Spin alignment of ϕ at BESIII and combined analysis in the open-strange channels of BESIII data

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Thesis Proposal Talk

2025.10.14

outline

- Work on spin alignment of ϕ measurement at BESIII
  - Introduction
  - Measurement of spin alignment
  - Systematic uncertainty
  - Summary
- Work on the open-strange channels of BESIII data
  - Introduction
- Summary and Prospects

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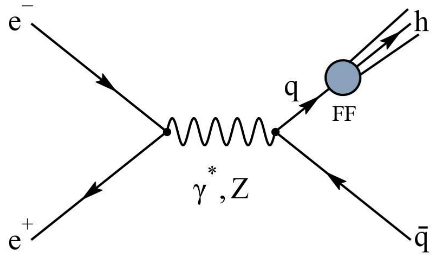
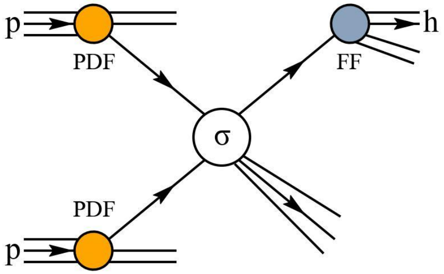
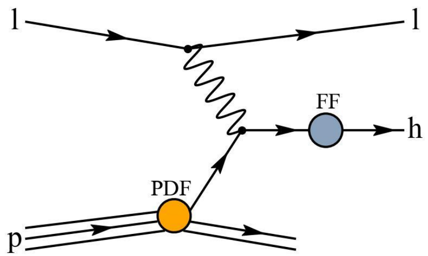
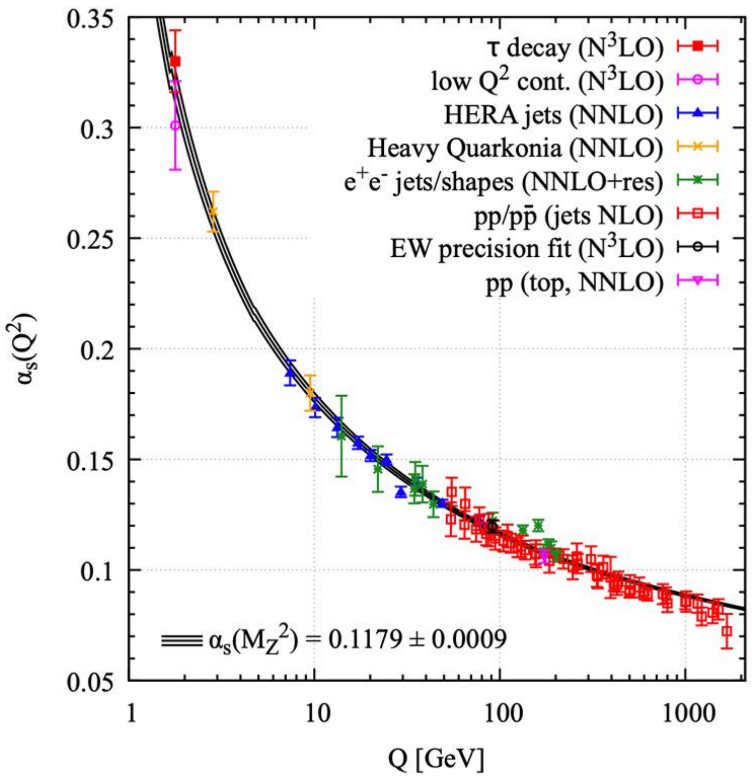
QCD

- QCD
  - High Q: asymptotic freedom, perturbative QCD
  - Low Q: non-perturbative QCD
- Color Confinement
  - Partons do not exist as free particles, but are confined in hadrons
- Fragmentation function $D_q^h(z)$
  - Probability that hadron h is found in the debris of a parton carrying a fraction z of parton's energy



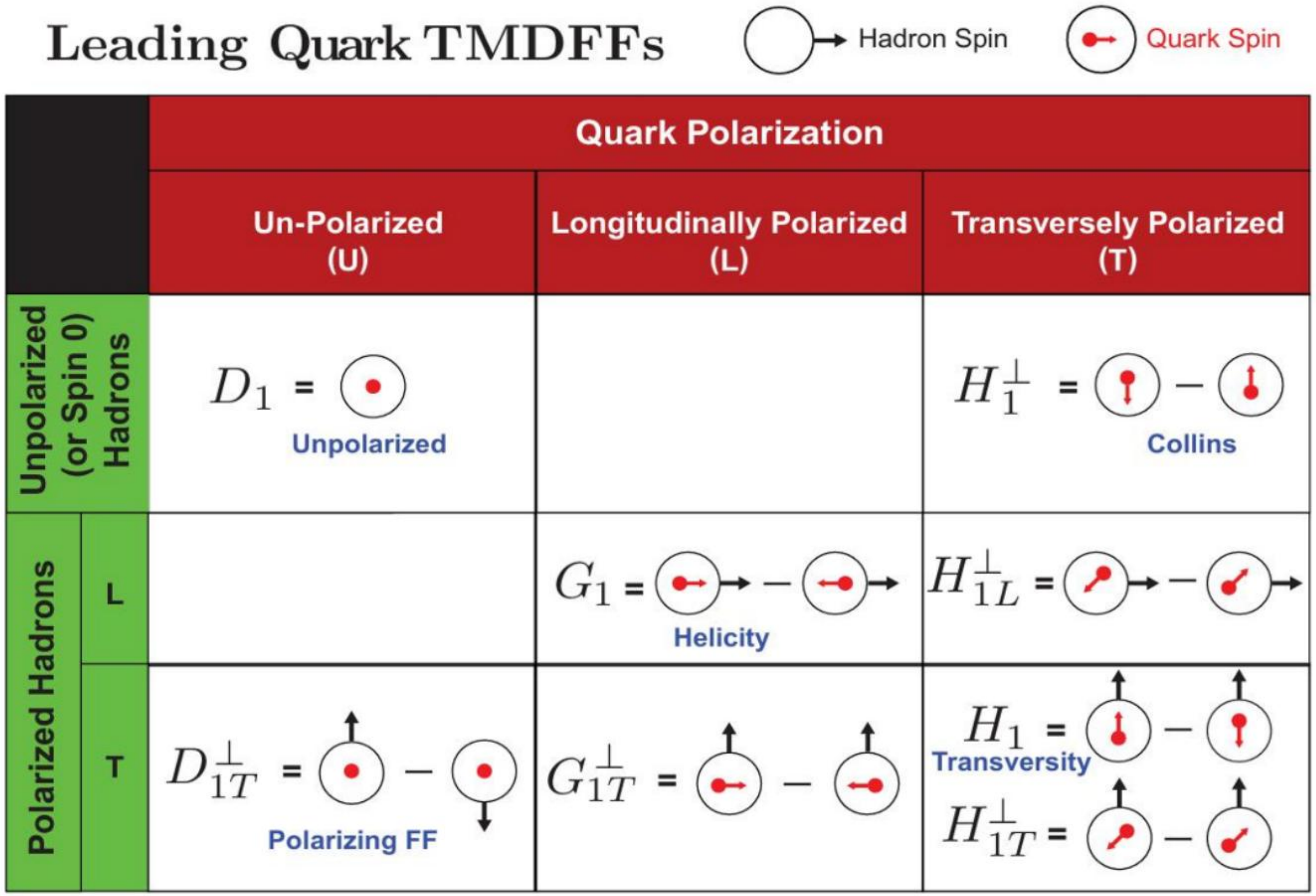






Fragmentation function

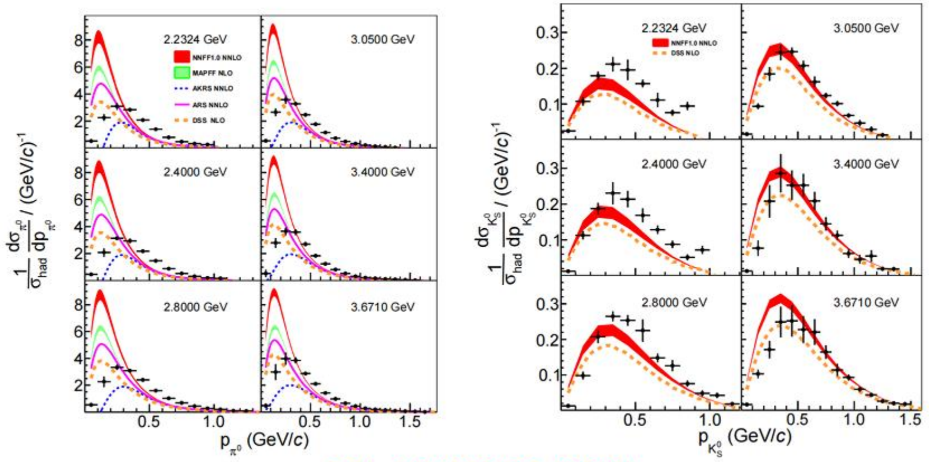
- Theoretically many more, in particular with polarized hadrons in the final state and transverse momentum dependence (TMD)



Study of Fragmentation Function

$$e^{+}e^{-} \rightarrow h + X$$

- **Spin-0** scalar meson FF(e.g., π, K, η)
  - Systematically measured at BESIII
- **Spin-dependence** FF(vector meson or baryon)
  - Spin: fundamental property of particles
  - Spin effect in hadronization
- How does the spin carry infomation at hadronization
  - Spin-1/2: polarzation
  - Spin-1: **spin alignment**



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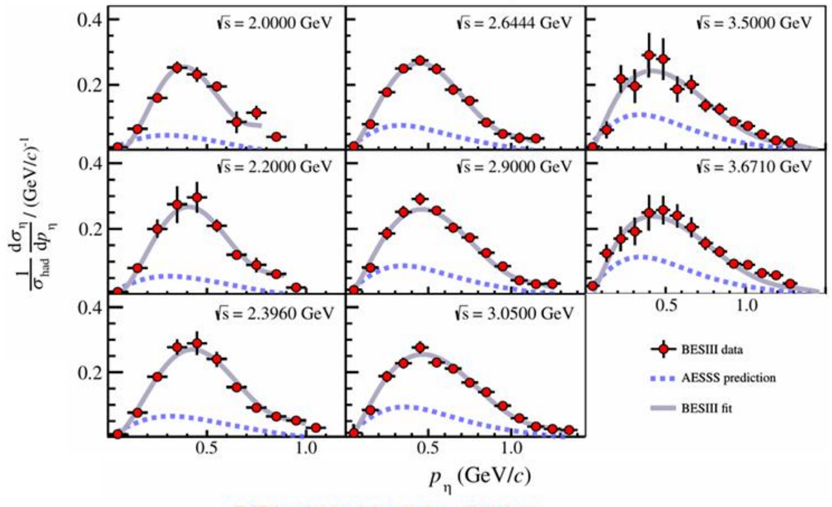

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Spin density matrix of vector meson

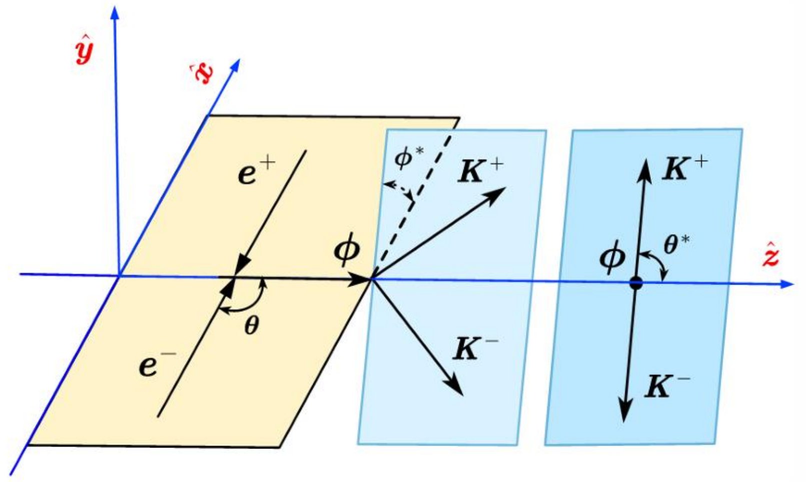
- The spin state of a vector state is described by 3×3 spin density matrix
  - ρ_{mm}: probability to be in $|s; s_z = m\rangle$ state
  - $\rho_{00} \neq 1/3$:spin alignment

$$\begin{pmatrix} \rho_{-1,-1} & \rho_{-1,0} & \rho_{-1,1} \\ \rho^*_{-1,0} & \rho_{00} & \rho_{01} \\ \rho^*_{-1,1} & \rho^*_{01} & \rho_{11} \end{pmatrix}$$

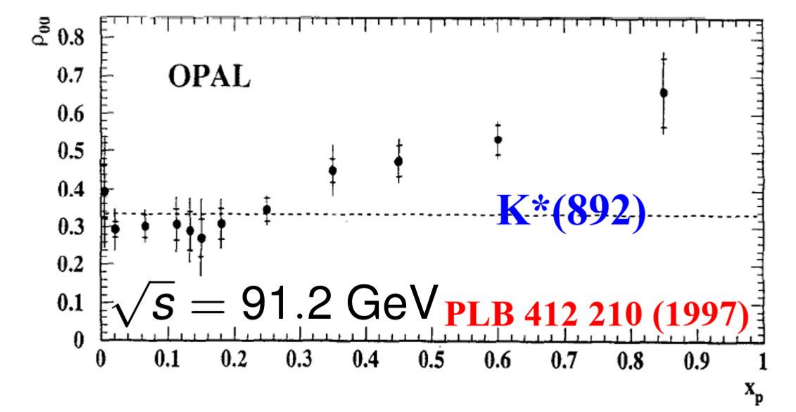
- The angle distribution of decay particle(kaon) at ϕ helicity frame:
  - extract spin density matrix elements, e.g. ρ_{00}

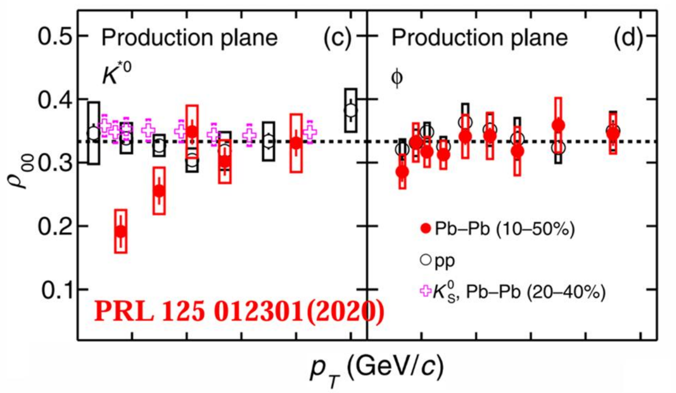
$$\begin{aligned}\frac{dN}{d\cos\theta^\star d\phi^\star} &= \frac{3}{4\pi}[\frac{1}{2}(1-\rho_{00}) + \frac{1}{2}(3\rho_{00}-1)\cos^2\theta^\star \\ &-\mathrm{Re}\rho_{1-1}\sin^2\theta^\star\cos 2\phi^\star - \frac{1}{\sqrt{2}}\mathrm{Re}(\rho_{10}-\rho_{0-1})\sin 2\theta^\star\cos\phi^\star \\ &+\mathrm{Im}\rho_{1-1}\sin^2\theta^\star\sin 2\phi^\star + \frac{1}{\sqrt{2}}\mathrm{Im}(\rho_{10}-\rho_{0-1})\sin 2\theta^\star\sin\phi^\star]\end{aligned}$$

$$\Longrightarrow \boxed{\frac{dN}{d\cos\theta^\star} = \frac{3}{4}[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^\star]}$$

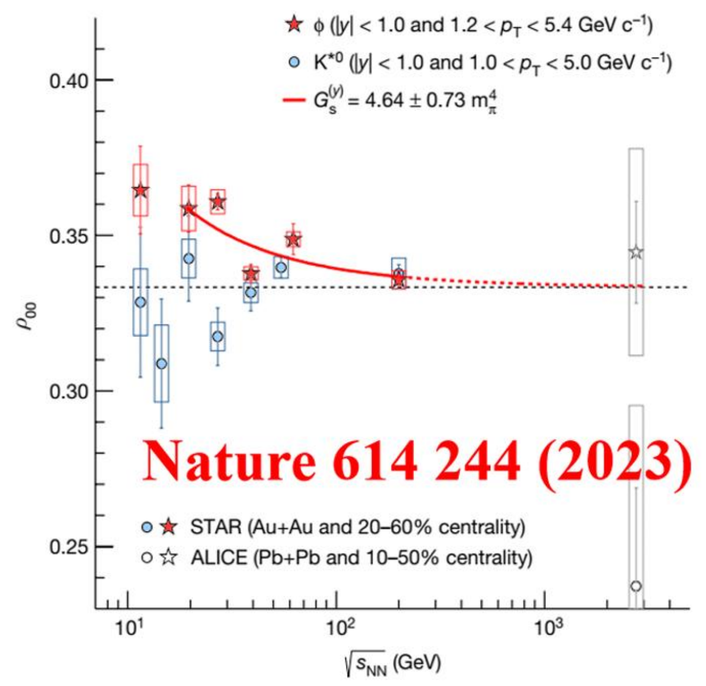


ρ_{00} of vector meson

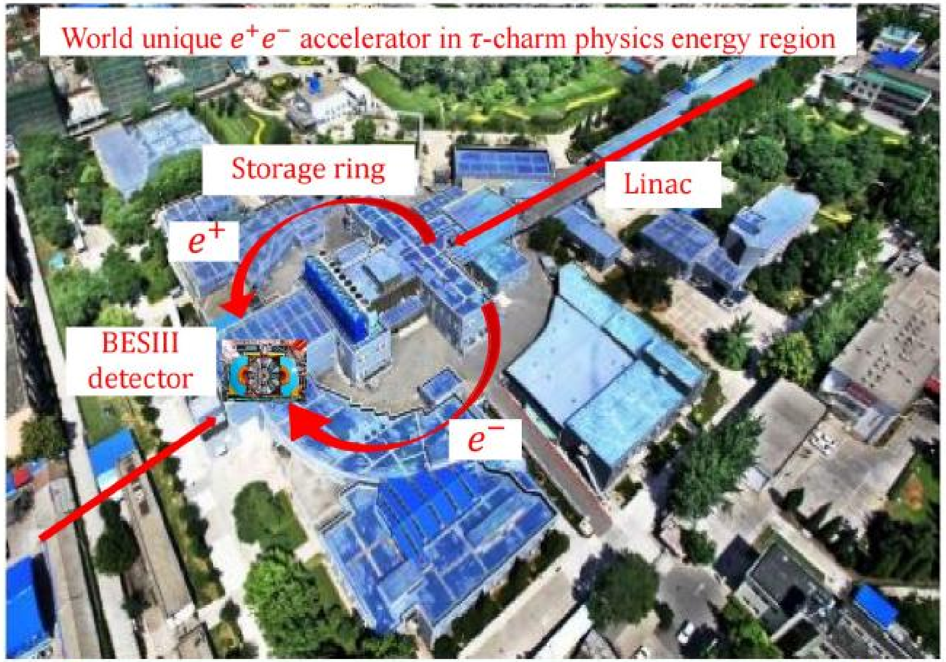




- Heavy ion collision: contribution from QGP(Quark-Gluon Plasma) & spin-orbital coupling
  - STAR: for ϕ unexpectedly large than 1/3
- e^+e^- collision: contribution from fragmentation, Z^0 dominant
  - LEP: in high x_p region, shows spin alignment
- pp collision: contribution from PDF fucntion & fragmentation
  - ALICE: for ϕ and K^* are consistant with 1/3
- **BESIII**:e^+e^-collision, fragmentation, γ^* dominant



BEPCII and BESIII



Double rings

$E_{cm} = 1.84 - 4.95$ GeV

Peak luminosity @$E_{cm} = 3.773$ GeV:

1.1×10^{33} cm^{-2}s^{-1}

Circumference: 237.53 m

Crossing angle: 2×11 mrad

Electromagnetic Calorimeter

CsI(Tl): L=28 cm

Barrel σ_E=2.5%

Endcap σ_E=5.0%

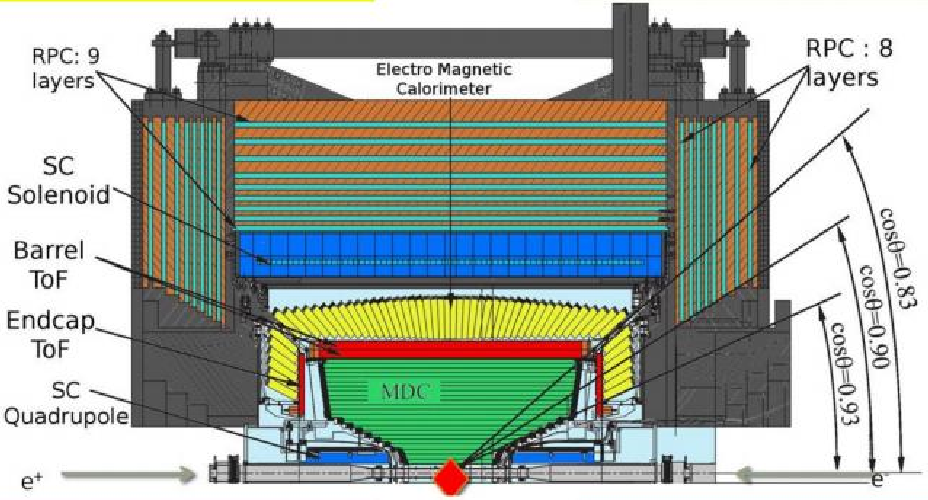
Muon Counter

RPC

Barrel: 9 layers

Endcap: 8 layers

$\sigma_{spatial}$: 1.48 cm



Main Drift Chamber

Small cell, 43 layer

σ_{xy}=130 μm

dE/dx~6%

σ_p/p= 0.5% at 1 GeV

Time Of Flight

Plastic scintillator

σ_T(barrel): 68 ps

σ_T(endcap): 110 ps

(update to 60 ps with MRPC)

Event selection

- Physical process: $e^{+}e^{-} \rightarrow \phi + X$
  - Data sets: 3 energy points, 3.08-3.65 GeV, 985.0 pb^{-1}
- MC
  - Hadronic MC: 50M at each point
  - QED MC
- Event selection
  - Same as R-value analysis
- PID (dE/dx + ToF)
  - Prob.(K)>Prob.(π/p)/0.001
- $\mathrm{N}(K^{+}) \geq 1$ and $\mathrm{N}(K^{-}) \geq 1$

Track Level

- **Veto Bhabha and Di-gamma events**
  - $N_{\text{shower}} \geq 2$
  - $E_1 \geq E_2 \geq 0.65 E_{\text{beam}}$
  - $|\Delta\theta| = |\theta_1 + \theta_2 - 180°| < 10°$
- **Isolated photon**
  - Energy deposition should be larger than 0.1 GeV
  - Angle from the nearest charged track should be larger than 20°
  - $0 < T_{\text{EMC}} < 700$ ns
- **Good charged hadronic tracks**
  - $|V_r| < 0.5$ cm , $|V_z| < 5.0$ cm , $|\cos\theta| < 0.93$
  - $p_{\text{track}} < 0.94 p_{\text{beam}}$, where $p_{\text{beam}} \approx E_{\text{beam}}$
  - $\chi_{\text{prob.}} = \left(\mathrm{d}E/\mathrm{d}x_{\text{measure}} - \mathrm{d}E/\mathrm{d}x_{\text{proton}}\right) / \sigma_{\text{proton}} > 10$
  - Remove charged tracks when $E/p > 0.8$ and $p > 0.65 p_{\text{beam}}$
  - Veto γ-conversions when $M(e^{+}e^{-}) < 0.1$ GeV and $\theta_{ee} < 15°$

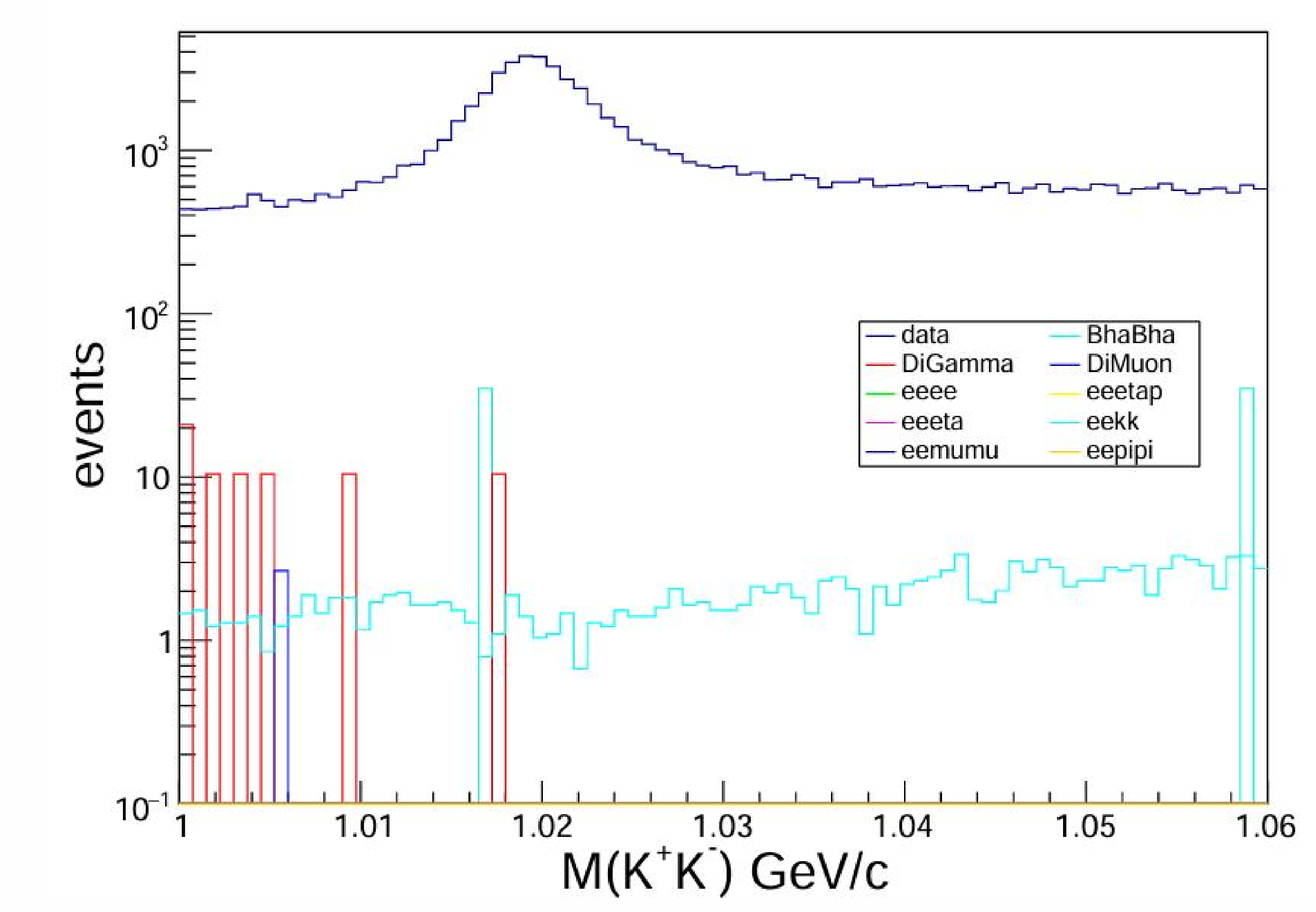
Event Level

At least 2 good charged hadronic tracks

- **Number of good charged hadronic tracks = 2:**
  - $|\Delta\theta| = |\theta_1 + \theta_2 - 180°| > 10°$ or $|\Delta\phi| = ||\phi_1 - \phi_2| - 180°| > 15°$
  - At least 2 isolated photons
- **Number of good charged hadronic tracks = 3:**
  - The two highest momentum tracks are required not back-to-back: $|\Delta\theta| = |\theta_1 + \theta_2 - 180°| < 10°$ or $|\Delta\phi| = ||\phi_1 - \phi_2| - 180°| < 15°$
  - (number of track with $E/p > 0.8$) ≤ 1
  - (number of track with PID ratio > 0.25) ≤ 1, where the PID ratio is defined as $r_{\text{PID}} = \frac{\text{Prob.}(e)}{\text{Prob.}(p)+\text{Prob.}(K)+\text{Prob.}(\pi)+\text{Prob.}(e)}$
- **Number of good charged hadronic tracks ≥ 4:**
  No additional requirements

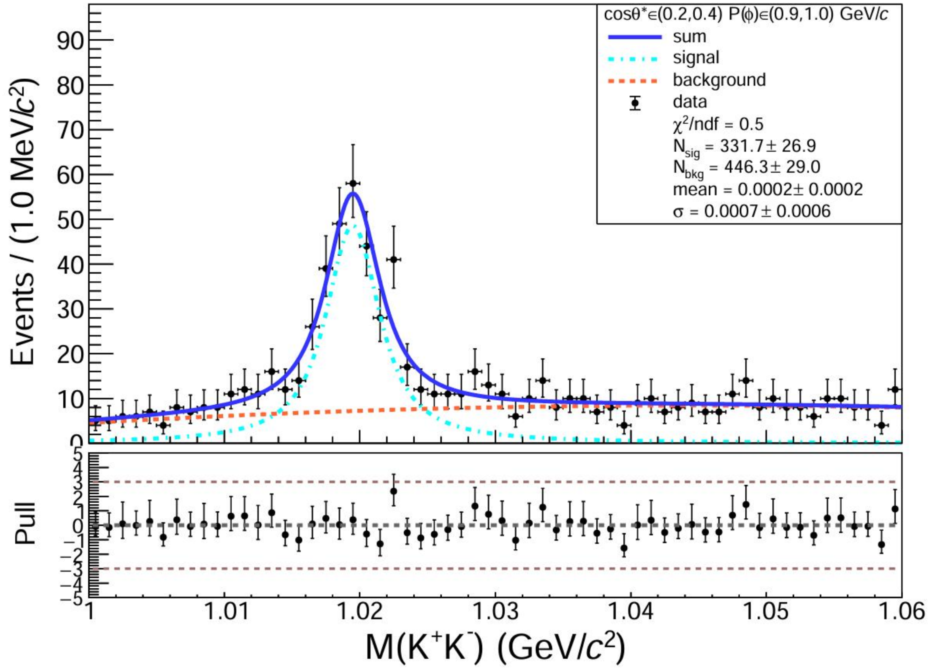
QED background

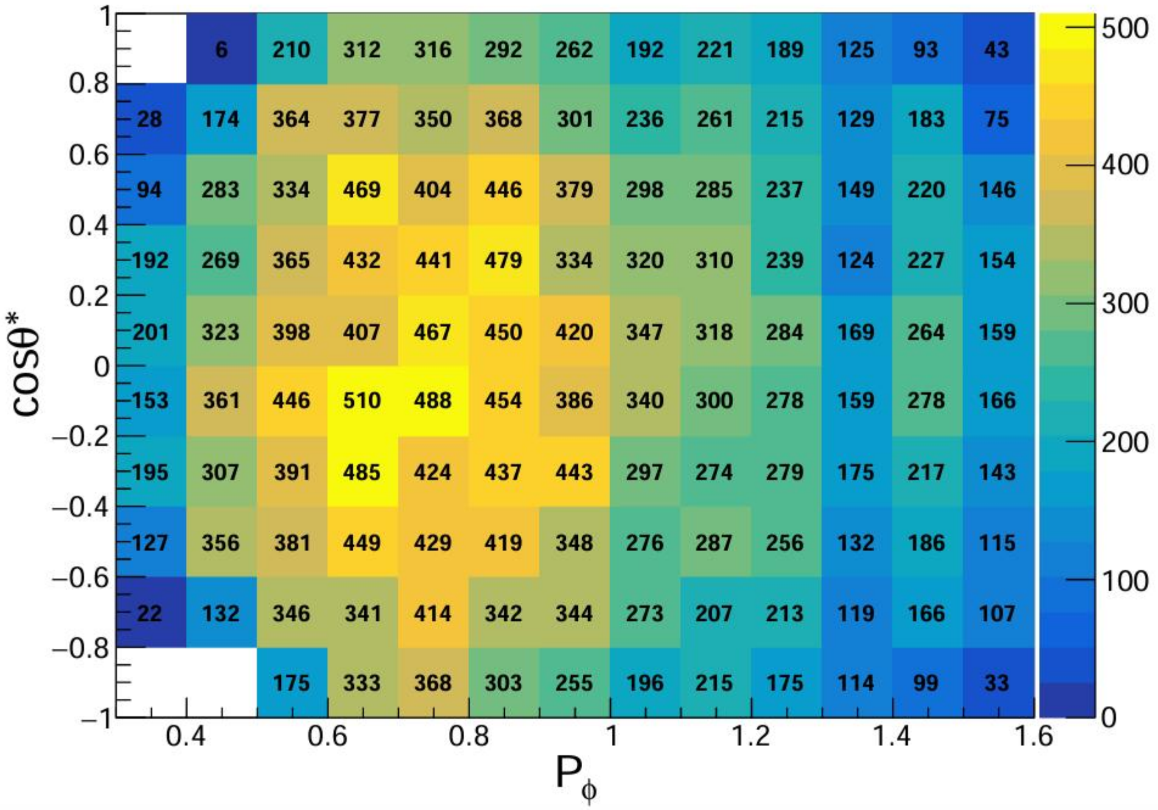
- The QED background which contribute to inclusive ϕ is less than1%



Signal extraction

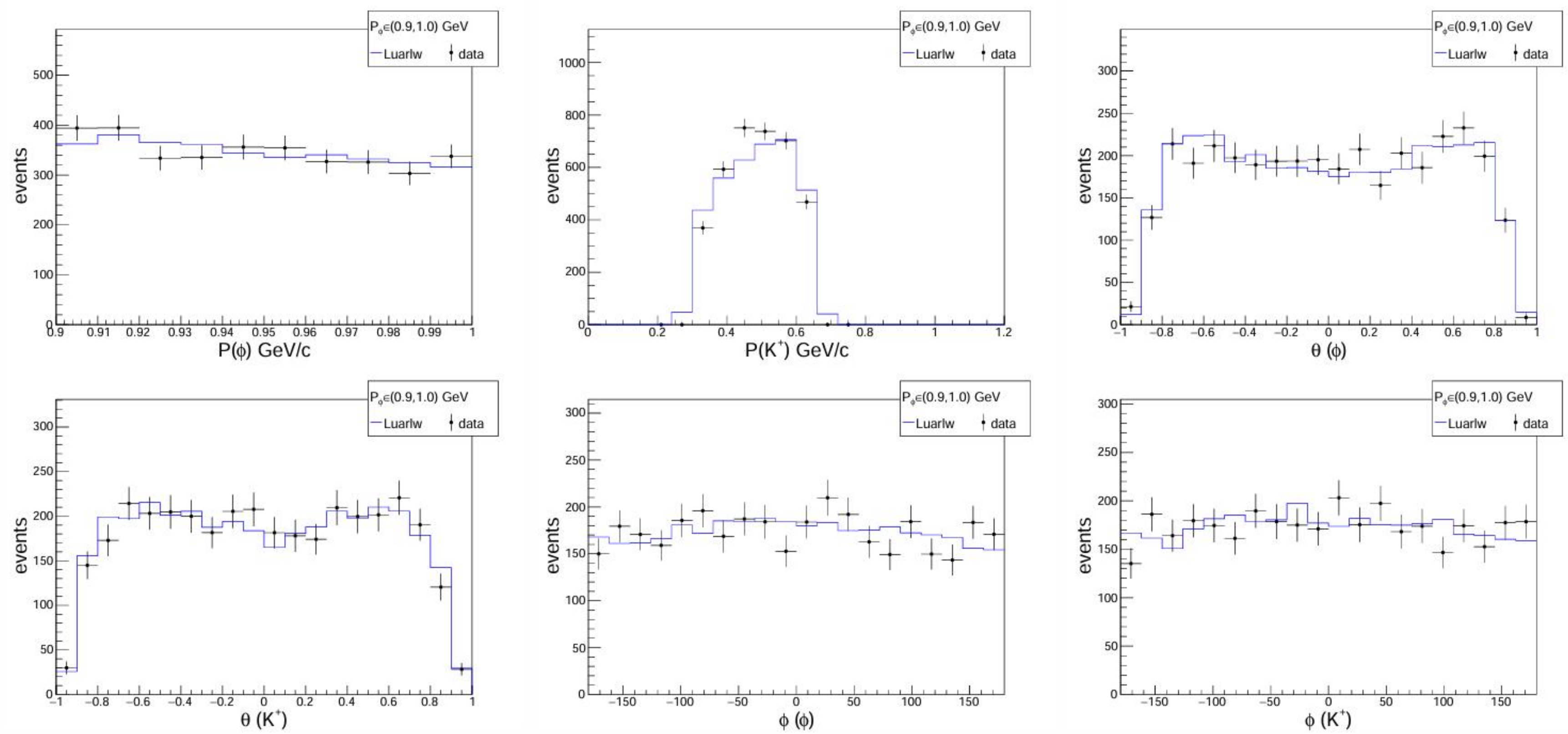
- No peaking background in $M(K^+K^-)$ spectrum
- Unbinned maximum-likelihood fit
  - Signal: Breit-Wigner ⊗ Gaussian
  - Background: 2th-order Chebyshev polynomial
  - Parameter of Breit-Wigner fixed to ϕ's PDG values





Comparison between data and MC

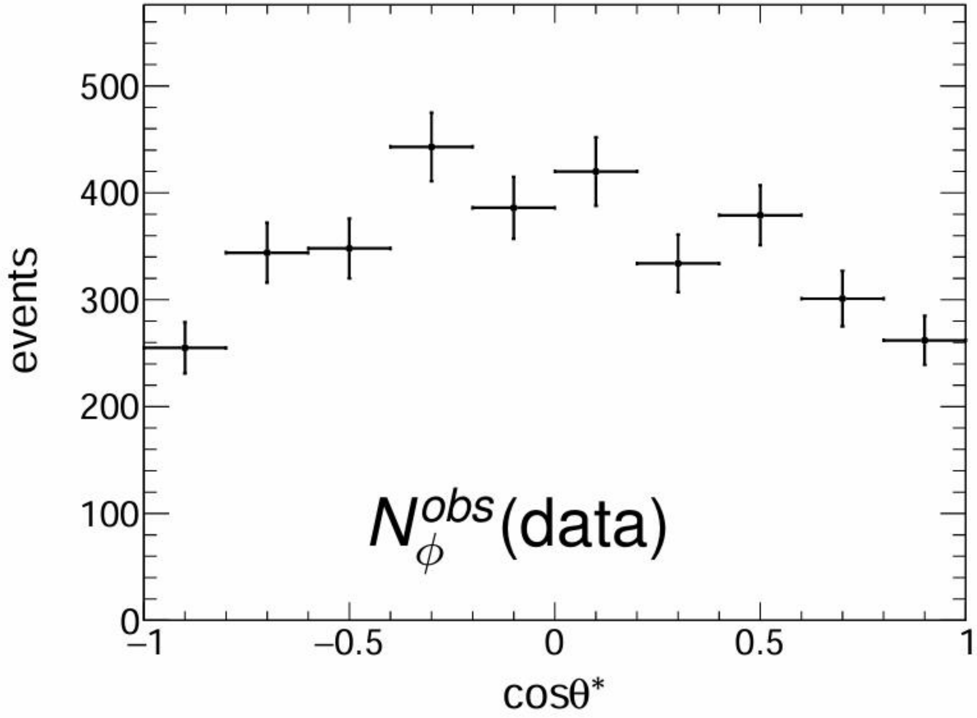
- sPlot method for data to extract ϕ distributionm
- MCtruth-match for MC to extract ϕ distribution



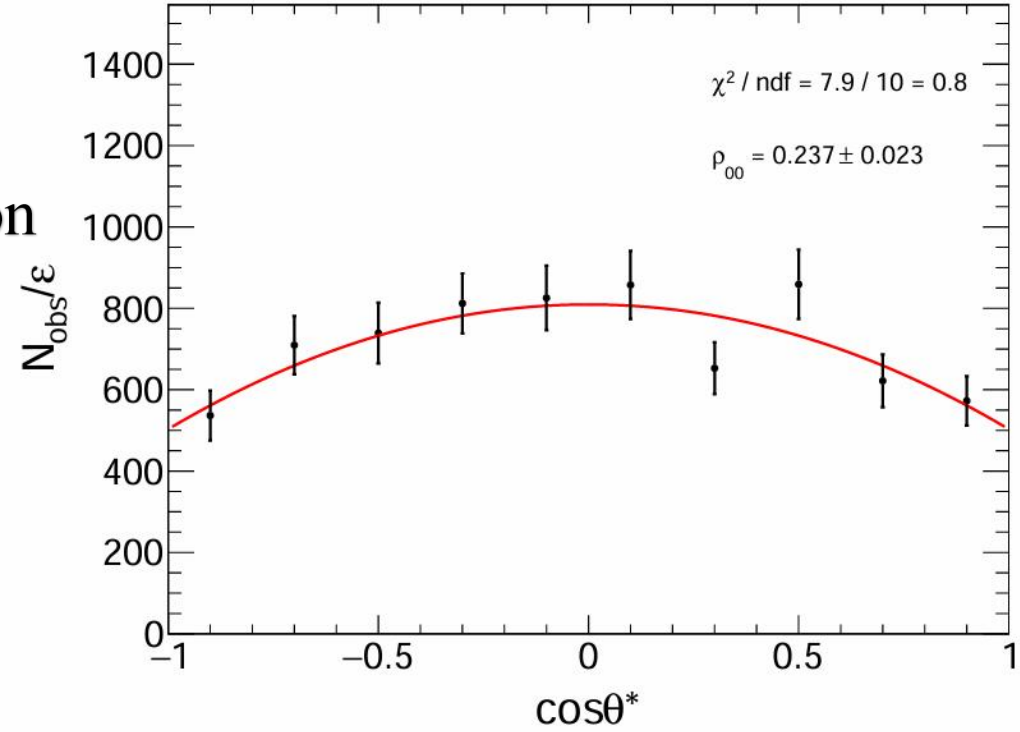
ρ_{00} extraction while $\boldsymbol{p_\phi}$@(0.9,1.0)GeV/c

- Extract the ρ_{00} from angular distribution

$$W(\theta^*)=\frac{3}{4}[(1-\rho_{00})+(3\rho_{00}-1)\cos^2\theta^*]$$



MC correction

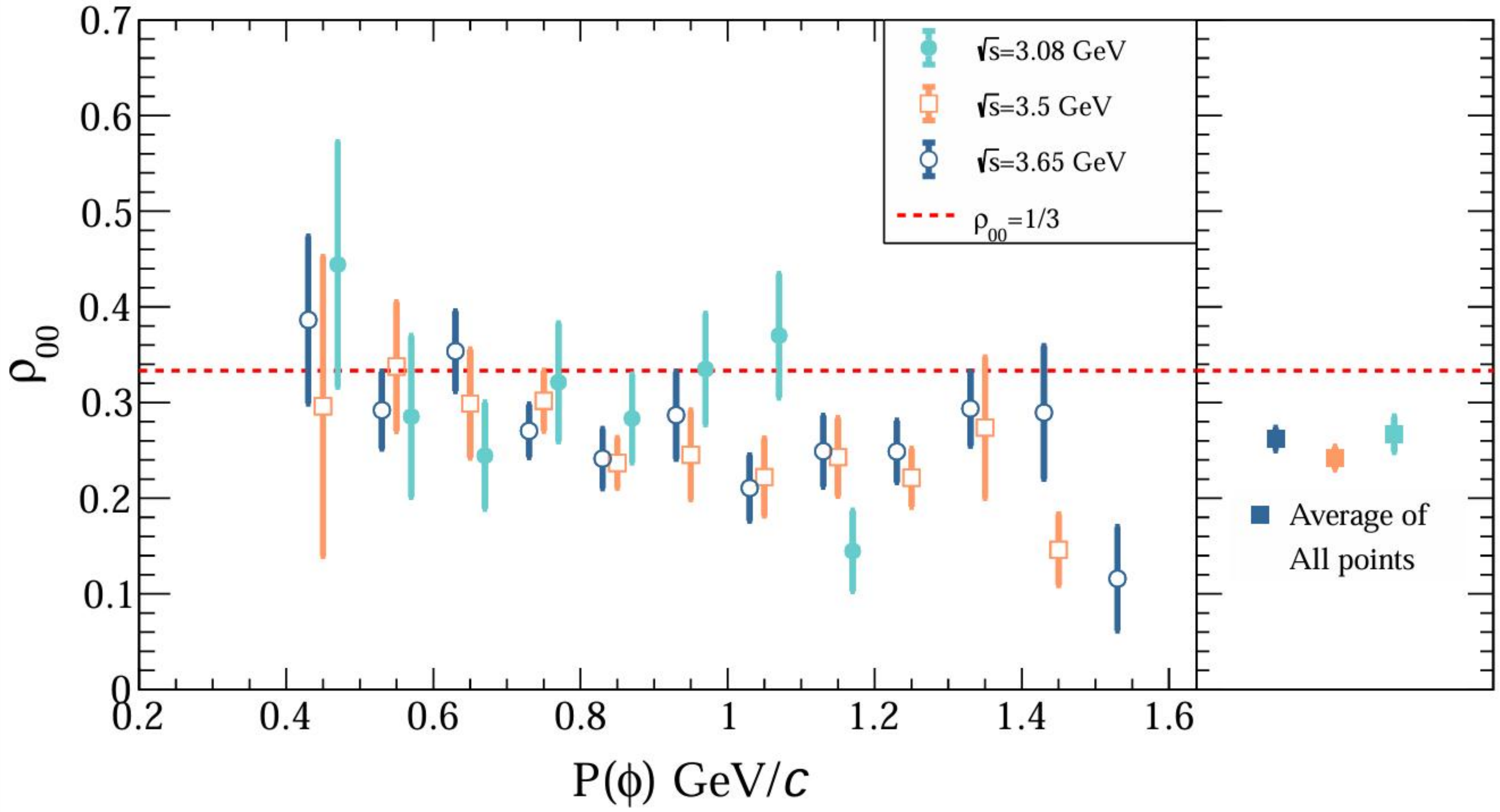


Systematic uncertainty for $\sqrt{s} = 3.5$ GeV

P_ϕ (GeV/c)	Hadron sel.	Sig.	Bkg.	beam	track	PID	MC model	Total
0.4-0.5	13.5%	6.1%	24.6%	24.4%	2.0%	2.0%	28.6%	47.3%
0.5-0.6	4.0%	7.6%	15.3%	0.8%	2.0%	2.0%	5.9%	18.7%
0.6-0.7	1.3%	3.3%	13.2%	1.9%	2.0%	2.0%	10.1%	17.3%
0.7-0.8	2.0%	1.0%	1.7%	5.0%	2.0%	2.0%	4.6%	7.7%
0.8-0.9	1.8%	2.2%	2.7%	4.2%	2.0%	2.0%	2.9%	6.9%
0.9-1.0	1.6%	16.4%	1.1%	1.7%	2.0%	2.0%	1.7%	16.9%
1.0-1.1	3.4%	1.6%	13.7%	0.9%	2.0%	2.0%	1.5%	14.5%
1.1-1.2	4.0%	3.8%	6.6%	1.9%	2.0%	2.0%	10.4%	13.3%
1.2-1.3	4.6%	1.7%	0.9%	3.5%	2.0%	2.0%	3.7%	7.5%
1.3-1.4	4.8%	4.2%	4.3%	16.6%	2.0%	2.0%	12.7%	22.3%
1.4-1.5	9.2%	0.1%	2.9%	6.7%	2.0%	2.0%	13.6%	18.2%

Summary for ρ_{00} measurement

- Spin alignment of ϕ is studied with total 985 pb^{-1} at $\sqrt{s}$ =3.08, 3.5 and 3.65 GeV
- Obtained 5σ statistical significance on spin alignment



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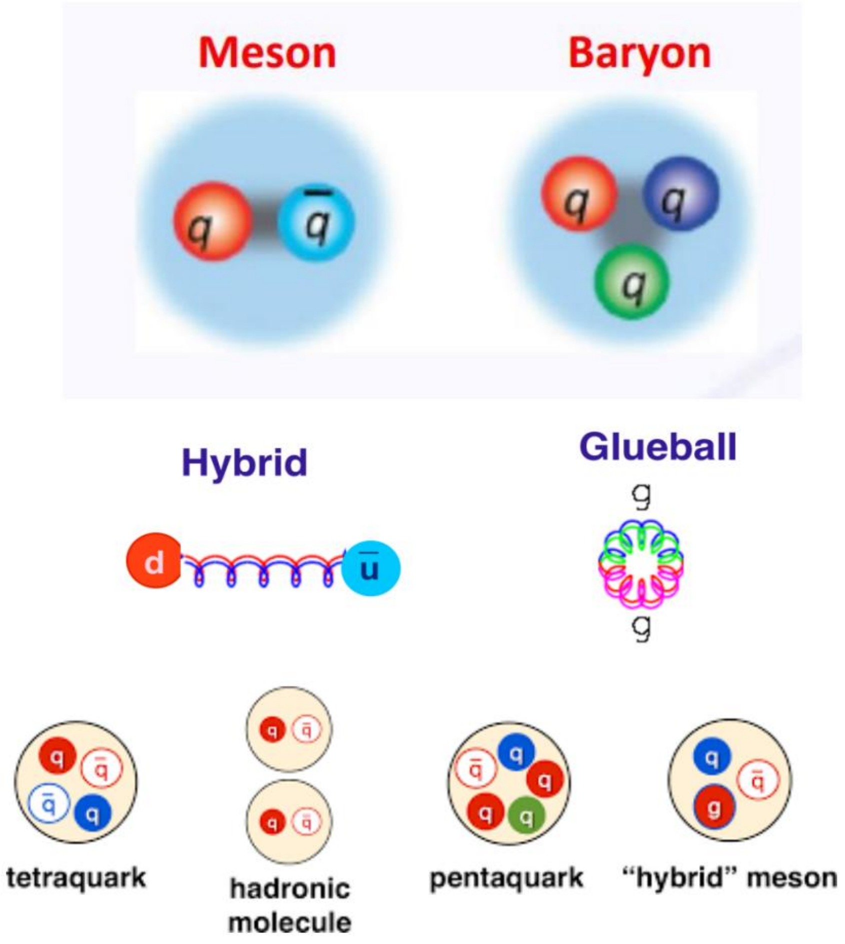
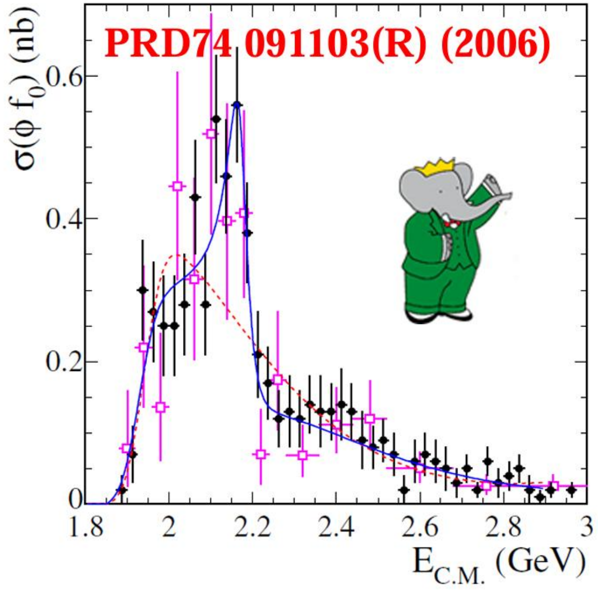
Forms of Hadrons

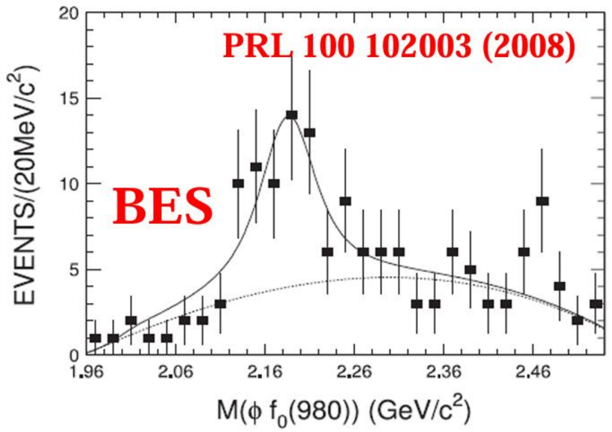
- **Normal Hadrons**
  - Meson: 2 quarks (qq-bar)
  - Baryon: 3 quarks (qqq)
- **Other configurations**
  - Glueball: Nquarks = 0 (gg, ggg, ...)
  - Hybrid: Nquarks = 2 (or more)
  - Multiquark state
  - Molecule
  - .....

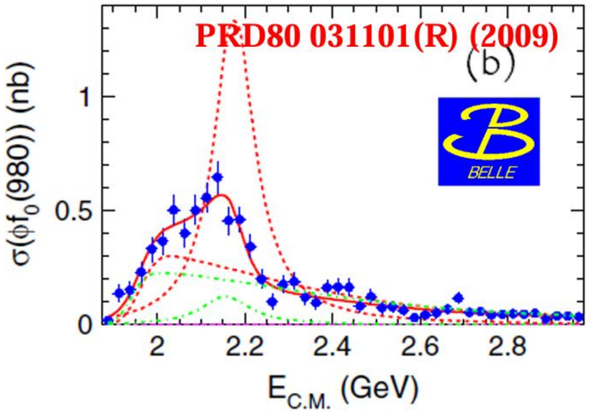


ϕ(2170)

- ϕ(2170) is discoverd at 2006 by BaBar
- Theorists explain ϕ(2170) as:
  - 2^3D_1 or 3^3S_1 $s\bar{s}$
  - $s\bar{s}g$ hybrid
  - tetraquark
  - molecularstate $\boldsymbol{\Lambda\bar{\Lambda}}$
  - .....
- Nature of ϕ(2170)?

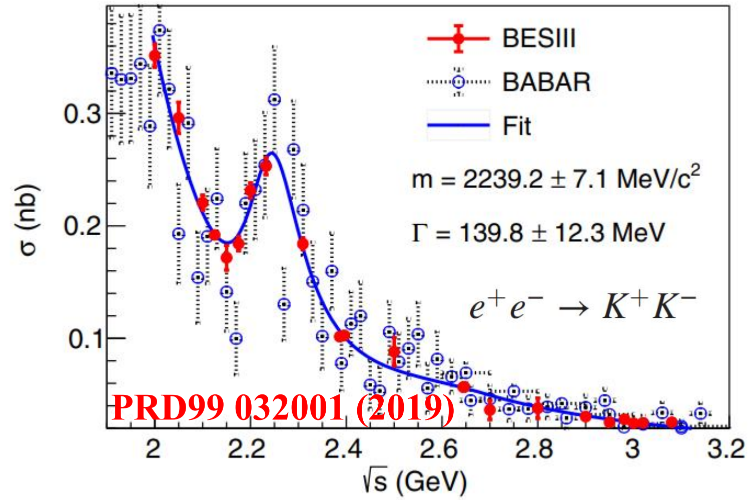


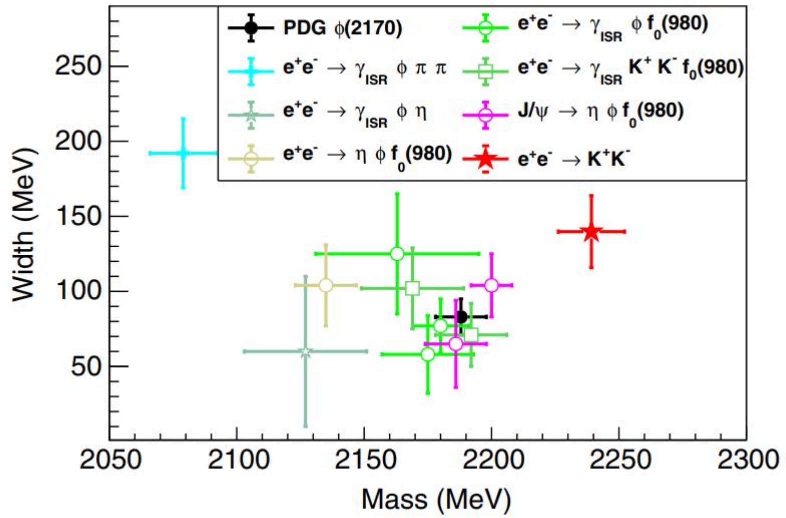




ϕ(2170)

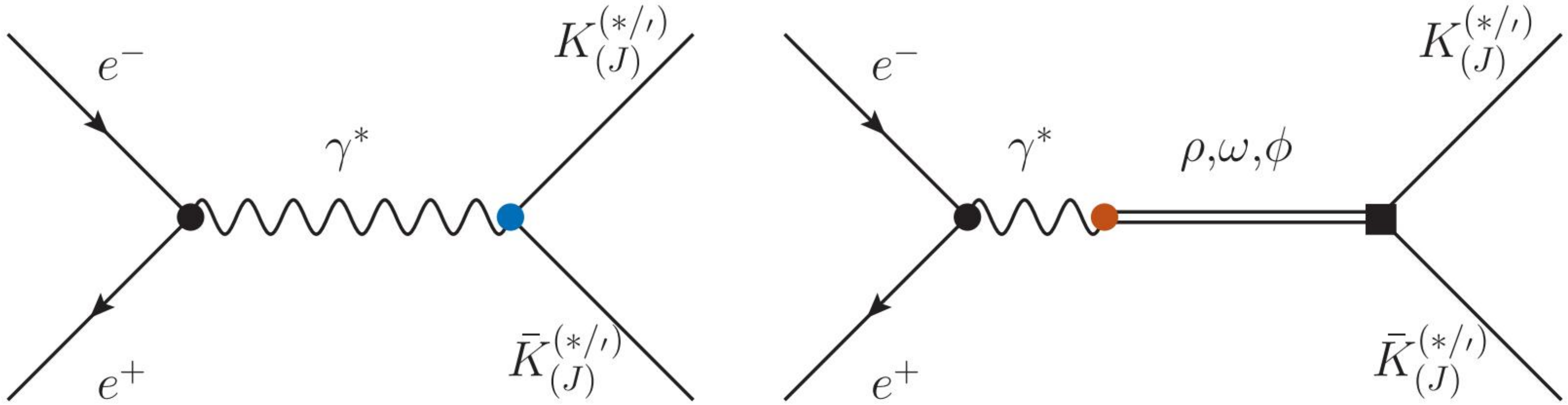
- $s\bar{s}g$ hybrid
  - K^+K^- channels strongly suppressed
- $s\bar{s}$ state
  - Theoretical total widths: 200-400 MeV
- Mass deviation in different measurements
  - Contribution of $\omega^*/\rho^*/\phi^*$
  - Only one Breit-Wigner fit involved
- **Combined fit to open-strange channels is needed**





Open-strange channels

- Open-strange process
  - A process with a strange quark/antiquark in the final state
- Present measurement data collects:
  - $e^+e^- \to K^+K^-$ $\qquad e^+e^- \to K\bar{K}^*$+c.c. $\qquad e^+e^- \to K^{*+}K^{*-}$+c.c.
  - $e^+e^- \to K_1(1270)^+K^-$ $\qquad e^+e^- \to K_1(1400)^+K^-$ $\qquad e^+e^- \to K_2^*(1400)\bar{K}$+c.c.
  - $e^+e^- \to K_1(1460)^+K^-$



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Summary and Prospects

- ☐ **Study of spin alignment of ϕ at BESIII**
  - ✓ Memo reviewed in collaboration

- ☐ **Combined fit to the open-strange channels**
  - ✓ present measurement data is collected
  - ☐ Prospect: Prepare a combined fit to the data