Parton showers and resummation for bottom-quark fragmentation in top decays

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Work by G.C., F.Mescia, V.Drollinger, A.Mitov, M. Cacciari, LEP/SLD/ATLAS/CMS heavy-quark/top working groups

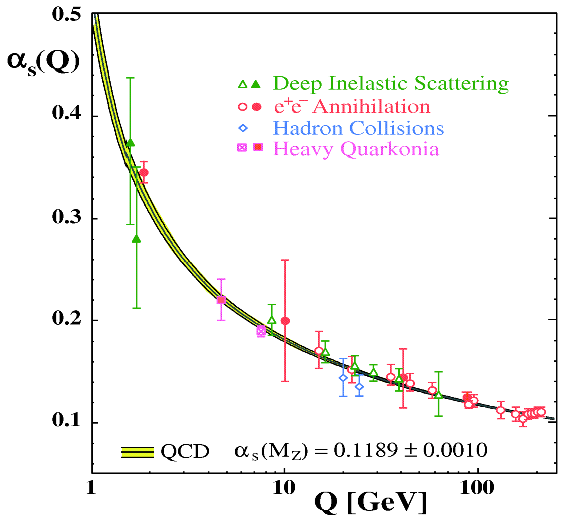
Heavy-quark (c, b, t) production interesting from theoretical and experimental viewpoints

Tests of QCD, electroweak interactions and parton model

Investigation of power corrections and hadronization to predict heavy-hadron spectra

$m \gg \Lambda_{\rm QCD} \sim \mathcal{O}(100 \text{ MeV})$: perturbative QCD can work

Asymptotic freedom allows perturbative expansion at large energies:

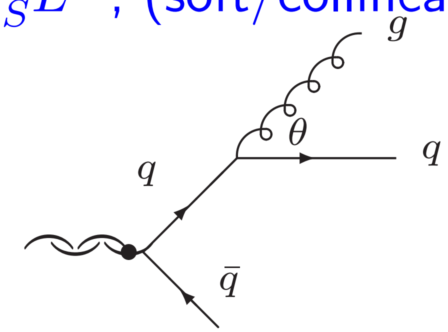


$$\sigma(Q) = c_0 + c_1 \alpha_S(Q) + c_2 \alpha_S^2(Q) + \ldots \text{ (LO, NLO, etc.)}$$

$$\alpha_S(Q) = \frac{1}{\beta_0 \ln \frac{Q^2}{\Lambda^2}} \left\{ 1 - \frac{\beta_1 \ln[\ln(Q^2/\Lambda^2)]}{\beta_0^2 \ln(Q^2/\Lambda^2)} \right\} \quad (\overline{\rm MS} \text{ ren. scheme})$$

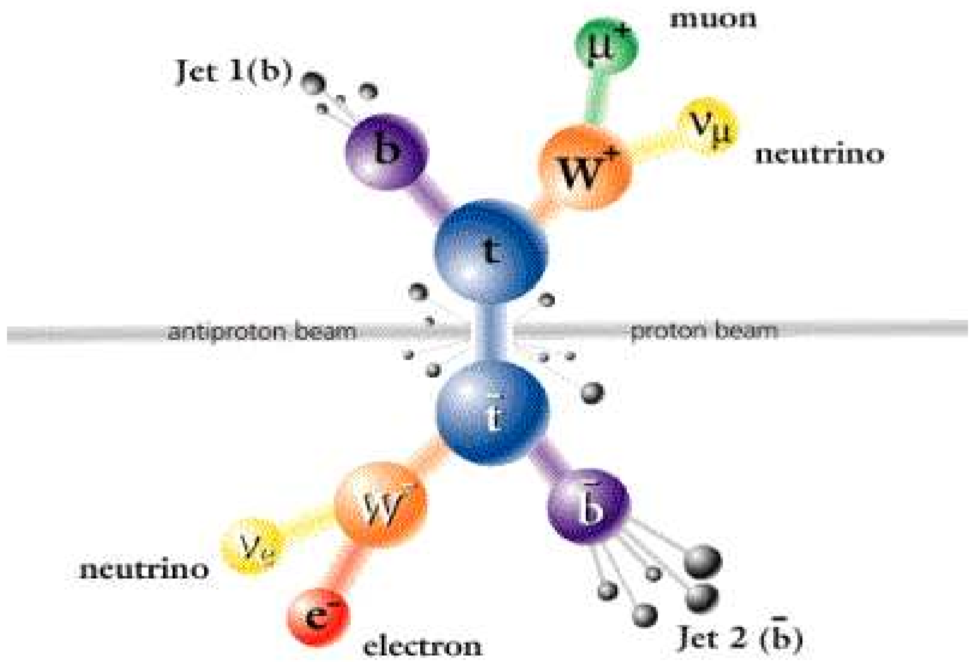
Fixed-order calculations reliable for total cross sections

Differential distributions $\sim \alpha_S^n L^m$, (soft/collinear emission): all-order resummation



$E_g \to 0$: soft radiation $\quad \theta \to 0$: collinear radiation ($\ln(m/Q)$ for heavy quarks)

The top quark was discovered in 1995 by CDF and D0 experiments at Tevatron (FNAL)



$Q = (2/3)\, e$, $T_3 = +1/2$, phenomenology driven by its large mass: $m_t \simeq 173$ GeV

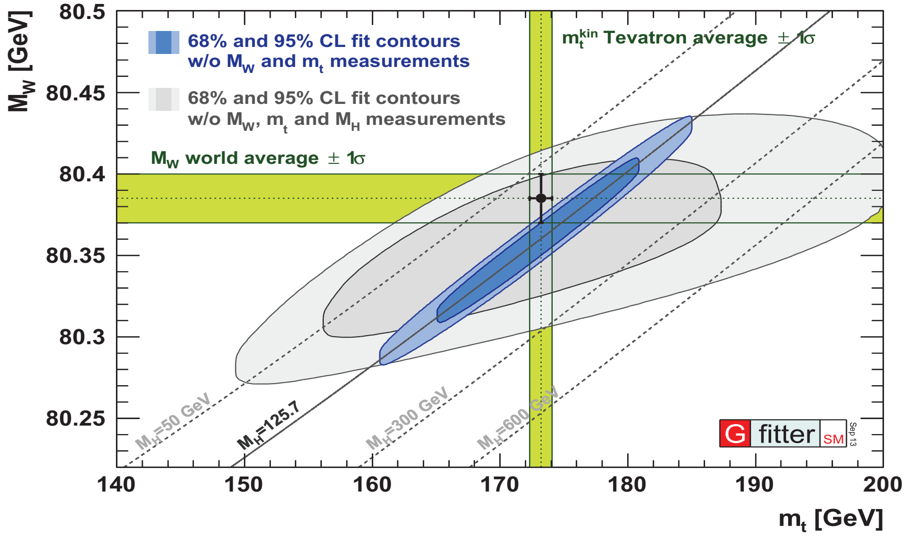
Large width $\Gamma_t \simeq 1.35\ \mathrm{GeV} \Rightarrow \tau_t \simeq 0.5 \times 10^{-24}\ \mathrm{s}$ (PDG'14)

The top quark decays before forming any T-hadron or $t\bar{t}$ resonance

Being $m_t \sim m_H$, the top Yukawa coupling is the only of order 1

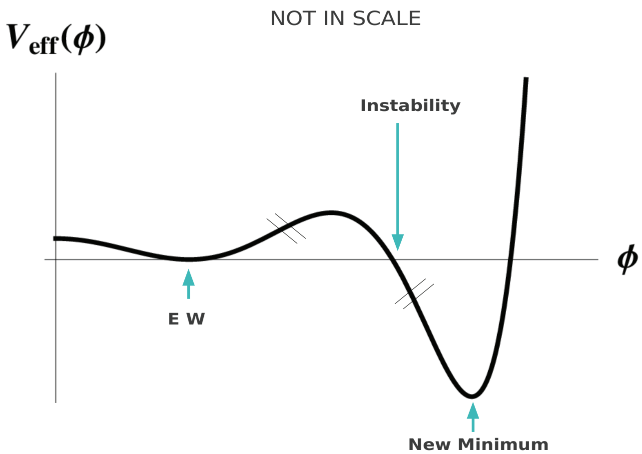
Processes with top quarks are background for many New Physics searches

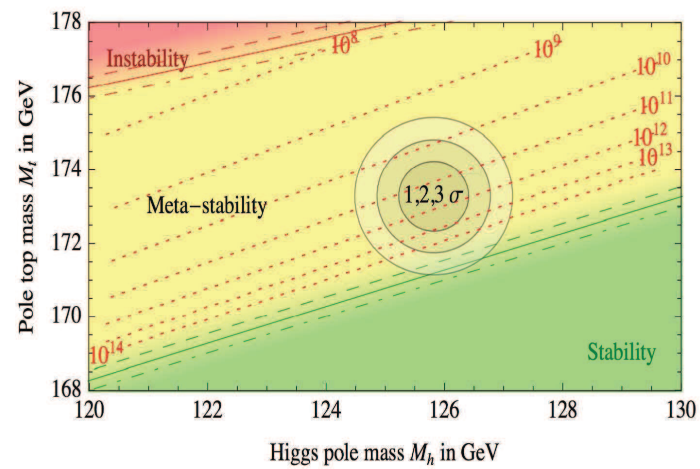
The top quark plays a crucial role in electroweak symmetry breaking



Stability of the SM vacuum depends on top and Higgs masses (Degrassi et al, JHEP'12)

$$V_{RG}(\phi) \simeq \frac{1}{2} m^2(\Lambda)\phi^2(\Lambda) + \frac{1}{4}\lambda^4(\Lambda)\phi^4(\Lambda)\ ,\ \phi \sim \Lambda \gg v$$





Stability: $V_{\rm eff}(v) < V_{\rm eff}(v')$; Instability: $V_{\rm eff}(v) > V_{\rm eff}(v')$; Metastability: $\tau > T_U$

Theoretical uncertainties on the top mass measurement

Monte Carlo systematics (MC); modelling QCD radiation effects (Rad); colour reconnection (CR); parton distribution functions (PDF)

All values in GeV	CDF	D0	ATLAS	CMS	Tevatron	LHC	WA
$m_{\rm top}$	173.19	174.85	172.65	173.58	173.58	173.28	173.34
Stat	0.52	0.78	0.31	0.29	0.44	0.22	0.27
iJES	0.44	0.48	0.41	0.28	0.36	0.26	0.24
stdJES	0.30	0.62	0.78	0.33	0.27	0.31	0.20
flavourJES	0.08	0.27	0.21	0.19	0.09	0.16	0.12
bJES	0.15	0.08	0.35	0.57	0.13	0.44	0.25
MC	0.56	0.62	0.48	0.19	0.57	0.25	0.38
Rad	0.09	0.26	0.42	0.28	0.13	0.32	0.21
$\Longrightarrow$ CR	0.21	0.31	0.31	0.48	0.23	0.43	0.31 $\Longleftarrow$
PDF	0.09	0.22	0.15	0.07	0.12	0.09	0.09
DetMod	<0.01	0.37	0.22	0.25	0.09	0.20	0.10
b-tag	0.04	0.09	0.66	0.11	0.04	0.22	0.11
LepPt	<0.01	0.20	0.07	<0.01	0.05	0.01	0.02
BGMC	0.10	0.16	0.06	0.11	0.11	0.08	0.10
BGData	0.15	0.19	0.06	0.03	0.12	0.04	0.07
Meth	0.07	0.15	0.08	0.07	0.06	0.06	0.05
MHI	0.08	0.05	0.02	0.06	0.06	0.05	0.04
Total Syst	0.85	1.25	1.40	0.99	0.82	0.92	0.71
Total	1.00	1.48	1.44	1.03	0.94	0.94	0.76
χ^2/ndf	1.09 / 3	0.13 / 1	0.34 / 1	1.15 / 2	2.45 / 5	1.81 / 4	4.33 / 10
χ^2 probability [%]	78	72	56	56	78	77	93

Overall theory error on world average mass: $\Delta m_t \simeq 0.54$ GeV

Bottom-quark fragmentation in top decays is fundamental to perform trustworthy measurements of top properties, e.g. m_t

Monte Carlo event generators (HERWIG/PYTHIA) widely used to simulate top production and decay and b hadronization

Novel top-mass reconstruction strategies crucially depend on $b \to B$ transition: J/ψ and $m_{b\ell}$ methods

$t \to bW$; $b \to B \to J/\psi\ X$; $J/\psi \to \mu^+\mu^-$; $W \to \ell\nu_\ell$

Clean signal (666 events at 8 TeV and $\mathcal{L} = 20$ fb^{-1}) , albeit $\mathrm{BR}(B \to J/\psi) \simeq 3 \times 10^{-4}$; $m_{J/\psi\ell}$ correlated with m_t

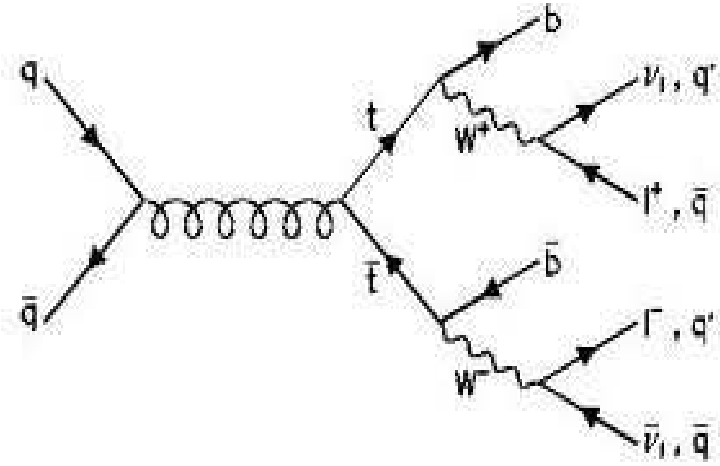
$\Delta m_t(\mathrm{syst}) \simeq 900$ MeV, with $\Delta m_t(b\text{-frag}) \simeq 300$ MeV

Invariant mass b-jet+lepton in dilepton channel - jets defined through anti-k_T algorithm, with R=0.5, $|\eta| < 2.4$, $p_T > 30$ GeV

$\Delta m_t(\mathrm{syst}) \simeq 1.8$ GeV, with $\Delta m_t(b\text{-frag}) \simeq 0.6$ GeV

Several calculations and tools available for b-fragmentation in top decays, but not unique strategy for the systematic error: comparing two tuned codes/computations, one program varying fragmentation parameters, etc.

Top production and decays at hadron colliders, e.g. in $q\bar{q}$ annihilation



Perturbative QCD allows one to calculate the parton-level (b-quark) spectrum

Phenomenological hadronization models are usually given in terms of non-perturbative fragmentation functions

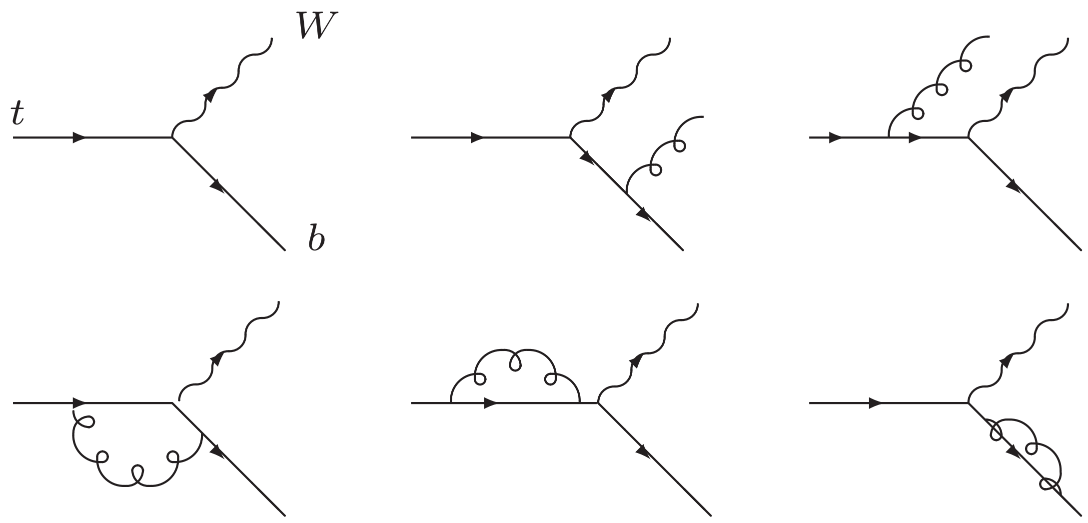
$$\sigma(t \to WB) = \sigma(t \to Wb) \otimes D_{np}(b \to B)$$

$D_{np}(b \to B)$ contains parameters to be fitted to experimental data

Narrow-width approximation:

$$\frac{d\sigma_{\rm had}}{dx_B}(t \to B) \simeq \frac{d\Gamma_{\rm had}}{dx_B}(t \to B) \quad ; \quad \frac{d\Gamma_{\rm had}}{dx_B}(t \to B) = \frac{d\Gamma_{\rm part}}{dx_b}(t \to b) \otimes D_{np}(b \to B)$$

Top decays at NLO (neglecting interference)



$t(q) \to b(p_b)W(p_W)\ (g(p_g))$

$$x_b = \frac{1}{1-m_W^2/m_t^2+m_b^2/m_t^2}\,\frac{2p_b\cdot p_t}{m_t^2}$$

$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dx_b} = \delta(1-x_b) + \frac{\alpha_S(\mu)}{2\pi}\left[P_{qq}(x_b)\ln\frac{m_t^2}{m_b^2} + A(x_b)\right] + \mathcal{O}\left[\left(\frac{m_b}{m_t}\right)^p\right]$$

$$P_{qq}(x_b) = C_F\left(\frac{1+x_b^2}{1-x_b}\right)_+ \ ; \ \int_0^1 dx_b f(x_b)[g(x_b)]_+ = \int_0^1 dx_b[f(x_b)-f(1)]g(x_b)$$

Large mass logarithms need to be resummed

Perturbative fragmentation functions

B. Mele and P. Nason, NPB 361 (1991) 626

$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dx_b}(x_b, m_b \neq 0) = \frac{1}{\Gamma_0}\sum_i \int_{x_b}^1 \frac{dz}{z}\frac{d\hat{\Gamma}_i}{dz}(z, m_i = 0, \mu_F) D_i\left(\frac{x_b}{z}, \mu_F, m_b\right) + \mathcal{O}\left[\left(\frac{m_b}{m_t}\right)^p\right]$$

$D_i(x_b, \mu_F, m_b)$: perturbative fragmentation function (PFF)

$$\frac{1}{\Gamma_0}\frac{d\hat{\Gamma}_b}{dz} = \delta(1-z) + \frac{\alpha_S(\mu)}{2\pi}\left[P_{qq}(z)\left(-\frac{1}{\epsilon} + \gamma_E - \ln 4\pi\right) + \hat{A}(z)\right]$$

$\overline{\mathrm{MS}}$ coefficient function:

$$\left(\frac{1}{\Gamma_0}\frac{d\hat{\Gamma}_b}{dz}\right)^{\overline{\mathrm{MS}}} = \delta(1-z) + \frac{\alpha_S(\mu)}{2\pi}\hat{A}(z)$$

$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dx_b}(m_b) = \left(\frac{1}{\Gamma_0}\frac{d\hat{\Gamma}_b}{dx_b}(m_b = 0)\right)^{\overline{\mathrm{MS}}} \otimes D_b^{\overline{\mathrm{MS}}}(m_b)$$

DGLAP equations for PFF's:

$$\frac{d}{d\ln\mu_F^2}D_i(x_b,\mu_F,m_b)=\sum_j\int_{x_b}^1\frac{dz}{z}P_{ij}\left(\frac{x_b}{z},\alpha_S(\mu_F)\right)D_j(z,\mu_F,m_b)$$

Initial condition $D(x_b,\mu_{0F})$ is process-independent - at NLO:

$$D_b(x_b,\mu_{0F},m_b)=\delta(1-x_b)+\frac{\alpha_S(\mu_0)C_F}{2\pi}\left[\frac{1+x_b^2}{1-x_b}\left(\ln\frac{\mu_{0F}^2}{m_b^2}-2\ln(1-x_b)-1\right)\right]_+$$

$$\frac{dD_N(\mu_F,m_b)}{d\ln\mu_F^2}=\frac{\alpha_S(\mu_F)}{2\pi}\left[P_N^{(0)}+\frac{\alpha_S(\mu_F)}{2\pi}P_N^{(1)}\right]D_N(\mu_F,m_b)$$

$$D_N(\mu_F,m_b)=D_N(\mu_{0F},m_b)\exp\left\{\frac{P_N^{(0)}}{2\pi b_0}\ln\frac{\alpha_S(\mu_{0F})}{\alpha_S(\mu_F)}+\frac{\alpha_S(\mu_{0F})-\alpha_S(\mu_F)}{4\pi^2 b_0}\left[P_N^{(1)}-\frac{2\pi b_1}{b_0}P_N^{(0)}\right]\right\}$$

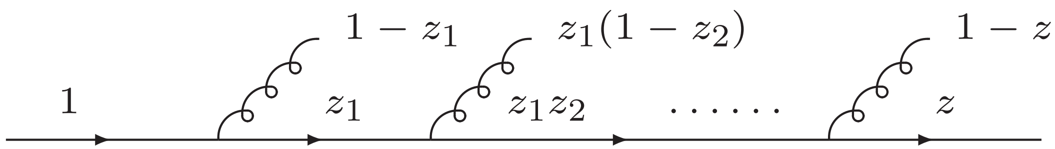
$$\begin{aligned}D_N(\mu_F,m_b) &= D_N(\mu_{0F},m_b)\exp\Big\{C_{1,0}\alpha_S(\mu_F)+C_{1,1}\alpha_S(\mu_F)\ln(\mu_F^2/\mu_{0F}^2)\dots\\ &+ C_{n,n-1}\alpha_S^n(\mu_F)\ln^{n-1}(\mu_F^2/\mu_{0F}^2)+C_{n,n}\alpha_S^n(\mu_F)\ln^n(\mu_F^2/\mu_{0F}^2)+\dots\Big\}\end{aligned}$$

Resummation of LLs $\alpha_S^n\ln^n(\mu_F^2/\mu_{0F}^2)$ and NLLs $\alpha_S^n\ln^{n-1}(\mu_F^2/\mu_{0F}^2)$

$\mu_{0F}\simeq m_b$ and $\mu_F\simeq m_t$: resummation of NLL $\ln(m_t^2/m_b^2)$ (collinear resummation)

Soft-gluon resummation ($x_b \to 1$)

$$t \to Wb\; g_1\; g_2\; \ldots g_n \quad ; \quad 1 - z_i \to 0 \quad ; \quad z = \Pi_i z_i$$



$$\frac{d\sigma^R}{dz} = \sigma_0 \left\{ \delta(1-z) + \sum_{n=1}^{\infty} \int dz_1 \ldots dz_n |\mathcal{M}(z_1, \ldots, z_n)|^2 \Phi_n(z, z_1, \ldots z_n) \right\}$$

Factorization soft matrix element

$$\mathcal{M}^{\mu,a}(t \to bWg) \simeq g_s T^a \left(\frac{p_t^\mu}{p_t \cdot p_g} - \frac{p_b^\mu}{p_b \cdot p_g} \right) \mathcal{M}_0(t \to bW) \quad ; \quad |\mathcal{M}(z_1, \ldots, z_n)|^2 = \frac{1}{n!} \Pi_i |\mathcal{M}(z_i)|^2$$

If one also has: $\Phi_n(z, z_1, \ldots z_n) = \Pi_i \Phi(z, z_i)$

$$\frac{d\sigma^R}{dz} = \sigma_0 \left\{ \delta(1-z) + \sum_{n=1}^{\infty} \frac{1}{n!} \left[\int_0^1 dz_i \; |\mathcal{M}(z_i)|^2 \; \Phi(z, z_i) \right]^n \right\} = \sigma_0 \exp \left\{ \int_0^1 dz_1 \; |\mathcal{M}(z_1)|^2 \; \Phi(z, z_1) \right\}$$

Virtual contributions from unitarity

$$\frac{d\sigma^V}{dz} = \sigma_0 \left\{ 1 - \int dx \frac{d\sigma^R}{dx} \right\} \delta(1-z)$$

Example of phase space factorization: $\int dz z^{N-1} \delta(z - z_1 z_2 \ldots z_n) = z_1^{N-1} z_2^{N-1} \ldots z_n^{N-1}$

Large-x radiation in top decays

Region $x_b \to 1$ corresponds to soft-gluon radiation

Bottom quark spectrum presents terms $1/(1-x_b)_+$ and $[\ln(1-x_b)/(1-x_b)]_+$

$$\frac{1}{(1-x_b)_+} \to \ln N \qquad \left[\frac{1}{1-x_b}\ln(1-x_b)\right]_+ \to \ln^2 N$$

$$\hat{\Gamma}_N(m_t,\mu,\mu_F) = 1+\frac{\alpha_S(\mu)C_F}{2\pi}\left\{2\ln^2 N + \left[4\gamma+2-4\ln(1-w)-2\ln\frac{m_t^2}{\mu_F^2}\right]\ln N + K(m_t,\mu_F) + \mathcal{O}\left(\frac{1}{N}\right)\right\}$$

$$z = 1-x_b, \quad k^2 = (p_b+p_g)^2(1-z) = 2E_g^2(1-\cos\theta_{bg}) \simeq E_g^2\sin^2\theta_{bg}$$

$$\begin{aligned}\Delta_N &= \exp\left\{\int_0^1 dz\frac{z^{N-1}-1}{1-z}\int_{\mu_F^2}^{m_t^2(1-w)^2(1-z)^2}\left[\frac{dk^2}{k^2}A\left[\alpha_S(k^2)\right] + S\left[\alpha_S\left(m_t^2(1-w)^2(1-z)^2\right)\right]\right]\right\}\\ &= \exp\left[\ln N g_1 + g_2\right]\end{aligned}$$

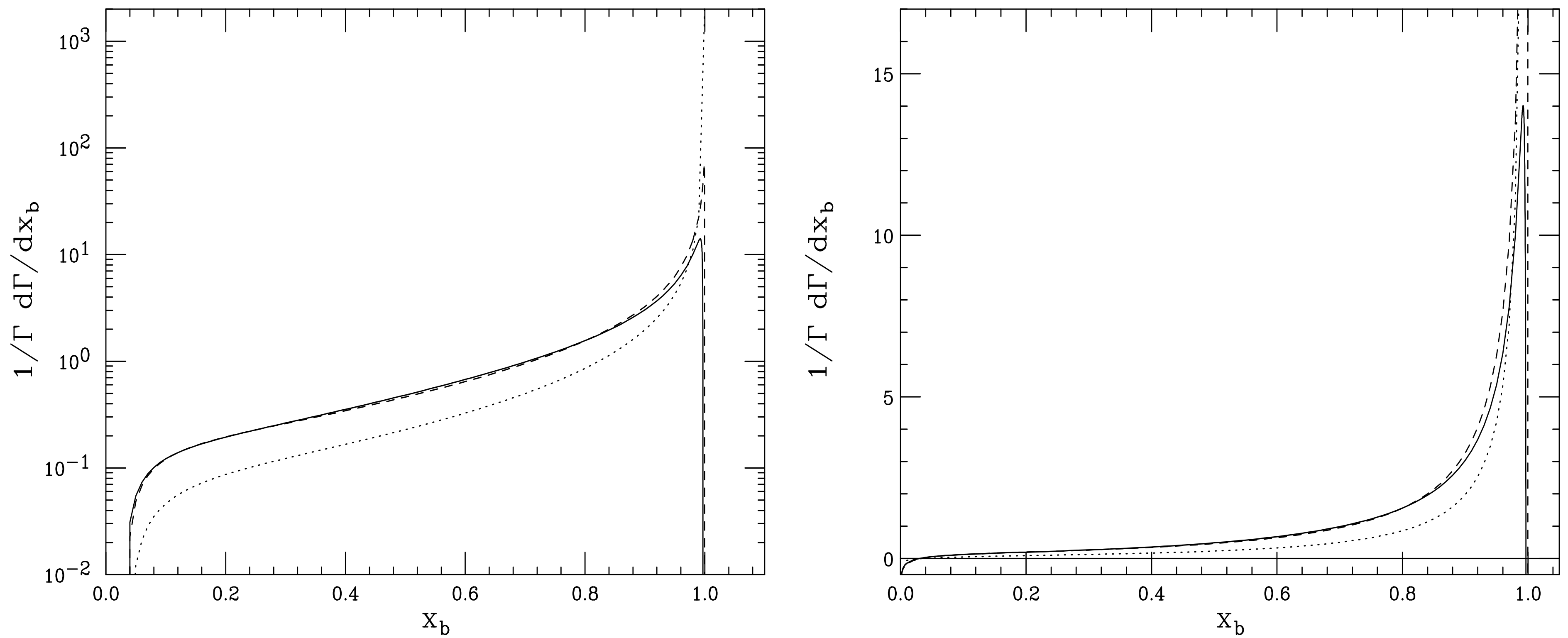
$$A(\alpha_S) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n A^{(n)} \quad ; \quad S(\alpha_S) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n S^{(n)}$$

$g_1 \ln N$ resums LL $A^{(1)}$: $\alpha_S \ln^2 N, \alpha_S^2\ln^4 N \ldots \alpha_S^n \ln^{n+1} N$

g_2 resums NLL $A^{(2)}, S^{(1)}$: $\alpha_S \ln N, \alpha_S^2 \ln^2 N \ldots \alpha_S^n \ln^n N$

b-quark energy spectrum in top decay

m_t=175 GeV, m_b=5 GeV, m_W=80.4 GeV ; $\mu_F = \mu = m_t$, $\mu_0 = \mu_{0F} = m_b$; $\Lambda_{\overline{\mathrm{MS}}}$=200 GeV



Solid: soft and collinear resummation Dashes: only collinear resummation

Dots: massive NLO without resummation

Left: logarithmic scale; right: linear scale

Standard Monte Carlo generators for high-energy colliders

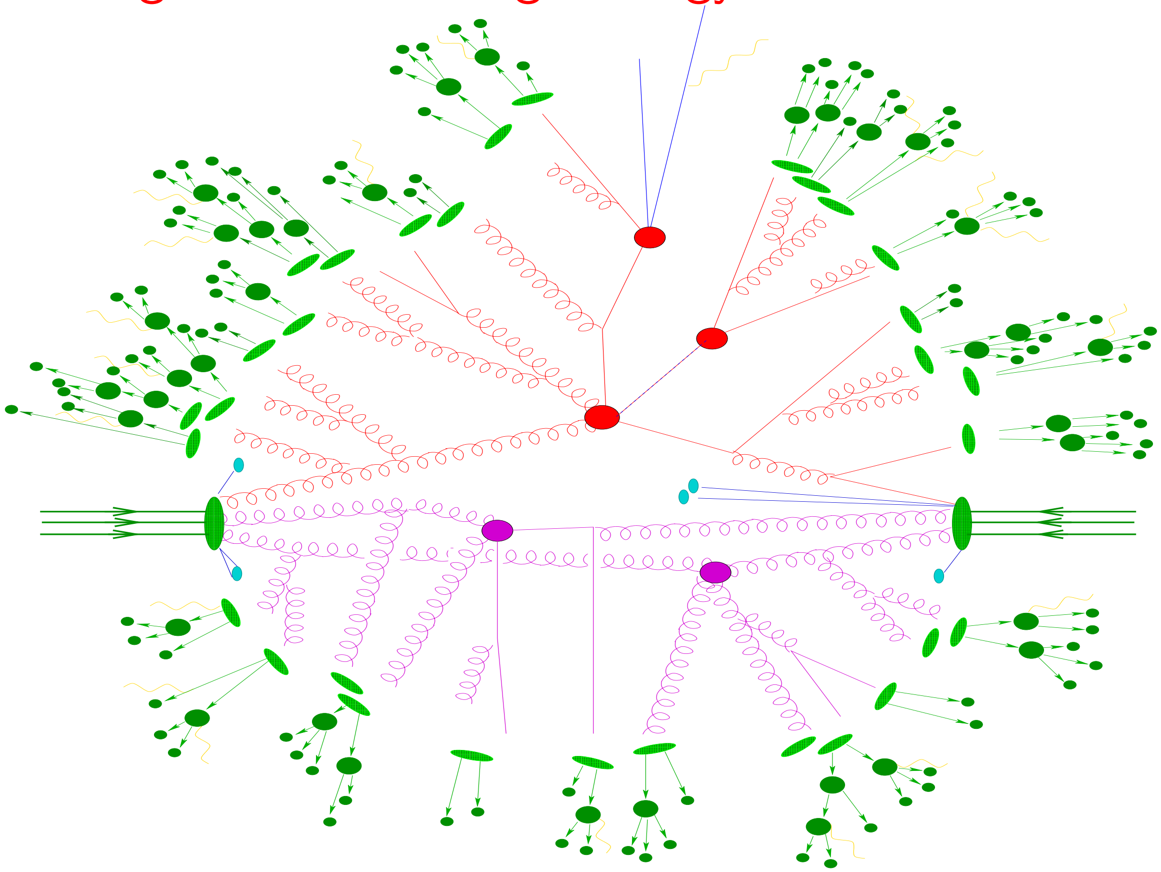


Figure by Frank Krauss

Hard $2 \to 2$ subprocess: leading-order (LO) matrix element

Parton showers in the soft or collinear approximation

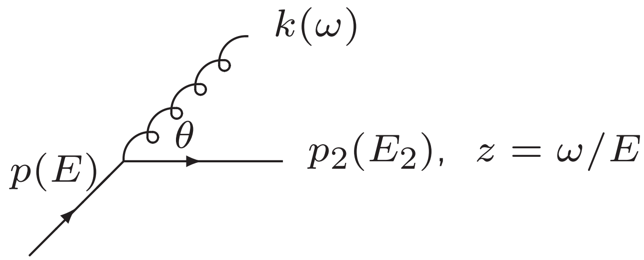
Matrix-element corrections for hard and large-angle parton radiation

Models for hadronization and underlying event

POWHEG and MC@NLO: NLO $t\bar{t}$ production - approximations for NLO top decays

Parton shower algorithms

Multiple radiation in the soft or collinear approximation



$$dP = \frac{\alpha_S}{2\pi}\,\hat{P}(z)dz\,\frac{dQ^2}{Q^2}\,\Delta_S(Q^2_{\rm max},Q^2)$$

Q^2: ordering variable

$\Delta_S(Q^2_{\rm max},Q^2)$ Sudakov form factor: no radiation in $[Q^2,Q^2_{\rm max}]$

$$\Delta_S(Q^2_{\rm max},Q^2) = \exp\left[-\frac{\alpha_S}{2\pi}\int_{Q^2}^{Q^2_{\rm max}}\frac{dQ'^2}{Q'^2}\int_{z_{\rm min}}^{z_{\rm max}} dz\,\hat{P}(z)\right]$$

HERWIG : $Q^2 = E^2(1-\cos\theta) \simeq E^2\theta^2/2$ Soft approximation: angular ordering

PYTHIA (up to 6.2 version): $Q^2 = p^2$

It includes angular ordering only by an additional veto

PYTHIA 6.3 and 8: $Q^2 = k_T^2$

Hard and large-angle radiation: matrix-element corrections

Implemented for top decay, not for top production

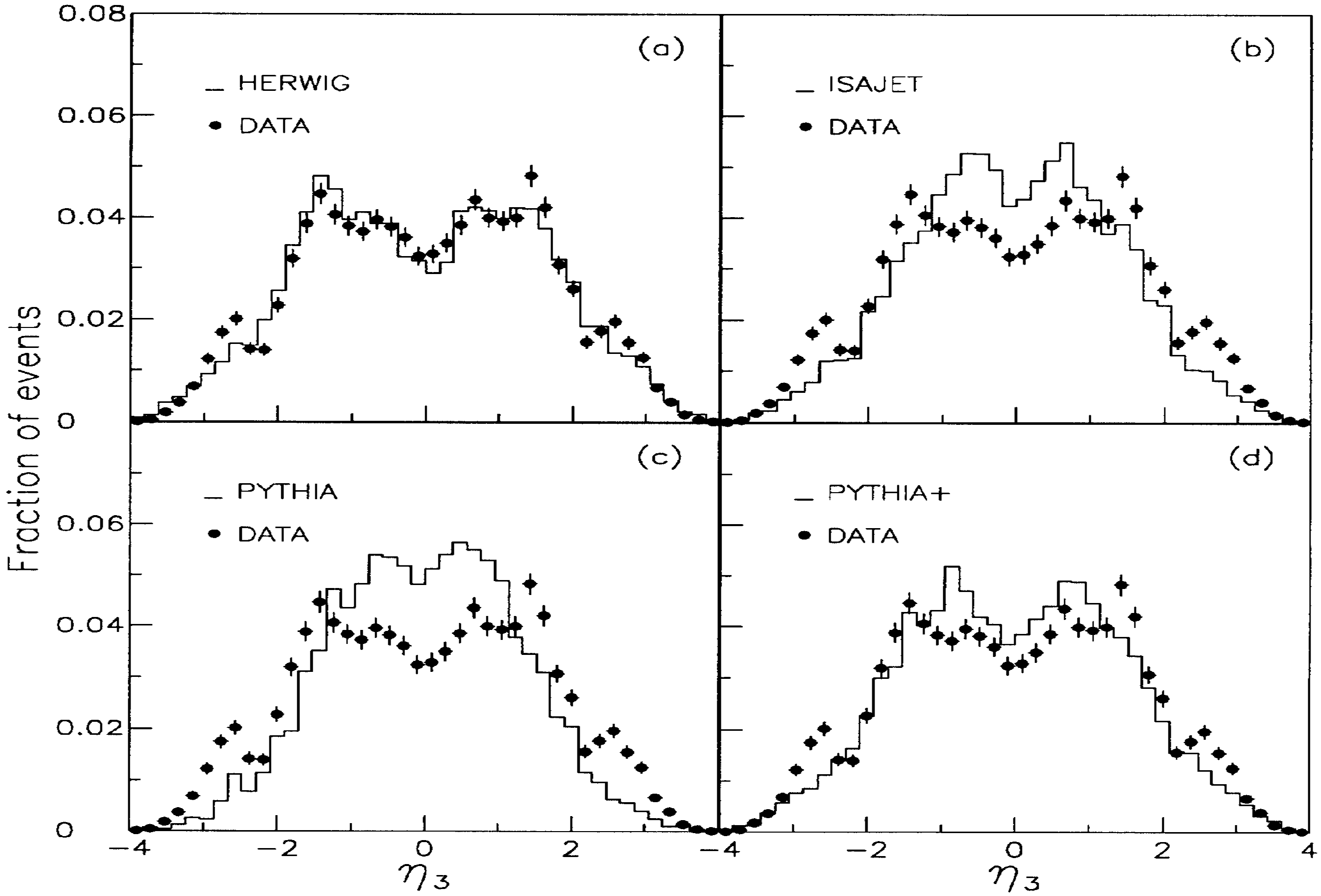


Figure 10:

Three-jet events at CDF:

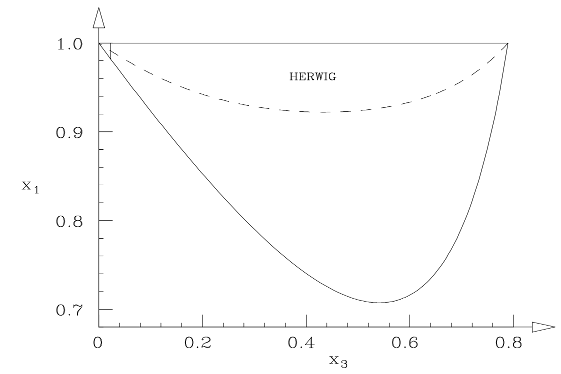
$E_{T1,2} > 100$ GeV ; $E_{T,3} > 10$ GeV

(Old-fashioned) matrix-element corrections for hard/large-angle radiation: implemented for top decay $t \to bW$, but not for production

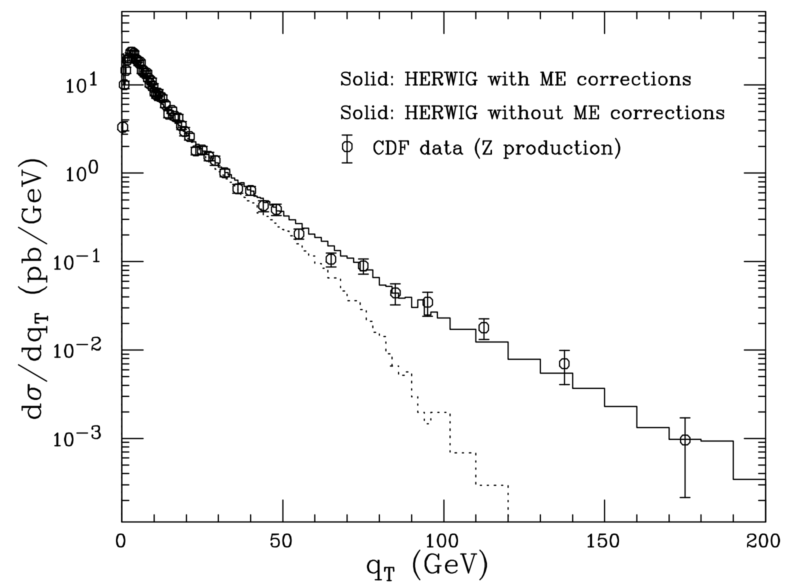
HW: exact amplitude in the dead zone (t rest frame)

PY: exact matrix element corrects first emission

Still LO total cross section



Background: matching for $W/Z+1$ jet, crucial to agree with data(G.C. and M.H.Seymour)



Processes in MC@NLO or POWHEG: total cross section is NLO

Parton showers and resummation: iterating dP for multiple radiation:

$$dP_1 = \frac{\alpha_S}{2\pi} dz_1 \hat{P}(z_1) \frac{dQ_1^2}{Q_1^2}, \; dP_2 = \frac{\alpha_S}{2\pi} dz_2 \hat{P}(z_2) \frac{dQ_2^2}{Q_2^2} dP_1, \ldots,$$

$$dP_n = dP_{n-1} \frac{\alpha_S}{2\pi} dz_n \hat{P}(z_n) \frac{dQ_n^2}{Q_n^2}$$

$$P_n \sim \alpha_S^n \int_{Q_0^2}^{Q^2} \frac{dQ_1^2}{Q_1^2} \int_{Q_0^2}^{Q_1^2} \frac{dQ_2^2}{Q_2^2} \ldots \int_{\epsilon_1}^{1-\epsilon_1} dz_1 \hat{P}(z_1) \int_{\epsilon_2}^{1-\epsilon_2} dz_2 \hat{P}(z_2) \ldots$$

Example: all $q \to qg$, $z \to 0$, $Q^2 \propto \theta^2 \to 0$

$$\hat{P}(z) = C_F \frac{1 + (1-z)^2}{z} \simeq \frac{2C_F}{z}$$

Soft and collinear limit: resummation of double logarithms $\sim \alpha_S^n L^{2n}$

Soft or collinear limit: resummation of single logarithms $\sim \alpha_S^n L^n$

S. Catani, G. Marchesini and B.R. Webber, NPB 349 (1991) 635:
HERWIG is equivalent to LL resummation, with the inclusion of some NLLs
$(\Lambda_{\overline{\rm MS}} \to \Lambda_{\rm MC} = \Lambda_{\overline{\rm MS}} \exp(4K\beta_0))$

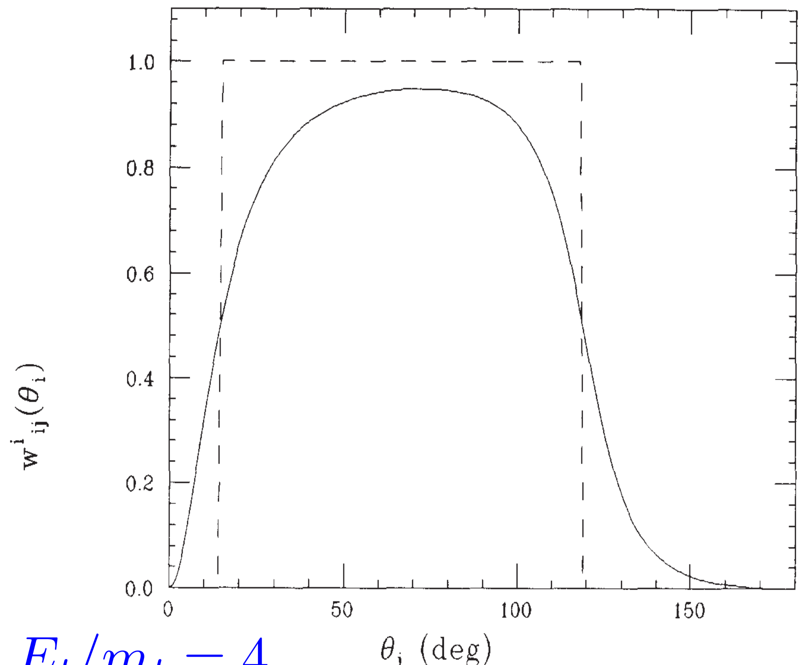
Soft gluons off heavy quarks: dead-cone approximation $t(p_t) \to W(p_W)b(p_b)g(p_g)$

Eikonal factor after azimuthal average:

$$W_{tb} = \left(\frac{p_t}{p_t \cdot p_g} - \frac{p_b}{p_b \cdot p_g}\right)^2 \to \langle W_t \rangle \Theta(R_t) + \langle W_b \rangle \Theta(R_b) \quad ; \quad W_i = \frac{1}{2} - \frac{m_i^2}{2\xi_i^2 E_i^2} + \frac{\xi_{ij} - \xi_i}{2\xi_i \xi_j}$$

$$\xi_{tb} = \frac{p_t \cdot p_b}{E_t E_b} = 1 - v_t \cos\theta_{tb} \; ; \; \xi_t = \frac{p_t \cdot p_g}{E_t E_g} = 1 - v_t \cos\theta_t \; ; \; \xi_b = \frac{p_b \cdot p_g}{E_b E_g} = 1 - v_b \cos\theta_b$$

Dominant phase space: $v_b \cos\theta_{tb} < \cos\theta_t < v_t \quad (R_t)$; $\quad v_t \cos\theta_{tb} < v_b \cos\theta_b < 1 \; (R_b)$

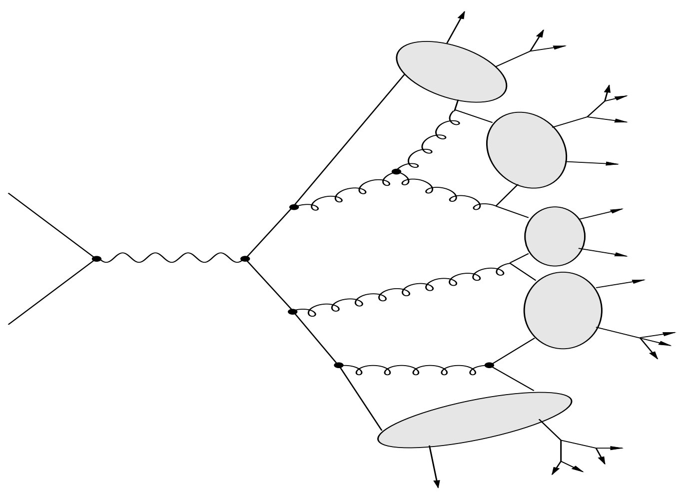


Example for $\theta_{tb} = 120°$, $E_t/m_t = 4$

Dead cone for $\theta < m_t/E_t \approx 15°$

Hadronization: NP fragmentation functions and Monte Carlo models

$$D_{\rm K}(x,\alpha) = (1+\alpha)(2+\alpha)x(1-x)^{\alpha} \quad ; \quad D_{\rm P}(x,\epsilon) = \frac{N_P}{x\,[1 - 1/x - \epsilon/(1-x)]}$$



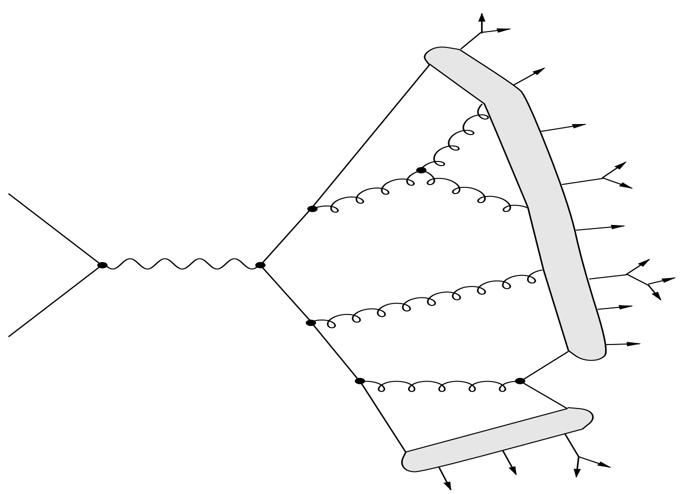
HERWIG: cluster model

Perturbative evolution ends at $Q^2 = Q_0^2$

Angular ordering $\Rightarrow$ colour preconfinement

Forced gluon splitting $(g \to q\bar{q})$

Colour-singlet clusters decay into the observed hadrons



PYTHIA: string model

q and $\bar{q}$ move in opposite direction

The colour field collapses into a string with uniform energy density

$q\bar{q}$ pairs are produced

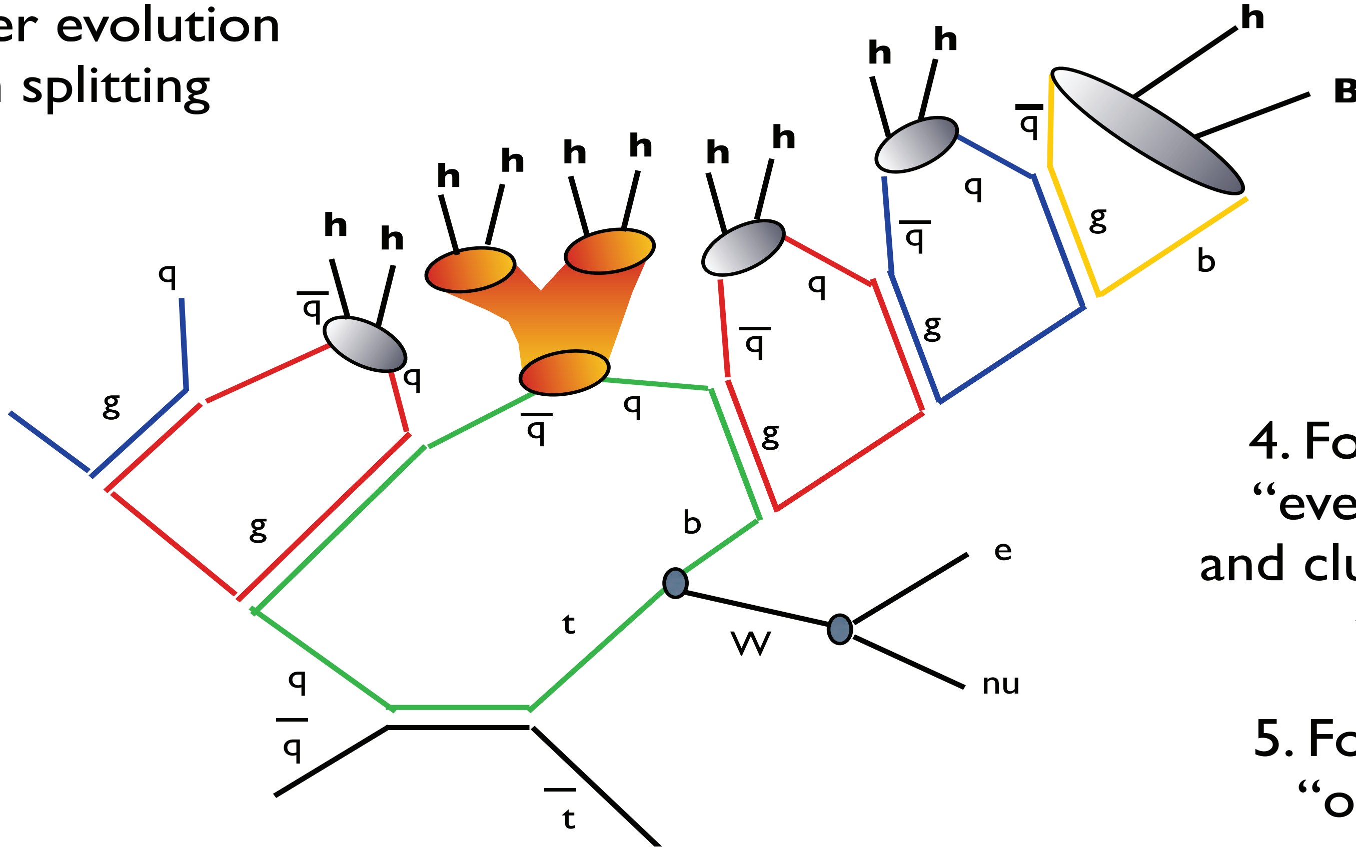
The string breaks into the observed hadrons

Possible interface with NP fragmentation functions

Tuning hadronic and perturbative parameters (Q_0, $\Lambda_{\rm MC}$, m_g, ...) to e^+e^- data
b-fragmentation is process independent, but pp is different from e^+e^-, because of ISR, pdfs, colour reconnection, etc.

Hadronization: hadrons can be formed via ‘even’ or ‘odd’ clusters: effects already studied at LEP for $e^+e^- \to W^+W^- \to 4$ jets M.L.Mangano, talk at TOP2013

1. Hard Process
2. Shower evolution
3. Gluon splitting



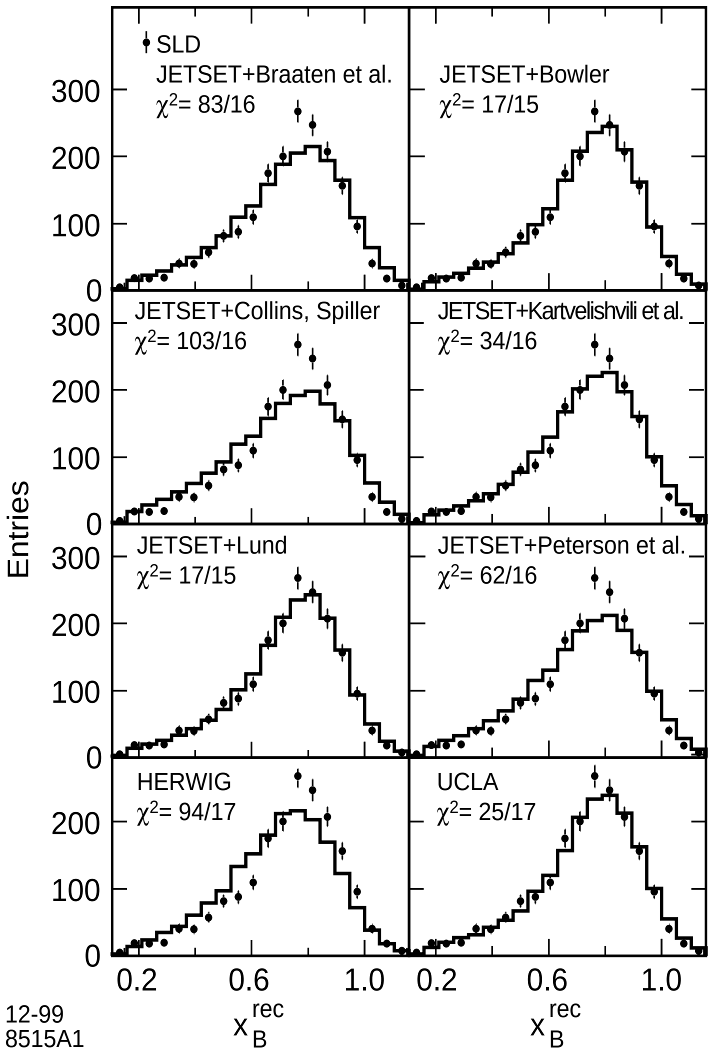
4. Formation of “even” clusters and cluster decay to hadrons

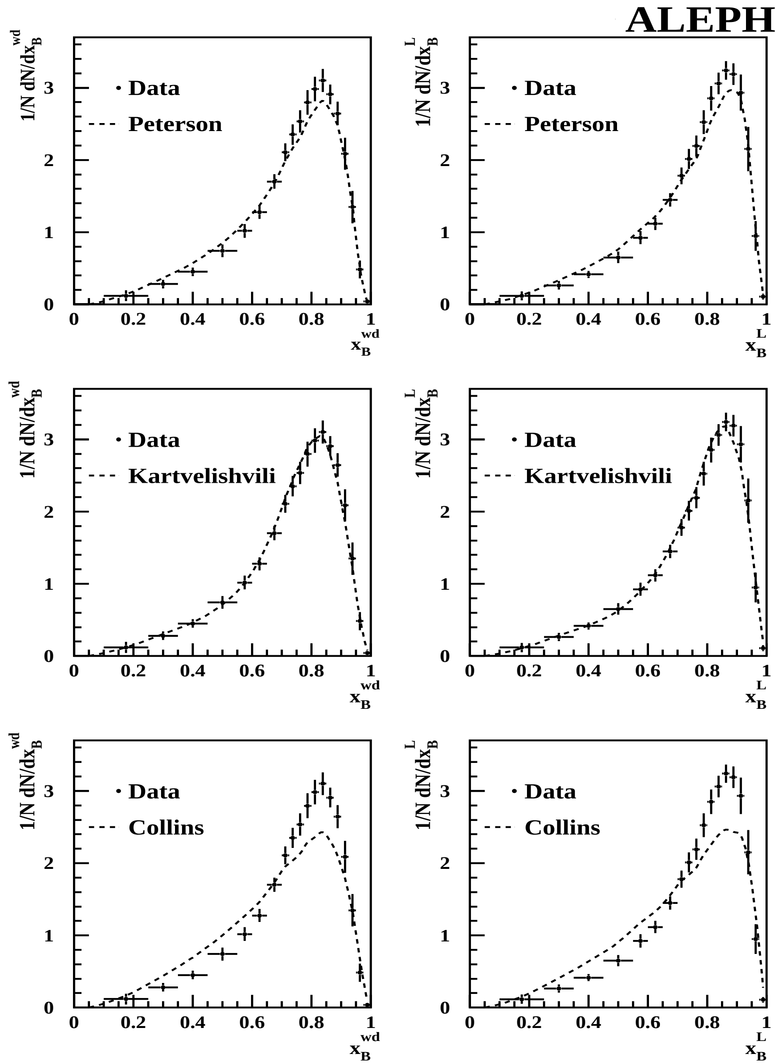
5. Formation of “odd” cluster

$m_t = (p_W + p_{b-\mathrm{jet}})^2$: the b-jet may come from either an even or an odd cluster

Colour reconnection can be investigated by varying relevant parameters in HERWIG and PYTHIA (so-called Perugia tunings) and affects the top mass about $\Delta m_t \leq 1$ GeV

Bottom-quark fragmentation at the Z^0 pole





LEP tuning of PYTHIA+Peterson used in $J/\psi + \ell$ analysis

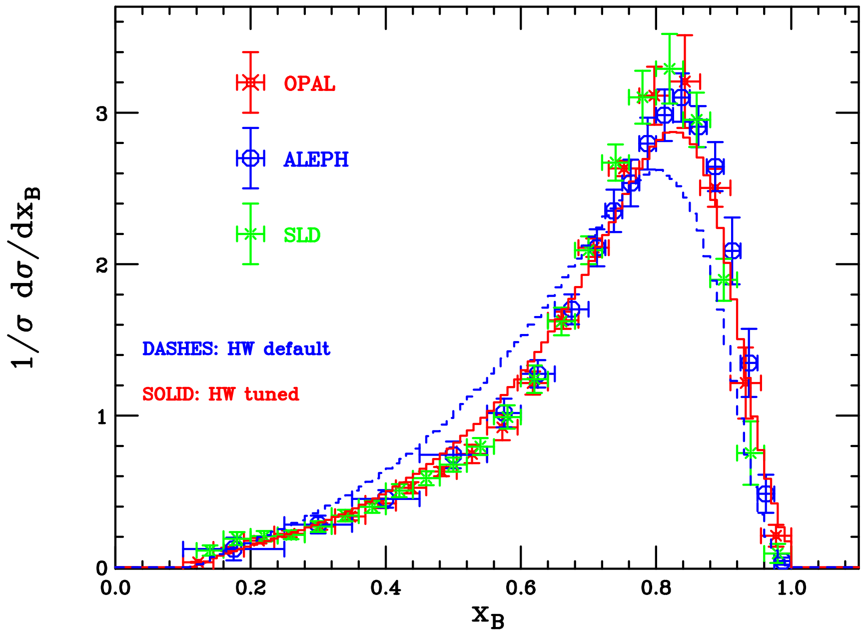
Best-fit parameters not the same, e.g. $\epsilon_b = 0.0033$ (ALEPH), 0.0055 (SLD); $\alpha_K = 11.9$ (OPAL), 13.7 (ALEPH), 10.0 (SLD)

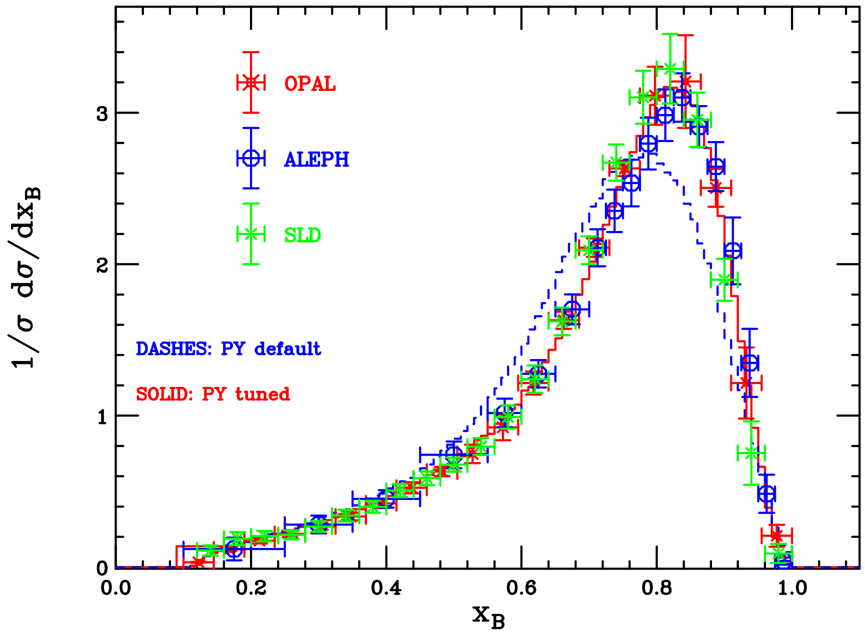
Monte Carlo tuning: $e^+e^- \to Z^0 \to b\bar{b} \to BX_{\bar{b}}$ $\quad x_B = \frac{2p_B \cdot p_Z}{m_Z^2} = \frac{2E_B}{m_Z}$

(G. C. and V. Drollinger)

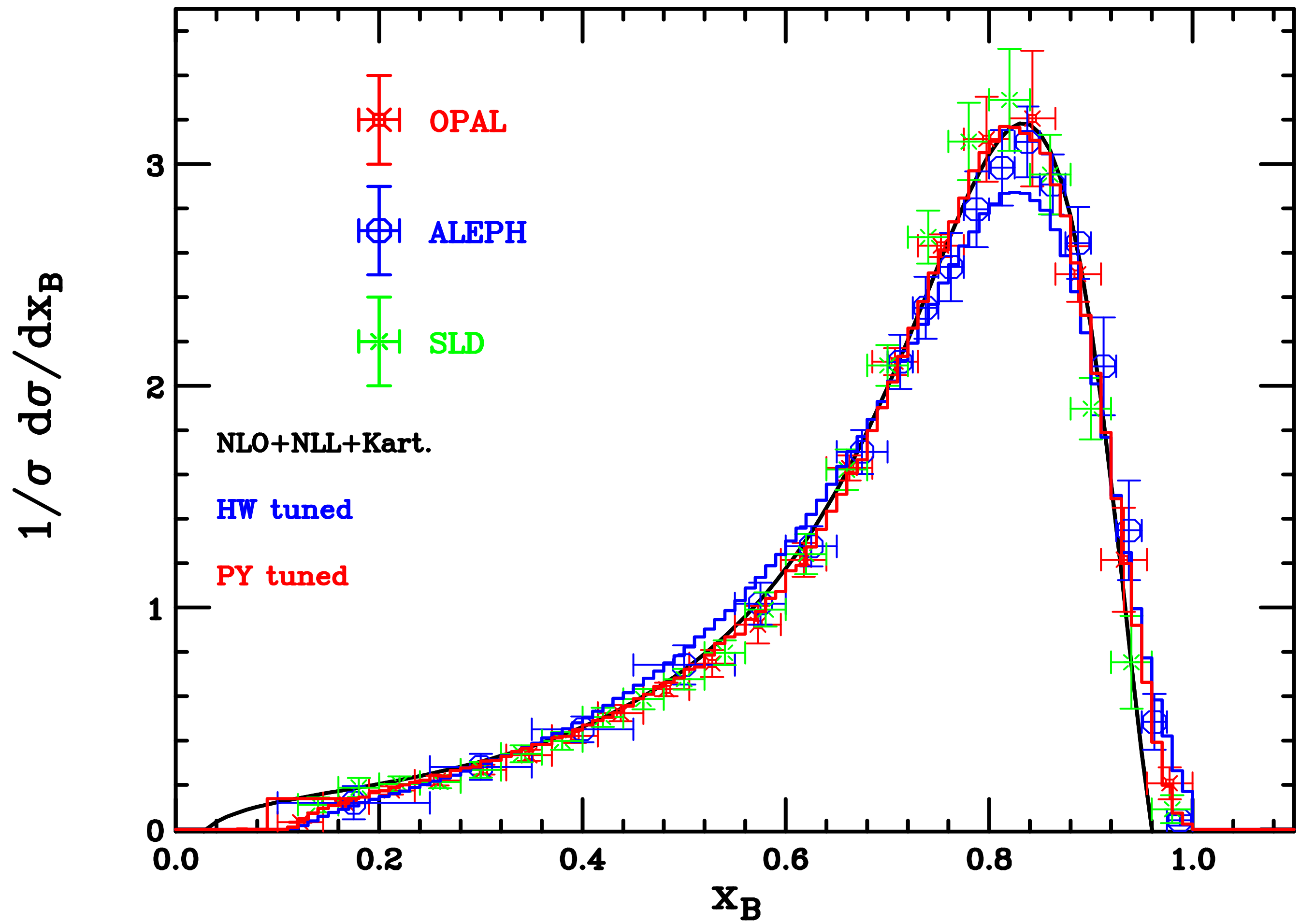
HERWIG	PYTHIA
CLSMR(1) = 0.4 (0.0)	
CLSMR(2) = 0.3 (0.0)	PARJ(41) = 0.85 (0.30)
DECWT = 0.7 (1.0)	PARJ(42) = 1.03 (0.58)
CLPOW = 2.1 (2.0)	PARJ(46) = 0.85 (1.00)
PSPLT(2) = 0.33 (1.00)	
χ^2/dof = 222.4/61 (739.4/61)	χ^2/dof = 45.7/61 (467.9/61)

Lund/Bowler fragmentation function : $f_B(z) \propto \frac{1}{z^{1+brm_b^2}}(1-z)^a \exp(-bm_T^2/z)$





Comparing tuned HERWIG and PYTHIA and resummed calculations

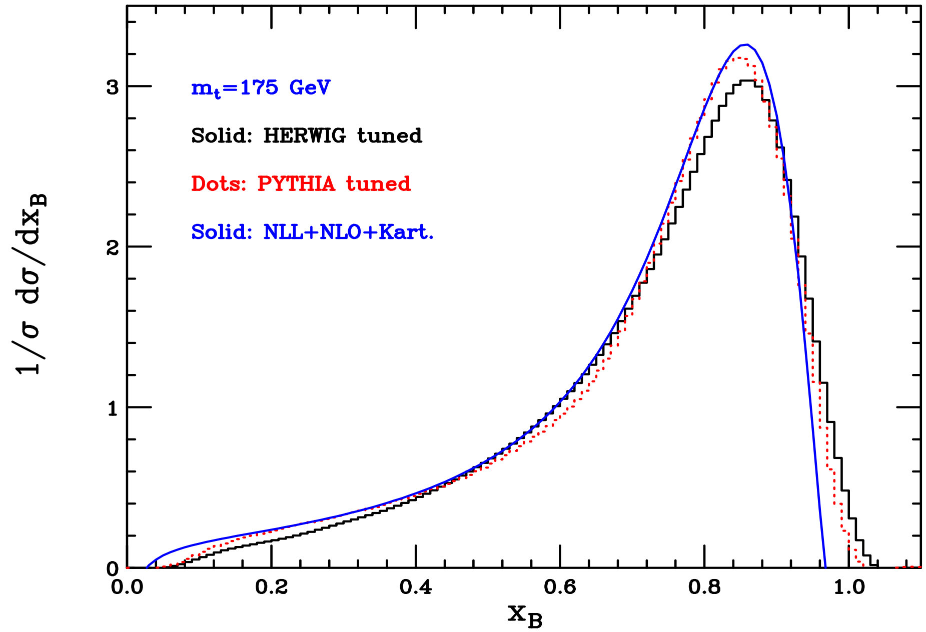


NLO+NLL+Kart.: M.Cacciari and S.Catani, NPB617 (2001) 253-290

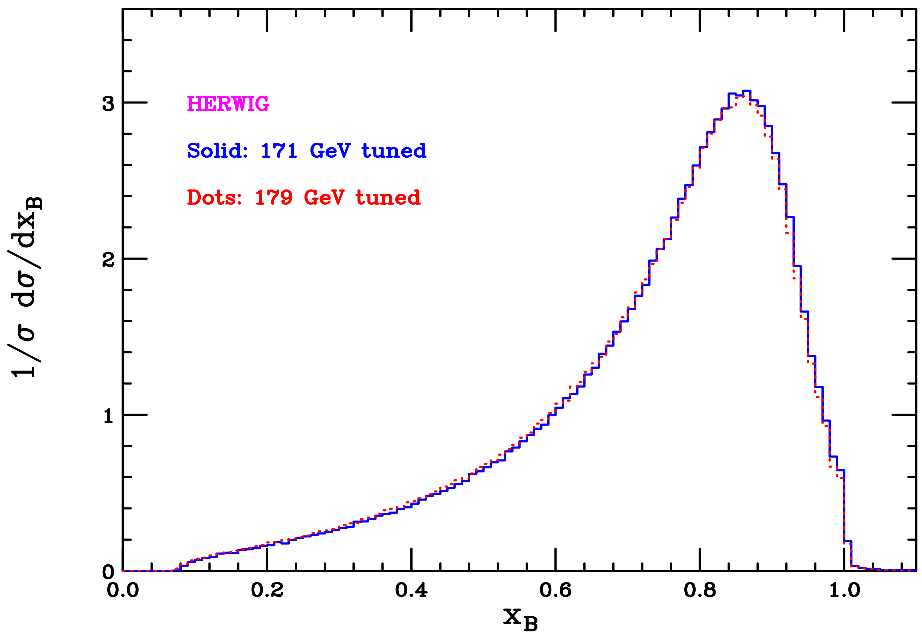
Best fit $(0.18 \leq x_B \leq 0.94)$: $\alpha = 17.178 \pm 0.303$, $\chi^2/\mathrm{dof} = 46.2/53$

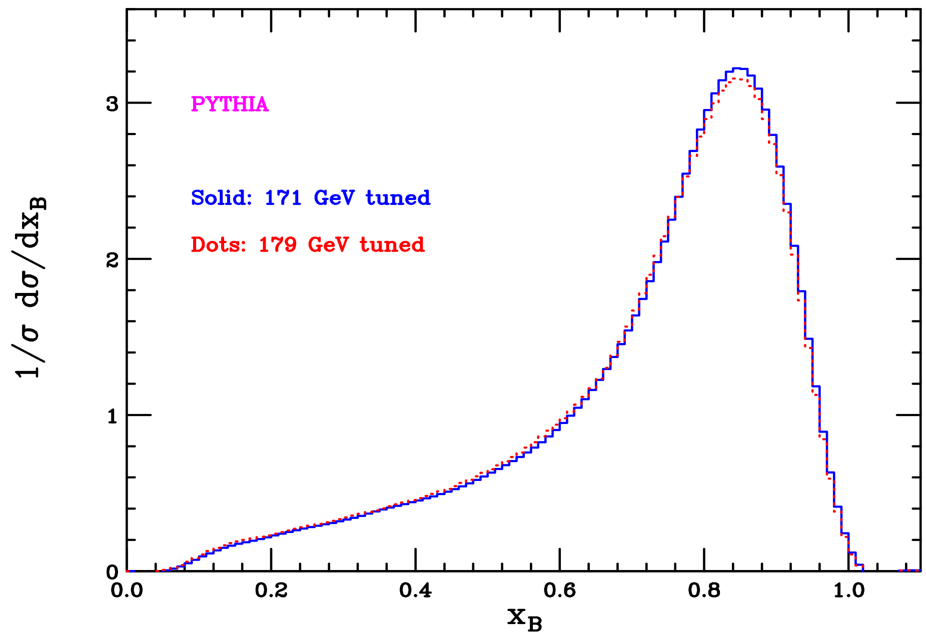
Reliability of perturbative calculation: $x_b < 1 - \Lambda/m_b \simeq 0.95$

B-hadron spectrum in top decays:



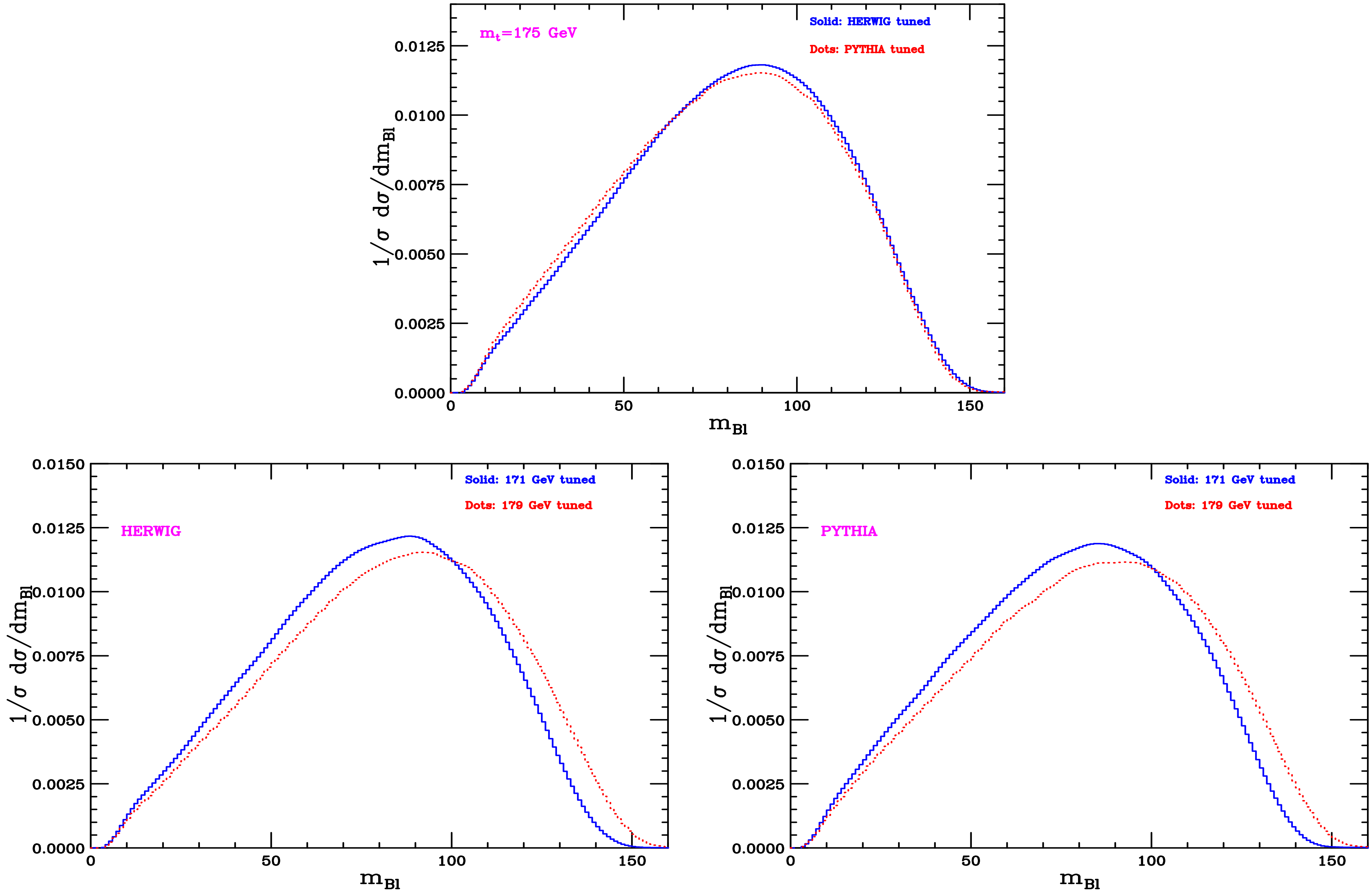
Mild dependence on the top mass in both HERWIG and PYTHIA:





Discussion with CMS/ATLAS folks: x_B hard to measure experimentally

B-lepton invariant mass according to tuned HERWIG and PYTHIA (G.C. and F. Mescia)



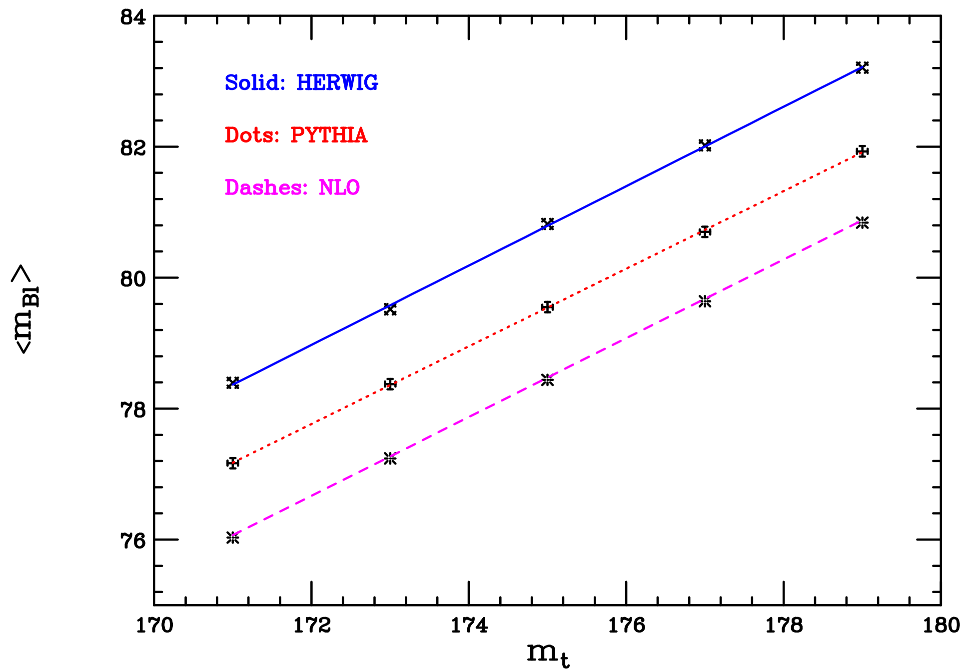
Linear fits to extract m_t from $m_{B\ell}$

HERWIG: $\langle m_{B\ell}\rangle_{\rm H} \simeq -25.31\ {\rm GeV} + 0.61\ m_t$; $\delta = 0.043\ {\rm GeV}$

PYTHIA: $\langle m_{B\ell}\rangle_{\rm P} \simeq -24.11\ {\rm GeV} + 0.59\ m_t$; $\delta = 0.022\ {\rm GeV}$

NLO: $\langle m_{B\ell}\rangle_{\rm NLO} \simeq -26.7\ {\rm GeV} + 0.60\ m_t$; $\delta = 0.004\ {\rm GeV}$

S.Biswas, K.Melnikov and M.Schulze, JHEP 1008 (2010): $m_{B\ell}$ at NLO using NLO+(N)LL fit (G.C. and A.Mitov)



$\Delta\langle m_{B\ell}\rangle_{\rm H,P} \simeq 1.2$ GeV ; $\Delta\langle m_{B\ell}\rangle_{\rm H,NLO} \simeq 2.2$ GeV ; $\Delta\langle m_{B\ell}\rangle_{\rm P,NLO} \simeq 1.1$ GeV

NLO+showers for top decays or C++ codes may shed light on this discrepancy

Results in moment space

$$\Gamma_N = \int_0^1 dz\ z^{N-1} \frac{1}{\Gamma}\frac{d\Gamma}{dz}(z)$$

e^+e^- annihilation $\sigma_N^B = \sigma_N^b D_N^{np}$

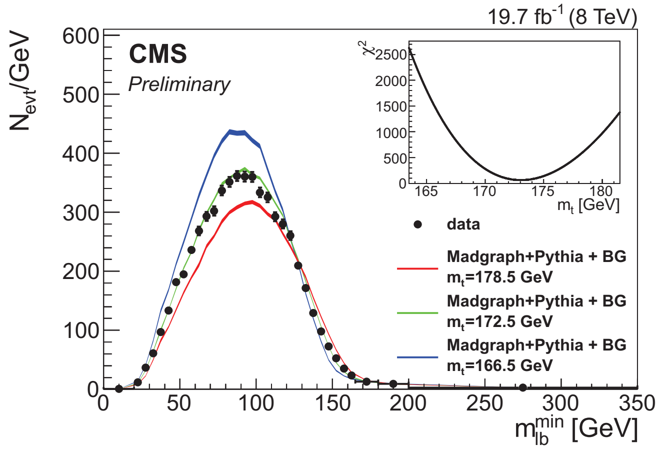
σ_N^B measured ; σ_N^b calculated ; D_N^{np} fitted

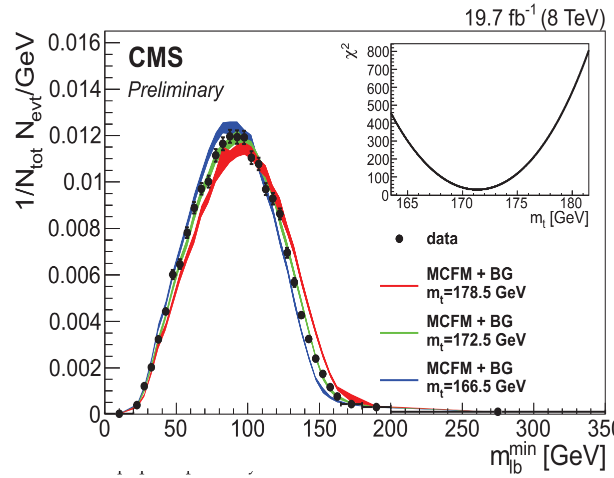
top decay: $\Gamma_N^B = \Gamma_N^b D_N^{np} = \Gamma_N^b \sigma_N^B / \sigma_N^b$

Fits to DELPHI data in moment space

	$\langle x \rangle$	$\langle x^2 \rangle$	$\langle x^3 \rangle$	$\langle x^4 \rangle$
e^+e^- data σ_N^B	0.7153$\pm$0.0052	0.5401$\pm$0.0064	0.4236$\pm$0.0065	0.3406$\pm$0.0064
e^+e^- NLL σ_N^b	0.7801	0.6436	0.5479	0.4755
D_N^{np}	0.9169	0.8392	0.7731	0.7163
e^+e^- HW σ_N^B	0.7113	0.5354	0.4181	0.3353
e^+e^- PY σ_N^B	0.7162	0.5412	0.4237	0.3400
t-dec. NLL Γ_N^b	0.7883	0.6615	0.5735	0.5071
t-dec. NLL $\Gamma_N^B = \Gamma_N^b D_N^{\mathrm{np}}$	0.7228	0.5551	0.4434	0.3632
t-dec. HW Γ_N^B	0.7325	0.5703	0.4606	0.3814
t-dec. PY Γ_N^B	0.7225	0.5588	0.4486	0.3688

Invariant mass $m_{b\ell}$ using MadGraph+PYTHIA (LO) and MCFM (LO or NLO)





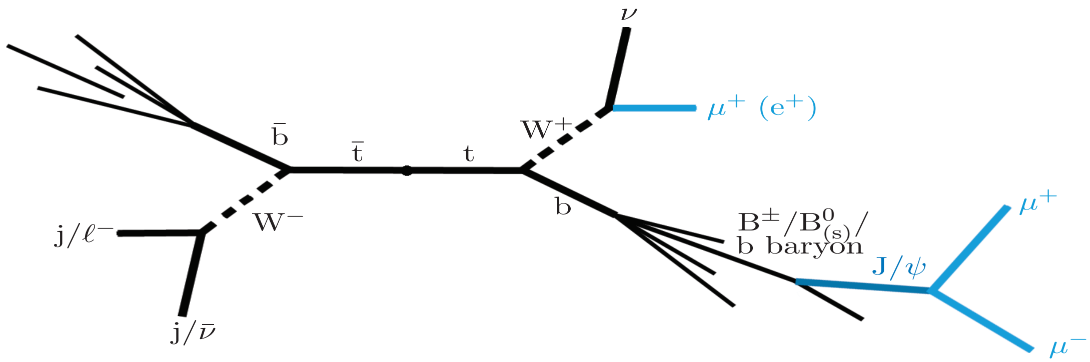
$$m_t(\mathrm{Mad + PY}) = 172.3^{+1.3}_{-1.3}\ \mathrm{GeV}$$

$$m_t(\mathrm{MCFM@LO}) = 171.4^{+1.0}_{-1.1}\ \mathrm{GeV}$$

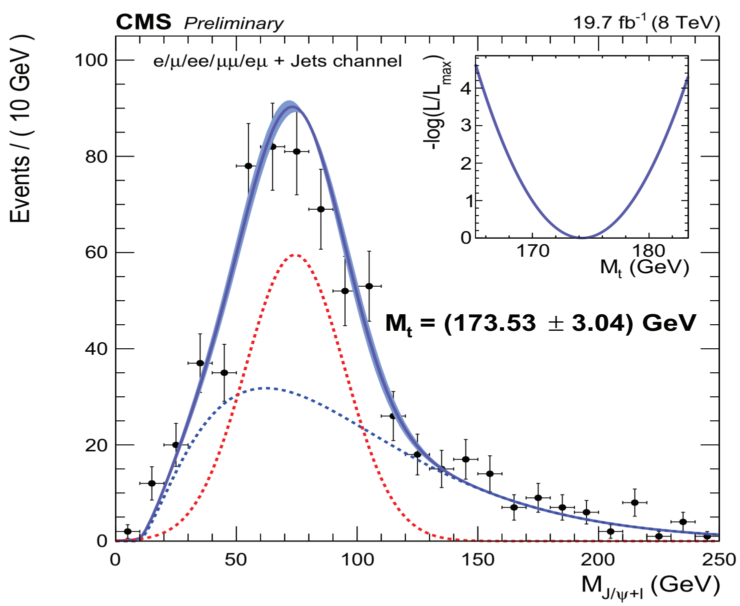
Source	Δm_t [GeV]				
	MadGraph +Pythia			MCFM shape	
	shape+rate	rate	shape	NLO	LO
Top p_T	$^{+0.01}_{-0.01}$	$^{-0.60}_{+0.60}$	$^{+0.66}_{-0.66}$	$^{+0.28}_{-0.28}$	$^{+0.27}_{-0.27}$
Fit parameterization m_t	$^{-0.04}_{+0.04}$	$^{-0.06}_{+0.06}$	$^{+0.07}_{-0.07}$	$^{+0.07}_{-0.07}$	$^{+0.07}_{-0.07}$
ME-PS matching threshold	$^{-0.10}_{+0.10}$	$^{-0.13}_{+0.43}$	$^{+0.13}_{-0.21}$	$^{+0.13}_{-0.24}$	$^{+0.15}_{-0.20}$
Renormalization and factorization (Q^2) scale	$^{-0.07}_{-0.11}$	$^{-0.55}_{+0.47}$	$^{+0.50}_{-0.59}$	$^{+0.50}_{-0.50}$	$^{+0.45}_{-0.51}$
b-fragmentation	$^{+0.57}_{-0.57}$	$^{+0.54}_{-0.54}$	$^{+0.62}_{-0.62}$	$^{+0.43}_{-0.43}$	$^{+0.40}_{-0.40}$
B branching fractions	$^{+0.07}_{-0.02}$	$^{-0.05}_{+0.05}$	$^{+0.20}_{-0.10}$	$^{+0.18}_{-0.10}$	$^{+0.17}_{-0.10}$
ME generator	$^{-0.73}_{+0.73}$	$^{-1.16}_{+1.16}$	$^{-0.19}_{+0.19}$	$^{-0.10}_{+0.10}$	$^{-0.08}_{+0.08}$
Color reconnection	$^{+0.22}_{-0.22}$	$^{+0.19}_{-0.19}$	$^{+0.12}_{-0.12}$	$^{+0.12}_{-0.12}$	$^{+0.12}_{-0.12}$
Underlying event	$^{-0.10}_{+0.21}$	$^{-0.14}_{+0.14}$	$^{-0.24}_{+0.14}$	$^{-0.24}_{+0.14}$	$^{-0.24}_{+0.14}$
$\mathrm{PDF_{MC}}$	$^{+0.20}_{-0.08}$	$^{+0.25}_{-0.15}$	$^{+0.20}_{-0.06}$	$^{+0.09}_{-0.02}$	$^{+0.04}_{-0.03}$
$\mathrm{scale_{NNLO\ normalization}}$	$^{+0.85}_{-0.88}$	$^{+1.65}_{-1.71}$	< 0.01		
$\mathrm{PDF_{NNLO\ normalization}}$	$^{+0.66}_{-0.67}$	$^{+1.27}_{-1.30}$	< 0.01		
$\mathrm{scale_{MCFM}}$				$^{+0.05}_{-0.03}$	$^{+0.04}_{-0.09}$
$\mathrm{PDF_{MCFM}}$				$^{-0.02}_{+0.03}$	$^{-0.01}_{+0.01}$
$\alpha_S(M_Z)$ variation				< 0.01	< 0.01
m_b variation				< 0.01	< 0.01
Total uncertainty	$^{+1.85}_{-1.83}$	$^{+3.45}_{-3.43}$	$^{+1.29}_{-1.33}$	$^{+1.04}_{-1.08}$	$^{+1.02}_{-1.11}$

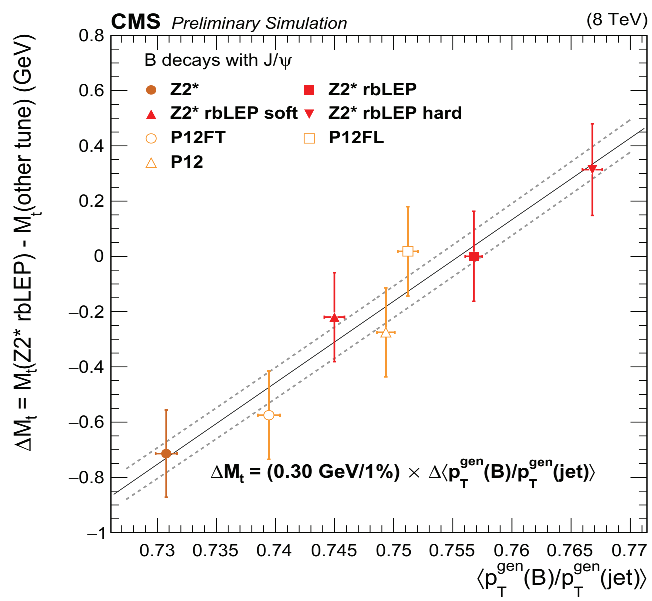
Methods on the top mass reconstruction relying on b-quark fragmentation

Final states with leptons and J/ψ: invariant mass $\ell + J/\psi$ yields m_t



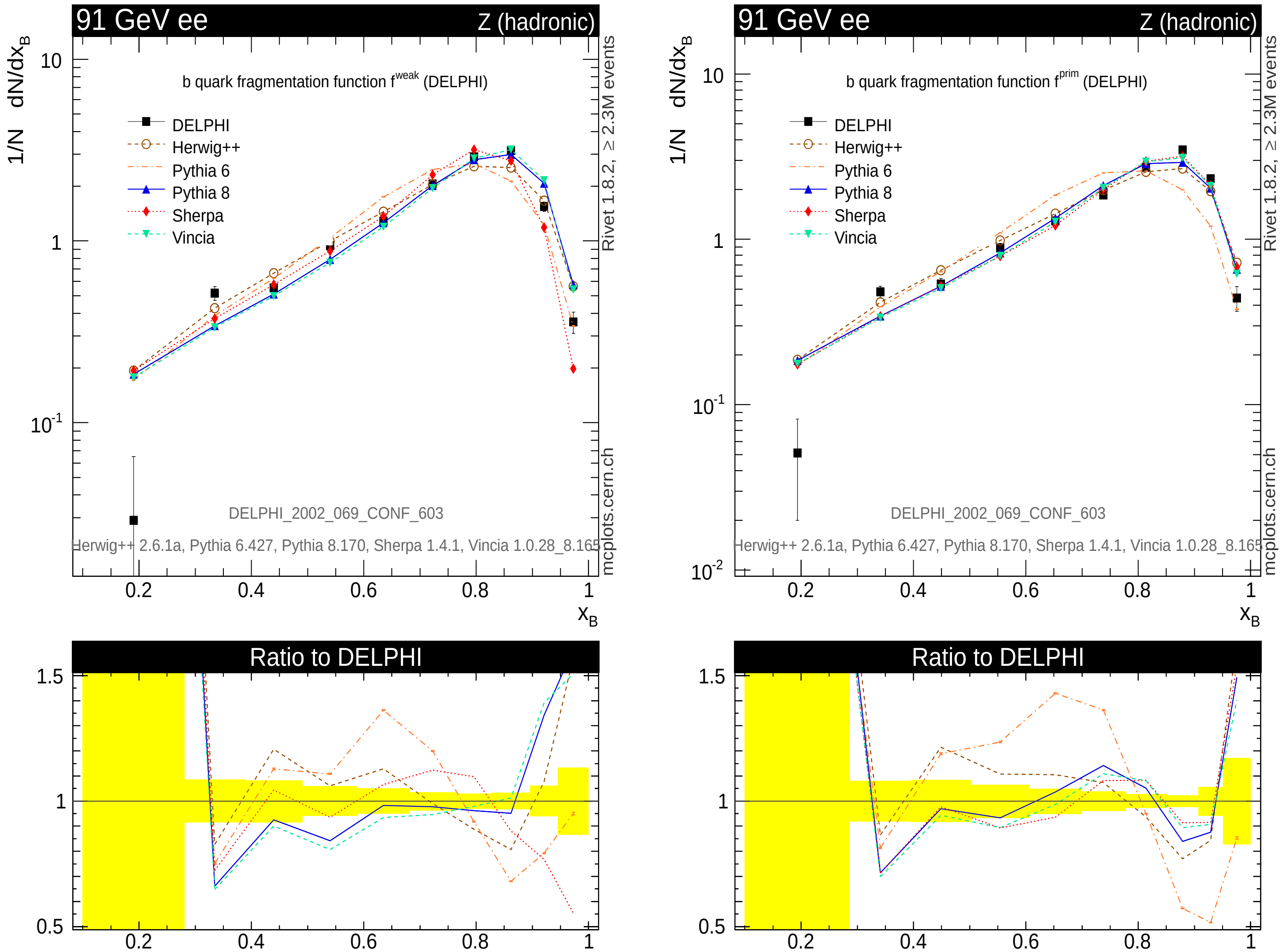
Fragmentation uncertainty: PYTHIA tunings vs. $\langle p_T(B)\rangle / \langle p_T(\text{b-jet})\rangle$





$\Delta m_t(b\text{-frag}) \simeq 300$ MeV ; $\Delta m_t(\text{col.rec.}) \simeq 120$ MeV ; $\Delta m_t(\mathrm{UE}) \simeq 130$ MeV

C++ generators for b-quark fragmentation in e^+e^- annihilation (mcplots.cern.ch)



Discrepancies call for tuning hadronization models

Other attempts to address b-fragmentation: run HERWIG with top-hadron states

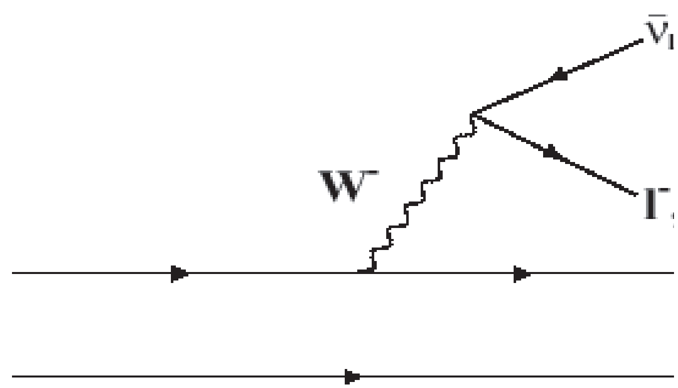
Pretend that top quarks hadronize and decay via the spectator model

Study the same observable R with T-hadrons and standard top samples and, e.g., compare the extracted masses : $m_{t,T}^{\rm MC} = m_t^{\rm MC} + \Delta m_{t,T}$

In the hadronized samples, the Monte Carlo mass can be related to the T-meson mass M_T and ultimately to the pole or $\overline{\rm MS}$ top-quark masses by using lattice, potential models, NRQCD, etc.

Spectator model decays: $T^- \to (\bar{b}d)\ell^-\bar{\nu}_\ell + X \ldots \quad p_T^2 = (p_{\bar{b}} + p_W + p_q + p_X)^2$

T^- $\bar{t}$ d

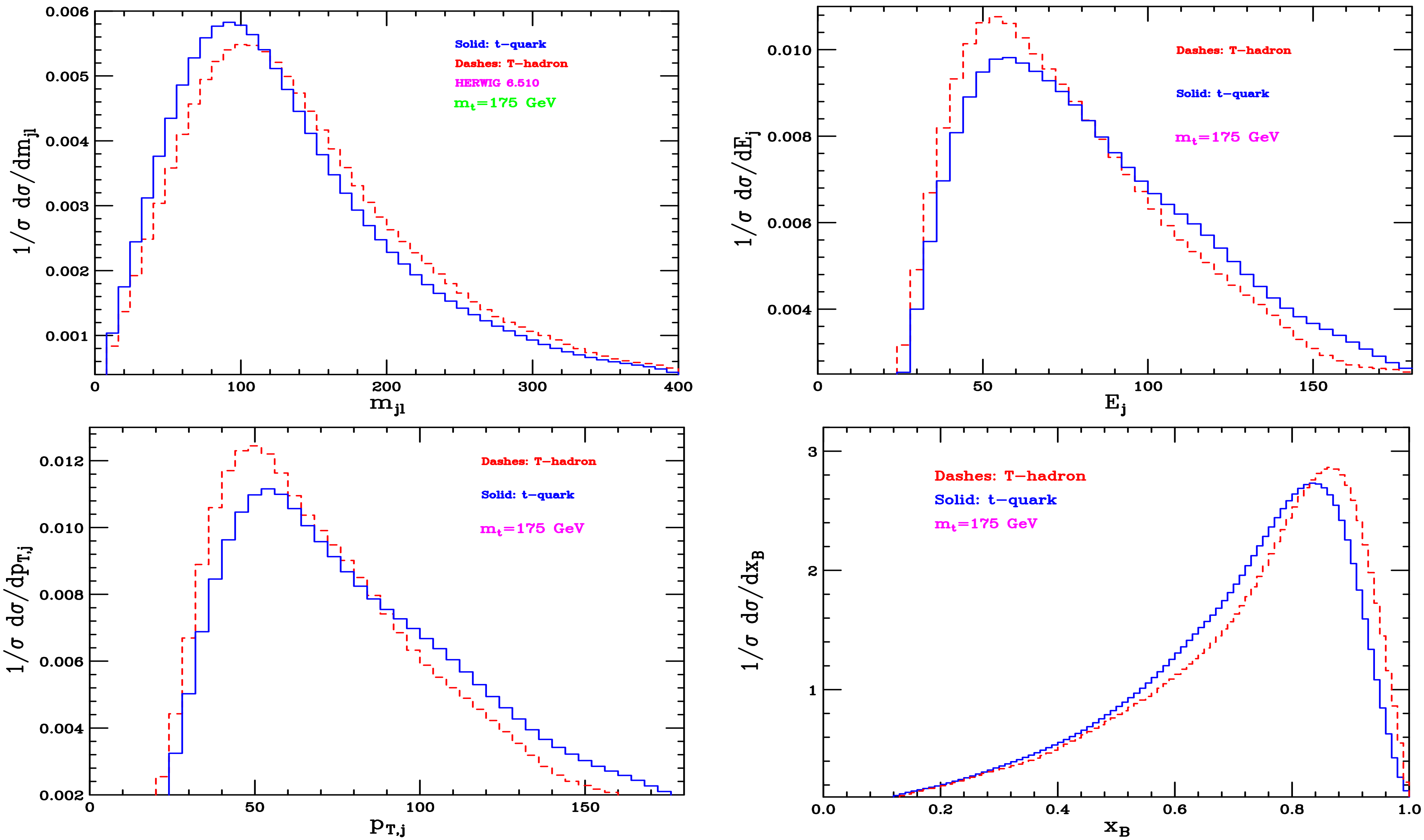


$\bar{b}$ d

Spectator does not radiate, few events where the b quark does not emit

$\bar{b}$ tends to form clusters with spectator quarks with invariant mass closer to $(p_T - p_W)^2$ with respect to standard top decays

pp collisions at $\sqrt{s} = 8$ TeV, dilepton channel, k_T algorithm, $R = 0.7$, $p_{T,j} > 30$ GeV, $p_{T,\ell} > 20$ GeV, MET> 20 GeV, $|\eta_{j,\ell,\nu}| < 2.5$ (HERWIG 6.510, preliminary)



In progress: relate $\langle \Delta m_{jl,Bl} \rangle$ with $\Delta m_{t,T}$ and using PYTHIA

Perspectives in NLO+shower codes

POWHEG: top production in pp collisions at NLO, $e^+e^- \to q\bar{q}$ (fundamental to tune hadronization) implemented, not yet public

NLO corrections to top decays in POWHEG are available, with approximate treatment of top width, but turned off in default version (work in progress)

Off-shell effects: 1) Breit–Wigner reweighting; 2) reweighting by the ratio of double-resonant (DR) and LO amplitude; 3) DR method and reweighting by ratio of full off-shell/on-shell Born matrix elements

aMC@NLO: NLO e^+e^- and hadronic top production for stable top quarks

No full NLO corrections to top decays, but finite-width effects available, for single-top production including both resonant and non-resonant (non-top) diagrams

Off-shellness impact competitive with NLO corrections to top decays

Code for $pp \to b\bar{b}\ell^+\nu_\ell\ell^-\bar{\nu}_\ell$ including resonant and non-resonant (non-top) diagrams soon available

Interest by the authors of NNLO exclusive top decays (J.Gao et al.'12, F.Caola et al.'12) to include b-fragmentation at NNLO, but not straightforward (NNLO perturbative fragmentation functions available in the $\overline{\rm MS}$ factorization scheme)

Conclusions and outlook

Bottom fragmentation in top decays as a source of uncertainty in the measurement of the top properties in inclusive and exclusive analyses ($J/\psi + \ell$, $m_{b\ell}, \dots$)

LO+shower codes and NLO+NLL calculations for b-fragmentation, tuning hadronization models to e^+e^- data

Predictions for top decays yielded by the different codes exhibit some discrepancies, mostly driven by unsatisfactory tunings

Preliminary results with object-oriented codes exhibit better description of b-fragmentation in e^+e^- collisions after the tuning

Comparison with resummed calculations, matched with fixed order, can be useful to validate event generation

Precise computations for top production and decay are increasingly necessary in view of LHC Run II

Simulation of fictitious top-hadron states may represent a useful benchmark to address the uncertainty on the top mass (MC vs pole mass) and bottom fragmentation