Singly Cabbibo suppressed charm decays at Belle and development of an amplitude calculation toolkit

Daniel Greenwald, Andreas Hönle, Dmytro Levit, Johannes Rauch, Arseniy Tsipenyuk

Physik Department E18
Technische Universität München
Germany

9th Annual Meeting of the Helmholtz Alliance
"Physics at the Terascale"
November 17-18, 2015
DESY, Hamburg

Bundesministerium
für Bildung
und Forschung

Outline

Technische Universität München

Singly-Cabibbo-Suppressed Decays as a Probe for New Physics

D Mesons at Belle

Our Channels

$D^{\pm} \to \pi^{\pm}\pi^{0}$
$D^{0} \to \pi^{+}\pi^{-}\pi^{+}\pi^{-}$
$D^{+} \to K^{0}_{S}K^{-}\pi^{+}\pi^{+}\pi^{0}$
$D^{+} \to K^{+}K^{-}\pi^{+}$

YAP–Yet Another Partial Wave Analysis Toolkit

Summary and Outlook

A Sign of New Physics?

The $\Delta\mathcal{A}_{\mathrm{CP}}$ surprise

The diagrams of $\mathrm{D}^0 \to \pi^+\pi^-$ and $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ are the same but for down quarks swapped for strange quarks. SU(3)$_\mathrm{I}$ of $\{\mathrm{u}, \mathrm{d}, \mathrm{s}\}$ leads to

$$\mathcal{A}_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-) \simeq -\mathcal{A}_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^+\pi^-) \simeq \frac{1}{2}\Delta\mathcal{A}_{\mathrm{CP}},$$

$$\begin{aligned}
\Delta\mathcal{A}_{\mathrm{CP}} &\equiv \mathcal{A}_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-) - \mathcal{A}_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^+\pi^-) \\
&= (-0.82 \pm 0.21 \pm 0.11)\ \% \qquad \text{[LHCb, arXiv:1112.0938]} \\
&= (-0.62 \pm 0.21 \pm 0.10)\ \% \qquad \text{[CDF, arXiv:1207.2158]} \\
&= (-0.43 \pm 0.30 \pm 0.11)_{\mathrm{K}^+\mathrm{K}^-}\ \% \\
&- (+0.43 \pm 0.52 \pm 0.12)_{\pi^+\pi^-}\ \% \qquad \text{[Belle, arXiv:0807.0148]}
\end{aligned}$$

Though current LHCb results shift smaller:

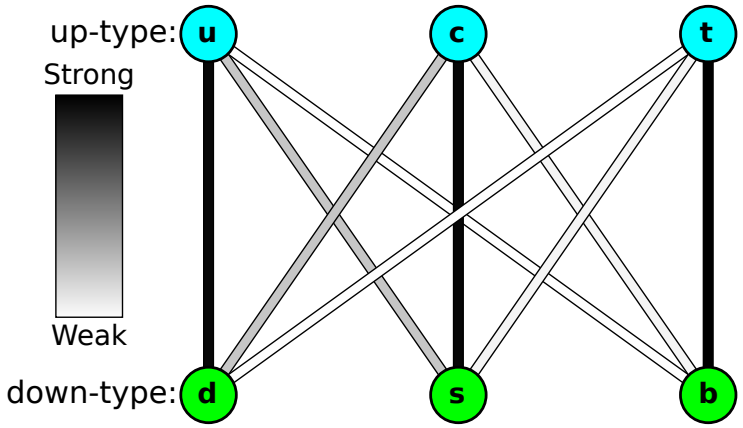
$$\begin{aligned}
(0.49 \pm 0.30 \pm 0.14)\ \% &\qquad \text{[from B, arXiv:1303.2614]} \\
(-0.34 \pm 0.15 \pm 0.10)\ \% &\qquad \text{[from D}^*\text{, LHCb-CONF-2013-003]} \\
(0.14 \pm 0.16 \pm 0.08)\ \% &\qquad \text{[from B, arXiv:1405.2797]}
\end{aligned}$$

Singly-Cabibbo-Suppressed Decays ...

A Singly Cabibbo Suppressed (SCS) decay involves *either* a vertex connecting c with d, *or* u with s.

This leads to amplitudes involving the CKM parameter V_{cd} *or* V_{us}, both of which have magnitude $\cos\theta_{\mathrm{c}} \simeq 22\%$.

These are suppressed relative to the decays involving only the diagonal elements of the CKM matrix. But are not as suppressed as decays involving V_{cd} *and* V_{us} ($\cos^2\theta_{\mathrm{c}} = 5\%$), which are called Doubly Cabibbo Suppressed (DCS).



... As a Probe for New Physics

The Standard Model predicts CPV smaller than $\mathcal{O}(10^{-3})$ for SCS D decays. A signal at the present level of experimental sensitivity, $\mathcal{O}(10^{-2})$, would be a signal for NP (arXiv:hep-ph/0609178).

Reasoning on SU(3) flavor symmetry, order-of-magnitude estimates and sum rules for the SCS D decays were calculated by
Grossman, Kagan, Zupan; arXiv:1204.3557
Atwood, Soni; arXiv:1211.1026

With these we can test NP models that generate CPV in the $\Delta I = 3/2$ reduced matrix elements.

OK, But Belle is a B Factory

Yes, Belle is a B Factory. But it produces just as much $\mathrm{c\bar{c}}$ as $\mathrm{b\bar{b}}$.

How do we find our decays?

We don't have the benefit of $\mathrm{e^-e^+ \to B\overline{B}}$ for nice event variables like M_{beam} and ΔE.

But if we look at the decay chain $\mathrm{D^* \to \pi_s D \to X}$, we can use the variables: M_{D} and

$$q \equiv M_{\mathrm{D}^*} - M_{\mathrm{D}} - m_{\pi_{\mathrm{s}}},$$

which is the energy released in the $\mathrm{D^*}$ decay. The charge of the π_{s} is used to determine the flavour of the D (i.e. if it is a D or a $\overline{\mathrm{D}}$).

In practice, it's often best to use $(M_{\mathrm{D}})^2$ and $\sqrt{q}$, since the first is a kinematic invariant and the second corresponds to phase space volume more closely.

$D^0 \to \pi^+\pi^-\pi^+\pi^-$

Measurements of Branching Ratios, Amplitude Analysis

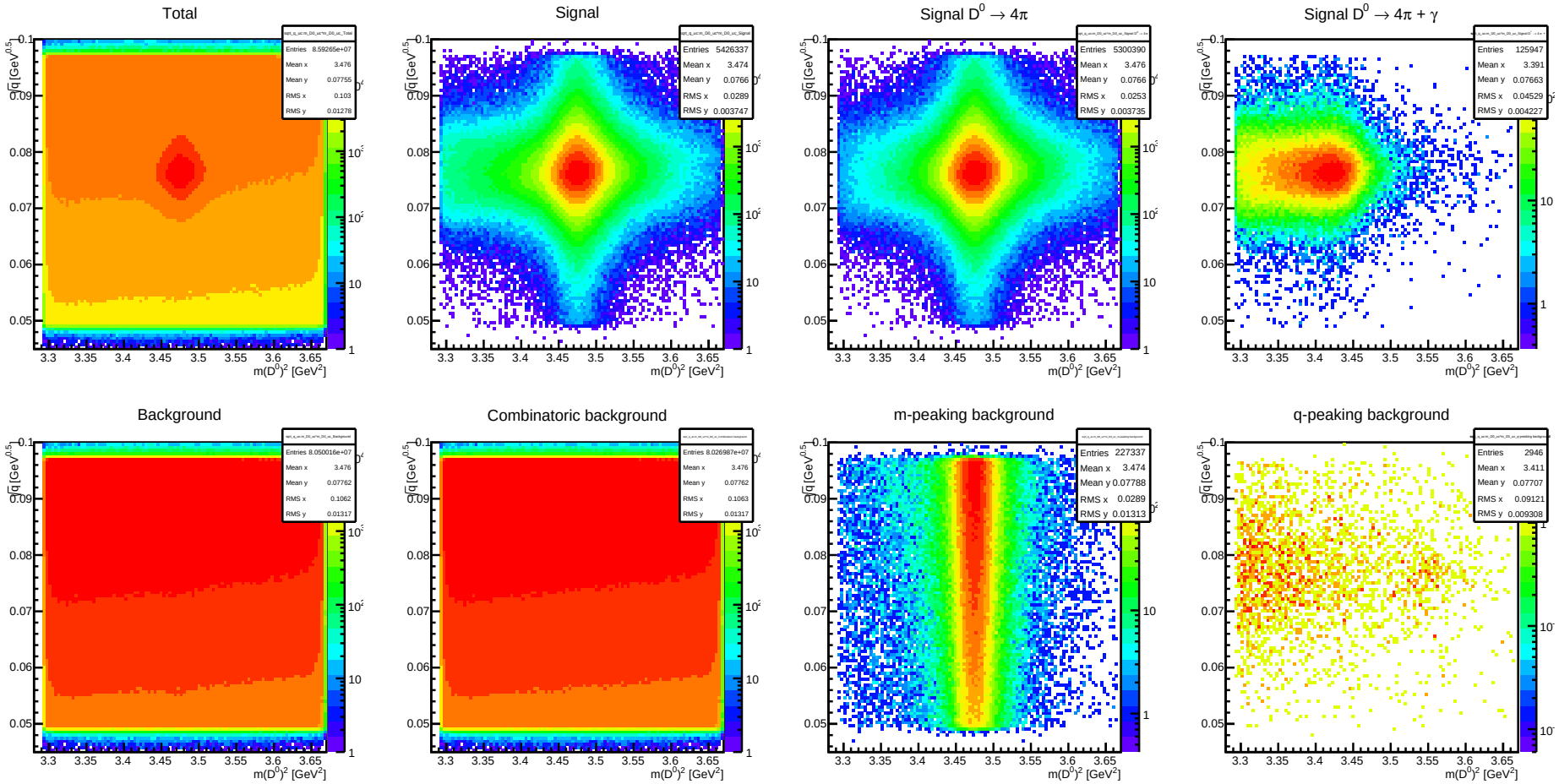
The channel $D^0 \to \pi^+\pi^-\pi^+\pi^-$ is interesting for its rich $\mathcal{A}_{CP}$ studies (for each resonance, and polarization) but also for its rich resonance structure, containing $a_1\pi$, $\rho\rho$, $\sigma\pi\pi$, $f_0\pi\pi$, $f_2\pi\pi$.

Previous measurements of branching rations and CPV:

Experiment	Number of events	Comments and link
BESII	$(274.4 \pm 31.8) - (112.5 \pm 19.0)$	arXiv:hep-ex/0502045
WA82	64 ± 12	http://dx.doi.org/10.1016/0370-2693(92)90791-2
CLEO	345 ± 50	http://dx.doi.org/10.1103/PhysRevD.44.3383
CLEO-c	7331 ± 130	arXiv:hep-ex/0512063
E691	66 ± 12	
E687	79 ± 17	http://dx.doi.org/10.1016/0370-2693(95)00693-F
E687	814 ± 52	http://dx.doi.org/10.1016/0370-2693(92)90292-C
FOCUS (E831)	6360 ± 115	Amplitude analysis. arXiv:hep-ex/0701001
LHCb	3.3×10^5	Model-independent search for CPV, consistent with no CPV. No amplitude analysis.
BaBar		–
Belle	4×10^5	Expected signal events for this analysis.

$D^0 \to \pi^+\pi^-\pi^+\pi^-$

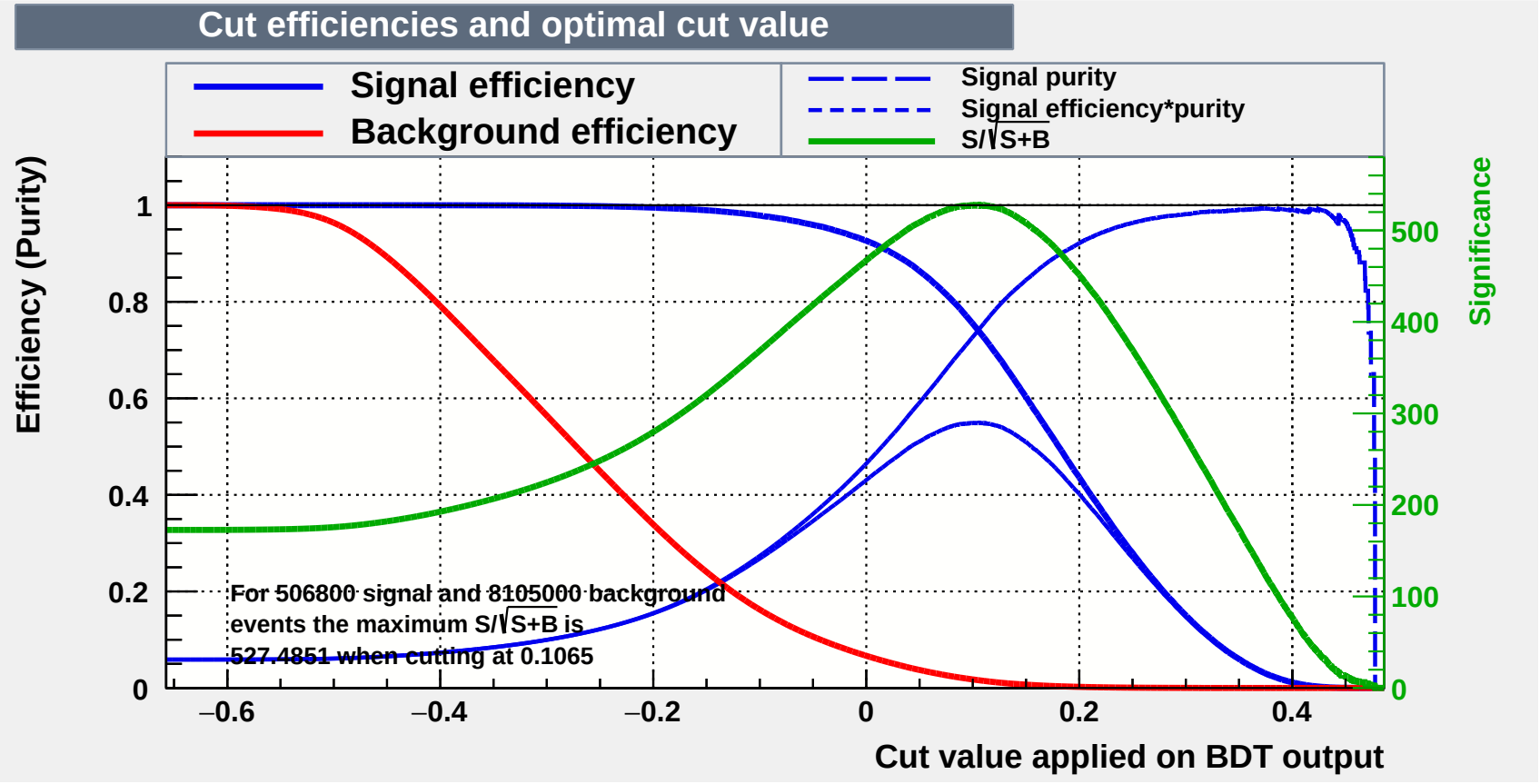
MC Signal and Background Distributions



MC Signal and background distributions, $\sqrt{q}$ vs. $m^2_{D^0}$

$D^0 \to \pi^+\pi^-\pi^+\pi^-$

Event Selection with TMVA



$\mathrm{D}^{\pm} \to \pi^{\pm}\pi^{0}$

Currently the only measurement of $\mathcal{A}_{\mathrm{CP}}(\pi^{\pm}\,\pi^{0})$ comes from CLEO-c:

$$\mathcal{A}_{\mathrm{CP}}(\mathrm{D}^{\pm} \to \pi^{\pm}\pi^{0}) = (2.9 \pm 2.9 \pm 0.3)\ \%$$

from arXiv:0906.3198, measured at the $\psi(3770)$ resonance with an integrated luminosity of 586 pb^{-1}.
2649 $\pm$ 76 decays with an efficiency of (48.69 $\pm$ 0.15)%.

Expectation for Belle: 40 000 to 100 000 events.

We also want to search for $\mathrm{D}_{\mathrm{s}}^{\pm} \to \pi^{\pm}\pi^{0}$.

$D^{\pm} \to \pi^{\pm}\pi^{0}$, $D^{0} \to \pi^{+}\pi^{-}\pi^{+}\pi^{-}$

Current Status of the Analyses

Current status:

- Developed event selection and analysis modules based on MC.
- Developed fitting routine for signal- and background-shapes and yields. The fits are done with the Bayesian Analysis Toolkit (BAT) with Markov Chains.
- Event selection with boosted decision trees (TMVA).

Next steps:

- amplitude analysis on real data with YAP.
- CPV analysis with amplitudes from amplitude analysis.

$D^+ \to K_S^0 K^- \pi^+ \pi^+ \pi^0$

The channels

$$\begin{aligned} D^+ &\to K^{*+} K^{*-} \pi^+ \\ D^+ &\to K^{*+} \overline{K}^{*0} \pi^0 \\ D^+ &\to K^{*0} \overline{K}^{*0} \pi^+ \end{aligned}$$

all can end up in the same final state, $K_S^0\ K^-\ \pi^+\ \pi^+\ \pi^0$.

According to arXiv:1204.3557, a non-vanishing CP violation difference

$$|\sqrt{2} A_{K^{*+}\overline{K}^{*0}\pi^0} + A_{K^{*+}K^{*-}\pi^+} + A_{K^{*0}\overline{K}^{*0}\pi^+}|^2 - |\sqrt{2}\overline{A}_{K^{*-}K^{*0}\pi^0} + \overline{A}_{K^{*-}K^{*+}\pi^-} + \overline{A}_{\overline{K}^{*0}K^{*0}\pi^-}|^2$$

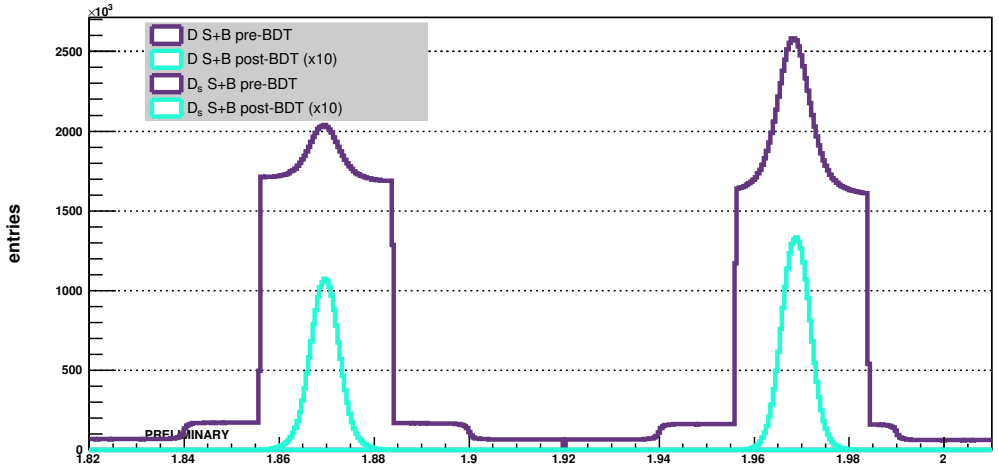
would indicate NP.

$D^+ \to K^+K^-\pi^+$

$D^+ \to K^+K^-\pi^+$ [+CP]
$D_s^+ \to K^+K^-\pi^+$ [+CP] (can be used as a CP normalizing channel, i.e. for calibrating π^- π^+ detection asymmetries)

A previous analysis in Belle only looked into this channel with K^+ K^- confined to the ϕ mass region.

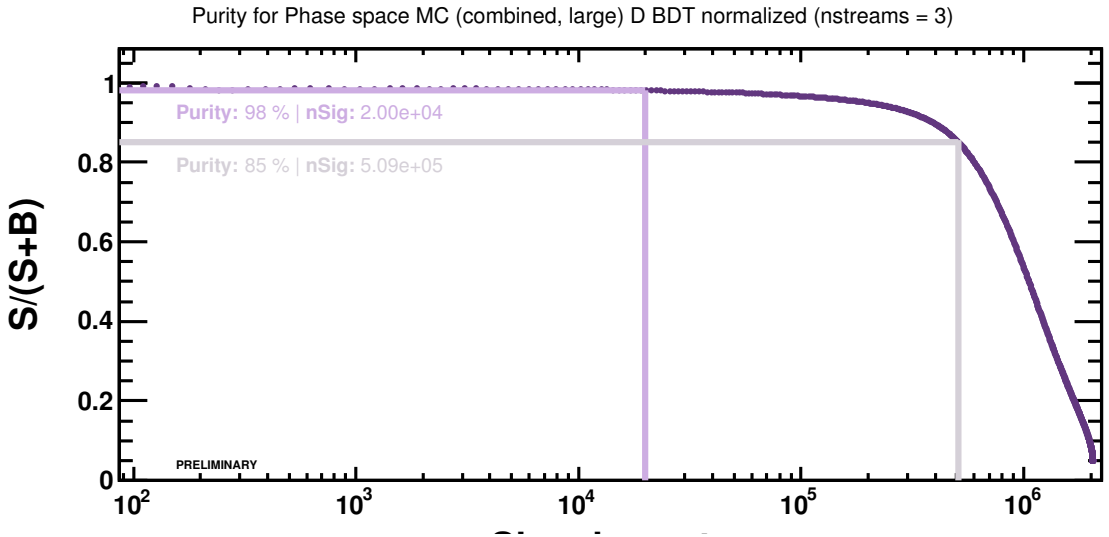
We are currently working event selection and cut optimization. We are planning to do amplitude analyses on these channels, which would be the first amplitude analyses of such decays at Belle.

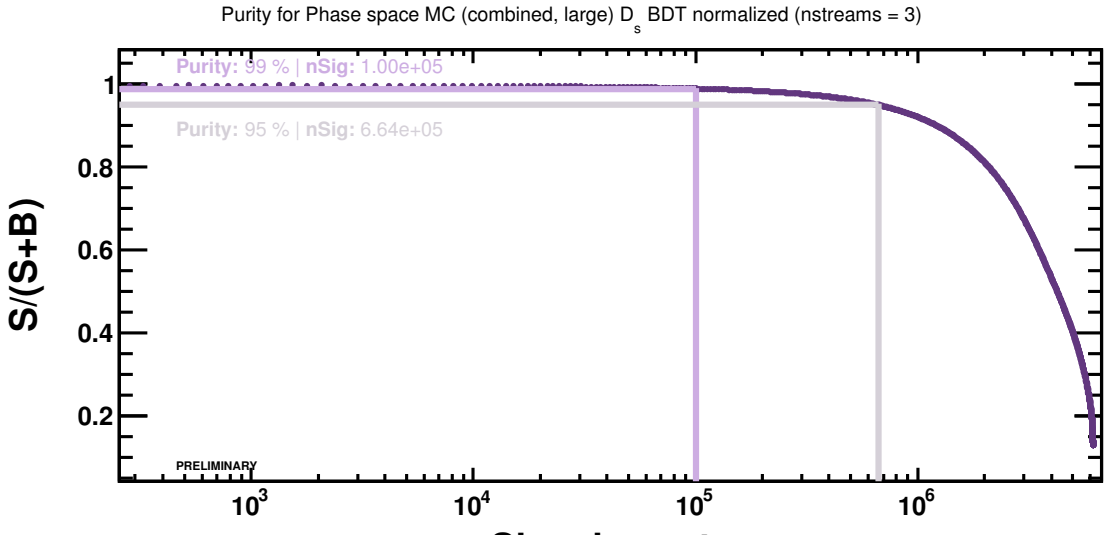


$D^+ \to K^+K^-\pi^+$

Purity vs. signal yield for D_s and D (MC)

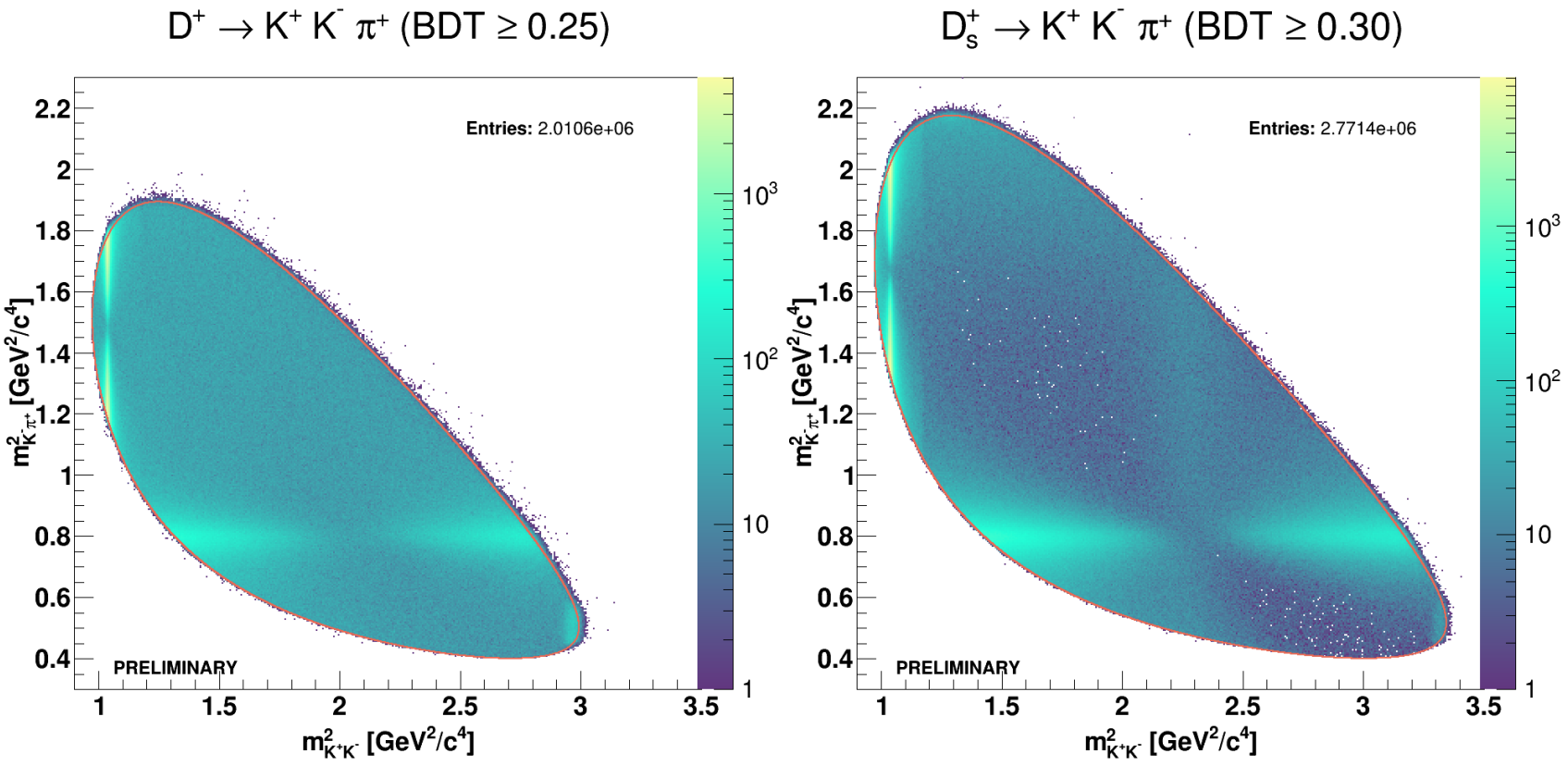
Technische Universität München





$D^+ \to K^+K^-\pi^+$

Dalitz plots after BDT cut (MC)



YAP

Yet Another Partial Wave Analysis Toolkit

YAP–Yet Another Partial Wave Analysis Toolkit

Technische Universität München

What is YAP?

- It's an amplitude calculation library
- Meant to efficiently calculate amplitudes for large data sets
- Open source, C++11, hosted on GitHub: `github.com/yap/`
- Minimal code dependencies (only ROOT, which will probably be removed)

Key features

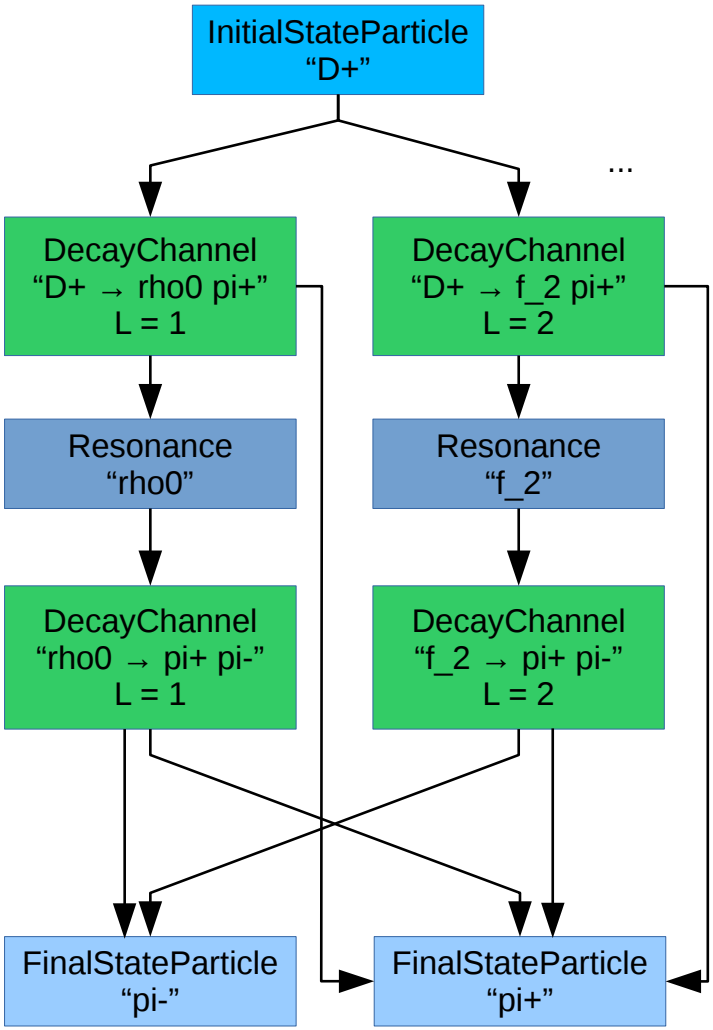
- Code structure mimics the math
- Human readable and easily expandable code
- E.g. mass base-class allows to implement (relativistic) Breit-Wigner, Flattè, Gounaris-Sakurai, Model-independent, etc.
- Calculate amplitude for decays with known initial state and 3 or more final state particles via isobar decomposition
- Uses Wigner *D* functions for spin amplitudes (Zemach formalism planned)
- Intelligent caching: If e.g. a free amplitude or mass is changed, only the components depending on it are recalculated
- Built-in multithreading

YAP–Yet Another Partial Wave Analysis Toolkit

$D^+ \to \pi^+\pi^-\pi^+$ Code example

Technische Universität München

```
yap::ParticleFactory factory("/evt.pdl");

// final state particles
auto piPlus = factory.createFinalStateParticle(211, {0, 2});
auto piMinus = factory.createFinalStateParticle(-211, {1});

// use common radial size for all resonances
double radialSize = 3.; // [GeV^-1]

// use only L up to 4
unsigned max2L(2 * 4);

// rho
auto rho = factory.createResonance(113, radialSize,
                        std::make_unique<yap::BreitWigner>());
rho->addChannels(piPlus, piMinus, max2L);

// f_2(1270)
auto f_2 = factory.createResonance(225, radialSize,
                        std::make_unique<yap::BreitWigner>());
f_2->addChannels(piPlus, piMinus, max2L);

// ...

// initial state particle
auto D = factory.createInitialStateParticle(411, radialSize);

// Add channels to D
D->addChannels(rho,  piPlus, max2L);
D->addChannels(f_2,  piPlus, max2L);
// ...

D->prepare();
```



YAP–Yet Another Partial Wave Analysis Toolkit

Technische Universität München

Ease of use

- User defines FinalStateParticles, Resonances and the InitialStateParticle.
- User adds DecayChannels to decaying particles.
- YAP takes care of isobar decomposition, Bose-Einstein symmetrization, etc.
- Data points can be created from 4-momenta or Dalitz coordinates.

Caveats

- YAP is NOT a fitter/generator.
- YAP can be coupled easily with fitters and samplers. Examples will be provided.

Todo

- Code validation
- Add more mass-shapes (model independent, K-matrix, non-resonant)
- Providing examples of interfaces to fitters and samplers (Minuit, BAT, etc.)
- Acceptances/integration, background

Summary and Outlook

Technische Universität München

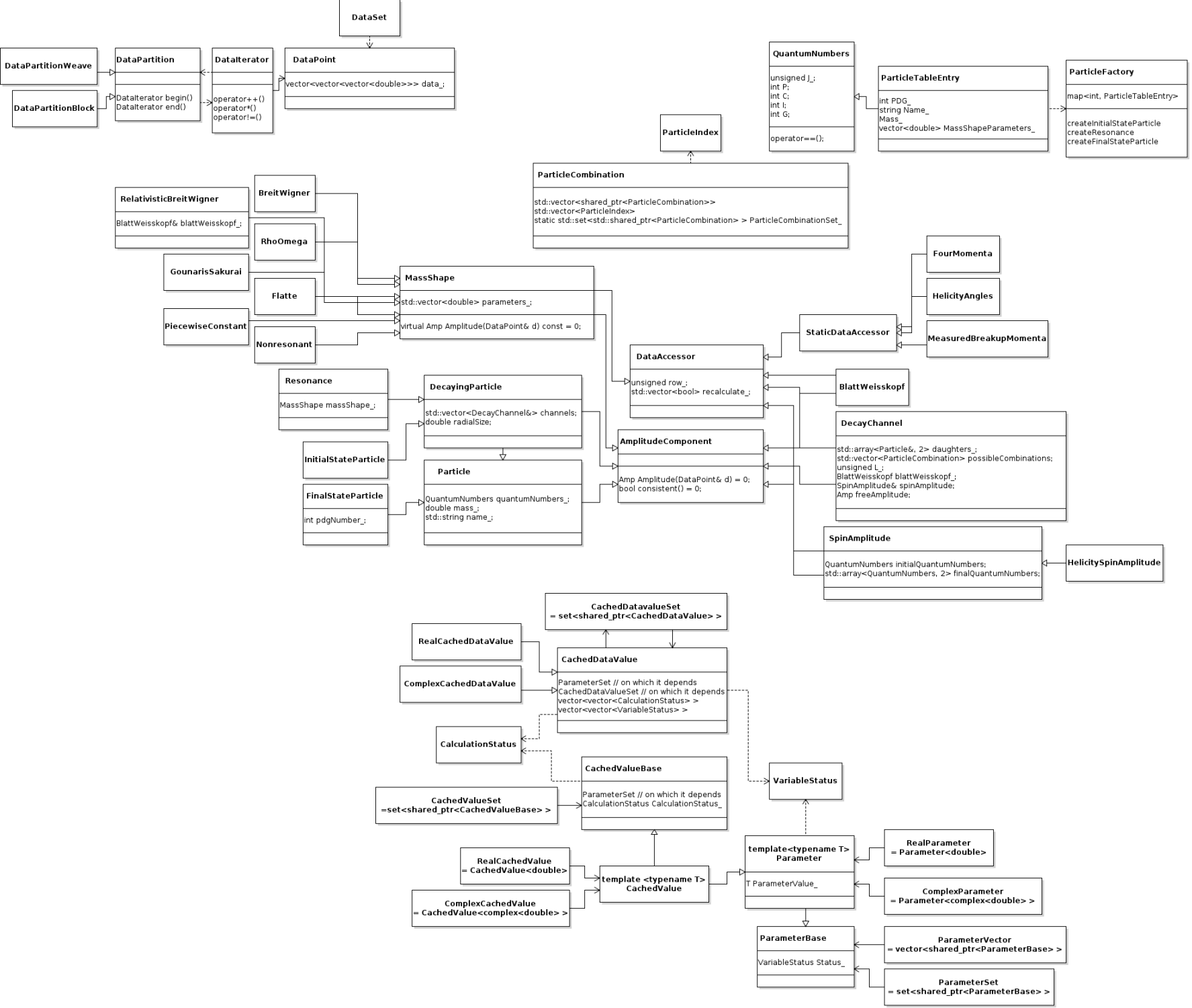
YAP

- A new open-source library for amplitude calculation: `github.com/yap/`.
- Flexible and expandable code.
- Already in a usable state.
- Still needs some work (more mass shapes etc.) and validation.
- Possible use for analyzing hadronic τ decays (two possible initial spin states, 0^- and 1^+, varying initial mass).

Physics

- SCS D decays provide a good probe for NP. The Standard Model predicts CPV smaller than $\mathcal{O}(10^{-3})$.
  A signal at the present level of experimental sensitivity, $\mathcal{O}(10^{-2})$, would be a signal for NP.
- We are analyzing several channels and want to search for CPV.
- We also want to do amplitude analyses of our channels, which have either not been done before, or with much smaller data sets.

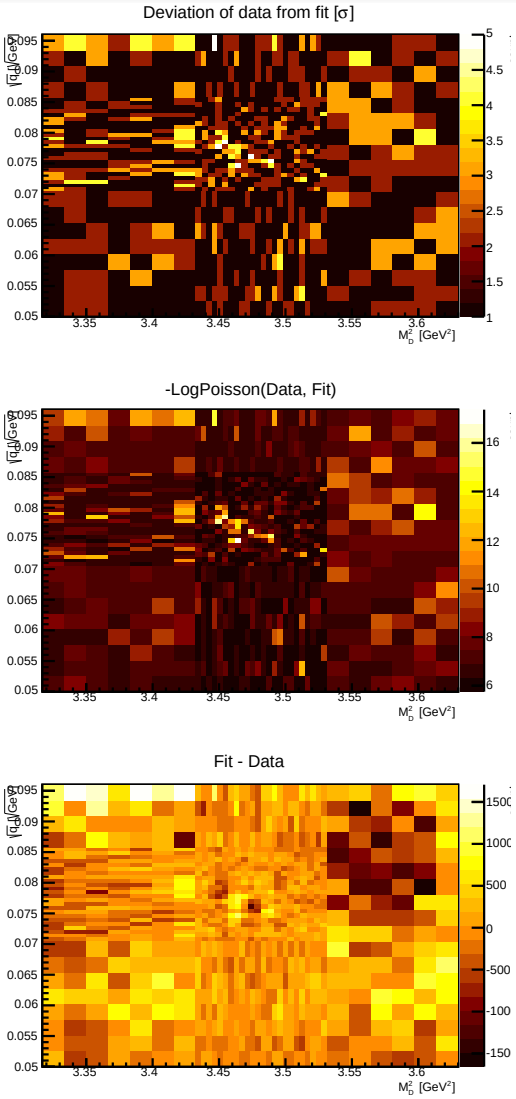
Thank you for your attention!

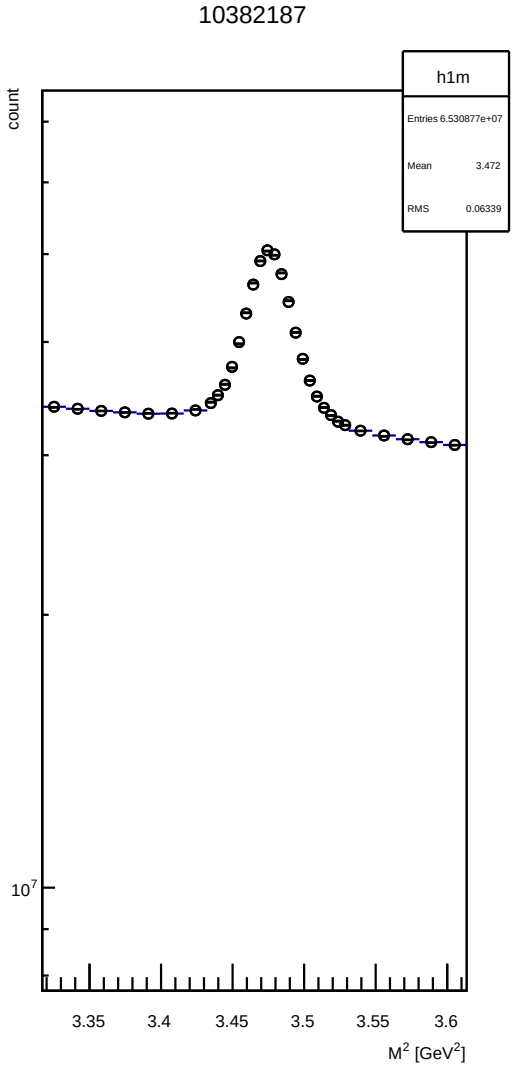

DataSet
DataPartitionWeave
DataPartition
DataIterator
DataPoint
vector<vector<vector<double>>> data_;
DataPartitionBlock
DataIterator begin()
DataIterator end()
operator++()
operator*()
operator!=()
QuantumNumbers
unsigned J_;
int P;
int C;
int I;
int G;
operator==();
ParticleTableEntry
int PDG_
string Name_
Mass_
vector<double> MassShapeParameters_
ParticleFactory
map<int, ParticleTableEntry>
createInitialStateParticle
createResonance
createFinalStateParticle
ParticleIndex
ParticleCombination
std::vector<shared_ptr<ParticleCombination>>
std::vector<ParticleIndex>
static std::set<std::shared_ptr<ParticleCombination> > ParticleCombinationSet_
RelativisticBreitWigner
BlattWeisskopf& blattWeisskopf_;
BreitWigner
RhoOmega
GounarisSakurai
Flatte
PiecewiseConstant
Nonresonant
MassShape
std::vector<double> parameters_;
virtual Amp Amplitude(DataPoint& d) const = 0;
FourMomenta
HelicityAngles
MeasuredBreakupMomenta
StaticDataAccessor
DataAccessor
unsigned row_;
std::vector<bool> recalculate_;
BlattWeisskopf
Resonance
MassShape massShape_;
DecayingParticle
std::vector<DecayChannel&> channels;
double radialSize;
InitialStateParticle
FinalStateParticle
int pdgNumber_;
Particle
QuantumNumbers quantumNumbers_;
double mass_;
std::string name_;
AmplitudeComponent
Amp Amplitude(DataPoint& d) = 0;
bool consistent() = 0;
DecayChannel
std::array<Particle&, 2> daughters_;
std::vector<ParticleCombination> possibleCombinations;
unsigned L_;
BlattWeisskopf blattWeisskopf_;
SpinAmplitude& spinAmplitude;
Amp freeAmplitude;
SpinAmplitude
QuantumNumbers initialQuantumNumbers;
std::array<QuantumNumbers, 2> finalQuantumNumbers;
HelicitySpinAmplitude
CachedDatavalueSet
= set<shared_ptr<CachedDataValue> >
RealCachedDataValue
CachedDataValue
ComplexCachedDataValue
ParameterSet // on which it depends
CachedDataValueSet // on which it depends
vector<vector<CalculationStatus> >
vector<vector<VariableStatus> >
CalculationStatus
CachedValueBase
ParameterSet // on which it depends
CalculationStatus CalculationStatus_
VariableStatus
CachedValueSet
=set<shared_ptr<CachedValueBase> >
template<typename T>
Parameter
T ParameterValue_
RealParameter
= Parameter<double>
RealCachedValue
= CachedValue<double>
template <typename T>
CachedValue
ComplexParameter
= Parameter<complex<double> >
ComplexCachedValue
= CachedValue<complex<double> >
ParameterBase
VariableStatus Status_
ParameterVector
= vector<shared_ptr<ParameterBase> >
ParameterSet
= set<shared_ptr<ParameterBase> >

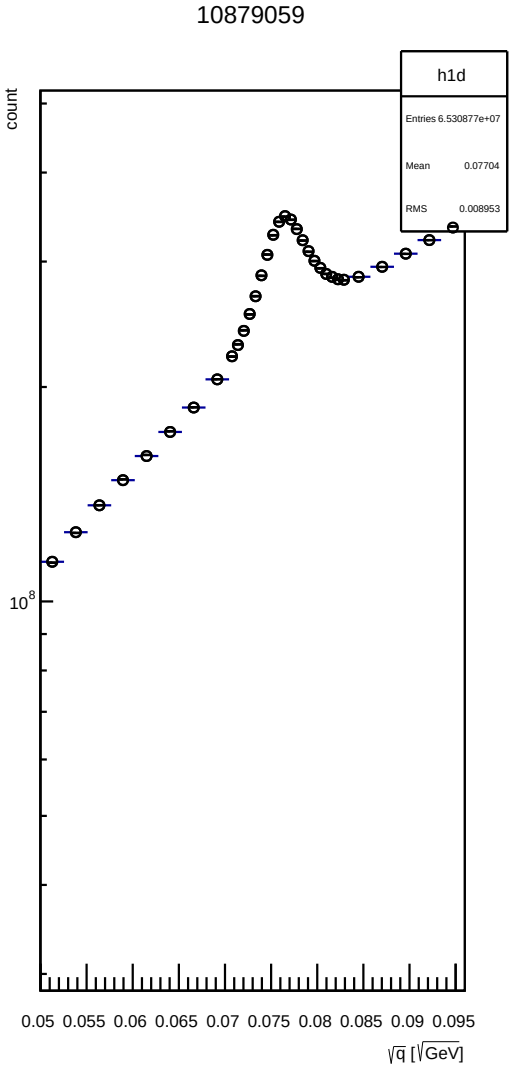
$D^0 \to \pi^+\pi^-\pi^+\pi^-$

Fits of Signal and Background Shapes

Technische Universität München



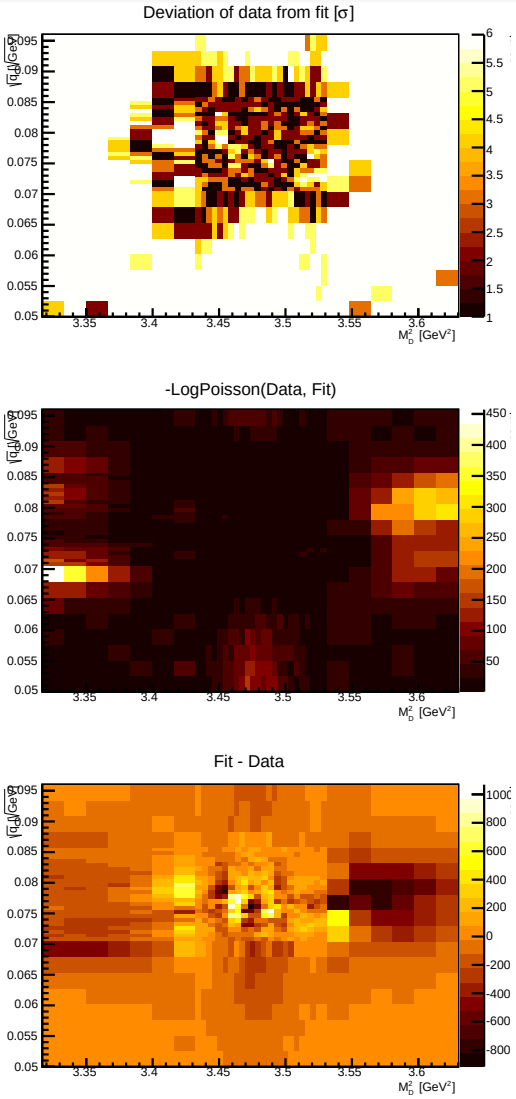


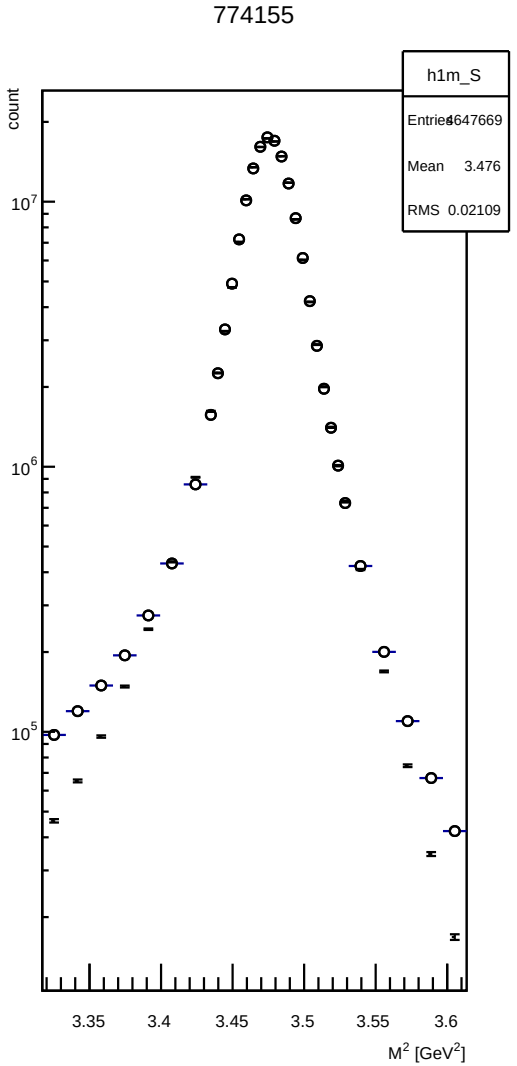


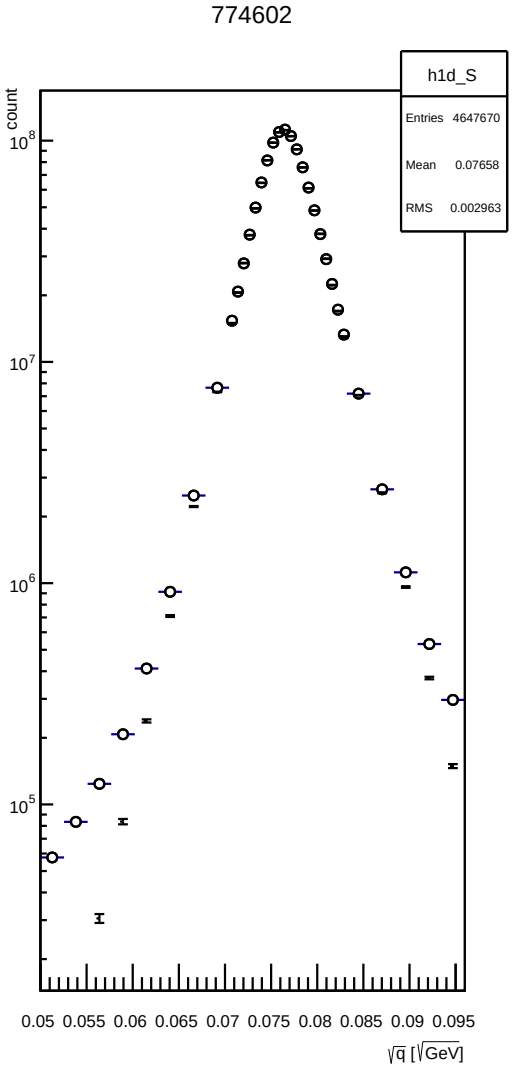
All

$D^0 \to \pi^+\pi^-\pi^+\pi^-$

Fits of Signal and Background Shapes





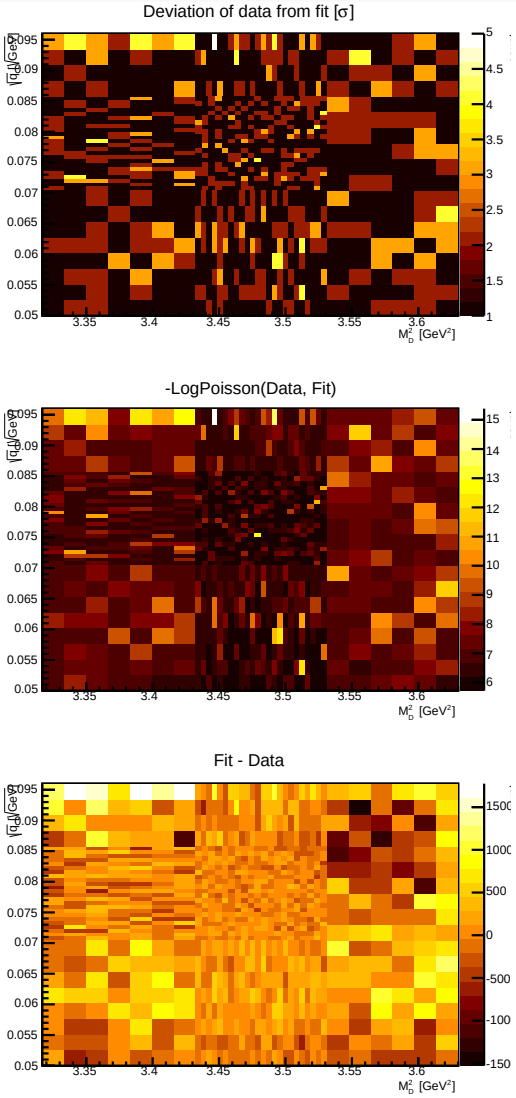


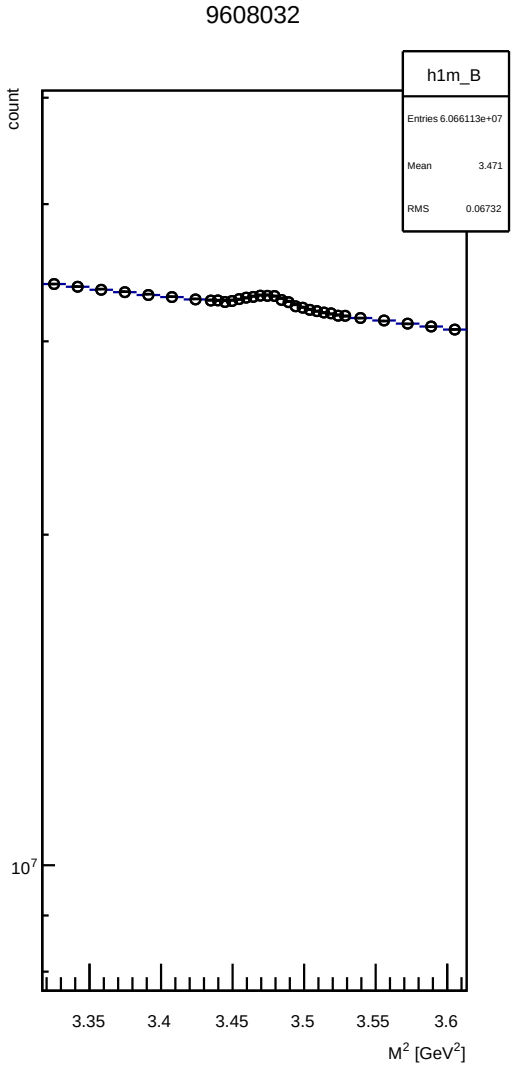
Signal. Double crystal ball (DCB) ($m^2_{D^0}$), DCB ($\sqrt{q}$), bivariate Gaussian ($m^2_{D^0}$, $\sqrt{q}$).

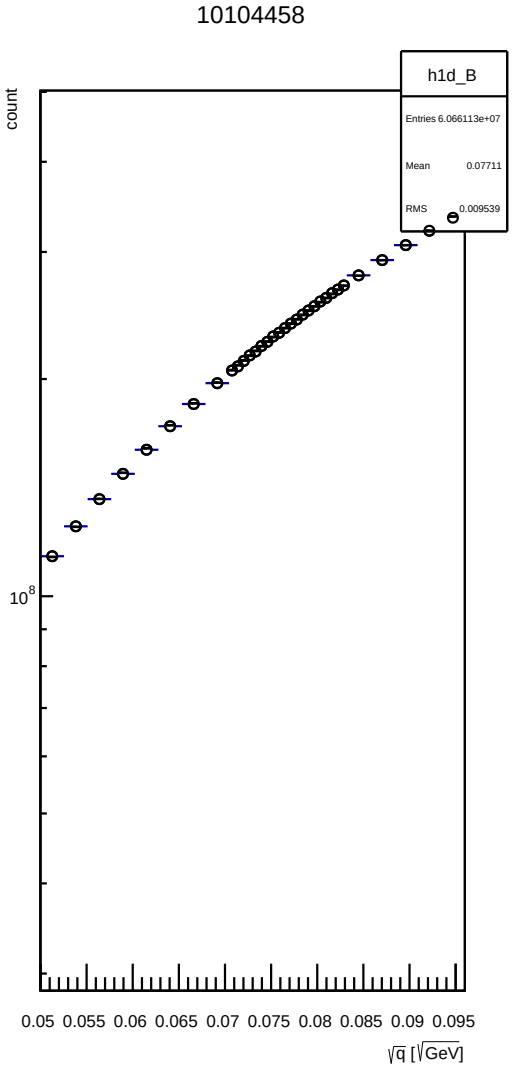
$D^0 \to \pi^+\pi^-\pi^+\pi^-$

Fits of Signal and Background Shapes

Technische Universität München





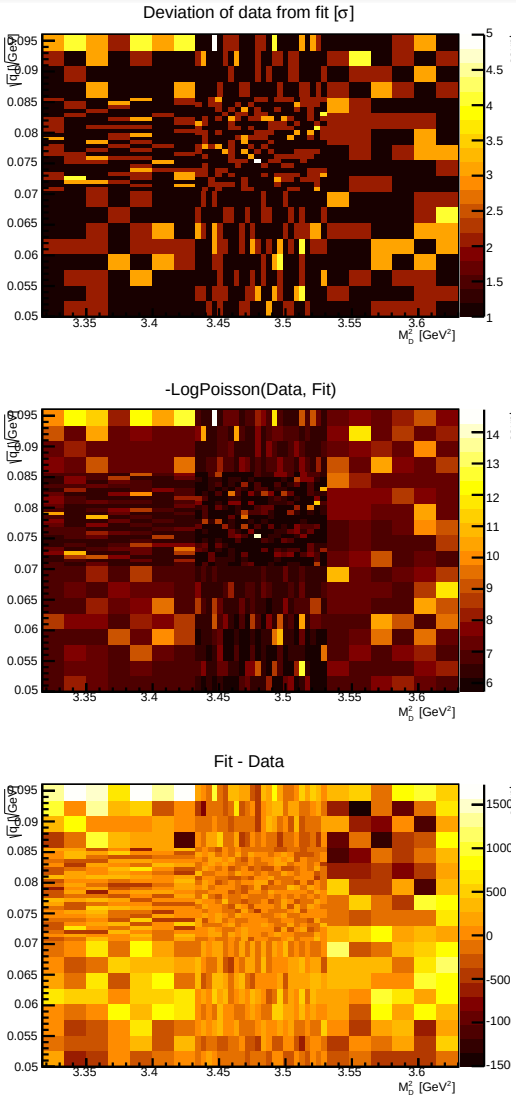


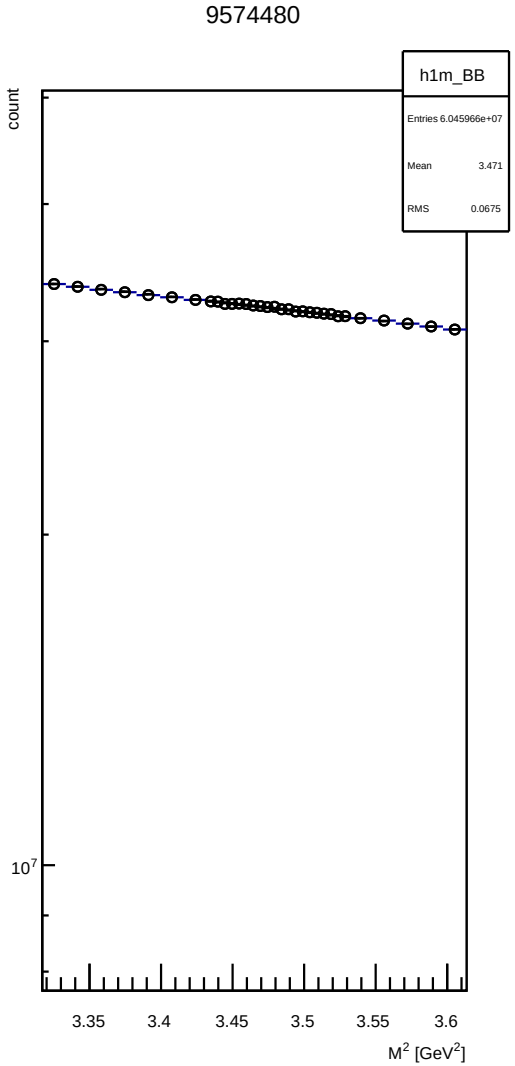
Total Background.

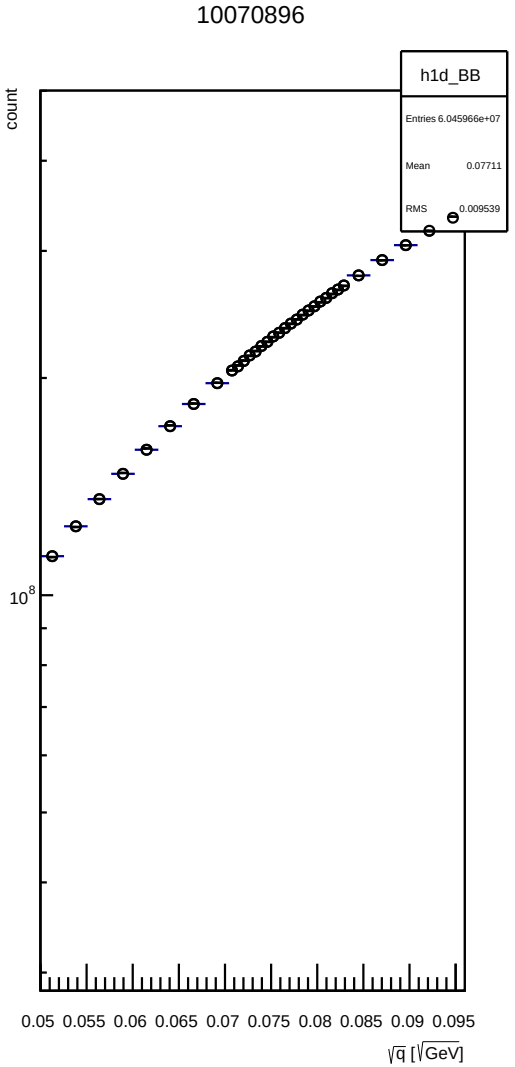
$D^0 \to \pi^+\pi^-\pi^+\pi^-$

Fits of Signal and Background Shapes

Technische Universität München





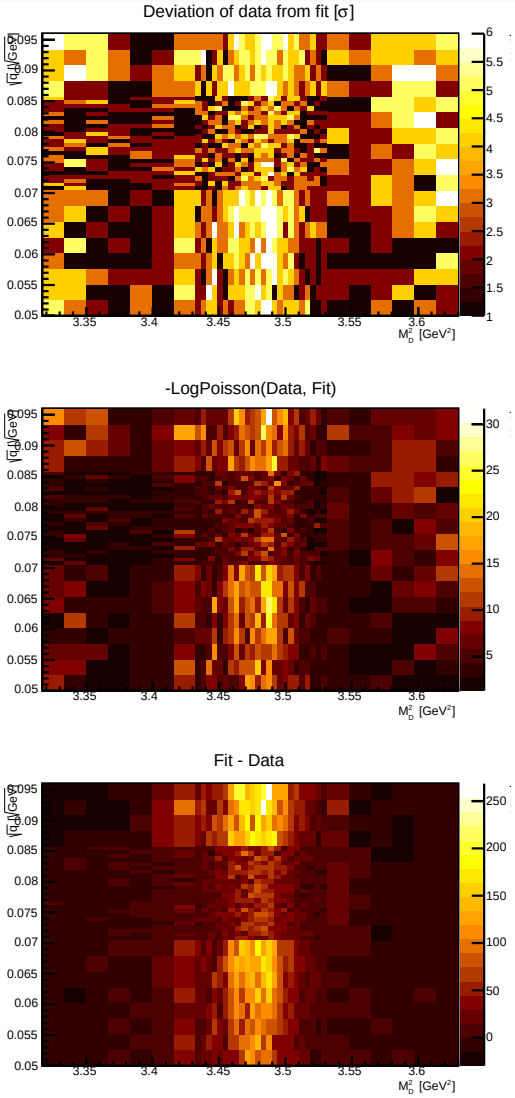


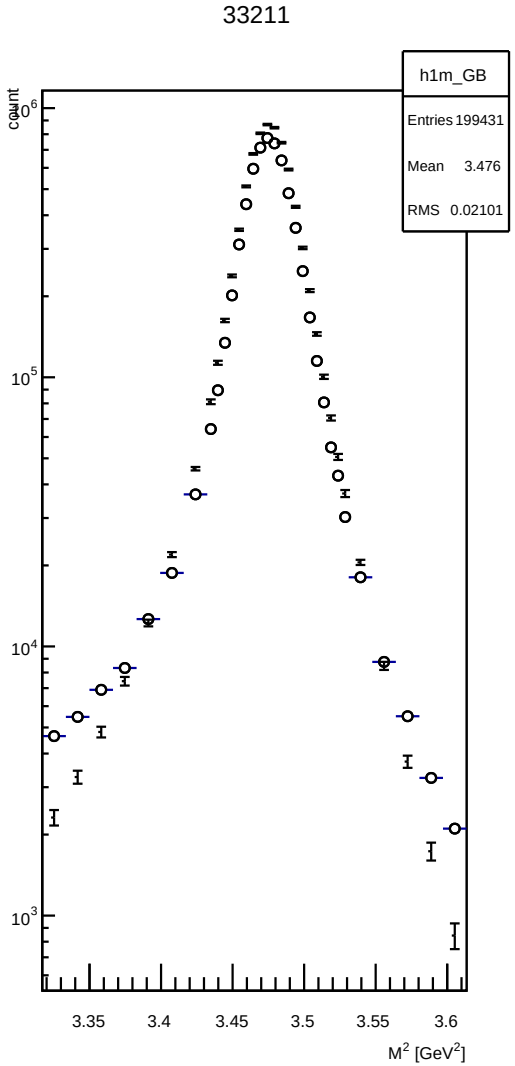
Combinatoric background. Linear ($m^2_{D^0}$), quadratic ($\sqrt{q}$).

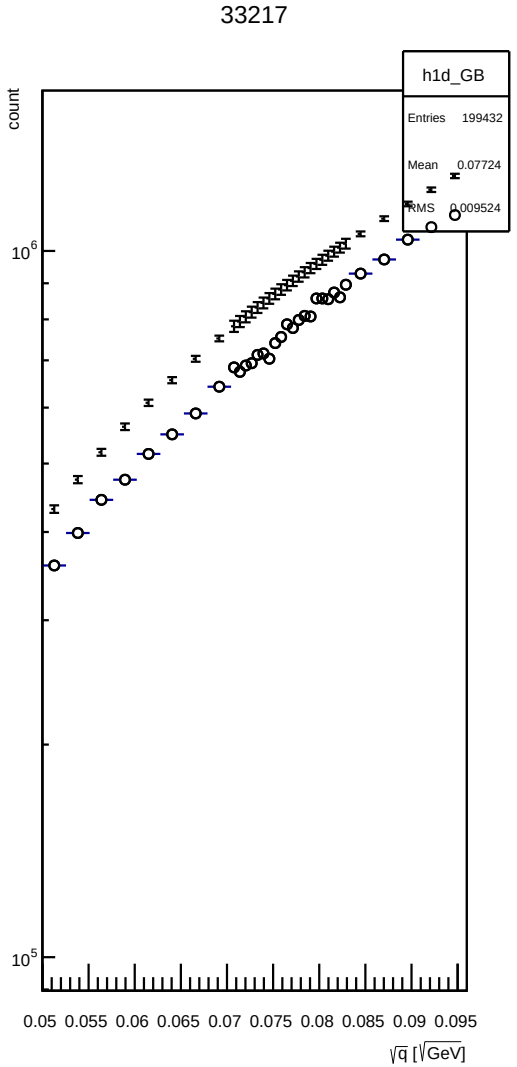
$D^0 \to \pi^+\pi^-\pi^+\pi^-$

Fits of Signal and Background Shapes

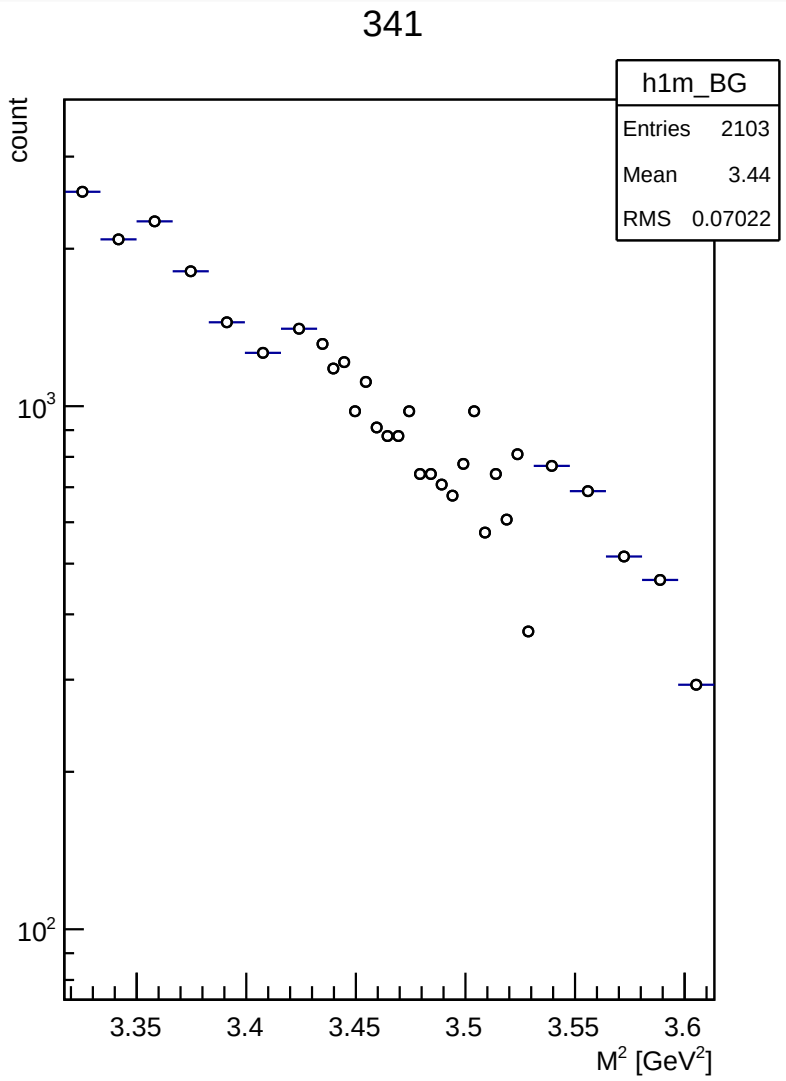
Technische Universität München

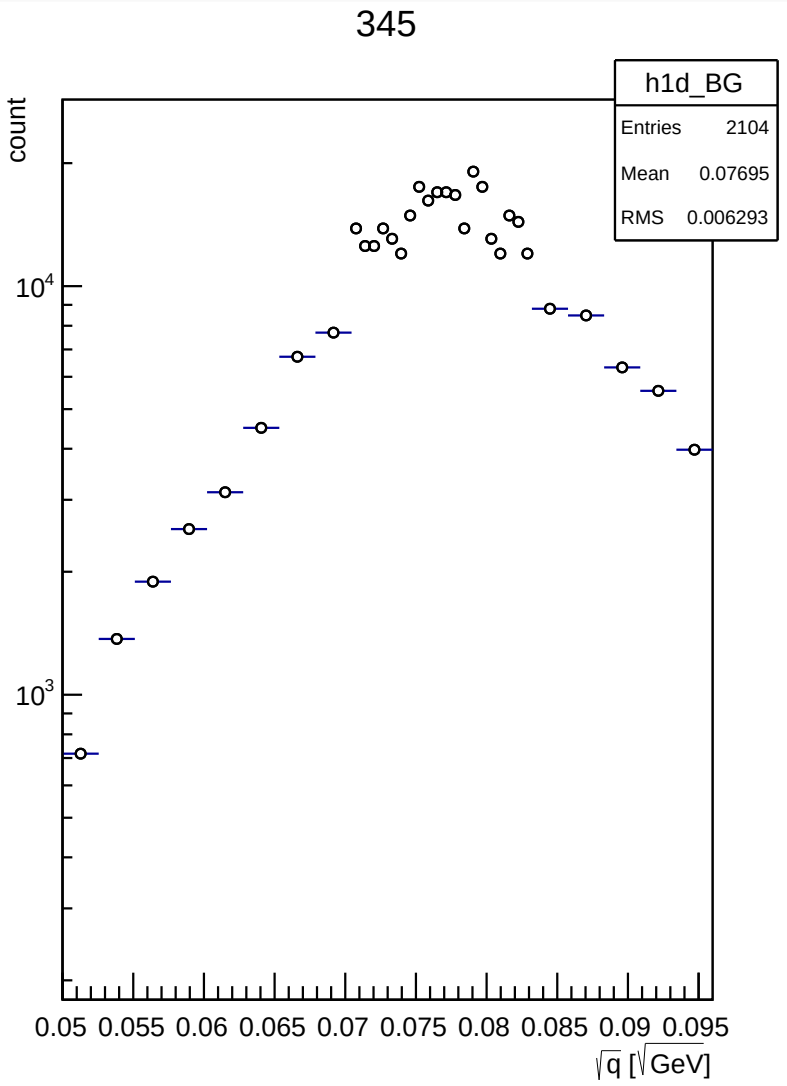


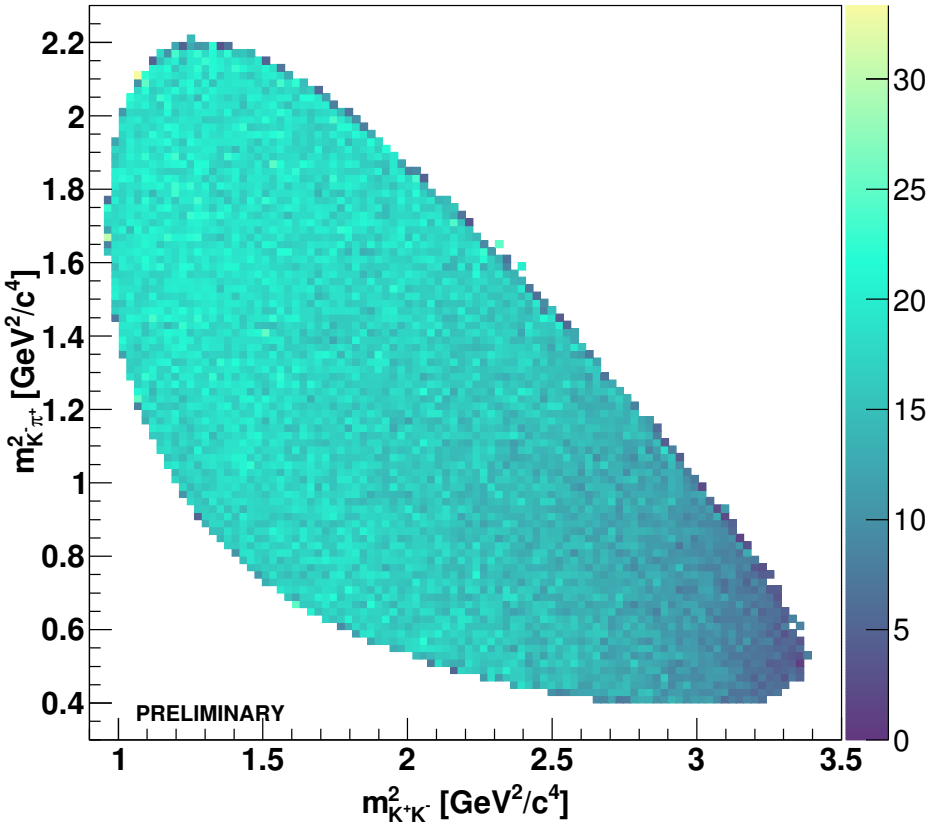




Mass-peaking background. Signal shape ($m^2_{D^0}$), combinatoric background shape ($\sqrt{q}$).





Q-peaking background (not fitted).

Remaining Signal in percent