Feasibility Studies for the Optimization of the PANDA Detector for the Identification of the Glueball Candidate X(2370)

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Overview and motivation

BES III observed X(2370):

$$e^+e^- \longrightarrow J/\psi \longrightarrow X(2370)\gamma$$

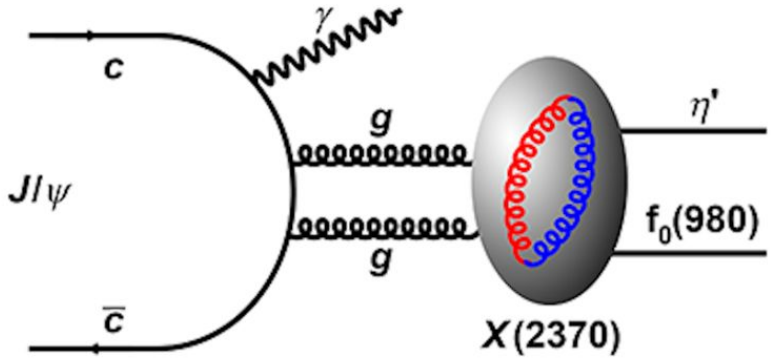
PANDA:

$$\bar{p}p \longrightarrow X(2370)$$

at beam momentum 1.85 GeV/c

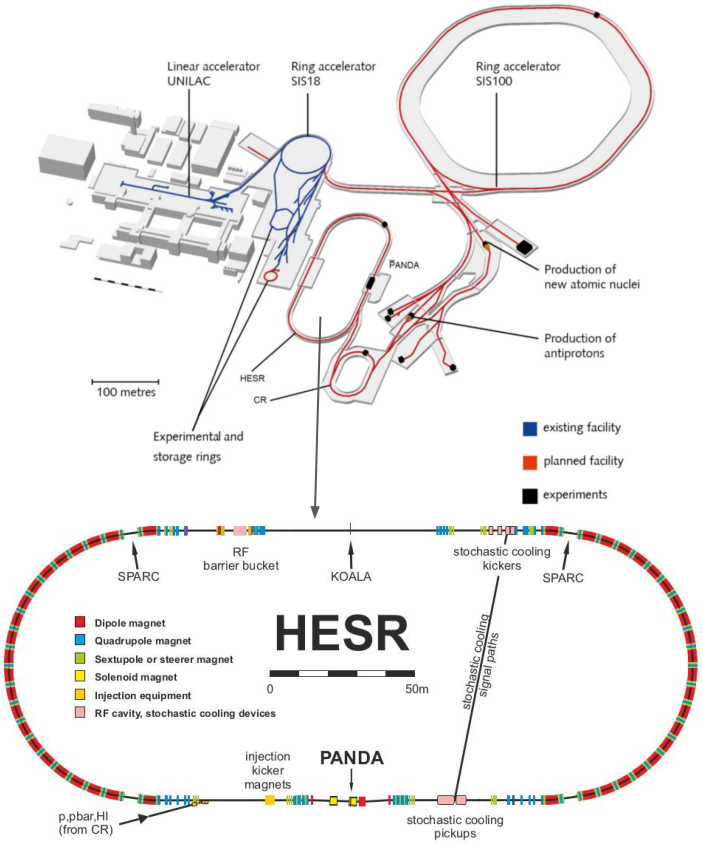
Feasibility study for the detection of the glueball candidate X(2370) with a minimal setup

Discovery of a Glueball-like particle X(2370) at BESIII
Yanping Huang (IHEP Beijing)



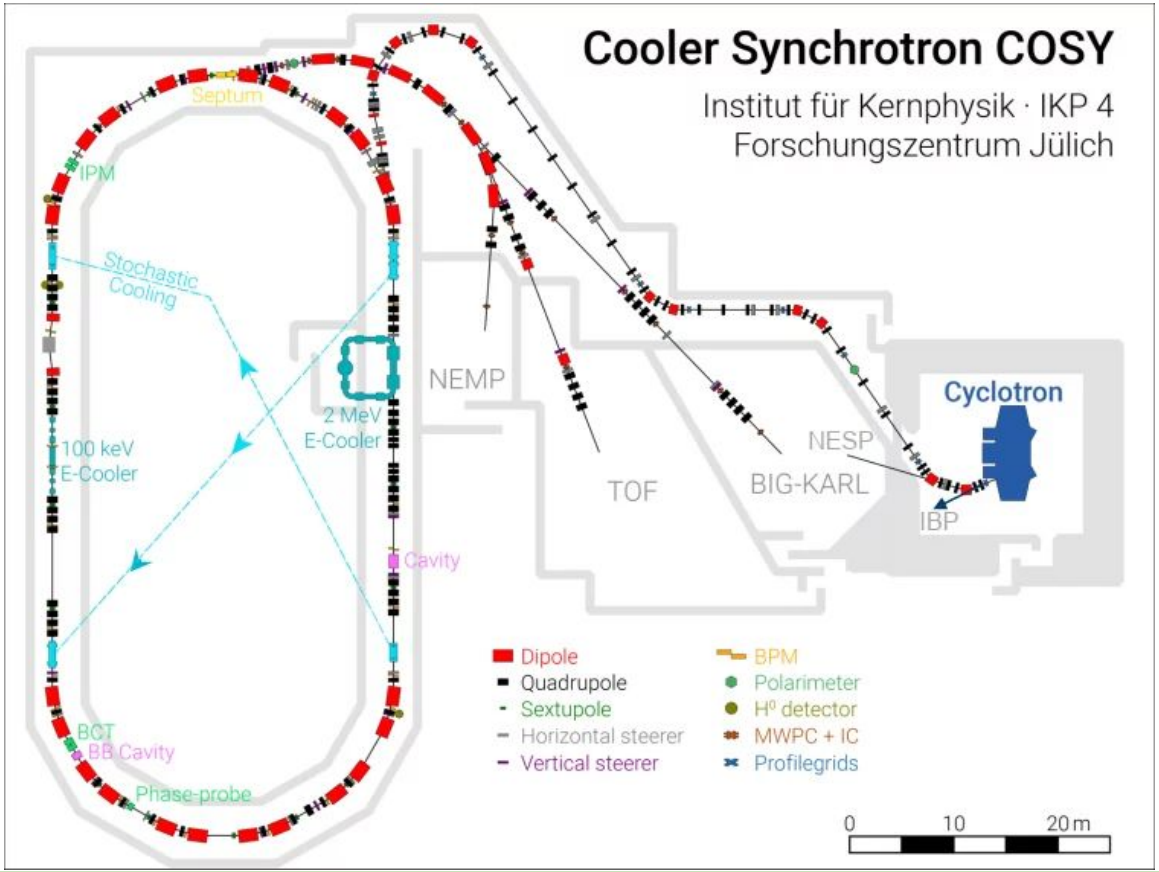
	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^+K^-\eta'$	seen
Γ_2	$K^0_S K^0_S \eta'$	seen
Γ_3	$\pi^+\pi^-\eta'$	seen
Γ_4	$\eta\eta\eta'$	not seen

PANDA at FAIR



- PANDA located in HESR at FAIR
- HESR antiproton momentum from 1.5 GeV/c to 15 GeV/c
  ↳ 5.5 GeV center-of-mass energy
- Accumulation of up to 10^{11} antiprotons
- First Science+ beam commissioning planned for 2028
- PANDA as a further step afterwards

COSY



- COoler SYnchrotron shutdown in 2023
- Beam momentum of up to 3.3 GeV/c
  ↳ sufficient for X(2370)
- Transition to FAIR
- Interim solution until full operation of PANDA

→ Smaller detector sufficient
→ Goal: Requirements of this setup at COSY for X(2370)

HepFastSim Framework

Developed by Klaus Götzen from GSI

- Experiment-independent framework
- Interaction with matter not simulated, simplified as smearing
  - ↳ Acceleration of simulation speed
- Detector
  - Geometry simple to set up
  - Optional details to increase accuracy
- No dependence on external generators, optional integration possible
- Split-off simulation as option
  - ↳ Additional Photons

Procedure	**Limitations**
• Simulation	• Output contains decay chains as recombinations
• Reconstruction	↳ No direct access to particle lists
• Analysis	• Only events with complete decay-chains are reconstructed
↳ Output	

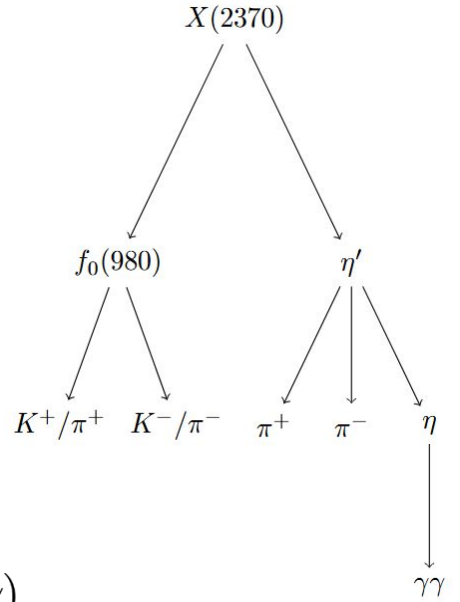
Two Signal processes

Kaon channel:

$$X(2370) \longrightarrow f_0(980)\,\eta'$$

$$f_0(980) \longrightarrow K^+K^- \qquad \eta' \longrightarrow \pi^+\pi^-\eta\,(\rightarrow \gamma\gamma)$$

Small phase space due to f_0 phase space limitations (36 MeV/c)



Pion channel:

$$X(2370) \longrightarrow f_0(980)\,\eta'$$

$$f_0(980) \longrightarrow \pi^+\pi^- \qquad \eta' \longrightarrow \pi^+\pi^-\eta\,(\rightarrow \gamma\gamma)$$

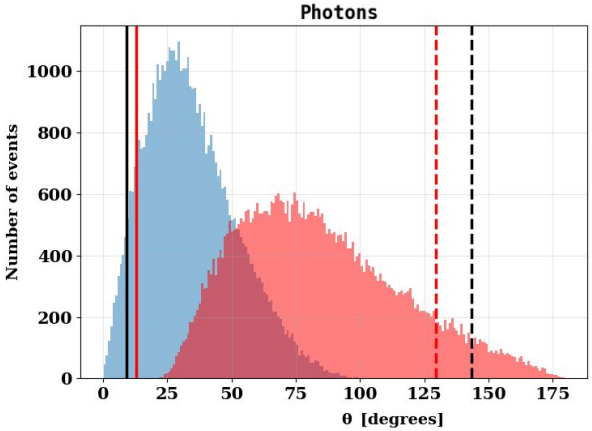
Large phase space due to f_0 phase space (476 MeV/c)

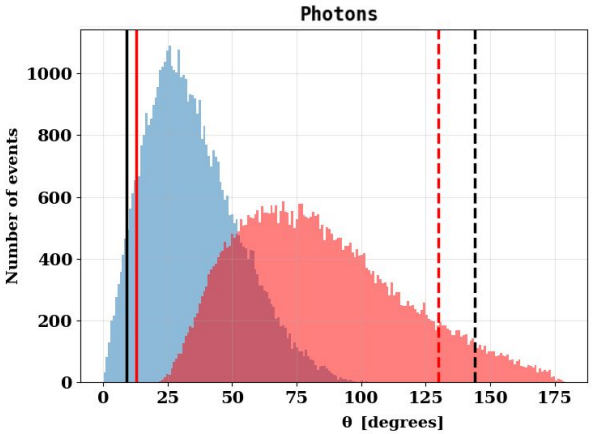
Angular coverage photons

Kaon channel

Pion channel

20.000 events simulated with 100% efficiency without split-offs





Generated minimal and maximal photon θ angle:
Approximately identical for both channels

Angular coverage charged tracks

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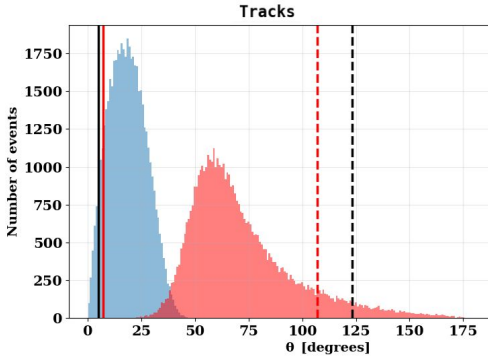
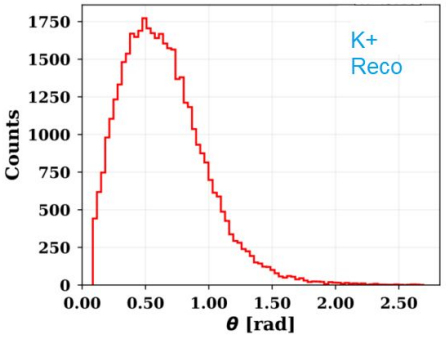
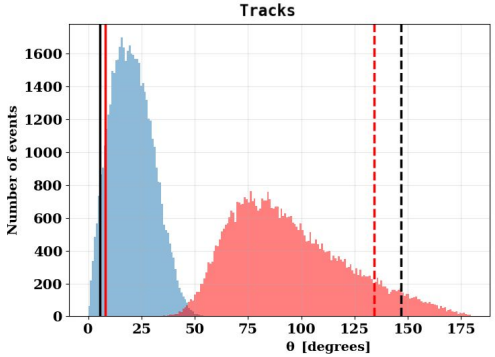
Kaon channel

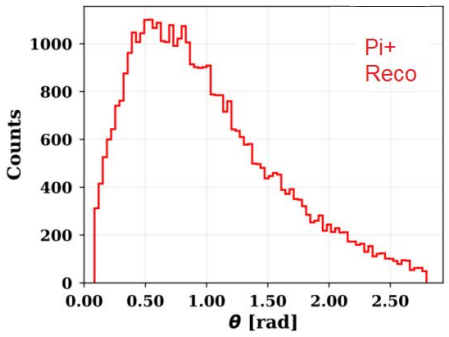
Pion channel

20.000 events simulated with 100% efficiency without split-offs









Generated minimal and maximal angles of charged tracks
→ Low angle Pions.
Pion channel: larger angles of $f_0(980)$ daughters

Determination of optimal geometry

Kaon channel

Pion channel

20.000 events simulated with 100% efficiency without split-offs

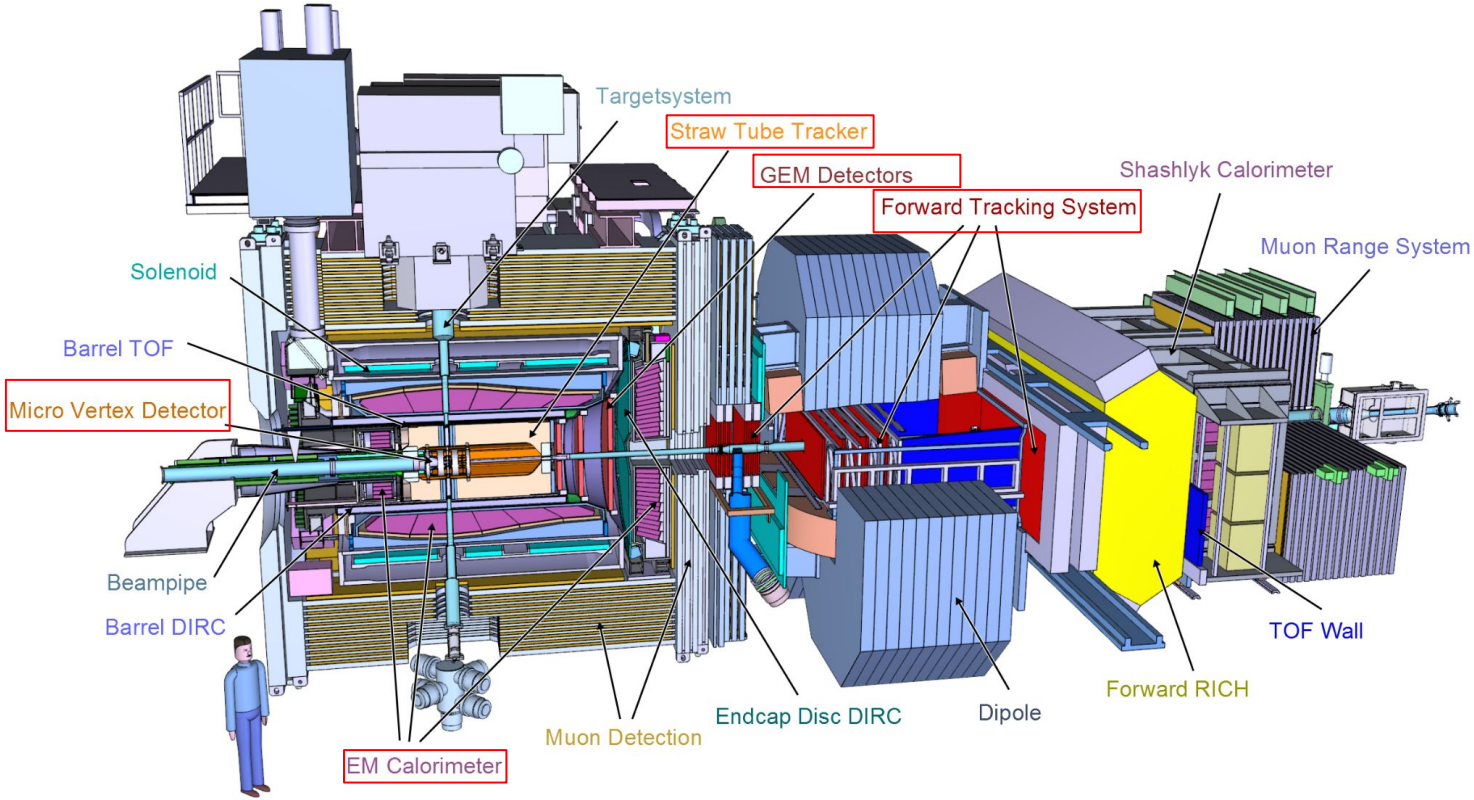
TRK θ [°]	EMC θ [°]	REC [Events]	REC %
[5, 95]	[5, 95]	10899	54.50 ±0.35
	[5, 125]	13813	69.07 ±0.33
	[5, 155]	15100	75.50 ±0.30
[5, 125]	[5, 95]	11931	59.66 ±0.35
	[5, 125]	15602	78.01 ±0.29
	[5, 155]	17149	85.75 ±0.25
[5, 155]	[5, 95]	12250	61.25 ±0.35
	[5, 125]	16032	80.16 ±0.28
	[5, 155]	17614	88.07 ±0.23

TRK θ [°]	EMC θ [°]	REC [Events]	REC %
[5, 95]	[5, 95]	6547	32.74 ±0.33
	[5, 125]	8893	44.47 ±0.35
	[5, 155]	10110	50.55 ±0.35
[5, 125]	[5, 95]	10129	50.65 ±0.35
	[5, 125]	13597	67.99 ±0.33
	[5, 155]	15160	75.80 ±0.30
[5, 155]	[5, 95]	11718	58.59 ±0.35
	[5, 125]	15598	77.99 ±0.29
	[5, 155]	17293	86.47 ±0.24

Reconstruction is in agreement with geometry based on truth information that covers 90% of the tracks and 90% of the photons for the Kaon channel

Geometry chosen: TRK [4, 125]° EMC[5, 155]°

The PANDA detector



Simplified reconstruction setup

Simplified detector parameters based on PANDA.
The simulation uses only one tracking detector and one EMC.

Tracking detector			**EMC detector**			**PID detector**		
Parameter	Value	Unit	Parameter	Value	Unit	Parameter	Value	Unit
Efficiency	96	%	Efficiency	93	%	Efficiency	100	%
θ	[4 125]	°	θ	[5, 155]	°	θ	[0,180]	°
dθ	2	mrad	dθ	2	mrad	mres	1	%
dϕ	2	mrad	dϕ	2	mrad	–	–	–
dp	1.5	%	dE	2	%	–	–	–
$p_{T,\mathrm{min}}$	20	MeV/c	E_{min}	0.02	GeV	–	–	–
dvtx [x,y,z]	0.1,0.1,0.1	cm	–	–	–	–	–	–

Signal Criterias

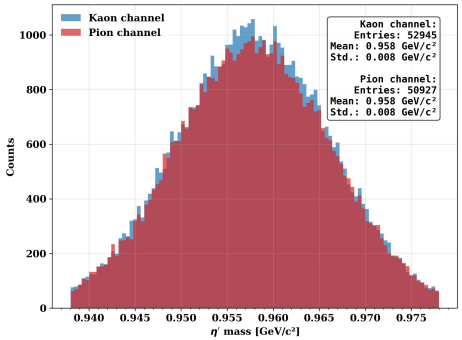
Simulation of 100.000 signal events using PANDA properties.

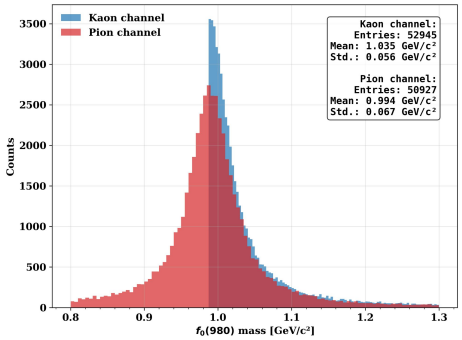
Number of tracks = 4 $p_T \geq 20$ MeV/c

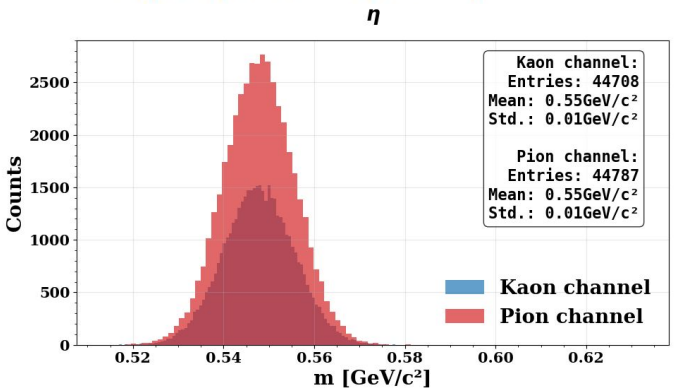
Number of photons ≥ 2 $E_\gamma \geq 50$ MeV

Window for composite particles:

$m(\eta') \in [938, 978]\ \mathrm{MeV}/c^2$ $m(f_0(980)) \in [800, 1300]\ \mathrm{MeV}/c^2$ $m(\eta) \in [500, 600]\ \mathrm{MeV}/c^2$

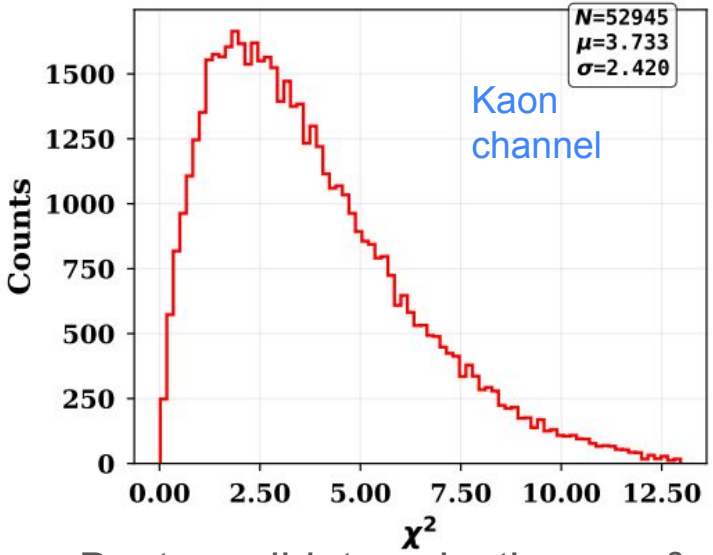


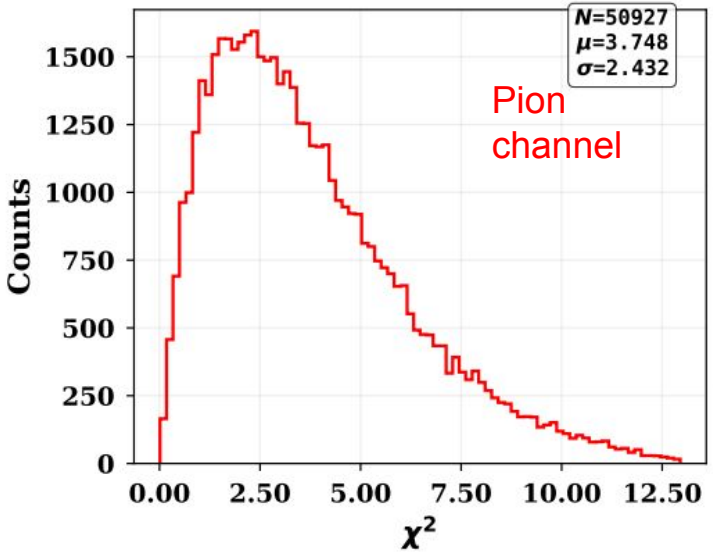




For Kaon channel: PID requirement: P(K) > P(π)

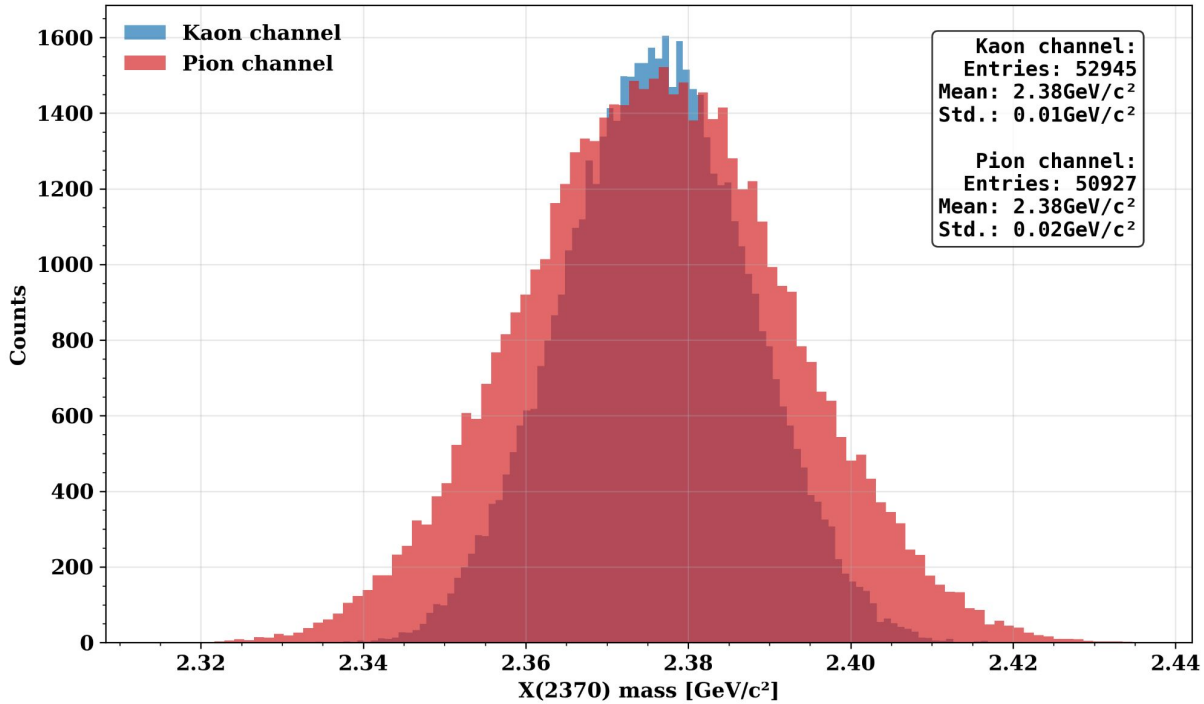
Kinematic fit with 4C





- Best candidate selection on χ^2 value
- Cut with $\chi^2 \leq 13$
- Reconstruction efficiency ~ 52.9% (K), ~ 50.9% (π)

Reconstruction of X(2370)



→ Resolution of the Pion channel is a bit worse due to large momenta

Background Analysis

- Simulation of 10^9 background events with DPM
- Split offs enabled
- Parallel reconstruction of both decay chains:

$$X(2370) \longrightarrow f_0(980)\,\eta'$$

$$f_0(980) \longrightarrow K^+K^- \qquad \eta' \longrightarrow \pi^+\pi^-\eta\,(\rightarrow \gamma\gamma)$$

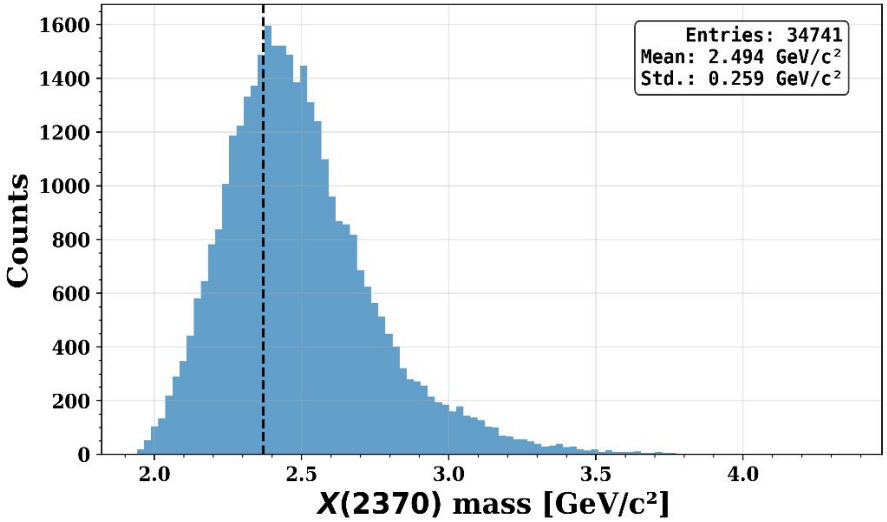
$$X(2370) \longrightarrow f_0(980)\,\eta'$$

$$f_0(980) \longrightarrow \pi^+\pi^- \qquad \eta' \longrightarrow \pi^+\pi^-\eta\,(\rightarrow \gamma\gamma)$$

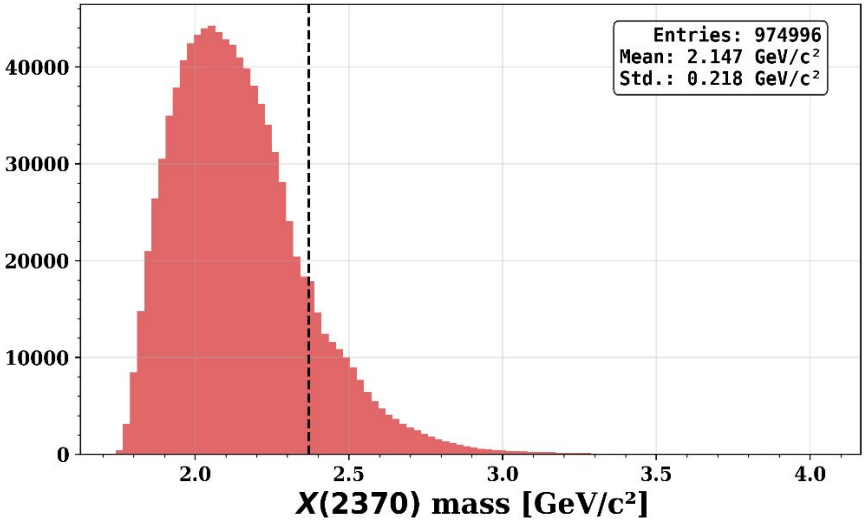
Background Distributions

10^9 events generated with split-offs
All candidates without any cuts applied

Kaon channel



Pion channel



Asymmetric distribution

Shifted distribution

Background Lists

10^9 events generated with split-offs

Pion channel background

Final State	Candidates [%]	Candidates	Events
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	44.5	434336	371234
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0$	14.8	144239	122612
$\pi^+\pi^+\pi^-\pi^-\pi^0$	13.6	132729	117381
$\pi^+\pi^+\pi^-\pi^-\pi^0\gamma\gamma$	5.6	54465	46213
$\pi^+\pi^+\pi^-\pi^-\pi^0\gamma$	3.6	35306	30872
$\pi^+\pi^-\pi^0\pi^0\pi^0$	3.3	32349	26609
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0\gamma$	2.6	25309	21486
$\pi^+\pi^-\pi^0\pi^0$	2.1	20227	17277
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0\gamma\gamma$	1.6	15881	13515
Others	6.3	61338	52239
$\pi^+\pi^+\pi^-\pi^-\gamma\gamma$	1.9	18817	16915

Kaon channel background

Final State	Candidates [%]	Candidates	Events
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	31.1	10816	9510
$\pi^+\pi^+\pi^-\pi^-\pi^0$	20.9	7265	6587
$K^+\pi^+K^-\pi^-\pi^0\pi^0$	6.5	2245	2018
$K^+\pi^+K^-\pi^-\pi^0$	6.0	2075	1861
$\pi^+\pi^-\pi^0\pi^0\pi^0$	4.6	1615	1349
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0$	4.4	1515	1331
$\pi^+\pi^+\pi^-\pi^-\pi^0\gamma$	3.1	1092	995
$\pi^+\pi^+\pi^-\pi^-\pi^0\gamma\gamma$	3.0	1036	904
$\pi^+\pi^-\pi^0\pi^0$	2.9	994	881
$\pi^+\pi^-\pi^0\pi^0$	2.4	827	691
Others	14.5	5037	2617
$K^+\pi^+K^-\pi^-\gamma\gamma$	0.6	224	213

Kinematic 4C and 5C (additional η mass constraint) fit of $\chi^2 \leq 13$

Pion channel Description	Amount [Ev]	Amount [%]
$\pi^+\pi^-\pi^0\pi^0$	8	0.5
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	18	1.1
$\pi^+\pi^+\pi^-\pi^-\pi^0\gamma$	74	4.6
$\pi^+\pi^+\pi^-\pi^-\gamma\gamma$	1501	93.8
Kaon channel $K^+\pi^+K^-\pi^-\gamma\gamma$	15	100

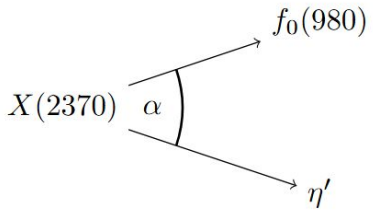
signal-like

Pion channel background reduced by ~ 99%, signal loss of ~ 0.15%

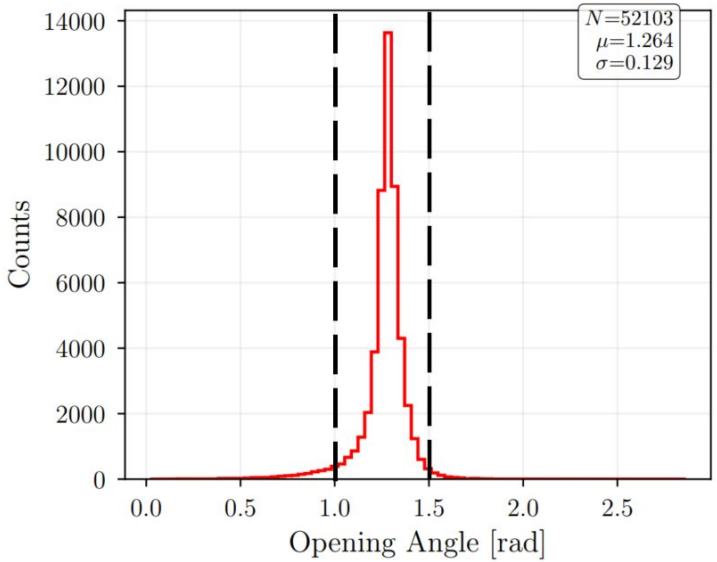
Kaon channel background reduced by ~99%, no signal loss

Opening Angle Cut

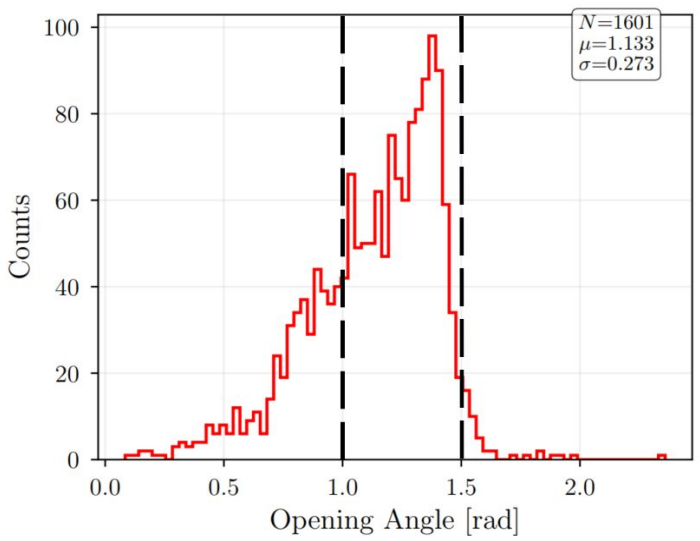
Pion Channel:



Signal



Background



Remaining background events

Pion channel Description	Amount [Ev]	Amount [%]
$\pi^+\pi^-\pi^0\pi^0$	5	0.45
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	15	1.36
$\pi^+\pi^+\pi^-\pi^-\pi^0\gamma$	53	4.82
$\pi^+\pi^+\pi^-\pi^-\gamma\gamma$	1027	93.36
Kaon channel $K^+\pi^+K^-\pi^-\gamma\gamma$	6	100

→ P(π) > P(e)

Kaon channel reconstruction efficiency is (56.212 ± 0.157)%

Pion channel reconstruction efficiency is (49.416 ± 0.158)%

Remaining Background Channels

Kaon channel:

$K^+K^-\pi^+\pi^-\gamma\gamma$ (signal-like)

Pion channel:

$\pi^+\pi^+\pi^-\pi^-\gamma\gamma$ (signal-like)

$\pi^+\pi^+\pi^-\pi^-\pi^0(->\gamma\gamma)\gamma$

$\pi^+\pi^+\pi^-\pi^-\pi^0(->\gamma\gamma)\pi^0(->\gamma\gamma)$

Both channels containing π^0 should be vetoed

→ Simultaneous reconstruction of signal and and background channels

Event is cut, if background reconstruction is fulfilled:

- Veto efficiency for the $\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$ channel: (31.91 ± 0.15)%
- Veto efficiency for the $\pi^+\pi^+\pi^-\pi^-\pi^0\gamma$ channel: (40.13 ± 0.16)%
- Signal efficiency loss of approximately $9.2\cdot10^{-5}$ %, which is negligible

Final Background Suppression

Description	Amount [Ev]	Generated [Ev]	Efficiency for signal hypothesis [%]
Pion channel			
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	10.214 ± 0.022	81664195	$(1.2507 \pm 0.0028) \cdot 10^{-5}$
$\pi^+\pi^+\pi^-\pi^-\pi^0\gamma$	31.73 ± 0.08	7767950	$(4.085 \pm 0.011) \cdot 10^{-4}$
$\pi^+\pi^+\pi^-\pi^-\gamma\gamma$	$1027 \pm 1.3 \cdot 10^{-6}$	5971595	$1.7198 \cdot 10^{-2} \pm 2 \cdot 10^{-11}$
Kaon channel			
$K^+\pi^+K^-\pi^-\gamma\gamma$	$6 \pm 1.1 \cdot 10^{-6}$	49800	$1.2048 \cdot 10^{-2} \pm 2 \cdot 10^{-7}$

Amount: Remaining background events after cuts
Generated: Total number of events in the 10^9 events sample

Cross Section Estimates

Taken from DPM from HepFastSim
Based on simulation data using DPM FullSim

Final state	σ [µb]	Efficiency [%]
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	5085.6862	1.250710^{-5}
$\pi^+\pi^+\pi^-\pi^-\pi^0\gamma$	326.5101	$4.085\ 10^{-4}$
$\pi^+\pi^+\pi^-\pi^-\gamma\gamma$	458.3179	$1.7198\ 10^{-2}$
$K^+\pi^+K^-\pi^-\gamma\gamma$	2.5226	1.204810^{-2}

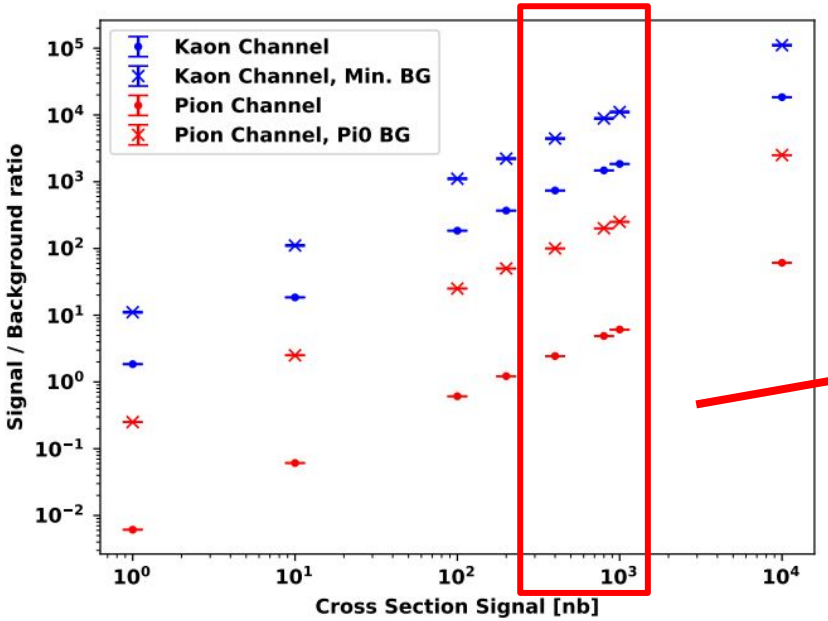
Kaon channel reconstruction efficiency is (56.212 ± 0.157)%

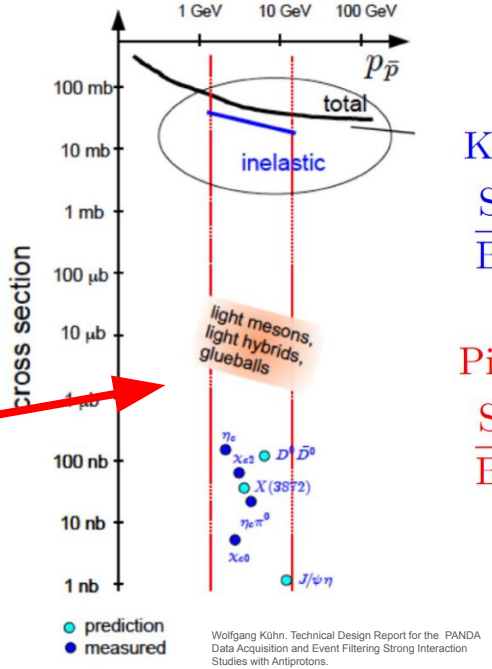
Pion channel reconstruction efficiency is (49.416 ± 0.158)%

Signal to background estimation

Including and excluding signal-like channels

Kaon channel: Single signal-like background event used as minimal background estimate





Wolfgang Kühn. Technical Design Report for the PANDA Data Acquisition and Event Filtering Strong Interaction Studies with Antiprotons.

Kaon channel:

$$\frac{S}{B} \quad 10^3 - 10^4$$

Pion channel:

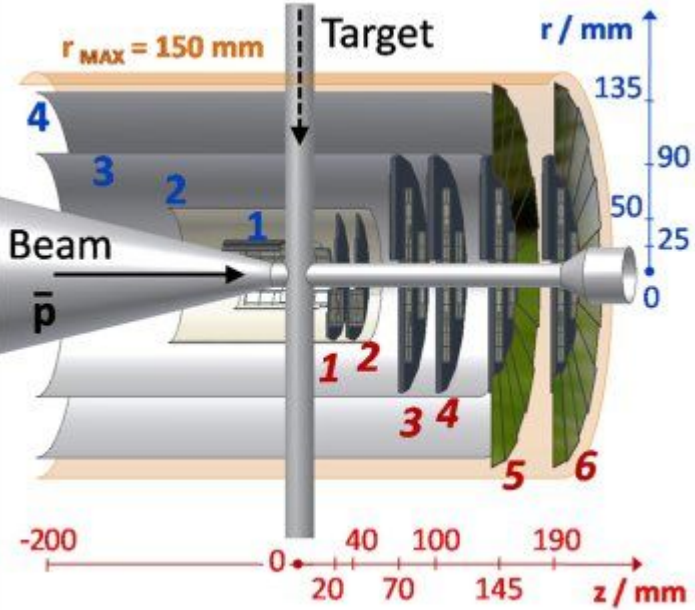
$$\frac{S}{B} \quad 10^0 - 10^2$$

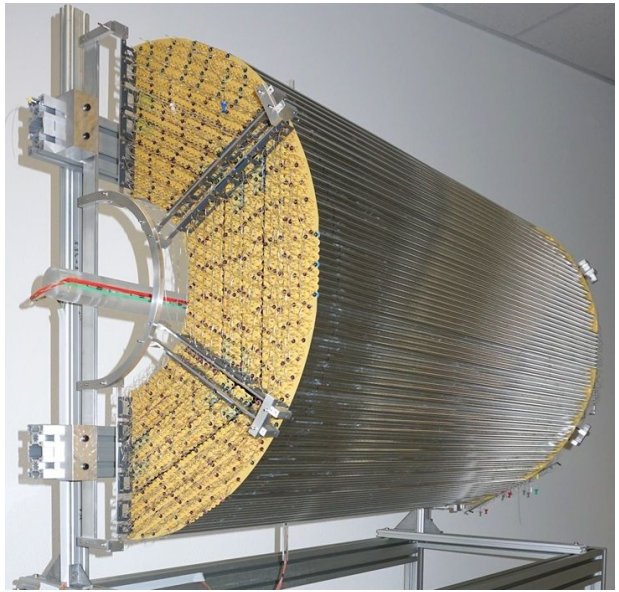
Resolution Studies

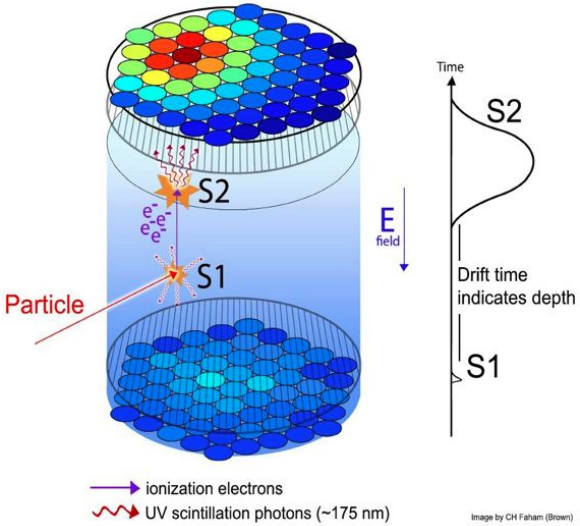
Multiple tracking detector options:

1. MVD (Microvertex detector)
2. Straw Tubes (STT)
3. Time Projection Chamber (TPC)

Important: HepFastSim does not model physical differences in detector response or detector-specific interaction effects.







One tracking detector

MVD-hvmaps			STT			TPC		
Parameter	Value	Unit	Parameter	Value	Unit	Parameter	Value	Unit
Efficiency	99	%	Efficiency	99	%	Efficiency	100	%
θ	[4, 125]	°	θ	[4, 125]	°	θ	[4, 125]	°
dθ	$\frac{9.95}{\sin(\theta)}$	mrad	dθ	2	mrad	dθ	4.9	mrad
dϕ	9.9	mrad	dϕ	2	mrad	dϕ	0.7	mrad
dp	0.9	%	dp	1.5	%	dp	1	%
$p_{T,\text{min}}$	20	MeV/c	$p_{T,\text{min}}$	20	MeV/c	$p_{T,\text{min}}$	0.01	MeV/c
dvtx [x,y,z]	0.1,0.1,0.1	cm	dvtx [x,y,z]	0.1,0.1,0.1	cm	dvtx [x,y,z]	0.015,0.015,0.1	cm

Micro-Vertex-Detector (MVD): simulation study
Straw Tube Tracker (STT): design report
Time-Projection-Chamber (TPC): prototype (2006-2011)

One EMC

PANDA EMC			BaBar EMC		
Parameter	Value	Unit	Parameter	Value	Unit
Efficiency	93	%	Efficiency	93	%
θ	[5, 155]	°	θ	[5, 155]	°
dθ	2	mrad	dθ	7	mrad
dϕ	2	mrad	dϕ	7	mrad
dE	2	%	dE	3	%
E_{min}	0.02	GeV	E_{min}	0.02	GeV

PANDA EMC: technical design report, $PbWO_4$

BaBar EMC: design and performance report, CsI

Results for Signal Reconstruction

100.000 signal events generated

	PANDA EMC		BaBar EMC	
Setup	Pion channel	Kaon channel	Pion channel	Kaon channel
MVD	55736	62694	50383	56947
STT	55662	62815	50266	56761
TPC	58207	66900	52820	60246

- MVD and STT similar
- TPC better ~ 4-6% due to higher efficiency
- Lower EMC resolution decreases the reconstruction by ~ 10%

Results for background channels

Pion channel

100 million background events generated

	MVD		STT		TPC	
Channel	PANDA EMC	BaBar EMC	PANDA EMC	BaBar EMC	PANDA EMC	BaBar EMC
$\pi^+\pi^+\pi^-\pi^-\gamma\gamma$	100	155	105	177	117	149
$\pi^+\pi^+\pi^-\pi^-\pi^0\gamma$	1	8	2	10	3	9
$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	1	3	1	4	0	6
Others	0	0	1	1	1	1

→ Mainly signal-like events, π^0 channels strong suppressed
Tracking detector: Only statistical fluctuations
EMC: resolution significant increase

Kaon channel

Only signal-like background → not considered

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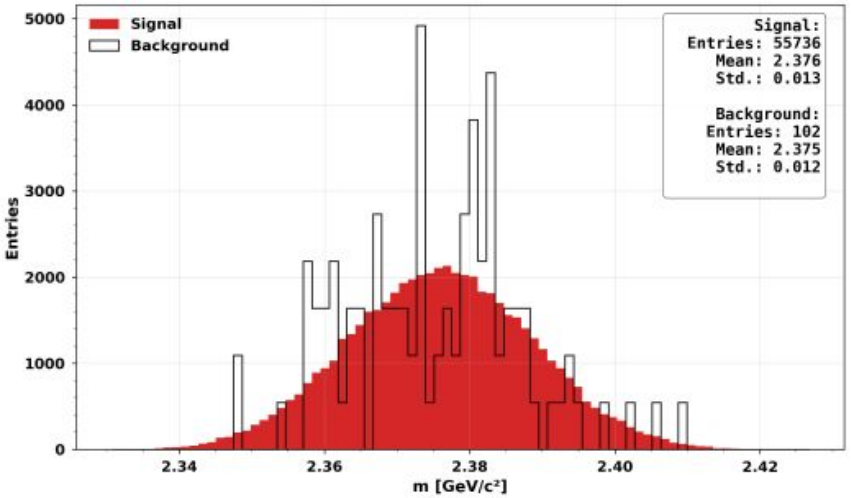
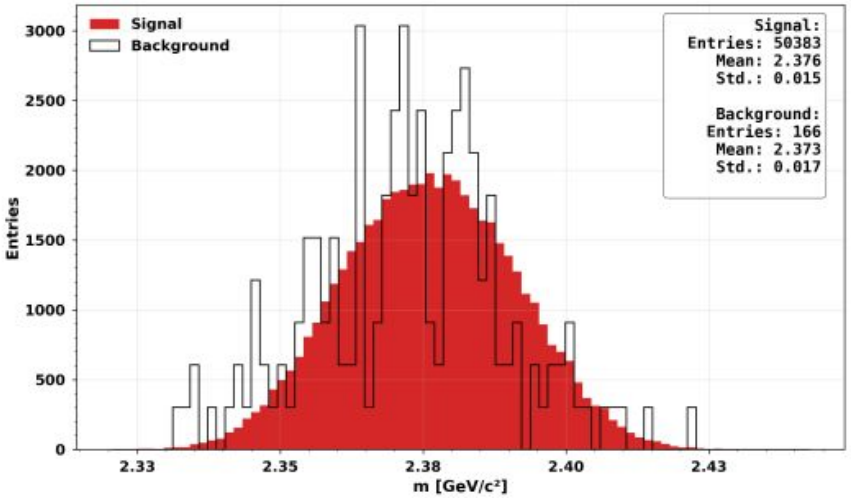
Pion channel

MVD with PANDA EMC



MVD with BaBar EMC



Background events normalized to number of signal events
Difference between signal and background distributions very similar

Conclusion

Detection of both channels feasible with tracking range [4,125]° and EMC range [5, 155]°
Reconstruction efficiency > 50% depending on setup

Kaon channel much cleaner (significantly smaller phasespace)
Pion channel background dominated by signal-like final states
→ Further methods e.g. amplitude analysis required

Signal to Background ratio above 1 for cross section estimates

High sensitivity to efficiency of components and low minimum p_T
Low sensitivity to tracking resolution
High sensitivity to EMC resolution for the efficiency of signal reconstruction and background suppression

Thank you for your attention!