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Forschungszentrum Jülich (DE)

Perspectives of Open Charm Physics at $\bar{P}$ANDA

Hirschegg 2014

Hadrons from Quarks and Gluons

International Workshop XLII on Gross Properties of Nuclei and Nuclear Excitations
Hirschegg, Kleinwalsertal, Austria, January 12 - 18, 2014

Outline

- Introduction

- Why the interest in charm physics
  - Strong interactions
    - QCD
    - Intermediate case between heavy and light quarks
    - Spectroscopy
    - Strong decay modes

  - Weak interactions
    - CP violation
    - Mixing
    - Possible window to search for New Physics beyond the Standard Model

- Future experiments: plans and perspectives

- Charm Physics at $\overline{P}ANDA$

- Conclusions

In this talk: ONLY simulations

Outline

- Introduction
- Why the interest in charm physics
  - Strong interactions
    - QCD
    - Intermediate case between heavy and light quarks
    - Spectroscopy
    - Strong decay modes

This talk is focused on strong interactions in charm physics

- Future experiments: plans and perspectives
- **Exotic states in Open Charm Physics** at $\overline{P}ANDA$
- Conclusions

In this talk: ONLY simulations

Introduction: QCD

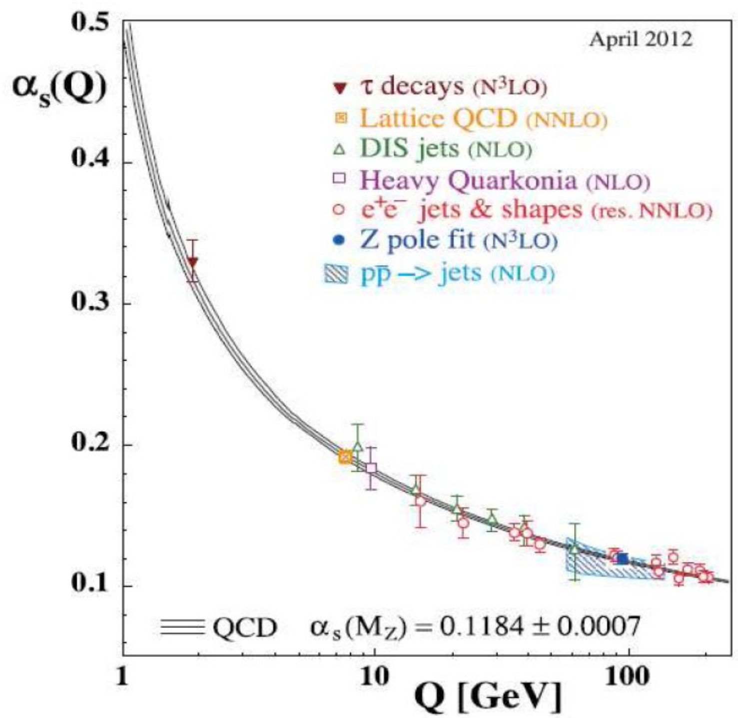
- The modern theory of strong interactions is the Quantum Chromo Dynamics (QCD)
  - QCD is the quantum field theory of quarks and gluons
  - It is based on the non-abelian gauge group SU(3)
  - It is part of the Standard Model

- At high energy QCD is well tested
  - The coupling constant α_s becomes small at high energy
  - Perturbation theory applies

- At low energy, QCD is still to be understood
  - Several theoretical approaches:
    - Potential models
    - Lattice QCD (LQCD)
    - Effective field theory (EFT)
    - ....

- Input from experimental physics
  - Several experimental techniques

PDG 2012



Experimental approach

Several experimental approaches:

- e^+e^- colliders
  (*BaBar, Belle, CLEO, BES III,...*)
  - direct formation
  - 2γ production
  - ISR (initial state radiation)
  - B meson decays

- $p\overset{(-)}{p}$ interactions
  (*LEAR, Fermilab, LHC, $\overline{\text{P}}$ANDA...*)

- Electro-photon production
  (*HERA, JLAB,...*)

Low hadronic background
High discovery potential

BUT

Direct formation limited to vector states
Limited mass and width resolution
for non vector states

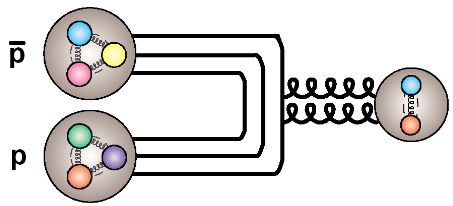
High hadronic background

BUT

High discovery potential
Direct formation for all (non exotic) states
Excellent mass and width resolution
for all states

Particle production in $p\bar{p}$ formation

In formation: all non exotic quantum numbers accessible in $p\bar{p}$ reactions

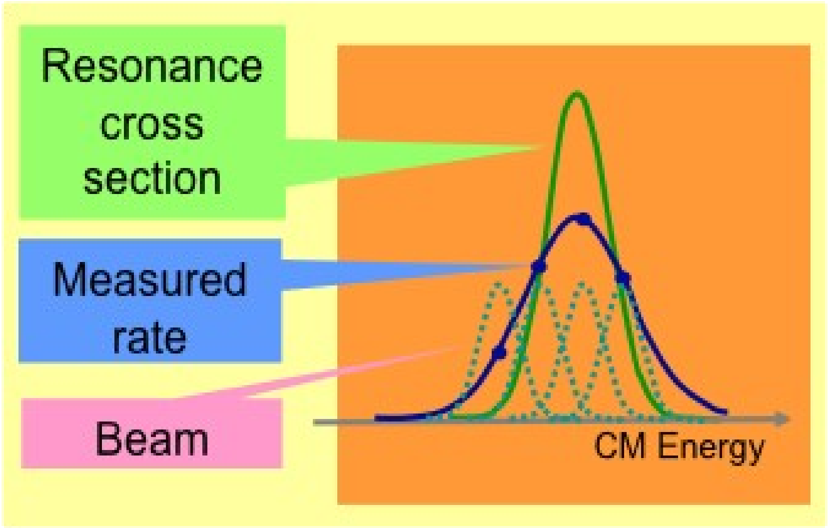


$J = 0, 2, \ldots$
$C = +$

$J = 1$
$C = -$

- High mass / width resolution
- Resonance scan technique: invariant mass resolution depends on the beam resolution
- *PANDA* is in a unique position to perform such a study!

Charm and Charmonium resonance mass scan



Charm Spectrum

- The charm spectrum was predicted in 1985 [**S. Godfrey, N. Isgur, PRD32, 189 (1985)**] and updated in 2001 [**M. Di Pierro, N. Eitchen, PRD64, 114004 (2001)**]
- The theoretical predictions are generally in qualitative agreement with observations
- Still discrepancies are seen for some of those states (experimental limitation in the measurement of the width, small statistics, large level of background in inclusive measurements)

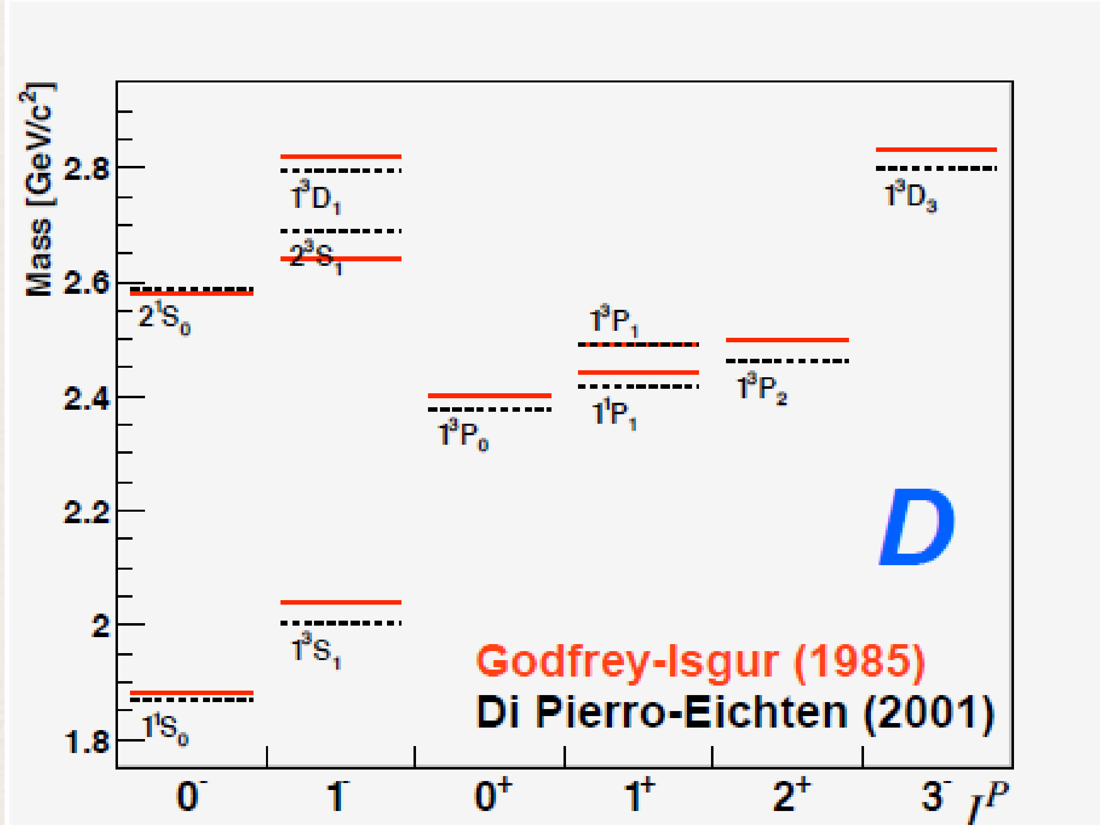
From PDG 2012:

D mesons: $|c\bar{u}\rangle$, $|c\bar{d}\rangle$

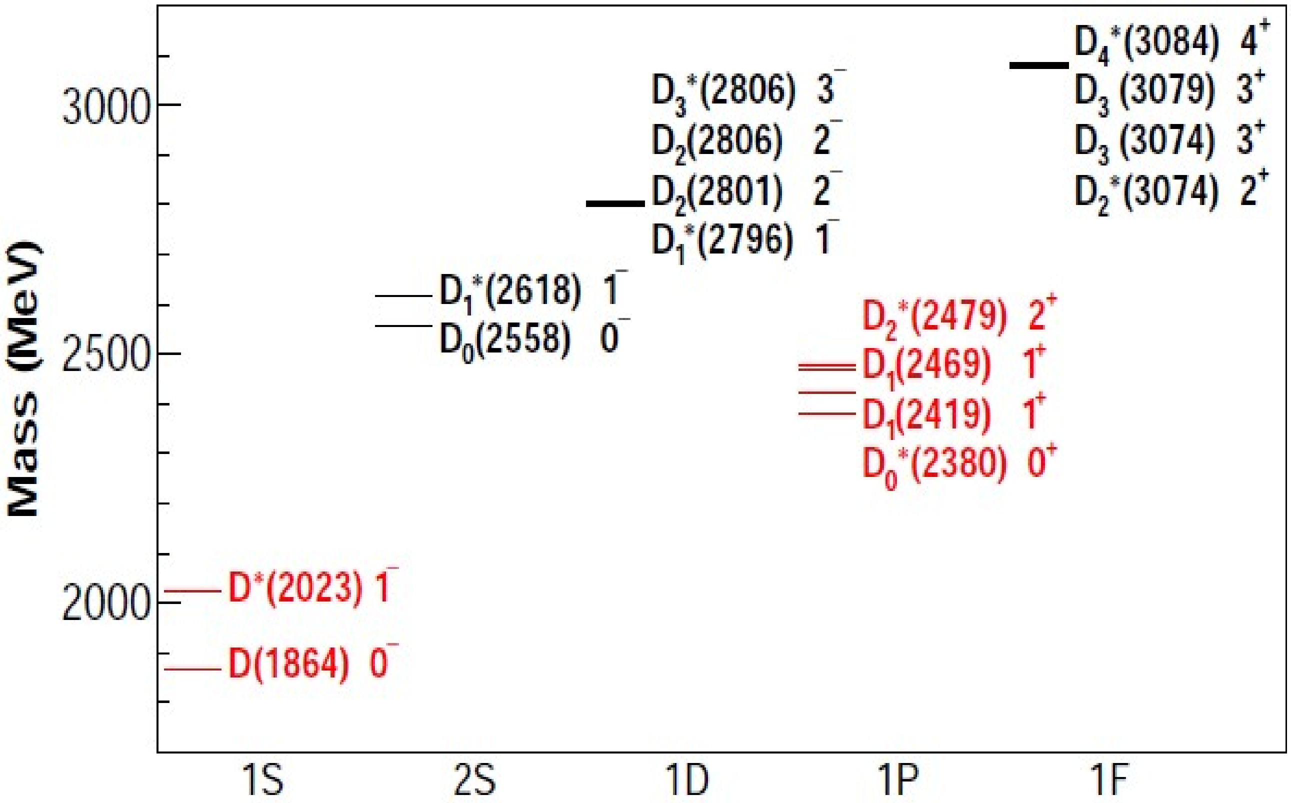
$\overline{M}_D = (1864.91 \pm 0.17)$ MeV/c^2

$M_{\pm} - M_0 = (4.74 \pm 0.28)$ MeV/c^2

$\overline{\tau} = (410.1 \pm 1.5) \times 10^{-15}$s

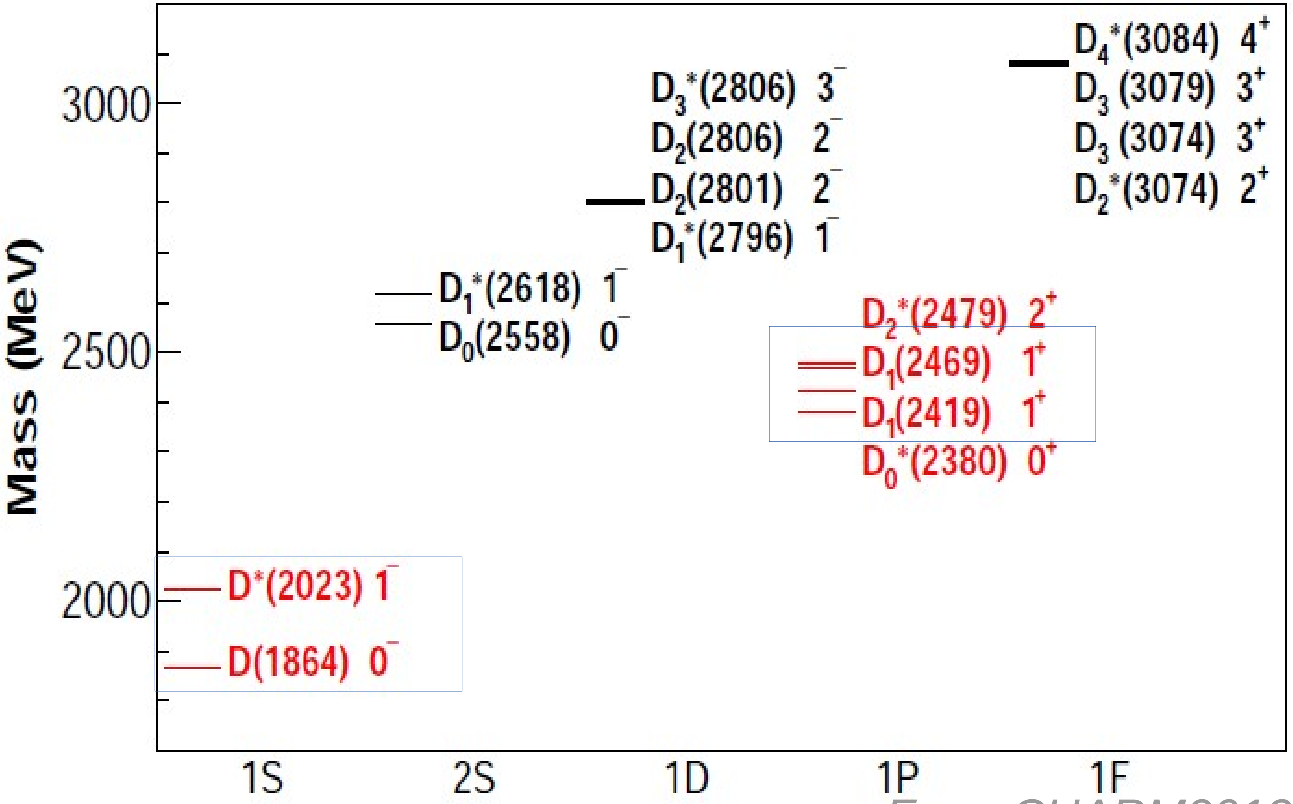


Charm Spectrum, today



- Ground states (D, D*), and two of *1P* states (D_1(2420) and D_2(2460)* experimentally well established: relatively small width (~30 MeV)
- Broad states with *L=1* (D^*_0(2400) and D'_1(2430)) are well established from BaBar and Belle in exclusive B decays
- BaBar recently found new states: D_0(2550), D_0(2560), D_0(2750) and D_0(2760) [**PRD82, 111101 (2010)**]

Charm Spectrum, today



From CHARM2013

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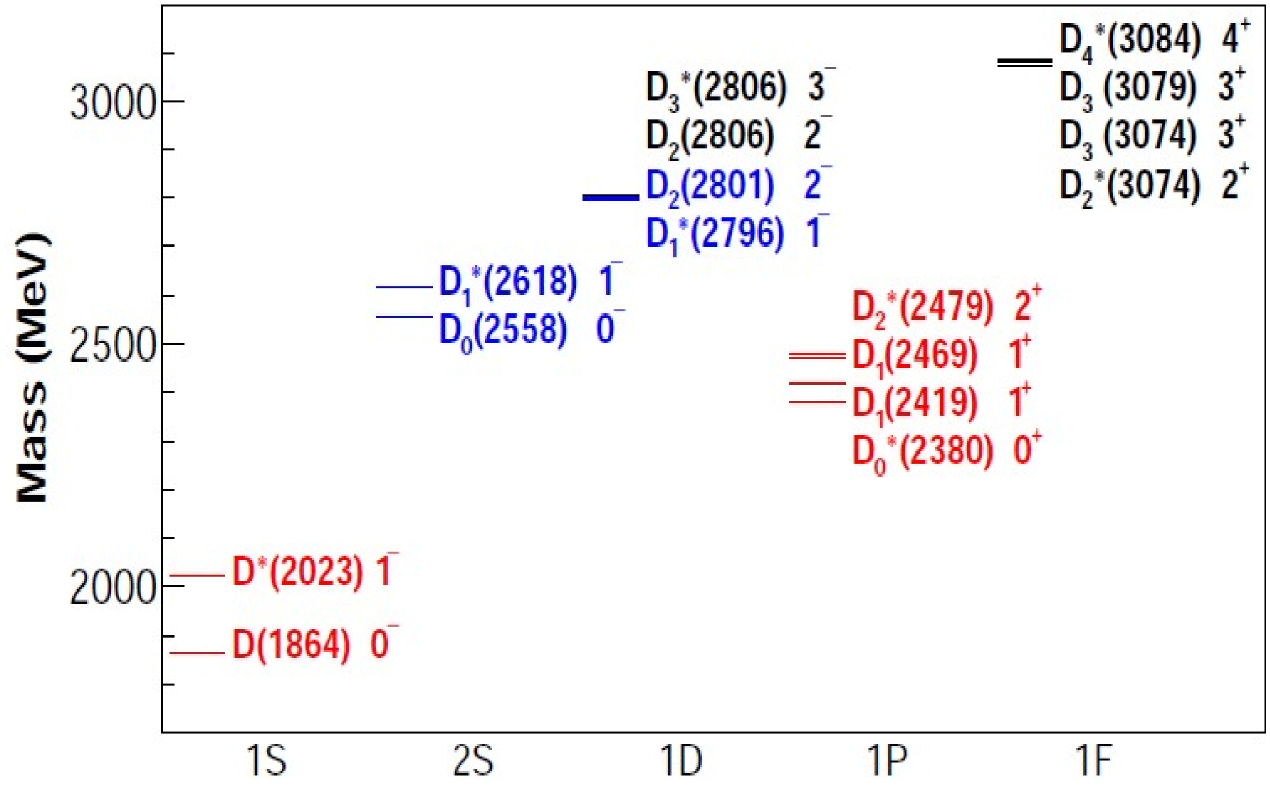
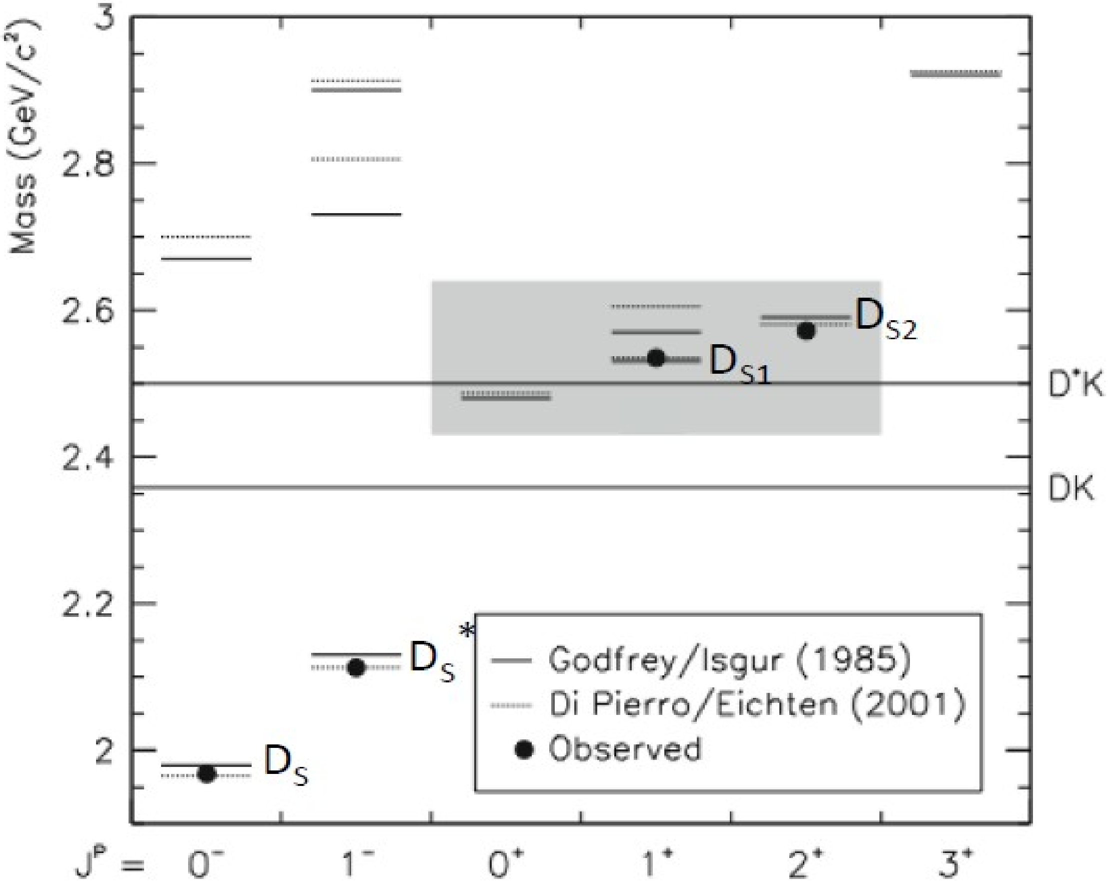
Interpretation of new D_J mesons



- The $D^*_J(2650)^0$ resonance could be identified as $J^P=1^-$ state (2S $D^*_1(2618)$)
- The $D^*_J(2760)^0$ could be identified as $J^P=1^-$ state (1D $D_1^*(2796)$)
- The $D_J(2580)^0$ could be identified with (2S $D^0(2558)$) state, although $J^P=0^-$ does not fit well the data
- The $D_J(2740)^0$ could be identified as $J^P=2^-$ (1D D2(2801) resonance
- Broad structures observed at 3.0 GeV in $D^{*+}\pi^-$ and $D\pi$ mass spectra. Are them superimposition of several other states?

Excited D_{SJ} mesons

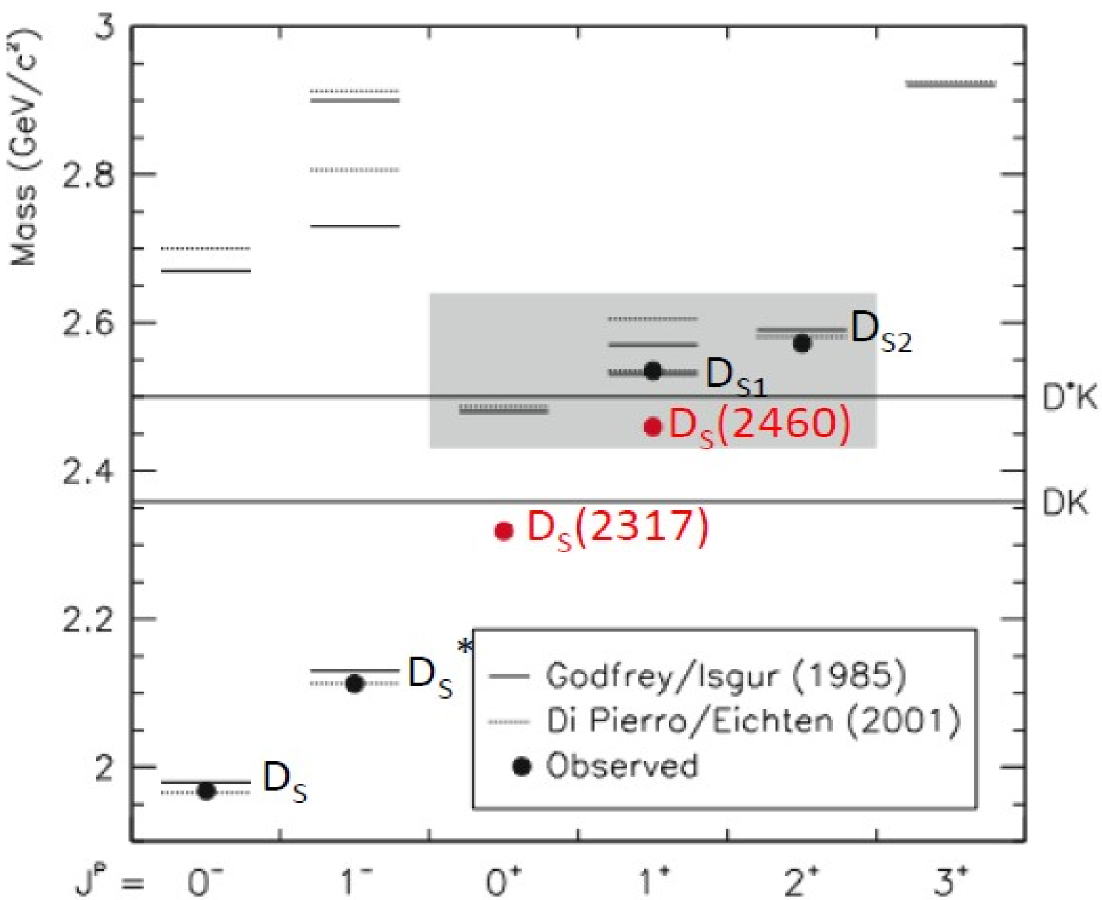


$|c\bar{u}\rangle$ $|c\bar{d}\rangle$ (D_J mesons): theory and experiments were in agreement

$|c\bar{s}\rangle$ (D_{SJ} states): the quark model describes the spectrum of unobserved heavy-light systems, expected to be predicted with good accuracy

until 2003!

Excited D_{SJ} mesons

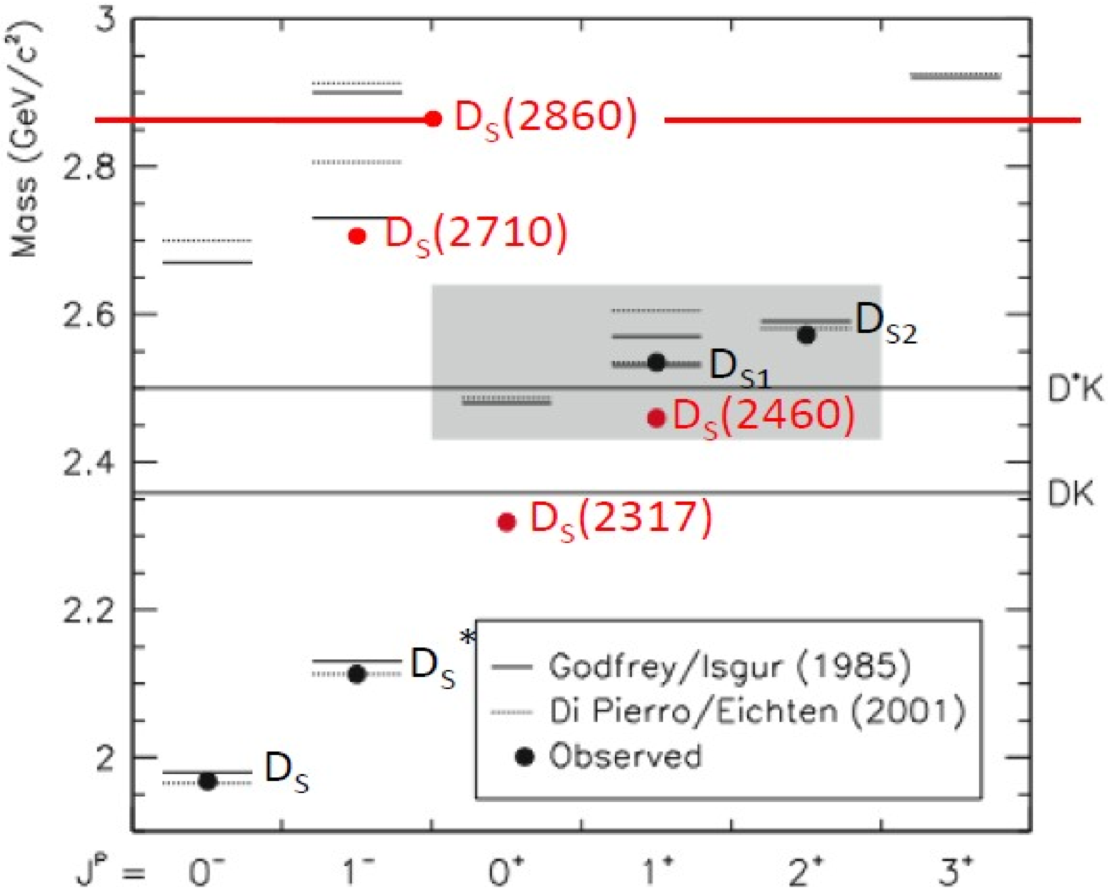


$|c\bar{u}\rangle$ $|c\bar{d}\rangle$ (**D_J** mesons): theory and experiments were in agreement

$|c\bar{s}\rangle$ (**D_{SJ}** states): the quark model describes the spectrum of unobserved heavy-light systems, expected to be predicted with good accuracy

$D_s(2317)^+$ discovered in $e^+e^- \to c\bar{c}$, then observed by BaBar [PRL 90 242001 (2003)], Belle [PRL 91 262002 (2003)], CLEO [PRB 340 (1994)]

Excited D_{SJ} mesons

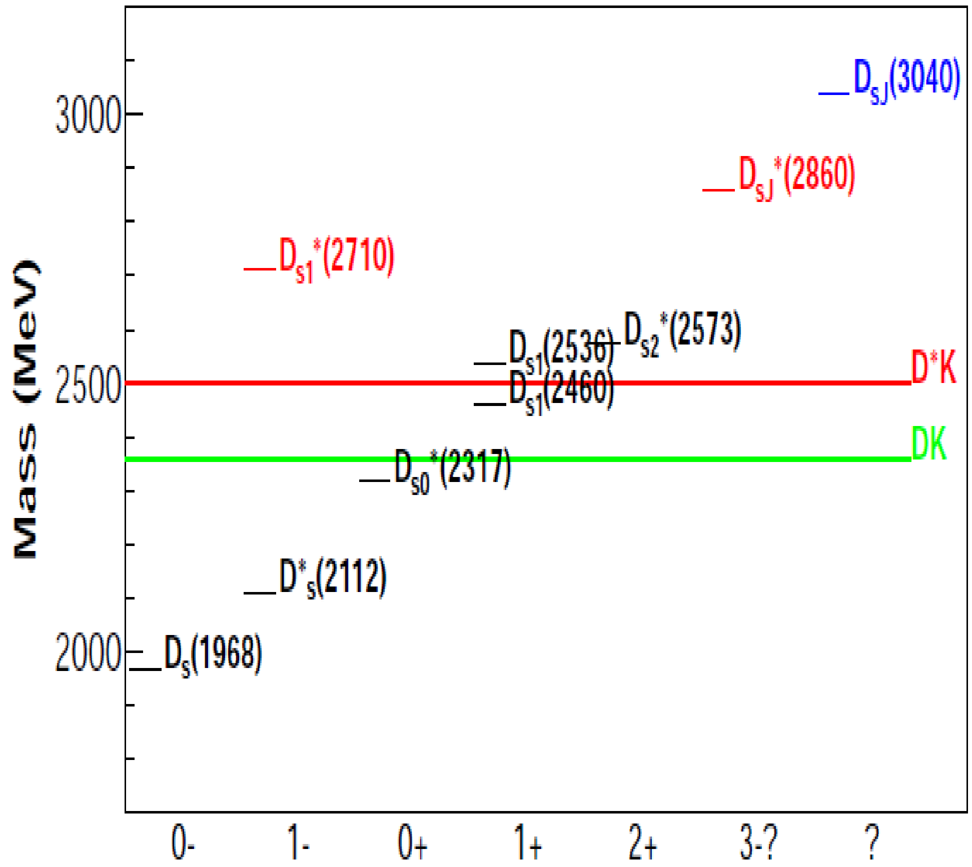


- |cū⟩ |cd̄⟩ (D_J mesons): theory and experiments were in agreement
- |cs̄⟩ (D_{SJ} states): the quark model describes the spectrum of unobserved heavy-light systems, expected to be predicted with good accuracy

Several others excited states have been found

The identification of these states as 0^+ or 1^+ $c\bar{s}$ states is difficult in the potential model

Excited D_{sJ} mesons, today



- $D_{s1}^{*}(2710)$ was found in the analysis of DK and $D^{*}K$
- In the same analysis another broad structure was observed: $D_{sJ}(3040)$
- The discovery of all these excited states brought the potential model into questions

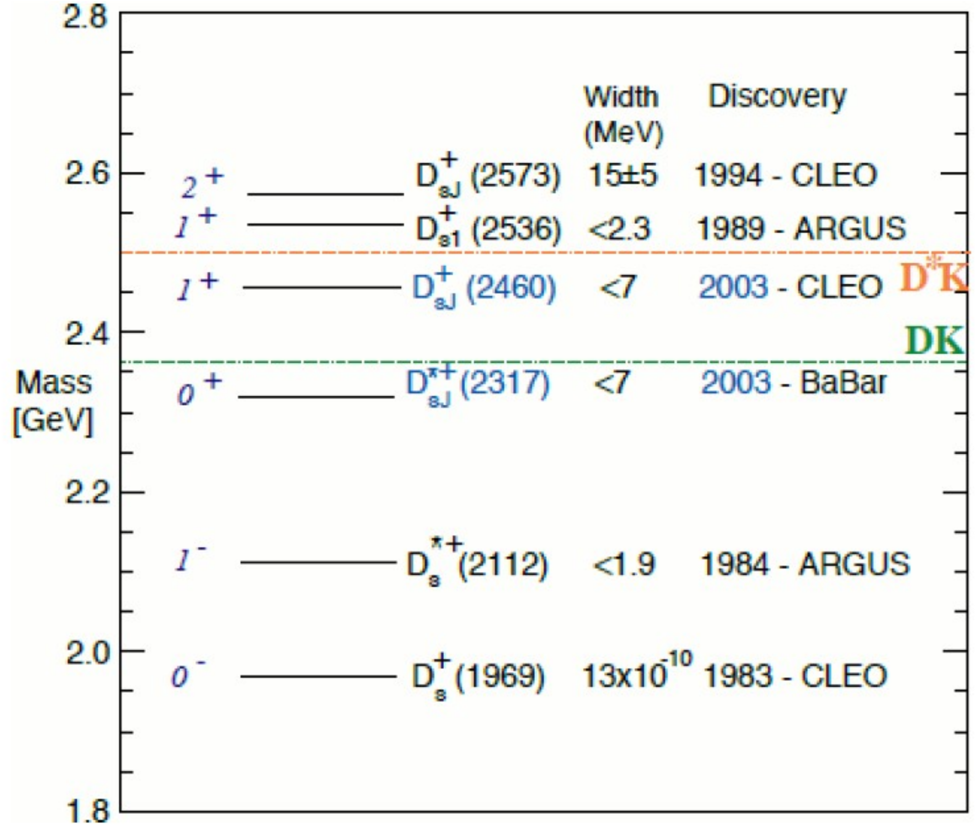
Search for D_{sJ} states

How PANDA can contribute?

- Wide and ambitious program: $p\bar{p} \rightarrow D^{(*)}\bar{D}^{(*)}$, $p\bar{p} \rightarrow D_s^{\pm} D_s^{\mp}$, $p\bar{p} \rightarrow D_s^{-} D_{sJ}^{+}$
- From experimental point of view, the study of D-mesons strongly depends on the ability to deconvolute the detector resolution on final product energies and momenta (general issue)
- $\bar{\text{P}}$ANDA will scan resonance mass to determinate precisely the width
- The extraction of a clean signal depends basically on three factors:
  1) low multiplicity of the final state
  2) good particle identification
  3) good vertex resolution
- Many new results and update recently from LHCb
- First simulations with PandaRoot (full detector simulartion) will be shown

D_{sJ} search

- Not understood the $D_{sJ}(2317)^+$ nature: 100 MeV lower than the predicted mass by potential model
- Very small width
- Observed in $D^{(*)+}\pi^0$ system ⇒ isospin violating
- Other similar states found
- $D_{s1}(2460)^+$ close to the D*K threshold
- Width of these states: only UL due to experimental limitations
- PANDA can reach mass resolution >20 times higher than the previous projects; expected high precision
- Depending on the determination of the width, there are several interpretations



D_{SJ} width: predictions

- The determination of the width of D_{SJ} states is important to understand their nature
  Particular case here under discussion: $D_{SJ}(2460)^+$

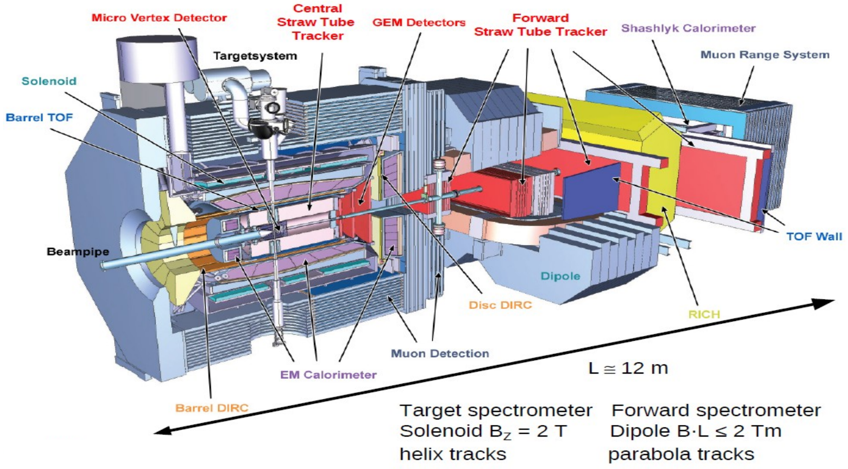
  - Pure cs state (Γ < 10 keV) PLB 568 (2003) 254
  - Tetraquark state (10< Γ < 100 keV) PLB 566 (2003) 193
  - DK hadronic molecule Γ=180±40±100 keV PLB 666 (2008) 251-255 or 79.3±32.6 keV PRD 76 (2007) 133
  - Dynamically generated resonance Γ = 140 keV Nucl. Phys. A 813:14-95 (2008)

$D_s^0(2317)^*$ theoretical overview

Approach	Γ(Ds0*(2317) → Dsπ0) (keV)
M. Nielsen, Phys. Lett. B 634, 35 (2006)	**6 ± 2**
P. Colangelo and F. De Fazio, Phys. Lett. B 570, 180 (2003)	**7 ± 1**
S. Godfrey, Phys. Lett. B 568, 254 (2003)	**10** Pure $c\bar{s}$ state
Fayyazuddin and Riazuddin, Phys. Rev. D 69, 114008 (2004)	**16**
W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D 68, 054024 (2003)	**21.5**
J. Lu, X. L. Chen, W. Z. Deng and S. L. Zhu, Phys. Rev. D 73, 054012 (2006)	**32**
W. Wei, P. Z. Huang and S. L. Zhu, Phys. Rev. D 73, 034004 (2006)	**39 ± 5**
S. Ishida, M. Ishida, T. Komada, T. Maeda, M. Oda, K. Yamada and I. Yamauchi, AIP Conf. Proc. 717, 716 (2004)	**15 - 70**
H. Y. Cheng and W. S. Hou, Phys. Lett. B 566, 193 (2003)	**10 - 100** Tetraquark state
A. Faessler, T. Gutsche, V.E. Lyubovitskij, Y.L. Ma, Phys. Rev. D 76 (2007) 133	**79.3 ± 32.6** DK had. molecule
Y. I. Azimov and K. Goeke, Eur. Phys. J. A 21, 501 (2004)	**129 ± 43 (109 ± 16)**
M.F.M. Lutz, M. Soyeaur, arXiv: 0710.1545 [hep-ph]	**140** Dynamically gen. res.
Feng-Kun Guo, Christoph Hanhart, Siegfried Krewald, Ulf-G. Meißner Phys Lett. B 666 (2008) 251-255	**180 ± 40 ± 100** DK had. molecule

D_{SJ} search with PANDA detector

- Panda is a fixed target detector
  - ❍ High boost $\beta_{cms} \geq 0.8$
  - ❍ Many tracks and photons in fwd acceptance ($\theta \leq 30°$) (high p_z, E_γ)



- High background from hadronic reactions
  - ❍ expected $S/\sqrt{(S+B)} \sim 10^{-6}$
  - ❍ S (signal) and B (background) have same signature
  - ❍ Hardware trigger not possible
  - ❍ Self-triggered electronics
  - ❍ Free streaming data
  - ❍ 20 MHz interaction rate
  - ❍ Complete real-time event reconstruction

Analysis Proposal: D_{sJ} mesons

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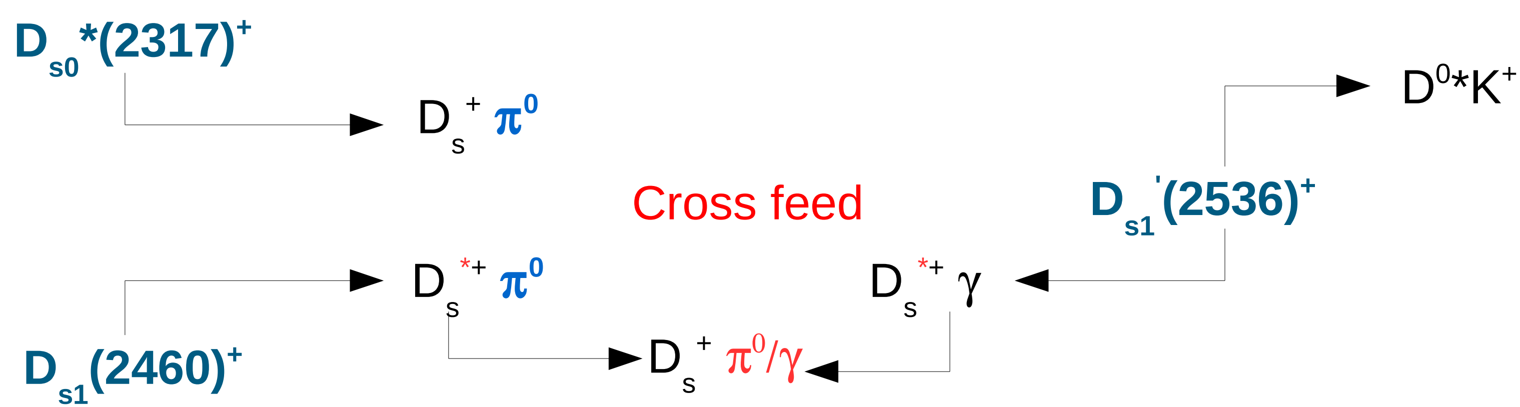
$D_{s0}^*(2317)^+$	$D_{s1}(2460)^+$	$D_{s1}'(2536)^+$
M = 2317.8±0.6 MeV/c^2	M = 2459.6±0.6 MeV/c^2	M = 2535.12±0.13 MeV/c^2
Γ < 3.8 MeV	Γ < 3.5 MeV	Γ =0.92±0.05 MeV
$M_{D^*s0} - M_{Ds\pm}$ = 349.3±0.6 MeV/c^2	$M_{Ds1\pm} - M_{D^*s\pm}$ = 347.2±0.7	$M_{D's1\pm} - M_{D^*s\pm}$ = 422.8±0.5
	$M_{Ds1\pm} - M_{Ds\pm}$ = 491.1±0.7	$M_{D's1\pm} - M_{D^*\pm}$ = 584.84±0.04
		$M_{D's1\pm} - M_{D^*0}$ = 528.14±0.08

- Study of the mixing of $D_{s1}(2536)^+$ and $D_{s1}(2460)^+$
- Study of chiral symmetry breaking
- Study of the excitation function of the cross section in $p\bar{p} \rightarrow D_s^- D_{sJ}^+$



Mixing

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- System of heavy-light quark (*c*= heavy; *s* = light)

  The angular momentum j = l+s (light quark) is conserved
  P wave states ⇨ j = 3/2 or j = 1/2

- Total angular momentum of the system with light quark + heavy quark: J=2 or 1
  States with J=2^+ or 1^+ are expected to have a small width ($D_{sJ}(2573)^+$, $D_{s1}(2536)^+$)

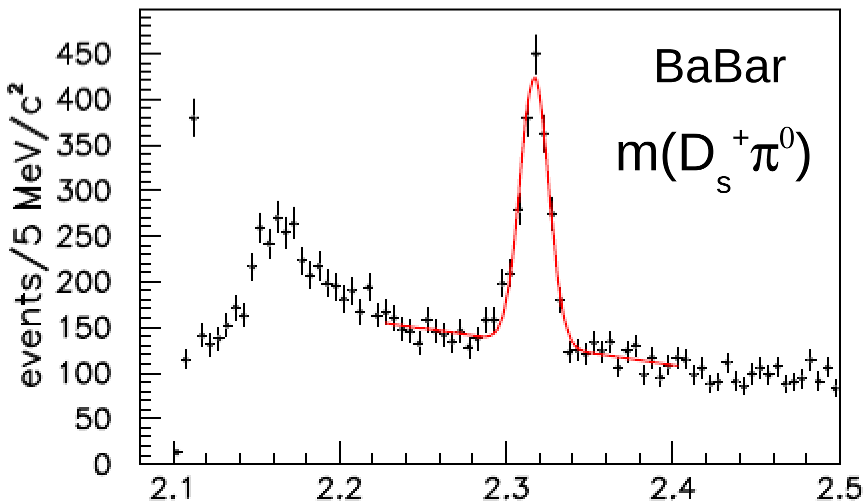
- $D_{s1}(2536)^+$ can include a small admixture of the j=1/2, $J^P=1^+$ state
  Admixture of 2 state, A and B, means basically that the state A is part A and part B, and viceversa; a|A> ± b|B>

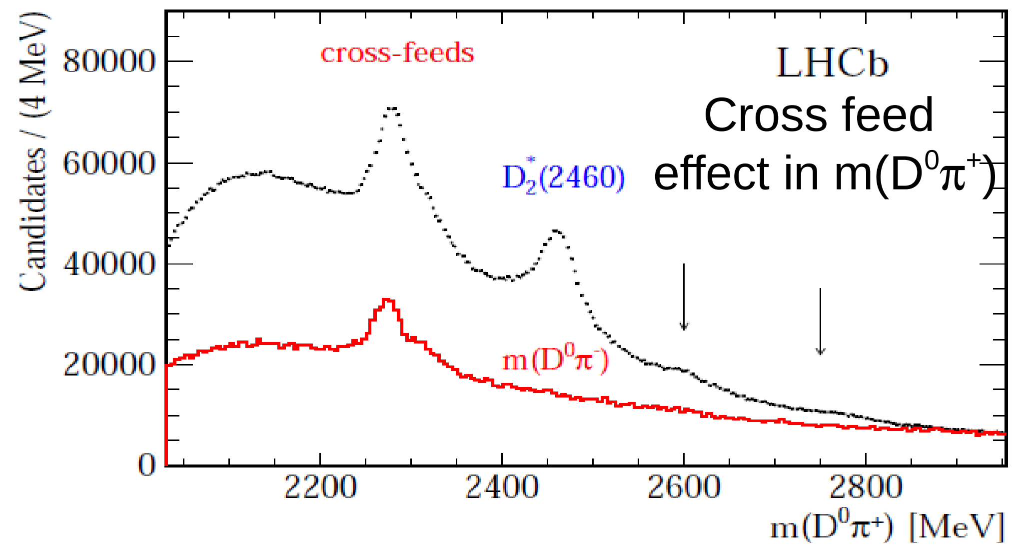
  $D_{s1}(2460)^+$ j=1/2 (supposed to be pure S-wave)
  $D_{s1}(2536)^+$ j=3/2 (supposed to be pure D-wave)

- Experiments showed an overlap between S- and D- waves
  $\Delta m = 78$ MeV/c^2. **Why are they so thin** (Γ <2.3 MeV), **and they mix**?

PANDA could solve this puzzle!

Chiral symmetry breaking





- The 2 states $D_s(2317)^+$ and $D_s(2460)^+$ can be interpreted as first chiral partners of hadrons built with heavy+light quarks.

- The sector of light quark mass is characterized by spontaneous breaking of chiral symmetry. The sector of heavy quark mass shows symmetry

- The spontaneous chiral symmetry breaking leads to a mass splitting for chiral doublets, expected to be ~ 345 MeV/c^2. Experiments quote:
$m(D_s^+\pi^0) - m(D_s) = (350.0\pm1.2\pm1.0)$ MeV/c^2 ($D_{sJ}(2317)^+$ was observed in $D_s^+\pi^0$)
$m(D_s^{*+}\pi^0) - m(D^*_s) = (351.2\pm1.7\pm1.0)$ MeV/c^2 ($D_s(2460)^+$ was observed in $D_s^{*+}\pi^0$)

Excitation function of the cross section

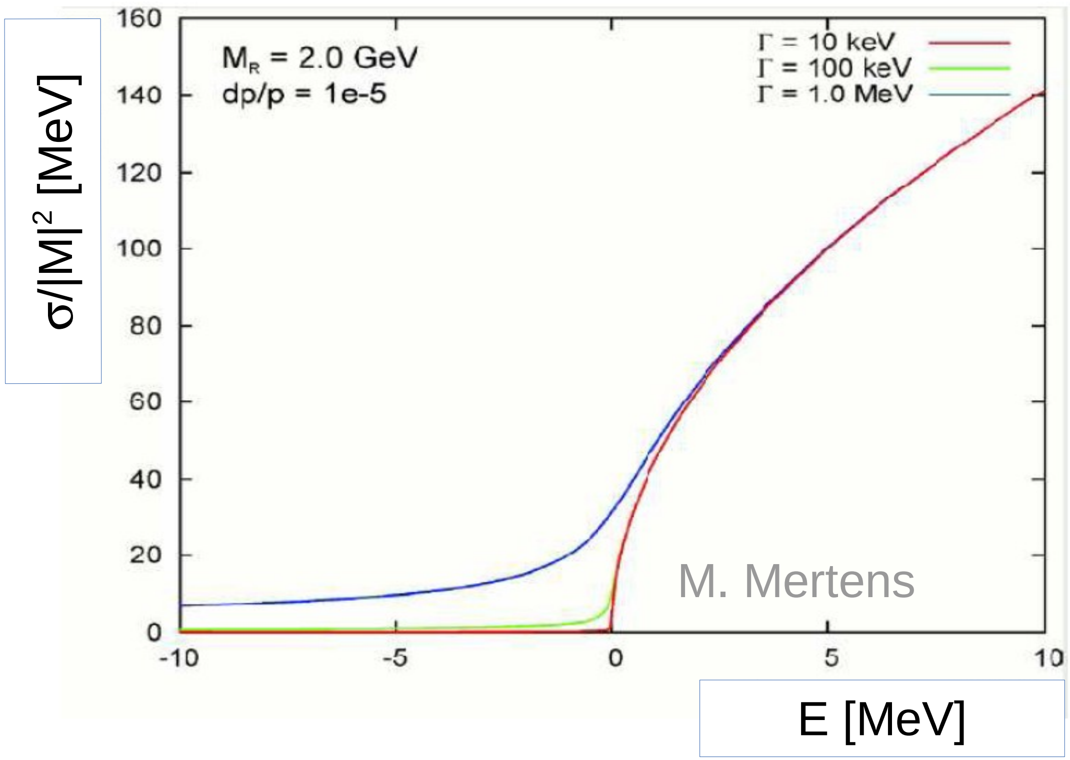
$$\sigma(\lambda) = \sqrt{m_R\Gamma}|M^2|\frac{1}{\pi}\int_{-\infty}^{\lambda} \mathrm{d}x, \frac{\sqrt{\lambda - x}}{x^2+1}$$

$$\sigma(0) = \sqrt{\frac{m_R\Gamma}{2}}|M^2|$$

$$\lambda = (\sqrt{s} - 2M_R)/\Gamma$$

M = proton mass

M_R = mass of D_{sJ}



- A precise measurement of the cross section gives a precise determination of the Γ

Goal of this study

- The main goal of this analysis is to measure the width of the D_{sJ} states
- Reconstruct the excitation function of the cross section
  Scan every 100-200 keV around the mass peak is required (only $\bar{P}$*ANDA* can do that!)
- **Advantage** in $\bar{P}$*ANDA*:
  very high statistics
  high mass resolution
- **Main problem**: high level of background, signal and bkg have same signature.
  Kinematic fit needed: several options in PandaRoot in this moment
  Good vertex resolution is needed
- **Challenge**: slow pions are present;
  need of a good tracking for low momentum tracks

Expectation in PANDA

- Expected number of events in PANDA = $\mathscr{L} * \sigma * \varepsilon$

Cross section:
20 ÷100 nb

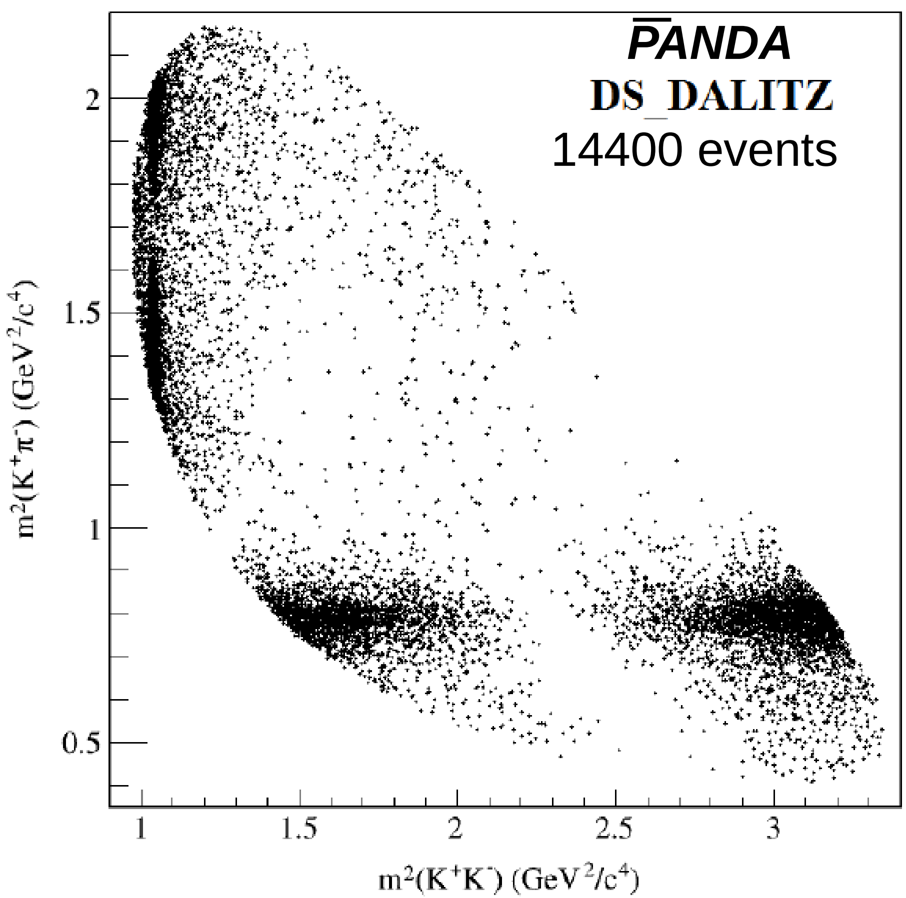
http://arxiv.org/abs/1111.3798
A. Khodjamirian, Ch. Klein, Th. Mannel, Y.M. Wang

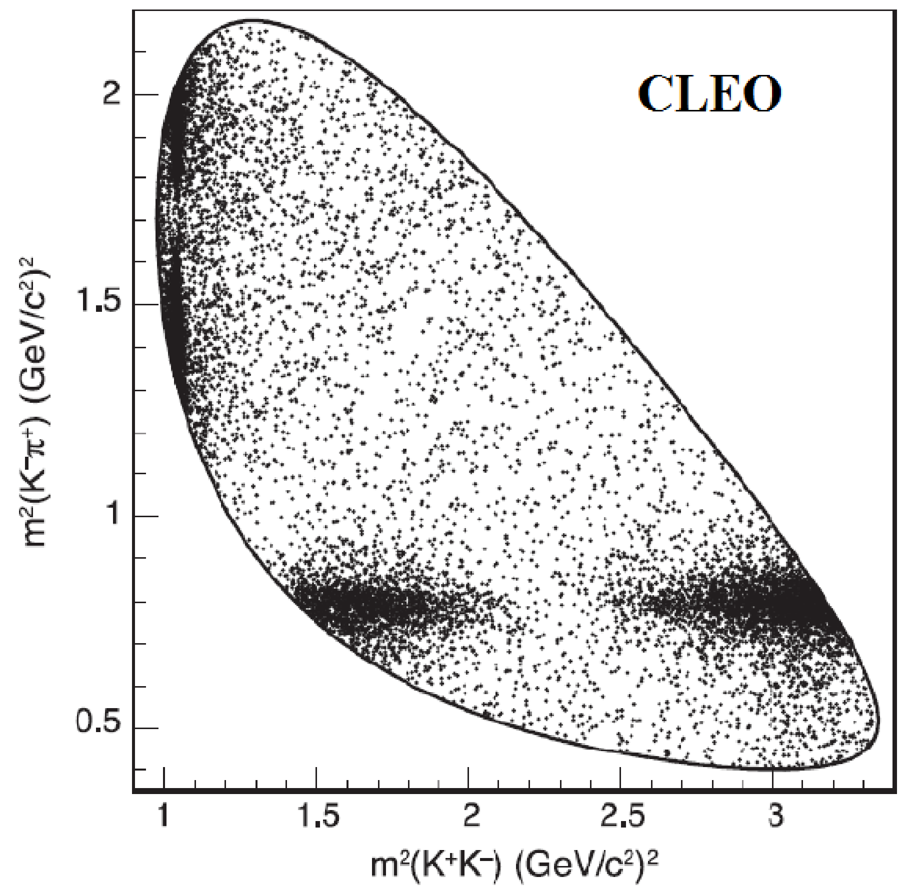
Luminosity = $2 * 10^{32}$ cm^{-2} s^{-1}
8.64 pb^{-1}/day

N expected = 8.64 pb^{-1}/day * (20÷100)nb * ε ~ (160k ÷1M) * $\boldsymbol{\varepsilon}$/day

NB. Estimation is valid in high resolution mode: otherwise we expect a factor 10 less
$\Delta p/p \sim 10^{-5}$

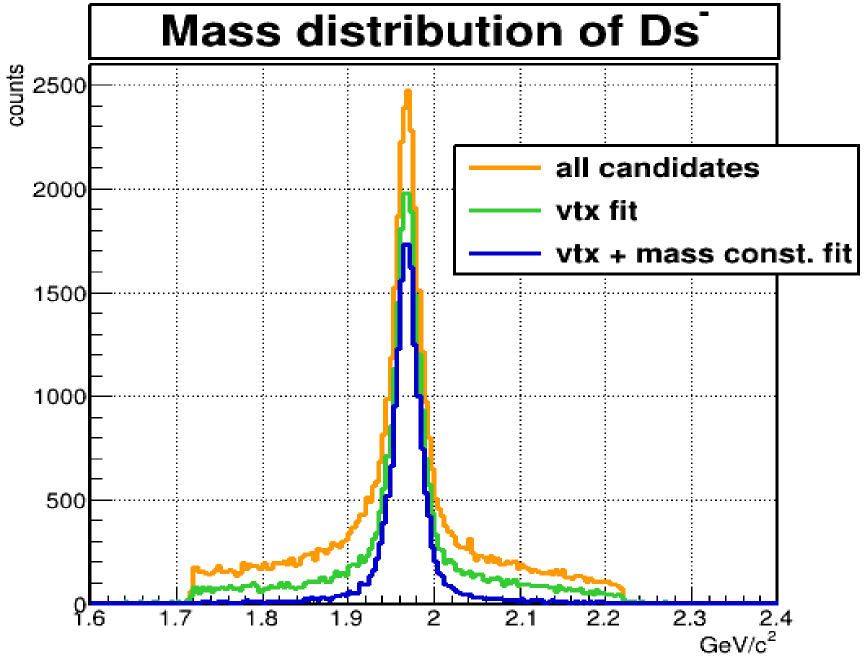
D_s recontruction: Dalitz model

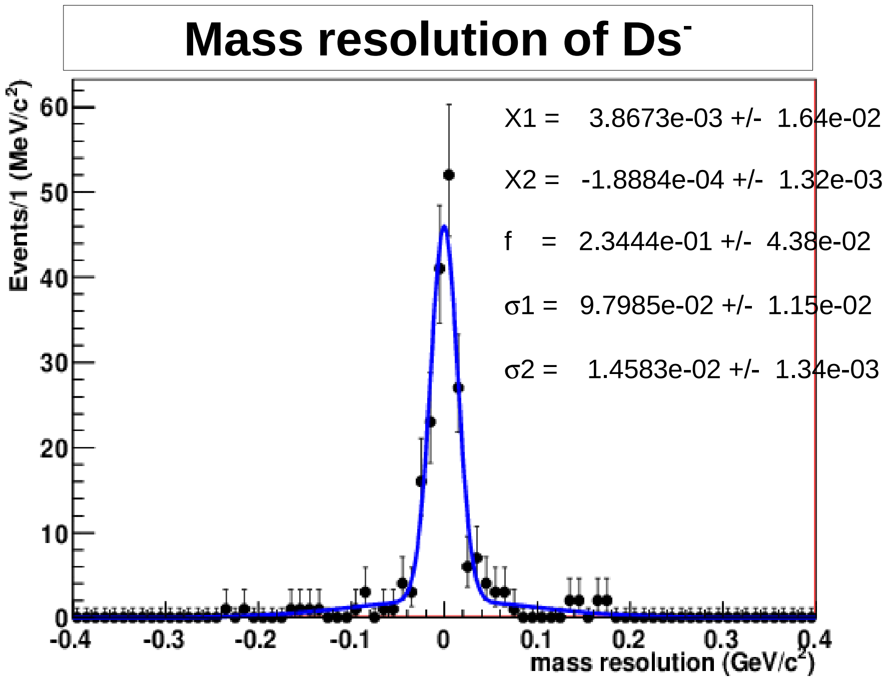


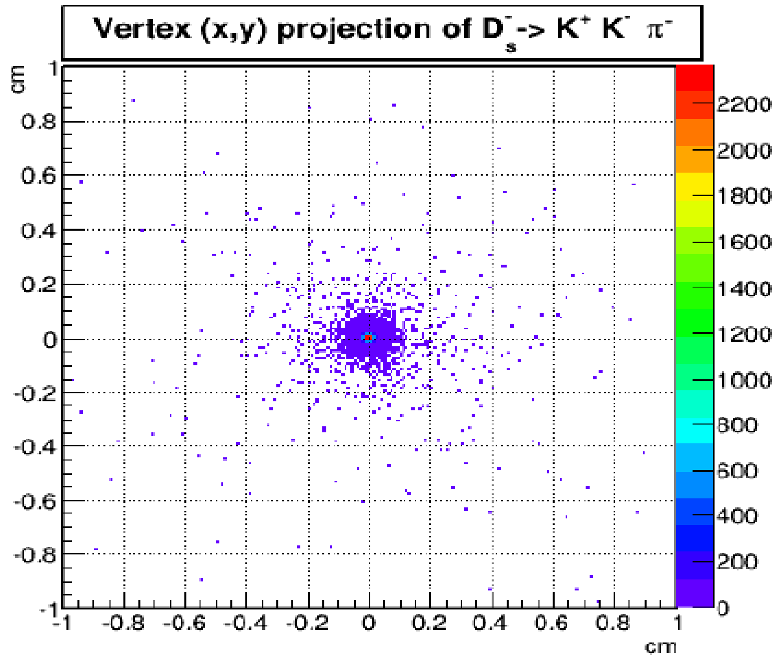


L.Cao

D_s mass resolution





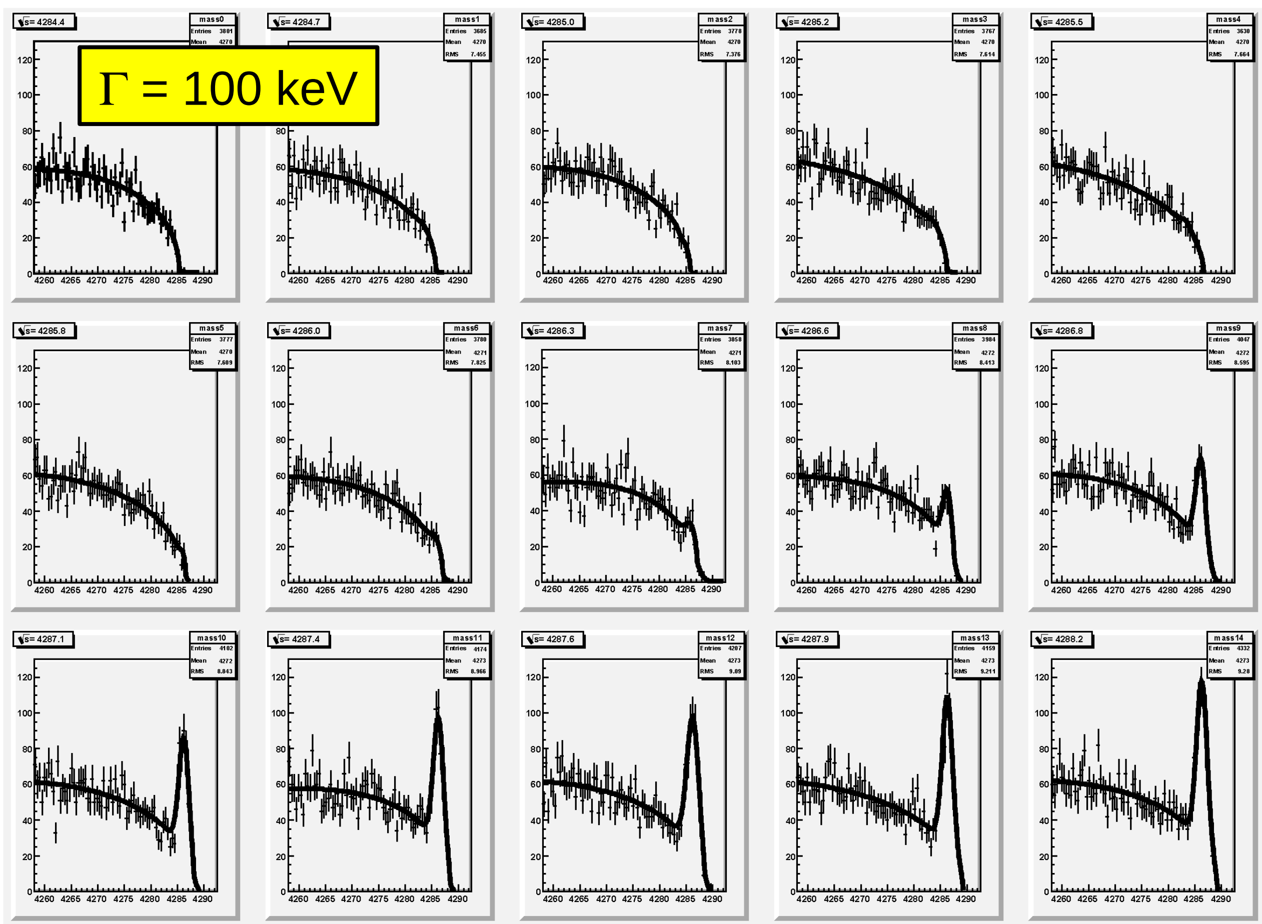


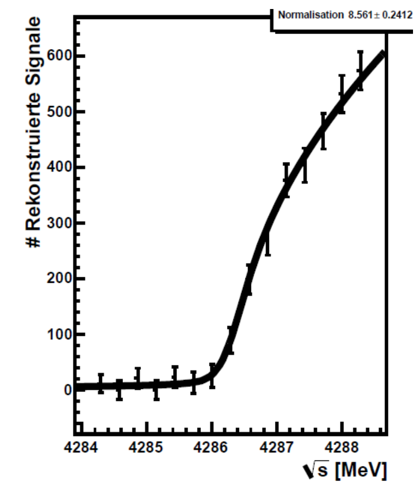
L. Cao, E. Prencipe

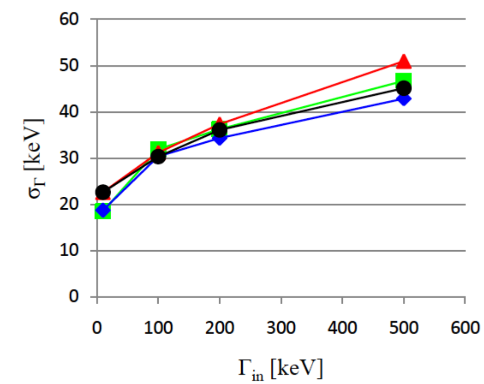
Scan of $D_{s0}^*(2317)^+$

$D_{s0}^*(2317)^+ \rightarrow D_s^+ \pi^0$

$M_{sum} = M_{miss}(Ds) + M(Ds)$







PRELIMINARY

M. Mertens

D_s and D_{SJ} reconstruction with PandaRoot

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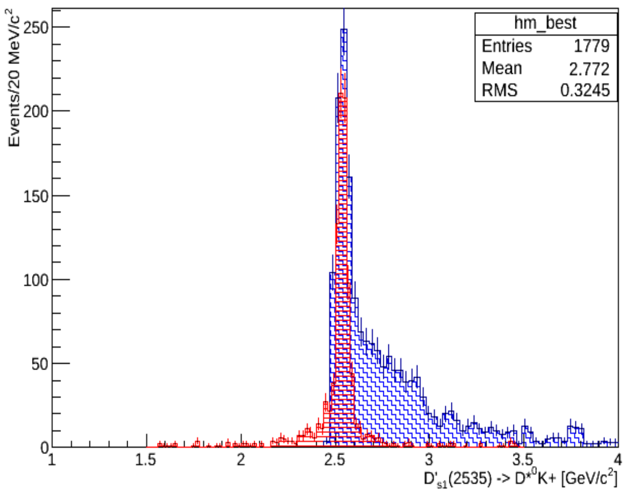
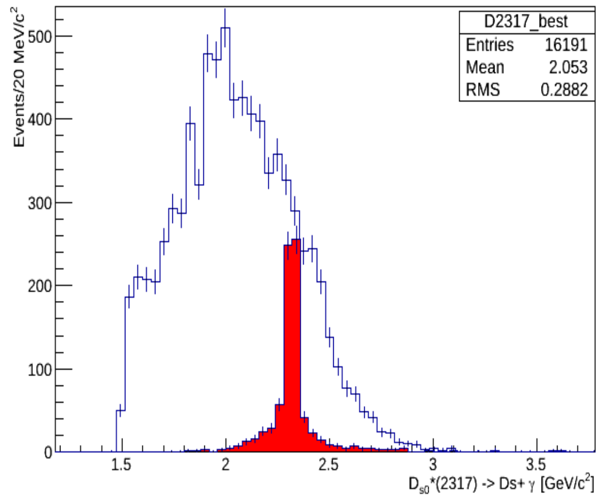
Work in progress...

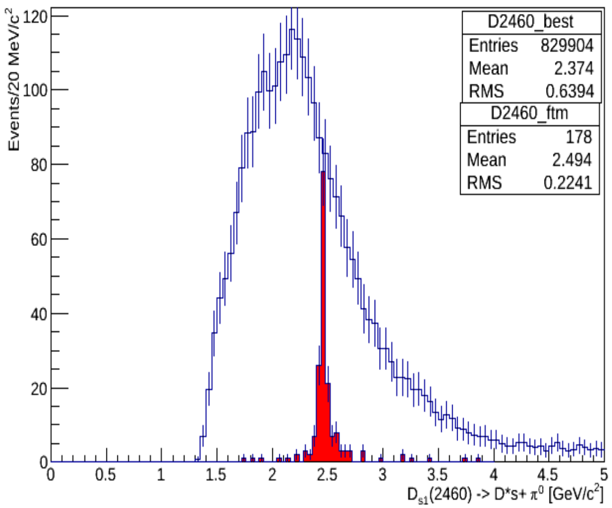
$D_{s1}'(2536)^+$



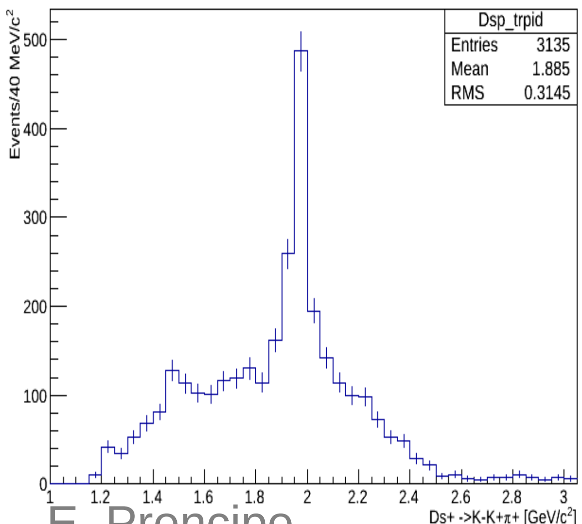
$D_{s0}^*(2317)^+$



$D_{s1}(2460)^+$

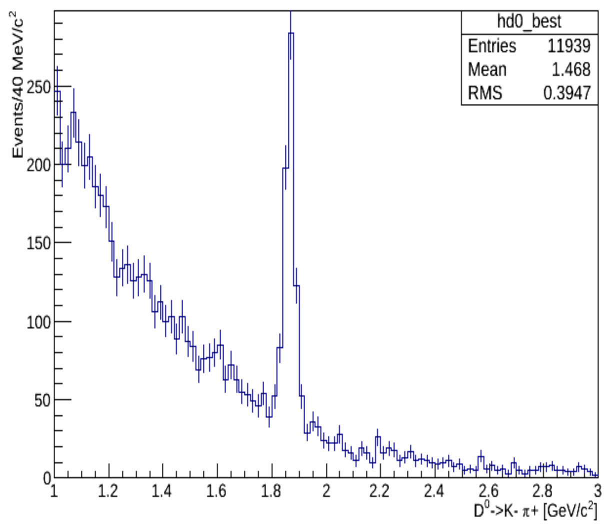


D_s^+

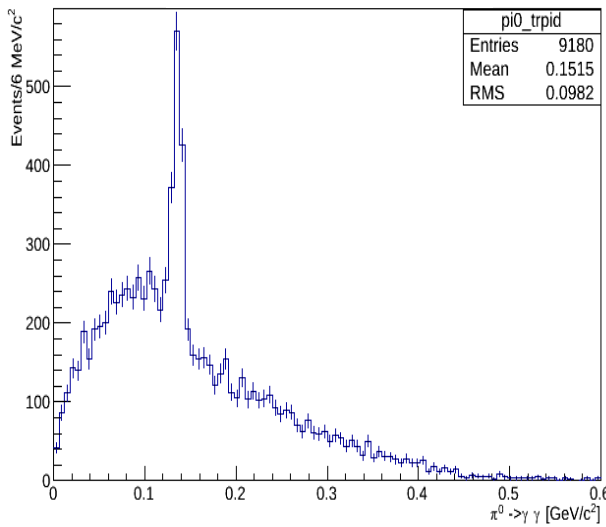


E. Prencipe

D_0



π^0



Conclusion

- After 10 years from the observation of $D_{sJ}^{*}(2317)^{+}$ still many opened questions
- Interpretation of D_{sJ} states still not clear:
  limitation due to statistics and lack of precision
- The precise measurement of the width of these D_{sJ} states is needed
- Progresses done at LHCb, after the B factory measurements: still not enough
- The future project *$\overline{\mathrm{P}}$ANDA* at *FAIR* will reach high level precision in mass/width evaluation at level never reached before
- In PandaRoot: simulations are ongoing...
- Studies to suppress backgrounds and maximize statistical significance are work in progress

"Genius is 1% talent and 99% hard work"

THANKS!