance of colour flow – "string effect" 3-jet difficult to study (event selection), identifying jets ... – can be improved with much higher energy + statistics + tagging possibility.
3) Instead can study correlations using whole sample: ($E^\alpha M^\beta$ ...)

← Moriond 1990 (on the bus)

Volume 245, number 2 PHYSICS LETTERS B 9 August 1990

Measuring colour flows in hard processes via hadronic correlations ☆

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[b] CERN, CH-1211 Geneva 23, Switzerland
[c] Dipartimento di Fisica, Università di Parma, and INFN, Gruppo Collegato di Parma, I-43100 Parma, Italy
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Received 8 May 1990

We propose a method for revealing the connection between observed hadronic distributions and the colour structure of an underlying hard process. The method does not require any special event selection or jet finding. It involves measuring a ratio of energy–multiplicity correlations which is especially sensitive to colour flows in jet formation. This quantity is infrared stable and can be calculated completely perturbatively. We discuss in detail the case of e^+e^- annihilation.

The first data on hadronic Z^0 decays from SLC [1] and LEP [2–5] appear to be in very good agreement with Monte Carlo simulations [6–8] based on a QCD parton shower mechanism of multihadron production in hard processes (see e.g. the reviews in refs. [9,10] and references therein). In this mechanism, hadron distributions are mainly determined by those of underlying parton cascades, whose properties can be calculated in detail using perturbative QCD. The conversion of partons into hadrons is supposed to occur at a low virtuality scale, independent of the scale of the primary hard process, and to involve only low momentum transfers, leading to a close similarity or "local duality" (LPHD) [11] between parton and hadron distributions. Such local duality follows naturally from the pre-confinement property of QCD [12].

A fundamental feature of the parton shower mechanism is the connection between the *colour flow* in the hard process and the observed flow of hadron multiplicity [9,10,13].

This connection was beautifully illustrated in e^+e^- annihilation at lower energies by the observation of the "string" or "drag" effect in three-jet final states. Here the colour flow gives rise to destructive interference in the "antenna pattern" of parton emission in the angular region between the quark and antiquark jets. The corresponding depletion of hadron flow into this region was confirmed both by comparison of hadron multiplicities between the jets [14] and by comparison of $q\bar{q}g$ and $q\bar{q}\gamma$ final states [15]. It should be possible to provide further evidence for colour interference in three-jet events by the same type of analysis of the LEP data, with greatly increased statistics, higher energy, and the possibility of identifying quark jets through the observation of heavy quark decays.

As a demonstration of the connection between colour and hadronic flows, the "string" analysis of three-jet events suffers from some inherent difficulties and weaknesses that one would prefer to avoid if possible. First of all, the necessity of selecting a three-jet event sample reduces the statistics and may introduce biases into the observed hadron flow. The need to define jet directions introduces a dependence on the jet-finding algorithm. Discrimination between quark and gluon jets on the basis of their relative energies reduces the effect and prevents the use of symmetrical jet configurations.

☆ Research supported in part by the UK Science and Engineering Research Council and in part by the Italian Ministero della Pubblica Istruzione.
[1] Supported in part by the World Laboratory Eloisatron Project.

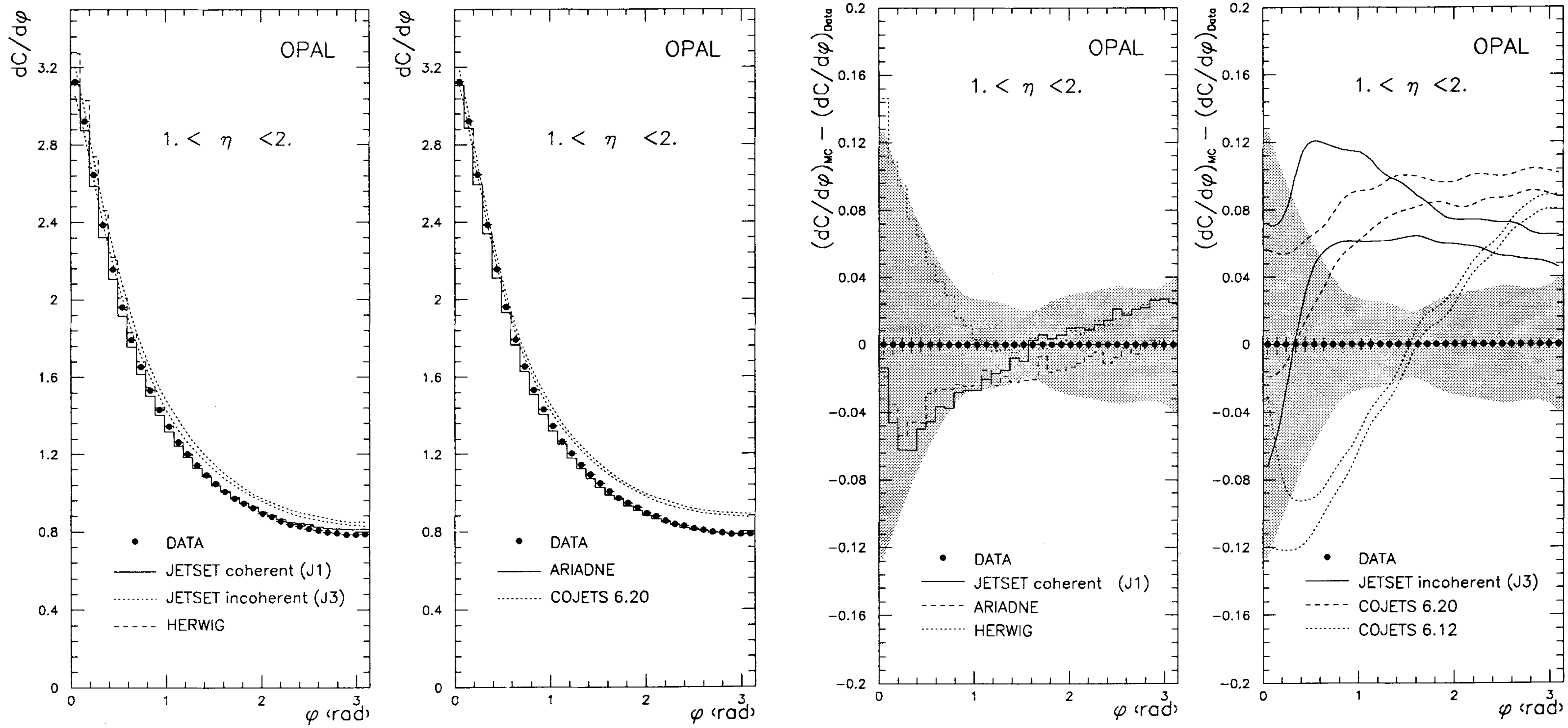
0370-2693/90/$ 03.50 © 1990 – Elsevier Science Publishers B.V. (North-Holland) 243

First collaboration 1990

QCD coherence studies using two particle azimuthal correlations

OPAL Collaboration

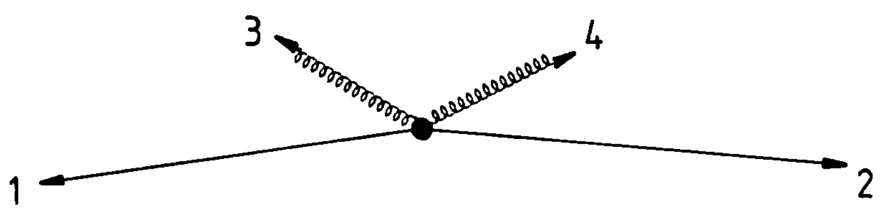
Z. Phys. C 58, 207–217 (1993)



Jet Algorithms

JADE algorithm

Durham Jet Workshop, December 1990



$$y_{ij} = 2E_iE_j(1-\cos\theta_{ij})/s \simeq M_{ij}^2/s$$

Jet cross sections at leading double logarithm in e^+e^- annihilation

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and

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Received 17 August 1990; revised manuscript received 8 October 1990

$$f_4 = \frac{1}{2!}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \ln^4 y \left(\frac{3}{4}\right),$$

$$f_3 = \frac{C_F\alpha_s}{\pi}\ln^2 y + \frac{1}{2!}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \ln^4 y \left(-\frac{19}{12}\right),$$

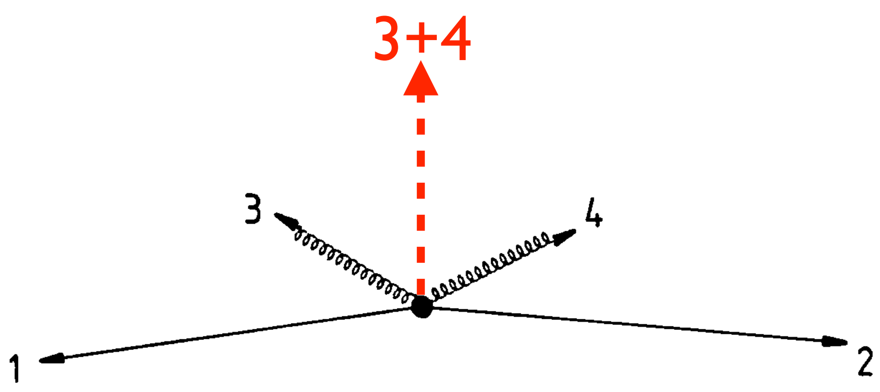
$$f_2 = 1 - \frac{C_F\alpha_s}{\pi}\ln^2 y + \frac{1}{2!}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \ln^4 y \left(\frac{5}{6}\right).$$

$$f_5 = \frac{1}{3!}\left(\frac{C_F\alpha_s}{\pi}\right)^3 \ln^6 y \left(\frac{31}{60}\right),$$

$$f_6 = \frac{1}{4!}\left(\frac{C_F\alpha_s}{\pi}\right)^4 \ln^8 y \left(\frac{571}{1680}\right).$$

- Parts of 2- and 4-jets were counted as 3-jets

JADE algorithm



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Durham Jet Workshop, December 1990

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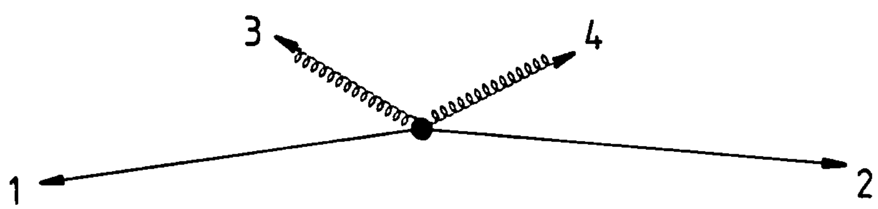
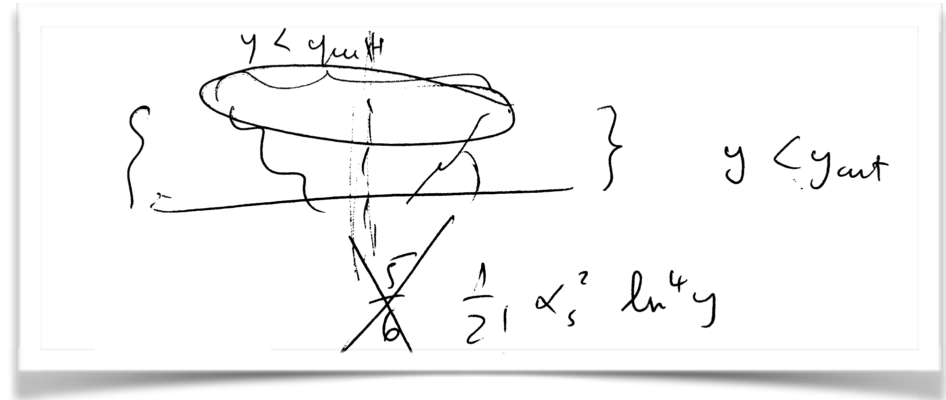
- Parts of 2- and 4-jets were counted as 3-jets, when 3 and 4 form a phantom jet

k_t (Durham) algorithm



$$y_{ij} = 2\min\{E_i^2, E_j^2\}(1-\cos\theta_{ij})/s \simeq k_{t,ij}^2/s$$



New clustering algorithm
for multijet cross sections in e^+e^- annihilation ☆

S. Catani [a,b,1], Yu.L. Dokshitzer [c,d], M. Olsson [d], G. Turnock [a] and B.R. Webber [a]

[a] *Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK*
[b] *INFN, Sezione di Firenze, Largo Fermi 2, I-50125 Florence, Italy*
[c] *Leningrad Nuclear Physics Institute, Gatchina, SU-188 350 Leningrad, USSR*
[d] *Department of Theoretical Physics, University of Lund, Sölvegatan 14A, S-22362 Lund, Sweden*

Received 2

$$f_4 = \frac{1}{2!}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \ln^4 y \left(1\right),$$

$$f_3 = \frac{C_F\alpha_s}{\pi}\ln^2 y + \frac{1}{2!}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \ln^4 y \left(-2\right),$$

$$f_2 = 1 - \frac{C_F\alpha_s}{\pi}\ln^2 y + \frac{1}{2!}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \ln^4 y \left(1\right).$$

$$f_5 = \frac{1}{3!}\left(\frac{C_F\alpha_s}{\pi}\right)^3 \ln^6 y \left(1\right),$$

$$f_6 = \frac{1}{4!}\left(\frac{C_F\alpha_s}{\pi}\right)^4 \ln^8 y \left(1\right).$$

- Leading logs exponentiate: resummation possible

k_t-jet rates

- q/g jet generating functions:

$$R_m^{(a)}(y_{\rm cut}=Q_0^2/Q^2)=\frac{1}{m!}\left(\frac{\partial}{\partial u}\right)^m \phi_a(Q,Q_0;u)\Big|_{u=0}$$

$$\phi_q(u,Q) = u\,\Delta_q(Q)\exp\left(\int_{Q_0}^{Q} dq\,\Gamma_q(Q,q)\phi_g(u,q)\right),$$

$$\phi_g(u,Q) = u\,\Delta_g(Q)\exp\left(\int_{Q_0}^{Q} dq\left[\Gamma_g(Q,q)\phi_g(u,q)+\Gamma_f(q)\frac{\phi_q(u,q)^2}{\phi_g(u,q)}\right]\right)$$

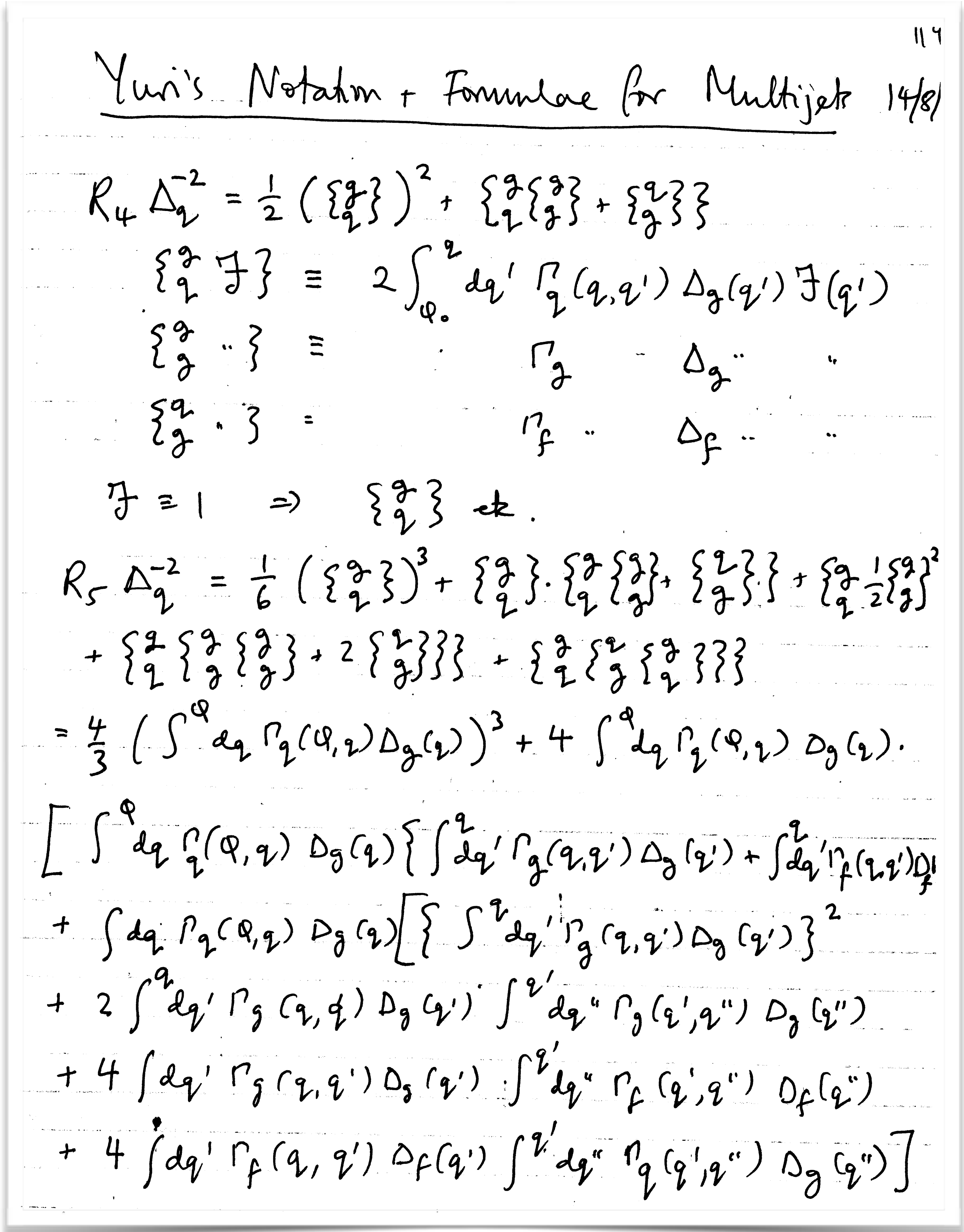
where Q is the jet scale, $Q_0 = Q\sqrt{y_{\rm cut}}$ is the resolution scale, and

$$\Gamma_q(Q,q) = \frac{2C_F}{\pi}\frac{\alpha_s(q^2)}{q}\left(\ln\frac{Q}{q}-\frac{3}{4}\right),$$

$$\Gamma_g(Q,q) = \frac{2C_A}{\pi}\frac{\alpha_s(q^2)}{q}\left(\ln\frac{Q}{q}-\frac{11}{12}\right),$$

$$\Gamma_f(q) = \frac{n_f}{3\pi}.$$

k_t-jet rates



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Yuri's Notation + Formulae for Multijets 14/8/

$$R_4 \Delta_q^{-2} = \frac{1}{2}\left(\left\{{}^g_q\right\}\right)^2 + \left\{{}^g_q\left\{{}^g_g\right\}\right\} + \left\{{}^g_q\left\{{}^q_g\right\}\right\}$$

$$\left\{{}^g_q\ \mathcal{J}\right\} \equiv 2\int_{Q_0}^{q} dq'\, \Gamma_q(q,q')\, \Delta_g(q')\, \mathcal{J}(q')$$

$$\left\{{}^g_g\ ..\right\} \equiv \quad \Gamma_g \quad \Delta_g$$

$$\left\{{}^q_g\ .\right\} = \quad \Gamma_f \quad \Delta_f$$

$\mathcal{J} \equiv 1 \Rightarrow \left\{{}^g_q\right\}$ etc.

$$R_5 \Delta_q^{-2} = \frac{1}{6}\left(\left\{{}^g_q\right\}\right)^3 + \left\{{}^g_q\right\}\cdot\left\{{}^g_q\left\{{}^g_g\right\} + \left\{{}^q_g\right\}\right\} + \left\{{}^g_q\,\frac{1}{2}\left\{{}^g_g\right\}^2\right\}$$

$$+ \left\{{}^g_q\left\{{}^g_g\left\{{}^g_g\right\} + 2\left\{{}^q_g\right\}\right\}\right\} + \left\{{}^g_q\left\{{}^q_g\left\{{}^g_q\right\}\right\}\right\}$$

$$= \frac{4}{3}\left(\int^{Q} dq\, \Gamma_q(Q,q)\Delta_g(q)\right)^3 + 4\int^{Q} dq\, \Gamma_q(Q,q)\, \Delta_g(q).$$

$$\left[\int^{Q} dq\, \Gamma_q(Q,q)\, \Delta_g(q)\left\{\int^{q} dq'\, \Gamma_g(q,q')\, \Delta_g(q') + \int^{q} dq'\, \Gamma_f(q,q')\Delta_f(q')\right\}\right.$$

$$+ \int dq\, \Gamma_q(Q,q)\, \Delta_g(q)\left[\left\{\int^{q} dq'\, \Gamma_g(q,q')\, \Delta_g(q')\right\}^2\right.$$

$$+ 2\int^{q} dq'\, \Gamma_g(q,q')\, \Delta_g(q') \int^{q'} dq''\, \Gamma_g(q',q'')\, \Delta_g(q'')$$

$$+ 4\int dq'\, \Gamma_g(q,q')\, \Delta_g(q') \int^{q'} dq''\, \Gamma_f(q',q'')\, \Delta_f(q'')$$

$$\left. + 4\int dq'\, \Gamma_f(q,q')\, \Delta_f(q') \int^{q'} dq''\, \Gamma_q(q',q'')\, \Delta_g(q'')\right]$$

k_t-jet rates: $Z^0 \to$ jets

- Z^0 2,3,4-jet rates:

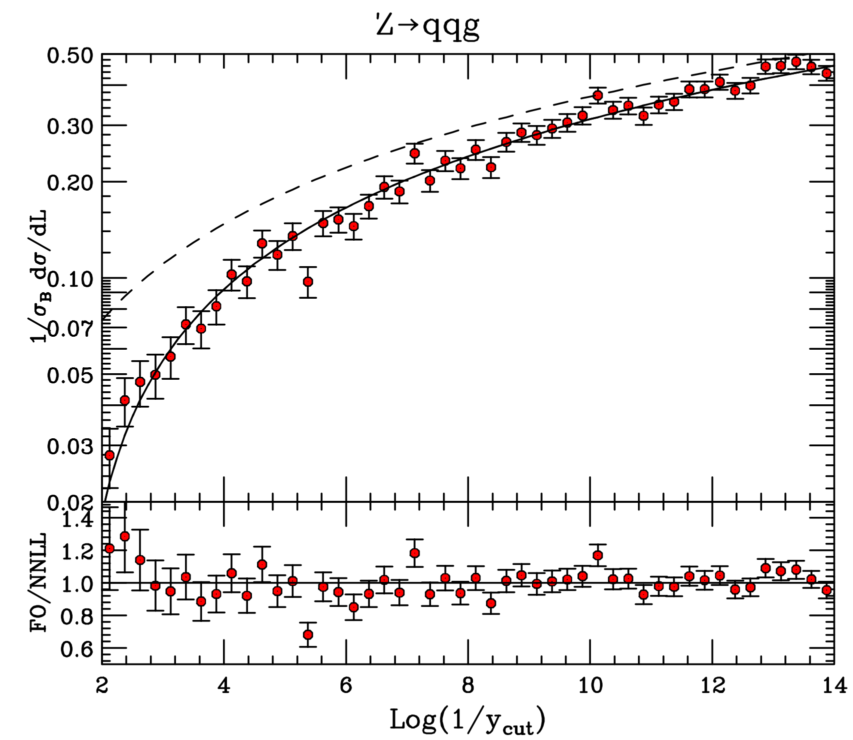
$$\begin{aligned}
R_2^Z &= 1+\frac{1}{2}a(3C_FL-C_FL^2)+\frac{1}{144}a^2(99C_AC_FL^2+162C_F^2L^2-44C_AC_FL^3\\
&\quad -108C_F^2L^3+18C_F^2L^4-18C_FL^2n_f+8C_FL^3n_f),\\
R_3^Z &= \frac{1}{2}a(-3C_FL+C_FL^2)+\frac{1}{48}a^2(-66C_AC_FL^2-108C_F^2L^2+28C_AC_FL^3\\
&\quad +72C_F^2L^3-C_AC_FL^4-12C_F^2L^4+12C_FL^2n_f-4C_FL^3n_f),\\
R_4^Z &= \frac{1}{144}a^2(99C_AC_FL^2+162C_F^2L^2-40C_AC_FL^3-108C_F^2L^3+3C_AC_FL^4\\
&\quad +18C_F^2L^4-18C_FL^2n_f+4C_FL^3n_f).
\end{aligned}$$

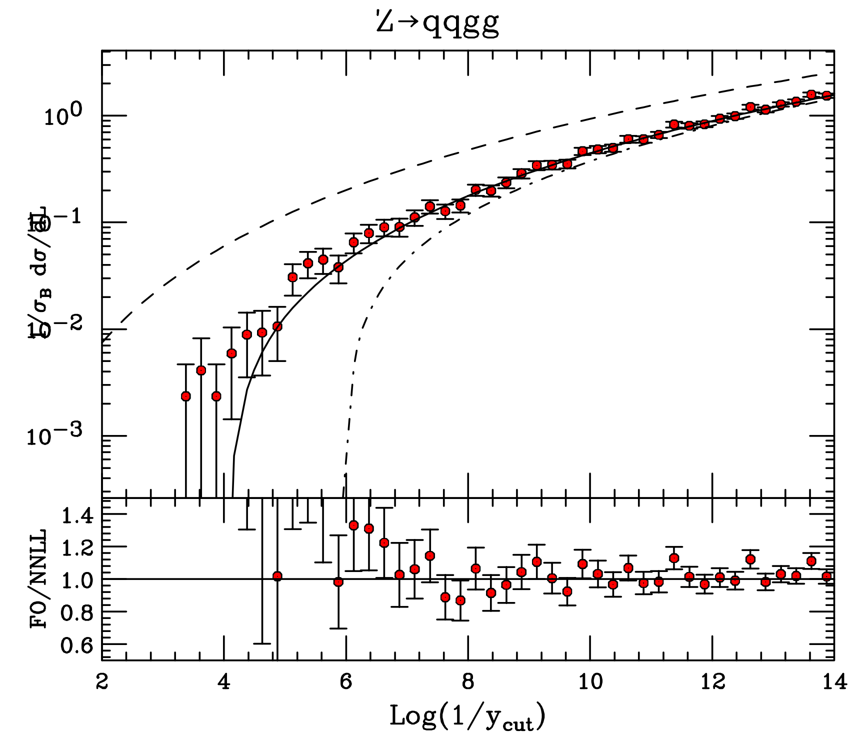
$$a=\alpha_S(Q^2)/\pi\,,\quad L=\log(1/y_{\rm cut})$$

$$R_n=\left(aL^2\right)^{n-2}\left(A+B/L+C/L^2\right)$$

- 'Data'=MG5 exact LO ME

- NNLL terms are helpful!



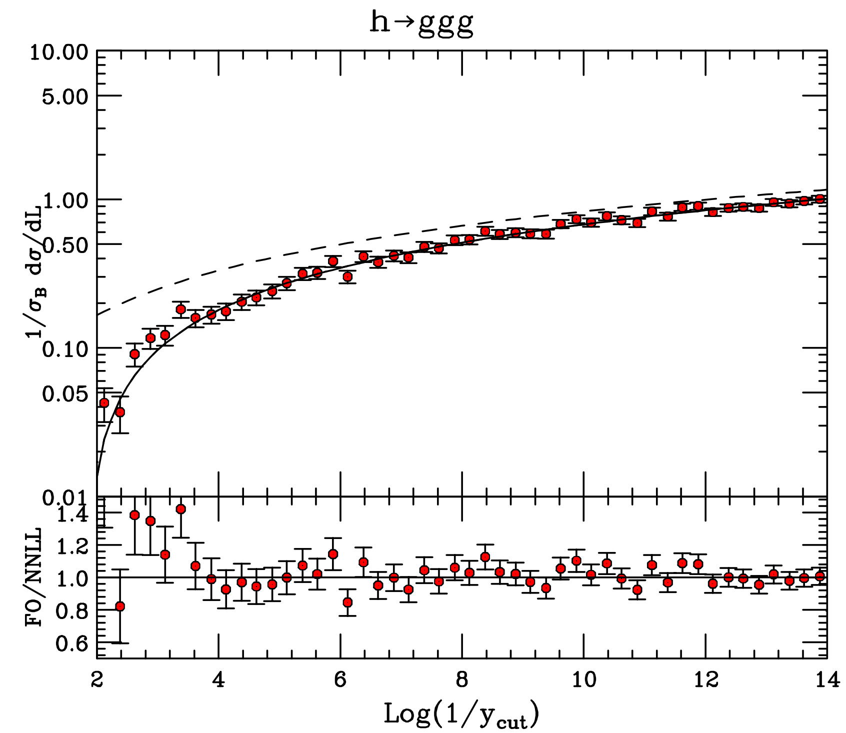


k_t-jet rates: Higgs→jets

- Higgs 2,3,4-jet rates:

$$
\begin{aligned}
R_2^h &= 1+\frac{1}{6}a(11C_AL-3C_AL^2-2Ln_f)+\frac{1}{144}a^2(363C_A^2L^2-176C_A^2L^3+18C_A^2L^4\\
&\quad -132C_AL^2n_f+32C_AL^3n_f+12L^2n_f^2),\\
R_3^h &= \frac{1}{6}a(-11C_AL+3C_AL^2+2Ln_f)+\frac{1}{144}a^2(-726C_A^2L^2+352C_A^2L^3-39C_A^2L^4\\
&\quad +220C_AL^2n_f+36C_FL^2n_f-56C_AL^3n_f-8C_FL^3n_f-16L^2n_f^2),\\
R_4^h &= \frac{1}{144}a^2(363C_A^2L^2-176C_A^2L^3+21C_A^2L^4\\
&\quad -88C_AL^2n_f-36C_FL^2n_f+24C_AL^3n_f+8C_FL^3n_f+4L^2n_f^2).
\end{aligned}
$$

$$a=\alpha_S(Q^2)/\pi\,,\quad L=\log(1/y_{\rm cut})$$



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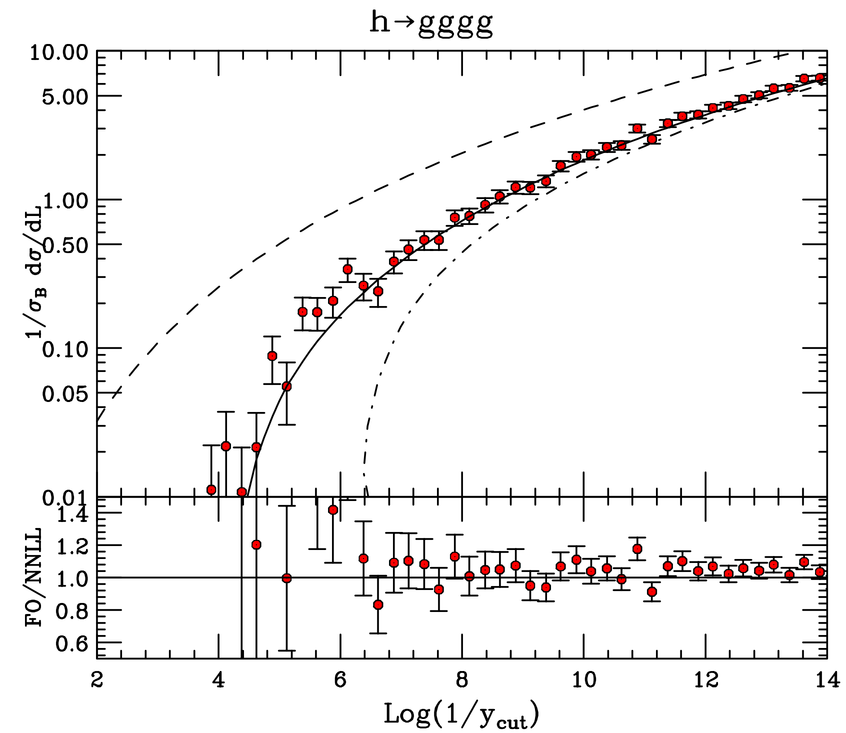

- 'Data'=MG5 exact LO ME
- NNLL terms again helpful!

k_t-type (pp) algorithms

- Compute list of $\{d_{ij}, d_{iB}\}$ Catani, Dokshitzer, Seymour, BW, NPB406(1993)187
  S Ellis, D Soper, PRD48(1993)3160

$$d_{ij} = \min\{p_{ti}^{2p}, p_{tj}^{2p}\}\frac{\Delta R_{ij}^2}{R^2}\;,\quad d_{iB} = p_{ti}^{2p}\;,\quad \Delta R_{ij}^2 \equiv (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

  - If d_{ij} is smallest, combine i & j
  - If d_{iB} is smallest, i is a jet: remove it from list
  - Repeat until list is empty

- $p = +1$: k_T algorithm (scale of running coupling)
- $p = 0$: Cambridge/Aachen algorithm (angular ordering)
- $p = -1$: anti-k_T algorithm (cone jets, not QCD dynamics)

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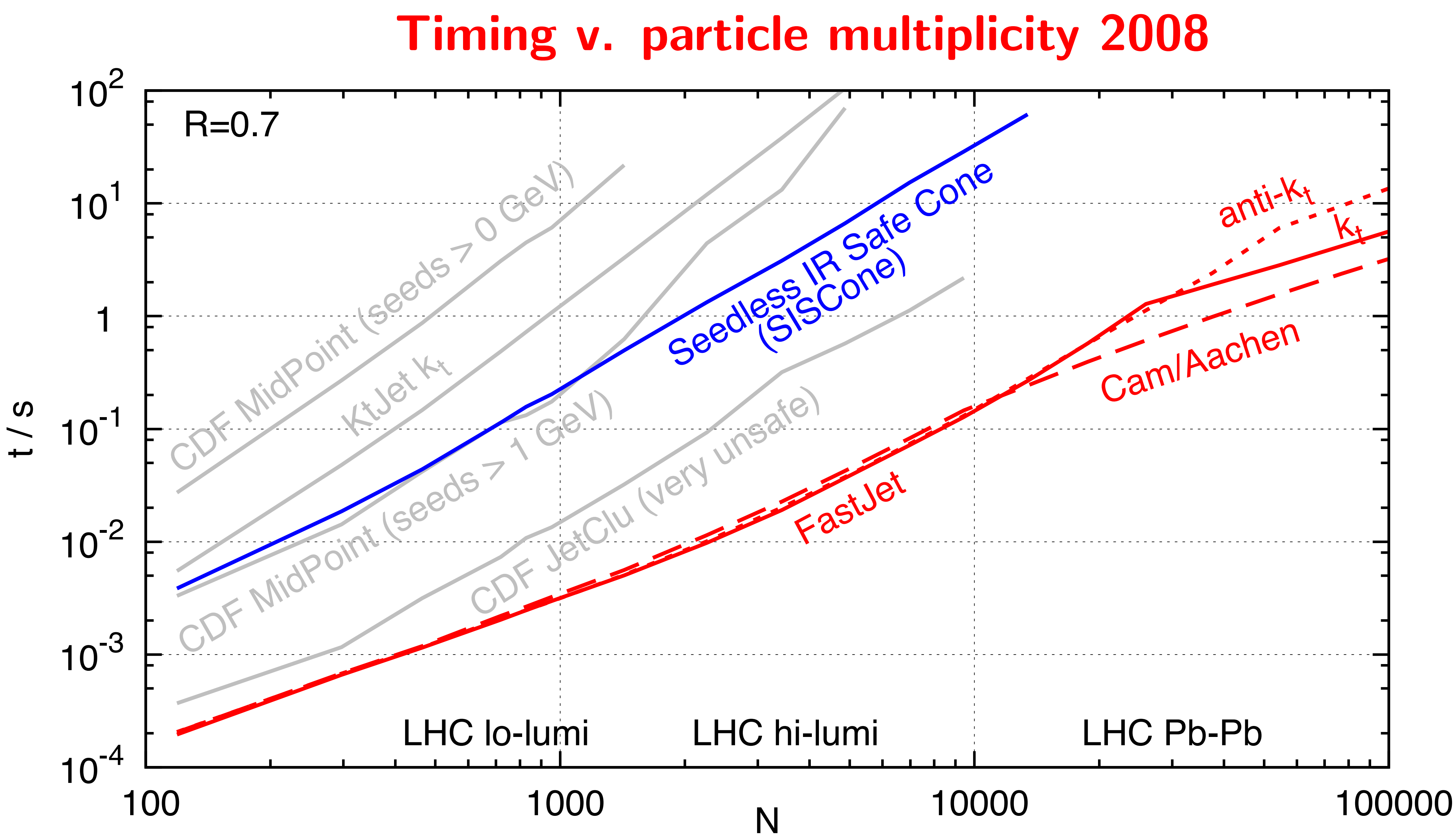
  Dokshitzer, Leder, Moretti, BW, JHEP08 (1997)001
- $p = 0$: Cambridge/Aachen algorithm (angular ordering)
  Wobisch, Wengler, hep-ph/9907280
- $p = -1$: anti-k_T algorithm (cone jets, not QCD dynamics)
  Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

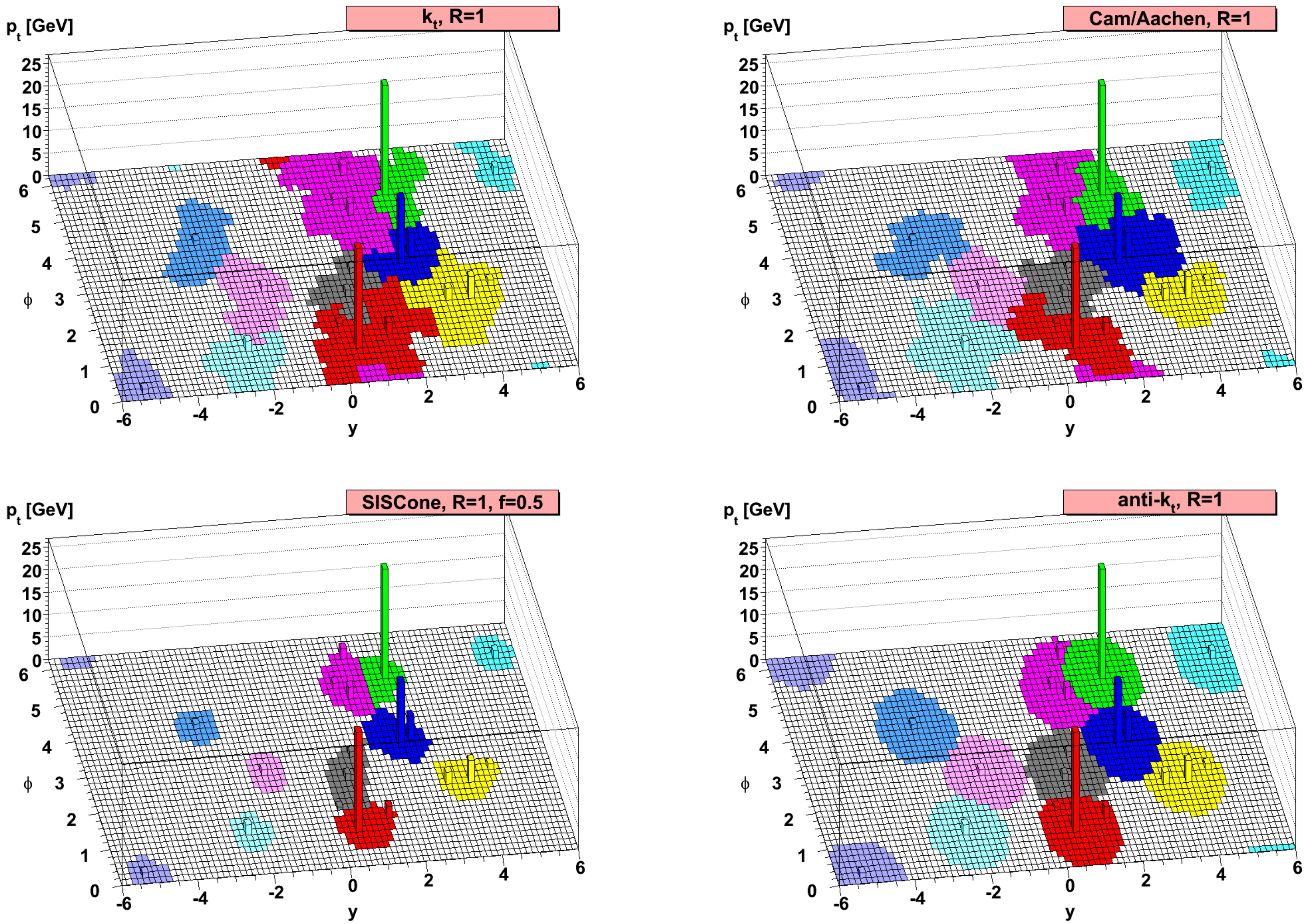
Jet algorithms: computation



$$N^3 \to N \log N$$

FastJet: Cacciari & Salam, Phys Lett B 641(2006)57

Jet algorithms: underlying event



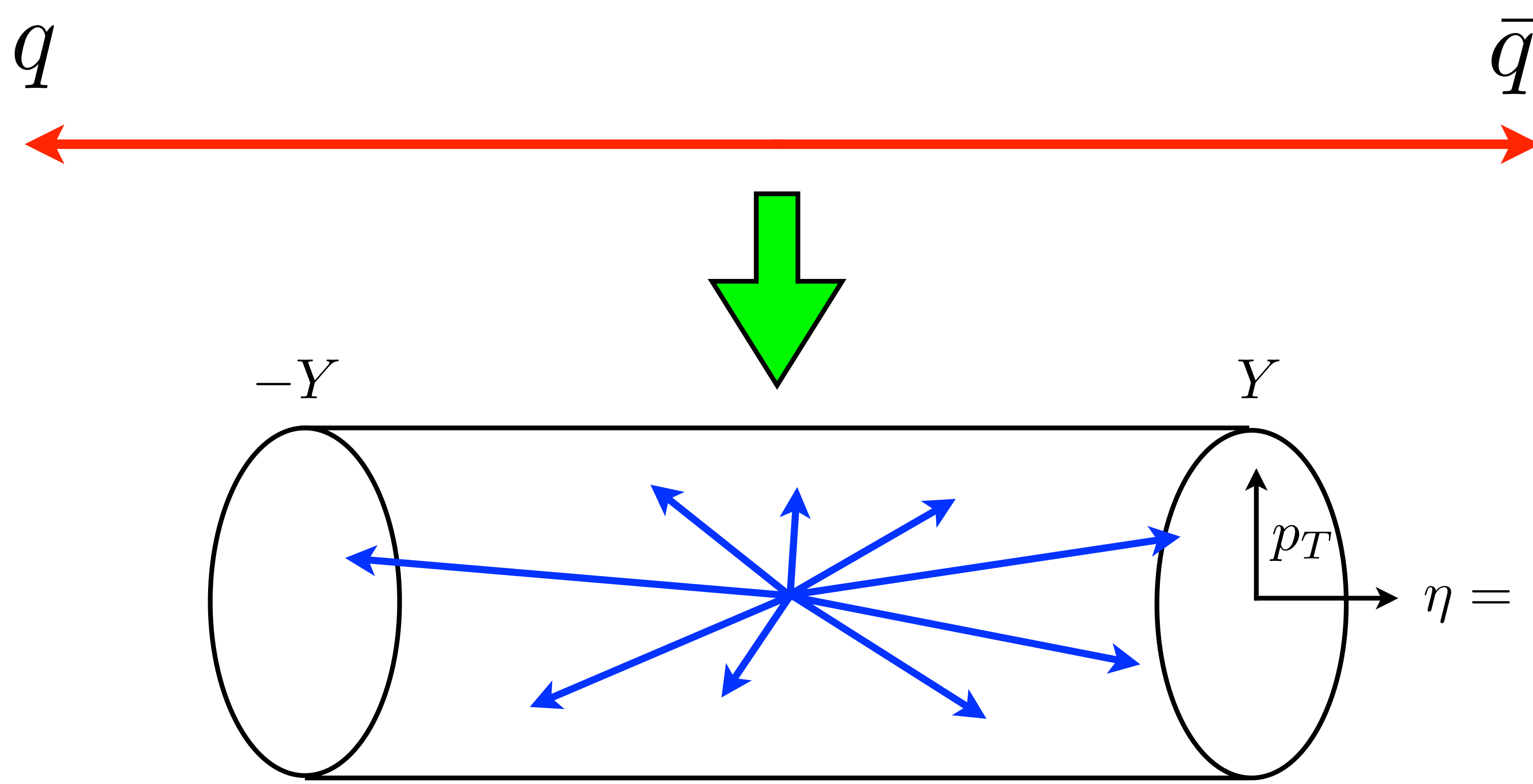
Cacciari, Salam, Soyez, JHEP04(2008)063

- Anti-k_T is best for controlled UE subtraction

Power Corrections

Jet hadronization

- Simple "tube" model describes many features



$$\eta = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

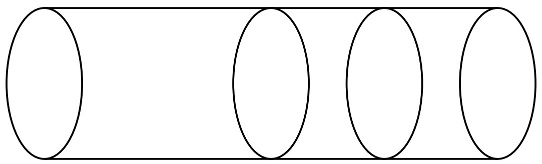
$$Q = E_{\rm cm} = \int d\eta\, d^2p_T\, \rho(p_T)p_T \cosh y = 2\lambda \sinh Y$$

$$\lambda = \int d^2p_T\, \rho(p_T)p_T = N_{\rm had}\langle p_T\rangle/2Y$$

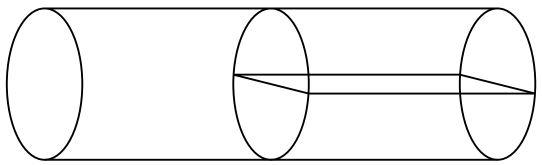
Jet hadronization

Dokshitzer, Leder, Moretti, BW, JHEP 08(1997)001

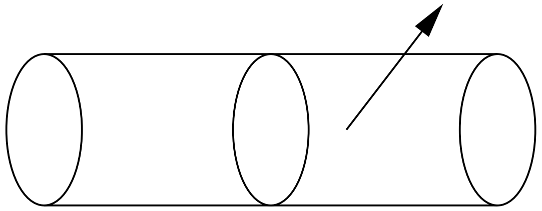
- Algorithm should classify tube as 2-jet
  - $\langle y_{3-\mathrm{jet}} \rangle$ smallest is best
- JADE: $\langle y_{3-\mathrm{jet}} \rangle \sim \lambda/Q$



- LUCLUS, k_T: $\langle y_{3-\mathrm{jet}} \rangle \sim (\lambda \ln Q/Q)^2$

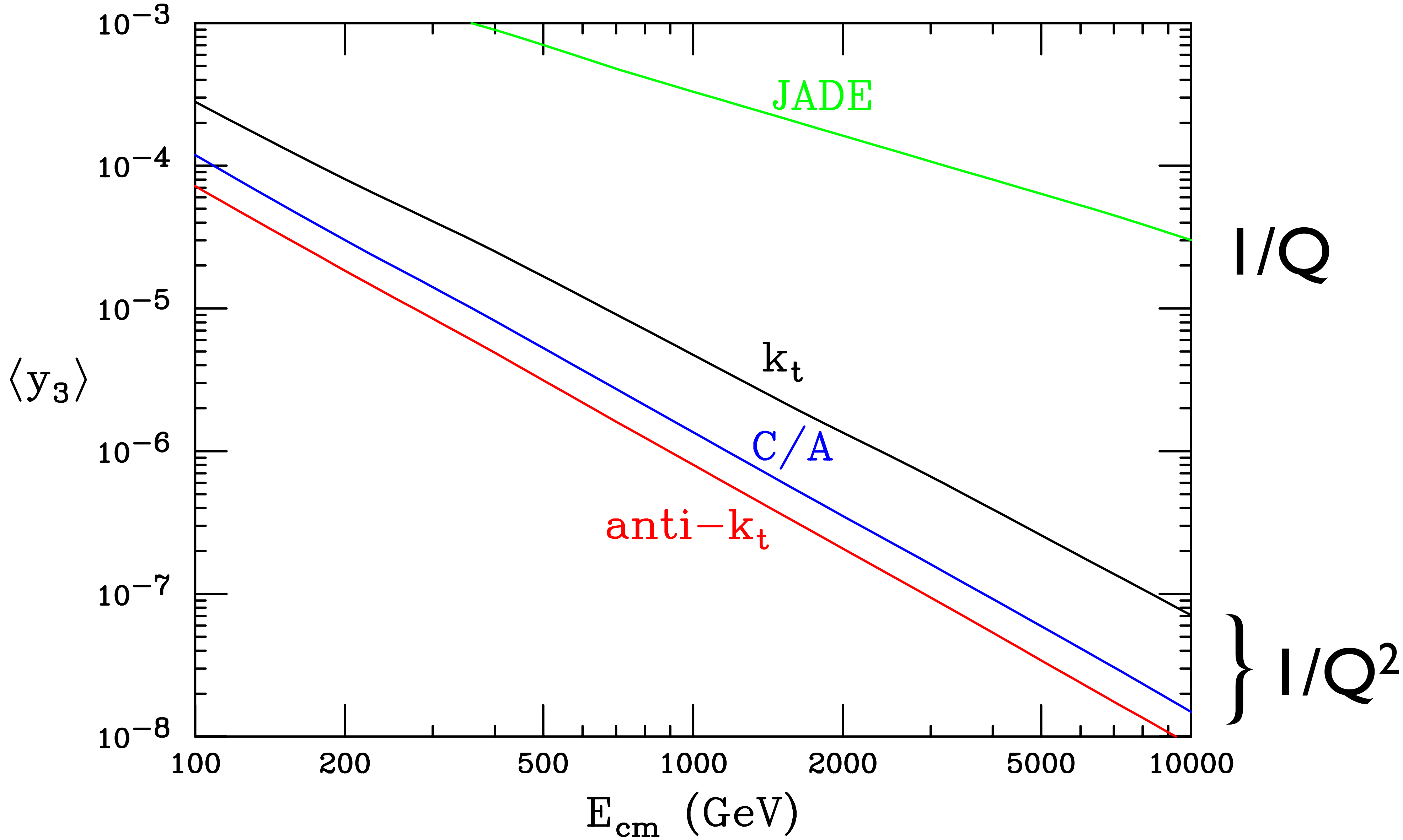


- Cambridge/Aachen: $\langle y_{3-\mathrm{jet}} \rangle \sim (\lambda \ln\ln Q/Q)^2$



- Anti-k_T: $\langle y_{3-\mathrm{jet}} \rangle \sim (\lambda/Q)^2$

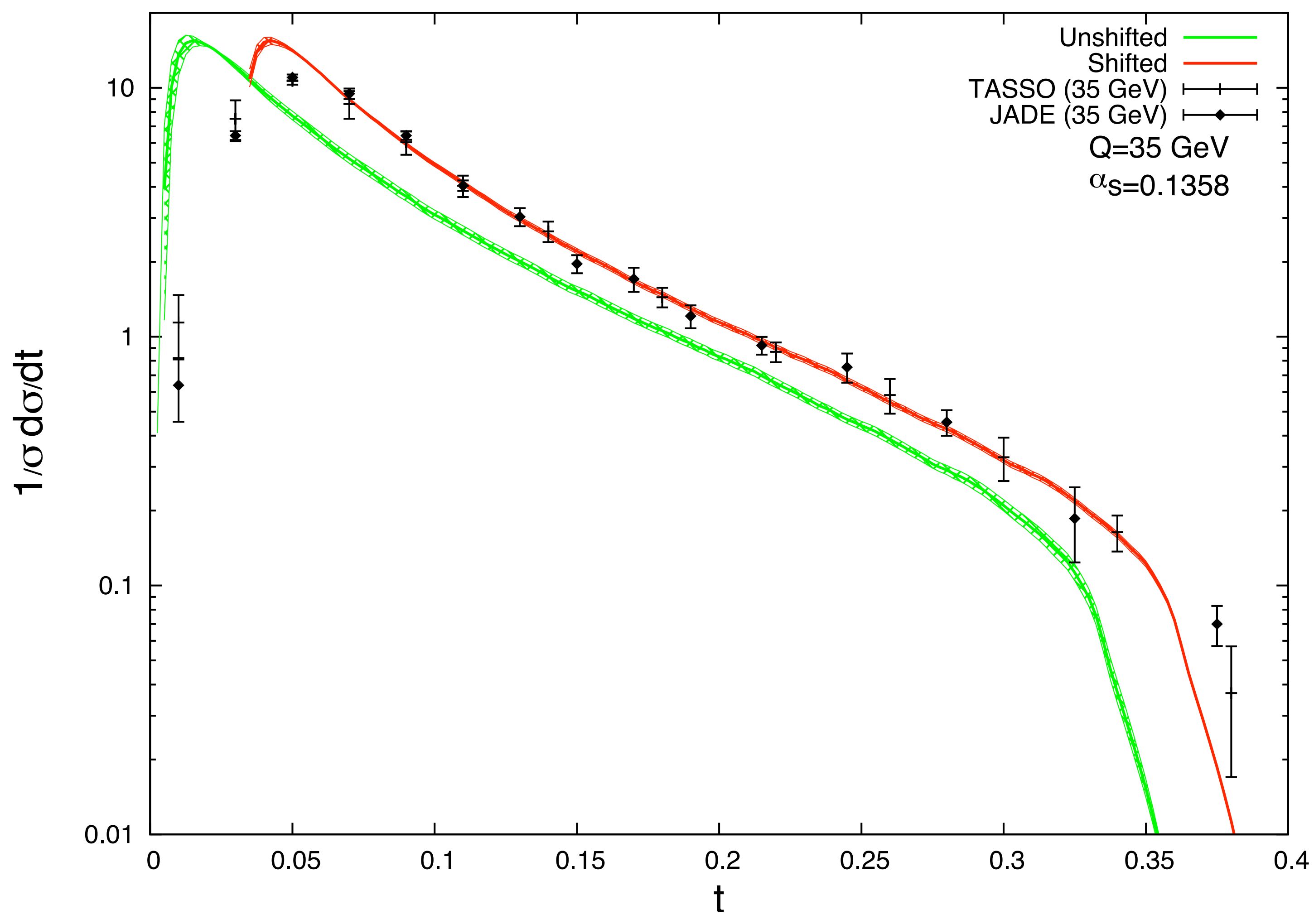
Jet algorithms: hadronization



- Anti-k_T is best for small hadronization effect

NP shift in Thrust

$$T = \max_{\vec{n}} \left(\frac{\sum_{i=1}^{N} |\vec{p_i} . \vec{n}|}{\sum_{i=1}^{N} |\vec{p_i}|} \right) \equiv 1 - t$$



DMW 1995

Dispersive approach to power-behaved contributions in QCD hard processes ★

Yu.L. Dokshitzer [a,1], G. Marchesini [b], B.R. Webber [c]

[a] *Theory Division, CERN, CH-1211 Geneva 23, Switzerland*

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Received 25 January 1996; accepted 18 March 1996

DMW 1995

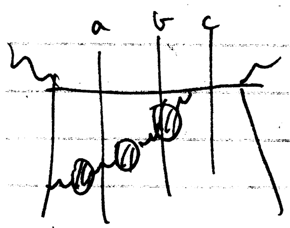
'Dispersive' approach

$$\alpha_s(k^2) = -\int \frac{d\mu^2}{\mu^2+k^2}\,\rho_s(\mu^2)$$

$$\rho_s(\mu^2) = \frac{1}{2\pi i}\,\mathrm{Disc}\left[\alpha_s(-\mu^2)\right] = \frac{1}{2\pi i}\left[\alpha_s(\mu^2 e^{i\pi}) - \alpha_s(\mu^2 e^{-i\pi})\right]$$

$$F = \alpha_s(0)\,\mathcal{F}(0) + \int \frac{d\mu^2}{\mu^2}\,\rho_s(\mu^2)\,\mathcal{F}(\mu^2/Q^2)$$

(a) (b+c)



$$= \int \frac{d\mu^2}{\mu^2}\,\rho_s(\mu^2)\left[\mathcal{F}(\mu^2/Q^2) - \mathcal{F}(0)\right]$$

$$= \frac{1}{2\pi i}\int \frac{d\mu^2}{\mu^2}\left[\alpha_s(\mu^2 e^{i\pi}) - \alpha_s(\mu^2 e^{-i\pi})\right]\left[\mathcal{F}(\mu^2/Q^2) - \mathcal{F}(0)\right]$$

$$= -\frac{1}{2\pi i}\int \frac{d\mu^2}{\mu^2}\,\alpha_s(\mu^2)\,\mathrm{Disc}\left[\mathcal{F}(-\mu^2/Q^2)\right]$$

check: $\alpha_s(\mu^2) \simeq \alpha_s(Q^2)$

$$\Rightarrow F \simeq -\frac{\alpha_s(Q^2)}{2\pi i}\int \frac{d\mu^2}{\mu^2}\,\mathrm{Disc}\left[\mathcal{F}(-\mu^2/Q^2)\right] = \alpha_s(Q^2)\,\mathcal{F}(0) \quad ✓$$

$\alpha_s(\mu^2) \to \alpha_{PT}(\mu^2) + \alpha_{NP}(\mu^2)$

$$\Rightarrow F_{NP} \sim \int \frac{d\mu^2}{\mu^2}\,\alpha_{NP}(\mu^2)\,\mathcal{G}(\mu^2/Q^2)$$

$$\mathcal{G}(\epsilon) = \lim_{\epsilon\to 0} -\frac{1}{2\pi i}\,\mathrm{Disc}\,\mathcal{F}(-\epsilon)$$

Denote the power correction to $\ln \tilde{\mathcal{J}}^q_\nu(Q^2)$ by

$$-\nu Q \cdot \frac{2C_F}{\pi} \cdot dQ\,\frac{\Lambda}{Q} = -\frac{C_F 2\nu Q^2 d\Lambda}{\pi\, Q} \equiv -\nu Q^2 a\frac{\Lambda}{Q}$$

$\left\{ \int d\Lambda \right.$ = power-corr'n to $\int^Q dq\,\alpha_s(q^2)$

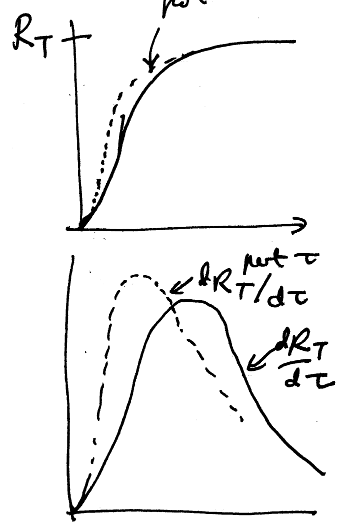
$$R_T(\tau) \simeq \frac{1}{2\pi i}\int \frac{d\nu}{\nu}\, e^{\nu\tau Q^2 - 2\nu Q^2 a\Lambda/Q}\left[\tilde{\mathcal{J}}^q_\nu\right]^2_{pert}$$

$$\Rightarrow R_T(\tau) \simeq R_T^{pert}(\tau - 2a\Lambda/Q)$$

$$R_T(\tau) = \sigma(T > 1-\tau)/\sigma_{tot}$$

$$\frac{1}{\sigma}\frac{d\sigma}{dT} = \frac{dR_T}{d\tau}\Big|_{\tau=1-T}$$

$$\langle\tau\rangle = \int d\tau\,\tau\,\frac{dR_T}{d\tau} = \int d\tau\,\tau\,\frac{dR_T^{pert}}{d\tau}\Big|_{\tau-2a\Lambda/Q} = \langle\tau\rangle_{pert} + 2a\Lambda/Q$$



$a = \frac{2C_F}{\pi}d$ Empirically $\frac{1\,\mathrm{GeV}}{Q}$

$$\Rightarrow \frac{4C_F}{\pi}d\Lambda \sim 1\,\mathrm{GeV} \underset{\Lambda\sim 250\,\mathrm{MeV}}{\Rightarrow} \frac{C_F d}{\pi} \sim 1.0 \Rightarrow d = \frac{3\pi}{4}$$

$$\int_0^Q dq\,\frac{\alpha_s(q^2)}{\pi} \sim Q\frac{\alpha_s(Q^2)}{\pi} + \frac{d\Lambda}{\pi} = \int_1^Q + \int_0^1$$

$\frac{3}{16} \simeq 0.2$

$$\Rightarrow Q\frac{\alpha_s(Q^2)}{\pi} - \frac{\alpha_s(1)}{\pi} + \int_0^1 = \frac{d\Lambda}{\pi}$$

$$\Rightarrow \int_0^1 dq\,\frac{\alpha_s(q^2)}{\pi} = \frac{\alpha_s(1)}{\pi} + \frac{d\Lambda}{\pi} = \sim 0.27 + \frac{1}{4C_F} \sim 0.47$$

NLL thrust resummation

$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma}{dT} = \frac{Q^2}{2\pi i}\int_C d\nu\, {\rm e}^{(1-T)\nu Q^2}\left[\tilde{J}^q_\nu(Q^2)\right]^2 ,$$

$$\ln \tilde{J}^q_\nu(Q^2) = \int_0^1 \frac{du}{u}\left({\rm e}^{-u\nu Q^2}-1\right)\left[\int_{u^2Q^2}^{uQ^2}\frac{dq^2}{q^2}A(\alpha_{\rm S}(q)) + \frac{1}{2}B(\alpha_{\rm S}(\sqrt{u}Q))\right]$$

- Leading PT contribution from $q < \mu_{\rm I}$

$$\delta \ln \tilde{J}^q_\nu(Q^2)\Big|_{\rm pert} = -\frac{2C_F}{\pi}\frac{\mu_{\rm I}}{Q}\Bigg\{\alpha_{\rm S}(\mu_R) + \alpha_s^2(\mu_R)\frac{\beta_0}{\pi}\left(\ln\frac{\mu_R}{\mu_I}+\frac{K}{2\beta_0}+1\right)$$
$$+\alpha_s^3(\mu_R)\left(\frac{\beta_0}{\pi}\right)^2\left[\ln^2\frac{\mu_R}{\mu_I}+\left(\ln\frac{\mu_R}{\mu_I}+1\right)\left(2+\frac{\beta_1}{2\beta_0^2}+\frac{K}{\beta_0}\right)+\frac{L}{4\beta_0^2}\right]\Bigg\}\nu Q^2.$$

0.116 + 0.087 + 0.071 = 0.274

NNLO

$$K = C_A\left(\frac{67}{18}-\frac{\pi^2}{6}\right)-\frac{5}{9}n_f = 3.5\,,\quad L = 11.0$$

Power correction to thrust

- Replace PT by NP for $q < \mu_{\rm I}$

$$\delta \ln \tilde{J}^q_\nu(Q^2)\Big|_{\rm n.p.} = \frac{2C_F}{\pi}\int_0^{\mu_{\rm I}} \frac{dq}{q}\alpha_{\rm eff}(q)\int_{q^2/Q^2}^{q/Q}\frac{du}{u}\left(e^{-u\nu Q^2}-1\right)$$

- For $\mu_{\rm I}\nu Q \ll 1$, i.e. $1-T \gg \mu_{\rm I}/Q$

$$\delta \ln \tilde{J}^q_\nu(Q^2)\Big|_{\rm n.p.} \simeq -\frac{2C_F}{\pi}\int_0^{\mu_{\rm I}} dq\,\alpha_{\rm eff}(q)\,\nu Q \equiv -\frac{2C_F}{\pi}\frac{\mu_{\rm I}}{Q}\alpha_0(\mu_{\rm I})\,\nu Q^2$$

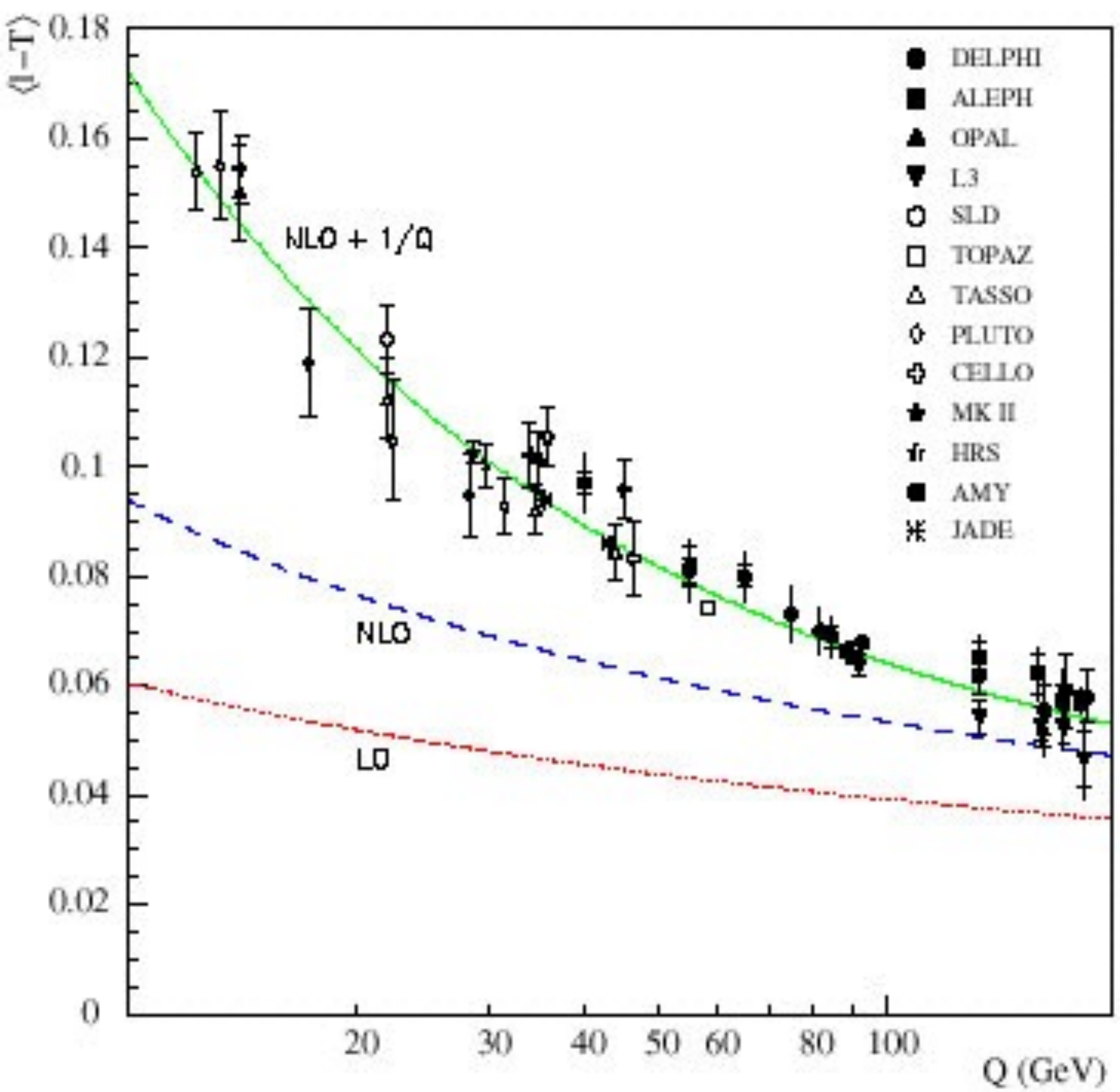
- `Milan Factor': $\alpha_0 \to 2\mathcal{M}\,\alpha_0/\pi = 0.95\,\alpha_0$

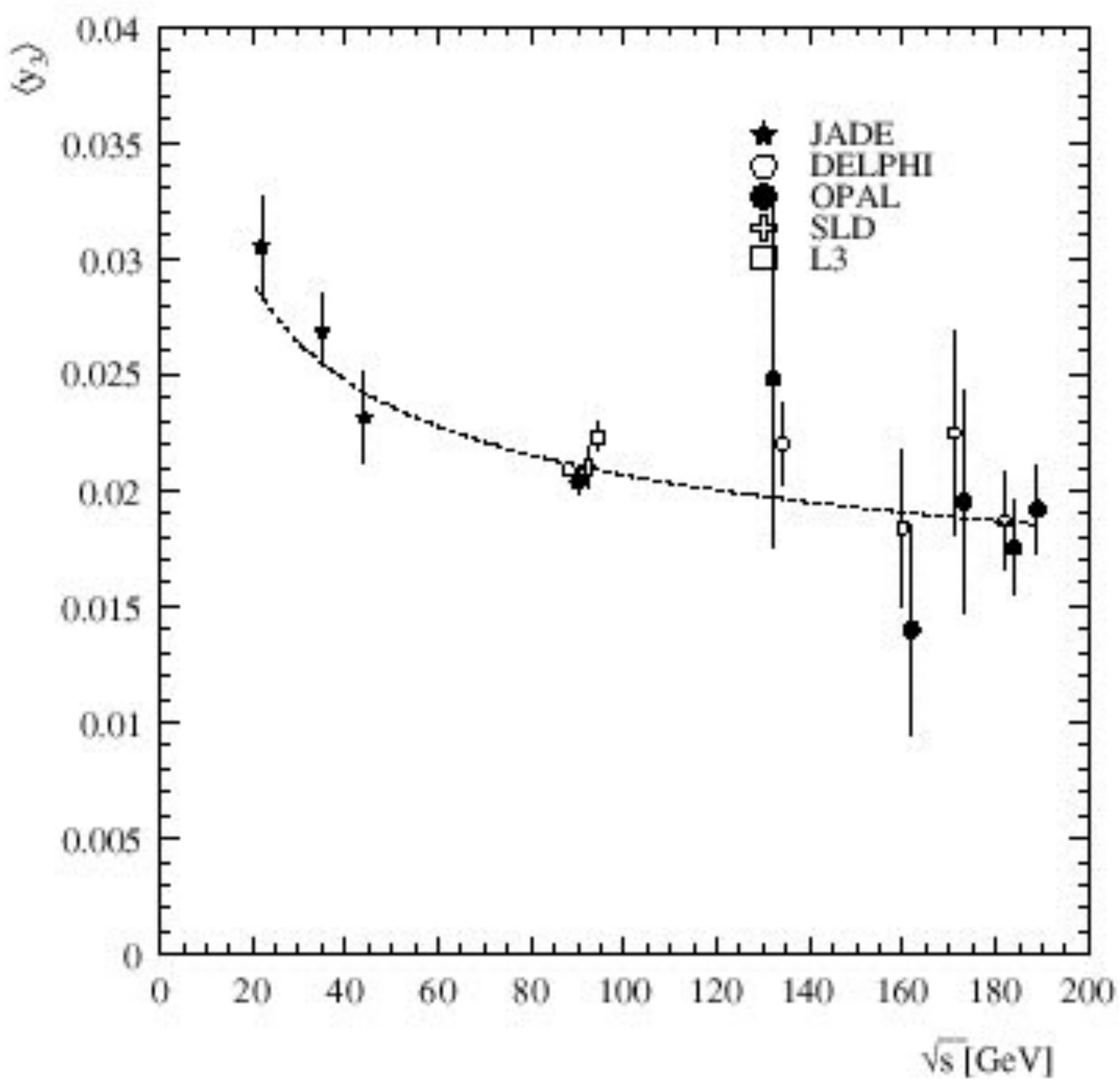
Dokshitzer, Lucenti, Marchesini, Salam, JHEP05(1998)003

$$\Rightarrow\ \delta \ln \tilde{J}^q_\nu(Q^2) = \delta \ln \tilde{J}^q_\nu(Q^2)\Big|_{\rm n.p.} - \delta \ln \tilde{J}^q_\nu(Q^2)\Big|_{\rm pert} = \delta T\,\nu Q^2$$

Power corrections to event shapes

- 1/Q correction to T, absent in y_3



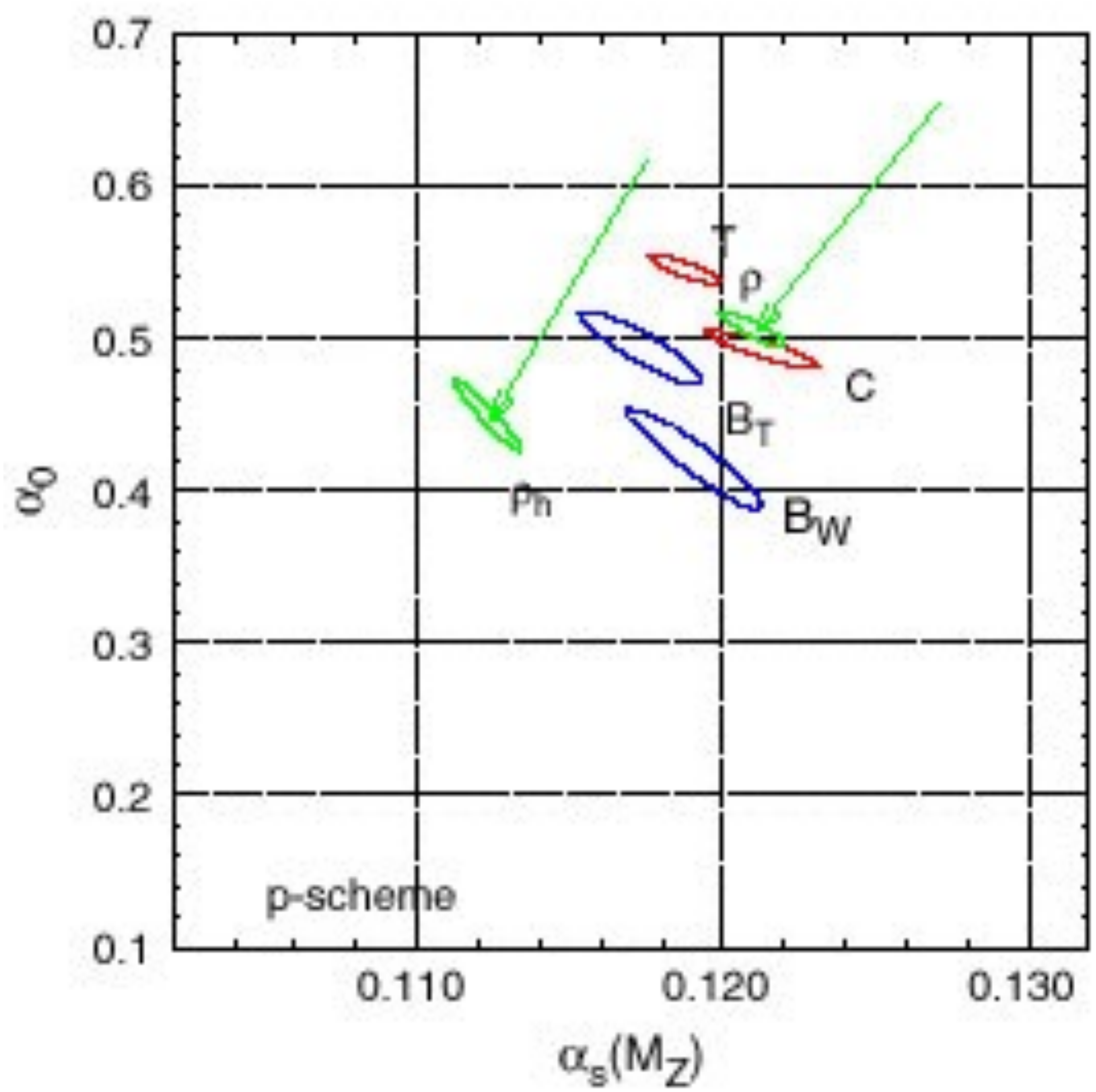


Dasgupta & Salam, J Phys G (2004) R143

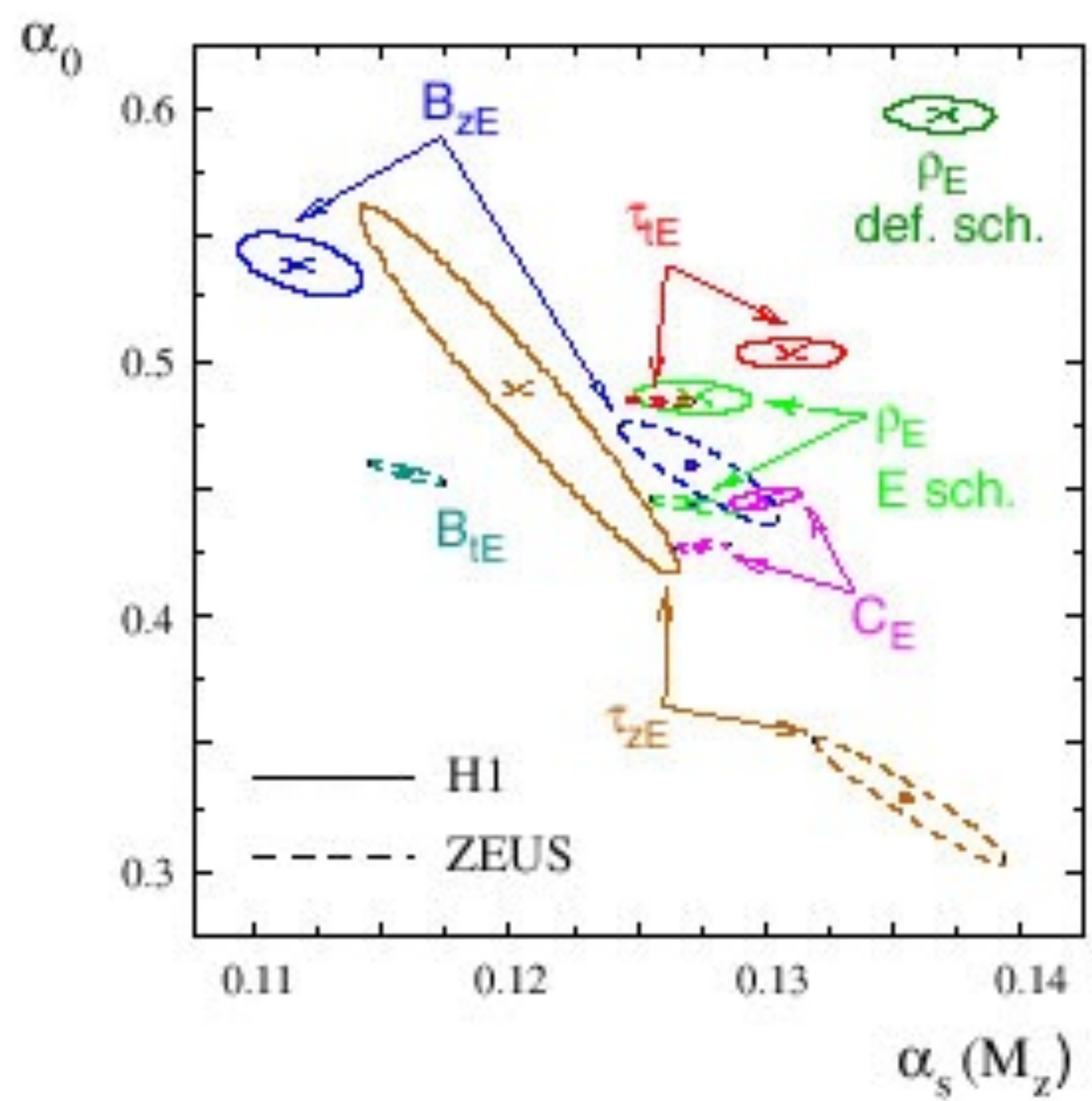
Power corrections to event shapes

- 1/Q corrections to mean values

e^+e^-



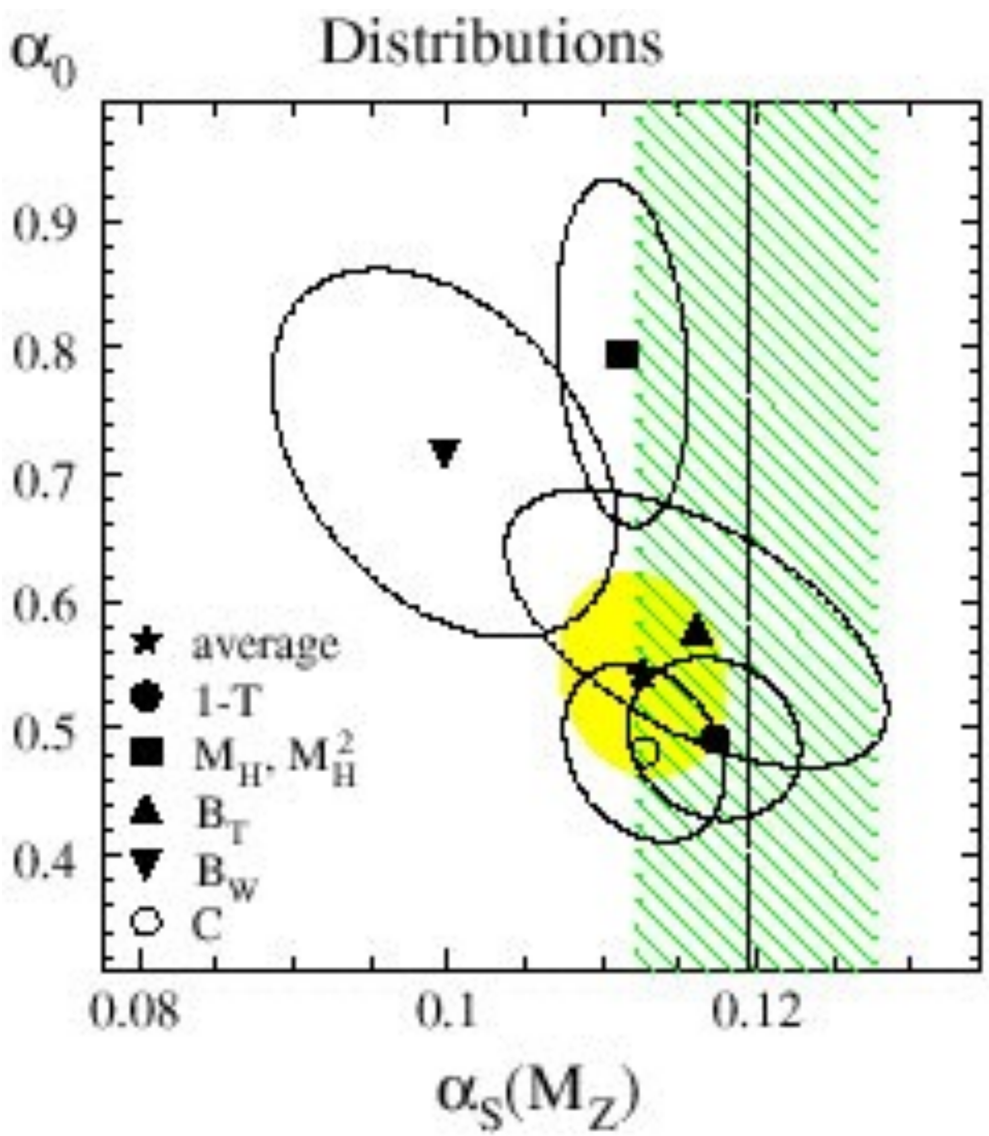
DIS



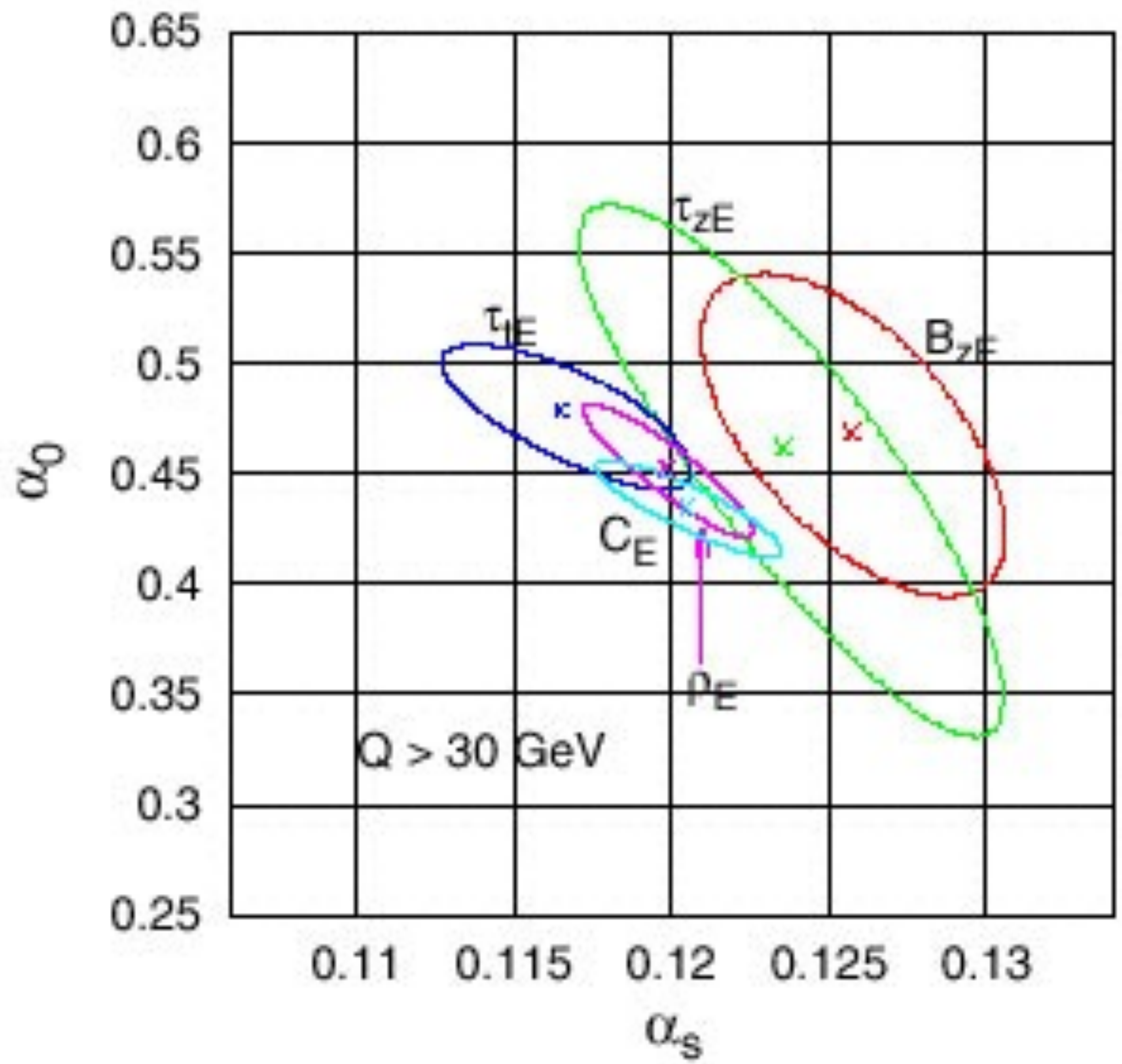
Power corrections to event shapes

- 1/Q corrections to distributions

e^+e^-

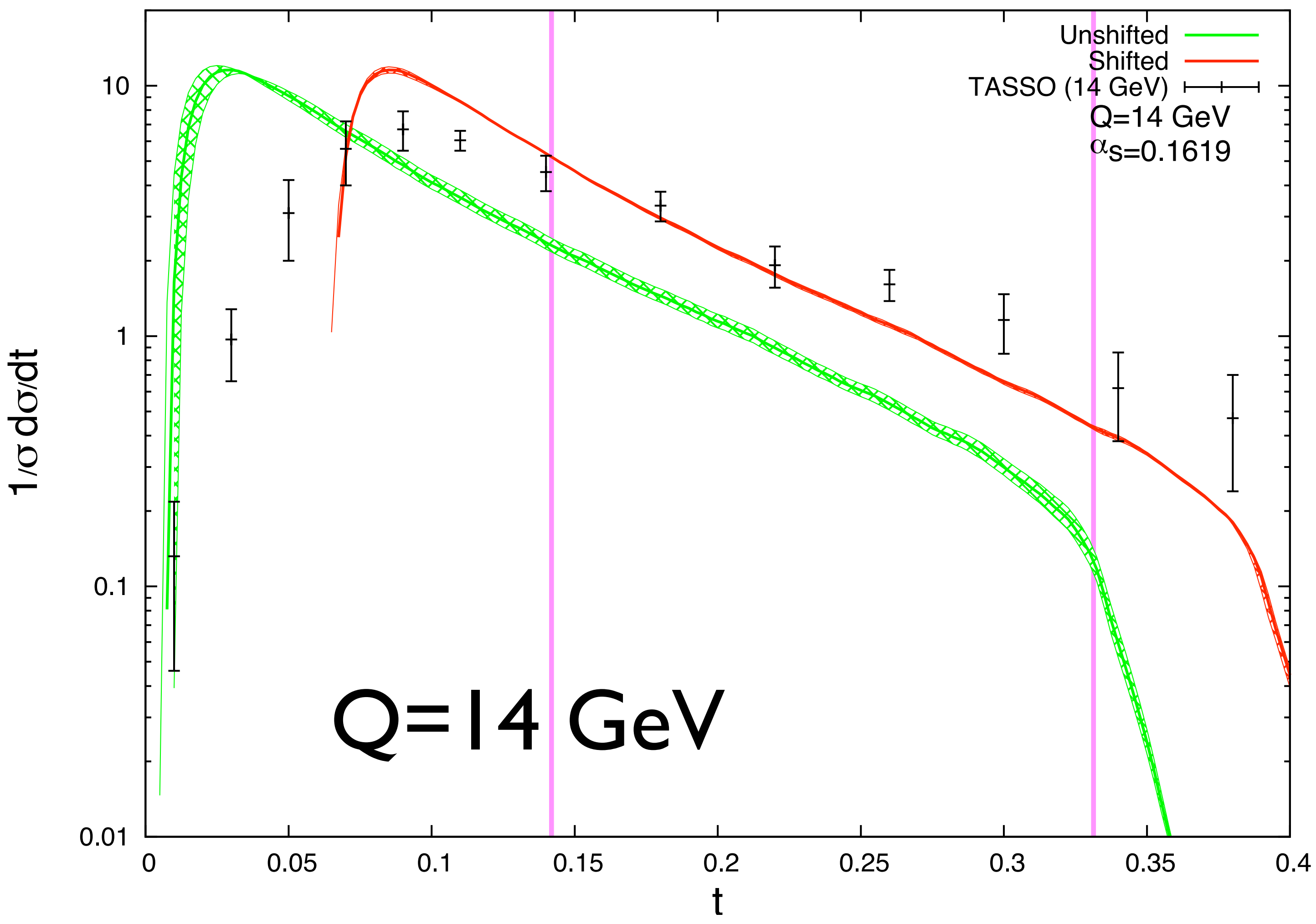


DIS



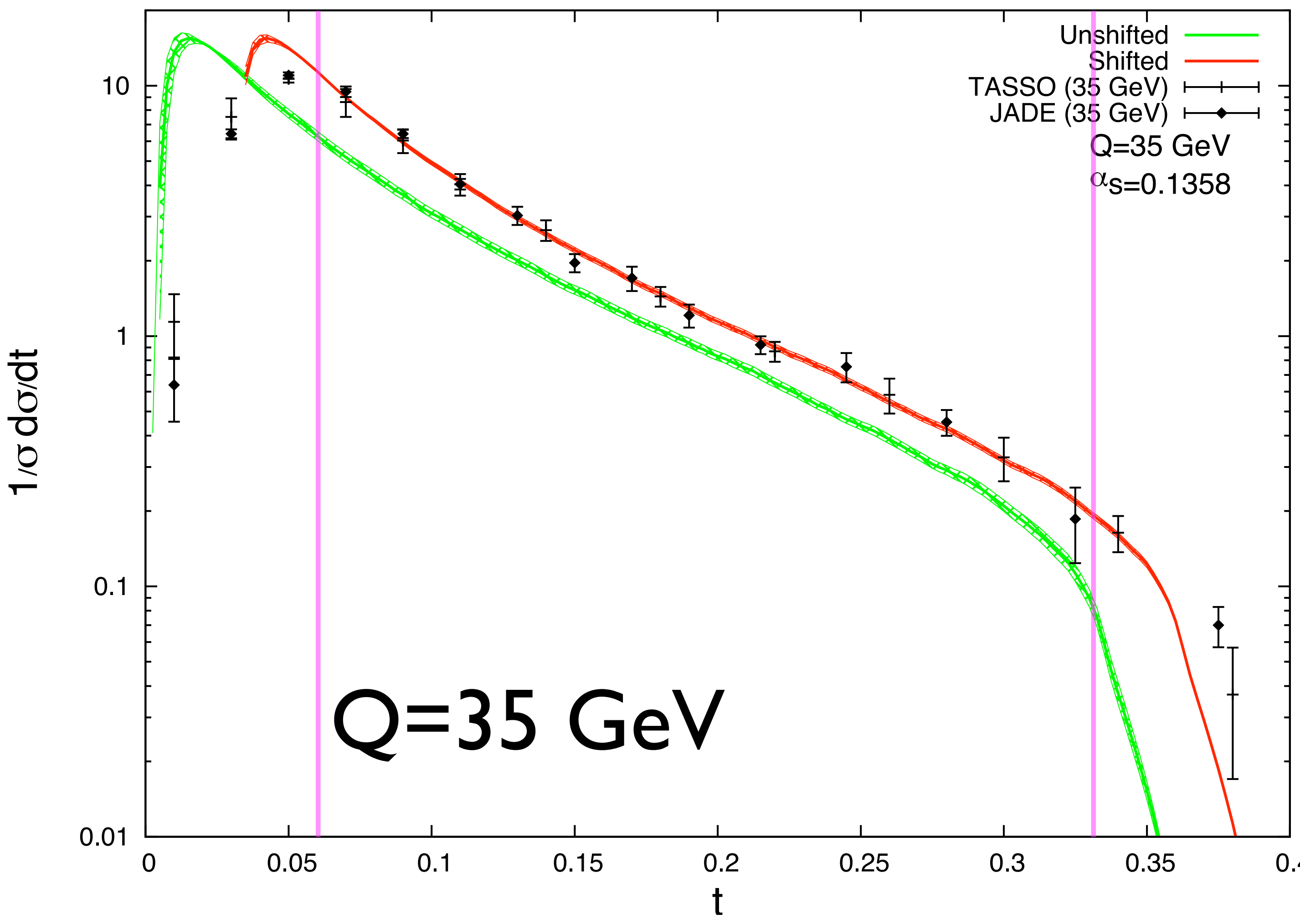
NNLO+NLL+NP fit to Thrust

- Fit range: $\max\{\mu_{\rm I}/Q, 0.05\} \leq t < 0.33$

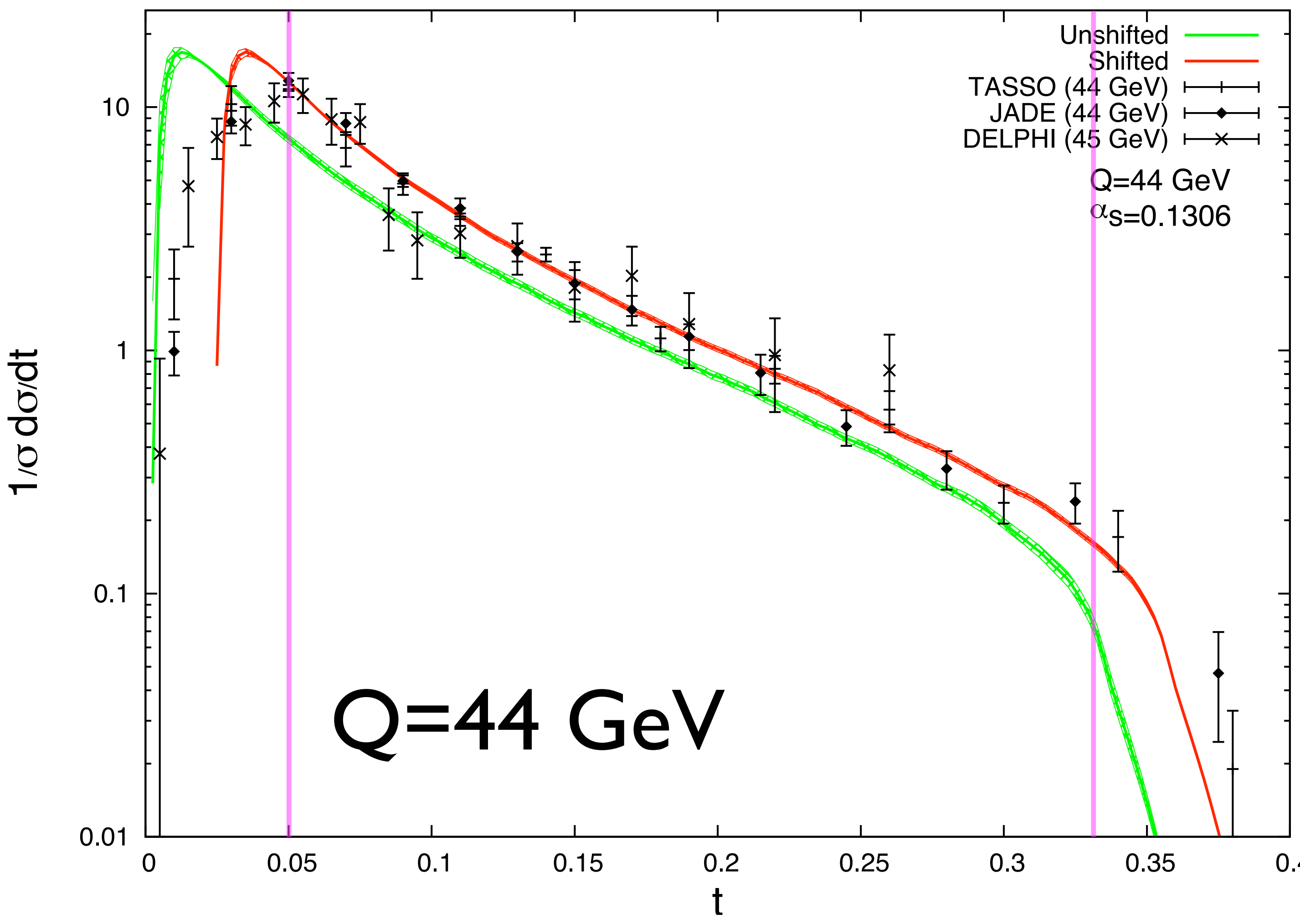


Davison & BW, EPJC59 (2009) 13

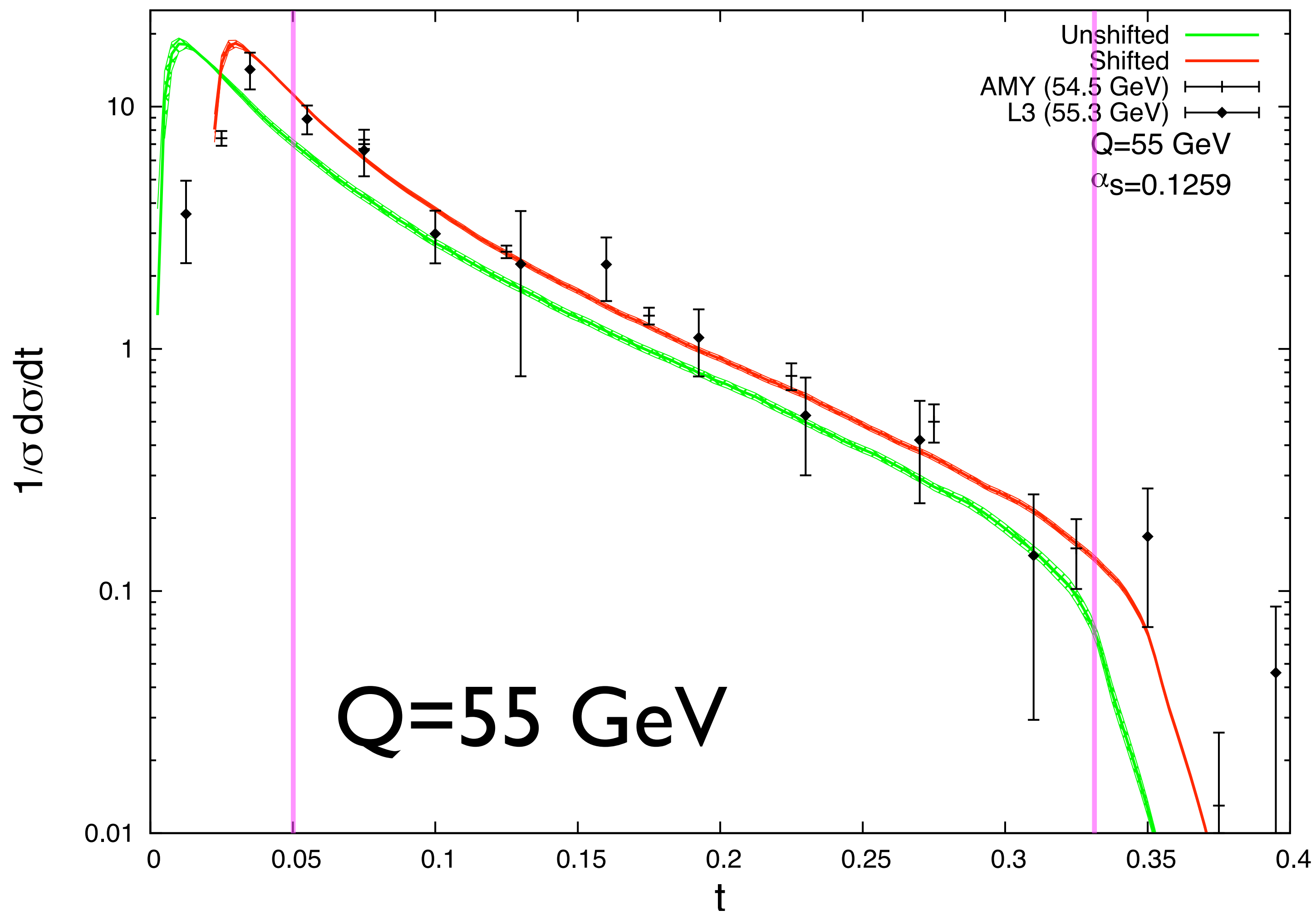
NP shift in Thrust



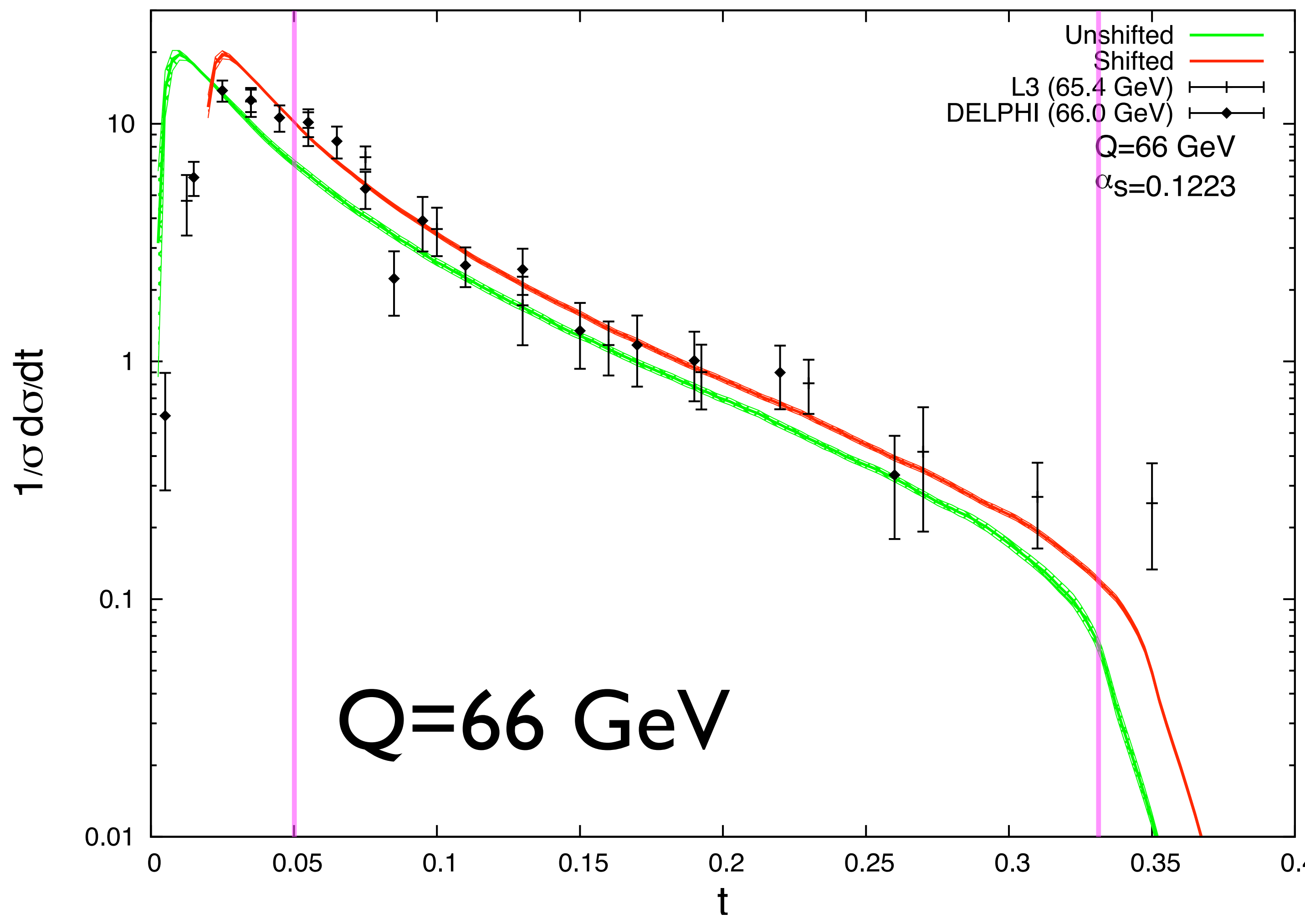
NP shift in Thrust



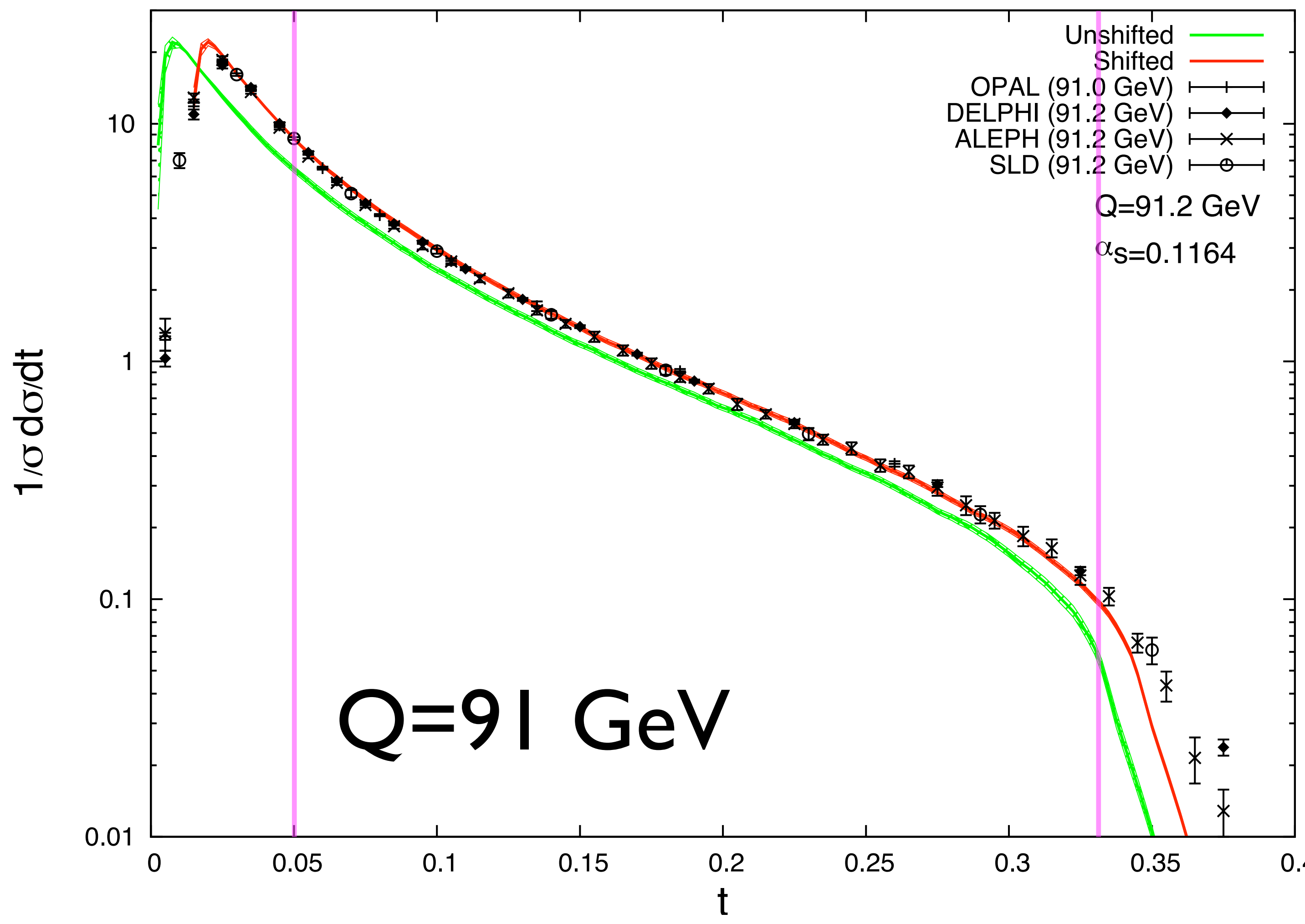
NP shift in Thrust



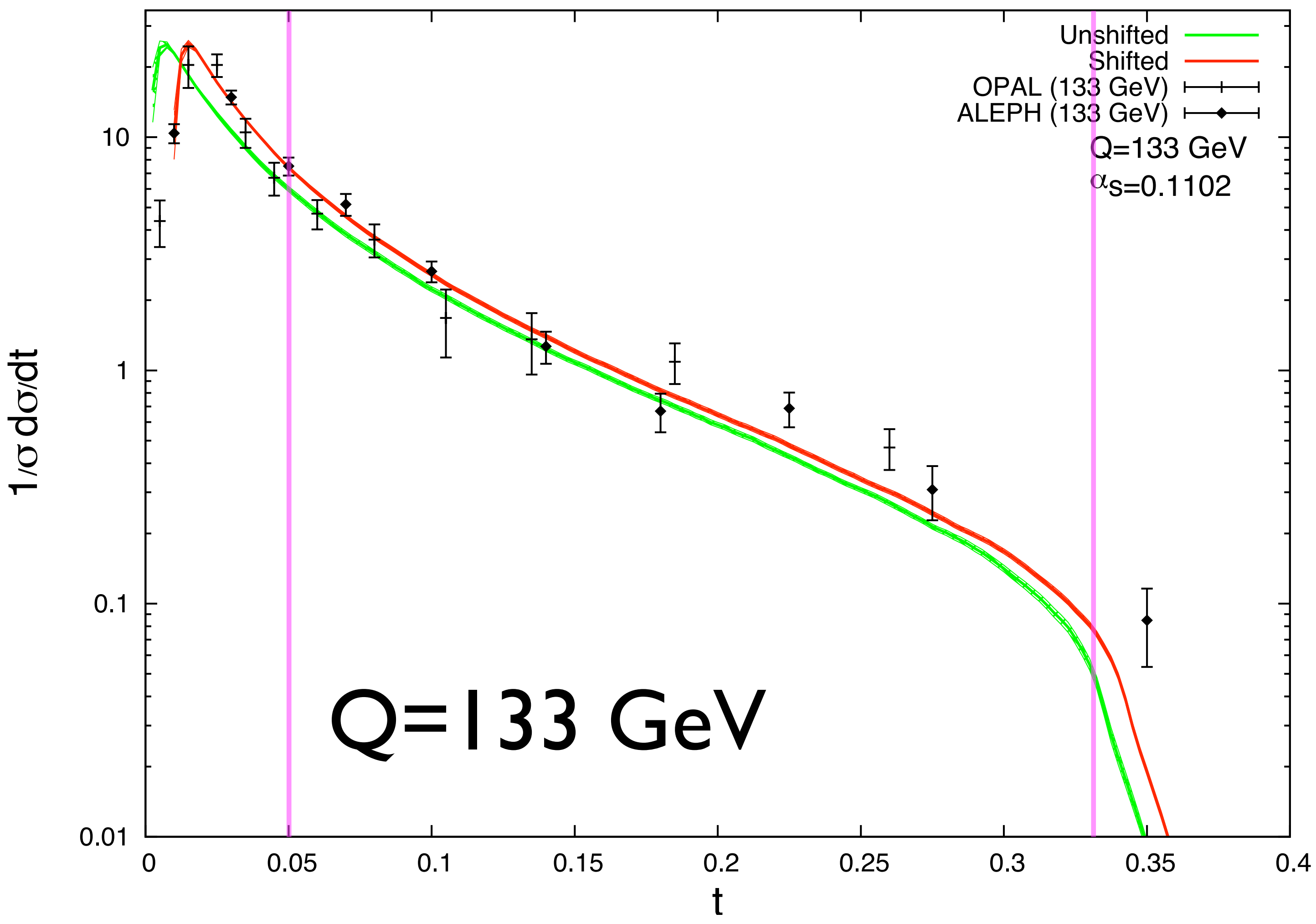
NP shift in Thrust



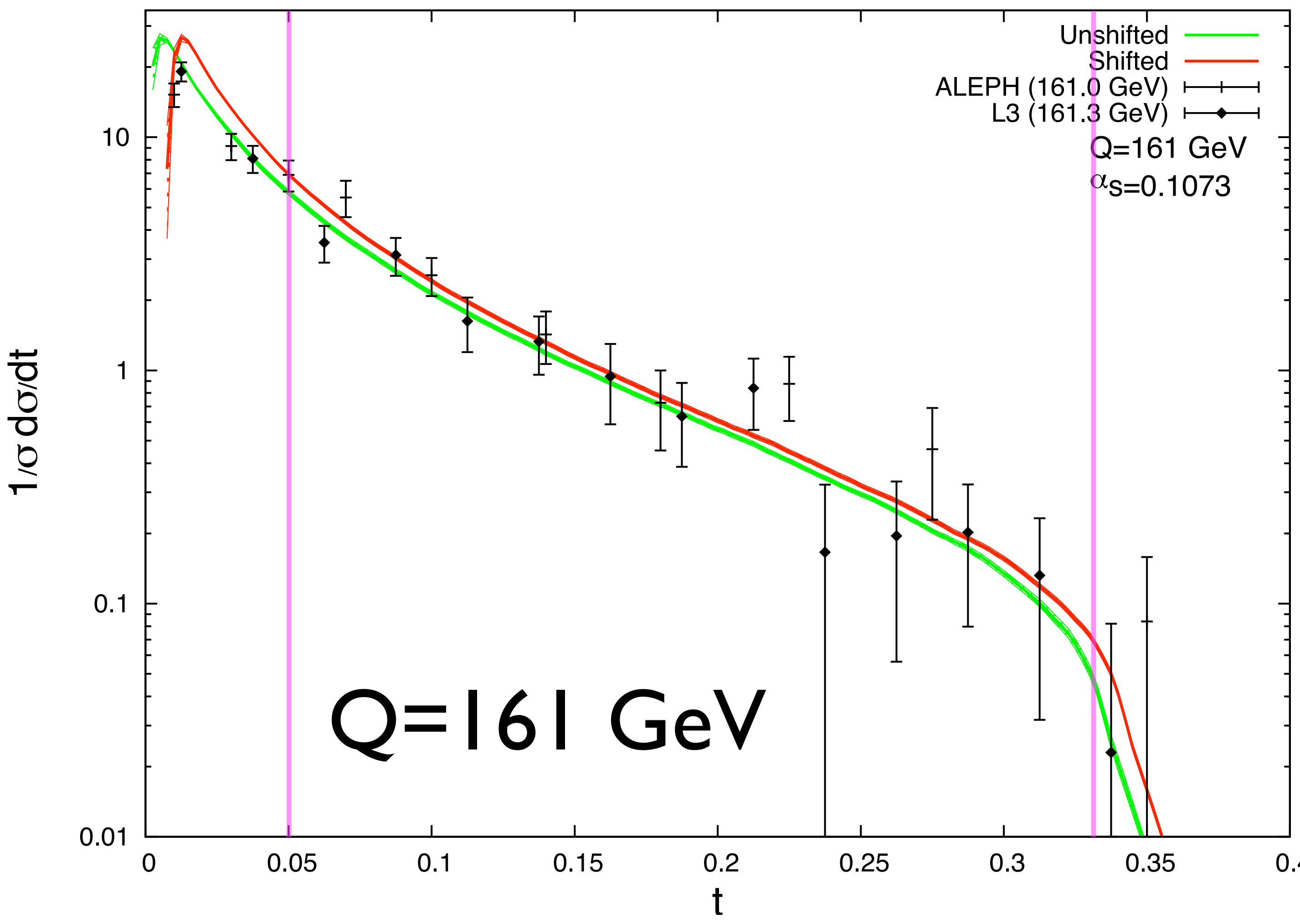
NP shift in Thrust



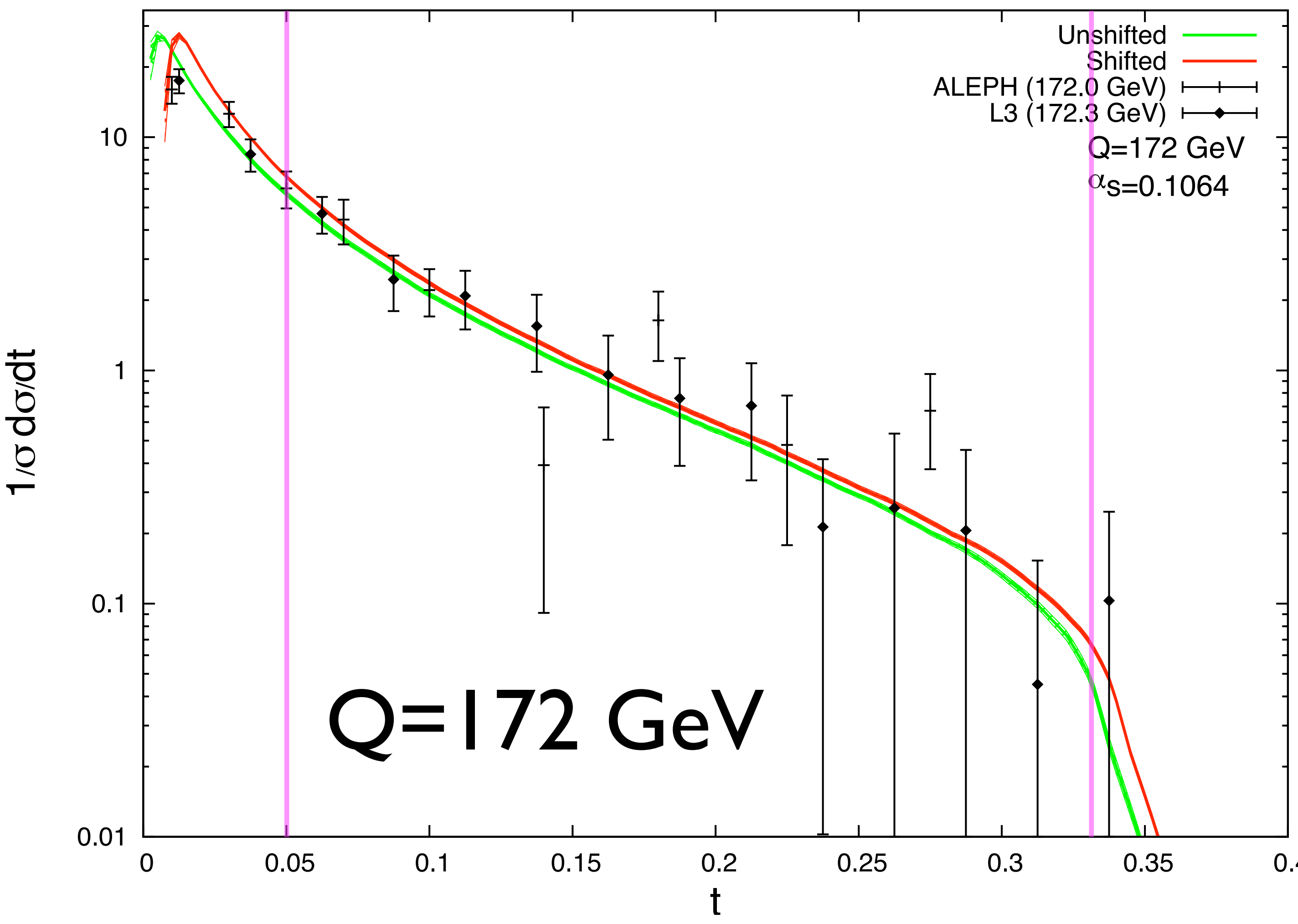
NP shift in Thrust



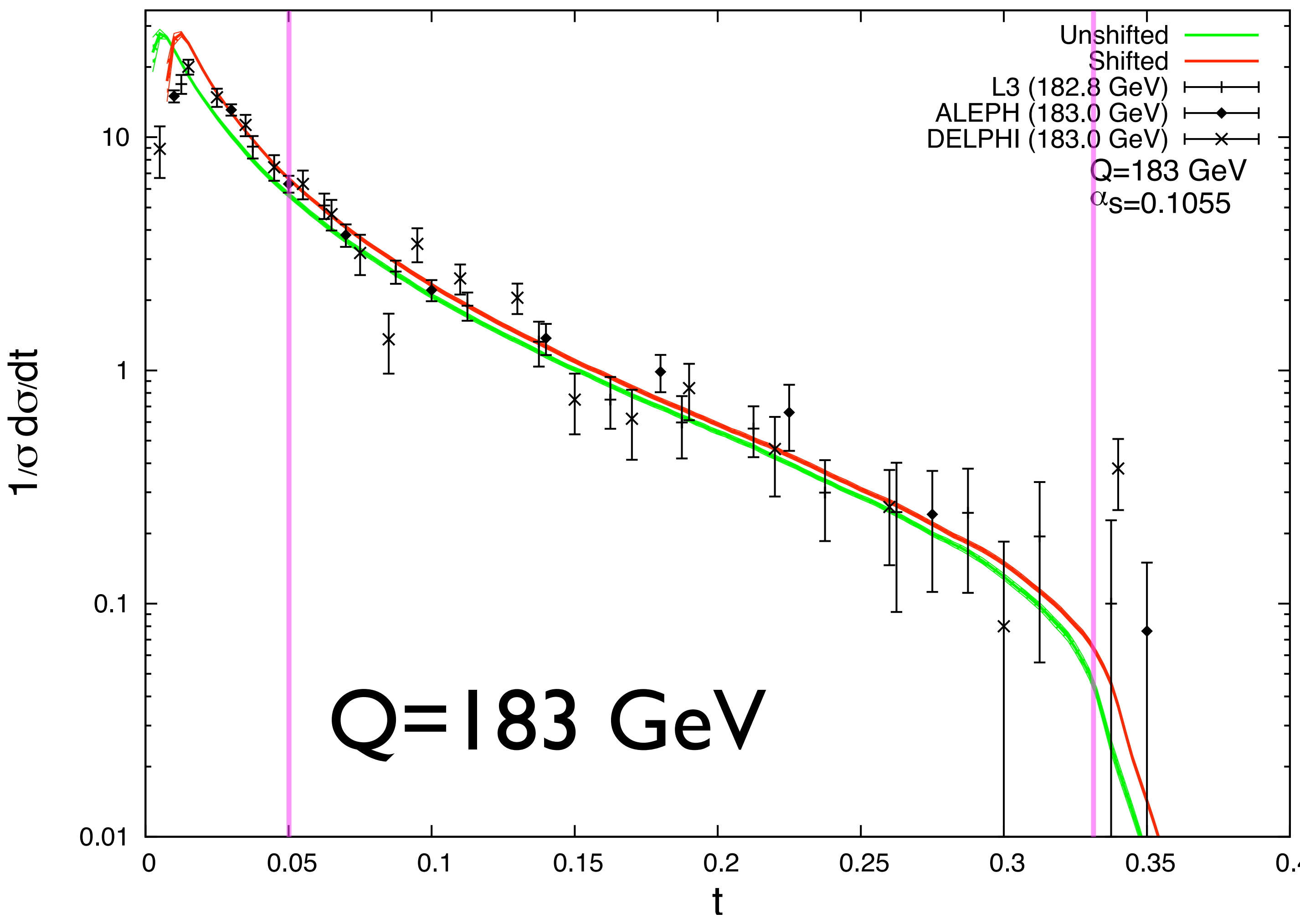
NP shift in Thrust



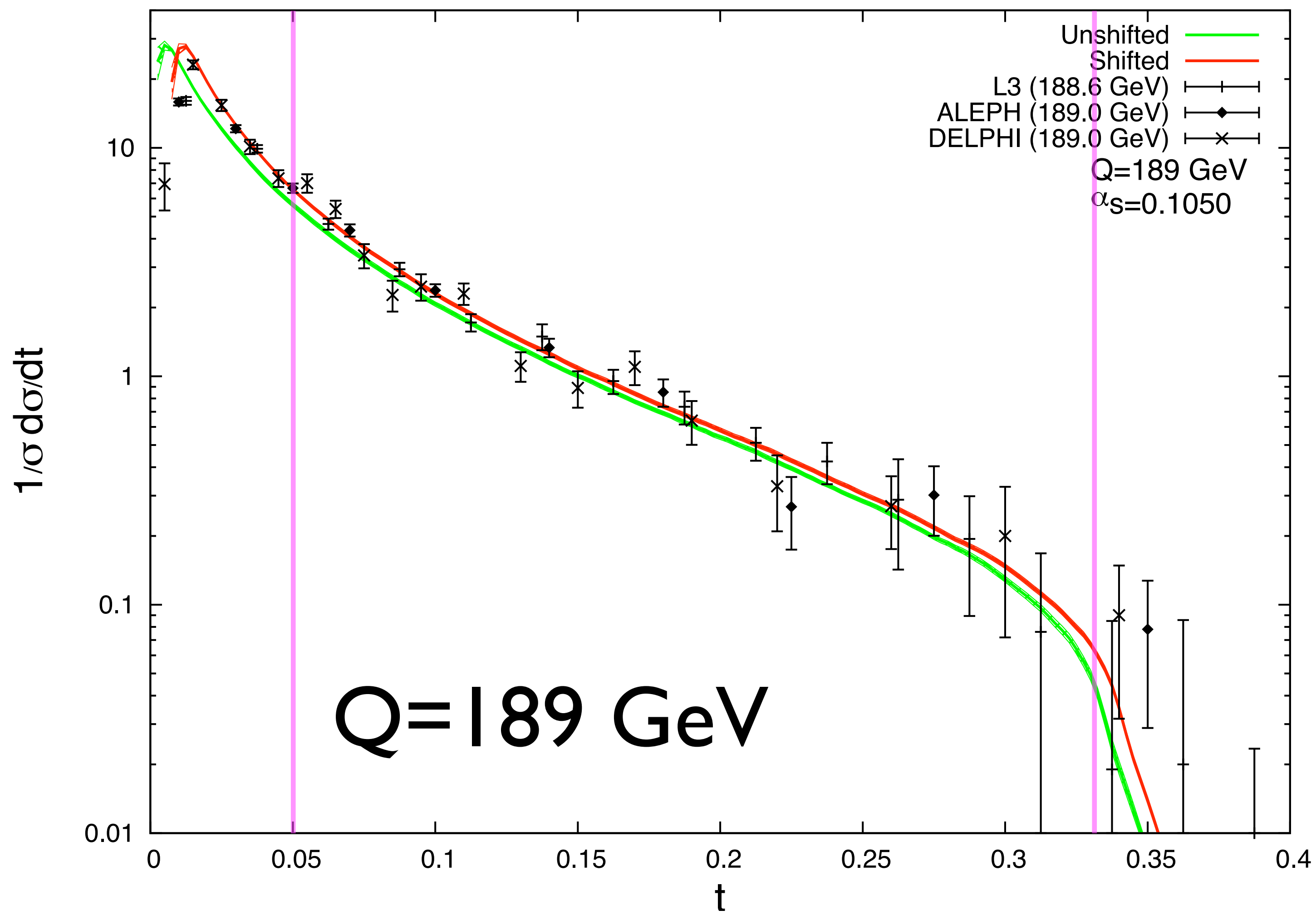
NP shift in Thrust



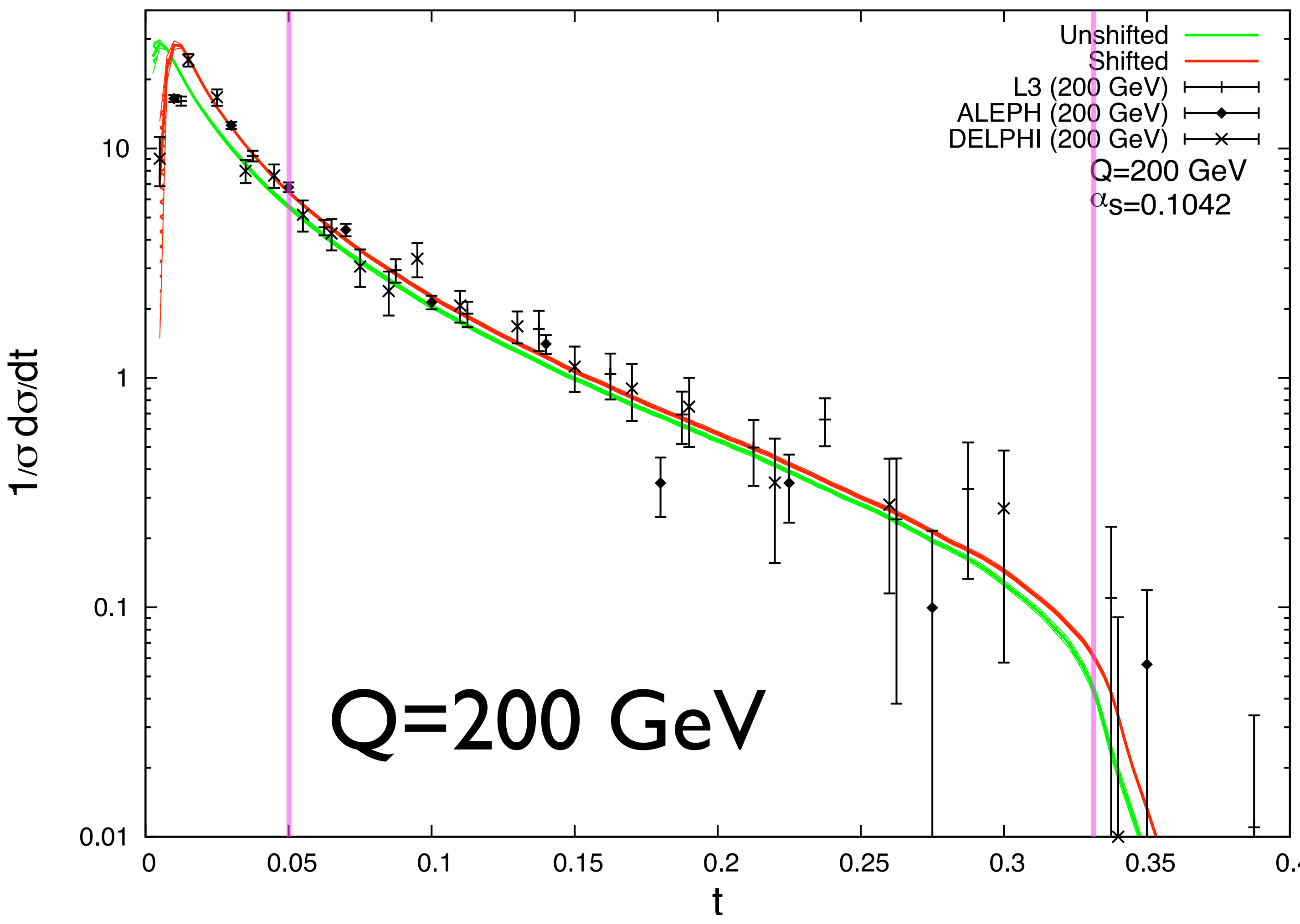
NP shift in Thrust



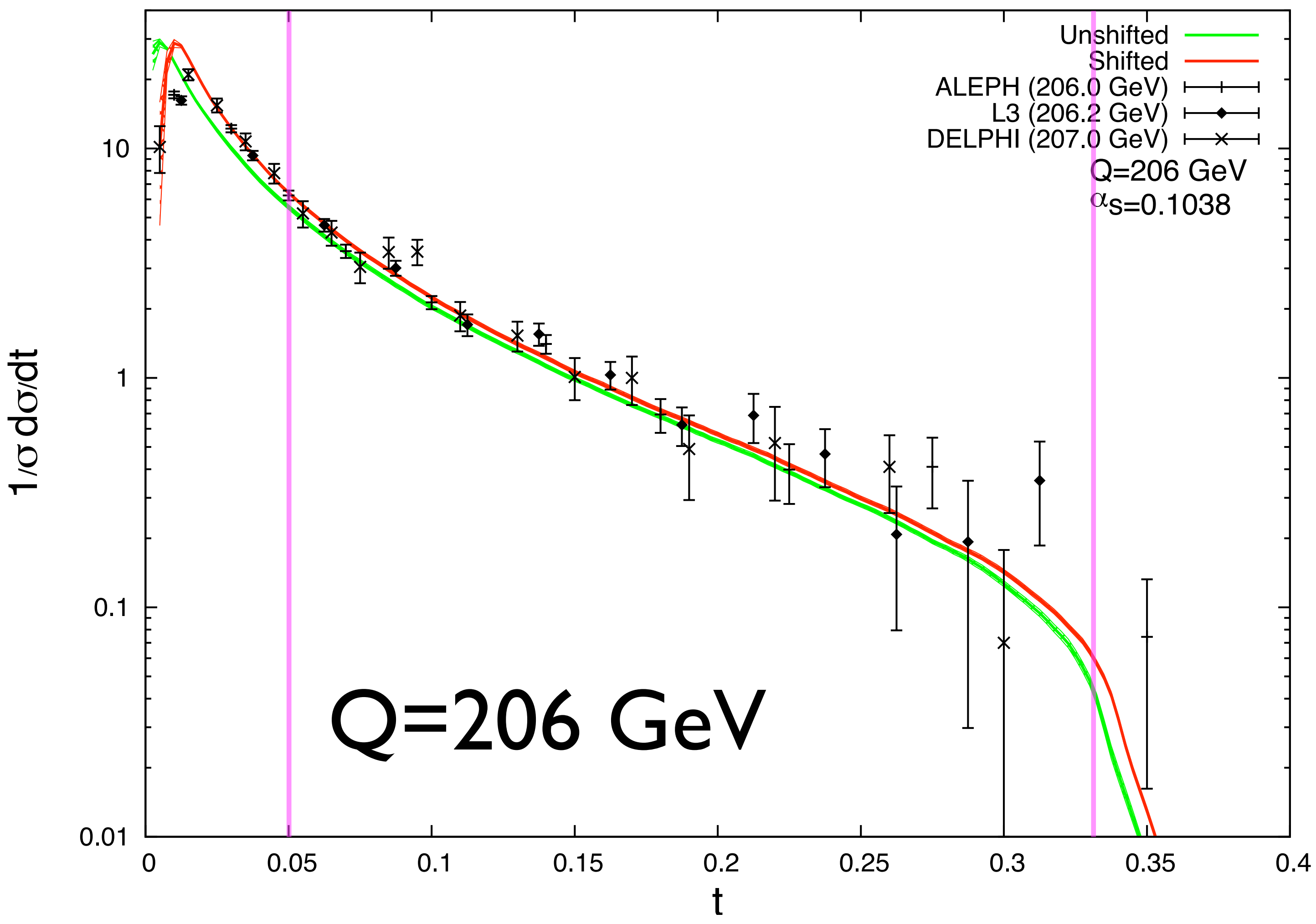
NP shift in Thrust



NP shift in Thrust

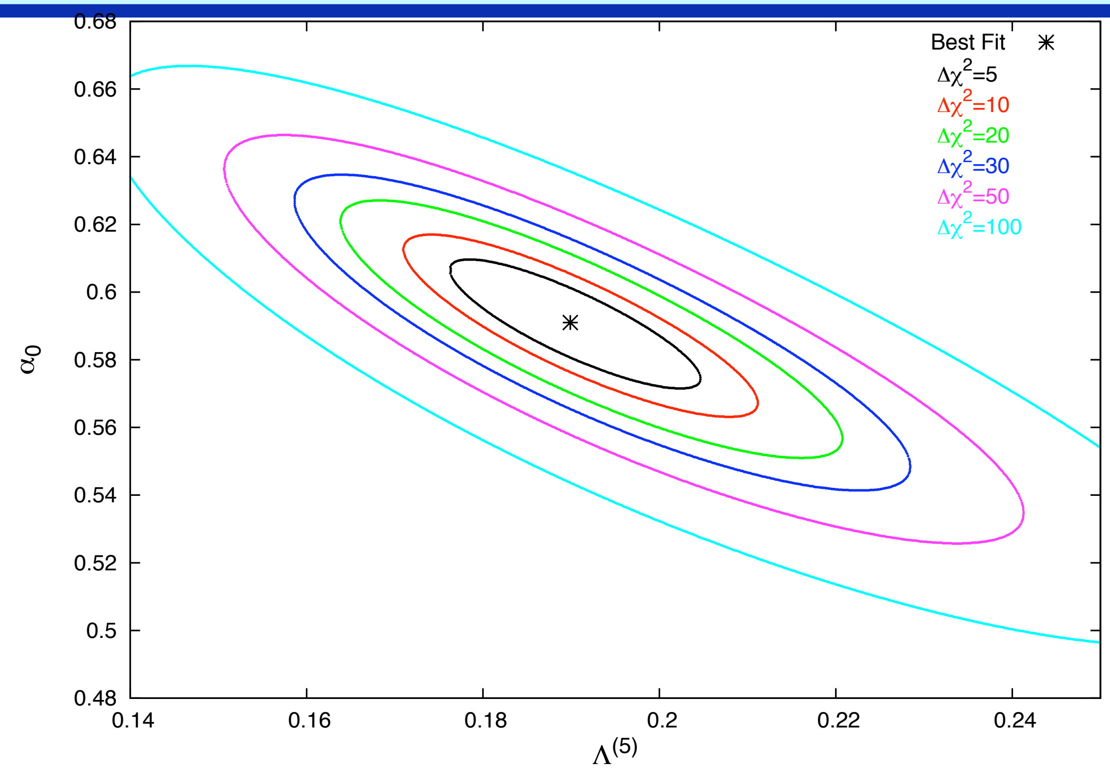


NP shift in Thrust



Results of NNLO+NLL+NP fit

Experiment	Q/GeV	Ref.	No. Pts.	χ^2
TASSO	14.0	[14]	4	8.2
TASSO	22.0	[14]	6	2.8
TASSO	35.0	[14]	8	0.7
JADE	35.0	[15]	10	10.5
L3	41.4	[16]	8	3.4
JADE	44.0	[15]	10	3.8
TASSO	44.0	[14]	8	6.8
DELPHI	45.0	[17]	11	11.6
AMY	54.5	[18]	4	4.9
L3	55.3	[16]	8	3.2
L3	65.4	[16]	8	7.5
DELPHI	66.0	[17]	11	14.5
L3	75.7	[16]	8	1.9
DELPHI	76.0	[17]	11	10.3
L3	82.3	[16]	8	4.0
L3	85.1	[16]	8	3.6
OPAL	91.0	[19]	5	11.9
ALEPH	91.2	[20]	27	16.1
DELPHI	91.2	[17]	11	18.8
SLD	91.2	[21]	6	2.7
L3	130.1	[16]	10	14.6
ALEPH	133.0	[20]	6	7.2
OPAL	133.0	[19]	5	6.5
L3	136.1	[16]	10	37.3
ALEPH	161.0	[20]	6	5.5
L3	161.3	[16]	10	4.0
ALEPH	172.0	[20]	6	14.0
L3	172.3	[16]	10	2.1
OPAL	177.0	[19]	5	1.1
L3	182.8	[16]	10	2.7
ALEPH	183.0	[20]	6	4.0
DELPHI	183.0	[17]	13	33.1
L3	188.6	[16]	10	3.4
ALEPH	189.0	[20]	6	6.7
DELPHI	189.0	[17]	13	22.7
DELPHI	192.0	[17]	13	12.1
L3	194.4	[16]	10	1.2
DELPHI	196.0	[17]	13	39.7
OPAL	197.0	[19]	5	10.0
ALEPH	200.0	[20]	6	21.0
DELPHI	200.0	[17]	13	7.1
L3	200.0	[16]	9	6.5
DELPHI	202.0	[17]	13	14.9
DELPHI	205.0	[17]	13	12.6
ALEPH	206.0	[20]	6	7.0
L3	206.2	[16]	10	10.0
DELPHI	207.0	[17]	13	11.7
Total			430	466.0



Varying the renormalisation scale $\mu_R^2 \in [Q^2/2, 2Q^2]$ gave best fit values in the range $\alpha_0\,(2\text{ GeV}) = 0.585$, $\Lambda^{(5)}_{\overline{MS}} = 0.173$ GeV to $\alpha_0\,(2\text{ GeV}) = 0.598$, $\Lambda^{(5)}_{\overline{MS}} = 0.210$ GeV with no significant change in the quality of fit. Thus we find

2 ⟶ 4

$$\Lambda^{(5)}_{\overline{MS}} = 0.190^{+0.025+0.020}_{-0.022-0.017}\text{ GeV} \qquad (39)$$

where the first error is the combined experimental statistical and systematic error and the second is due to the theoretical renormalisation scale uncertainty. The corresponding strong coupling constant is

$$\alpha_s\,(91.2\text{ GeV}) = 0.1164^{+0.0022+0.0017}_{-0.0021-0.0016}\,, \qquad (40)$$

or, combining all the errors in quadrature,

$$\alpha_s\,(91.2\text{ GeV}) = 0.1164^{+0.0028}_{-0.0026}\,, \qquad (41)$$

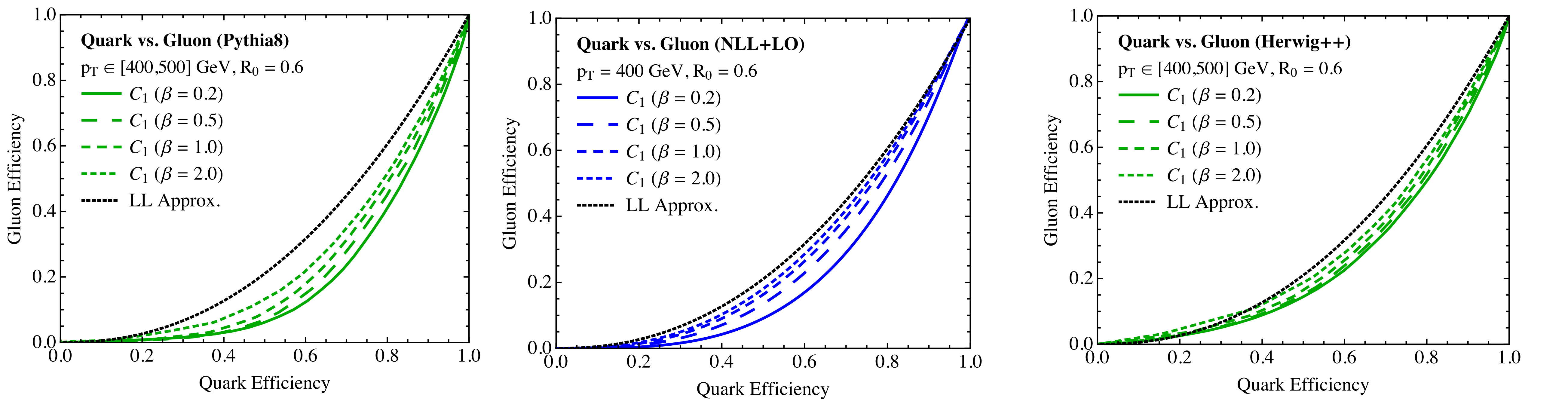
+0.0040
- 0.0038

Quark-Gluon Jet Discrimination

C_1 for q/g discrimination

$$C_1(\beta) = e_2^{(\beta)} \simeq \sum_{i<j\in J} z_i z_j \theta_{ij}^{\beta}$$

Larkoski, Salam, Thaler, JHEP06(2013)108



- Leading-log (LL) $\epsilon_g = \epsilon_q^{9/4}$ independent of β
- At NLL small β gives more q/g discrimination
  - Pythia8, Herwig++ show same trend, but
  - Pythia more, Herwig less than NLL

Track multiplicity

- Compare Z+q, Z+g (R=0.4, min p_{Ttk}=1GeV)

$$P_{q/g}(n) = \left(\frac{k_{q/g}\,n}{\langle n\rangle_{q/g}}\right)^{k_{q/g}} \frac{\exp\left(-k_{q/g}\,n/\langle n\rangle_{q/g}\right)}{n\,\Gamma(k_{q/g})},$$

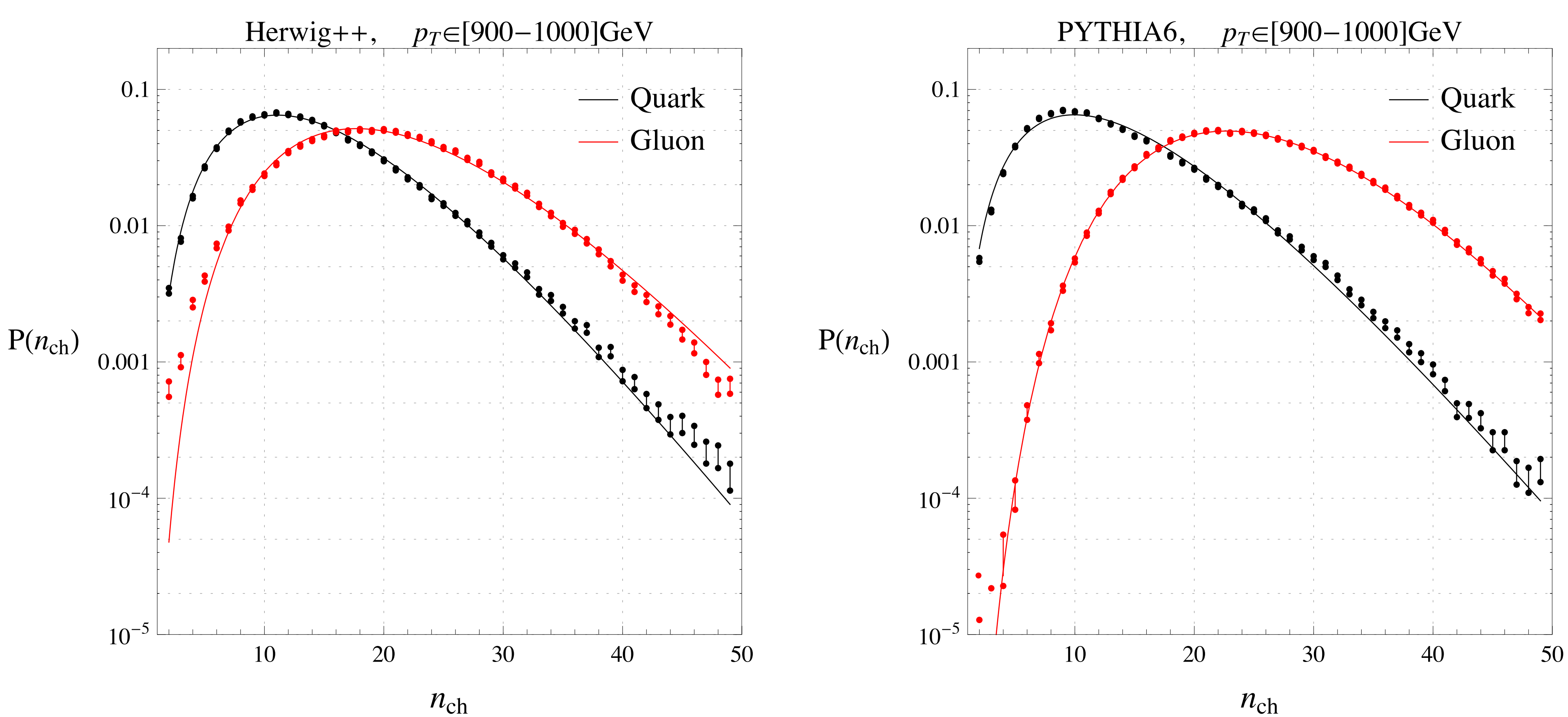
(gamma distribution)

Malaza & BW NPB267(1986)702

$$\langle n\rangle_i = N_i\left(1 + d_i\,a + d_i'\,a^2\right) a^p \exp(c/a), \qquad a = \sqrt{\alpha_S\left(p_T^2\right)/6\pi}$$

Mueller, PLB 104(1981)161, NPB241(1984)141

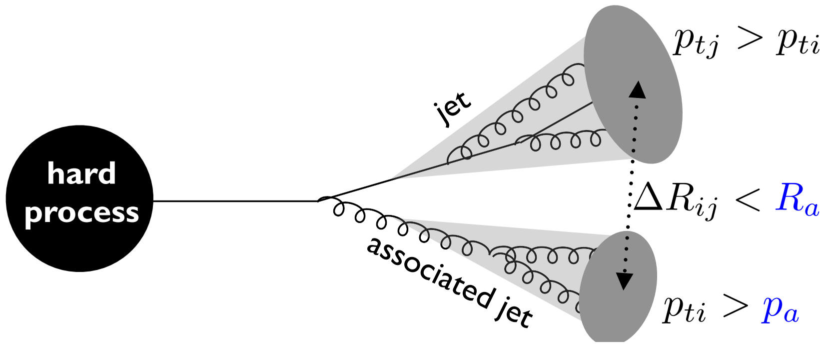
- Again Pythia discriminates more than Herwig

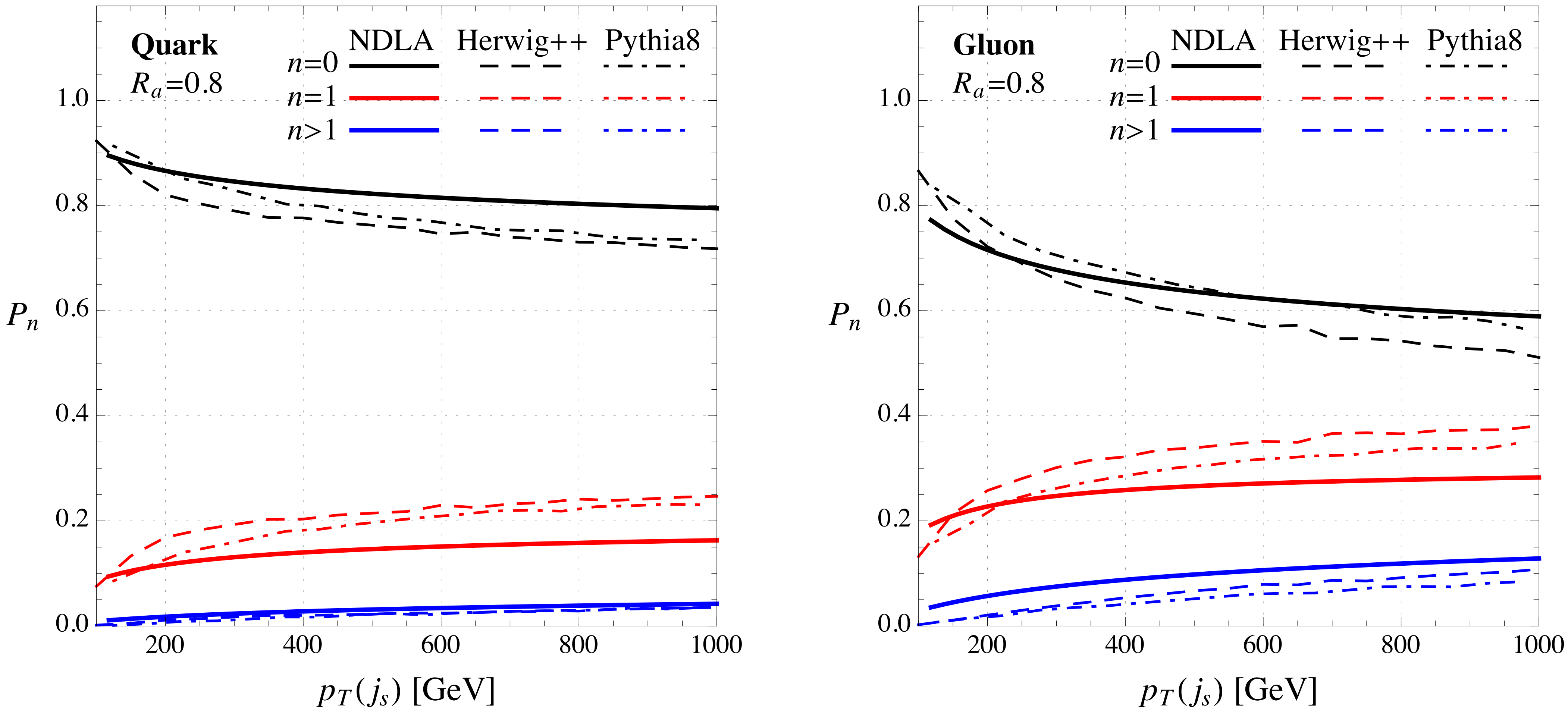


Associated Jets

Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, BW, JHEP 1504 (2015) 131

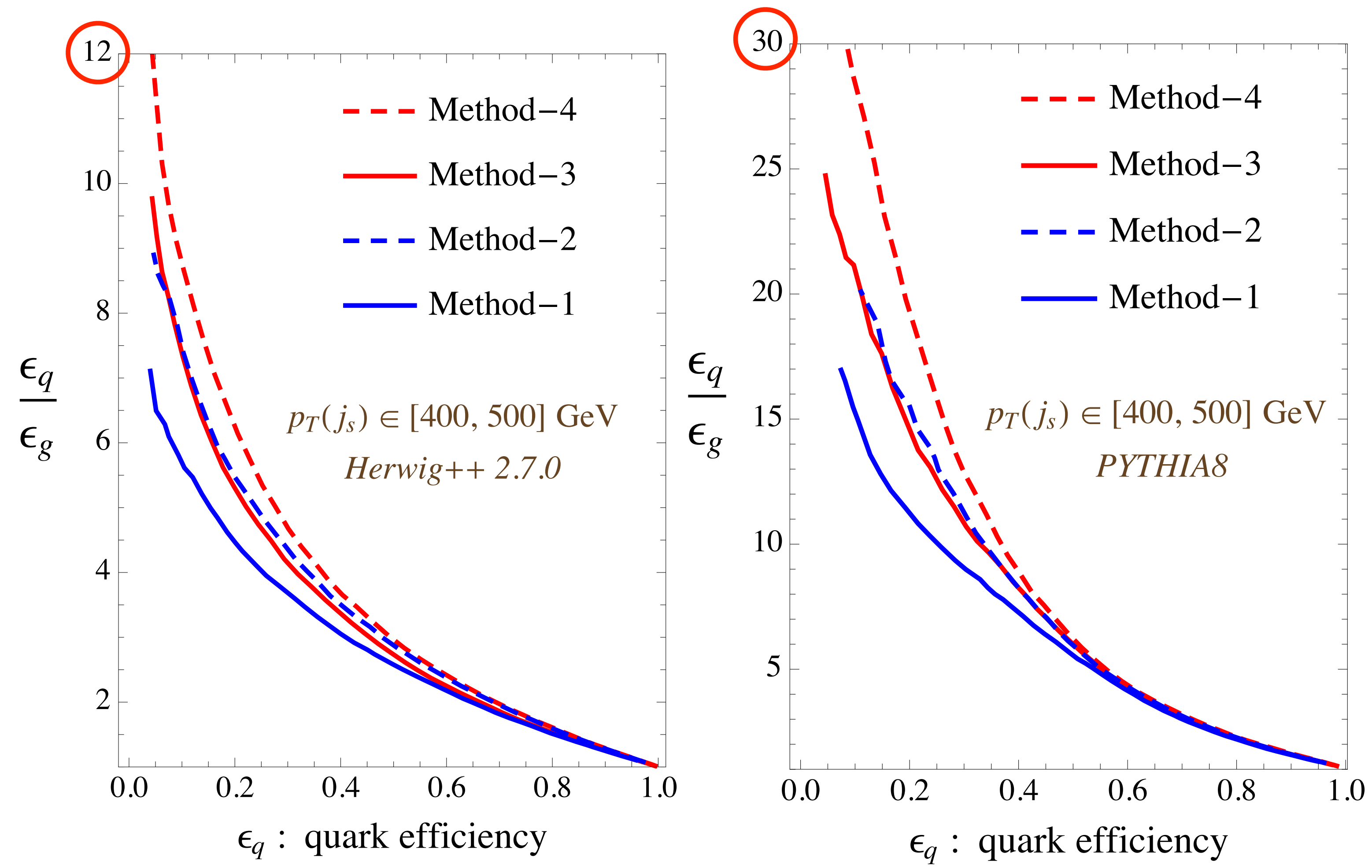
- Z+q vs Z+g (R=0.4)
- Gluons have more 'nearby' jets: $\Delta R < R_a = 0.8$, $p_T > p_a = 20$ GeV





Multivariate Analysis

- Boosted Decision Tree analysis
  - Method 1: n_{trk}, $C_1(\beta=0.2)$
  - Method 2: n_{trk}, $C_1(\beta=0.2)$, assoc
  - Method 3: n_{trk}, $C_1(\beta=0.2)$, m_J/p_{TJ}
  - Method 4: n_{trk}, $C_1(\beta=0.2)$, m_J/p_{TJ}, assoc
- Again Herwig < Pythia
  - Note change of scale!



q/g discrimination in SUSY

Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, BW, arXiv:1609.08781

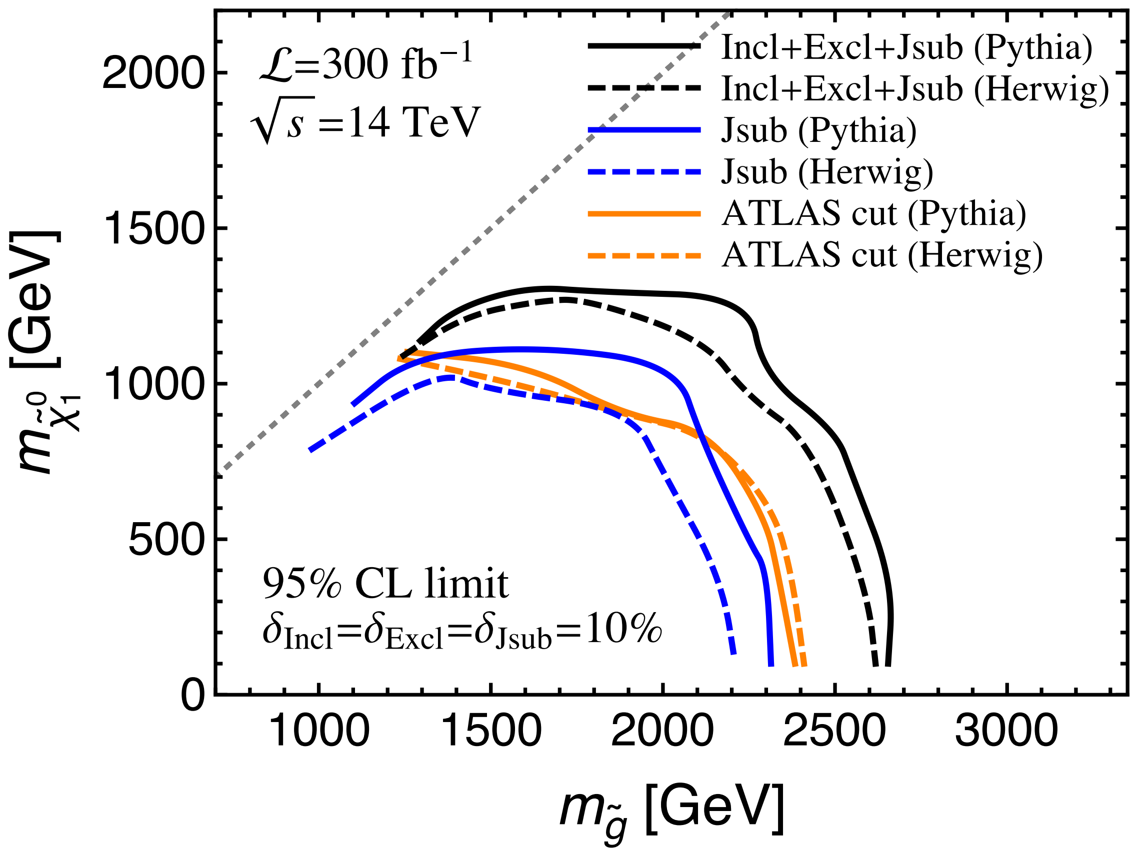


Figure 6. *The 95% C.L. exclusion contours predicted by* `Pythia6` *(solid lines) and* `Herwig++` *(dashed lines) using either only the jet substructure subset (blue curves) or the full variable set (black curves). For reference, the exclusion contours based on ATLAS cuts [24] are also shown (orange curves), and they are almost identical for* `Pythia6` *and* `Herwig++`.

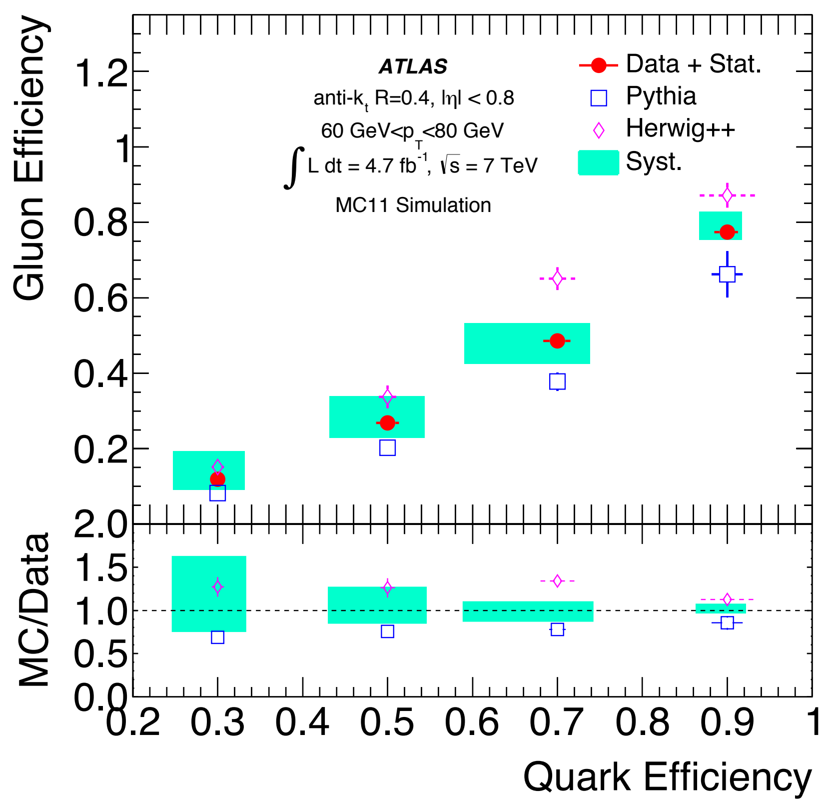
ATLAS q/g analysis

ATLAS, EPJC 74 (2014) 3023

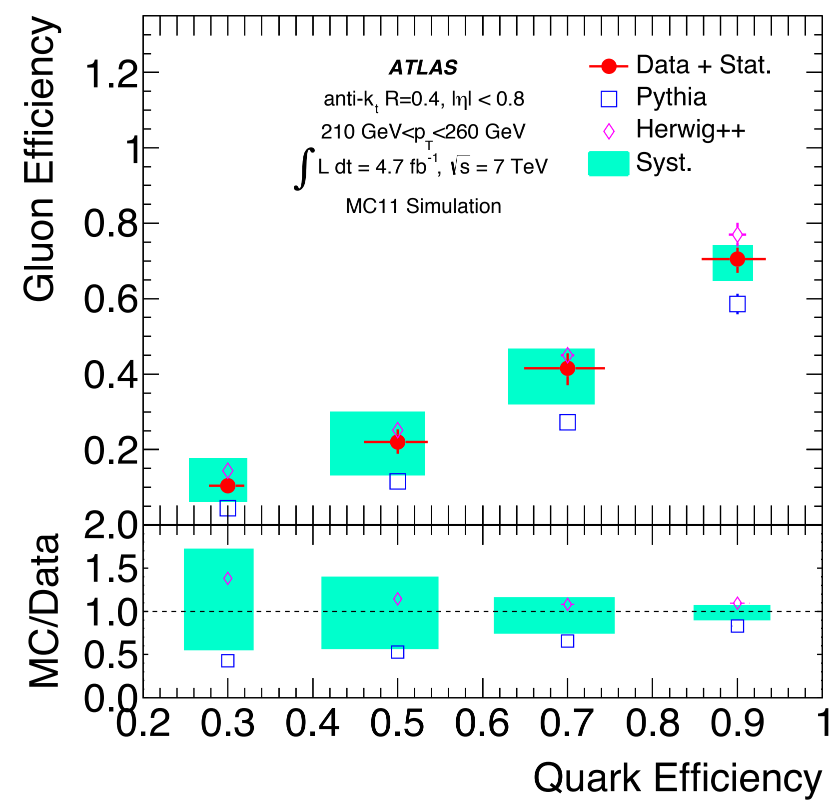
- Likelihood based on n_{trk} and track jet width

$$w = \frac{\sum_i p_{\mathrm{T},i} \times \Delta R(i, \mathrm{jet})}{\sum_i p_{\mathrm{T},i}}$$

60<p_{TJ}<80 GeV



210<p_{TJ}<260 GeV

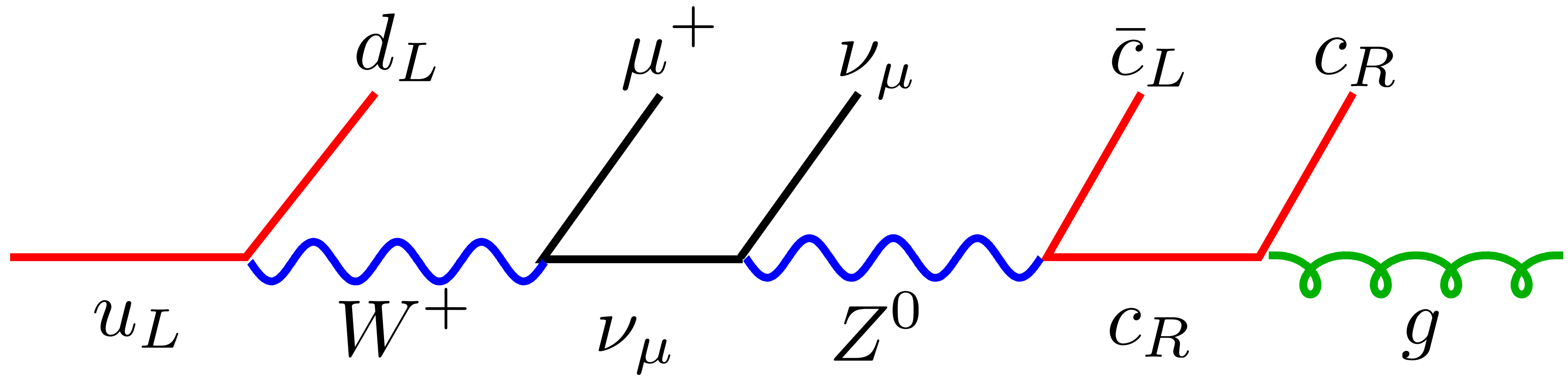


- Data closer to Herwig++ (less discrimination than Pythia)

Electroweak DGLAP

Electroweak DGLAP

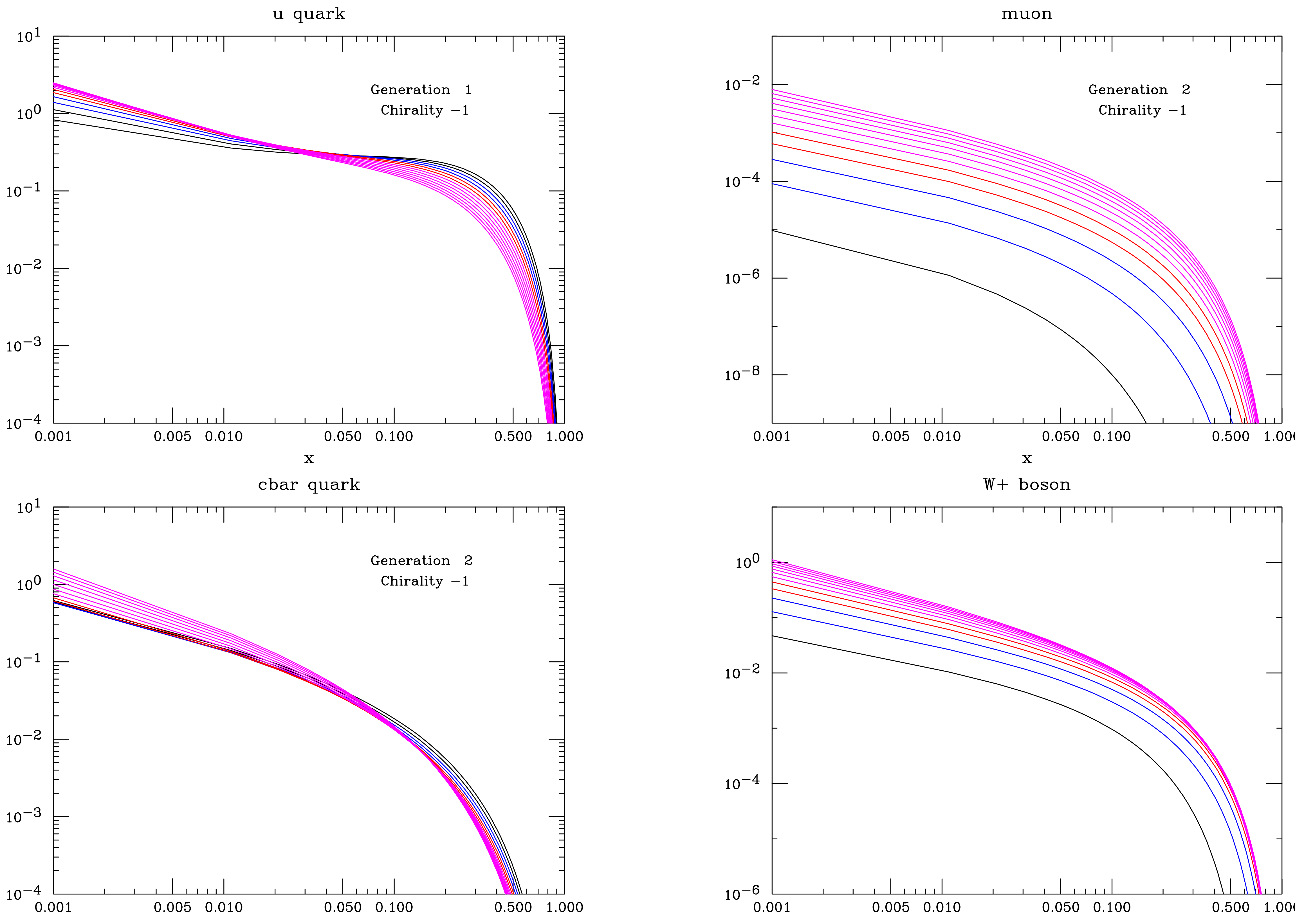
- High-scale PDFs evolve into all species (with double logs)



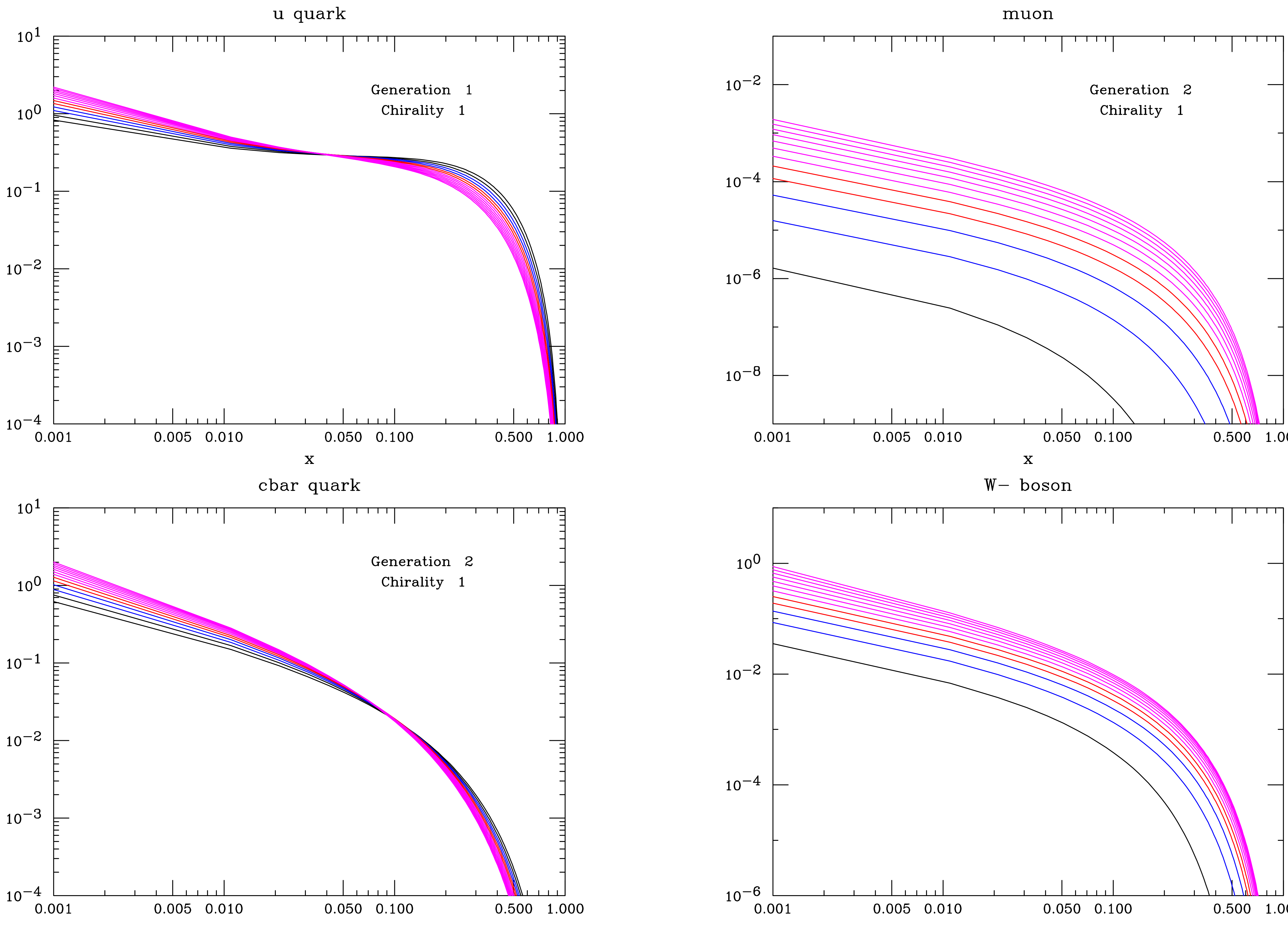
- Evolving MSTW2008LO from 100 GeV to 100 PeV ......

C Bauer, N Ferland, BW, in preparation

Electroweak DGLAP



Electroweak DGLAP



Conclusions

- Yuri's contributions to jet physics underpin a large part of present-day particle physics
    - Not just QCD!
- Yuri's low-scale effective α_S describes a wide range of non-perturbative phenomena
- Quark-gluon discrimination: great interest for new physics searches
- DGLAP with electroweak: just starting!

Conference

Giuseppe Marchesini Memorial Conference

Register   First Bulletin

Organizers:

Stefano Catani (INFN Florence) , Marcello Ciafaloni (Florence U.) , Daniele Dominici (Florence U.) , Alberto Lerda (Piemonte Orientale U. Alessandria) , Antonio Masiero (Padua U.) , Enrico Onofri (Parma U.) , Eliezer Rabinovici (Hebrew U.) , Bryan Webber (Cambridge U.)

Period: from 19-05-2017 to 19-05-2017

Deadline: 19-04-2017

Contact(s):
catani@fi.infn.it
webber@hep.phy.cam.ac.uk

Abstract

The conference will celebrate the scientific contributions of Giuseppe Marchesini through invited talks on current research related to his work. There will also be a session for contributed short talks and reminiscences.

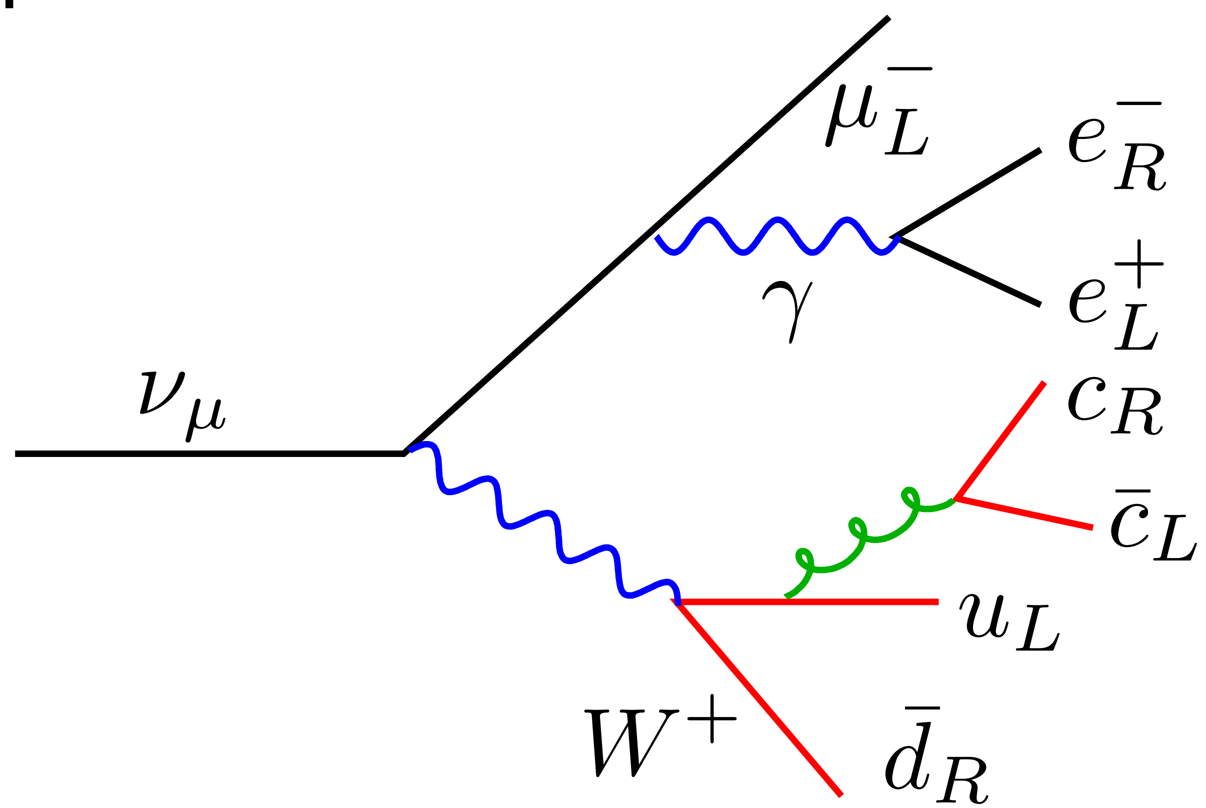
Speakers:

Andrea Banfi
Yuri Dokshitzer
Francesco Hautmann (t.b.c.)
Hannes Jung
Al Mueller
Francesco Di Renzo
Gavin Salam
Mike Seymour
Gabriele Veneziano
Giulia Zanderighi (t.b.c.)

Backup

Electroweak jets

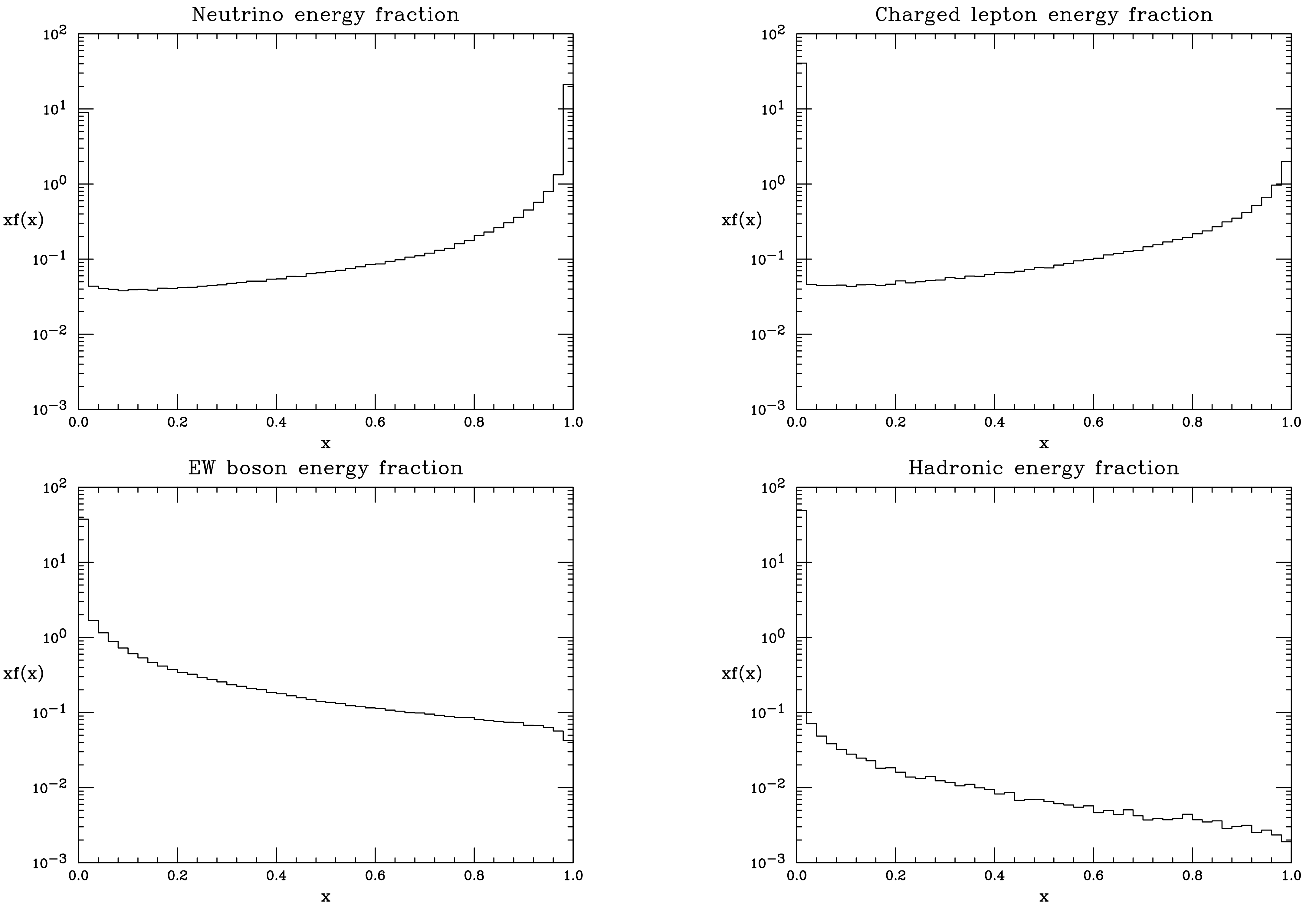
- At super-high scales, leptons fragment into jets containing all species of particles



C Bauer, N Ferland, BW, in preparation

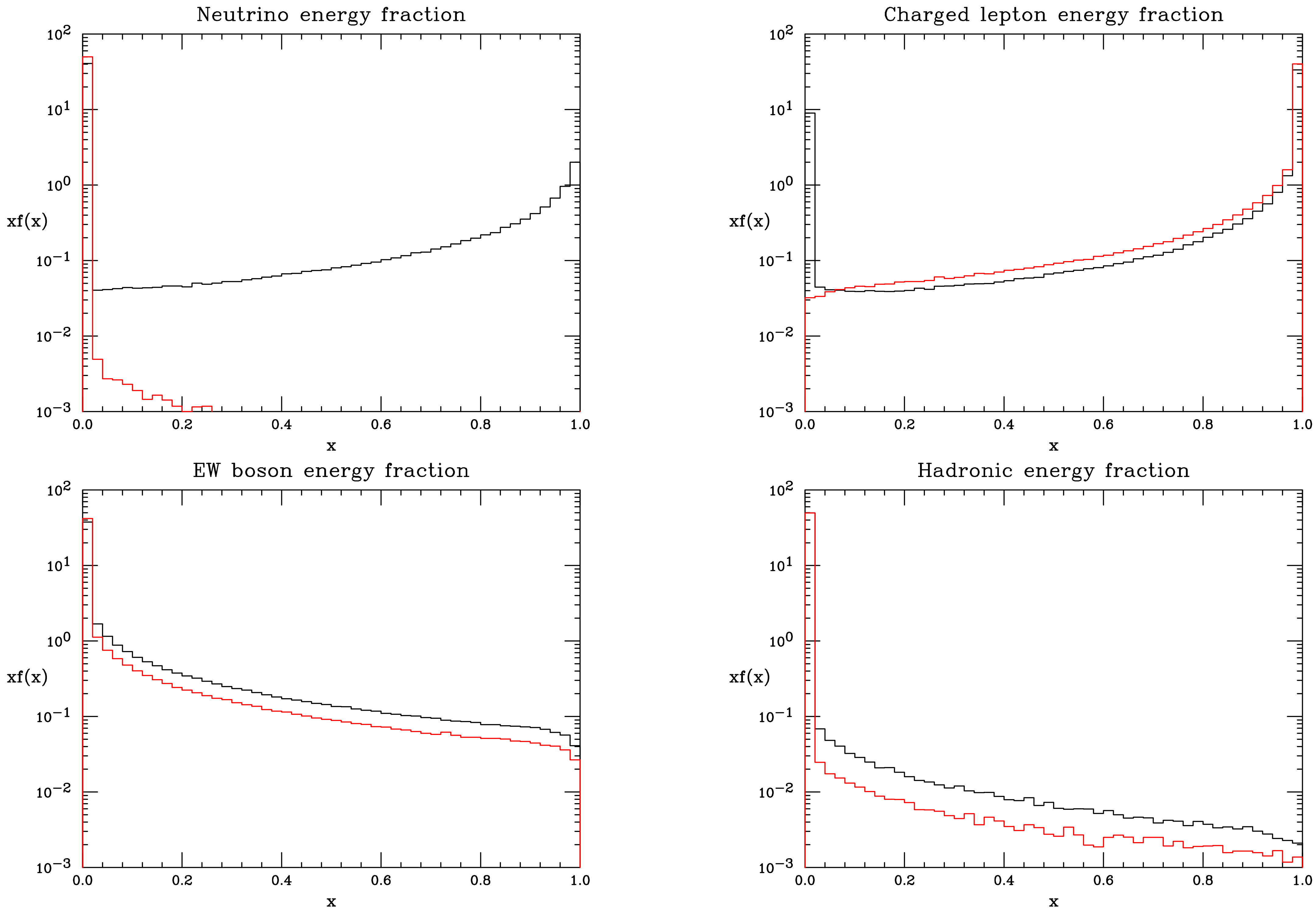
Electroweak jets

- Contents of a 100 TeV neutrino jet



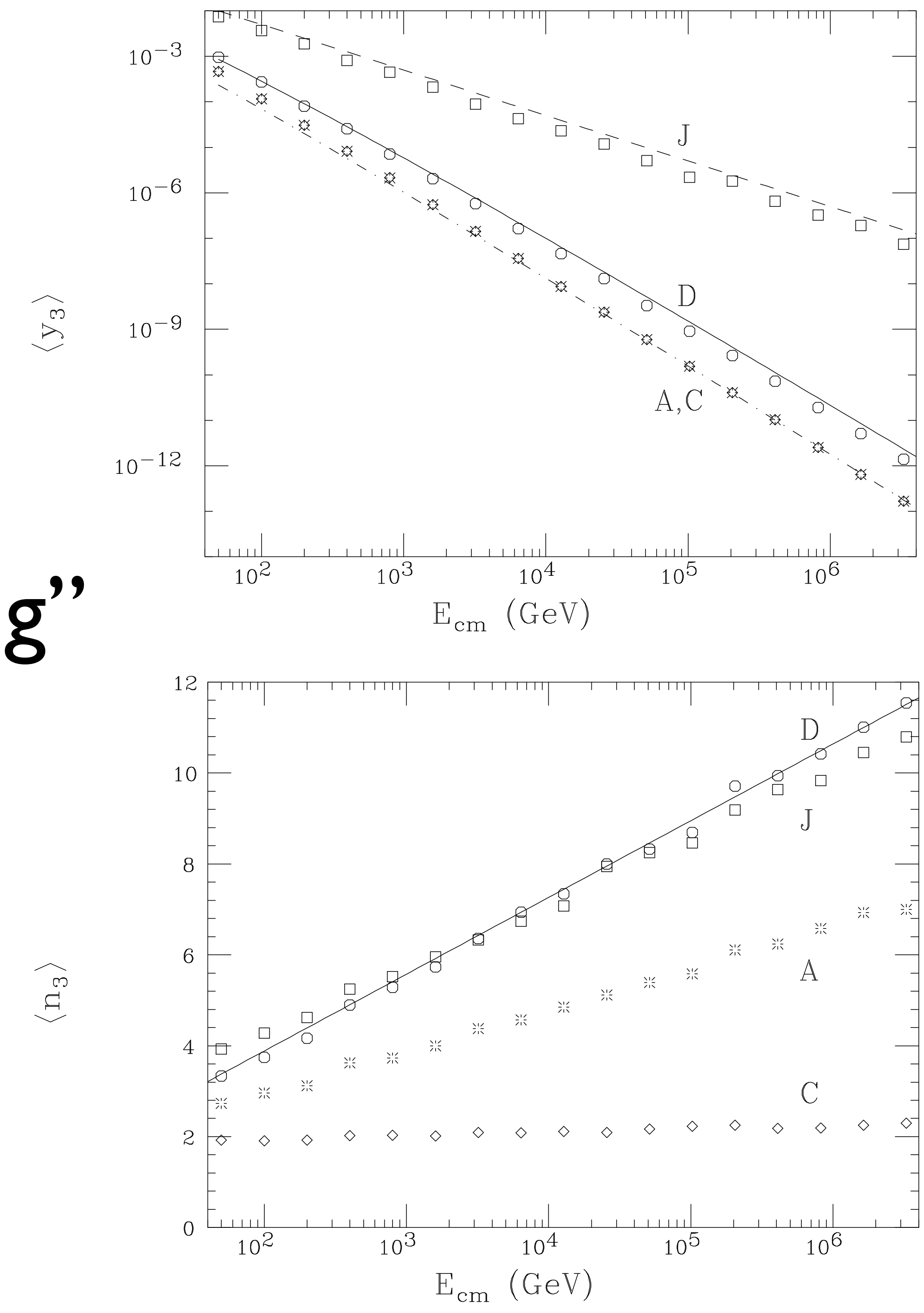
Electroweak jets

- Contents of a 100 TeV L- or R-handed muon jet



Real Cambridge Algorithm

- A = angular algorithm
- C= A + “soft jet freezing”
  - prevents growth of “junk jets”



Subjets in jets

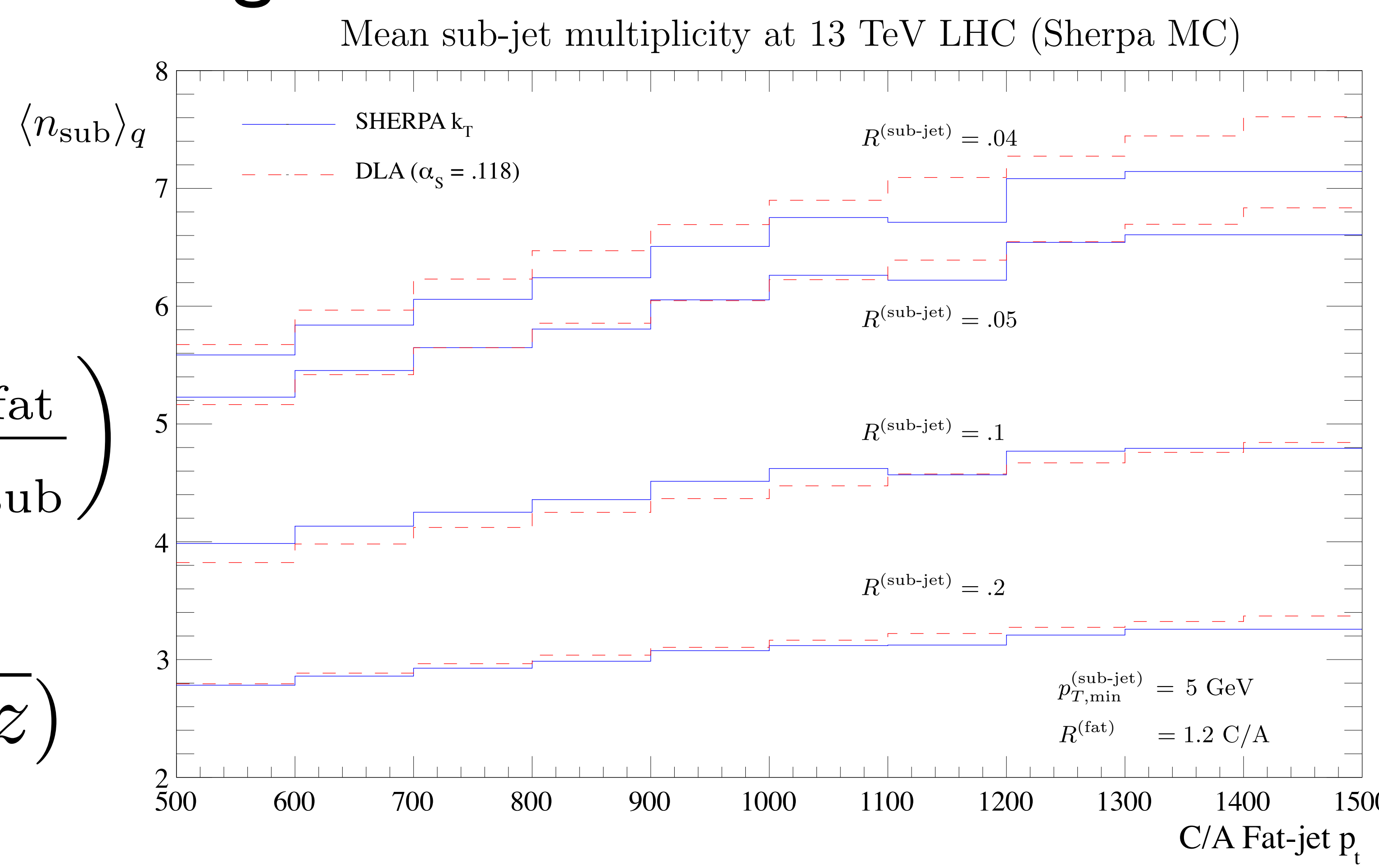
Gerwick, Gripaios, Schumann, BW, arXiv:1212.5235

- Summing leading double logs:

$$\langle n_{\rm sub}\rangle_g \sim I_0(\sqrt{z})$$

$$z = 24\frac{\alpha_S}{\pi}\ln\left(\frac{p_{T\rm fat}}{p_{T\rm sub}}\right)\ln\left(\frac{R_{\rm fat}}{R_{\rm sub}}\right)$$

$$\langle n_{\rm sub}\rangle_q \sim \frac{5}{9}+\frac{4}{9}I_0(\sqrt{z})$$



- Agrees quite well with quark jets from Sherpa MC

Subjets in jets

Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, BW, arXiv:1501.04794

- Subjets at k_t-resolution y_{cut}

$$y_{ik} = \min\{p_{ti}^2, p_{tk}^2\}\frac{\Delta R_{ik}^2}{R^2 p_j^2} > y_{\rm cut}$$

- Perturbatively calculable and less MC dependent than n_{trk} (for $L=-\ln(y_{cut})<6$)
- L~6: $\min\{p_{Ti},p_{Tk}\}\ \Delta R_{ik}$~10 GeV
- Not yet used for q/g tagging

500<p_{TJ}<600 GeV, R=0.4