Soft Physics in Sherpa – Hadron Decays Update

Frank Siegert

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Features of the HADRONS module

Choose decay channel

According to given branching ratios (usually from PDG)
$\rightsquigarrow$ later

Choose kinematics according to differential decay rate of chosen process

$$d\Gamma(P \to p_1 \dots p_n) = \underbrace{\frac{1}{2P}}_{\text{flux factor}} \cdot \underbrace{|\mathcal{M}(P, p_1 \dots p_n)|^2}_{\text{squared matrix element}} \cdot \underbrace{d\text{LiPS}}_{\text{Lorentz invariant phase space}}$$

$\rightsquigarrow$ later

Other features

- Spin correlations
- Kinematics with offshell masses for intermediate resonances
- Mixing of neutral mesons

Spin correlations in $h \to \tau^-\tau^+ \to \pi^-\nu_\tau\pi^+\bar{\nu}_\tau$

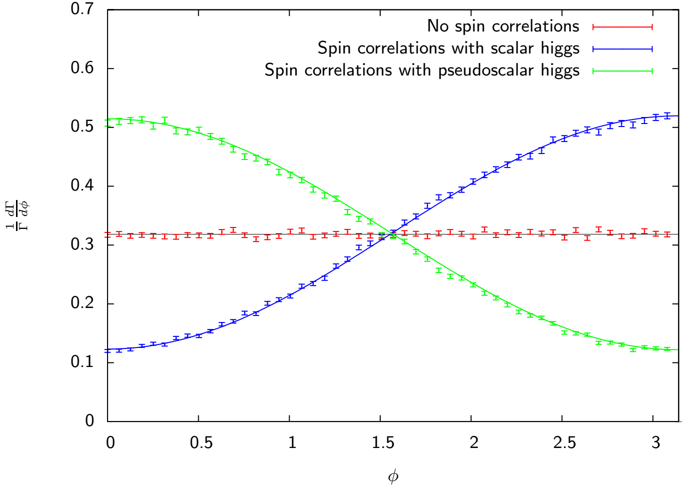


Figure: Angle between τ decay planes (theoretical predictions: M. Worek hep-ph/0305082)

Spin correlations in $Z \to \tau^- \tau^+ \to \pi^- \nu_\tau \pi^+ \bar{\nu_\tau}$

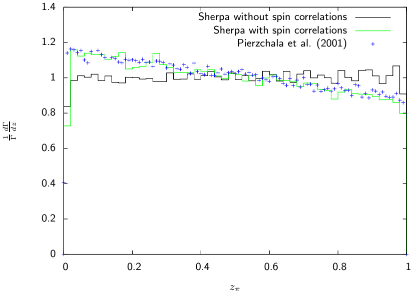


Figure: Energy of the π (in Z rest frame)

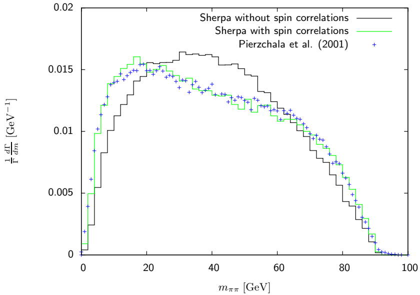


Figure: Mass of the outgoing $\pi\pi$ pair

Comparison with TAUOLA: T. Pierzchala et al. hep-ph/0101311

Spin correlations in $W^- \rightarrow \tau^- \bar{\nu}_\tau \rightarrow \pi^- \nu_\tau \bar{\nu}_\tau$

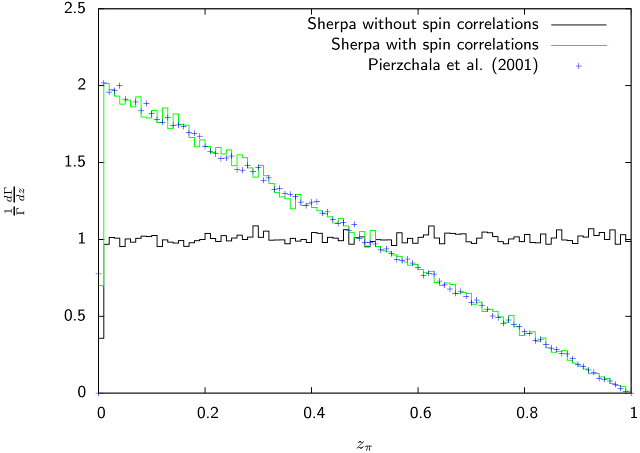


Figure: Energy of the π^- (in the W^- rest frame)

Mixing of neutral B mesons

mass eigenstates $\neq$ flavour eigenstates

$$|B_H\rangle = p\,|B^0\rangle - q\,\left|\overline{B^0}\right\rangle \qquad |B_H(t)\rangle = e^{-iM_H t} e^{-\Gamma_H \frac{t}{2}}\,|B_H\rangle$$

$$|B_L\rangle = p\,|B^0\rangle + q\,\left|\overline{B^0}\right\rangle \qquad |B_L(t)\rangle = e^{-iM_L t} e^{-\Gamma_L \frac{t}{2}}\,|B_L\rangle$$

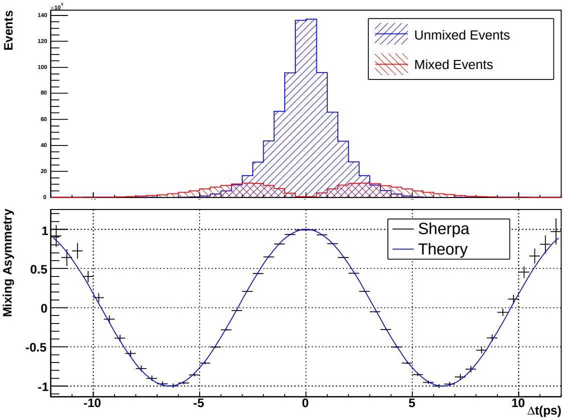
$$\Rightarrow |B^0_{\rm phys}(t)\rangle \sim \left(e^{i\Delta m \frac{t}{2}} e^{\Delta\Gamma \frac{t}{4}} + e^{-i\Delta m \frac{t}{2}} e^{-\Delta\Gamma \frac{t}{4}}\right)|B^0\rangle + \frac{q}{p}\left(e^{i\Delta m \frac{t}{2}} e^{\Delta\Gamma \frac{t}{4}} - e^{-i\Delta m \frac{t}{2}} e^{-\Delta\Gamma \frac{t}{4}}\right)|\bar{B}^0\rangle$$

$$\Rightarrow |\bar{B}^0_{\rm phys}(t)\rangle \sim \frac{p}{q}\left(e^{i\Delta m \frac{t}{2}} e^{\Delta\Gamma \frac{t}{4}} - e^{-i\Delta m \frac{t}{2}} e^{-\Delta\Gamma \frac{t}{4}}\right)|B^0\rangle + \left(e^{i\Delta m \frac{t}{2}} e^{\Delta\Gamma \frac{t}{4}} + e^{-i\Delta m \frac{t}{2}} e^{-\Delta\Gamma \frac{t}{4}}\right)|\bar{B}^0\rangle$$

Explicit mixing

$$P(B^0 \to \bar{B}^0) = \left|\left\langle \bar{B}^0 \right| B^0_{\text{phys}}(t) \right\rangle\Big|^2 \sim \left|\frac{q}{p}\right|^2 \left(\cosh\frac{\Delta\Gamma\, t}{2} - \cos\Delta m\, t\right)$$

$$P(\bar{B}^0 \to B^0) = \left|\left\langle B^0 \right| \bar{B}^0_{\text{phys}}(t) \right\rangle\Big|^2 \sim \left|\frac{p}{q}\right|^2 \left(\cosh\frac{\Delta\Gamma\, t}{2} - \cos\Delta m\, t\right)$$



CP violation in the interference

Decays to common final state f

- Decay amplitudes:

$$\mathcal{M}\left(B^0_{\text{phys}}(t) \to f\right) = \left\langle B^0 \middle| B^0_{\text{phys}} \right\rangle \cdot \langle f | \, B^0 \rangle + \left\langle \bar{B}^0 \middle| B^0_{\text{phys}} \right\rangle \cdot \langle f | \, \bar{B}^0 \rangle$$

$$\mathcal{M}\left(\bar{B}^0_{\text{phys}}(t) \to f\right) = \left\langle B^0 \middle| \bar{B}^0_{\text{phys}} \right\rangle \cdot \langle f | \, B^0 \rangle + \left\langle \bar{B}^0 \middle| \bar{B}^0_{\text{phys}} \right\rangle \cdot \langle f | \, \bar{B}^0 \rangle$$

- Asymmetry:

$$A_{CP}(t) = \frac{\Gamma(B^0_{\text{phys}}(t) \to f) \; - \; \Gamma(\bar{B}^0_{\text{phys}}(t) \to f)}{\Gamma(B^0_{\text{phys}}(t) \to f) \; + \; \Gamma(\bar{B}^0_{\text{phys}}(t) \to f)}$$

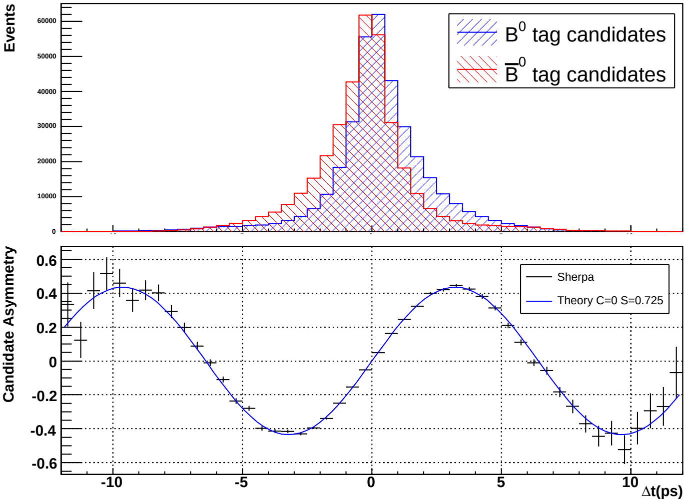
For CP-eigenstate f_{CP} with $\lambda_{f_{CP}} = \eta_{\text{CP}} \frac{q}{p} \frac{\langle f | \, \bar{B}^0 \rangle}{\langle f | \, B^0 \rangle}$

$$A_{CP}(t) = \Im(\lambda_{f_{CP}}) \sin(\Delta m_B t)$$

More general:

$$A_{CP}(t) = S \cdot \sin(\Delta m_B t) - C \cdot \cos(\Delta m_B t)$$

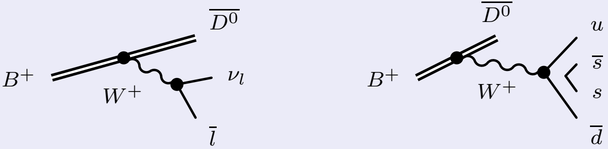
Example: $B_d \to J/\Psi K_S$: $\Im(\lambda_{f_{CP}}) = \sin(2\beta)$



Getting the matrix elements into HADRONS

Features

- very slim structure to quickly implement matrix elements
- ability to re-use existing currents for different matrix elements, e. g.

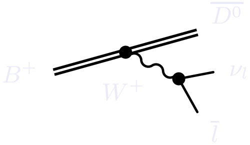


$$\mathcal{M} = \left(\frac{-ig}{2\sqrt{2}}\right)^2 J_1^\mu \frac{g_{\mu\nu} - \frac{q_\mu q_\nu}{M_W^2}}{q^2 - M_W^2} J_2^\nu \approx \frac{G_F}{\sqrt{2}} J_1^\mu J_{2,\mu}$$

Status

- τ decays implemented by Thomas Laubrich
- B meson decays, most D meson decays, many light-meson decays
- two-body decay matrix elements according to spin structure
- all others can be done according to phasespace ($\mathcal{M} = 1$)

Parametrisation example: $B \to \bar{D}\nu_l\bar{l}$



For energies $\ll m_{\mathrm{W}}$ $\longrightarrow$ Factorisation

$$\mathcal{M} = -\mathrm{i}\frac{G_F}{\sqrt{2}} V_{cb}\, L_\mu\, H^\mu$$

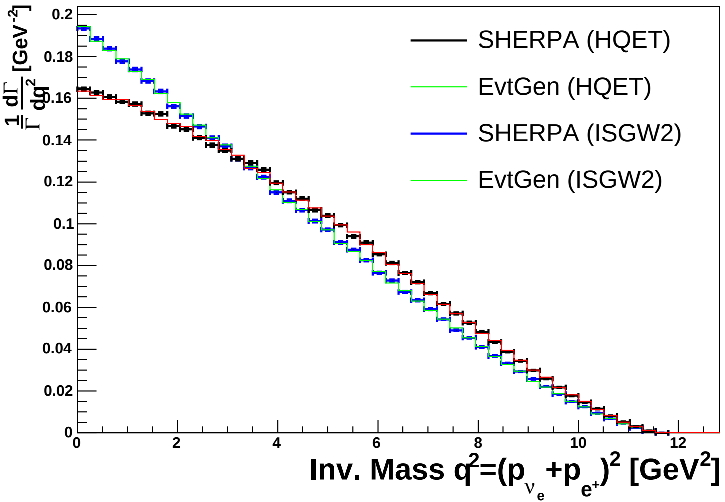
Leptonic current via helicity amplitudes

$$L_\mu = \bar{u}_\nu\, \gamma_\mu\, (1-\gamma_5)\, v_l$$

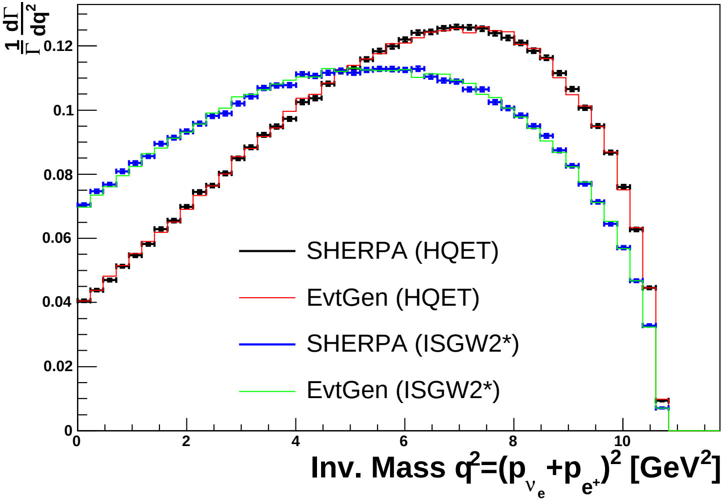
Hadronic current via form factor decomposition

$$\begin{aligned} H^\mu &= \langle D(p_D)\,|\bar{c}\,\gamma^\mu\,(1-\gamma_5)\,b|\,B(p_B)\rangle \\ &= f_+(q^2)\left((p_B+p_D)^\mu - \frac{m_B^2-m_D^2}{q^2}(p_B-p_D)^\mu\right) \\ &\quad + f_0(q^2)\,\frac{m_B^2-m_D^2}{q^2}\,(p_B-p_D)^\mu \end{aligned}$$

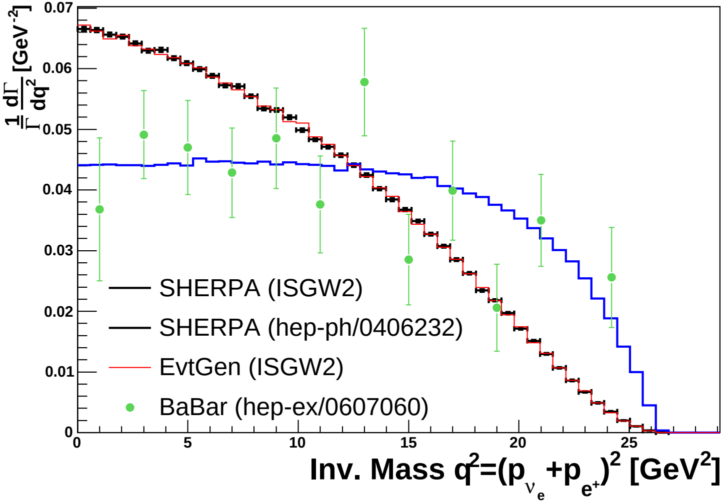
Results: $B \to \bar{D}\nu_l\bar{l}$



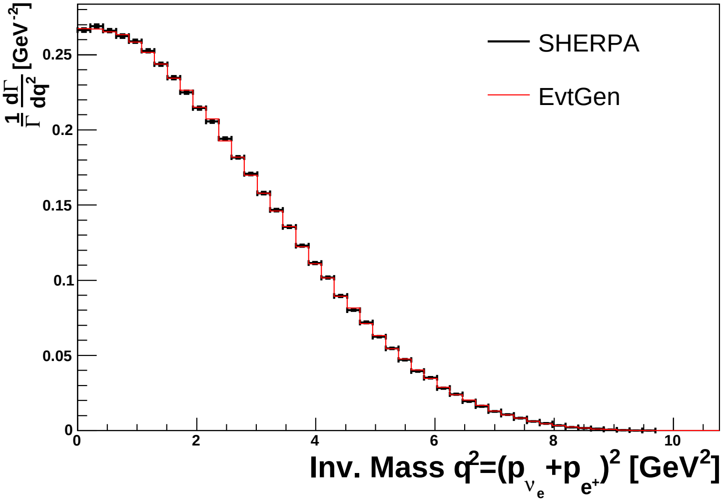
Results: $B \to \bar{D}^* \nu_l \bar{l}$



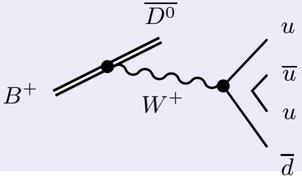
$B \to \pi \nu_l \bar{l}$: Results

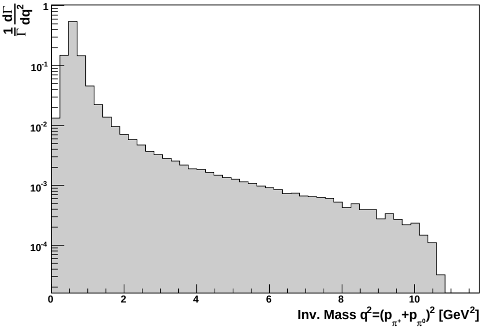


Results: $B \to \bar{D}^* \pi \nu_l \bar{l}$



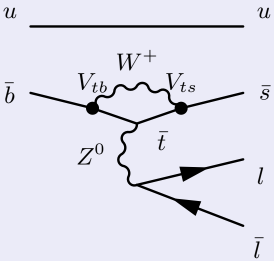
- reuse existing currents from semileptonic B decays and τ decays, e. g. $B \to \bar{D}\nu\bar{l}$ and $\tau \to \nu_\tau \pi^+\pi$ $\Longrightarrow$ $B \to \bar{D}\pi^+\pi$





Structure of rare decays

Feynman diagram



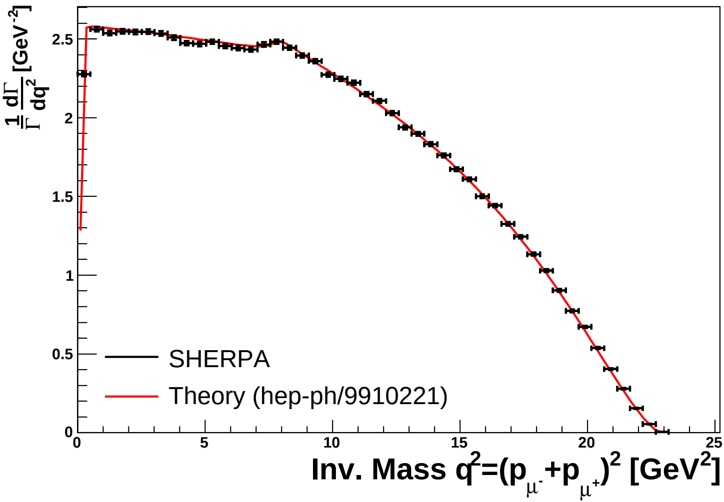
- flavour-changing neutral current in Standard Model only in higher orders
- highly suppressed SM amplitude (four vertices, one of them V_{ts}!)

$\Rightarrow$ high sensitivity to BSM physics $\Rightarrow$ need to get SM contribution right

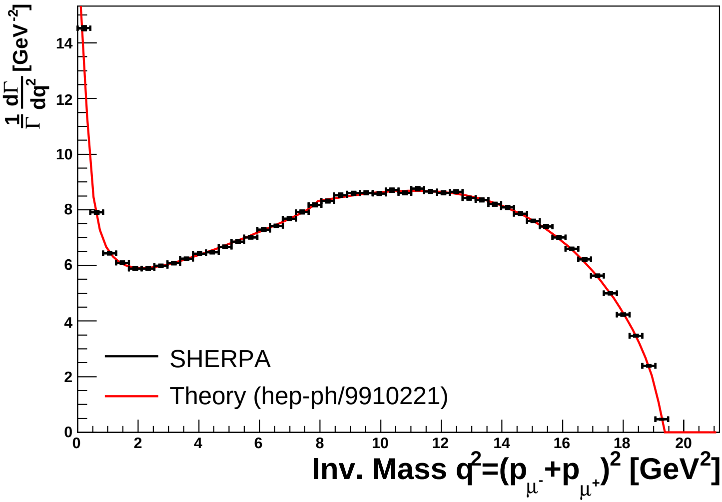
Parametrisation of the matrix element

Ali, Ball, Handoko, Hiller: *A comparative study of the decays $B \longrightarrow (K, K^*)l^+l^-$ in standard model and supersymmetric theories.* (hep-ph/9910221)

Results: $B^+ \to K^+\mu^+\mu^-$ (non-resonant)



Results: $B^+ \to K^{*+}_{(892)} \mu^+ \mu^-$ (non-resonant)



Decay tables: Features and Status

Features

- branching ratios specified through plain text files
- independent of matrix element used for kinematics
- typically taken from PDG or theory predictions

Status

- $\approx$ 140 decayers
- $\approx$ 2500 decay channels
- $\approx$ 400 decay channels with matrix elements

Inclusive observables

Necessary "ingredients"

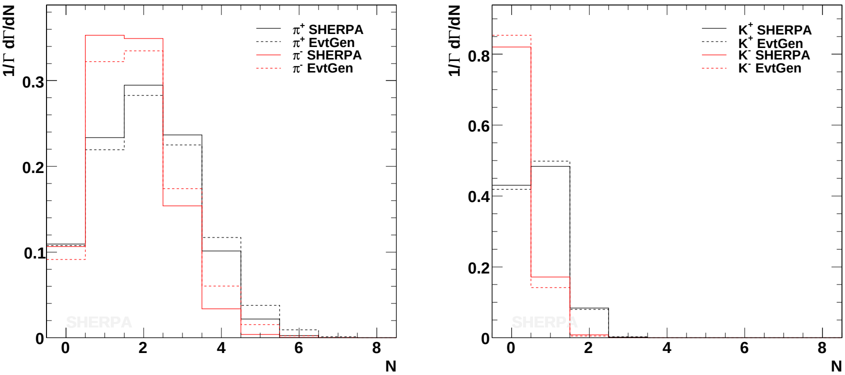
- complete decay tables for all particles
- if exclusive channels don't add up to 100 %:
  - partonic decays
  - + shower (e. g. APACIC++)
  - + fragmentation (e. g. AHADIC++)

  $\Longrightarrow$ need properly tuned fragmentation (multiplicities)
- correct matrix elements for characteristic channels
  (e. g. semileptonic channels $\Longrightarrow$ impact on electron spectrum)

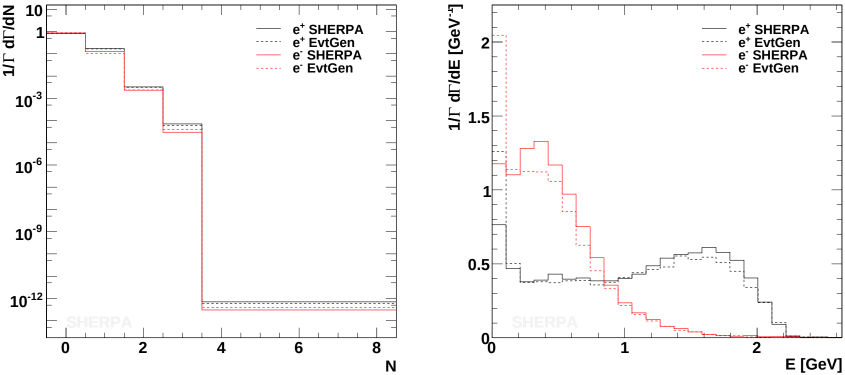
Results

- looking at stable hadrons and leptons after a fully inclusive B^+ decay
- typical observables: multiplicities, energy spectra
- comparison with EvtGen (specialised hadron decay simulation used in the BaBar, Belle and CLEO experiments)

Results for B^+ decay: π and K multiplicities



Results for B^+ decay: Electron multiplicities and spectrum



Outlook

HADRONS

- HADRONS fairly complete, especially in the τ and meson area
- TODO:
  - make partonic decays (of B, B_s, B_c, $c\bar{c}$, ...) more robust
  - improve baryon decays, only few form factors implemented so far
- Writing detailed physics documentation right now

SHERPA – near future

- Release of the HADRONS decay and AHADIC++ fragmentation module
- Improved underlying event model
- Fully self-contained SHERPA 1.1 in April 2008