SHERPA: physics and technical aspects

Frank Siegert [1]

Institute for Particle Physics Phenomenology, Durham University;
Department of Physics & Astronomy, University College London

2 June 2010, LHCb Gauss Workshop

[1] For the SHERPA collaboration: J. Archibald, T. Gleisberg, S. Höche, H. Hoeth, F. Krauss, M. Schönherr, S. Schumann, FS, J. Winter, K. Zapp

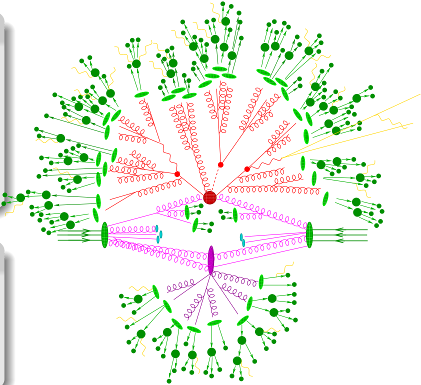
Table of Contents

The SHERPA Monte-Carlo

- Full-featured multi-purpose event generator
- Current version: 1.2.1
- Developed in C++ by ≈10 authors
- Modular in the different event phases

Disclaimer

This talk will focus solely on the LHCb-relevant features.
I will not talk about some major features like ME+PS merging.



Feature summary

Matrix elements and parton showers

- $k_\perp$ ordered shower based on Catani-Seymour dipoles JHEP 0803 (2008) 038
- High multiplicity matrix elements from two different automated generators:
  - COMIX JHEP 0812 (2008) 039
  - AMEGIC++ JHEP 0202 (2002) 044
- ME+PS merging for QCD (JHEP 0905 (2009) 053) and QED (Phys.Rev. D81 (2010) 034026) radiation
- Automated Catani-Seymour subtraction for QCD NLO calculations

Underlying Event

- Multiple parton interactions based on Phys. Rev. D36 (1987) 2019
- Minor modifications, e.g. for ME+PS merging hep-ph/0601012

Hadronisation

- Cluster fragmentation model AHADIC++ Eur. Phys. J. C36 (2004) 381
- Extensive hadron decay module
- Higher order QED corrections for decays JHEP 0812 (2008) 018

Input files

Example run card `Run.dat` for inclusive QCD events

```
(beam){
  BEAM_1 = 2212; BEAM_ENERGY_1 = 900;
  BEAM_2 = -2212; BEAM_ENERGY_2 = 900;
}(beam)

(processes){
  Process 93 93 -> 93 93
  Order_EW 0
  End process
}(processes)

(selector){
  NJetFinder  2  2.45  0.0  1.0
}(selector)

(me){
  ME_SIGNAL_GENERATOR = Comix
}(me)

(mi){
  MI_HANDLER = Amisic
  SCALE_MIN = 2.45;
}(mi)
```

- **Many examples** provided in the distribution
- Comprehensive **manual** available

Collection of example setups in the distribution

- Tevatron_DiBoson
- Tevatron_QCD
- Tevatron_TopPair
- Tevatron_UE
- Tevatron_WJets
- Tevatron_ZJets
- LHC_4thGen
- LHC_AGC
- LHC_ADD
- LHC_SUSY
- LHC_SUSY
- LHC_TTH
- LHC_ZJets
- LEP91
- HERA_DIS
- PEPII_BaBar
- EGamma
- NLO_W

Output formats and interfaces

Output formats

- Internal event format similar to HepMC
- Translation into HepEvt and HepMC events provided

Interfaces available

- Interfaces to SHERPA in LHCb, CMS and ATLAS software
- Built-in interface to Rivet analysis library
- Internal analysis module for simple analyses

Inclusive QCD events

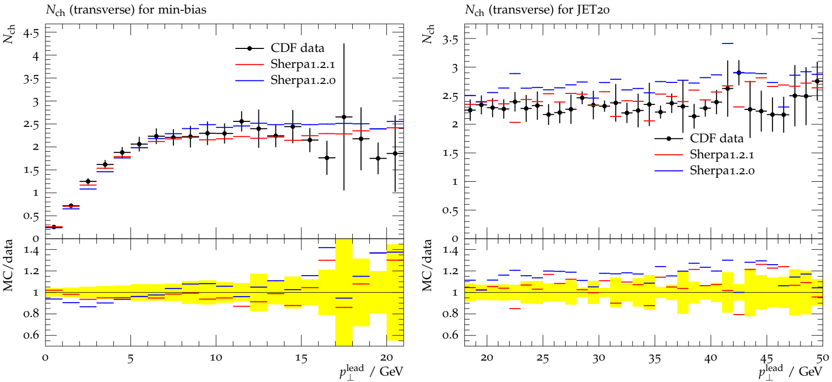
How to produce inclusive QCD in SHERPA

- $2 \to 2$ QCD matrix elements for primary scattering
- Cut $p_\perp$ as soft as allowed
- Multiple parton interactions (secondary QCD $2 \to 2$ scatterings)
- MPI tuned to UE data from Tevatron and extrapolated to LHC energies

Underlying Event model (multiple parton interactions)

- Based on Sjostrand/van Zijl model Phys. Rev. D36 (1987) 2019
- Parton showers attached to secondary interactions
- With ME+PS: Starting scale for evolution $\mu_{\rm MI}$ chosen according to $p_\perp$ of QCD partons in $k_\perp$-clustered core process

Results for UE data Phys.Rev.D65:092002,2002



Future: Improved model for inclusive QCD F. Krauss, K. Zapp

What is missing for minimum bias simulation?

- elastic scattering
- single diffraction
- double diffraction

Full minimum bias in SHERPA

- most complete view of physics
  intimate connection to underlying event
- need model embedding hard and semi-hard QCD, diffraction, elastic scattering
- convincing model for inclusive properties by Khoze-Martin-Ryskin
- started implementing model inspired by KMR in SHERPA
- goal: complete description of QCD

Disclaimer

Not released with SHERPA yet, still in development!

Improved model for inclusive QCD in SHERPA F. Krauss, K. Zapp

Optical theorem

- relates total cross section $\sigma_{\rm tot}$ to elastic forward scattering amplitude $\mathcal{A}(s,t)$ through

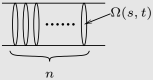
$$\sigma_{\rm tot}(s) = \frac{1}{s}\,\mathrm{Im}[\mathcal{A}(s,t=0)]$$

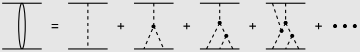
- rewrite $\mathcal{A}(s,t)$ as $A(s,b)$ in impact parameter space
- in eikonal model elastic amplitude given by sum of all Regge exchange diagrams:

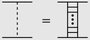
$$A(s,b) = i\left(1 - e^{-\Omega(s,b)/2}\right)$$

- pictorially:

$$\mathrm{Im}A(s,b) = \sum_{n=1}^{\infty}$$

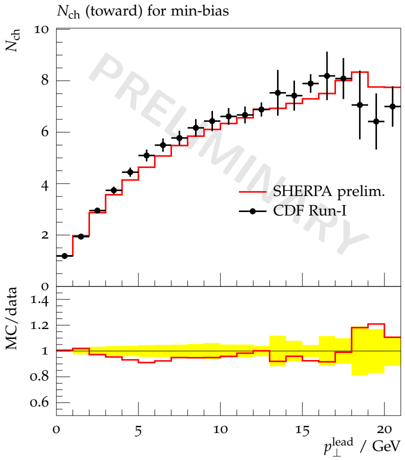


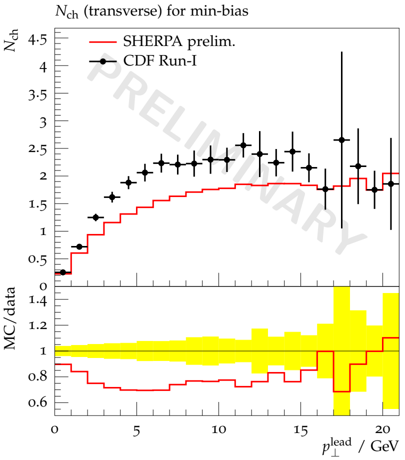
- leading contribution: Pomeron exchange + rescattering 

- pomeron in pQCD represented by gluon ladder diagrams 

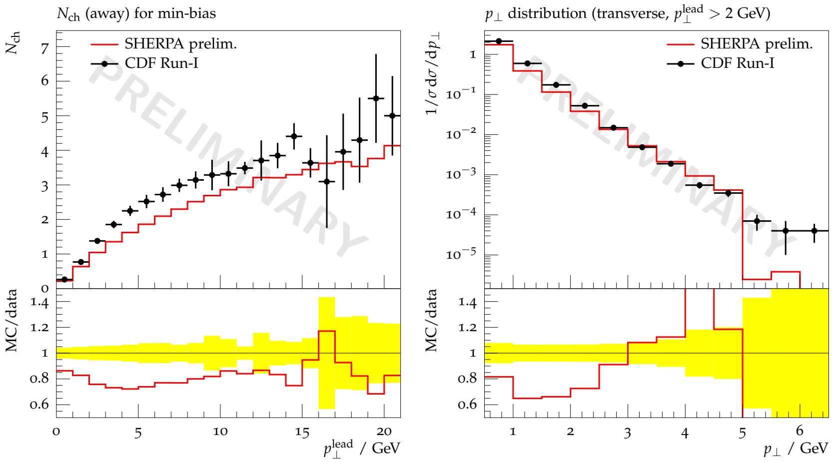
  ⇒ Cut elastic amplitude and identify effective gluons with real gluons for inclusive QCD production

New MinBias model: First preliminary results Phys.Rev.D65:092002,2002

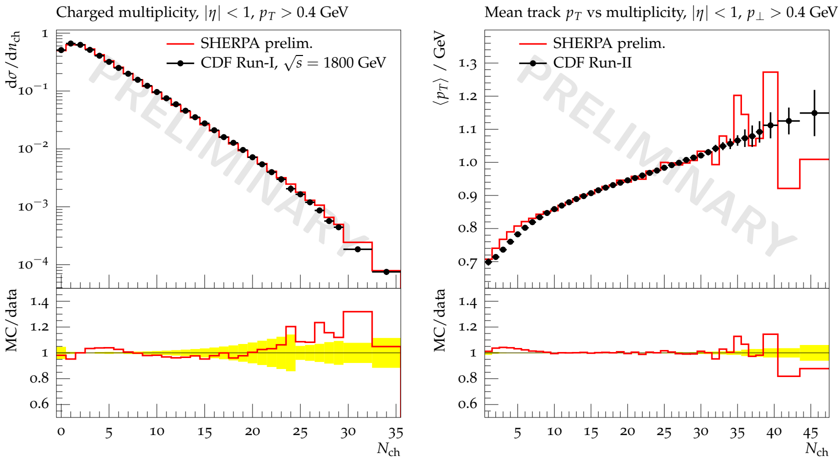




New MinBias model: First preliminary results Phys.Rev.D65:092002,2002



New MinBias model: First preliminary results



Phys.Rev.D65:072005,2002 Phys.Rev.D79:112005,2009

Hadronisation

Default model: AHADIC++

- "Cluster fragmentation"
- Formation of colourless clusters
- Dynamic cluster-hadron boundary
  $\Rightarrow$ cluster decay or transition
- Extensively tuned to LEP data

Alternative option: Lund interface

- "String fragmentation"
- Built-in interface to Pythia 6.4.18
- Crude tune to LEP data
- By default not compiled
- Can not be combined with SHERPA's hadron decays at the moment
  (probably not so important for Production tool in LHCb)

Hadron and τ decay module HADRONS++

Highlights

- **Branching ratios** fixed e.g. from PDG in decay table files
- **Decay kinematics** according to amplitudes $\mathcal{M}$ (with form factors)

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

- Kinematical corrections for **spin correlations**
- Treatment of neutral meson **mixing** and related **CP violation**

Other features

- Mass smearing of unstable resonances
- Partonic decays for incomplete decay tables
- Alias functionality to define signal particles/decays

Status

- Decay tables for $\approx$ 400 hadrons
- $\approx$ 2500 decay channels
- $\approx$ 400 decay channels with dedicated form factors

Decay data example

Decayers: HadronDecays.dat

```
[...]
# Beautiful Pseudoscalars
511     -> B/              Decays.dat;
521     -> B+/             Decays.dat;
531     -> Bs/             Decays.dat;
541     -> Bc+/            Decays.dat;
[...]
```

- Contains list of all particles and their decay table files
- Similarly a file listing **alias** particles and their decay tables may exist
  $\Rightarrow$ **Signal decay chains** can be specified and used in the LHCb interface

Decay table B+/Decays.dat

```
## (semi)leptonic decays
# b -> c l nu
{-423,12,-11}  | 0.065(0.005)[PDG]  | B+_Dstar2007bnu_ee+.dat;
[...]
# b -> u l nu (scalar)
{111,12,-11}  | 7.4e-05(1.1e-05)[PDG]  | B+_pinu_ee+.dat;
[...]
```

Contains all decay channels for that decayer with:

- branching ratio, its error and reference
- the file containing details about the decay channel

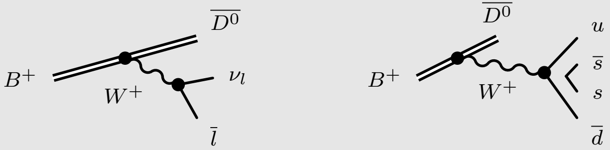
Form factors and other decay channel settings

Decay channel file specifies:

- Amplitude for decay channel
- Settings for amplitude, like form factors
- Phase space integrator
- Integration result (width, maximum), automatically generated but doesn't overwrite BR

Amplitudes

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



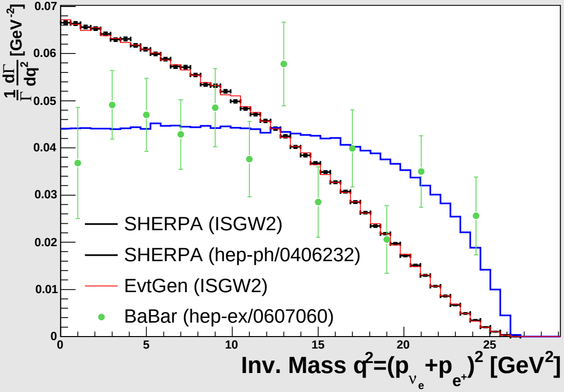
$$\mathcal{M} = \left(\frac{-ig}{2\sqrt{2}}\right)^2 \mathbf{J_1^\mu} \frac{g_{\mu\nu} - \frac{q_\mu q_\nu}{M_W^2}}{q^2 - M_W^2} \mathbf{J_2^\nu} \approx \frac{G_F}{\sqrt{2}} \mathbf{J_1^\mu J_{2,\mu}}$$

Semileptonic meson decays

Parametrisation

- Leptonic current via helicity amplitudes
- Hadronic current via form factor decomposition

Example: $B \to \pi \nu_\ell \bar{\ell}$ and two different FF models

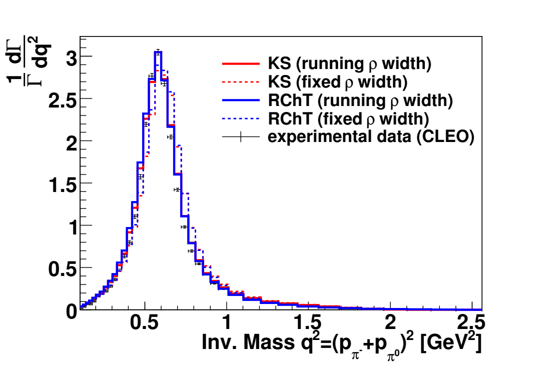


τ decays

Parametrisation

- Complicated resonance structures in hadronic currents
- Different form factor models available:
  - Kühn-Santamaria Z. Phys. C48 (1990) 445
  - Resonance chiral theory, e.g. Nucl. Phys. B321 (1989) 311
  - Novosibirsk Comput.Phys.Commun. 146 (2002) 139-153

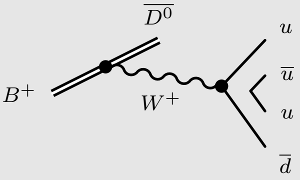
Example: $\tau^- \to \pi^- \pi^0 \nu_\tau$ compared to CLEO data Phys. Rev. D61 (2000) 112002

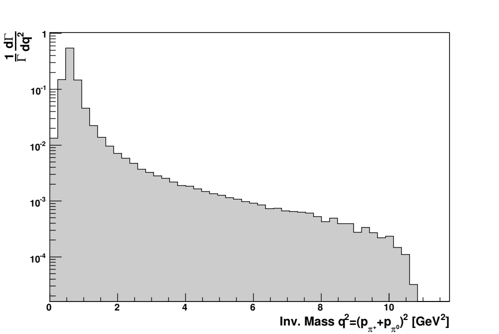


Hadronic decays

A priori not well known (non-perturbative QCD), but idea:

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

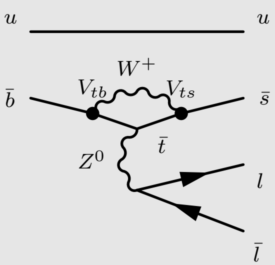


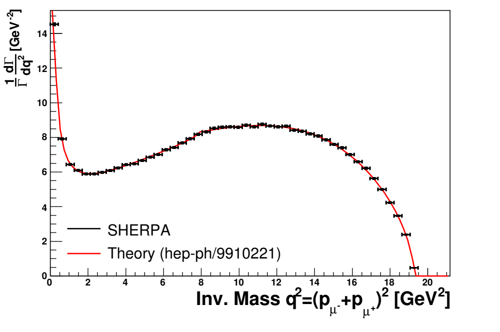


Rare decays

Example: $B \to K^* l^+ l^-$

- 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
- Matrix element parametrisation: Ali, Ball, Handoko, Hiller (arXiv:hep-ph/9910221)





Inclusive observables

Necessary "ingredients"

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

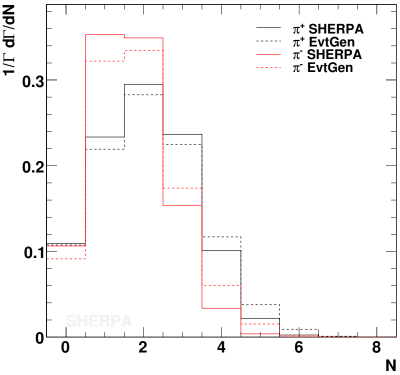
  $\Longrightarrow$ need properly tuned fragmentation (multiplicities)
- correct matrix elements for characteristic channels
  (e. g. semileptonic channels $\Longrightarrow$ impact on electron spectrum)

Comparison with EvtGen

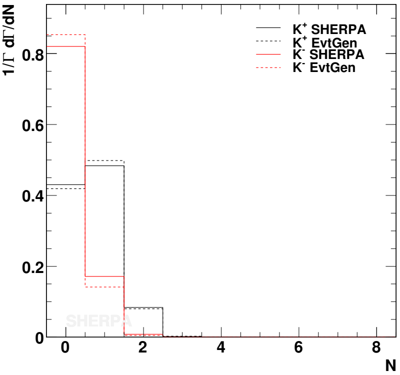
- looking at stable hadrons and leptons after a fully inclusive B^+ decay
- typical observables: multiplicities, energy spectra

Inclusive observables for B^+ decay

$\pi^{\pm}$ multiplicity

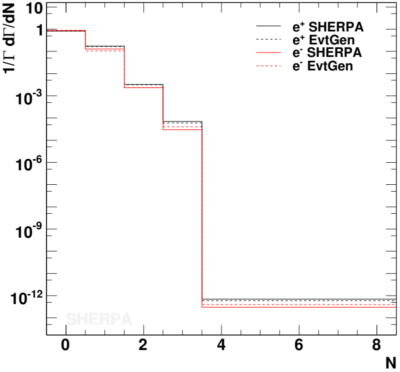


$K^{\pm}$ multiplicity

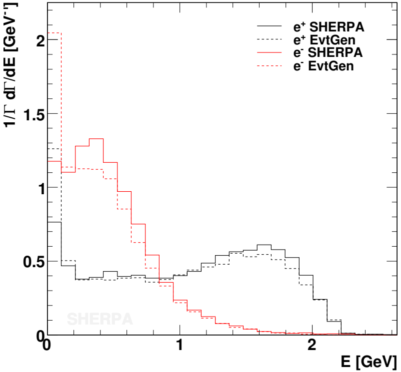


Inclusive observables for B^+ decay

Electron multiplicity



Electron energy spectrum

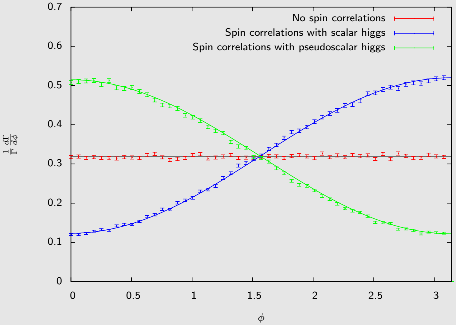


Spin correlations

What are spin correlations about?

- Decay cascade ⇔ cutting propagators into polarisation vectors/spinors/...
- Correlation between polarisation in "left" ME and "right" ME not accounted for if they are done independently ⇒ correction applied by spin correlation algorithm

Example: $h \to \tau^-\tau^+ \to \pi^-\nu_\tau\pi^+\bar{\nu}_\tau$



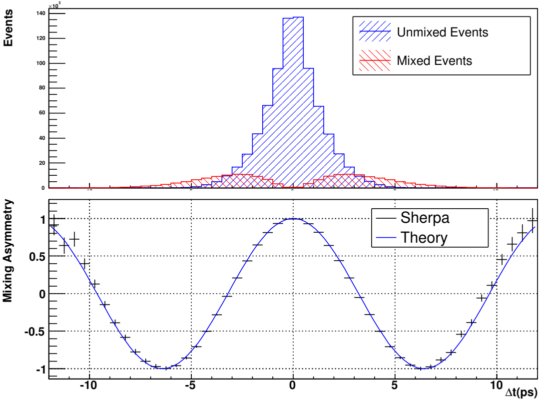
Angle between τ decay planes (Analytical results: Z.Phys.C64:21-30,1994)

Neutral meson mixing

Explicit mixing probabilities

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

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



CP violation in the interference

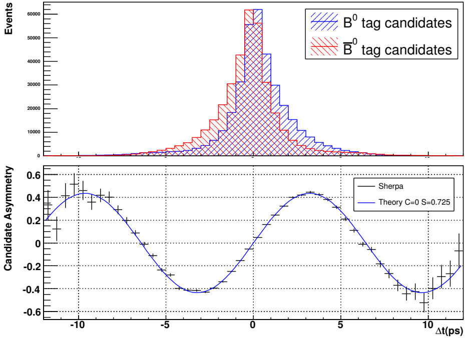
Asymmetry in decays to common final state f

$$A_{CP}(t) = \frac{\Gamma(B^0(t)\to f) \; - \; \Gamma(\bar{B}^0(t)\to f)}{\Gamma(B^0(t)\to f) \; + \; \Gamma(\bar{B}^0(t)\to f)} \to S\cdot\sin(\Delta m_B t) - C\cdot\cos(\Delta m_B t)$$

- Implemented in a very basic way
- Still needs improvements to work with signal decays

Example: $B_d \to J/\Psi K_S$

$$\begin{aligned} S &= \Im(\lambda_{f_{CP}}) \\ &= \sin(2\beta) \\ &= 0.725 \\ C &= 0 \end{aligned}$$



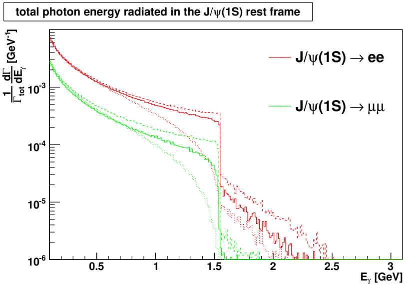
QED corrections in decays

JHEP 0812 (2008) 018

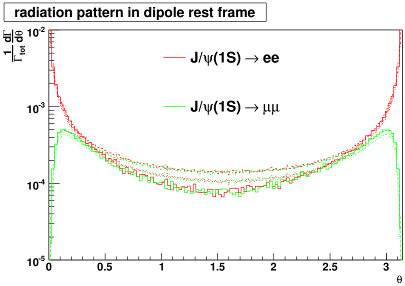
Module PHOTONS++

- Sums all contributions of soft photon radiation (real and virtual) using the Yennie-Frautschi-Suura-Formalism (YFS)
  $\Rightarrow$ exact as $k \to 0$, perturbative series for hard emission effects
- Hard emission effects up to $\mathcal{O}(\alpha)$ incorporated generally via approximated matrix elements in the quasi-collinear limit
- Important cases with $\mathcal{O}(\alpha)$ real and/or virtual exact matrix elements
  $V \to FF$, $V \to SS$, $S \to FF$, $S \to SS$, $\tau \to \ell\nu_\ell\nu_\tau$
- ME corrections for radiative semi-leptonic meson decays $(1 \to 3 + \gamma)$ under way (form factor model)
- Applied to all hadron and τ decays
- No limitation on final state complexity

Leptonic hadron decays: $J/\psi \to \ell\bar{\ell}$



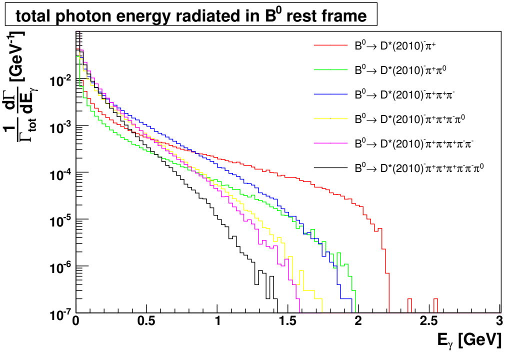
total radiated energy in the J/ψ rest frame

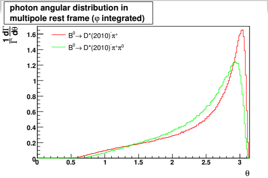


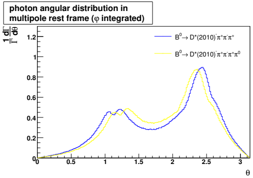
angular spectrum in the rest frame of the dipole

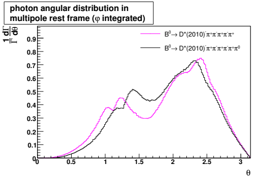
- soft only (dotted)
- collinear approximated ME (dashed)
- exact ME (solid)

Multipoles: $(B \to D^{*-}$+Pions)









Energy spectrum and angular radiation patterns for fixed kinematical configurations.

Conclusions + Outlook

Conclusions

- SHERPA is a full-featured multi-purpose event generator
- Useful as decay tool for LHCb due to wealth of hadron decay features
- Also interfaced as production tool for inclusive QCD events and B signal events
- No full minimum bias description yet
- I have skipped all features related to hard scattering processes in this talk

Outlook

- Implementation of new KMR-based model for full minimum bias simulation
- More work on hadron decay features relevant for LHCb, e.g. CP violation in signal decays
- A lot more testing of Sherpa within LHCb for different combinations of Production/Decay tool
  $\rightarrow$ Julian+Tobias next

If you have any problems/requests, please feed them into our bug tracker!
`http://sherpa-mc.de`
`info@sherpa-mc.de`