# Sensitivity studies on S/B for the channel $\bar{p}p \rightarrow D_{s0}^{*}(2317)^{+}D_{s}^{-}$

August 19th, 2015 | Elisabetta Prencipe, Forschungszentrum Jülich | Charm meeting

# Outline

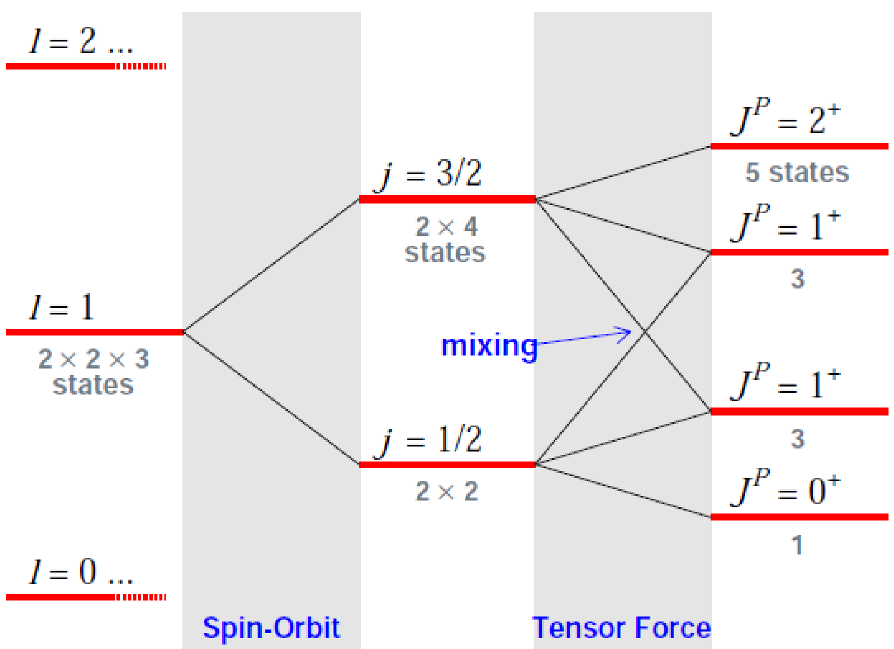
- Motivation
- On the interference in $\bar{p}p \rightarrow D_{s0}^{*}(2317)^{+} D_{s}^{-}$
- Analysis strategy
- Background characterization
- Rate estimates
- Systematic uncertainties
- Summary and future plans

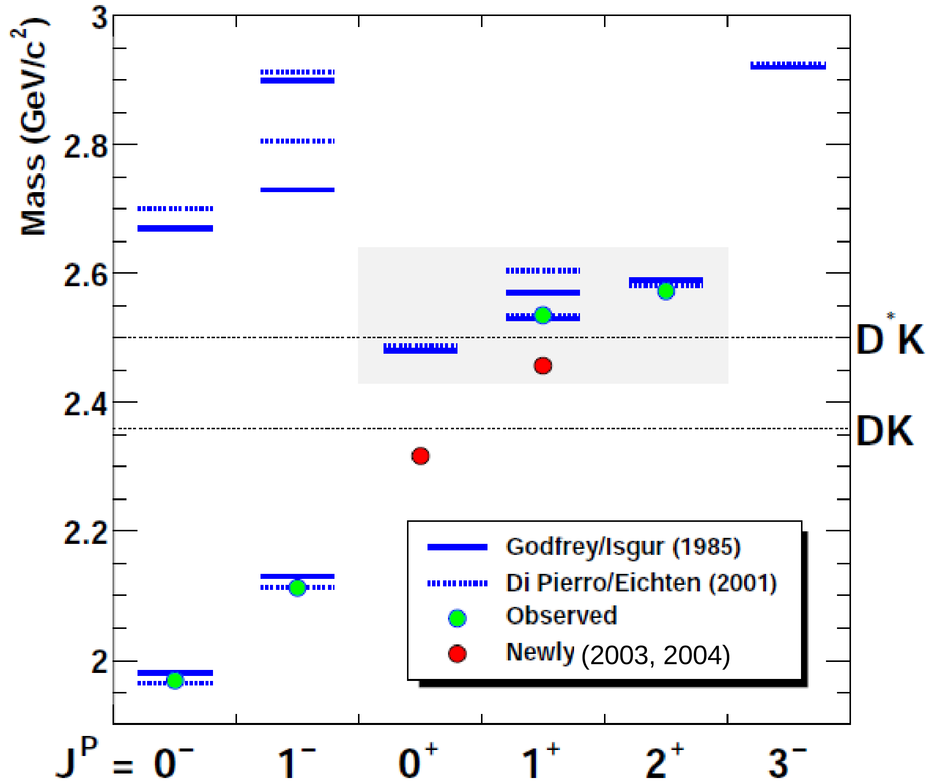
# $D_s$ level scheme

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

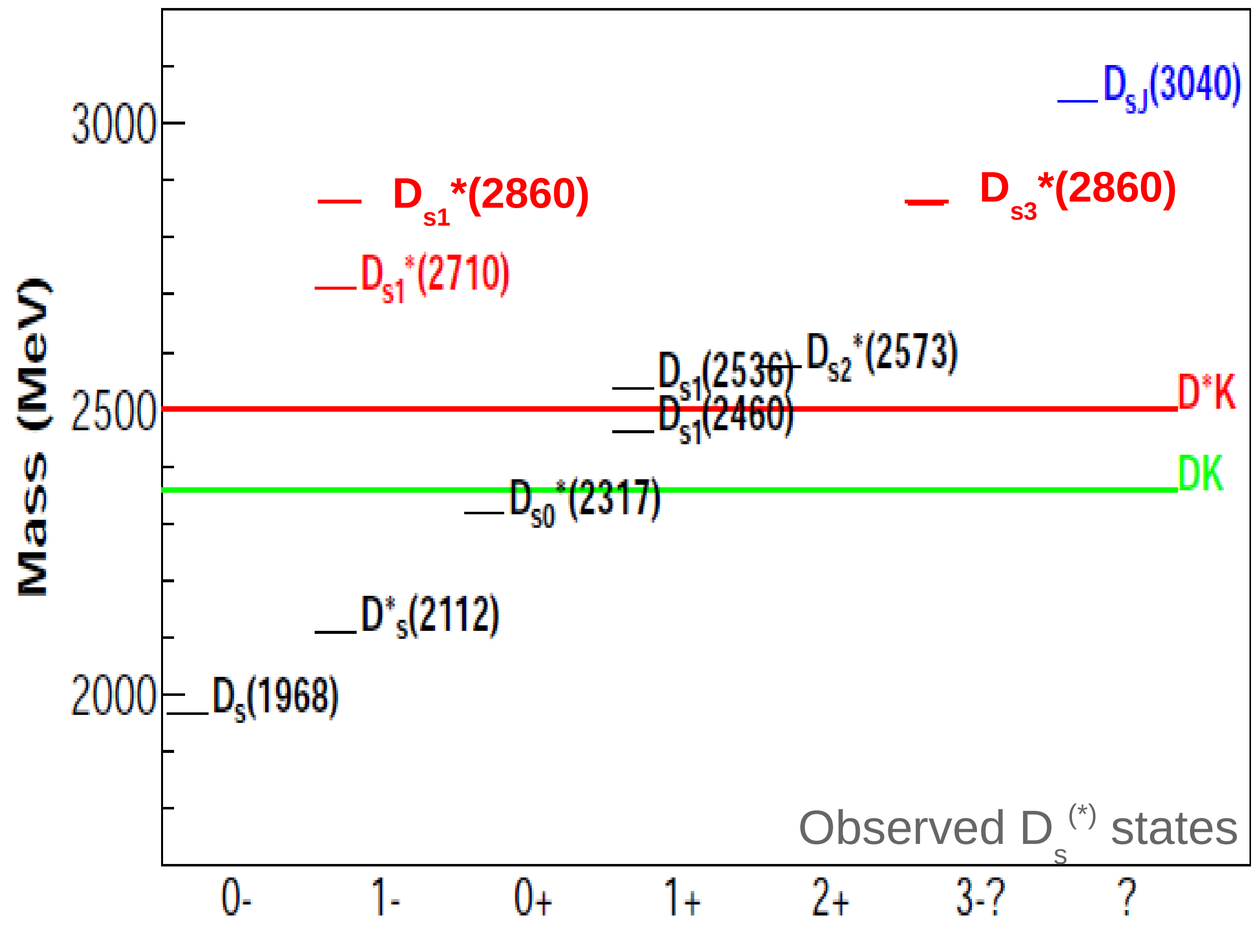
$D_s$ mesons: $|c\bar{s}\rangle$

*P*-wave multiplet



# $D_s$ spectroscopy, today



# Highlighted papers: $D_{s0}^{*}(2317)^{+}$

“Observation of a narrow meson decaying to $D^{+}_{s}\pi^{0}$ at a mass of 2.32-GeV/$c^{2}$ “

**Phys.Rev.Lett. 90 (2003) 242001**

e-Print: hep-ex/0304021 | PDF

Experiment: SLAC-PEP2-BABAR

**719 citations**

BaBar: experiment optimized for CP violation, measurement of angles and sides of the CKM matrix. For comparison:

“Observation of CP violation in the $B^{0}$ meson system”

**Phys.Rev.Lett. 87 (2001) 091801**

e-Print: hep-ex/0107013| PDF

Experiment: SLAC-PEP2-BABAR

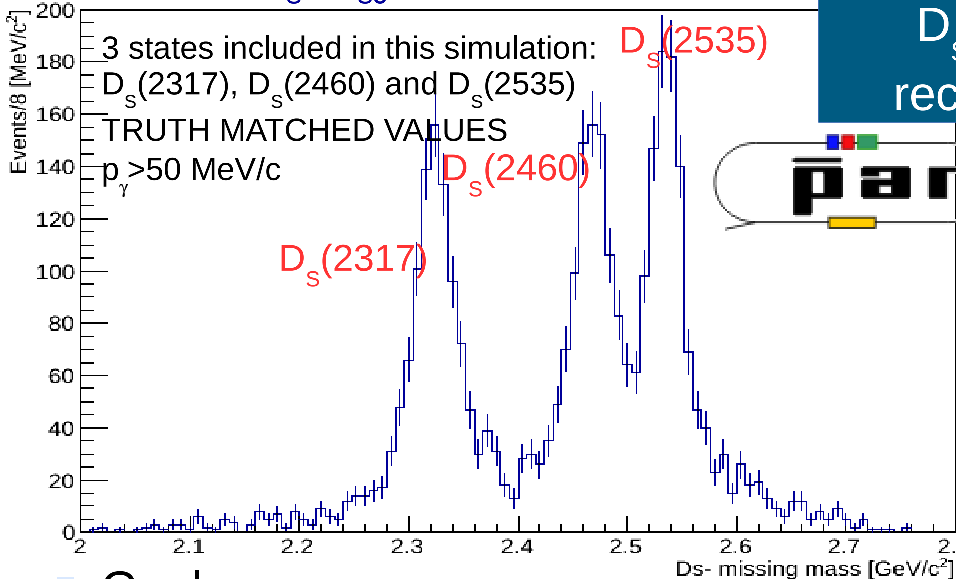
**720 citations**

The more a paper is cited,
the more the topic is challenging!

# $D_s$ meson spectroscopy at $\bar{P}$ANDA

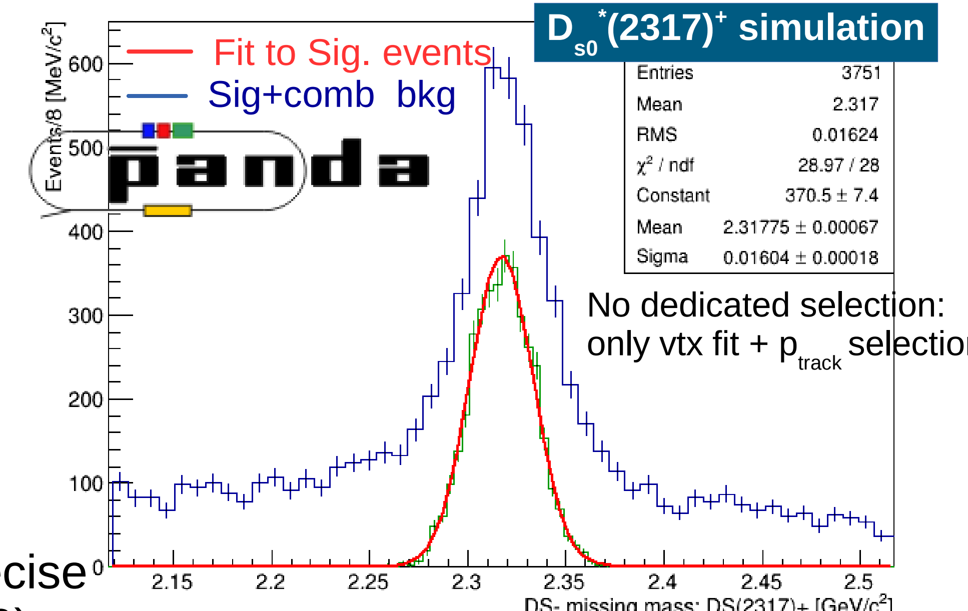
E.P., arXiV:1410.5201 [hep-ex]

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




$D_s^-$ 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



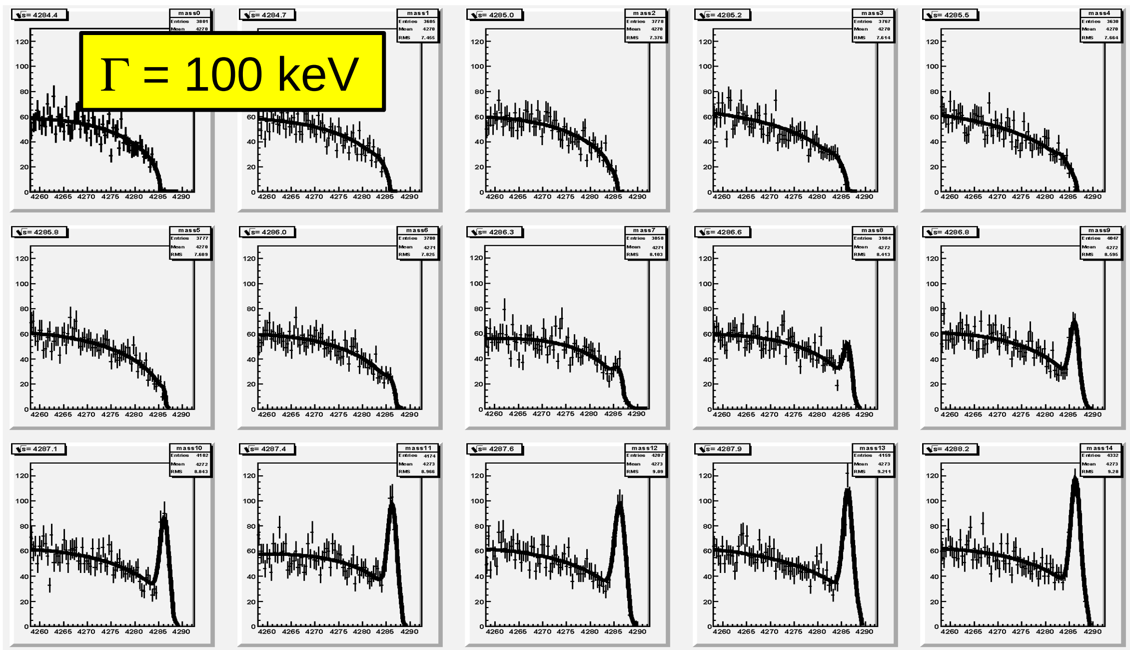

No dedicated selection: only vtx fit + $p_{track}$ selection

- 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 $D_s^- D_s^{*+}$

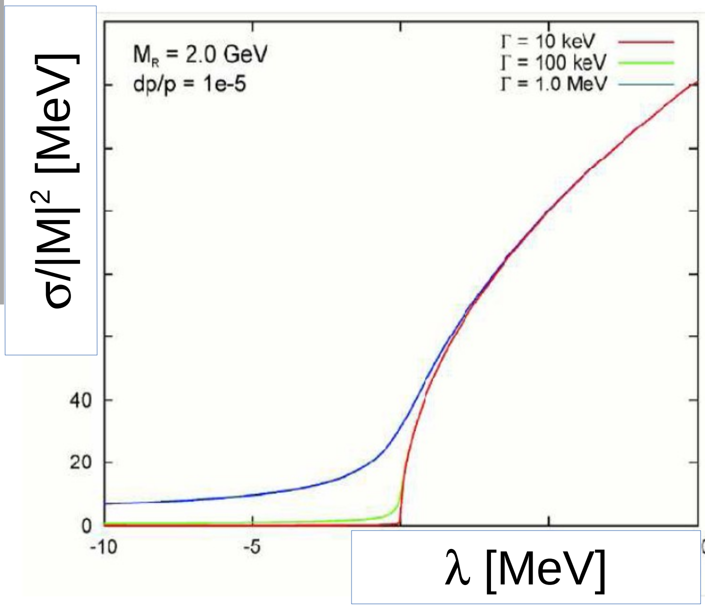
# Width of the $D_{s0}^{*}(2317)^{+}$ with $\bar{P}$ANDA

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




PhD thesis, M. Mertens

**What do we want to measure?**




- PDG: $\Gamma$ <3.8 MeV at 95% c.l.
- Excitation function of the cross section(*):

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

$$\sigma(0) = \sqrt{\frac{m_R\Gamma}{2}}\,|M^2| \qquad \lambda = \sqrt{s} - 2m_R$$

$\bar{p}p \rightarrow D_s(2317)^{+} D_s(2317)^{-}$

(*) easy formula, assuming identical final states: $\bar{p}p \rightarrow D(2317)^{-}D(2317)^{+}$

# Width of the $D_{s0}^{*}(2317)^{+}$ with PANDA

$\bar{p}p \rightarrow D_s(2317)^+ D_s^-$ , $D_s(2317) \rightarrow D_s^+ \pi^0$

$$\sigma \propto |\mathcal{M}|^2 \sqrt{2\mu}\Gamma^* \frac{1}{\sqrt{s}} \times \int_{-\infty}^{\lambda} dx \frac{1}{x^2 + \frac{\Gamma^2}{m^2}} \sqrt{(\lambda+1)^{\frac{1}{2}} - (x+1)^{\frac{1}{2}}}$$

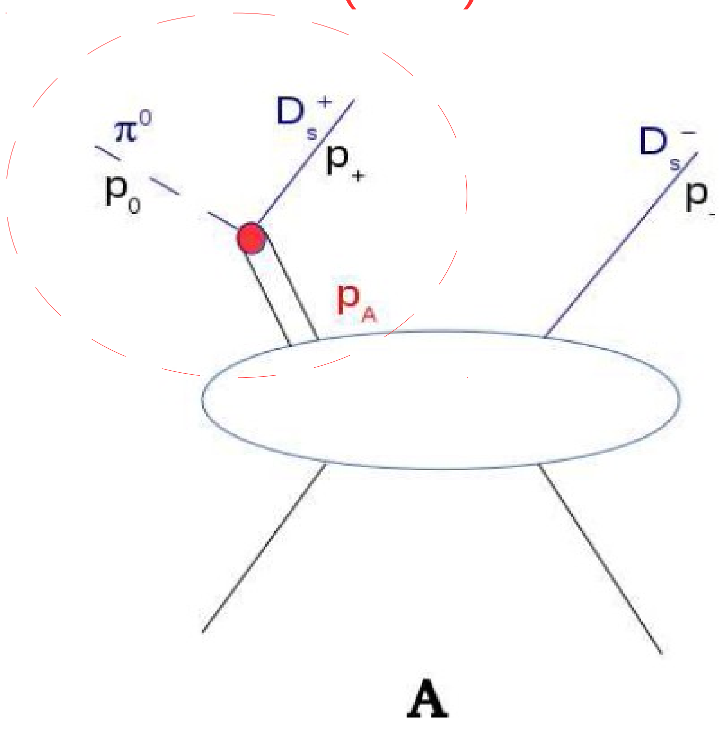
$\Gamma^*$ = width of the $D_s$

$\Gamma$ = width of the $D_s(2317)$

$$\mu = \frac{m \cdot m_{Ds}}{m + m_{Ds}} \approx \frac{m \cdot m_{Ds}}{\sqrt{s}}$$

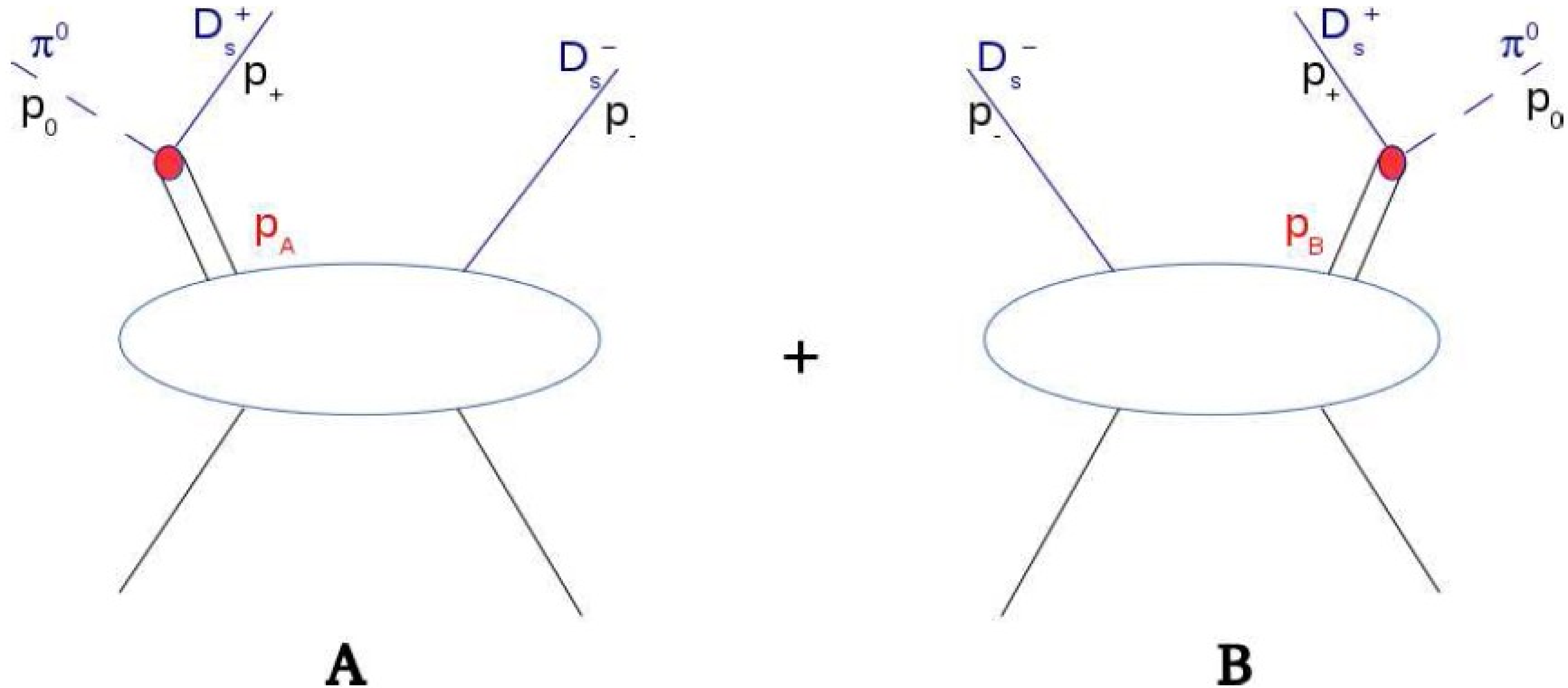
$$\bar{\lambda} = \sqrt{s} - M_{Ds}$$

$$\lambda = \frac{\bar{\lambda}^2 - M^2_{Ds2317}}{M^2_{Ds2317}}$$




- Calculation is performed in absence of interference effects

# Interference effects: graphs




$D_s^- D_{s0}^*(2317)^+$ and $D_s^+ D_{s0}^*(2317)^-$ systems decay to $D_s^- D_s^+ \pi^0$

$$(2317 - 135 - 1968)\ \mathrm{MeV}/c^2 = 214\ \mathrm{MeV}/c^2 \Rightarrow \frac{\Gamma}{2 \cdot E_R} \ll 1$$

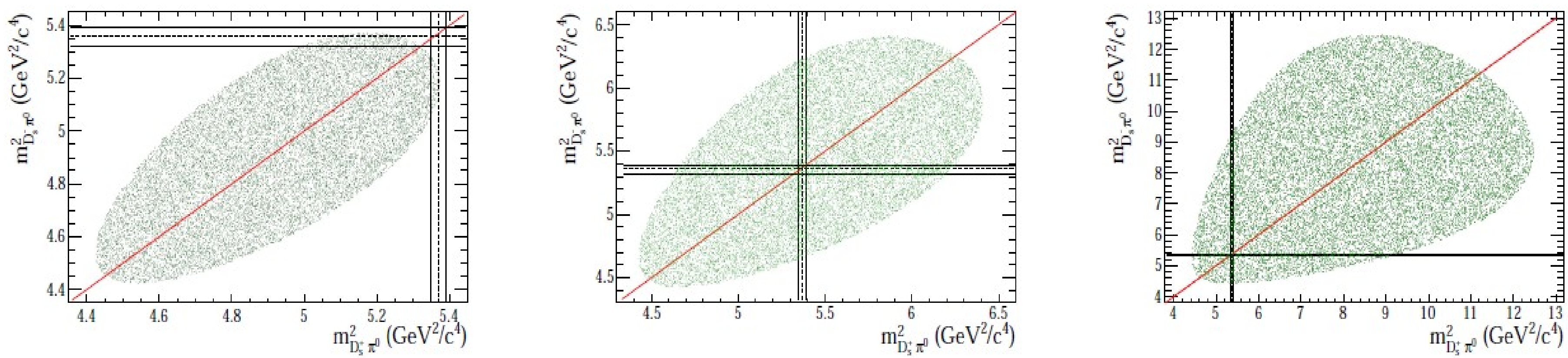
$D_s(2317)^+$ $\pi^0$ $D_s^+$

# Interference effects: $D_s^+ D_s^- \pi^0$ Dalitz

$\bar{p}p \to D_s(2317)^+ D_s^-$ , $D_s(2317) \to D_s^+ \pi^0$

Interference occurs if $m(D_s^+\pi^0) = m(D_s^-\pi^0) = m(D^*_{s0}(2317))$

$\sqrt{s_1}$ and $\sqrt{s_2}$: the higher and lower energy limits ⟶ Interference occur!




(a) $\sqrt{s} = 4.286$ GeV (b) $\sqrt{s} = 4.500$ GeV (c) $\sqrt{s} = 5.500$ GeV

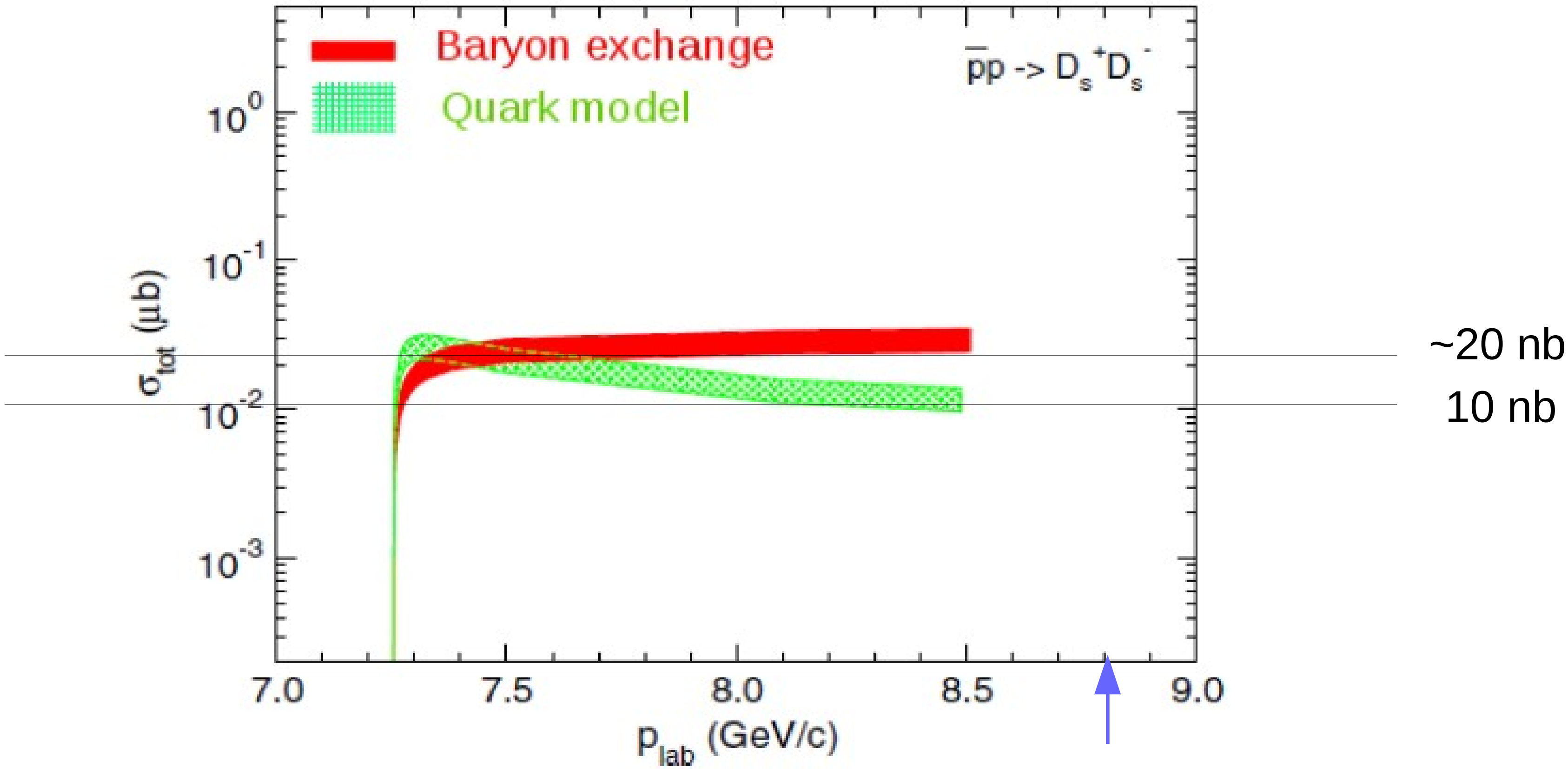
- $\sqrt{s} < \sqrt{s_1}$: no interference
- $\sqrt{s_1} \le \sqrt{s} \le \sqrt{s_2}$: interference can occur
- $\sqrt{s} > \sqrt{s_2}$: no interference

$$\sqrt{s_1} - \sqrt{s_{th}} = 12.027 \text{ MeV}$$

$$\sqrt{s_2} - \sqrt{s_{th}} = 6.777 \text{ GeV}$$

Interference in our case does not occur!

# Theoretical cross section estimate




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

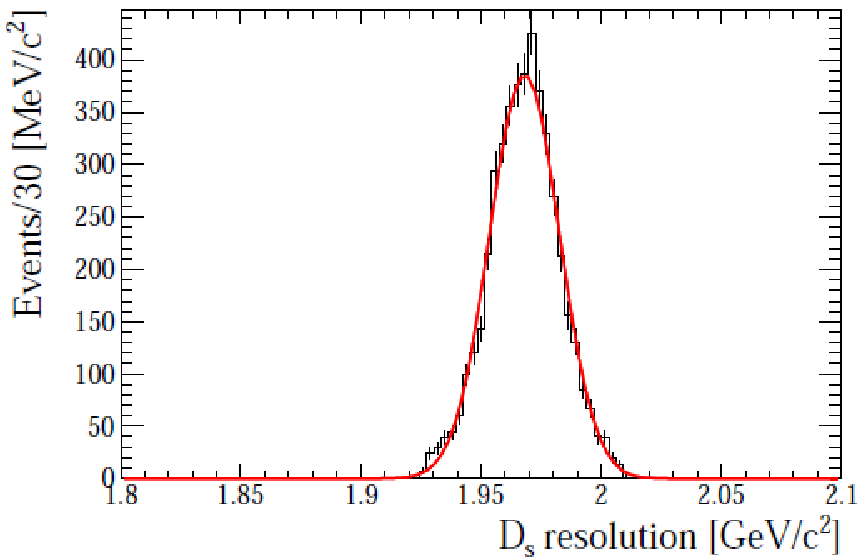
Hypothesis: SU(4) symmetry is valid
Nothing is known about Ds(2317)
Our assumption: $1<\sigma<20$ , p $\geq$8.80225 Gev/c

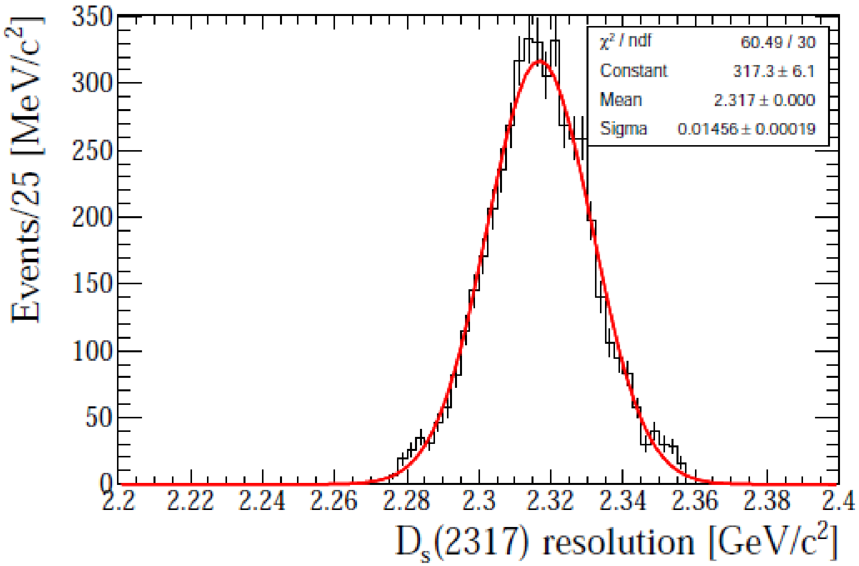
# Strategy

- (semi)inclusive analysis    Single tag mode
- $p_{beam} \geq 8.8$ GeV/c.    8 scan points!
  $p_{beam} = 8.80235$ GeV/c,  $M_{tot} = 4.28629$ GeV/c$^2$
- $Geant3$
- Monte Carlo (MC) generator EvtGen: 200k signal events, each scan point
- Dual Parton Model (DPM) : 40M bkg events
- reconstruction chain under study is $\bar{p}p \rightarrow D_s^- D_{s0}^*(2317)^+$
  $D_s^- \rightarrow K^+ K^- \pi^-$
- model used to simulate $D_s$ events: DS-DALITZ
- PandaRoot release: $oct14$
- PID: “best”
- Fisher, Likelihood or Neutral Network discriminant to suppress the background

# $D_{s0}^{*}(2317)^{+}$ as recoil of $D_s^{-}$

$$m_{recoil} = \sqrt{(M_{tot} - E^{*}_{D_s})^2 - p^{*2}_{D_s}}$$

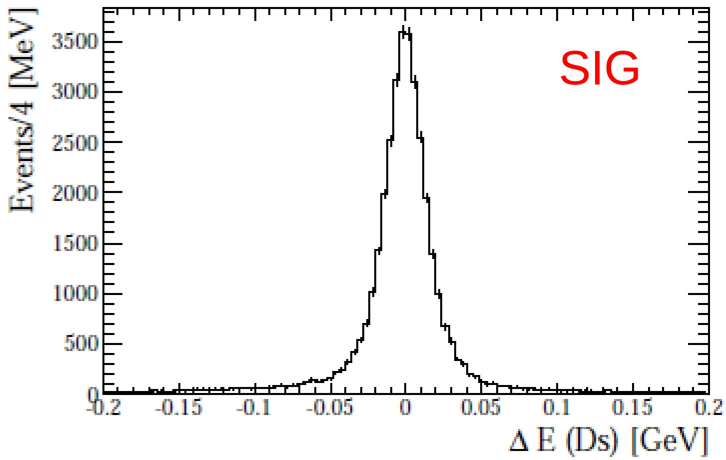


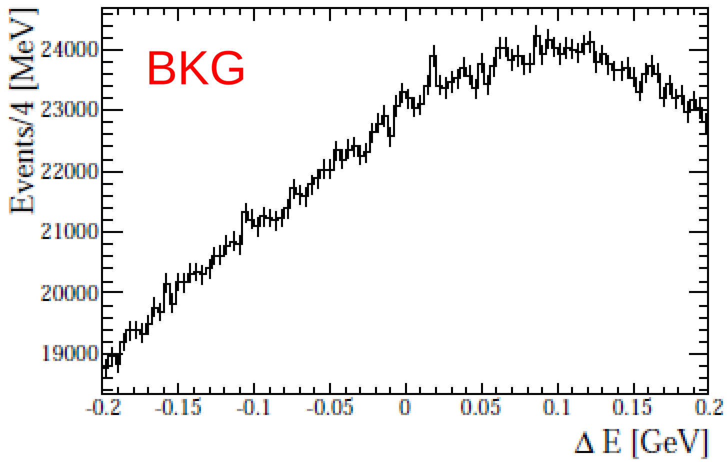




$$D_s^- \to K^+ K^- \pi^-$$

Mass resolution: 14.56 MeV/c$^2$

# Interesting variable: $\Delta E$

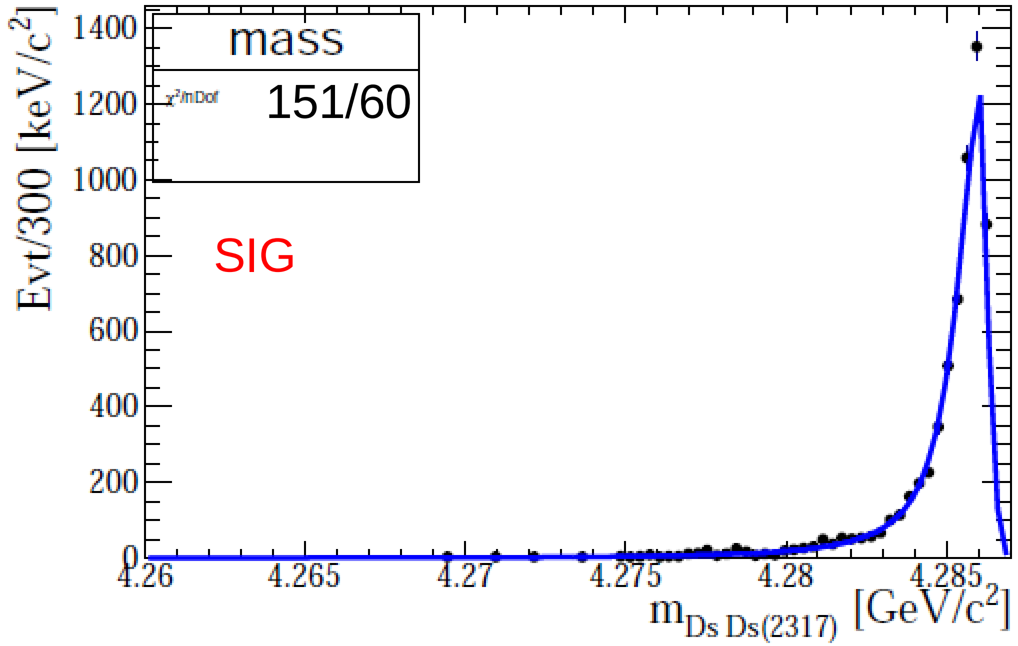



Difference between the energy of the $D_s$ in the c.m. and its nominal value

Double gaussian parametrization for signal; polynomial for bkg

# Interesting variable: $D_s + D_s(2317)$



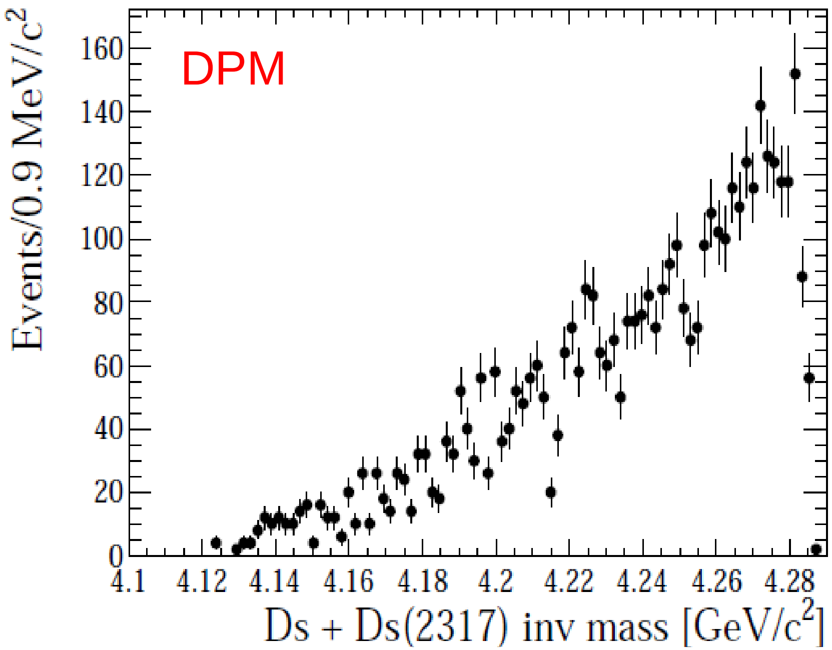

$$\frac{dn}{dm} = \frac{q}{(m_r^2 - m^2)^2 + m_R^2 \times G^2}$$

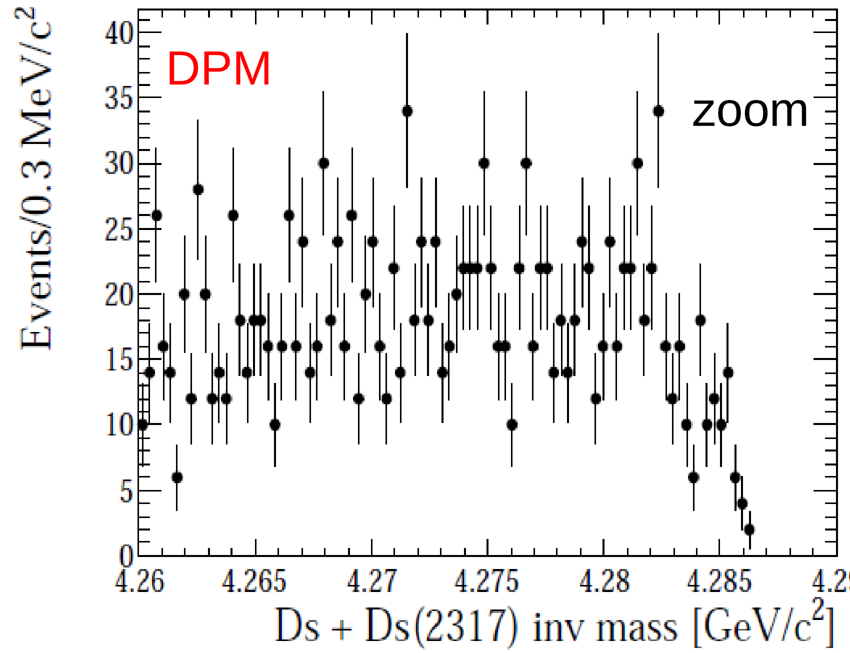
This is simplified for spin = 0

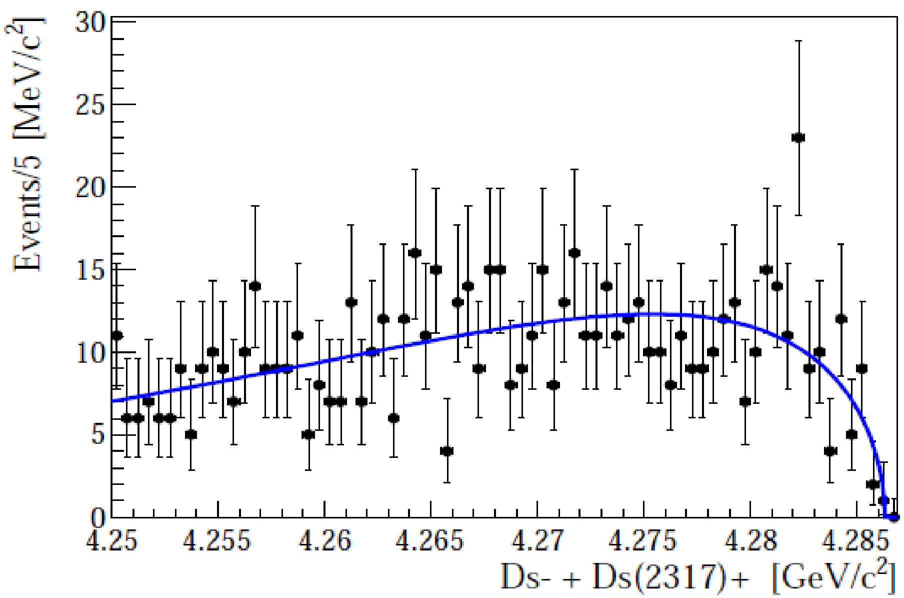
$$q = [m^2 - (m_{Ds} + m_{Ds(2317)})^2]^2 \cdot [m^2 - (m_{Ds} - m_{Ds(2317)})^2]^2$$

$$G = [G(R) \times \frac{q}{m} \cdot \frac{m_R}{q(R)}] \qquad \mathrm{R} = \text{resonant state} = D_s D_{s0}^*(2317)$$

# Interesting variable: $D_s + D_s(2317)$



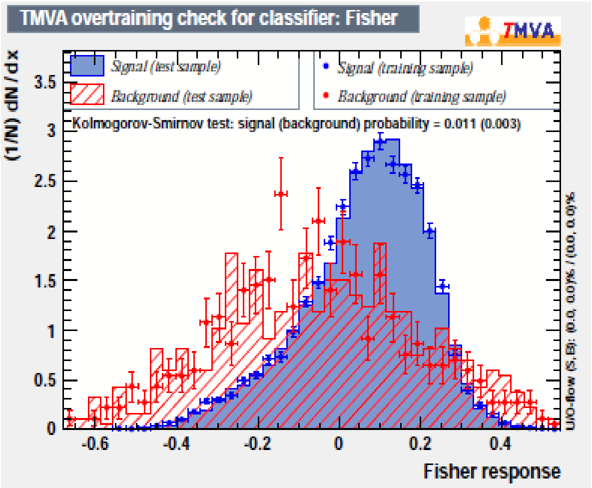



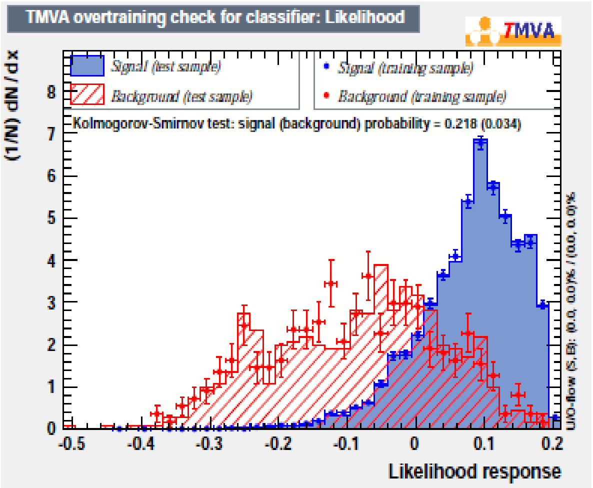



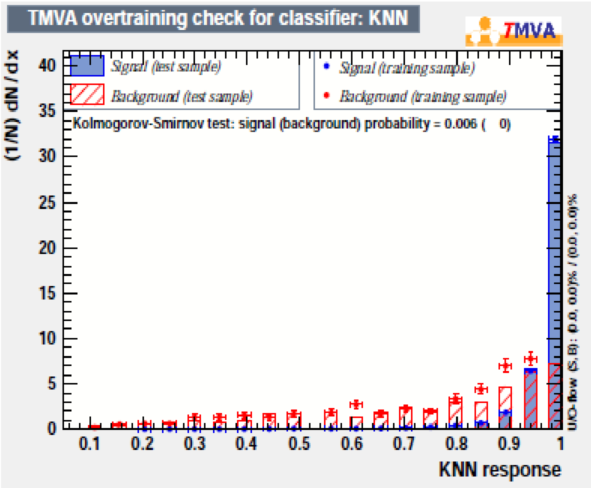

After selection, bkg scaled
ARGUS is used: not good $\chi^2$

# Interesting variable: Fisher discr.






<u>5 variables</u>:

$D_s$ mass

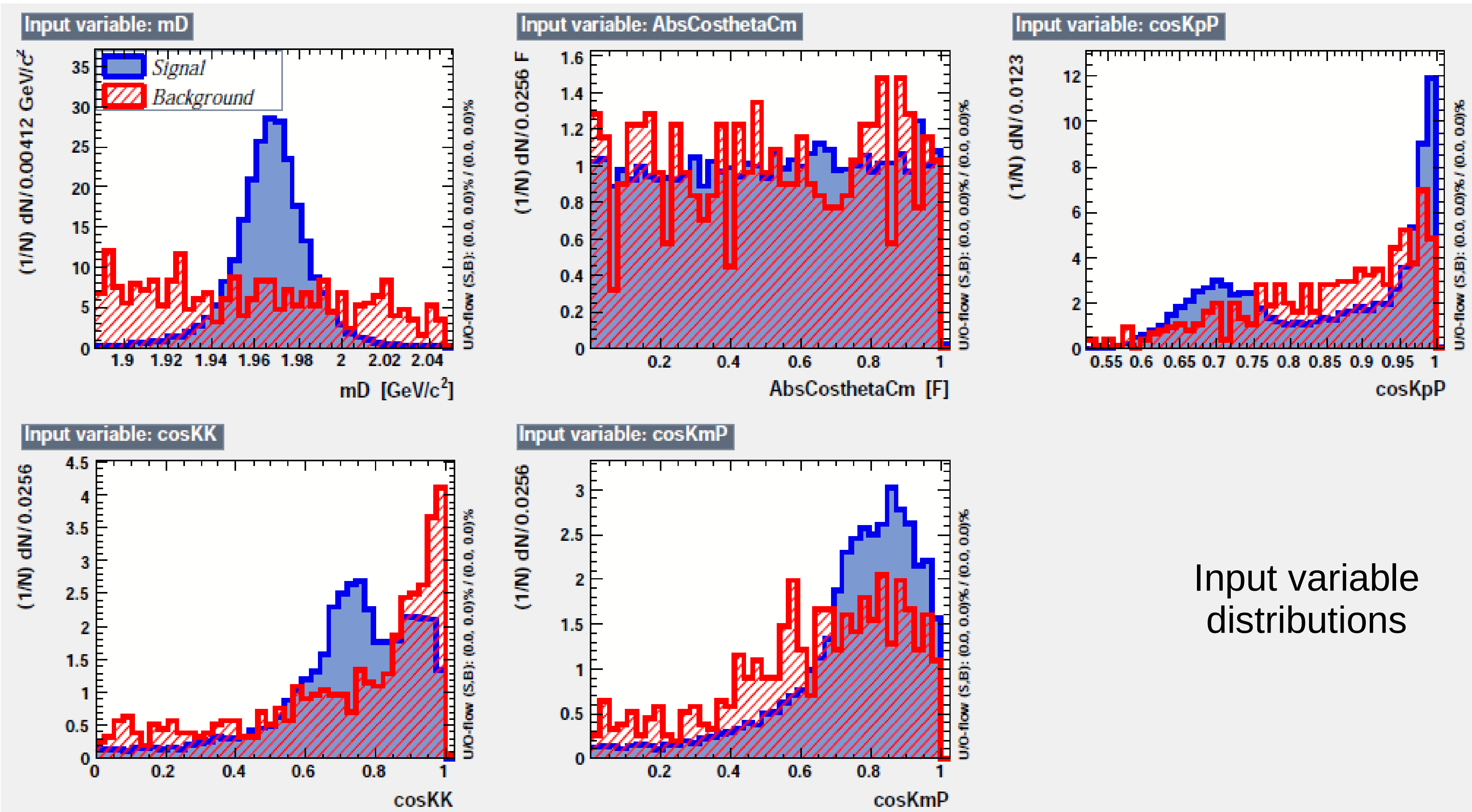
absolute value of the cosine of the polar angle of the $D_s$

absolute values of the cosine of the angle $\widehat{K^+K^-}$

absolute values of the cosine of the angle $\widehat{K^+\pi^-}$

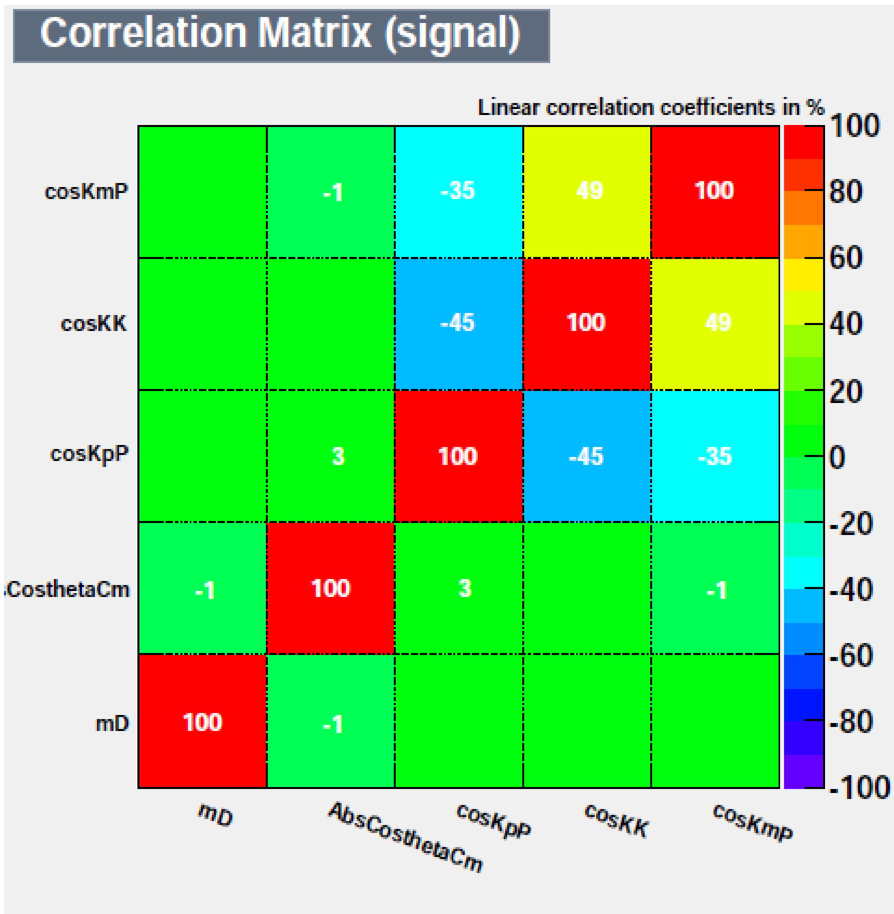
absolute values of the cosine of the angle $\widehat{K^-\pi^-}$

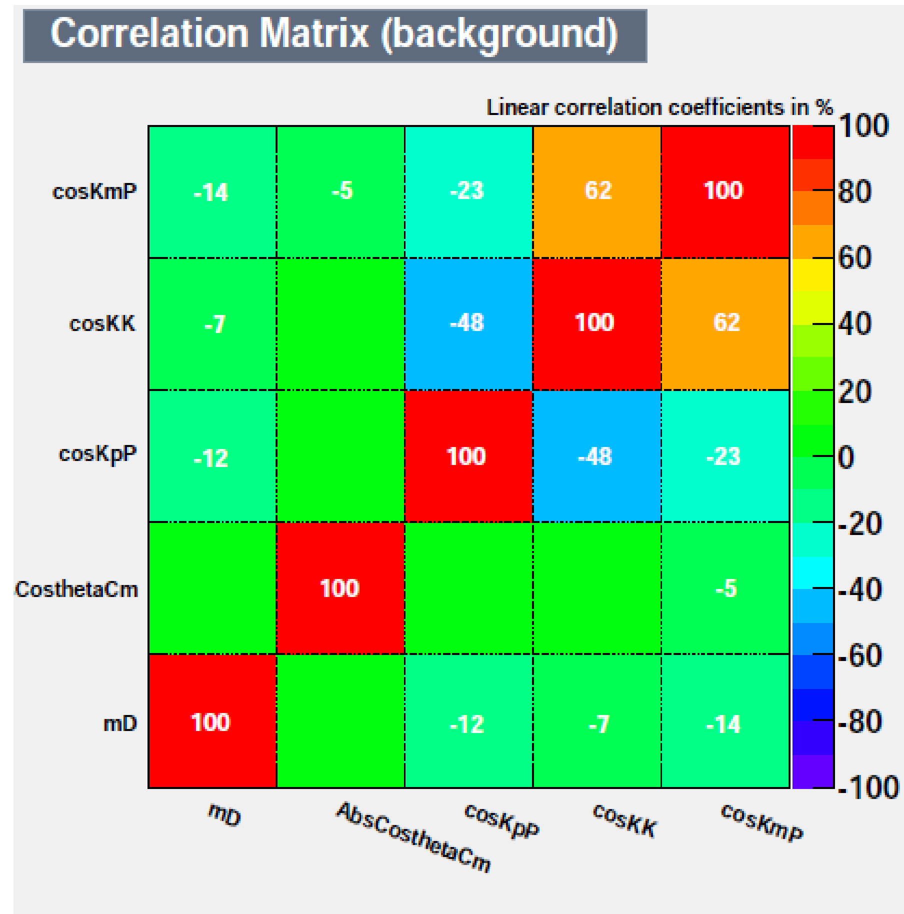
# Interesting variable: Fisher discr.



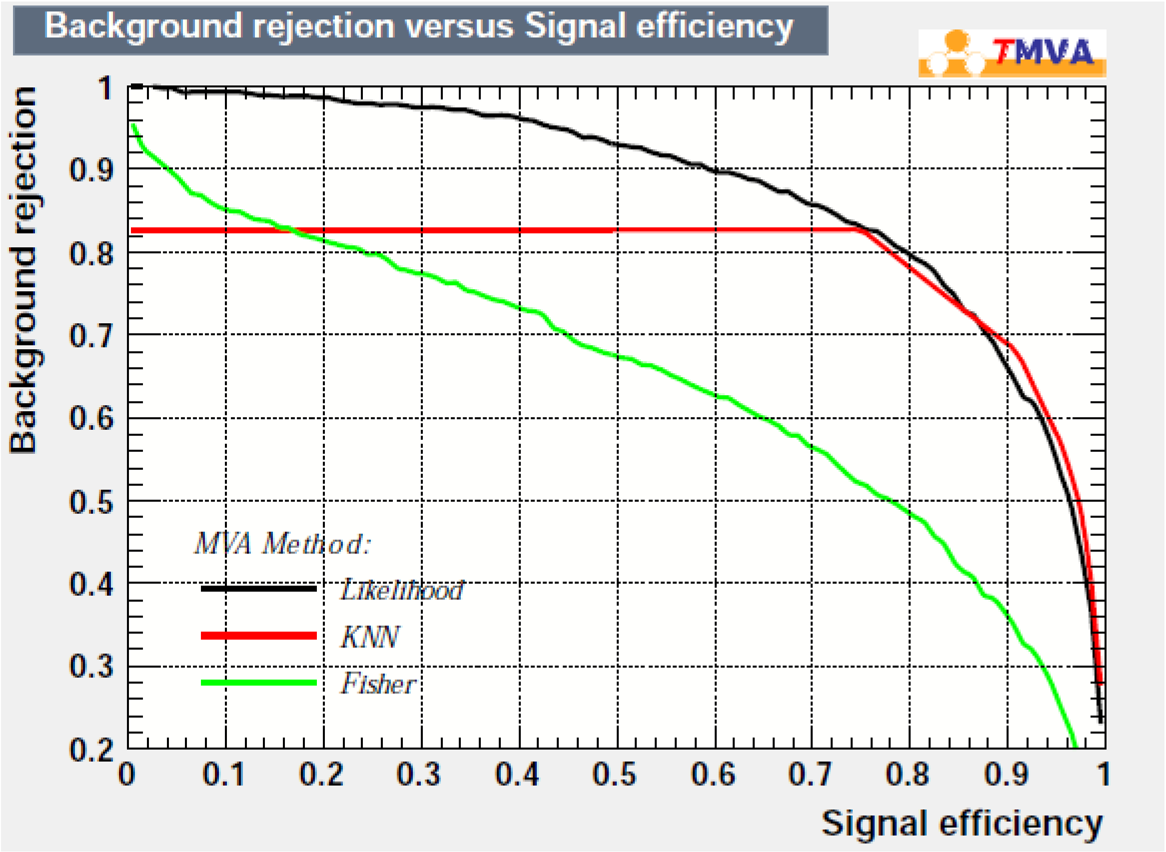

Input variable distributions

# Interesting variable: Fisher discr.



# Interesting variable: Fisher discr.



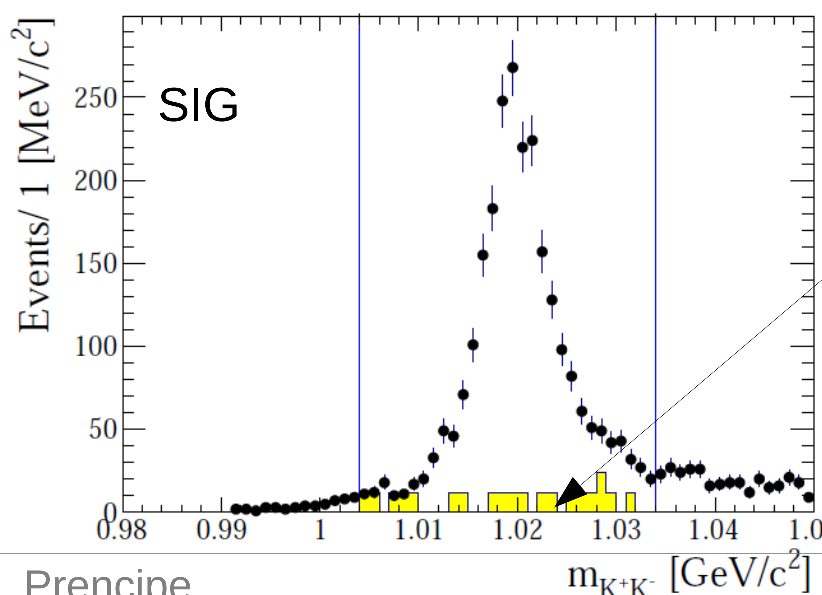

$$\mathcal{F} = 4.293 \cdot m_{Ds} + 0.014 \cdot |Cos\theta| + 0.195 \cdot |Cos\widehat{K^+K^-}| + 0.217 \cdot |Cos\widehat{K^+\pi^-}| + 0.776 \cdot |Cos\widehat{K^-\pi^-}|$$

Optimized cut: +0.038

# Selection

BKG = 40M is scaled to SIG = 200 000; σ (BKG) = 2.2 mb;

| Selection cut | $\sigma = 20$ (bkg) | $\sigma = 10$ (bkg) | $\sigma = 5$ (bkg) | $\sigma = 2$ (bkg) | $\sigma = 1$ (bkg) | signal events | signal $\epsilon$ (%) |
|---|---|---|---|---|---|---|---|
| pre-selection | $2.9{\cdot}10^9$ | $2.9{\cdot}10^9$ | $1.2{\cdot}10^{10}$ | $2.9{\cdot}10^{10}$ | $1.2{\cdot}10^{11}$ | 39860 | $(17.93\pm0.09)\%$ |
| \|POCA radius\| <0.1 | $1.6{\cdot}10^9$ | $3.3{\cdot}10^9$ | $6.6{\cdot}10^9$ | $1.6{\cdot}10^{10}$ | $3.3{\cdot}10^{10}$ | 24137 | $(12.07\pm0.07)\%$ |
| \|POCA z\| <0.2 | $1.6{\cdot}10^6$ | $3.2{\cdot}10^6$ | $6.5{\cdot}10^6$ | $1.6{\cdot}10^7$ | $3.2{\cdot}10^7$ | 14379 | $(7.60\pm0.06)\%$ |
| $m_{Ds\ Ds(2317)}>4.25$ | $1.5{\cdot}10^9$ | $3.1{\cdot}10^9$ | $6.2{\cdot}10^9$ | $1.5{\cdot}10^{10}$ | $3.1{\cdot}10^{10}$ | 15212 | $(7.46\pm0.06)\%$ |
| $\|p_z^*\|<0.1$ | $9.9{\cdot}10^5$ | $2.0{\cdot}10^6$ | $4.0{\cdot}10^6$ | $9.9{\cdot}10^6$ | $2.0{\cdot}10^7$ | 14913 | $(7.19\pm0.06)\%$ |
| $\|\Delta E\|<0.04$ | $9.7{\cdot}10^5$ | $1.9{\cdot}10^6$ | $3.9{\cdot}10^6$ | $9.7{\cdot}10^6$ | $1.9{\cdot}10^6$ | 13179 | $(6.59\pm0.06)\%$ |
| $1.92< m_{Ds} <2.01$ | $9.4{\cdot}10^5$ | $1.9{\cdot}10^6$ | $3.8{\cdot}10^6$ | $9.4{\cdot}10^6$ | $1.9{\cdot}10^6$ | 13179 | $(6.59\pm0.06)\%$ |
| $\mathcal{F}>0.038$ | $7.6{\cdot}10^5$ | $1.5{\cdot}10^6$ | $3.1{\cdot}10^6$ | $7.6{\cdot}10^6$ | $1.5{\cdot}10^6$ | 12532 | $(6.27\pm0.05)\%$ |
| $p_t\ (D_s)<0.2$ | $5.5{\cdot}10^5$ | $1.1{\cdot}10^6$ | $2.2{\cdot}10^6$ | $5.5{\cdot}10^6$ | $1.1{\cdot}10^6$ | 12530 | $(6.27\pm0.05)\%$ |
| $1.004< m_{K+K-} <1.04$ | 12075 | 24150 | 48300 | 120750 | 241500 | 4401 | $(2.2\pm0.05)\%$ |




- Preselection:
  $p_{track}$ cut, POCA volume, Kin fitter
- Background is scaled assuming a signal cross section = 20 nb in this plot
- $\phi$ mass resolution: 5 MeV/$c^2$

# PndKinfitter before selection

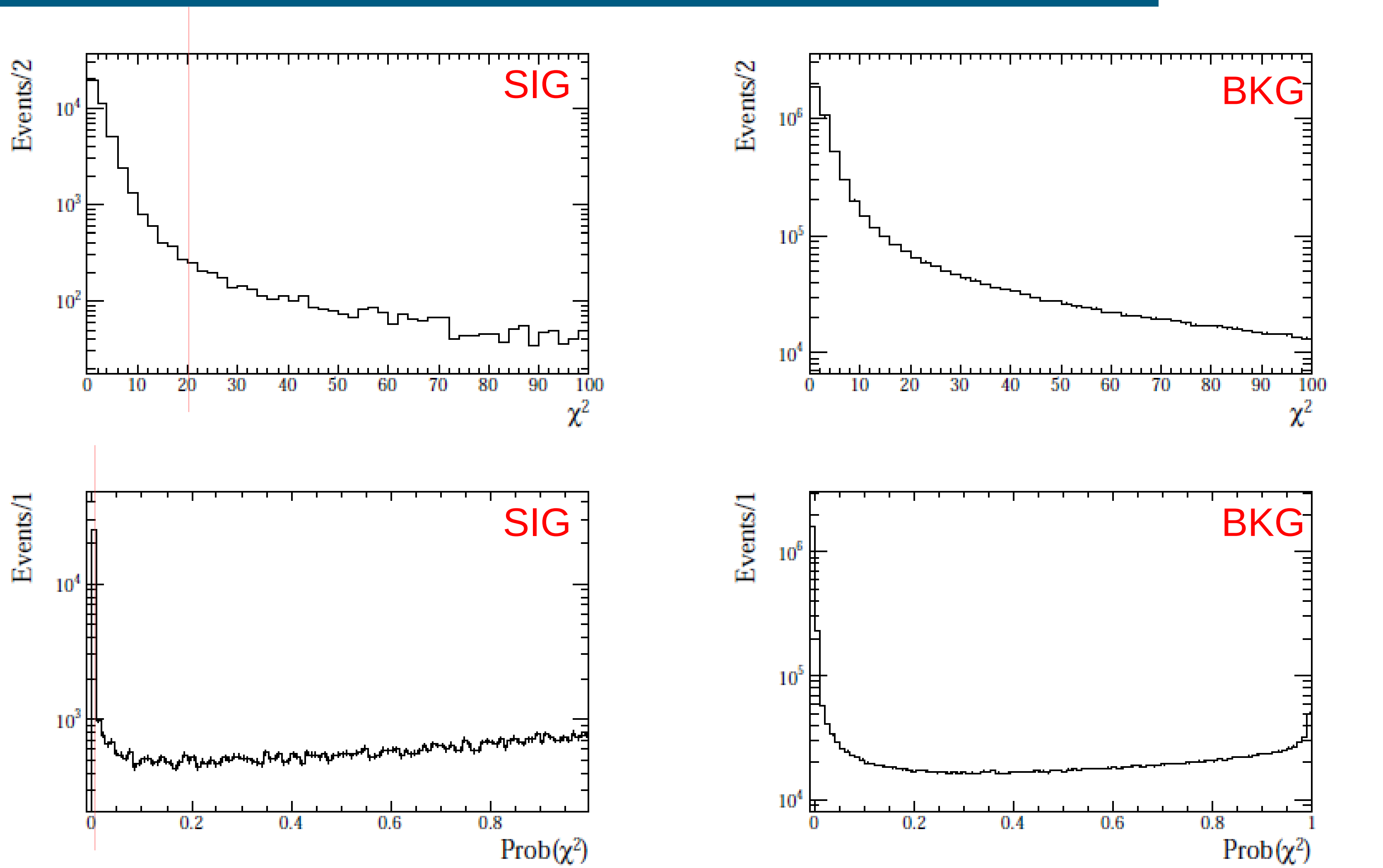



Figure 14: $\chi^2$ distribution of (a) signal events and (b) combinatorial background, after the pre-selection described in the text is applied. Prob($\chi^2$) distribution of (c) signal events and (d) combinatorial background. An optimization study shows that a good selection cut is $\chi^2<20$. All plots are drown in logarithmic scale.

# Check: background samples

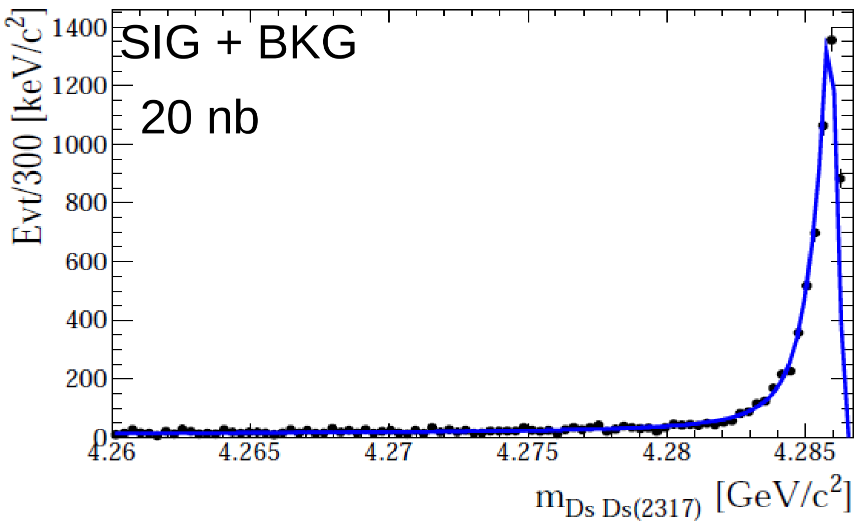
Table 5: DPM consistency check. Selection (1) shows the number of events, surviving to the pre-selection, before the $\chi^2$ cut is applied. Selection (2) shows the number of events, surviving to the pre-selection, with Prob($\chi^2$)>1%. The first skim column shows the efficiency of our pre-selection skim. The skim column with mass cut shows the efficiency of our pre-selection skim, with the additional requirement that the invariant mass of the $K^+K^-\pi^-$ system (i.e., $m_{D_s}$) is restricted in 500-MeV-window from the $D_s$ nominal value: $|m_{D_s}^{reco} - m_{D_s}^{PDG}| < 500\ \text{MeV}/c^2$.

| Sample ID | Generated events | Selection (1) | Selection (2) | skim efficiency (%) | skim efficiency (%) (with mass cut) |
|---|---|---|---|---|---|
| A | 5 143 500 | 1 927 141 | 663 512 | 13% | 7% |
| B | 4 966 000 | 1 675 052 | 614 790 | 12% | 6% |
| C | 2 922 500 | 1 343 355 | 362 683 | 12% | 6% |
| D | 1 633 000 | 329 520 | 210 494 | 13% | 7% |
| E | 5 263 000 | 2 375 941 | 841 939 | 16% | 8% |
| F | 4 968 000 | 1 738 805 | 552 794 | 12% | 6% |
| G | 4 761 500 | 1 733 178 | 556 487 | 12% | 6% |
| H | 1 489 500 | 509 402 | 163 845 | 11% | 6% |
| I | 4 032 500 | 1 358 953 | 514 964 | 13% | 7% |
| L | 5 439 000 | 2 077 698 | 673 414 | 12% | 6% |

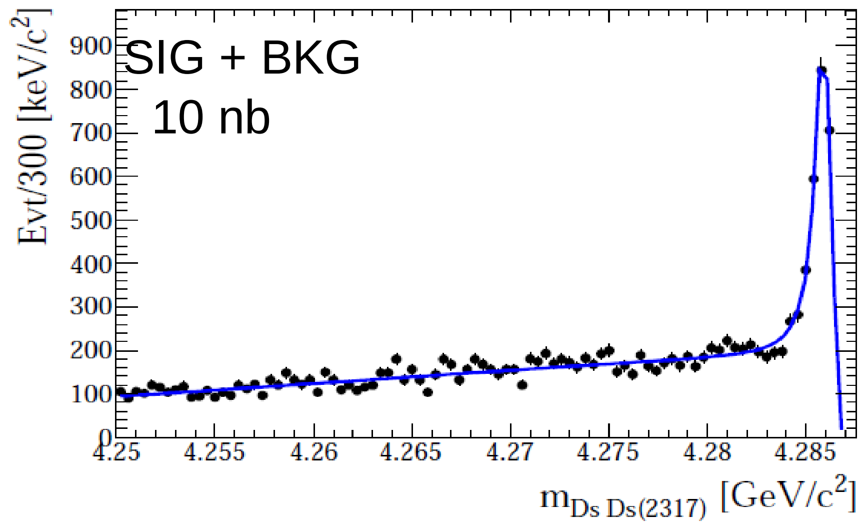
2.8M skimmed over 40M DPM events, with our pre-selection!

# Preliminary mass fits: SIG + BKG

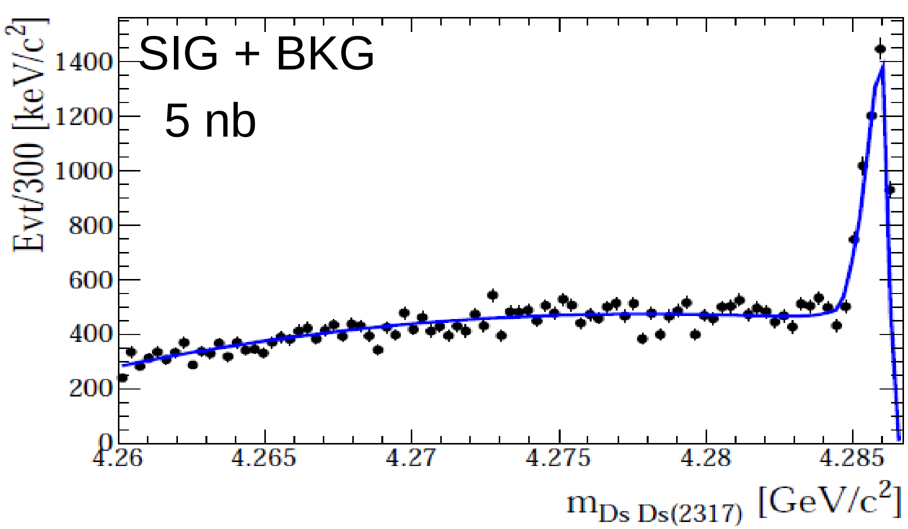





(a) input $\sigma = 20$ nb




(b) input $\sigma = 10$ nb




(c) input $\sigma = 5$ nb

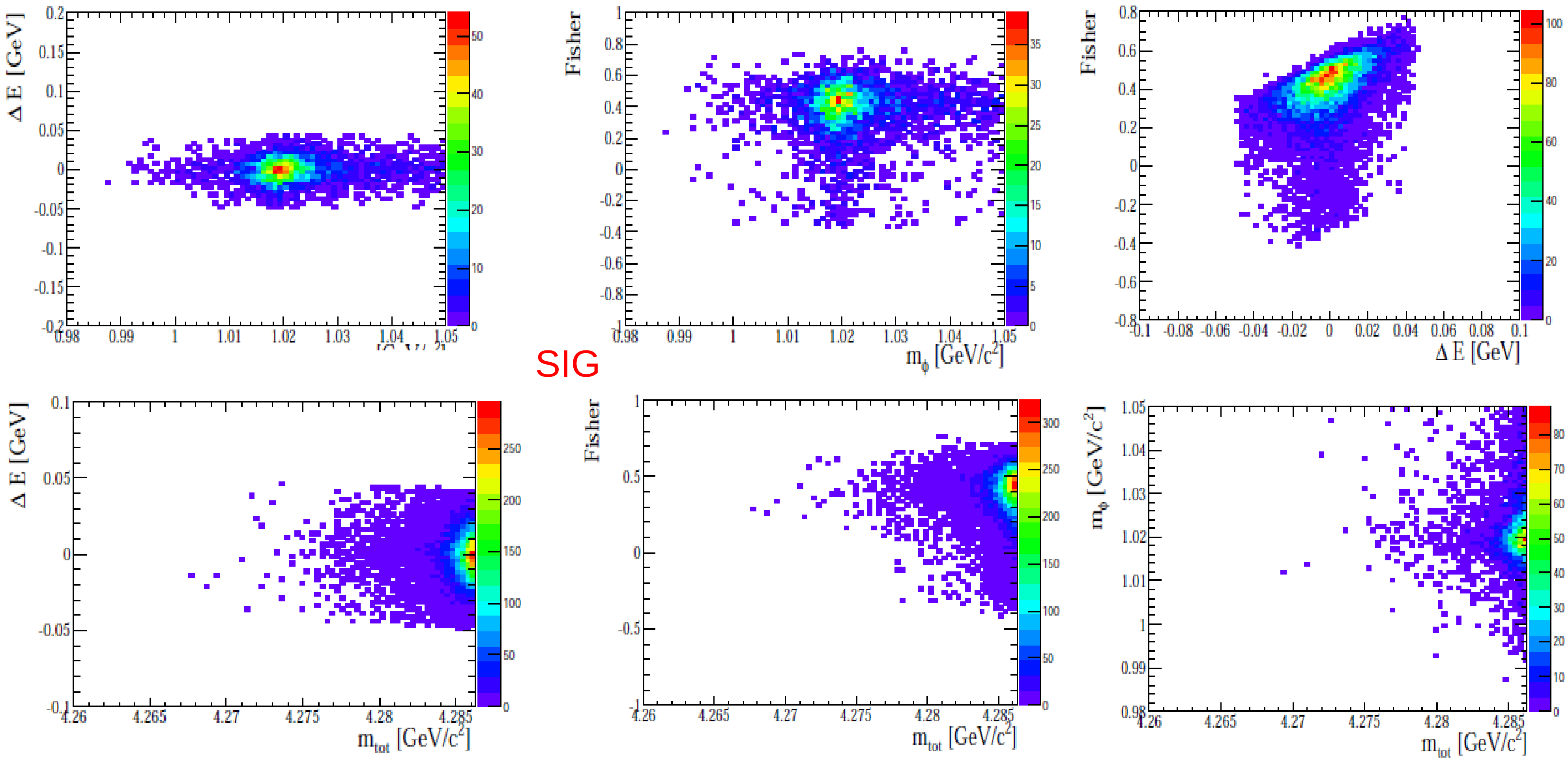
Threshold distributions, after selection

For $\sigma$ =1, or 2 nb, the fit does not well converge.
Need to study a better strategy in these 2 cases.

# 4D-fit



The signal-bkg discriminant, in case of σ(signal) =1, or 2 nb, cannot be a Fisher discriminant.
We propose a 4-Dim fit, writing likelihood, build with ΔE, F, M, $\phi$



# Expectations with $\overline{\text{P}}$ANDA

SCRUT14


- General remarks:
  ① analysis proposed: single-tag mode ($D_s^-$ is tagged to $K^+K^-\pi^-$);
  ②(semi-)inclusive approach;
  ③ unknown cross section, but $\sigma$ expected in **[10-100] nb**;
- ④ if $\varepsilon$ = **100%**, in $\overline{\text{P}}$ANDA $\mathscr{L}$= **0.864** $pb^{-1}$/day N = $\mathscr{L} \cdot \sigma \cdot \varepsilon \in$ [8640-86400]/day
  ❺ but we need to scale by BR($D_s \to KK\pi$) = 5.34% ⇨ [461-4610] $D_s$ events/day!

- Specific simulation of this talk:
- Proposed 15 scan points;
  assuming $\sigma$ = **[10-100] nb**, $\varepsilon$ = **17.5%** and $\mathscr{L}$= **0.864** $pb^{-1}$/day,
  $D_s^- \to K^+K^-\pi^-$ only (PID, vertexing, tracking, dedicated selection)
  BR($D_s \to KK\pi$)~ 5.34% ⇨ **[81-807] events/day**
- For comparison, at B factories:
  BABAR: in $e^+e^- \to c\bar{c}X$, $\mathscr{L}$=91 $fb^{-1}$, **1267** $D_s$(2317) selected;
  BELLE II (future): expected on $\mathscr{L}$=10 $ab^{-1}$ **87 000** $D_s$(2317) in 2020.

# Expectations with $\overline{\text{P}}$ANDA

OCT14

Table 8: Sensitivity study to evaluate the number of produced and reconstructed events per day, for different input cross section values. The calculation is done in the assumpion to run in high luminosity mode (HL, $\mathcal{L} = 8.640\ pb^{-1}/\text{day}$) and high resolution mode (HR, $\mathcal{L} = 0.864\ pb^{-1}/\text{day}$). BR($D_s \rightarrow K^+K^-\pi^-$) = 5.34% [10].

| Input $\sigma$ (nb) | Produced events per day (HL) | Produced events per day (HR) | Reco. events per day (HL) | Reco. events per day (HR) |
|---|---|---|---|---|
| 20 | 172 800 | 17 280 | 203 | 20 |
| 10 | 86 400 | 8640 | 103 | 10 |
| 5 | 43 200 | 4320 | 52 | 5 |
| 2 | 17 280 | 1728 | 20 | 2 |
| 1 | 8 640 | 864 | 10 | 1 |

62 days (HR) to reach what BaBar achieved in 4 years ($\sigma$ = 20 nb)!
A detector duty factor 50% is included in this calculation.

# Summary

- General remarks:
  ① analysis proposed: single-tag mode ($D_s^-$ is tagged to $K^+K^-\pi^-$);
  ②(semi-)inclusive approach;
  ③ unknown cross section, but $\sigma$ expected in **[1-100] nb**;
- ④ if $\varepsilon$ = **100%**, in PANDA $\mathscr{L}$= **0.864** $pb^{-1}$/day $N = \mathscr{L} \cdot \sigma \cdot \varepsilon \in$ [8640-864000]/day
  ❺ but we need to scale by BR($D_s \rightarrow KK\pi$) = 5.34% ⇨ [46-4610] $D_s$ events/day!

- Specific simulation of this talk:
- Proposed 15 scan points;
  assuming $\sigma$ = **[1-100] nb**, $\varepsilon$ = **2.2%** and $\mathscr{L}$= **0.864** $pb^{-1}$/day,
  $D_s^- \rightarrow K^+K^-\pi^-$ only (PID, vertexing, tracking, dedicated selection)
  BR($D_s \rightarrow KK\pi$)~ 5.34% ⇨ **[ 1 – 102 ]** **events/day**
- A likelihood selector for $\sigma$<5 nb is still work in progress....
- For comparison, at B factories:
  BABAR: in $e^+e^- \rightarrow ccX$, $\mathscr{L}$=91 $fb^{-1}$, **1267** $D_s$(2317) selected;
  BELLE II (future): expected on $\mathscr{L}$=10 $ab^{-1}$ **87 000** $D_s$(2317) in 2020.

# Ongoing study: systematics

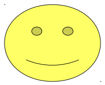
- indetermination of the model

  Simulations with $\bar{p}p$ system spin =1 are performed;
  Simulation with a resonant state in the DsDs(2317) invariant mass are performed

- tracking

- PID method

- efficiency. $$\Delta\epsilon = \sqrt{\epsilon(1-\epsilon)/N_{gen}}$$

- Data point errors in our plots are estimates using a frequentistic Poissonian asymmetric error calculator (Roofit)..... I am "bayesian" 

Analysis note v2 is ready. Shall I upload, for convenor review?

*"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!*