Hadrons with *c-s* quark content: present, past, and future

January 29th, 2015 | Elisabetta Prencipe, Forschungszentrum Jülich | *LIII* International winter Meeting on Nuclear Physics - Bormio

Outline

- Motivation
- Theoretical overview
- Recent observations
- The role of the $\overline{\text{P}}$ANDA experiment
- Future perspectives
- Conclusion

Introduction

Since 2003

- Unexpected observations posed the potential models into questions
- Charm (cq) and Charmonium ($c\bar{c}$ + $q\bar{q}$) sectors populated by several new states
- Strangeness in Charm and Charmonium physics still to be exploited;
  recent highlights in Charmonium: Y(4140) and Y(4270), and study of m(J/ψϕ).
  [BaBar, Belle, BES III, CDF, CMS, D0, LHCb]:
  - still to be understood
  - different interpretations
- Charm sector: D mesons interesting for weak- and strong- interactions.
  D and D_s mesons predicted;
  D_s mesons below DK threshold still of unclear interpretation [BaBar, Belle, CLEO2]:
  limitations due to the past experiments to measure the D_s line shape.

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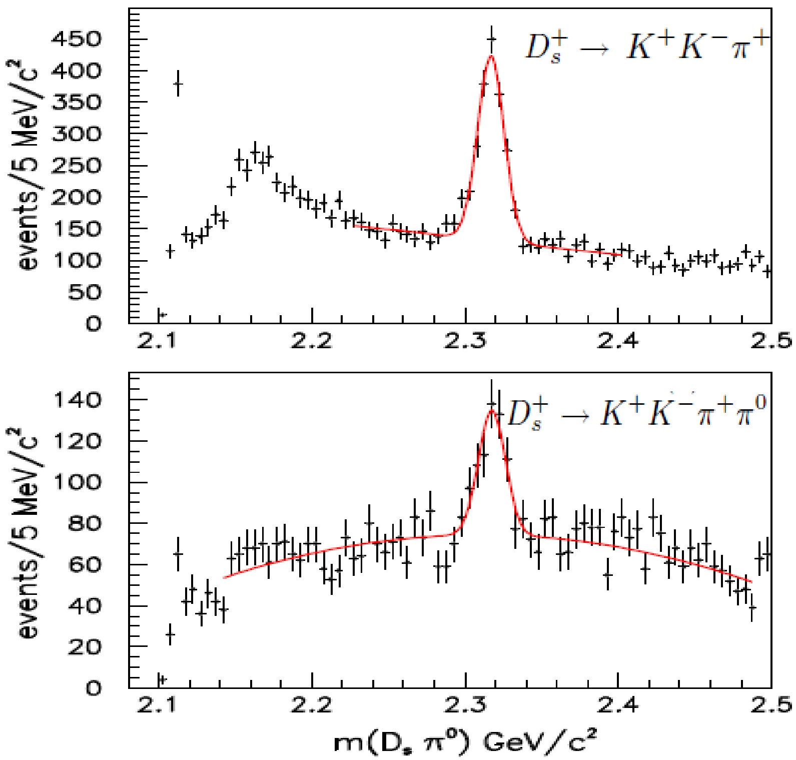
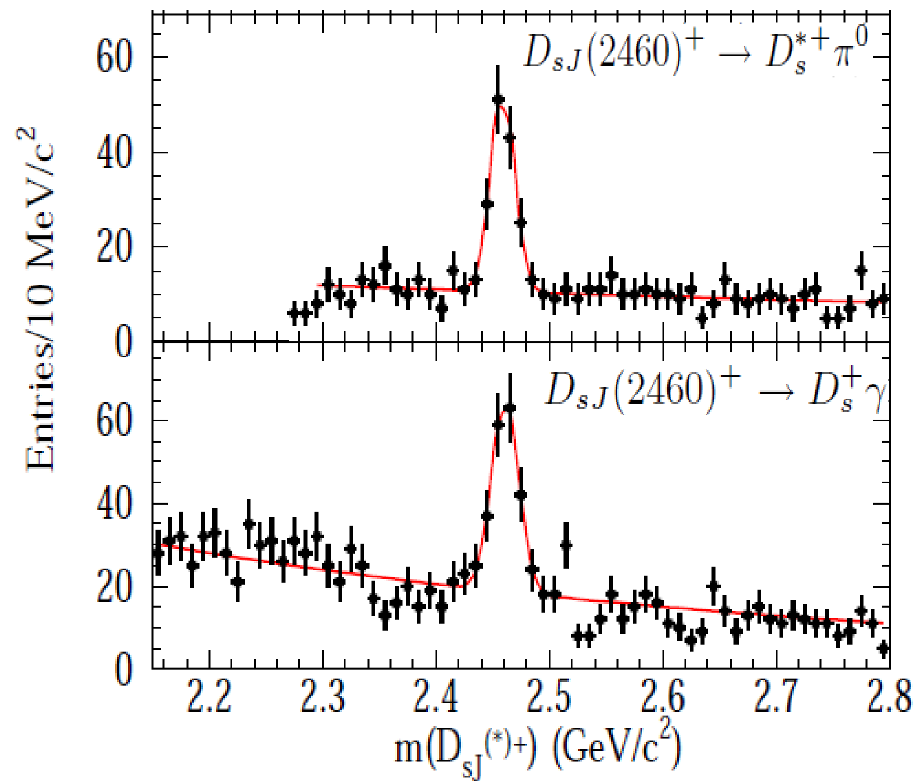
This talk is mainly devoted to the D_s spectroscopy challenges
STRONG INTERACTIONS

Observation of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

BABAR, PRL 90 (2003) 242001



BABAR, PRL 93 (2004) 181801



$m(D_{s0}^*(2317)^+) = (2317.7 \pm 0.6)$ MeV/c^2

$m(D_{s0}^*(2317)^+ - m(D_s^+)) = (349.4 \pm 0.6)$ MeV/c^2

$\Gamma < 3.8$ MeV CL=95.0%

$m(D_{s1}(2460)^+) = (2459.5 \pm 0.6)$ MeV/c^2

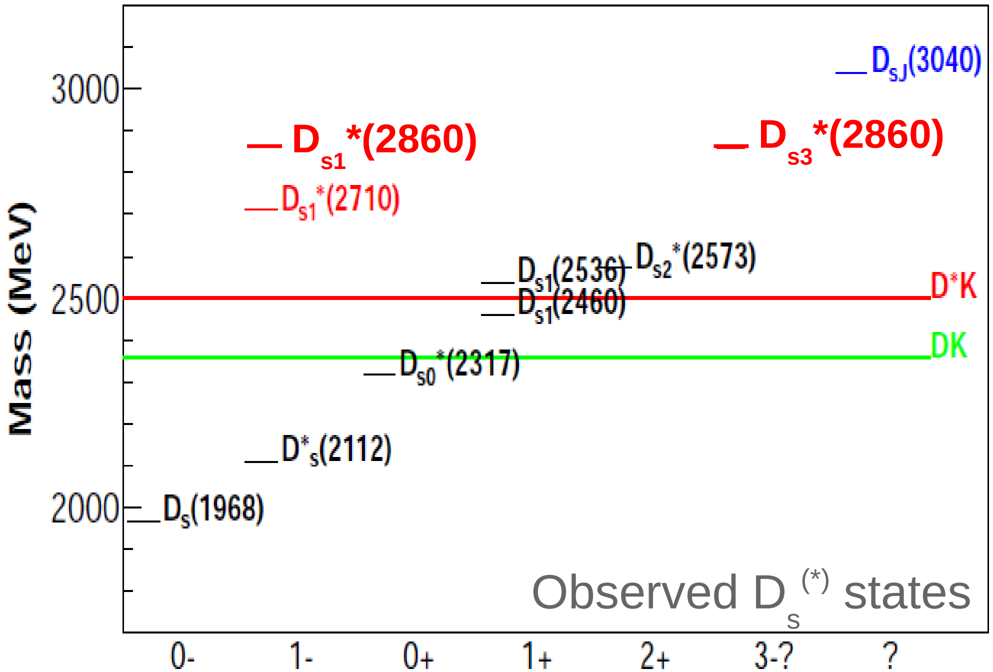
$m(D_{s1}(2460)^+ - m(D_s^{*+})) = (347.3 \pm 0.7)$ MeV/c^2

$m(D_{s1}(2460)^+ - m(D_s^+)) = (491.2 \pm 0.6)$ MeV/c^2

$\Gamma < 3.5$ MeV CL=95.0%

- What did we learn after 12 years?

D_s spectroscopy, today



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

D_s mesons: $|c\bar{s}\rangle$

Predicted from Godfrey-Isgur (1985);
Update: Di Pierro- Eichten (2001)

- Many excited D_s states have been found:

  some of these not in agreement with potential models (→below the DK threshold); the identification of $D_{s0}*(2317)$ and $D_{s1}(2460)$ states as 0^+ or 1^+ *cs* states is difficult to accommodate in the potential models.

- LHCb recently performed amplitude analyses:

  $D_{s2}(2573)$ confirmed with J=2;

  $D_{s1-3}*(2860)$: for the first time a heavy flavored J=3 state is observed.

Experimental overview of D_{s0}*(2317) and D_{s1}(2460)

Decay Channel	$D^*_{sJ}(2317)^+$	$D_{sJ}(2460)^+$
$D_s^+\pi^0$	Seen	Forbidden
$D_s^+\gamma$	Forbidden	Seen
$D_s^+\pi^0\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\pi^0$	Forbidden	Seen
$D^*_{sJ}(2317)^+\gamma$	—	Seen
$D_s^+\pi^0\pi^0$	Forbidden	Allowed
$D_s^+\gamma\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\gamma$	Allowed	Allowed
$D_s^+\pi^+\pi^-$	Forbidden	Seen

(a) Non-resonant only

- Most of theoretical works treat *$c\bar{s}$-systems* as the hydrogen atom (potential models, c=heavy quark):
- $D_{s1}(2317)^+$ and $D_{s2}(2460)^+$ are predicted, found with good accuracy <u>but</u>:

m(D_{s0}*(2317)$^+$) found 180 MeV lower

m($D_{s1}(2460)^+$) found 70 MeV lower

than predicted by potential models

- $D_{s0}^*(2317)^+$ is found below the DK threshold:
- $D_{s0}^*(2317)^+$ can in principle decay
  - electromagnetically (no exp. evidence); or
  - through isospin-violation $D_s^+\pi^0$ strong decay

- $D_{s1}(2460)^+$ is found in the inv. mass $D_s^+\gamma$
- Spin <u>at least</u> 1
- We can exclude the hypothesis 0^+, because $D_{s1}(2460)^+ \rightarrow D_s^+\gamma$

Is D_{s0}^* the missing 0^+ state of the *$c\bar{s}$-spectrum*?

Is D_{s1} the missing 1^+ of the *$c\bar{s}$-spectrum*?

Do these 2 particles belong to the same family of exotics?

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

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Different theoretical approaches, different interpretations	$\Gamma(D_{s0}^*(2317)^+ \to D_s \pi^0)$ (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
M.F.M. Lutz, M. Soyeaur, Nucl. Phys. A 813, 14 (2008)	**140** Dynamically gen. resonance
L. Liu, K. Orginos, F. K. Guo, C. Hanhart, Ulf-G. Meißner Phys. Rev. D 87, 014508 (2013)	**133 ± 22** DK had. molecule
M. Cleven, H. W. Giesshammer, F. K. Guo, C. Hanhart, Ulf-G. Meißner Eur. Phys. J A (2014) 50 -149	NEW! Strong and radiative decays of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

- The measurement of the **narrow width** plays a leading role in the interpretation of D_s^*

D_{S0}^* and D_{s1} theoretical overview: Hadronic width

M. Cleven, H. W. Griesshammer, F.-K. Guo, C. Hanhart, Ulf-G. Meissner, Eur. Phys. J. A(2014) 50, 149

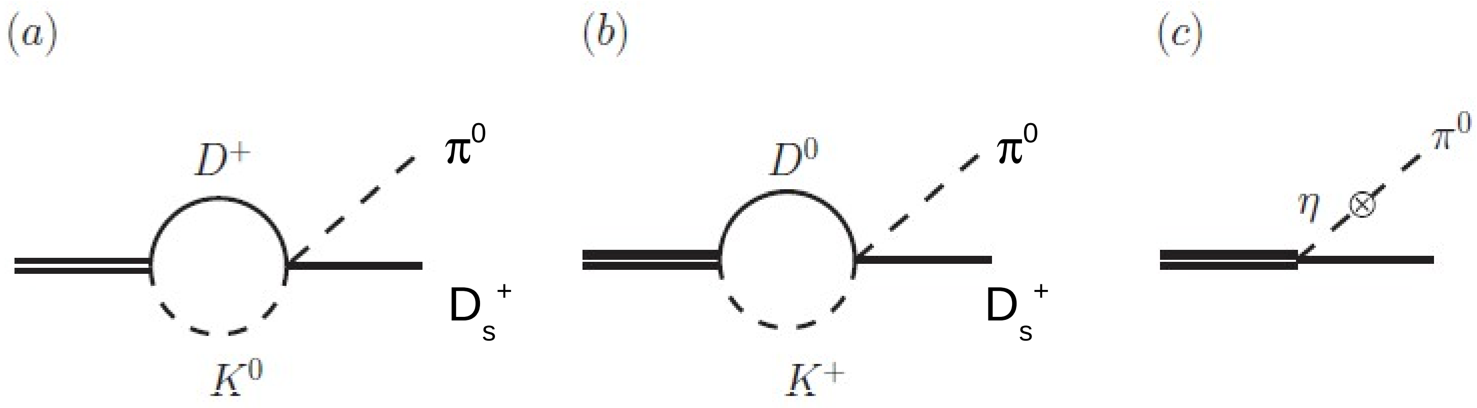


Figure 2: The two mechanisms that contribute to the hadronic width of the D_{s0}^*. (a) and (b) represent the nonvanishing difference for the loops with D^+K^0 and D^0K^+, respectively. (c) depicts the decay via π^0-η mixing.

- Contribution (a) – (b) non-zero for $m_{D+} \neq m_{D0}$, $m_{K+} \neq m_{K0}$; this applies to molecular states

Table 2: Hadronic decay widths from different mechanisms.

Decays	loops	π^0-η mixing	full result
$D_{s0}^* \to D_s\pi^0$	(26 ± 3) keV	(23 ± 3) keV	(96 ± 19) keV
$D_{s1} \to D_s^*\pi^0$	(20 ± 3) keV	(19 ± 3) keV	(78 ± 14) keV

D_{S0}^* and D_{s1} theoretical overview: Radiative width

M. Cleven, H. W. Griesshammer, F.-K. Guo, C. Hanhart, Ulf-G. Meissner, Eur. Phys. J. A(2014) 50, 149

Table 3: The decay widths (in keV) calculated only from the coupling to the electric charge (EC), from the magnetic moments (MM) and from the contact term (CT), respectively, compared to the total (including interference). The CT strength for the transitions to odd parity mesons is fixed to data, while that to even parity states, marked as '?', is undetermined and part of the uncertainty.

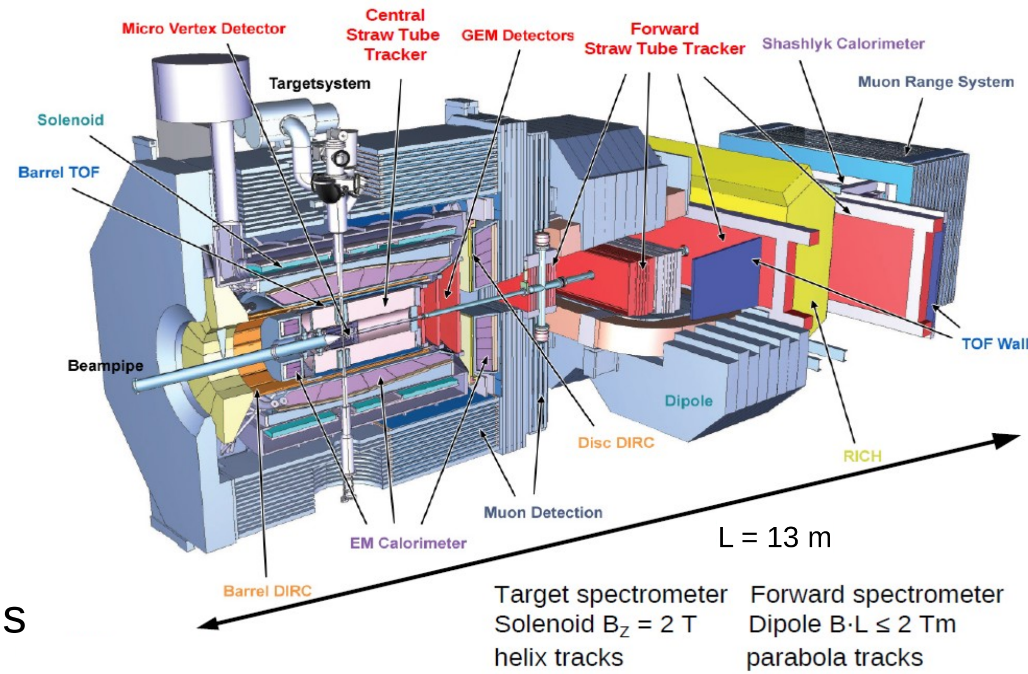
Decay Channel	EC	MM	CT	Sum	[1]	[2]	[3,4,5]
$D_{s0}^* \to D_s^* \gamma$	2.0	0.03	3.3	9.4	4 – 6	1.94(6.47)	0.55-1.41
$D_{s1} \to D_s \gamma$	4.2	0.2	11.3	24.2	19 – 29	44.50(45.14)	2.37-3.73
$D_{s1} \to D_s^* \gamma$	9.4	0.5	10.3	25.2	0.6 – 1.1	21.8(12.47)	–
$D_{s1} \to D_{s0}^* \gamma$	–	1.3	?	1.3	0.5 – 0.8	0.13(0.59)	–

[1] P. Colangelo, F. De Fazio, A. Ozpineci. PRD 72, 074004 (2005);
[2] M. F. M. Lutz, M. Soyeur, Nucl. Phys. A 813, 14 (2008);
[3] A. Faessler, T. Gutsche, V. E. Lyubovitskij and Y. L. Ma, PRD 76, 014005 (2007);
[4] A. Faessler, T. Gutsche, V. E. Lyubovitskij and Y. L. Ma, PRD 76, 114008 (2007);
[5] A. Faessler, T. Gutsche, V. E. Lyubovitskij and Y. L. Ma, PRD 77, 114013 (2008).

- **Only hadronic decays are sensitive to a possible molecular component of D_{s0}^* and D_{s1}**
- **Hadronic width of ≥ 100 keV: unique feature for molecular state**
- **Demand for a new generation machine: Δm ~100 keV, 20 times better than attained at B factories**

The detector $\bar{P}$ANDA @ FAIR

- $\bar{P}$ANDA is a fixed target detector, with antiproton beam up to p = 15 GeV/c
  - Why antiprotons?
    access to all quantum numbers!
  - Particles in formation:
    mass resolution ~ 100 KeV
  - $\Delta p/p$: $[10^{-4} - 10^{-5}]$
  - High boost $\beta_{cms} \geq 0.8$
  - Many tracks and photons in fwd acceptance ($\theta \leq 30°$), high p_z, E_γ

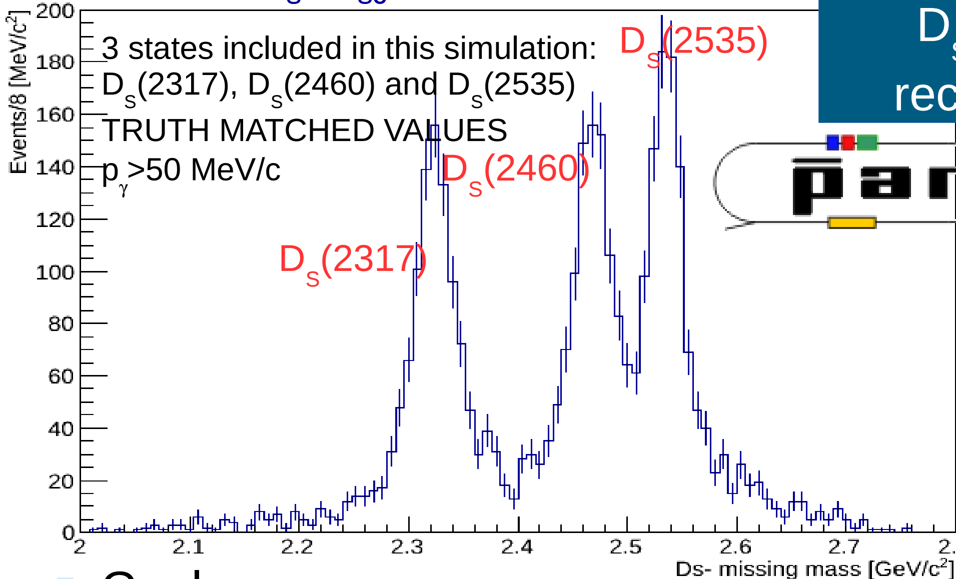


- High background from hadronic reactions
  - Expected S/B ~ 10^{-6}
  - S (signal) and B (background) have same signature
  - Hardware trigger not possible
  - Self-triggered electronics
  - Free streaming data
  - 20 MHz interaction rate
  - Complete real-time event reconstruction

Challenges in D_s meson spectroscopy

arXiV:1410.5201 [hep-ex]

- $\bar{p}p \rightarrow D_s^- D_{sJ}^{(*)+}$



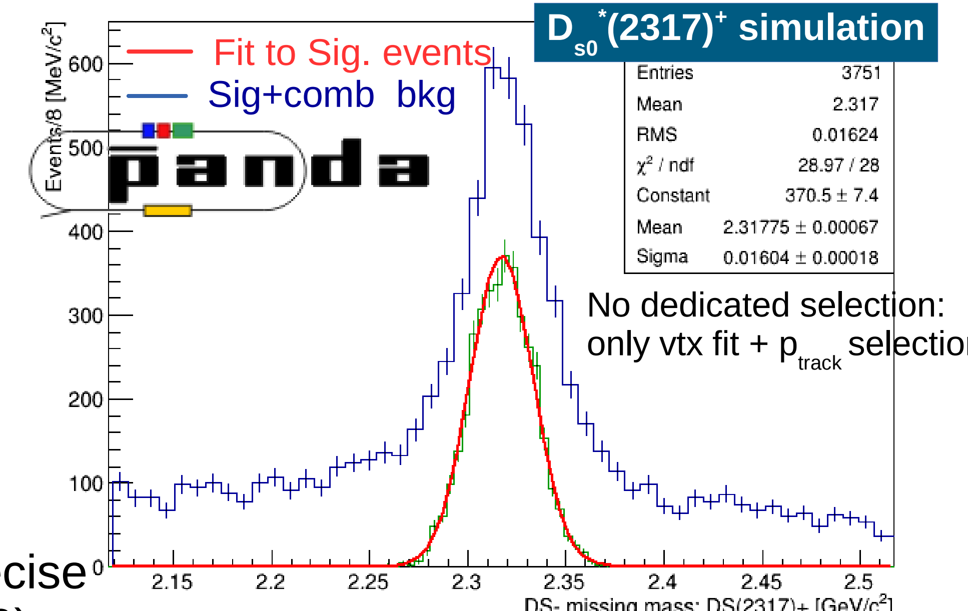
D_s^- recoil

- Missing mass of D_s^-: improve mass resolution and efficiency
- D_{SJ} reconstructed exclusively to evaluate the width
- Bkg cross section > thousand times than expected on signal

- Goals:

1. Cross section measurement in $\bar{p}p$ (unknown, difficult predictions: [1-100] nb)
2. Measurement of the width with mass scan and the excitation function of cross section
3. Mixing between D states with same J^P, e.g. $D_{S1}(2460)$ and $D_{S1}(2535)$
4. Chiral symmetry breaking, involving very precise mass measurement: $D_{S0}(2317)$ and $D_{S1}(2460)$ can be interpreted as chiral partners of the same heavy-light system
5. Study of the invariant mass system $D_s^- D_s^{*+}$

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

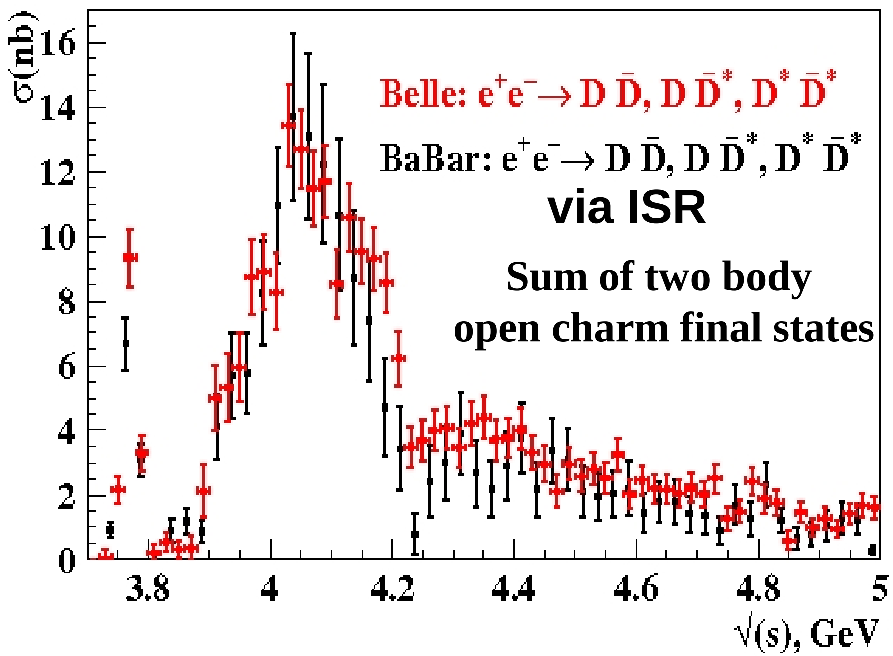


No dedicated selection: only vtx fit + p_{track} selection

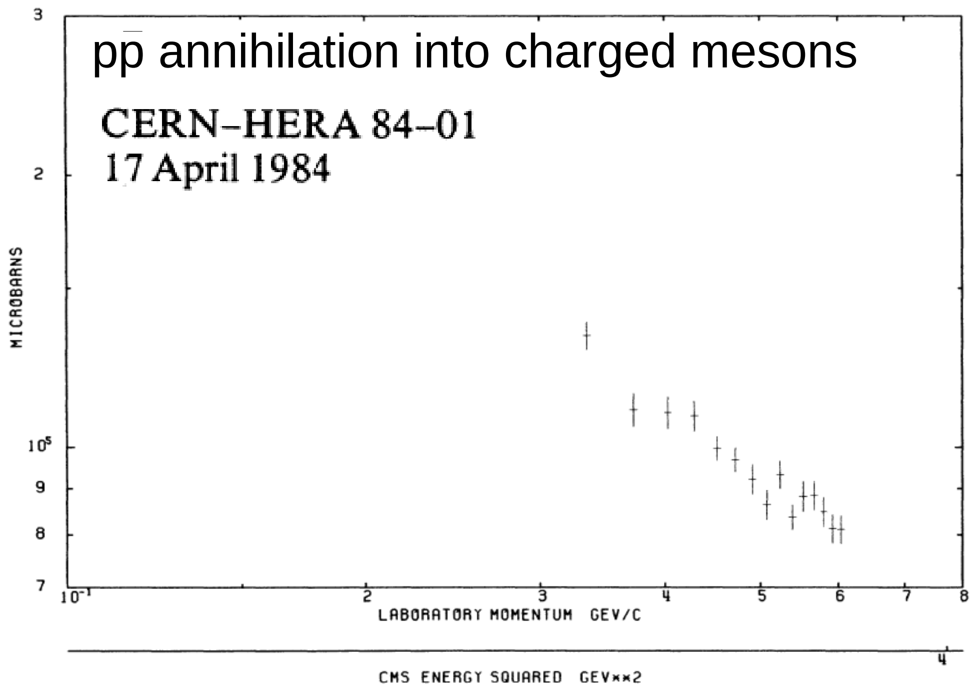
1. Cross section

- Predictions are difficult due to presence of *s*-quark in D_{sJ} mesons:
  $\sigma(\bar{p}p \rightarrow \bar{D}D)$ expected <100nb
- Inclusive search: better for cross section measurement, but higher background. Challenge!
- Exclusive cross section measurement: theoretical predictions are difficult

Phys. Rev. Lett. 98, 092001 (2007)
Phys.Rev. D79, 092001(2009)



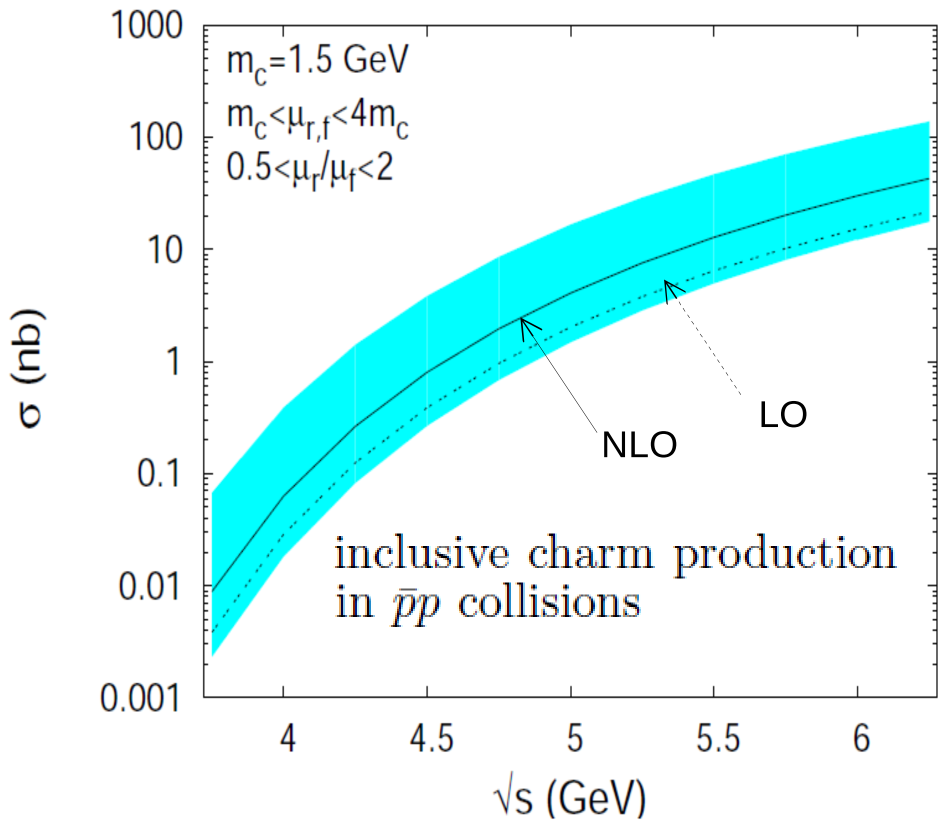
V. Flaminio, W.G. Moorhead, D.R.O. Morrison, N. Rivoire



- Simulations in $\bar{P}$*ANDA* for the $D_{s0}*$ and D_{s1} cross section: p > 8.8 GeV/c

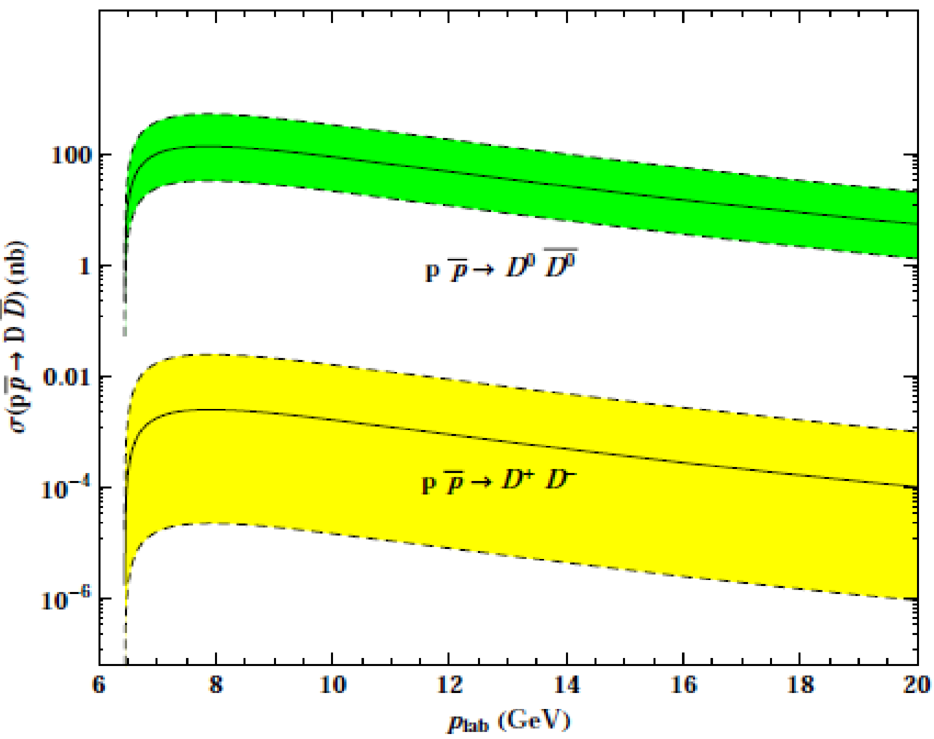
1. Cross section

- Theoretical predictions for the charmed ground states (D^+, D^0).
- Calculations for excited D states (no s-quark) are difficult:
  calculations in perturbative regime can under-estimate the real cross section



Phys. Rev. D 79 (2009) 114005

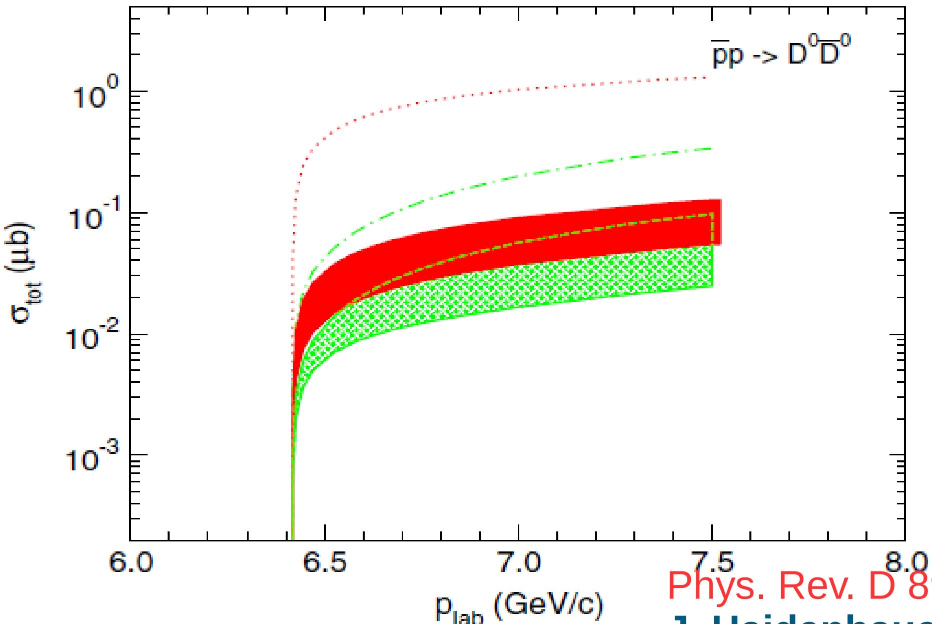
E. Braaten, P. Artoisenet

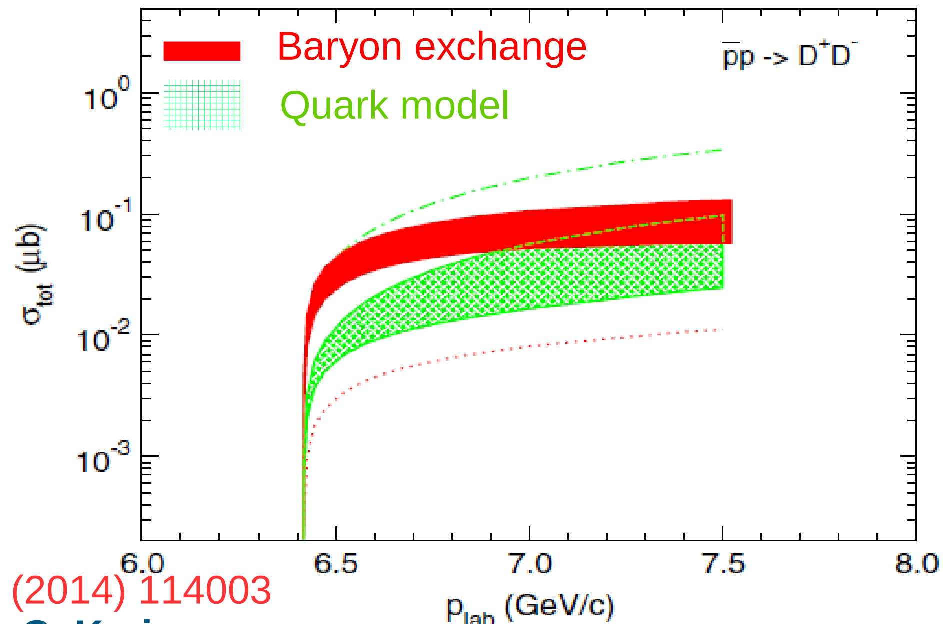


Eur. Phys. J. A 48 (2012) 31

A. Khodjamirian, C. Klein, T. Mannel, Y.M. Wang

1. Cross section

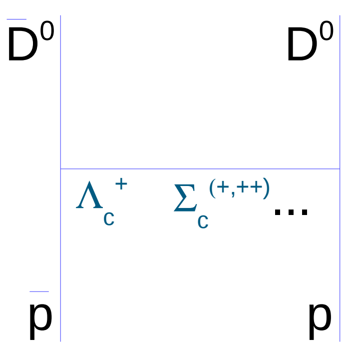




Phys. Rev. D 89 (2014) 114003

J. Haidenbauer, G. Krein

- Cross section predictions described in the PRD 89 (2014) 114003 are higher than in the paper cited as EPJ A 48 (2012) 31
  → different assumption: here (PRD paper) they rely in SU(4); coupling constant is fixed



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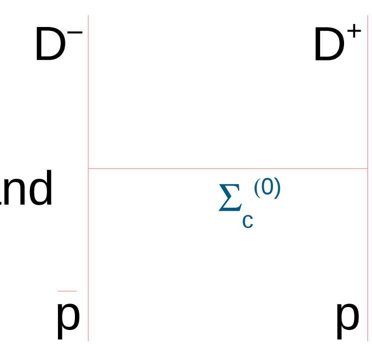
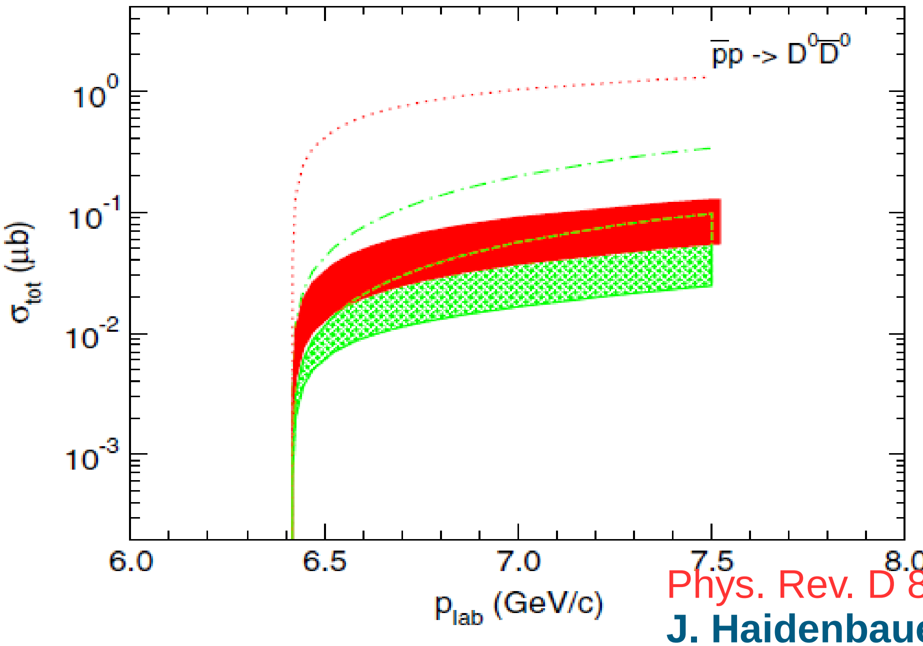
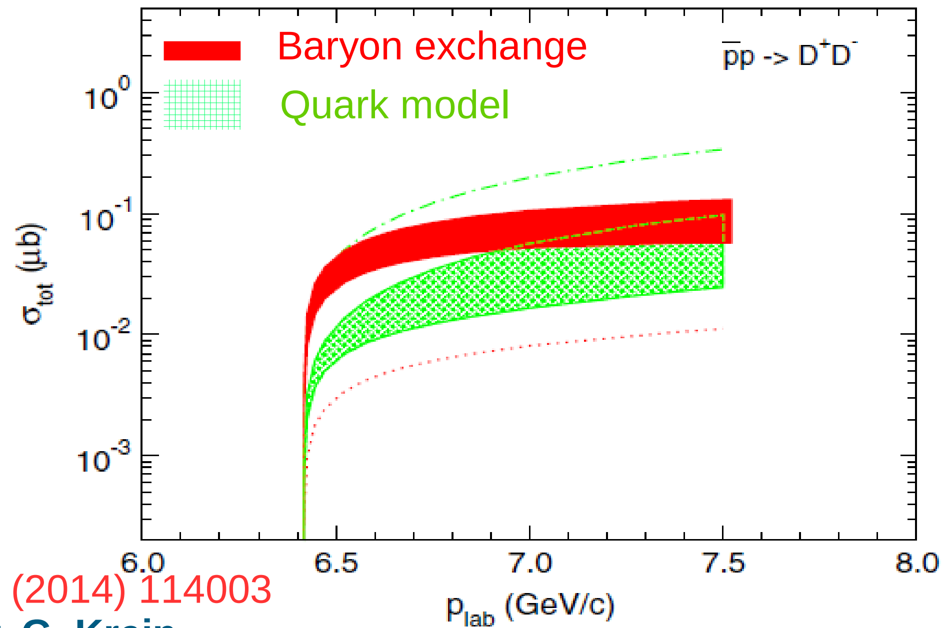


This contribution this contribution

1. Cross section





Phys. Rev. D 89 (2014) 114003
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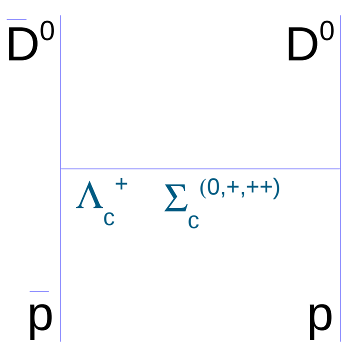
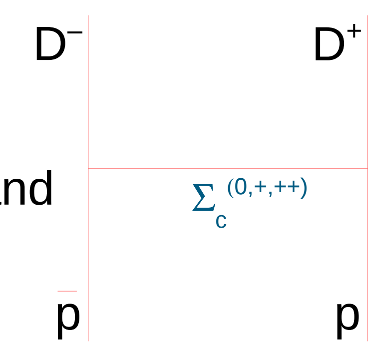
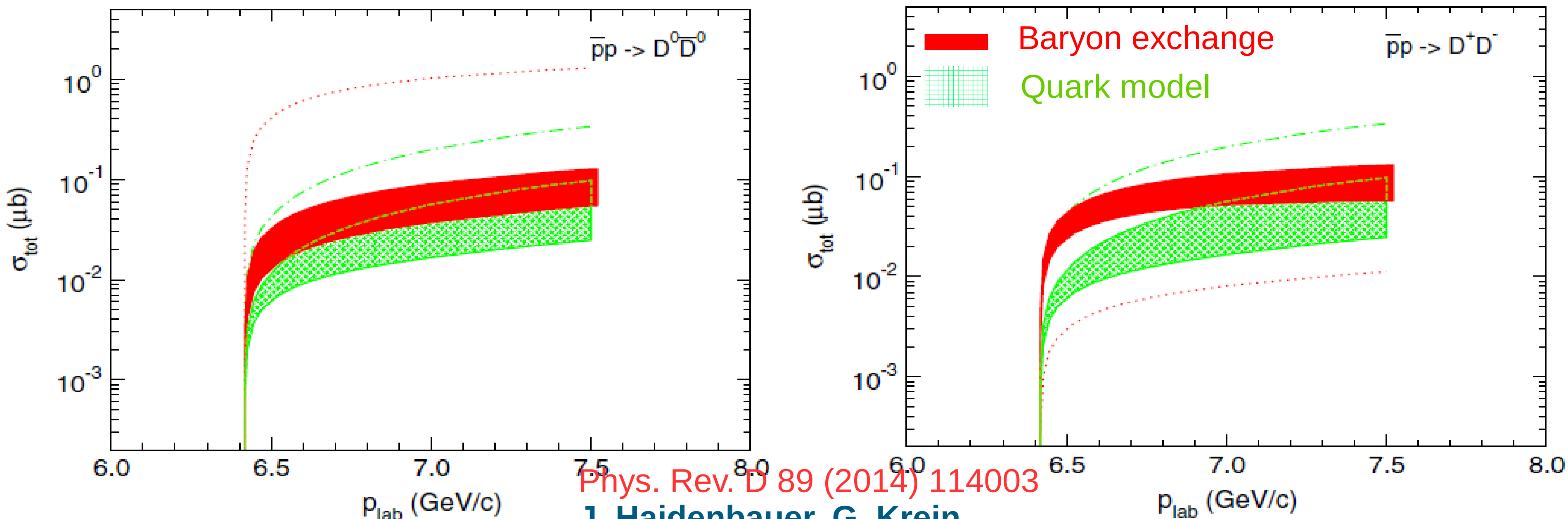


, and



This contribution is ≫10 larger than this contribution

1. Cross section



Phys. Rev. D 89 (2014) 114003

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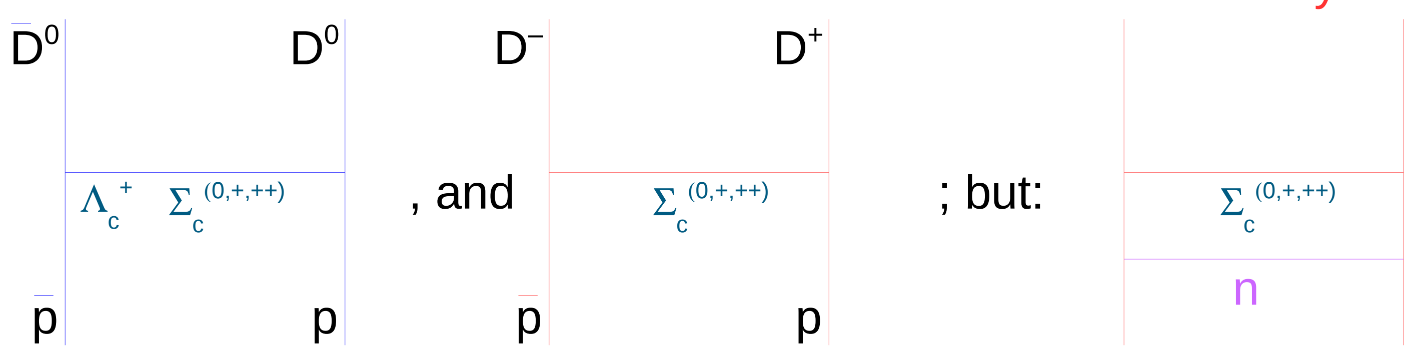
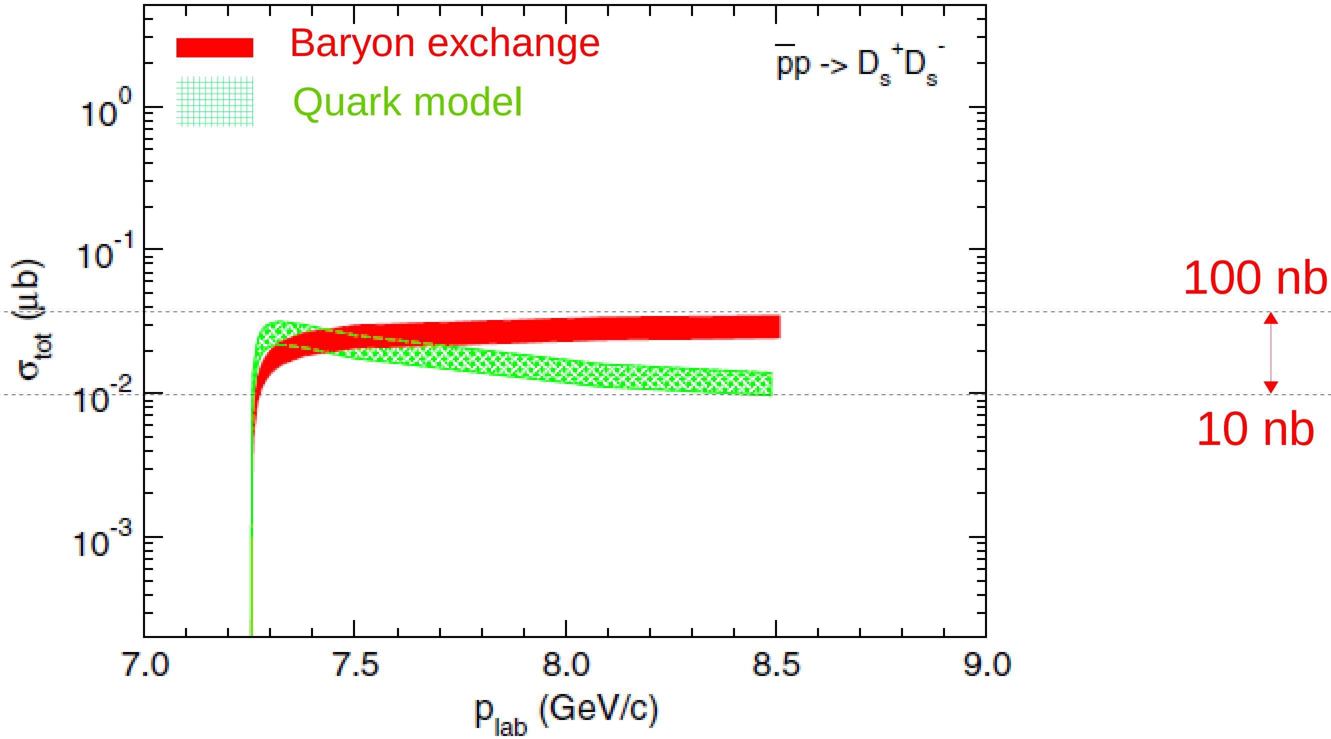
Can we rely in SU(4)?



This contribution is >10 larger than this contribution; but a neutron in the loop as intermediate state can rise up the $\sigma(\bar{p}p \to D^+D^-)$ at same level as $\sigma(\bar{p}p \to \bar{D}^0D^0)$

1. Cross section

Phys. Rev. D 89 (2014) 114003
J. Haidenbauer, G. Krein



- With the approach described in slide 17, $\sigma(\bar{p}p \to D_s^+ D_s^-)$ should be more feasible

What about the cross section of $\bar{p}p$ to excited **D_s** state?

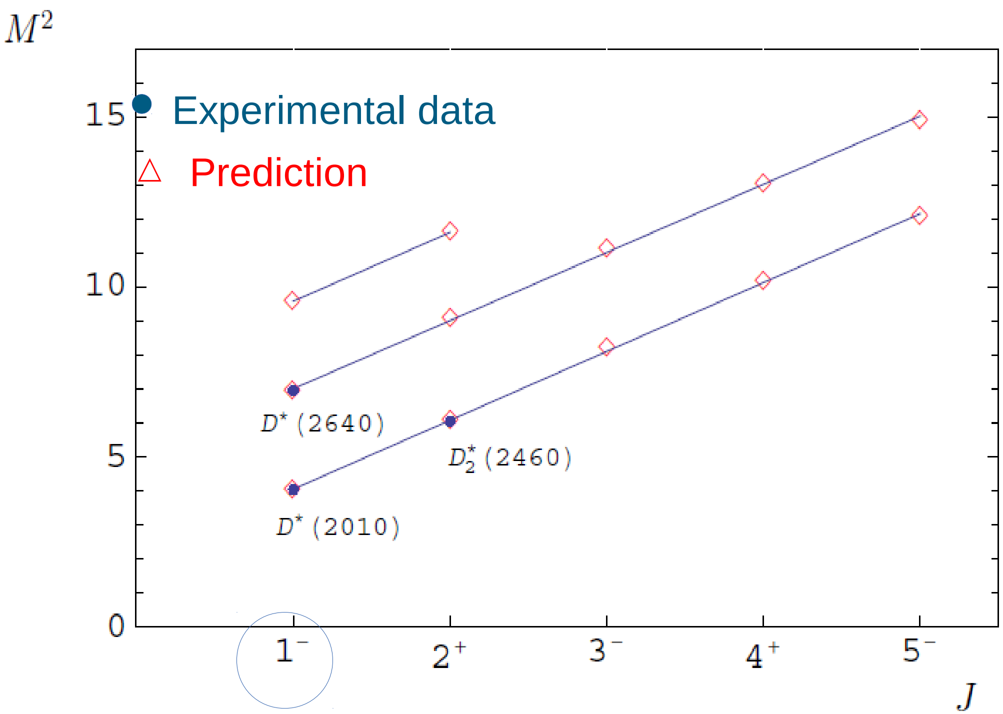
It is more complicated!

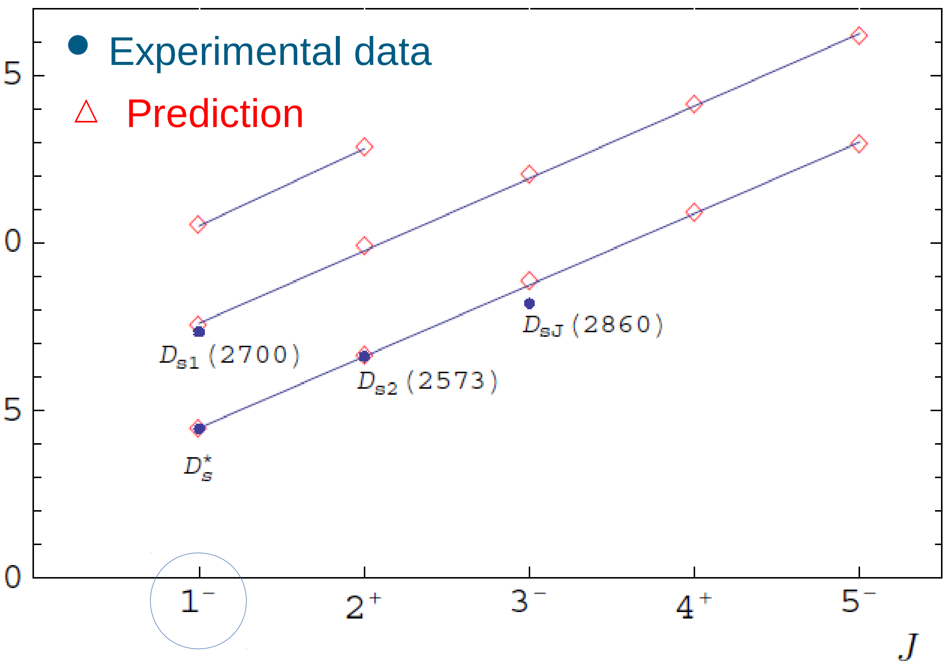
We do not know anything about the coupling constant for D_s^* ⇨ we need REAL data!
Coupling constants are not fixed....

1. Cross section

- In the theoretical calculation for the cross section of $\bar{p}p \to \bar{D}D$ states, vector states could be involved in the loop, but technical problems occur.
- There are divergences difficult to cure.
- *Ragge trajectories* are introduced for this purpose (α).

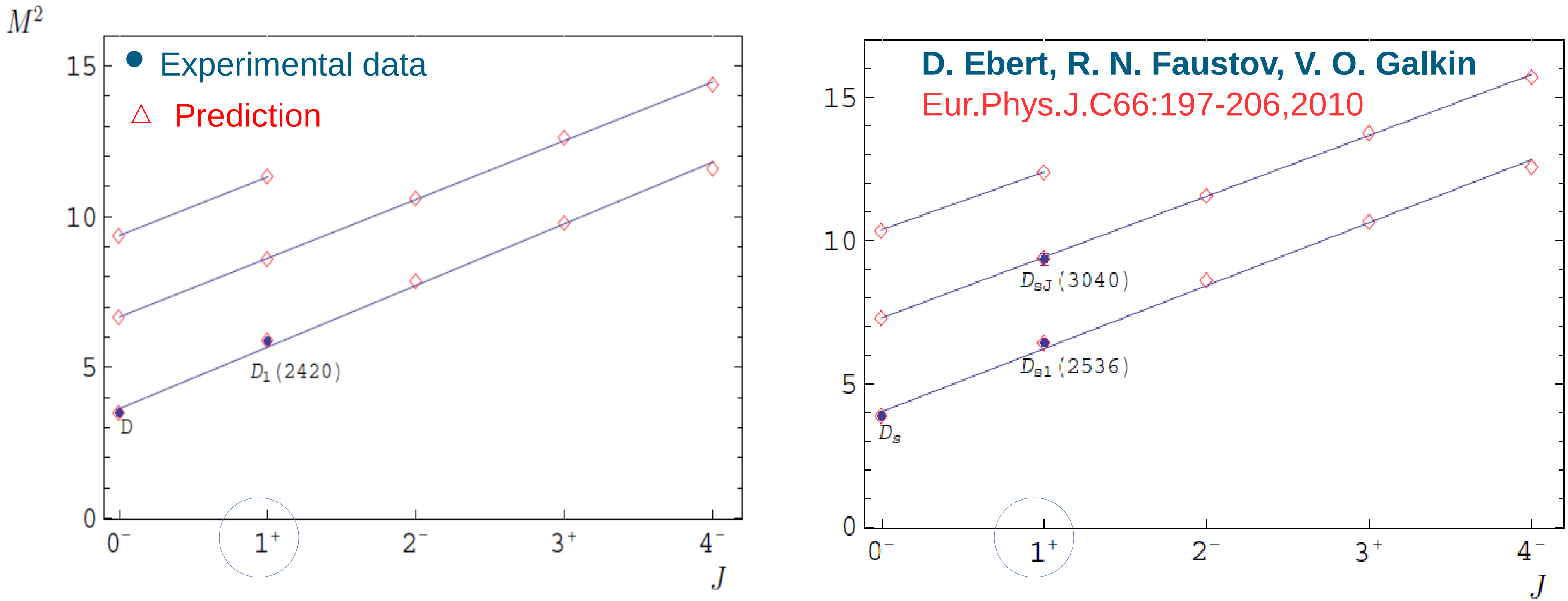
D. Ebert, R. N. Faustov, V. O. Galkin
Eur.Phys.J.C66:197-206,2010





- Ragge trajectories for D(s) mesons with natural parity
- Both light (q=u,d,s) and heavy (Q=c,b) quarks are treated fully relativistically without application of the heavy quark $1/m_Q$ expansion.

1. Cross section



- Ragge trajectories for D(s) mesons with unnatural parity

We calculated the masses of ground, orbitally and radially excited heavy-light mesons up to rather high excitations. This allowed us to construct the Regge trajectories both in (J, M^2) and (n_r, M^2) planes. It was found that they are almost linear, parallel and equidistant. Most of the available experimental data nicely fit to them. Exceptions are the anomalously light $D^*_{s0}(2317)$, $D_{s1}(2460)$ and $D^*_{sJ}(2860)$ mesons, which masses are 100-200 MeV lower than various model predictions. The masses of the charmed-strange $D^*_{s0}(2317)$, $D_{s1}(2460)$ mesons almost coincide or are even lower than the masses of the partner charmed $D^*_0(2400)$ and $D_1(2427)$ mesons. These states thus could have an exotic origin. It will be very important to find the bottom counterparts of these states in order to reveal their nature.

Status of $\bar{P}$ANDA simulations

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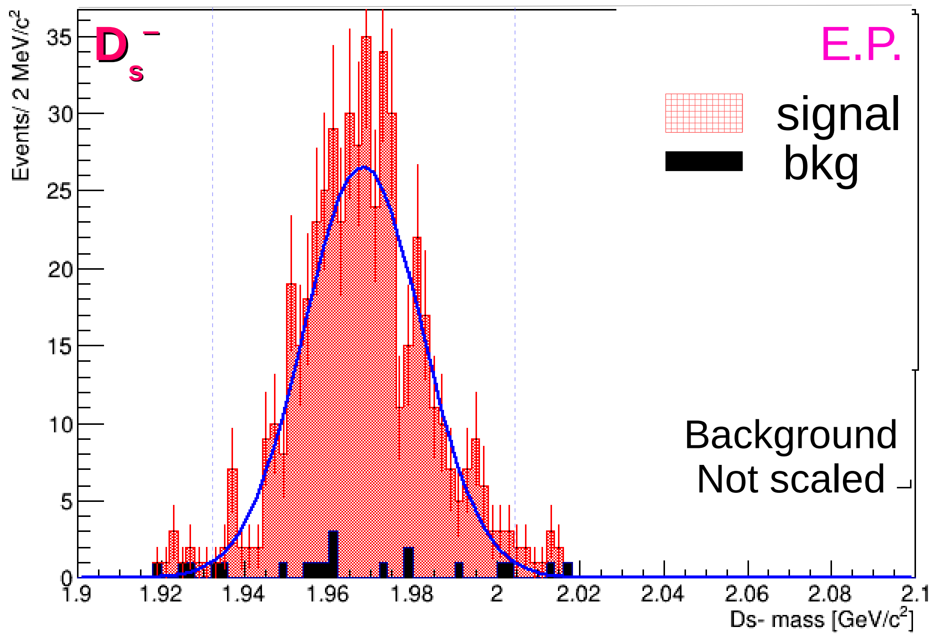
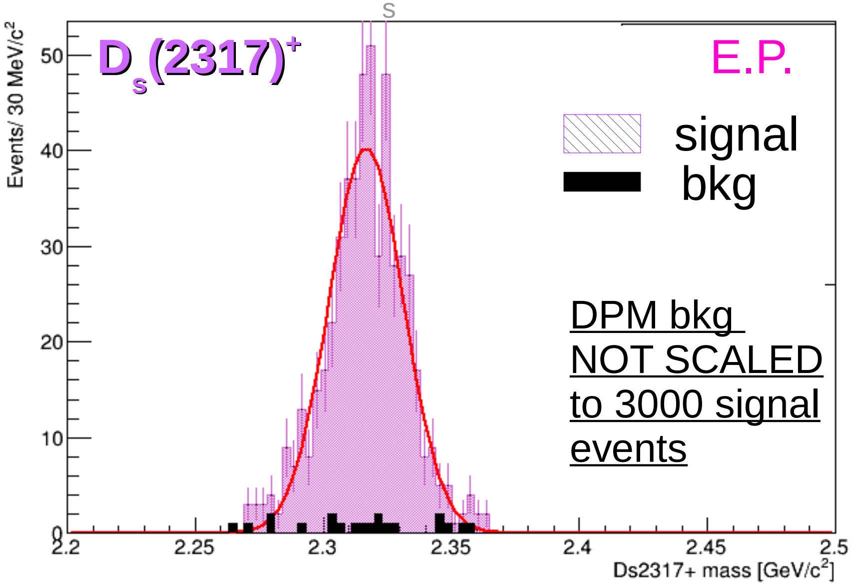
After a dedicated selection:



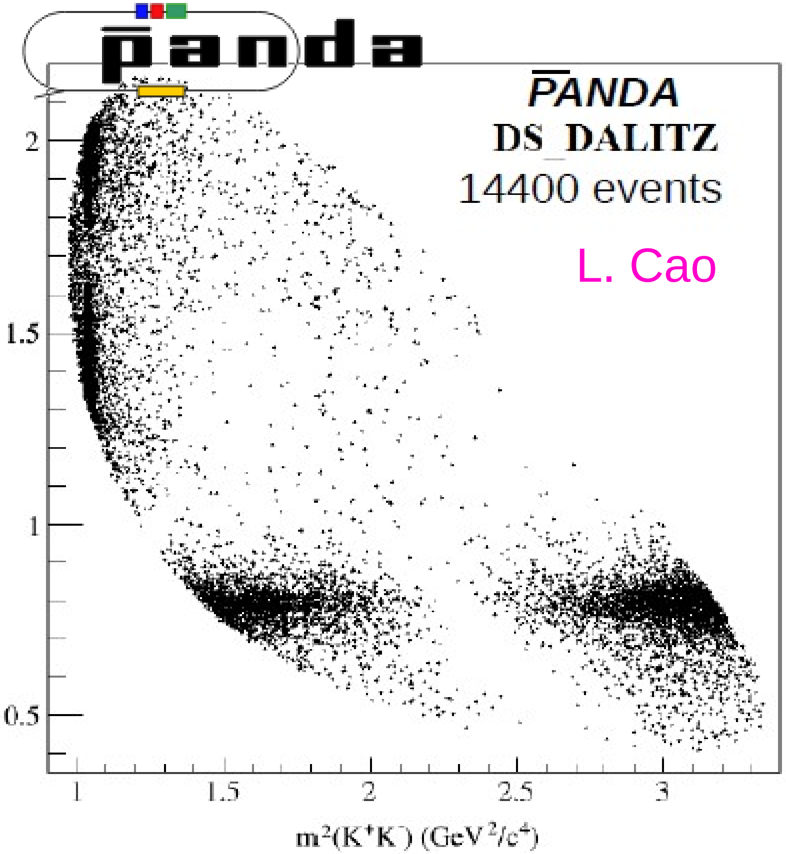
- $\bar{p}p \rightarrow D_s^- D_{s0}^*(2317)^+$
  - $\rightarrow K^- K^+ \pi^-$
- **Efficiency: (17.53± 0.69)%**
- **Full PandaRoot simulation**
- Figure of merit: D_s mass
- Bkg sample for this study: arbitrary
  Bkg needs to be scaled ~10^3

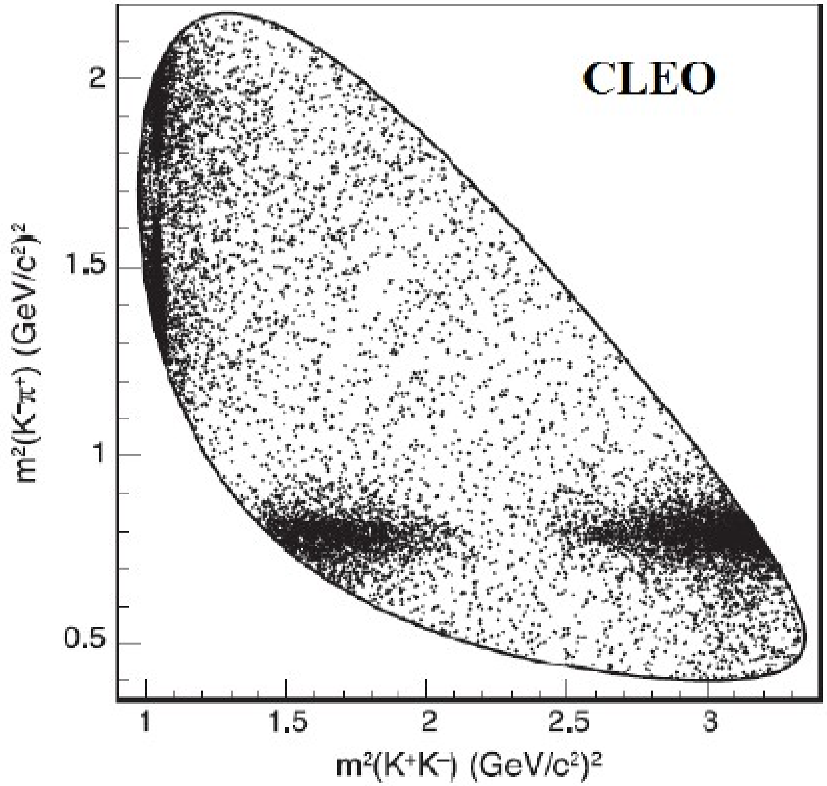
Recoil of the D_s^-



- dedicated selection with kin. variables in the center of mass
- assumption for the calculation: **σ(signal) = 40 nb**; **σ(bkg) = 40 mb**.
- MC generator for signal events: EvtGen; model: DS_DALITZ
- MC generator for bkg events: DPM
  $\bar{p}p \rightarrow \bar{q}q \quad q = u, d, s$

Realistic amplitude model in our simulations





- Full detector simulation
- PID: likelihood method

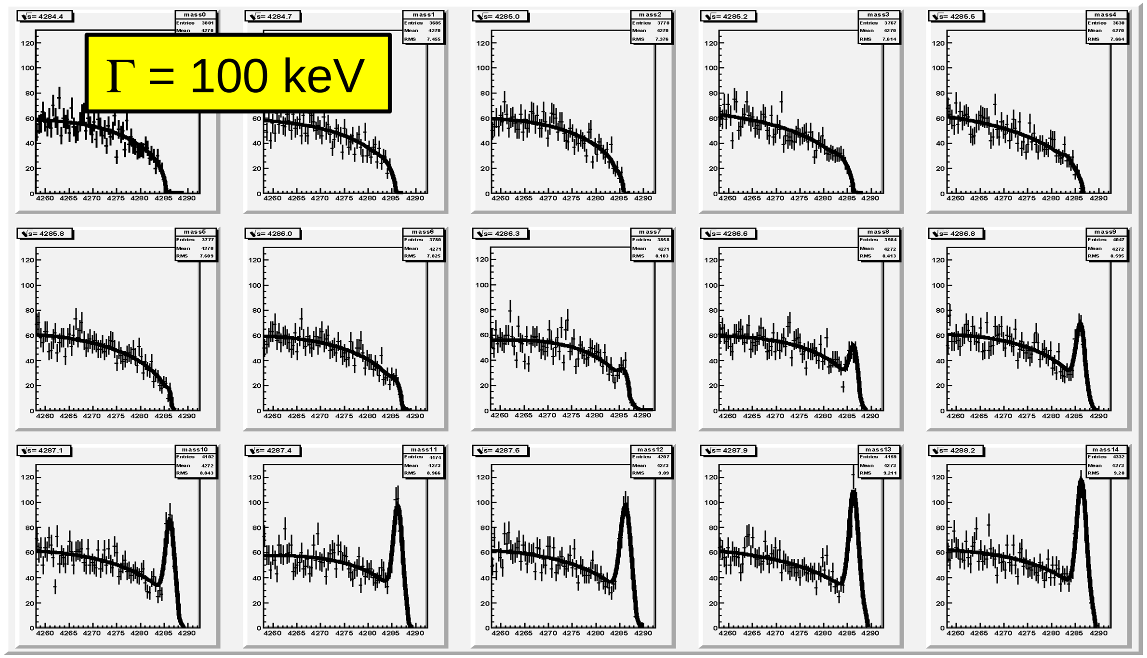
PandaRoot = Root-based framework developed inside the FairRoot project, for FAIR experiments and P̄ANDA

- D. Bertini, M. A-Turany, I. Koenig and F. Uhlig , Journal of Physics: Conference Series 119 (2008) 032011
- S. Spataro, Journal of Physics: Conference Series 396 (2012) 022048

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

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

M. Mertens



What do we want to measure?

- PDG: Γ <3.8 MeV at 95% c.l.
- Excitation function of the cross section:

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

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

$\lambda = \sqrt{s} - m[D_s^-] - m[D_s(2317)^+]$

Expectations with $\overline{\mathrm{P}}$ANDA

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- General remarks:
  ① analysis performed in single-tag mode (D_s is tagged);
  ②semi-inclusive approach;
  ③ unknown cross section, but σ expected in **[10-100] nb**;
  ④ ε = **17.5%** and $\mathscr{L}$= **0.86** pb^{-1}/day, with a dedicated selection;
  ⑤ 3000 events/scan point;
  ⑥ but <u>we need to scale by</u> BR(D_s →KKπ)~<u>6%</u> ⇨ **[3-32] <u>days/scan point</u>!**

- <u>Specific simulation of this talk</u>:
  3000 events/scan point;
  collect 15 points for the $D_{s0}*(2317)^+$ mass scan ⇒
  correspond to ~ 12 hours/ point (using the values obtained from this simulation in PandaRoot , <u>single tag mode</u>, all D_s decay channels) ⇒
  assuming σ = **40 nb**, ε = **17.5%** and $\mathscr{L}$= **0.86** pb^{-1}/day,
  $D_s^- \rightarrow K^+K^-\pi^-$ only (PID, vertexing, tracking, dedicated selection)
  <u>we need to scale by</u> BR(D_s →KKπ)~<u>6%</u> ⇨ **<u>8 days/scan point</u>!**

Conclusion

- Charm and Charmonium Physics are sectors of high interest
- Many unsolved questions
- Strangeness in Charm and Charmonium spectroscopy gained recent attention
- Subsequent theoretical papers in the past decade
- Charm Spectroscopy: interesting from strong- and weak- interactions
- In Hadron Spectroscopy: need to clarify the D_s nature
- D_s width is a unique feature to identify unambiguously its nature
- The $\bar{P}$ANDA experiment is in a unique position to perform this measurement: mass resolution x20 better than at B factories
- Challenge of $\bar{P}$ANDA: **to scan in 100 keV steps the mass of narrow states**. Simulations with PandaRoot at advanced stage; bkg study is ongoing.

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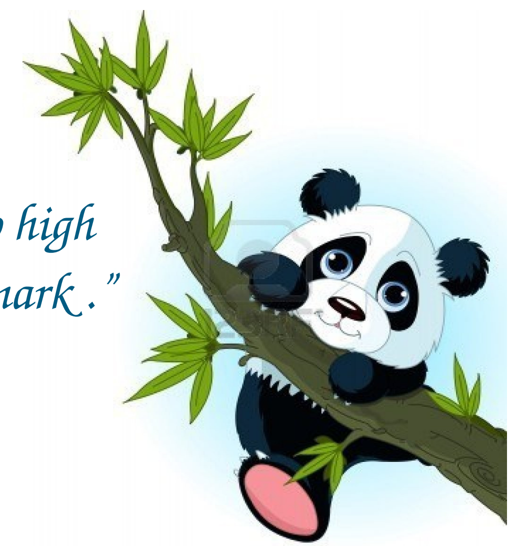
The PANDA Collaboration (2015): 540 physicists, 18 Countries



"The greatest danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieve our mark."

(Michelangelo, 1475 - 1564)

THANK YOU
for your attention!