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on behalf of the PANDA Coll.
Forschungszentrum Jülich (DE)

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

Hirscheegg 2014

Hadrons from Quarks and Gluons

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

- 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{PANDA}
- Conclusions

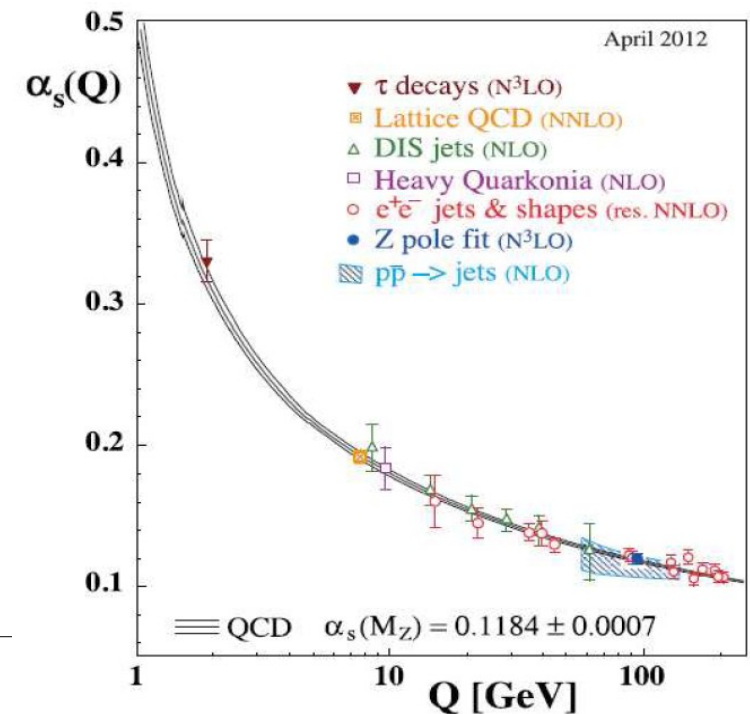
- Introduction
- Why the interest in charm physics
 - ▶ Strong interactions
 - QCD
 - Intermediate case between heavy and light quarks
 - Spectroscopy
 - Strong decay modes

This talk is focused on strong interactions in charm physics

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

- 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



Several experimental approaches:

- e^+e^- colliders
(*BaBar, Belle, CLEO, BES III,...*)
 - direct formation
 - 2γ production
 - ISR (initial state radiation)
 - B meson decays
- pp annihilation and hadron production
(*LEAR, Fermilab, LHC, PANDA...*)
- Electro-photon production
(*HERA, JLAB,...*)

Low hadronic background
High discovery potential

BUT

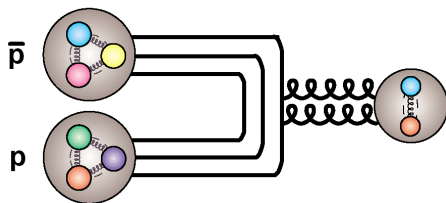
Direct formation limited to vector states
Limited mass and width resolution
for non vector states

High hadronic background

BUT

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

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



$$J = 0, 2, \dots$$

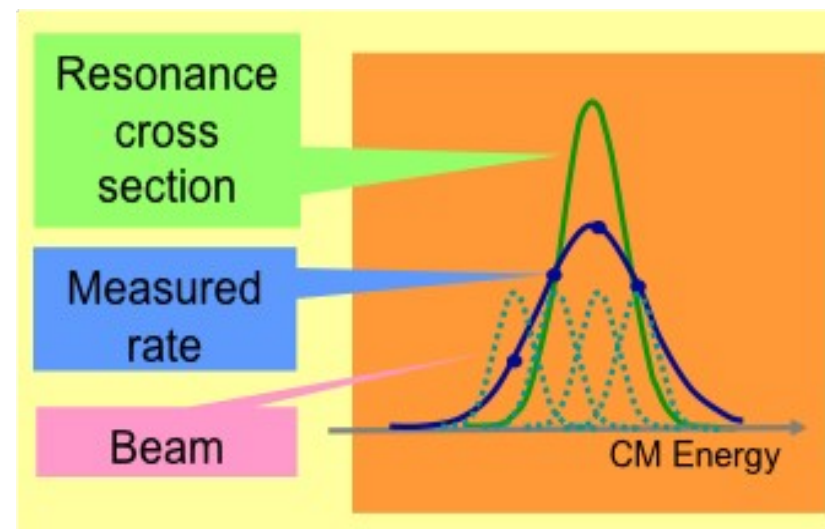
$$C = +$$

$$J = 1$$

$$C = -$$

- 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 2011 [M. Di Pierro, N. Eichten, 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:

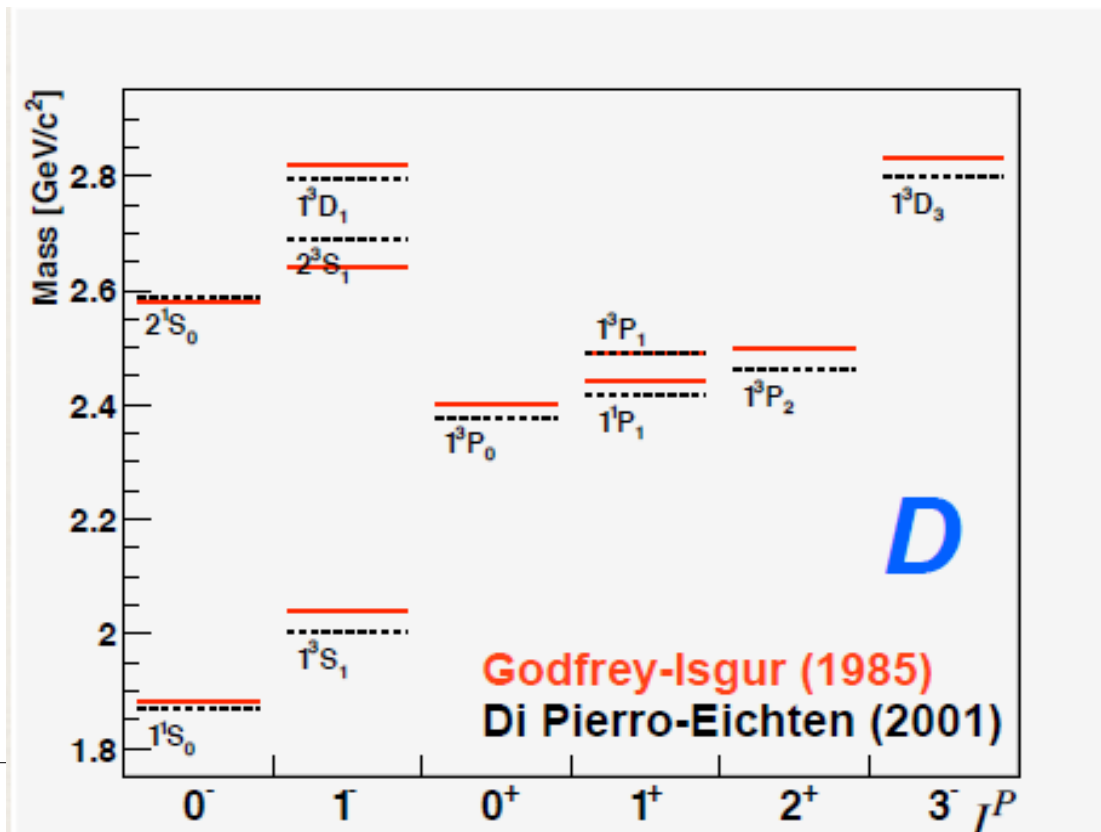
D mesons: $|c\bar{u}\rangle, |c\bar{d}\rangle$

$$M_D = (1864.91 \pm 0.17) \text{ MeV}/c^2$$

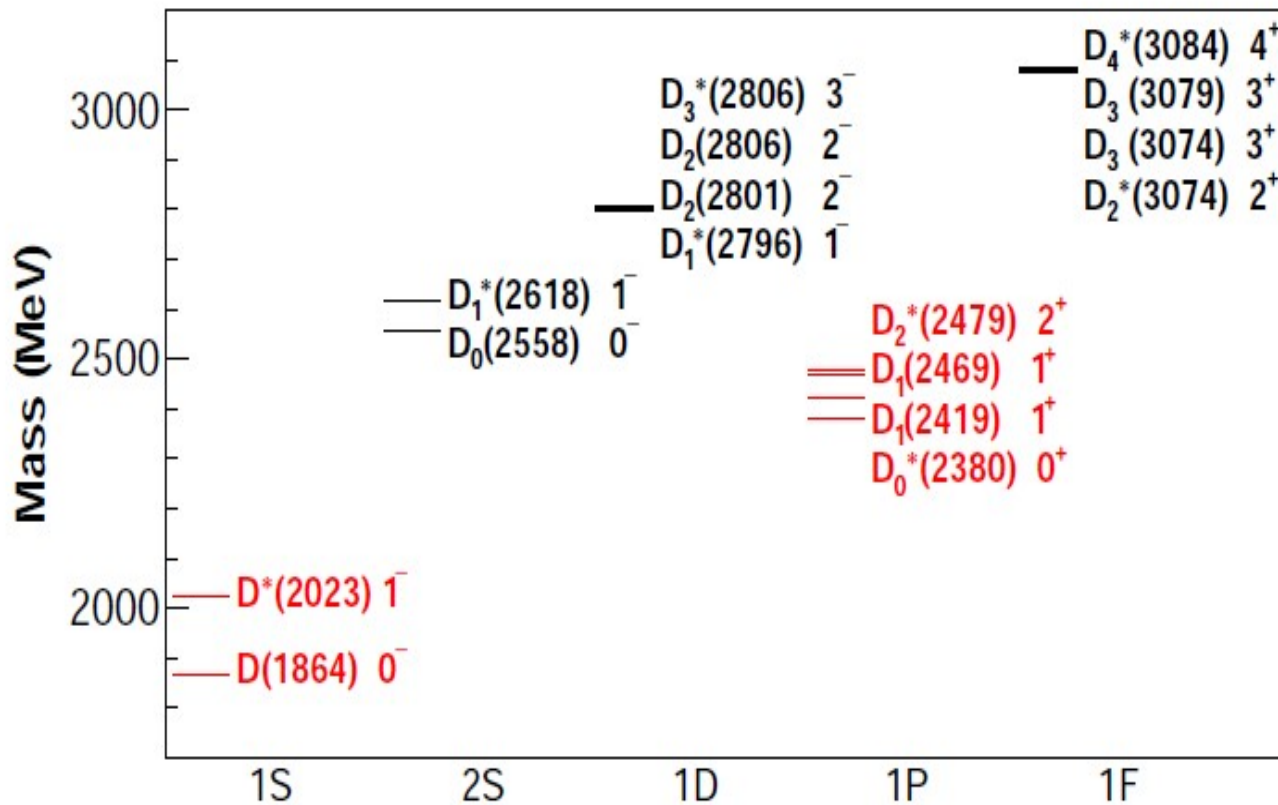
$$M_{\pm} - M_0 = (4.74 \pm 0.28) \text{ MeV}/c^2$$

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

E. Prencipe

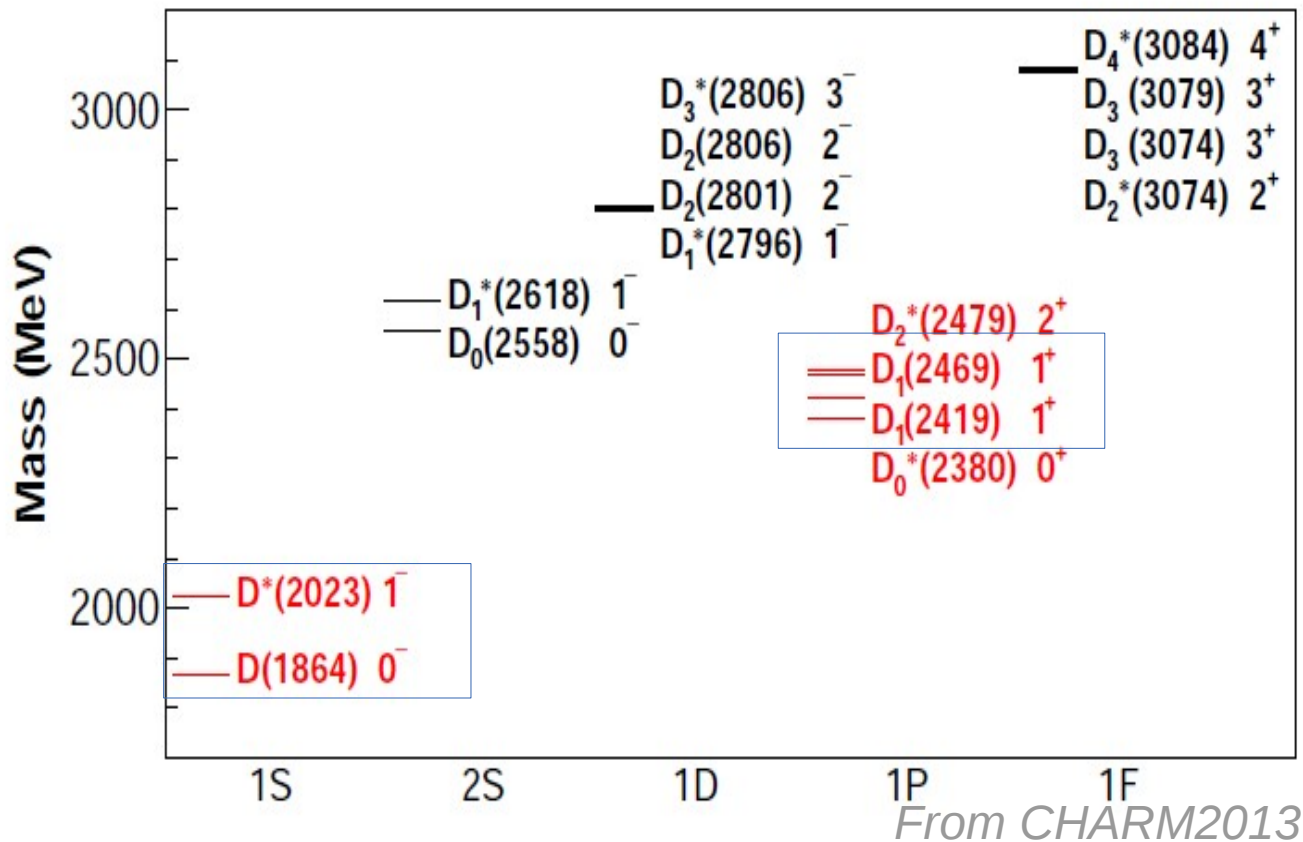


Charm Spectrum, today



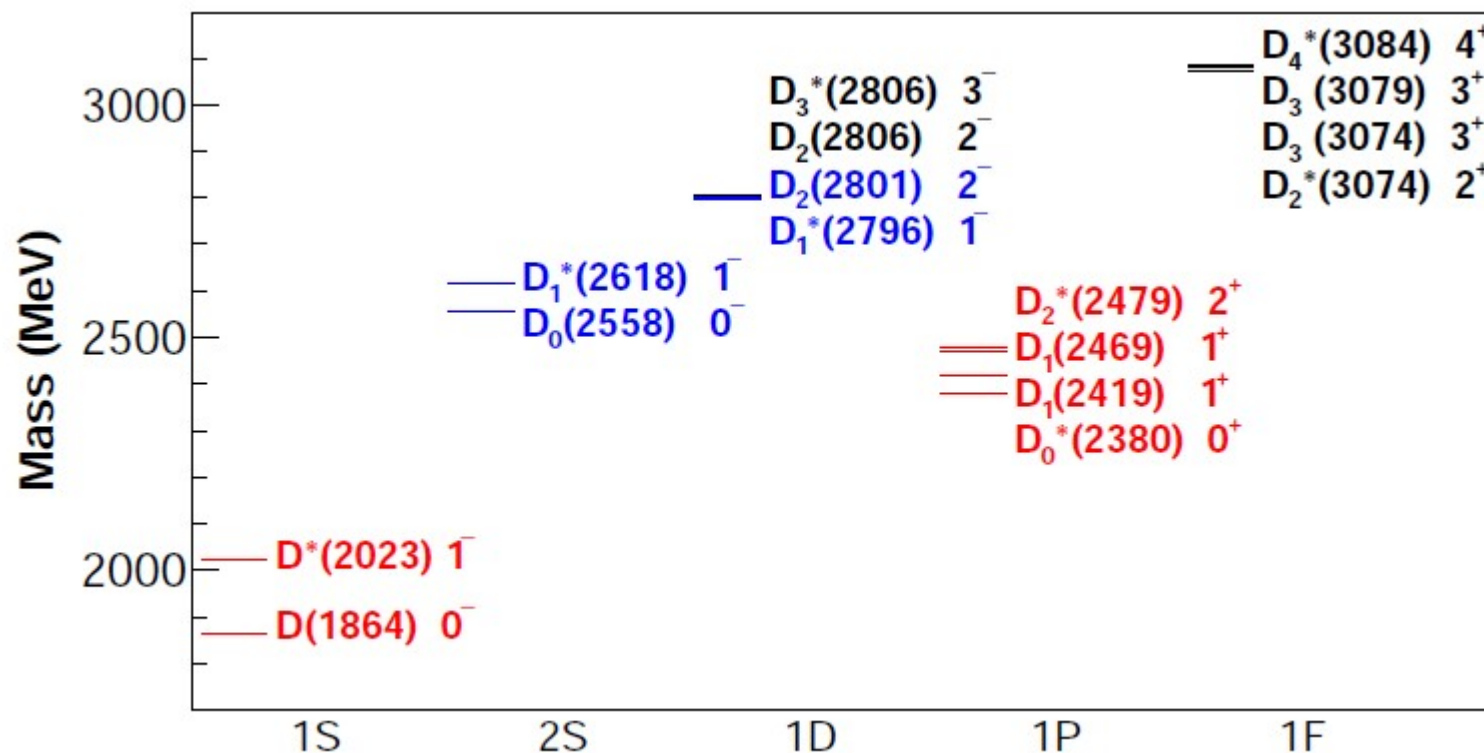
- Ground states (D, D*), and two of 1P states (D₁(2420) and D₂(2460)* experimentally well established: relatively small width (~30 MeV)
 - Broad states with L=1 (D₀*(2400) and D₁'(2430)) are well established from BaBar and Belle in exclusive B decays
 - BaBar recently found new states: D₀(2550), D₀(2560), D₀(2750) and D₀(2760)
- [PRD82, 111101 (2010)]

Charm Spectrum, today



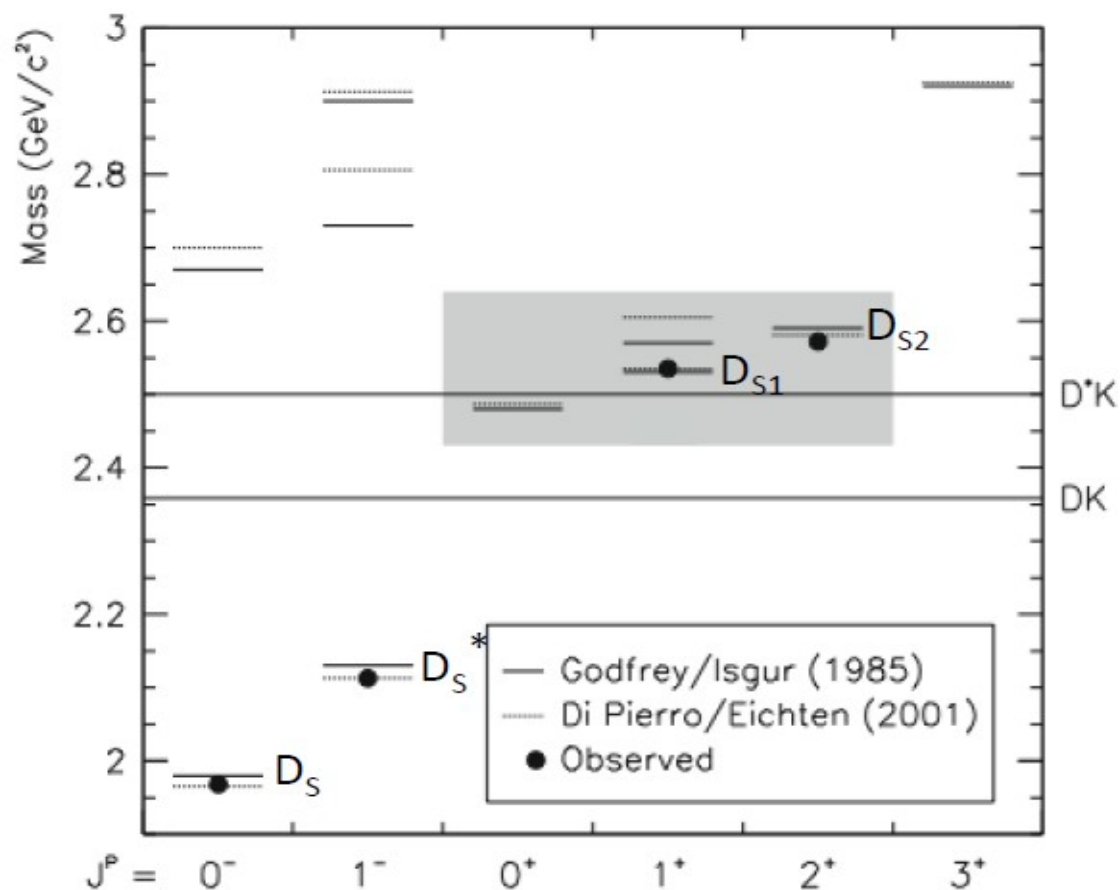
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Interpretation of new D_J mesons



- 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 $D_2(2801)$) 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

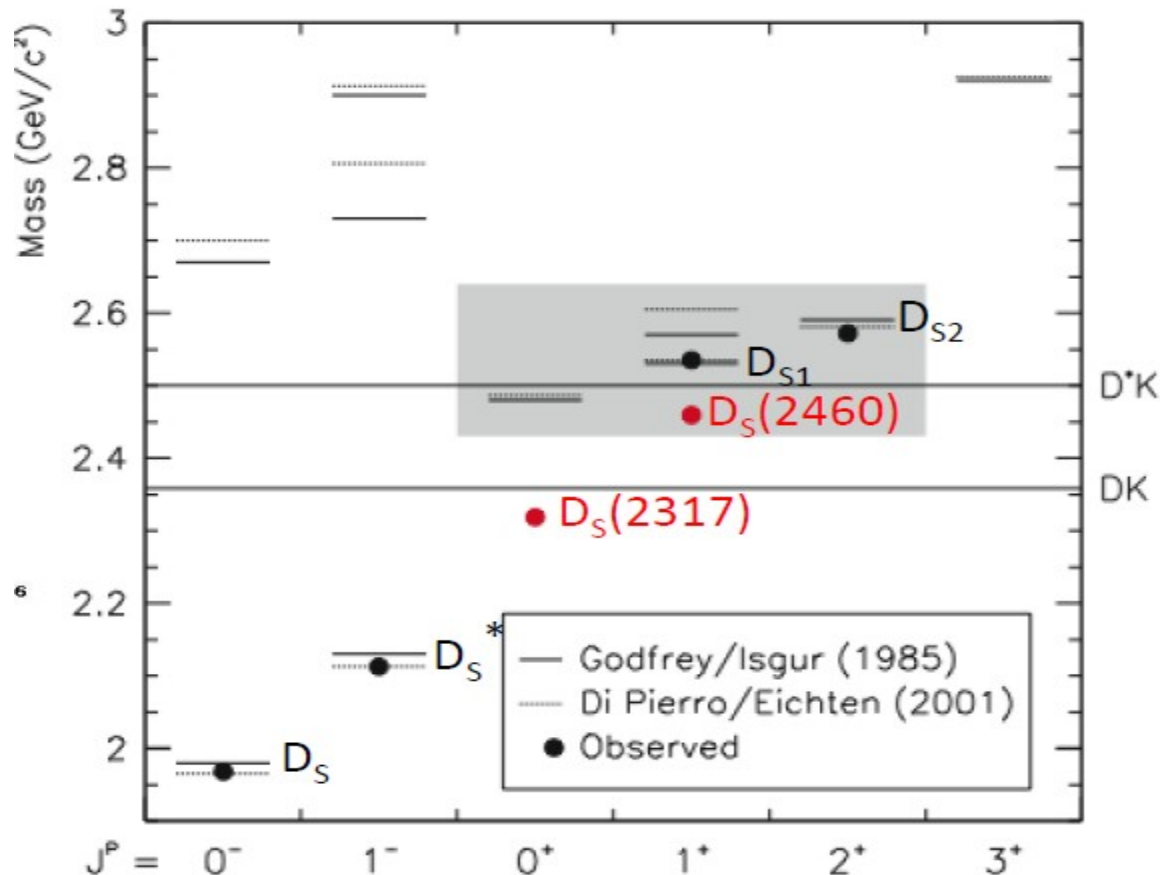


$|\bar{c}u\rangle$ $|\bar{c}d\rangle$ (D_J mesons): theory and experiments were in agreement

$|\bar{c}s\rangle$ (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

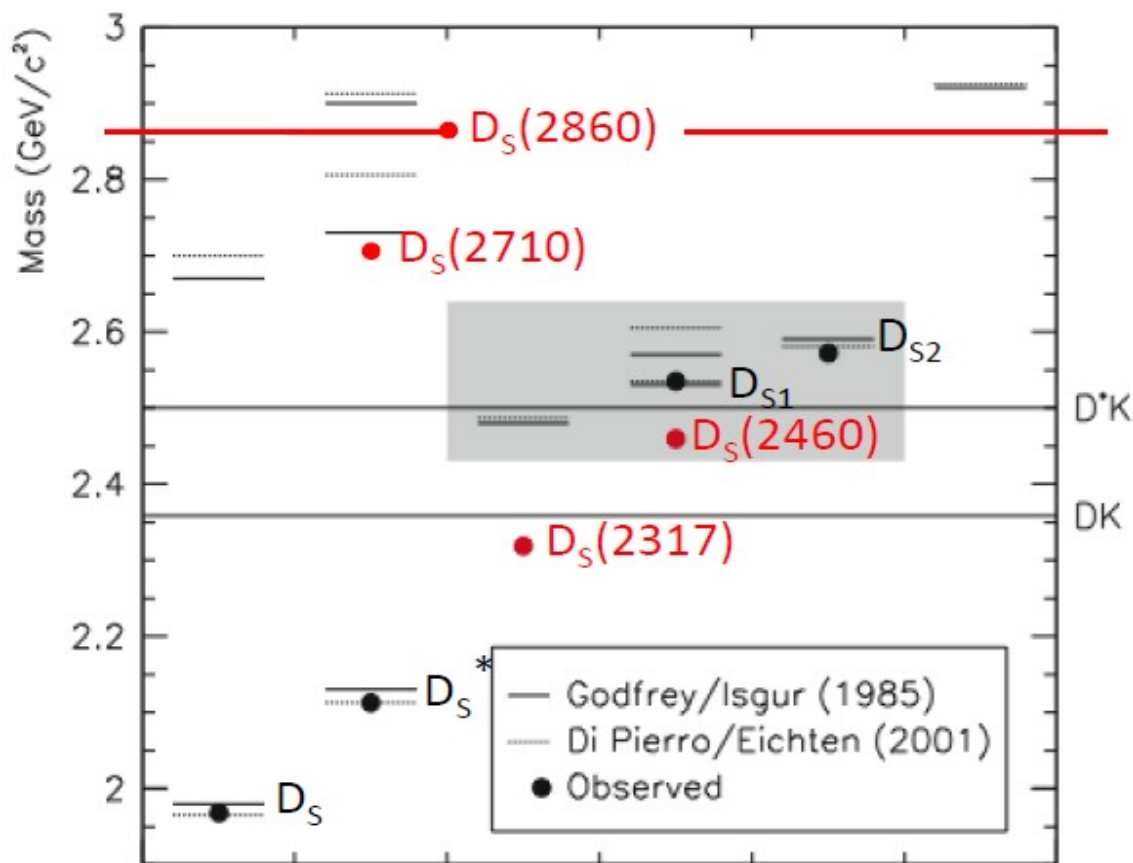


$|\bar{c}u\rangle$ $|\bar{c}d\rangle$ (D_J mesons): theory and experiments were in agreement

$|\bar{c}s\rangle$ (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 $e^+e^- \rightarrow c\bar{c}$, then observed by BaBar [PRL 90 242001 (2003)], Belle [PRL 91 262002 (2003)], CLEO [PRB 340 (1994)]

Excited D_{SJ} mesons



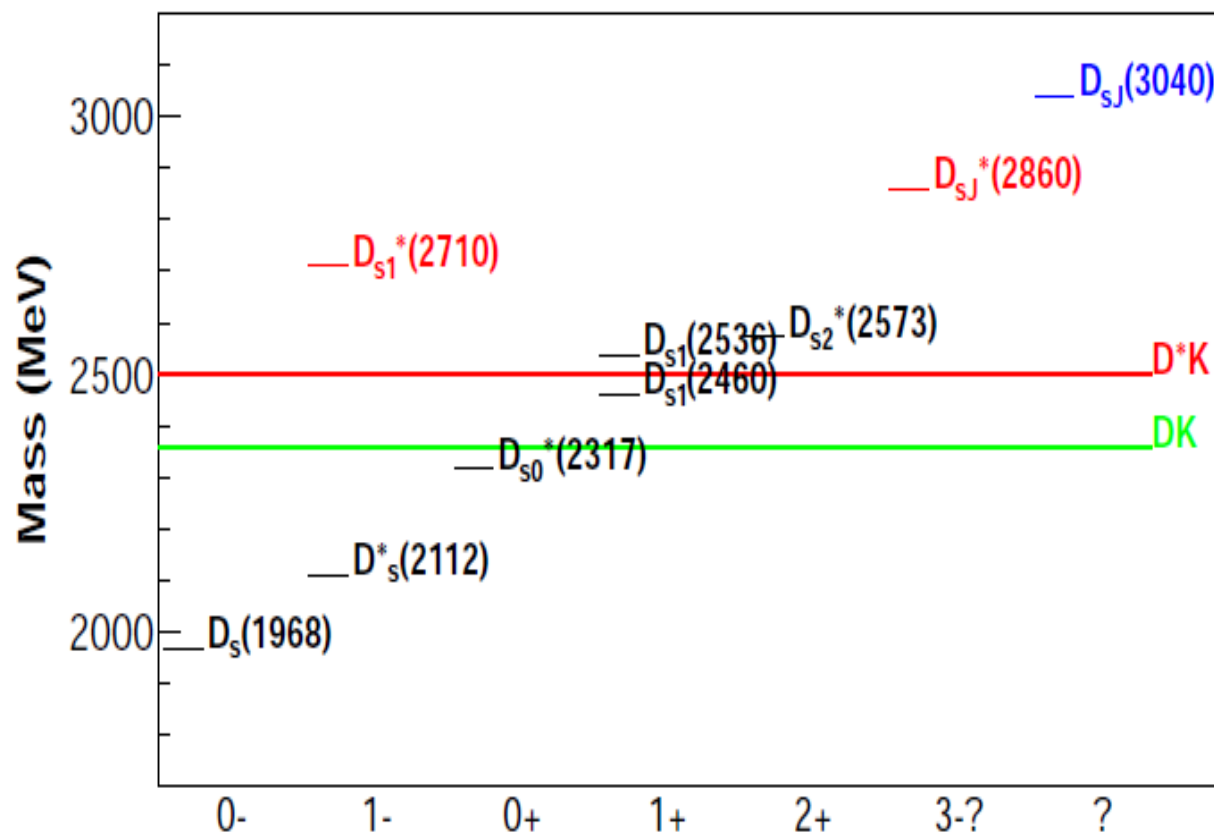
$|\bar{c}u\rangle$ $|\bar{c}d\rangle$ (D_J mesons): theory and experiments were in agreement

$|\bar{c}s\rangle$ (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

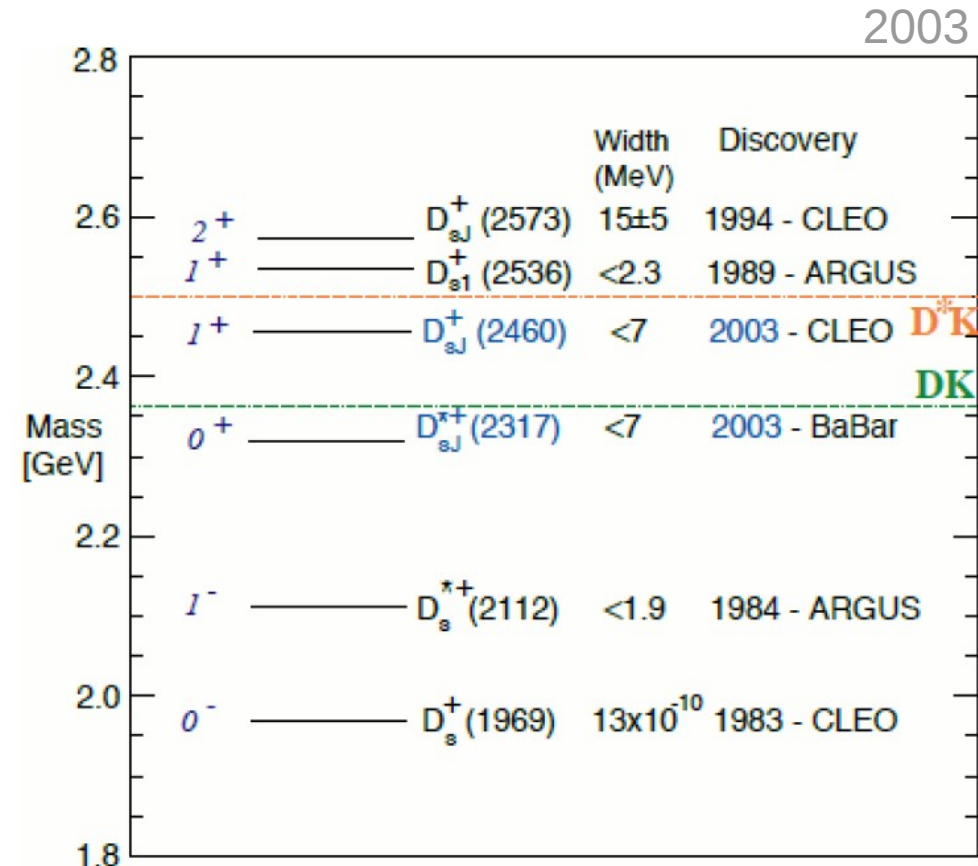


- $D_{s1}^*(2710)$ was found in the analysis of DK and D^*K
- In the same analysis another broad structure was observed: $D_{sJ}(3040)$
- The discovery of all these excited states brought the potential model into questions

How PANDA can contribute?

- Wide and ambitious program: $p\bar{p} \rightarrow D^{(*)}D^{(*)}$, $p\bar{p} \rightarrow D_s^\pm D_s^\mp$, $p\bar{p} \rightarrow D_s^- D_{sJ}^+$
- 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)
- PANDA 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 simulation) will be shown

- Not understood the $D_{sJ}(2317)^+$ nature: 100 MeV lower than the predicted mass by potential model
- Very thin width
- Observed in $D^{(*)+}\pi^0$ system \Rightarrow 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



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

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

Approach	$\Gamma(D_s^0(2317) \rightarrow D_s \pi^0)$ (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. Goetze, Eur. Phys. J. A 21, 501 (2004)	129 ± 43 (109 ± 16)
M.F.M. Lutz, M. Soyeur, 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	$180 \pm 40 \pm 100$ DK had. molecule

- Panda is a fixed target detector
 - High boost $\beta_{\text{cms}} \geq 0.8$
 - Many tracks and photons in fwd acceptance ($\theta \leq 30^\circ$)
(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

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

$$\begin{aligned}
 M &= 2317.8 \pm 0.6 \text{ MeV}/c^2 \\
 \Gamma &< 3.8 \text{ MeV} \\
 M_{D_{s0}^*} - M_{D_{s\pm}} &= 349.3 \pm 0.6 \text{ MeV}/c^2
 \end{aligned}$$

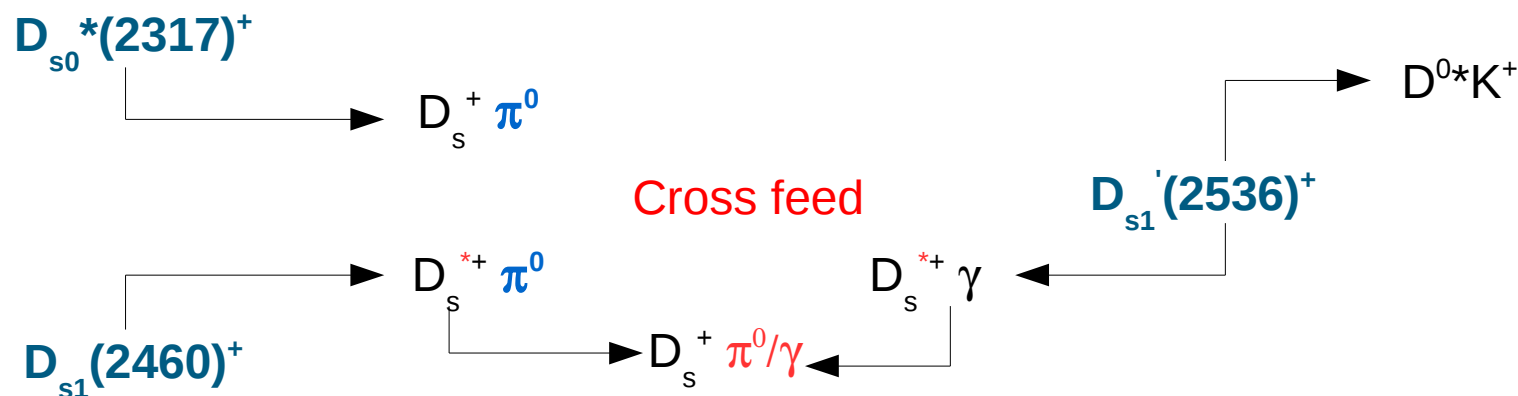
$D_{s1}(2460)^+$

$$\begin{aligned}
 M &= 2459.6 \pm 0.6 \text{ MeV}/c^2 \\
 \Gamma &< 3.5 \text{ MeV} \\
 M_{D_{s1\pm}} - M_{D_{s\pm}} &= 347.2 \pm 0.7 \\
 M_{D_{s1\pm}} - M_{D_{s\pm}} &= 491.1 \pm 0.7
 \end{aligned}$$

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

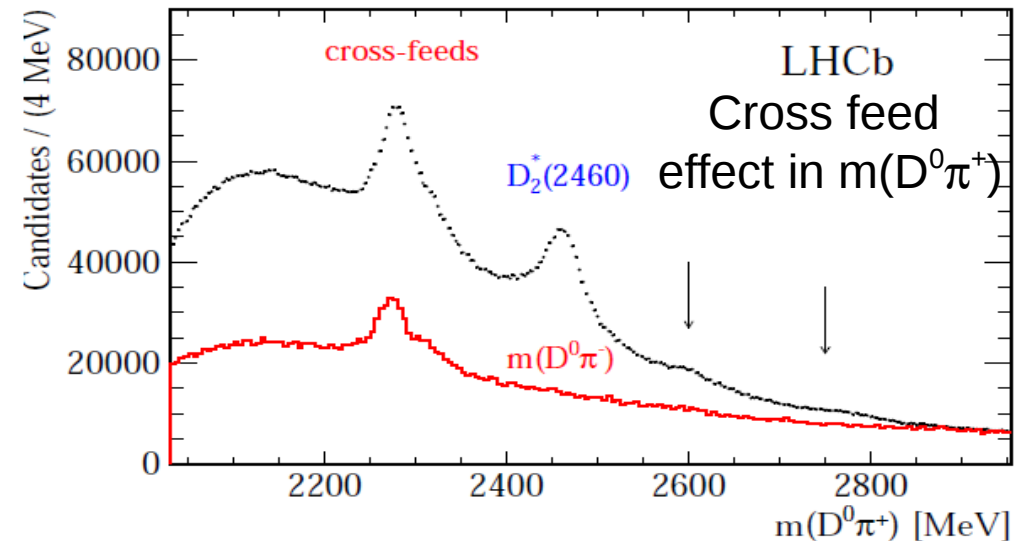
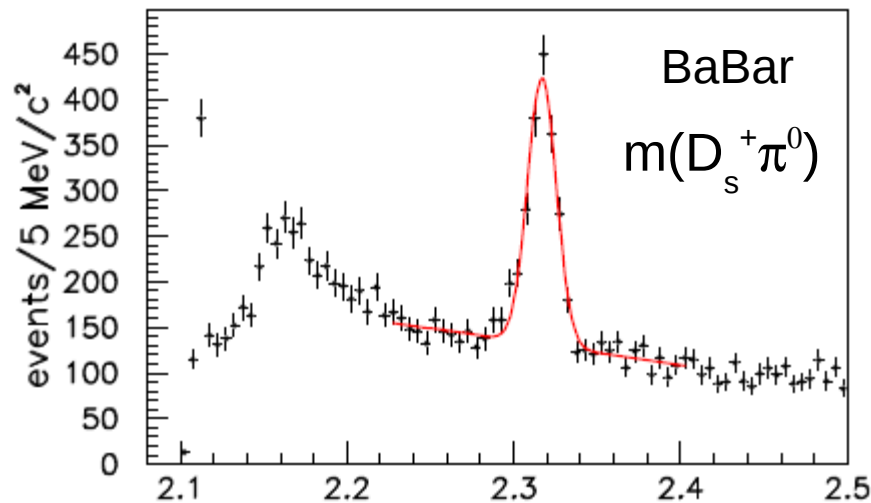
$$\begin{aligned}
 M &= 2535.12 \pm 0.13 \text{ MeV}/c^2 \\
 \Gamma &= 0.92 \pm 0.05 \text{ MeV} \\
 M_{D_{s1\pm}'} - M_{D_{s\pm}^*} &= 422.8 \pm 0.5 \\
 M_{D_{s1\pm}'} - M_{D_{s\pm}} &= 584.84 \pm 0.04 \\
 M_{D_{s1\pm}'} - M_{D_{s0}^*} &= 528.14 \pm 0.08
 \end{aligned}$$

- 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 $pp \rightarrow D_s^- D_{sJ}^+$



- System of heavy-light quark ($c = \text{heavy}; s = \text{light}$)
The angular momentum $j = l + s$ (light quark) is conserved
P wave states $\Rightarrow j = 3/2$ 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; $a|A\rangle \pm b|B\rangle$
 $D_{s1}(2460)^+ \quad j=1/2$ (supposed to be pure S-wave)
 $D_{s1}(2536)^+ \quad j=3/2$ (supposed to be pure D-wave)
- Experiments showed an overlap between S- and D- waves
 $\Delta m = 78 \text{ MeV}/c^2$. **Why are they so thin ($\Gamma < 2.3 \text{ MeV}$), and they mix?**

PANDA could solve this puzzle!



- 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 $\sim 345 \text{ MeV}/c^2$. Experiments quote:
 $m(D_s^+ \pi^0) - m(D_s) = (350.0 \pm 1.2 \pm 1.0) \text{ MeV}/c^2$ ($D_{sJ}(2317)^+$ was observed in $D_s^+ \pi^0$)
 $m(D_s^{*+} \pi^0) - m(D_s^*) = (351.2 \pm 1.7 \pm 1.0) \text{ MeV}/c^2$ ($D_s(2460)^+$ was observed in $D_s^{*+} \pi^0$)

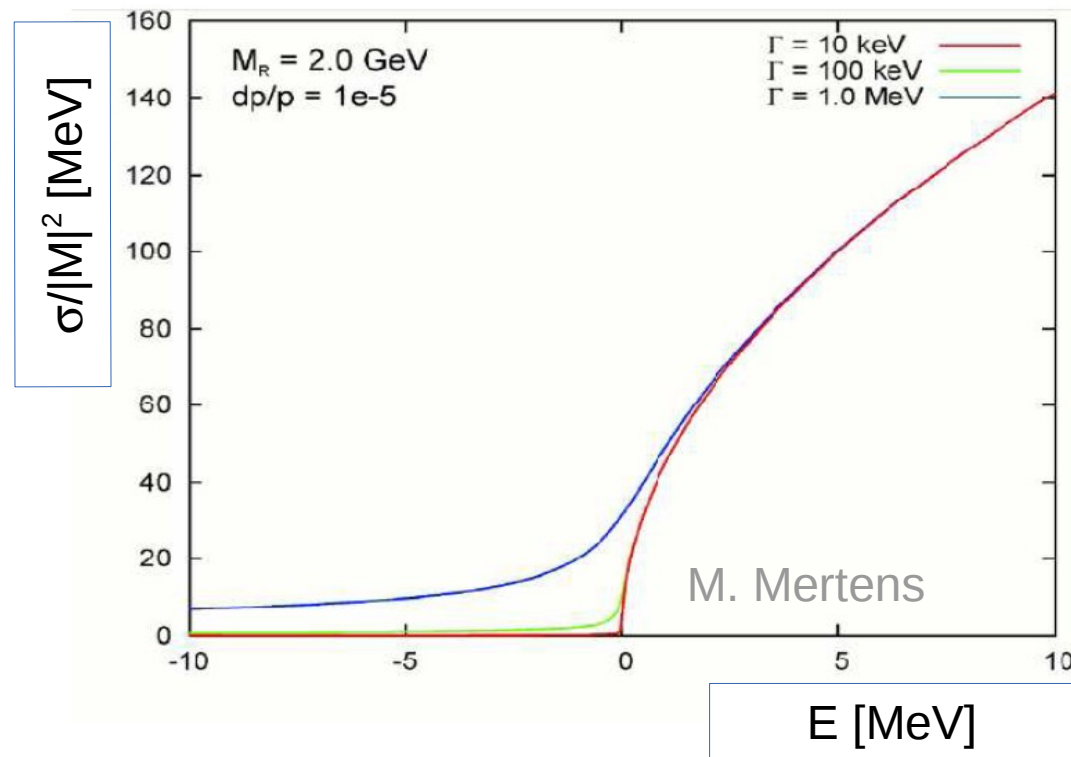
$$\sigma(\lambda) = \sqrt{m_R \Gamma} |M^2| \frac{1}{\pi} \int_{-\infty}^{\lambda} dx, \frac{\sqrt{\lambda - x}}{x^2 + 1}$$

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

M = proton mass

M_R = mass of D_{sJ}

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



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

- 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 \overline{PANDA} can do that!)
- **Advantage** in \overline{PANDA} :
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

- Expected number of events in PANDA = $\mathcal{L} * \sigma * \epsilon$

Cross section:

20 ÷ 100 nb

<http://arxiv.org/abs/1111.3798>

A. Khodjamirian, Ch. Klein, Th. Mannel, Y.M. Wang

Luminosity = $2 * 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

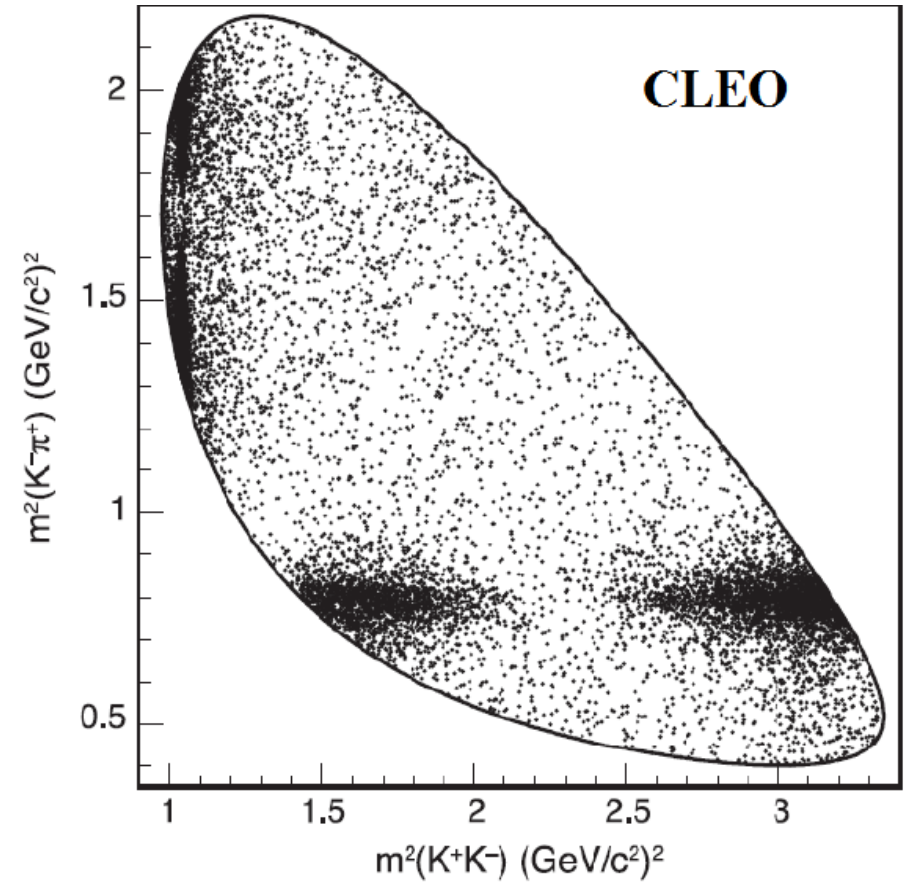
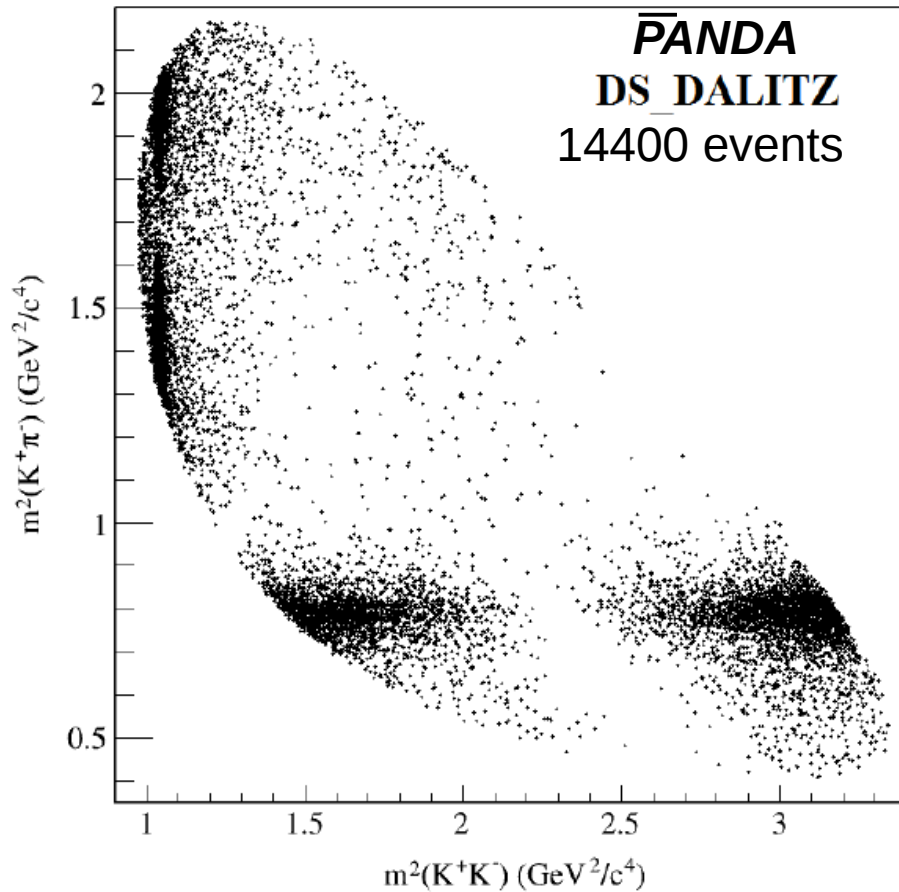
8.64 pb⁻¹/day

N expected = 8.64 pb⁻¹/day * (20 ÷ 100)nb * ϵ ~ (160k ÷ 1M) * ϵ /day

NB. Estimation is valid in high resolution mode: otherwise we expect a factor 10 less

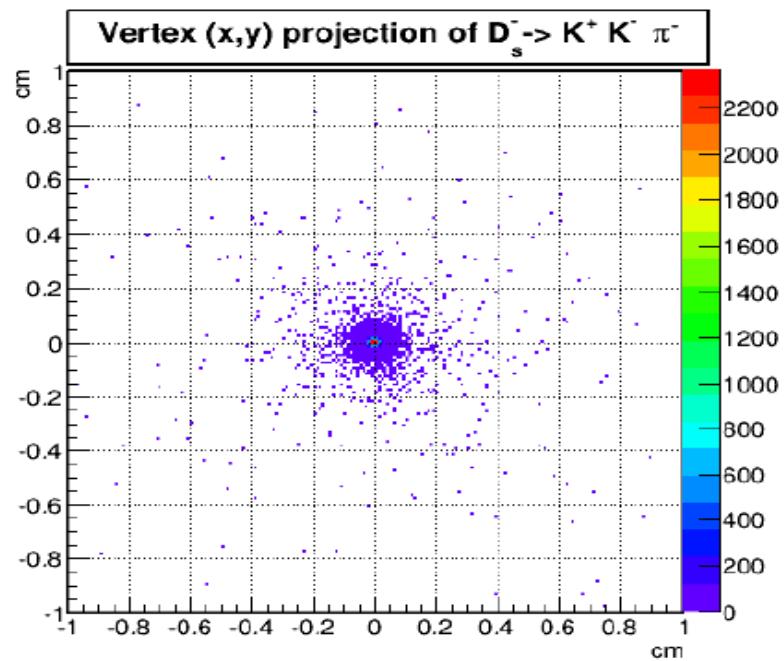
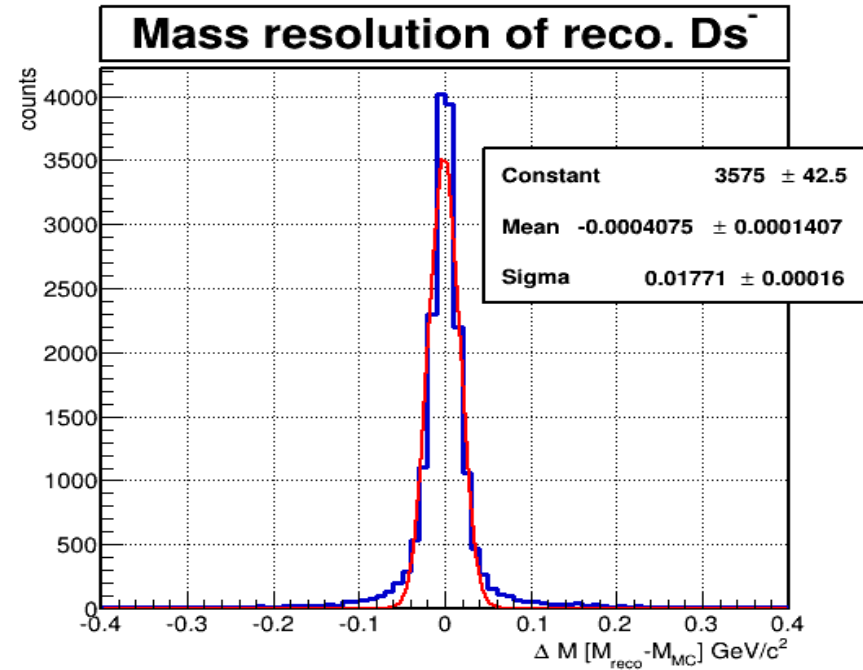
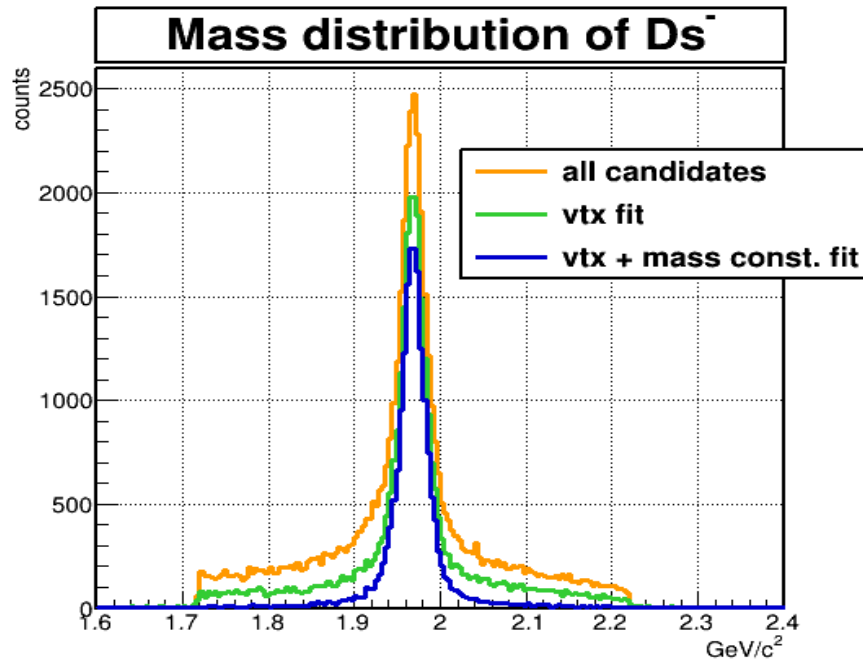
$\Delta p/p \sim 10^{-5}$

D_s reconstruction: Dalitz model



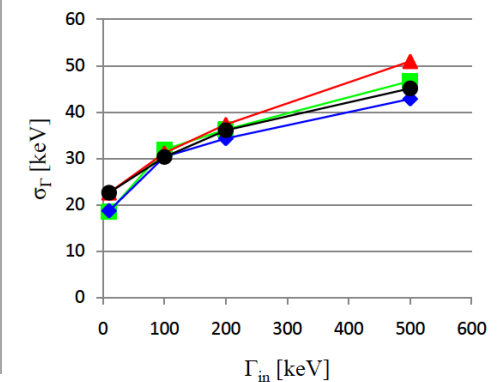
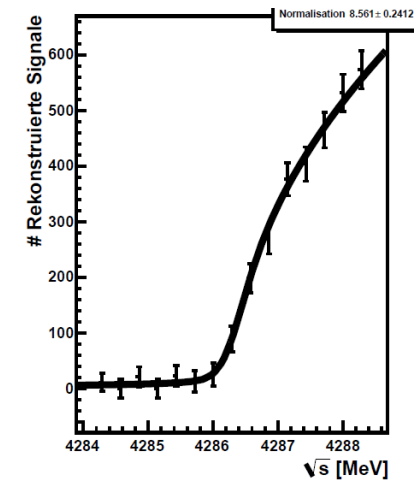
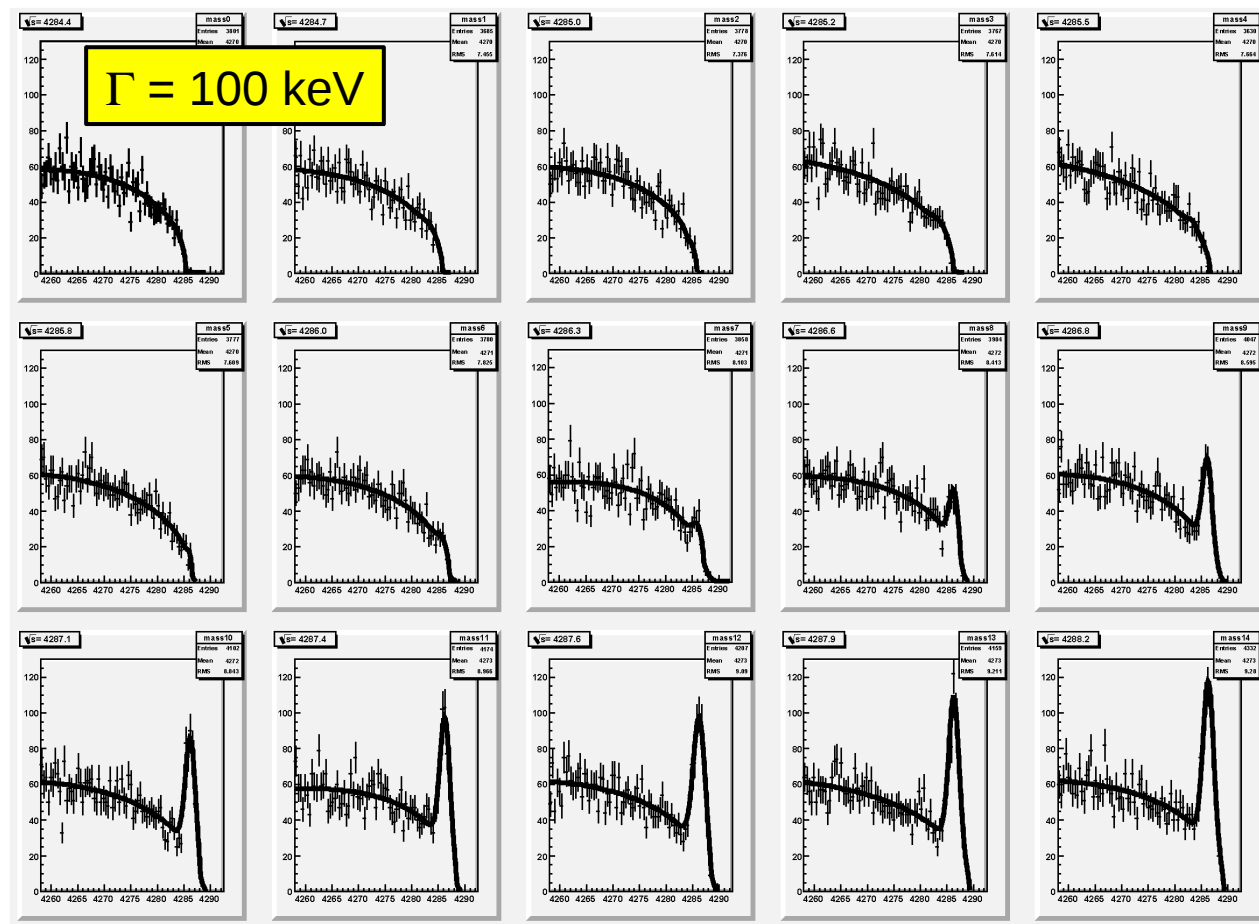
L.Cao

Mass resolution



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

$$M_{\text{sum}} = M_{\text{miss}}(D_s) + M(D_s)$$



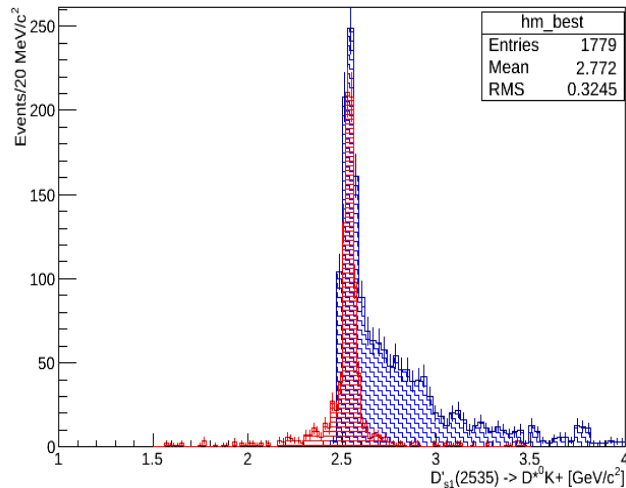
PRELIMINARY

M. Mertens

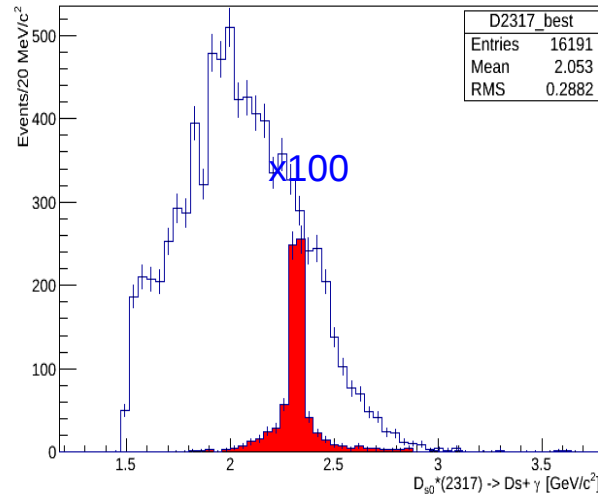
D_s and D_{sJ} reconstruction with PandaRoot

Work in progress...

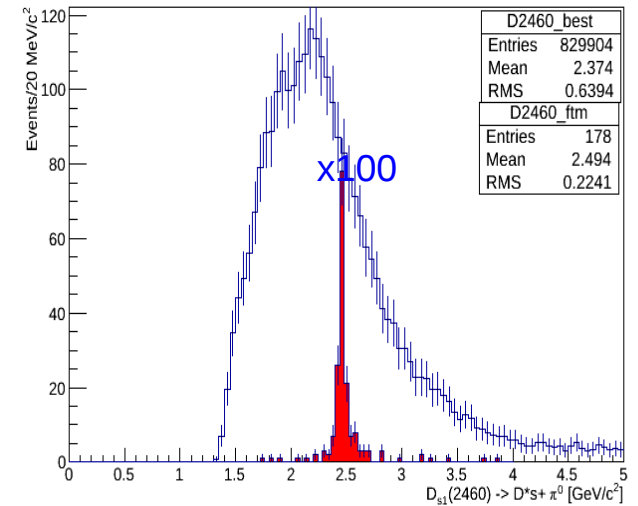
$D_{s1}'(2536)^+$



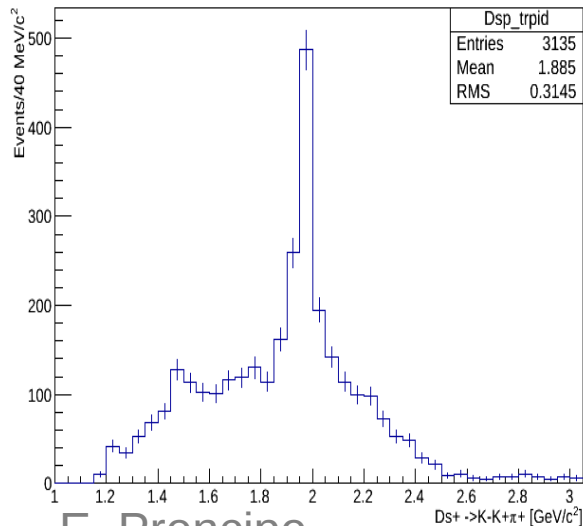
$D_{s0}^*(2317)^+$



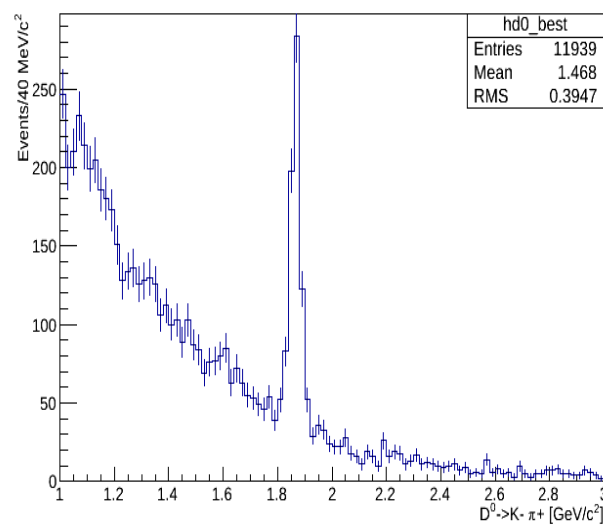
$D_{s1}(2460)^+$



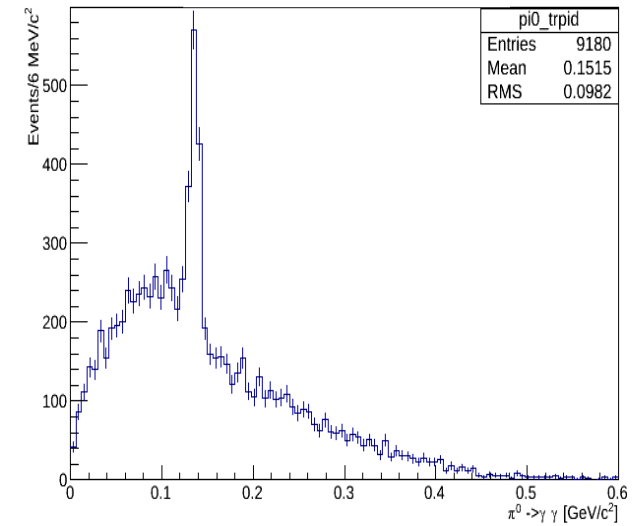
D_s^+



D_0



π^0



E. Prencipe

- 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 states is needed
- Progresses done at LHCb, after the B factory measurements: still not enough
- The future project *PANDA* 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!