Measurement of the Differential Luminosity at 3 TeV CLIC

– Status Report –

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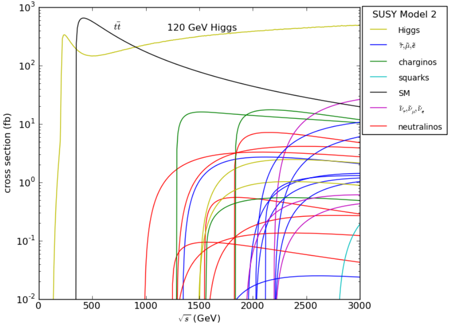
Goal and Limits of our Study

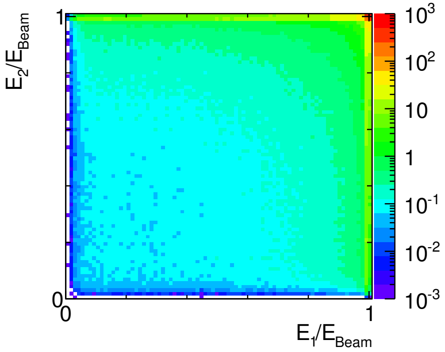
- How does the uncertainty in the luminosity spectrum affect measurements at CLIC 3 TeV?
  - Benchmark processes far above threshold, very few events with $\sqrt{s'} < 1.5$ TeV
  - Integrated Luminosity 2 ab^{-1}
- Studied lumi spectrum in light of these benchmarks
- Including relevant effects for reconstruction
- Can use a minimal model to describe the luminosity spectrum, do not need a complete and global description of the spectrum from $\sqrt{s'} = 0$ TeV – 3 TeV



What is the Goal of this Measurement?

- Goal: The distribution of the pairs of particle energies prior to initial state radiation $L(x_1, x_2)$
  - Only reconstructing the centre-of-mass energy ignores the longitudinal boost of the system
  - Strong correlation between the two particle energies
  - Account for Asymmetric beams
  - Initial state radiation depends on the specific process and centre-of-mass energy
- Note: We mostly show the c.m.s. luminosity spectrum $L(\sqrt{s'})$ because it is easier to compare and interpret

Particle Energy Spectrum from GUINEAPIG



$$L(\sqrt{s'}) = \int \mathrm{d}x_1 \int \mathrm{d}x_2 L(x_1, x_2)\delta\left(\frac{\sqrt{s'}}{\sqrt{s_{\mathrm{nom}}}} - \sqrt{x_1 x_2}\right)$$

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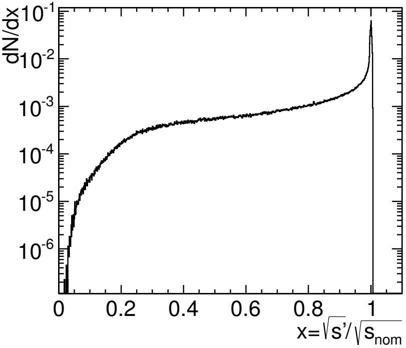
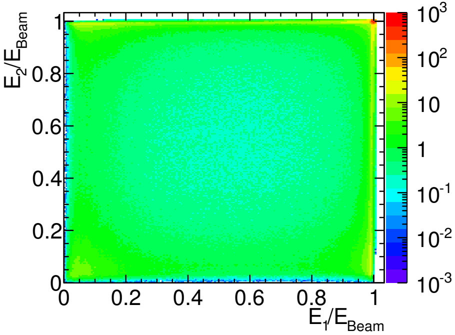


$$L(\sqrt{s'}) = \int dx_1 \int dx_2 L(x_1, x_2) \delta\left(\frac{\sqrt{s'}}{\sqrt{s_{nom}}} - \sqrt{x_1 x_2}\right)$$

What Do We Measure in the Detector?

- Need large cross-section and well known process: Bhabha scattering
- In the detector we measure the final state particles affected by the cross-section (initial state radiation, final state radiation, $\sqrt{s'}$ dependence)
- There is no way, for an individual event, to know if the energy was lost from initial state radiation or Beamstrahlung
- The measured values are also affected by the resolution of the respective subdetector

Distributions after Bhabha scattering and cross-section (without detector resolutions)



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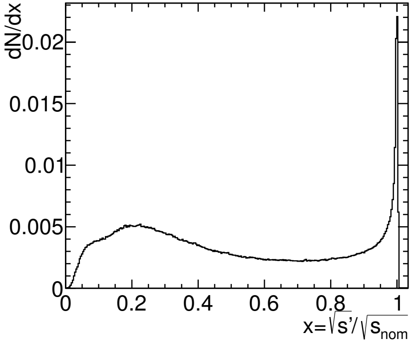
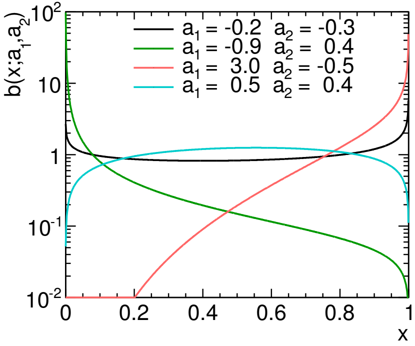


Beta-Distributions

- Mostly using Beta-Distributions for the description of the luminosity spectrum

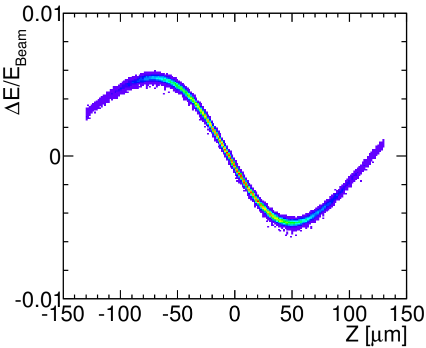
$$b(x) = \frac{1}{N} x^{a_1} (1-x)^{a_2}$$

  with different parameter bounds
- Limited to $0 < x < 1$



Beam-Energy Spread I

Particle energy vs. longitudinal position from the accelerator simulation



- Energy distribution mostly due to intra-bunch wakefields and RF phase offset
- Bunch travelling towards the left
- Front of bunch gains more energy and wakefields reduce effective gradient for the tail

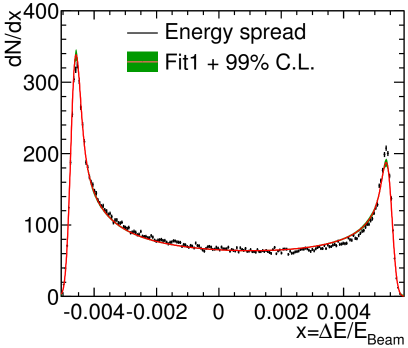
Beam-Energy Spread II

- Tried several different functions to fit, settled on beta-distribution convoluted with Gauss

$$\mathrm{BES}(x) = \int_{x_{\min}}^{x_{\max}} b(\tau)\,\mathrm{Gauss}(x-\tau)\,\mathrm{d}\tau$$

- 5 parameters, including min. and max. of beta-distribution range

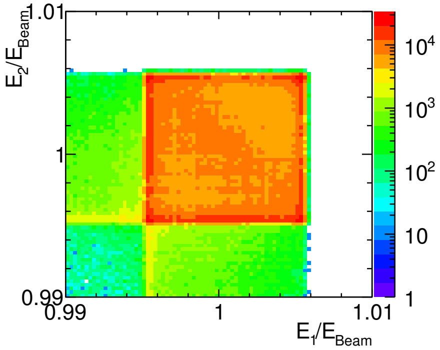
Particle energy distribution from accelerator simulation



Beam-Energy Spread III

- Due to the correlation, Beamstrahlung, and beam-beam effects two vastly different beam-energy spread distributions emerge for the luminosity spectrum
- *Peak* Region: Both particles with $E > 0.995 E_{\text{Beam}}$
- *Arms* Region: Only one of the particles with $E > 0.995 E_{\text{Beam}}$
- Both can be fit with a beta-distribution convoluted with a Gauss

Peak of the luminosity spectrum



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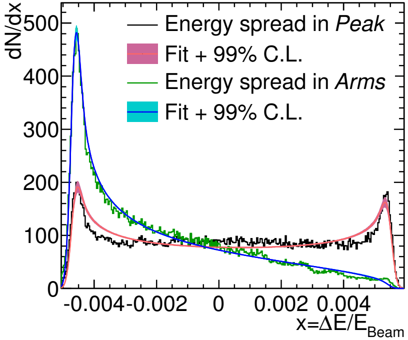
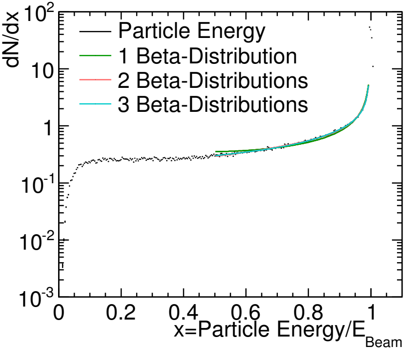
Particle energy distribution from the GUINEAPIG simulation



Beamstrahlung

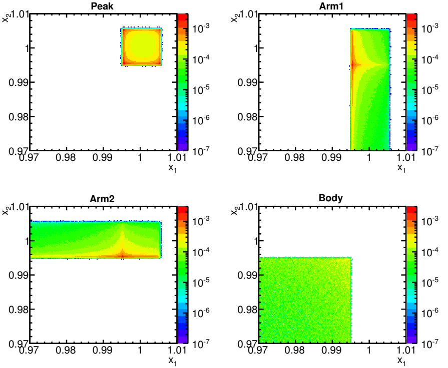
- Second contribution to luminosity spectrum is energy loss due to Beamstrahlung
- Potentially large loss of energy for some particles
- 30% in the top 1%
- Currently limited to $0.5\sqrt{s_{\mathrm{nom}}}$ and a single beta-distribution
- Particle energy is convolution of Beamstrahlung and beam-energy spread effect



Description of the MODEL

For the Function:

- Divide the luminosity spectrum in four different regions
- Individual regions described by convolutions of beam-energy spread functions and Beamstrahlung functions (or just Beamstrahlung functions)
- Created a 2D probability density function which enables the generation of the luminosity spectrum according to the MODEL
- For this model: 20 free parameters



Fit Procedure

For an efficient extraction of the parameters a reweighting fit is used

- Create 'real' spectrum, taken from GUINEAPIG (GP-Sample)
- Create a luminosity spectrum according to MODEL (MODEL-Sample)

Fit Level a) Use the particle energy spectra directly

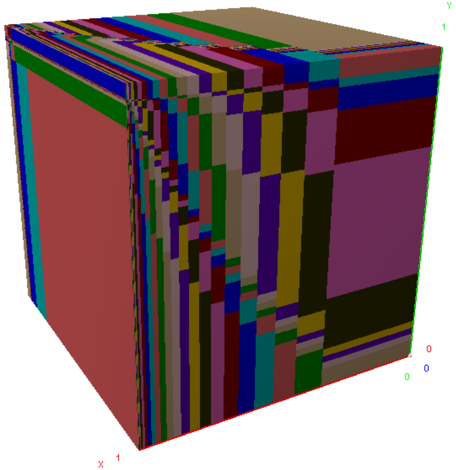
Fit Level b) Simulate Bhabha events, add detector effects, use observables for fit

- Vary the parameters and change the weight of all events to minimize the χ^2 between GP-Sample and MODEL-Sample

Technicalities

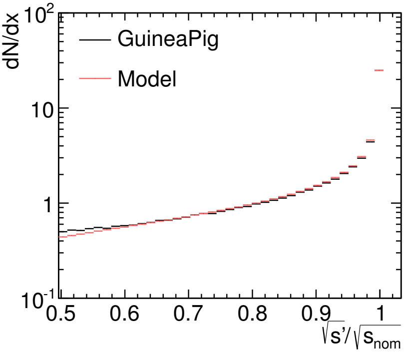
Example for 3D binning structure

- Implemented re-weighting loop to allow for parallelization with OpenMP
  - Running happily on 16 cores on lxplus machines
  - No systematic study, but it still scales
- Implemented Equi-Probability Binning in 2 and 3 Dimensions
  - Statistically optimal use of available events



Fitting Spectrum Directly

- Fit the 2D distribution of *Particle energies*
- 1 million GP events and 3 million according to MODEL
- No cross-section, initial state radiation, or detector effects
- Spectrum reconstructed within 5% down to $0.6\sqrt{s_{\mathrm{nom}}}$, but few percent offset in the tail
  - Only statistical errors from GUINEAPIG sample
  - Error due to parameters smaller
- In the topmost bin: $\Delta L/L = 0.0038 \pm 0.0017(\mathrm{stat}) \pm 0.0006(\mathrm{par})$



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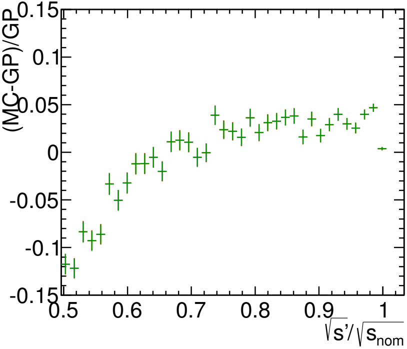

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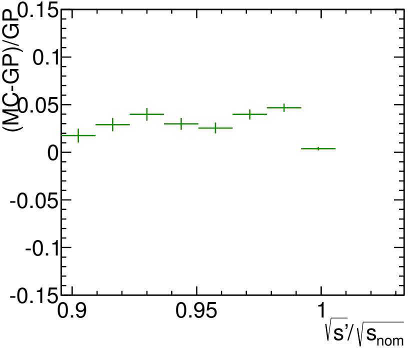
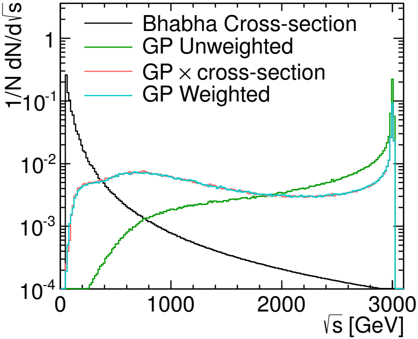


Simulation of Bhabha Scattering

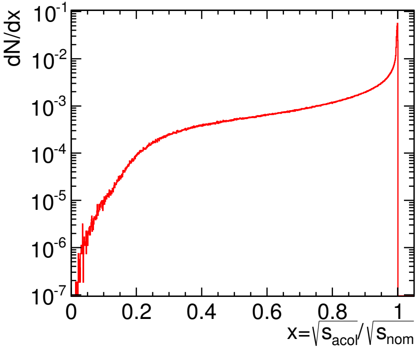
- Effective Cross-Section $\sigma(\sqrt{s'} > 1.5\ \text{TeV}, 7^\circ < \theta < 173^\circ) = 10\ \text{pb}$
- About 1 million events in 100 fb^{-1}
- Create luminosity events scaled with $1/s'$ in GUINEAPIG and the MODEL to have unweighted events following the Bhabha cross-section
- Use energy pairs from GUINEAPIG and MODEL as input to BHWIDE and simulate Bhabha scattering



Observables in the Detector I

- Use the angles of the outgoing electrons to reconstruct precisely the spectrum around the peak
- Reconstruct relative centre-of-mass energy from acollinearity
- High resolution tracker with angular resolution below 20 μrad above $E = 200$ GeV

Relative c.m.s. Energy



$$\frac{\sqrt{s_{\mathrm{acol}}}}{\sqrt{s_{\mathrm{nom}}}} = \sqrt{\frac{\sin(\theta_1)+\sin(\theta_2)+\sin(\theta_1+\theta_2)}{\sin(\theta_1)+\sin(\theta_2)-\sin(\theta_1+\theta_2)}},$$

Assuming photon radiation only by one of the particles

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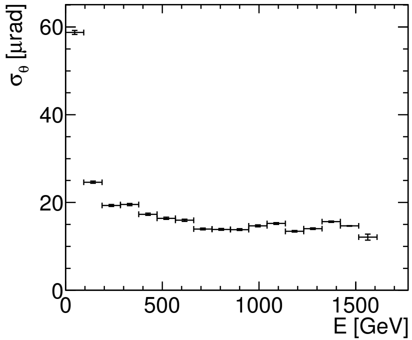
Angular Resolution ($e^{\pm}, \theta \geq 7^{\circ}$)



$$\frac{\sqrt{s_{\mathrm{acol}}}}{\sqrt{s_{\mathrm{nom}}}} = \sqrt{\frac{\sin(\theta_1) + \sin(\theta_2) + \sin(\theta_1 + \theta_2)}{\sin(\theta_1) + \sin(\theta_2) - \sin(\theta_1 + \theta_2)}},$$

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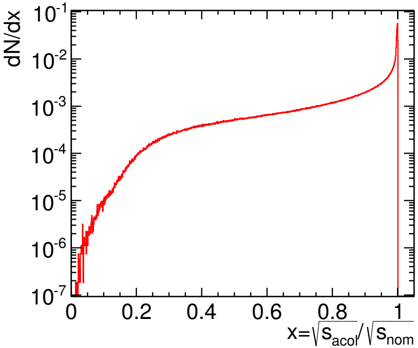
Relative c.m.s. Energy: Smeared



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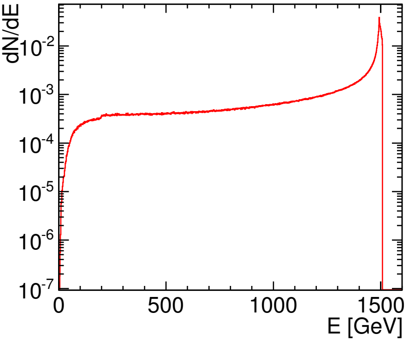
Observables in the Detector II

- Additional information from electron energies measured in the calorimeters (at low angle momentum resolution is worse)
- Include detector effects via 4-vector smearing, using resolutions obtained from Full-Detector Simulation, Background overlay, and full reconstruction

Particle Energy



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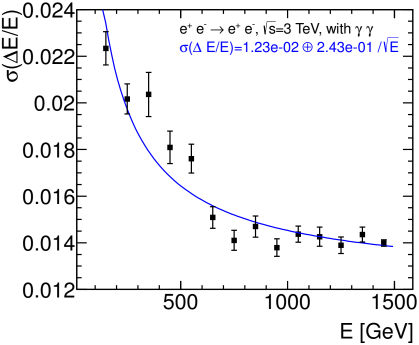
Energy Resolution



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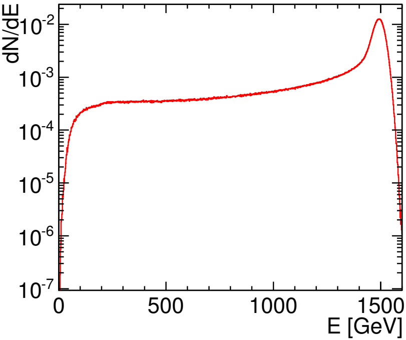
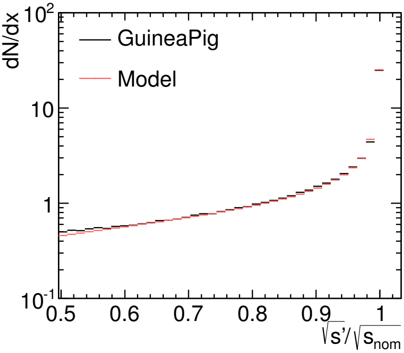


Reconstructed Spectrum

- Including Cross-section, initial/final state radiation (some photon recovery), and detector resolutions
- 2 Million Bhabha Events
  400 fb^{-1}(selection efficiency 50%)
- Use 3D histogram for χ^2 minimisation: $\sqrt{s_{\text{acol}}}$, E_1, E_2
- Spectrum reconstructed within 5% down to $0.6\sqrt{s_{\text{nom}}}$, but few percent offset (the opposite way than in the pure spectrum fit)
- Larger deviation just below the peak
- In the topmost bin: $\Delta L/L = 0.016 \pm 0.0017(\text{stat}) \pm 0.0009(\text{par})$



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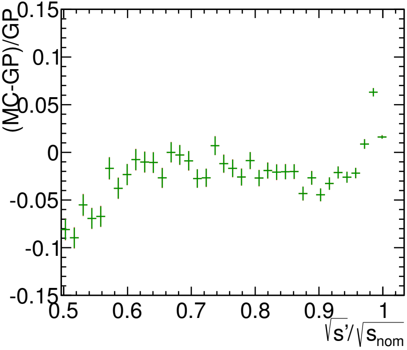

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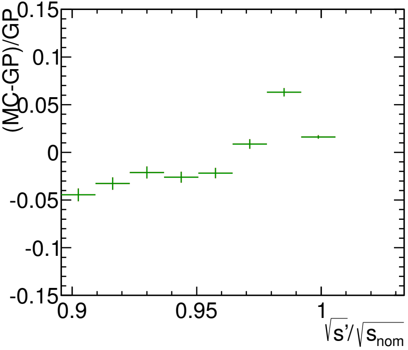


Impact on Smuon Mass Measurement(LCD-Note-2011-018)

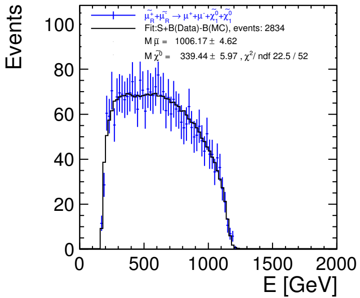
- $e^+e^- \rightarrow \widetilde{\mu}^+\widetilde{\mu}^- \rightarrow \mu^+\mu^-\widetilde{\chi}_1^0\widetilde{\chi}_1^0$
- Fit background subtracted muon energy distribution to extract smuon and neutralino mass with $f(E_\mu; m_{\widetilde{\mu}}, m_\chi) = \mathrm{Box} \otimes \sigma(\sqrt{s'}) \otimes L(\vec{p}) \otimes \mathrm{ISR} \otimes \mathrm{DetRes}$
- Fit with all parameters of luminosity spectrum varied by $\pm\sigma_p^i/2$ individually
- Error on smuon mass from luminosity:

$$\sigma_m^2 = \sum_{i,j} \delta_i C_{ij} \delta_j$$

$$\delta_i = m\left(\vec{p} + \vec{e}^i \frac{\sigma_p^i}{2}\right) - m\left(\vec{p} - \vec{e}^i \frac{\sigma_p^i}{2}\right),$$

with the correlation matrix

$$C = \begin{pmatrix} 1 & -0.6 & \dots & -0.02 \\ -0.6 & 1 & \dots & 0.04 \\ \dots & \dots & \dots & \dots \\ -0.02 & 0.04 & \dots & 1 \end{pmatrix}.$$



- Using L_{GP}: $m_{\widetilde{\mu}} = (1006.2 \pm 4.6(\mathrm{stat}))$ GeV, $m_\chi = (339.4 \pm 6.0(\mathrm{stat}))$ GeV
- Using L_{Reco}: $m_{\widetilde{\mu}} = (1005.0 \pm 2.0(\mathrm{par}))$ GeV, $m_\chi = (339.1 \pm 1.8(\mathrm{par}))$ GeV

Summary, Conclusion, and Outlook

- The CLIC beams produce a rather peculiar luminosity spectrum
- The reconstruction of spectrum is possible
- The error from the reconstruction of the spectrum for CLIC-3 TeV-benchmark smuon mass measurement is significantly smaller than the statistical error
- Depending on the analysis a more detailed model for the spectrum is needed, our MODEL can be extended there is room for improvement

Backup Slides

Mathematical Description

$$
\begin{aligned}
L(x_1, x_2) = \quad & p_{\mathrm{Peak}} && \delta(1-x_1) \otimes \mathrm{BES}\left(x_1; [p]_1^{\mathrm{Peak}}\right) \\
& && \delta(1-x_2) \otimes \mathrm{BES}\left(x_2; [p]_2^{\mathrm{Peak}}\right) \\
+ \quad & p_{\mathrm{Arm1}} && \delta(1-x_1) \otimes \mathrm{BES}\left(x_1; [p]_1^{\mathrm{Arm}}\right) \\
& && \mathrm{BB}\left(x_2; [p]_2^{\mathrm{Arm}}, \beta_{\mathrm{limit}}^1\right) \\
+ \quad & p_{\mathrm{Arm2}} && \mathrm{BB}\left(x_1; [p]_1^{\mathrm{Arm}}, \beta_{\mathrm{limit}}^1\right) \\
& && \delta(1-x_2) \otimes \mathrm{BES}\left(x_2; [p]_2^{\mathrm{Arm}}\right) \\
+ \quad & p_{\mathrm{Body}} && \mathrm{BG}\left(x_1; [p]_1^{\mathrm{Body}}, \beta_{\mathrm{limit}}^2\right) \\
& && \mathrm{BG}\left(x_2; [p]_2^{\mathrm{Body}}, \beta_{\mathrm{limit}}^2\right)
\end{aligned}
$$

With

$$\mathrm{BB}(x) = (b \otimes \mathrm{BES})(x)$$