# Comments on D* measurements in B decays

**Motivation**

our preprint : arXiv:1806.09853

## Need for high accuracy

- $B \to D^* \pi$ is a normalization channel at LHC
- $V_{cb}$ is obtained from $B \to D^* l \nu$ decays

we make a proposal to measure the D*

- R(D*) our studies do not explain the measured anomaly

## « Background » in other reactions

- the $D^*_V$ component is about 10% in 3-body B decays; what about in s.l. decays?
- the broad $D\pi$ component in $B \to D\pi l\nu$ decays still needs to be understood :

we propose an interpretation

**Layout**

**NL decays**

**SL decays**

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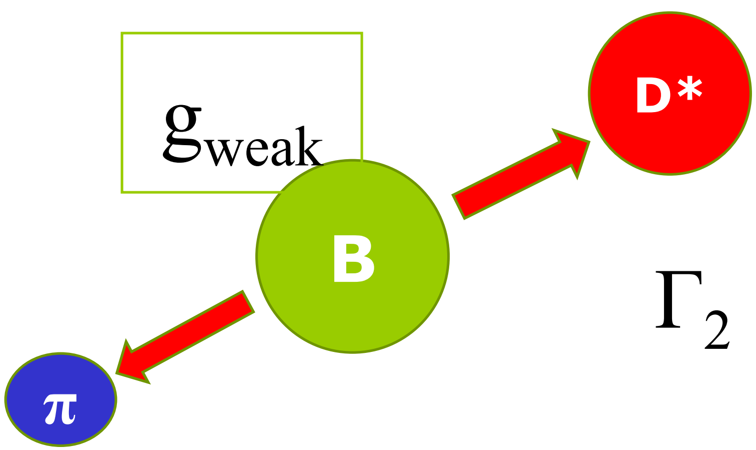
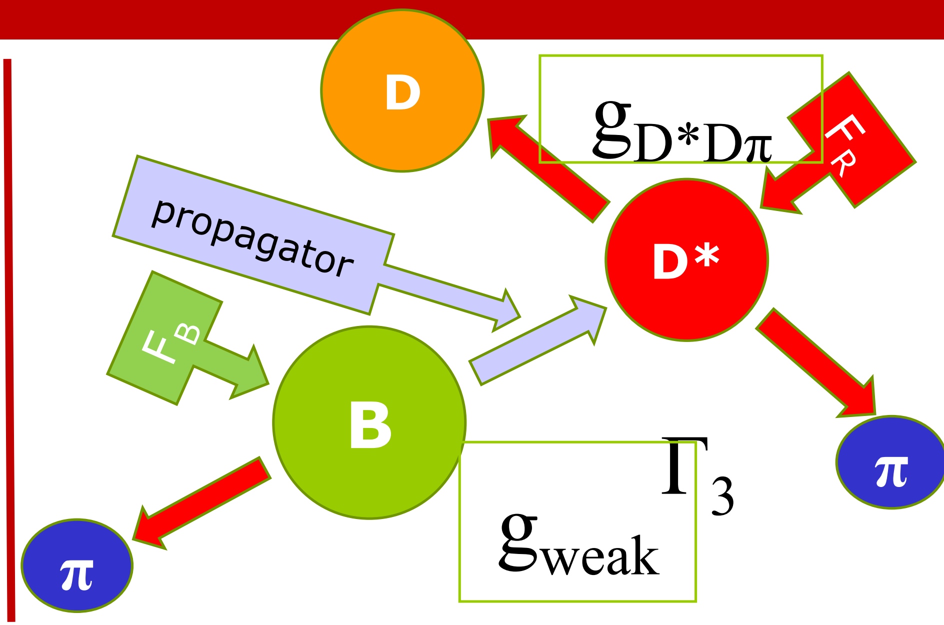
# What is a D*?




**Theory** ? **Experiment**

- 2-body decay, the D* is considered as a stable particle (Ex: F(1) computation in s.l. B decays). Usually expressed by : $\Gamma_{D^*} = 0$

$R(\Delta m) = \Gamma_3(\Delta m) / (\Gamma_2 \times BR)$
(this ratio does not depend on $g_{weak}$)

$R(\Delta m) = 1$ if $\Gamma_{D^*} = 0$ BUT …

this limit is ambiguous

- 3-body decay, the D* is reconstructed within a Dπ mass interval. The D* is virtual and the Dπ mass distribution is, by convention, the sum of a resonance part (D*) and a tail ($D^*_V$) that need to be distinguished for practical reasons.

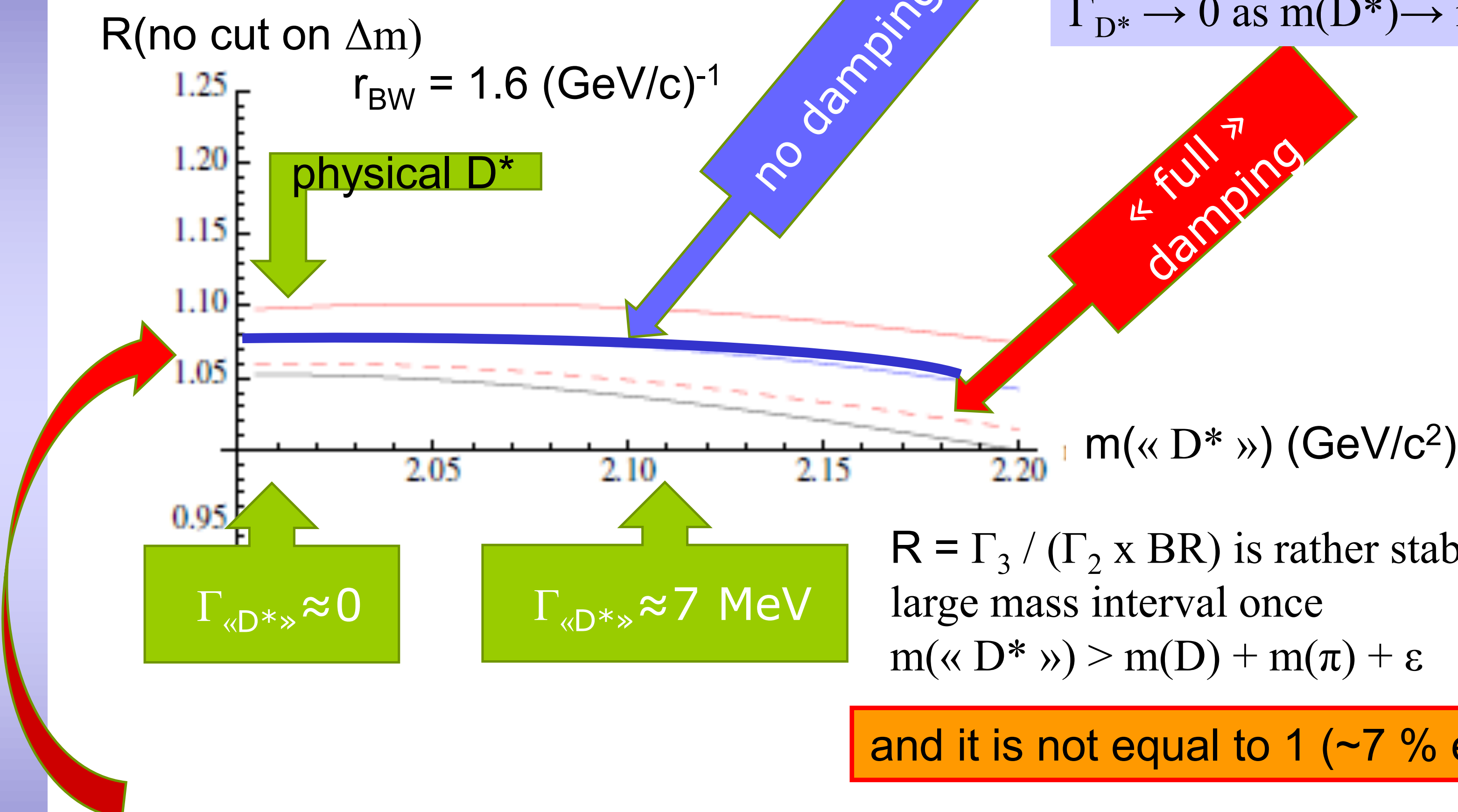
- worries: the mass interval is usually not clearly specified. Are there corrections applied, using simulated events, to account for the selection? How is done the simulation? Effects of damping factors?

# $\Gamma_3$ from an integral over all the phase space

**« physical » situation**

Consider an hypothetical « D* » with arbitrary mass and a width determined by the coupling $g_{D^*D\pi}$.

$\Gamma_{D^*} \rightarrow 0$ as $m(D^*) \rightarrow m(D)+m(\pi)$




R = $\Gamma_3 / (\Gamma_2 \times BR)$ is rather stable over a large mass interval once $m(« D^* ») > m(D) + m(\pi) + \varepsilon$

and it is not equal to 1 (~7 % excess)

The value of R is very slowly dependent on the D* width, this comes from the virtuality of the D*. It depends on the B mass and on damping factors.

# $\Gamma_3$ integral over a restricted mass interval

**PDG**

$BR(B^0_d \to D^{*-}\pi^+;\ D^{*-} \to \bar{D}^0\pi^-) = (1.855 \pm 0.089)\ 10^{-3}$ (**5%** relative uncertainty)

**Expected BR for different mass intervals and dampings**

| $r_{BW}$ or α $(GeV/c)^{-1}$ | 0 | 1.6 | 4.0 | |
|---|---|---|---|---|
| $\lvert\Delta m\rvert < 3\ MeV/c^2$ (Belle) | 1.843<br>1.843 | 1.843<br>1.843 | 1.843<br>1.843 | stable |
| $\Delta m < 10\ MeV/c^2$ (BaBar) | 1.866<br>1.866 | 1.865<br>1.866 | 1.863<br>1.866 | stable |
| $m(\bar{D}^0\pi^-) < 2.1\ GeV/c^2$ (LHCb) | 1.890<br>1.890 | 1.884<br>1.889 | 1.876<br>1.885 | ~stable |

2.6 % difference

For the considered Δm intervals, R(Δm) is almost independent on damping factors. Meanwhile, R varies with Δm.

Exponential damping : $\exp[-\alpha(p-p_0)]$ (used at B-factories)

Blatt-Weisskopf damping : $F^2 = 1+(r_{BW}\, p_0)^2 / 1+(r_{BW}\, p)^2$

# Measuring D* production in n.l. B decays

## Our comments

- few % of the D* are expected at large Dpi mass values and cannot be accurately estimated at present (depending on damping factor hypotheses and on other dynamical effects)
- few % differences between measurements done within different mass intervals (used in experiments) but almost independent of damping factors

## Our proposal to improve present situation

- measure the D* only within a specified mass interval and do not correct for events that are outside this range (apart for resolution effects)

- when combining different experiments which use different ranges, correct for the range dependence before averaging

- **to compare with theory, use an interval such that $R(\Delta m) = 1$**
We find that : **$\Delta m$ = 9-10 MeV. This value is almost independent of the hypotheses used for damping factors (uncertainties below 1%).** It corresponds to about 100 times the nominal D* width.

# The $D^*_V$ component

## Definition

Events ($J^P=1^-$) with $m>m_{cut}$ coupled to the same channels as the $D^*$ and not including radial excitations.

## Main comments

- fitted BR are compatible with theoretical expectations, normalized on the measured D* production.

- measured and expected rates are not accurately determined because of uncertainties on damping factors

| Experiment | $BR(B_d^0 \to D_V^{*-}\pi^+)$ $\times BR(D_V^{*-} \to \bar{D}^0\pi^-) \times 10^4$ | our evaluation (exponential/Blatt-Weisskopf) | $r_{BW}$ or $\alpha$ $(GeV/c)^{-1}$ |
|---|---|---|---|
| Belle [9] | $0.88 \pm 0.13\,(no\,syst.)$ | $0.90^{+0.63}_{-0.29}$ / $1.25^{+0.28}_{-0.36}$ | $1.6^{+1.4}_{-1.6}$ |
| BaBar [13] | $1.39 \pm 0.08 \pm 0.16 \pm 0.35 \pm 0.02$ | $0.30^{+0.11}_{-0.07}$ / $0.52^{+0.14}_{-0.10}$ | $4 \pm 1$ |
| LHCb [14] | $0.78 \pm 0.05 \pm 0.02 \pm 0.15$ | $0.49$ / $0.79$ | $1.60 \pm 0.25$ |

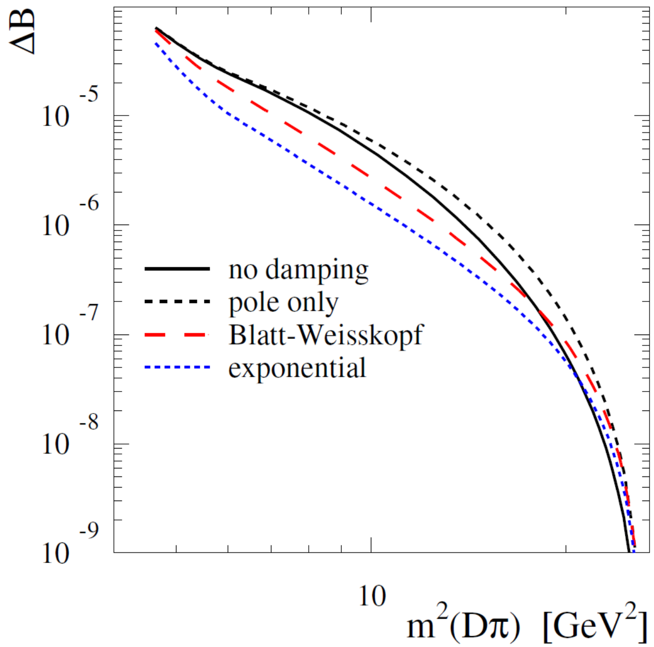
measurements

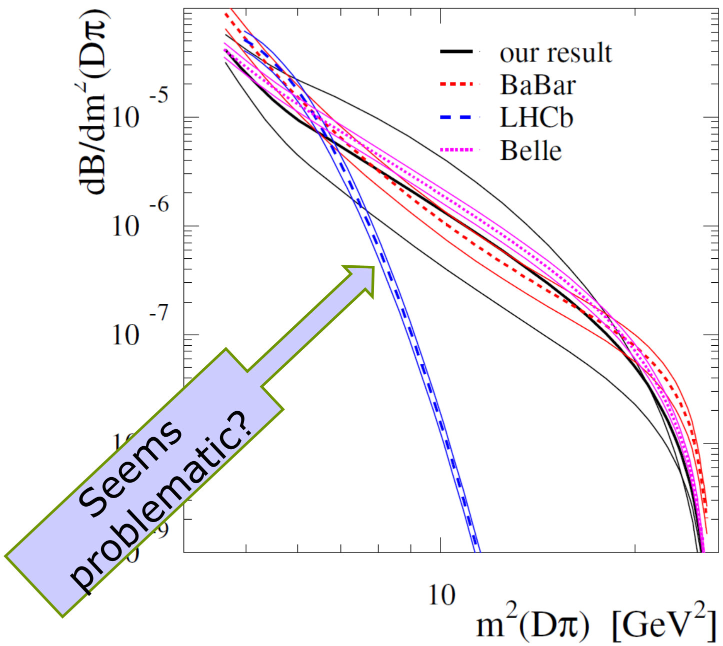
expected from D* production

# The $D^*_V$ mass distribution

**Pole behaviour is expected**

$B^0_d \rightarrow D^{*-}\pi^+$; $D^{*-} \rightarrow \bar{D}^0\pi^-$




The $D^*_V$ component is peaked at low mass values, therefore its rate is tightly related to the $D^*$.
Its mass dependence is governed by the $D^*$ pole, damping factors and other dynamical effects. Therefore it cannot be accurately predicted. In addition … what are « damping factors »?

**Need for direct measurements of the $1^-$ $D\pi$ component**

# The D* propagator ?

$$\frac{1}{s - m_{D^*}^2 + i\sqrt{s}\Gamma_{D^*}(s)}$$

x $\left[ g_{\mu\nu} - \frac{(p_D + p_1)_\mu (p_D + p_1)_\nu}{s} \right]$ « standard »

or ?

x $\left[ g_{\mu\nu} - \frac{(p_D + p_1)_\mu (p_D + p_1)_\nu}{m_{D^*}^2} \right]$ « old standard »

+ same result when integrating over a limited m(Dpi) interval

+ « enormous » $D^*_V$ component ( 2-3 times D* production), which cannot be suppressed using « classical » damping factors and is a S-wave component.

We have understood that this « old standard » choice was proposed (arXiv:1806.06997) to explain the $R_{D^*}$ anomaly ?

# B $\rightarrow D\pi l\nu$

## B $\rightarrow D^* l\nu$

Values for $R^{sl}(\Delta m)$ when integrating over all phase space
$R^{sl}(\Delta m) = \Gamma_4(\Delta m) / \Gamma_3\ (\Gamma_{D^*}=0)$

| channel | no damping | 1 | 1.85 | 3 | 5 |
|---|---|---|---|---|---|
| $\bar{B}_d^0 \rightarrow D^{*+} e^- \bar{\nu}_e$ | 1.098 | 1.077 | 1.058 | 1.042 | 1.027 |
| $B^- \rightarrow D^{*0} e^- \bar{\nu}_e$ | 1.093 | 1.073 | 1.054 | 1.039 | 1.025 |

## $V_{cb}$ measurement

Same comments as for B $\rightarrow D^* \pi$ : to compare with theory, measure the $D^* \rightarrow D\ \pi$ signal within a $\pm$ 10 MeV mass interval.

## B $\rightarrow D^*_V l\nu$, $D^* \rightarrow D\pi$

The B $\rightarrow D^*_V\ \pi$ channel is well identified experimentally and its rate agrees with our expectations.
Therefore, the $D^*_V$ component must be present by a similar mechanism and with similar magnitude in semileptonic decays.

# B →Dπlν

## B →Dπlν

Long standing problem: origin of the broad Dπ component? $\underbrace{D_0^*, D_1'}$, $D^*_V$ ?

$$BR(\bar{B}_d \to [D\pi]_{broad}\ell\bar{\nu}_\ell) = (0.42 \pm 0.06)\,\%$$

$$BR(\bar{B}_d \to [D\pi]_{narrow}\ell\bar{\nu}_\ell) = (0.18 \pm 0.02)\,\%$$

narrow : $D_2^*$

Expected to be small,therefore $D\pi_{\mathrm{broad},D^{**}} << D\pi_{\mathrm{narrow},D^{**}}$

**Expected B →$D^*_V$lν, normalized to D***

| branching fractions (%) | $r_{BW}$= 0 | 1 | 1.85 | 3 | 5 |
|---|---|---|---|---|---|
| $\bar{B}^0_d \to D^{*+}_V e^-\bar{\nu}_e$ | 0.48 | 0.38 | 0.28 | 0.21 | 0.13 |
| $B^- \to D^{*0}_V e^-\bar{\nu}_e$ | 0.49 | 0.39 | 0.29 | 0.21 | 0.13 |

In our opinion, the B →$D^*_V$lν, $D^*_V$l→Dπ expected rate can explain all or a large fraction of the Dπ broad component…. thus solving this « problem »?

# $B \to D^*\tau\nu$ and $B \to D^*_V\tau\nu$

## Expected $B \to D^*\tau\nu$, $D^*\to D\pi$

To account for the tau mass we add another form factor (see S. Fajfer et al., arXiv:1203.2654).
Restricting the integration to $\Delta m$ = 9 MeV, the result agrees with the value expected from theory ($\Gamma_{D^*}$=0), as already observed for light leptons.

## Expected $B \to D^*_V\tau\nu$, $D^*\to D\pi$

Fractions of the decay widths contained outside $\Delta m$=9 MeV computed for light and tau leptons are given in the table.

| | $r_{BW}$=0 | $r_{BW}$=1 | $r_{BW}$=1.85 | $r_{BW}$=3 | $r_{BW}$=5 |
|---|---|---|---|---|---|
| $B \to D^*_V l\nu$ | 9.8% | 7.7% | 5.5% | 4.1% | 2.7% |
| $B \to D^*_V \tau\nu$ | 5.8% | 5.1% | 4.3% | 3.3% | 2.3% |

We find a significant difference on the relative importance of the $D^*_V$ component for light and tau leptons but no difference for the $D^*$ itself.

# Damping factor: $F_B(p)$

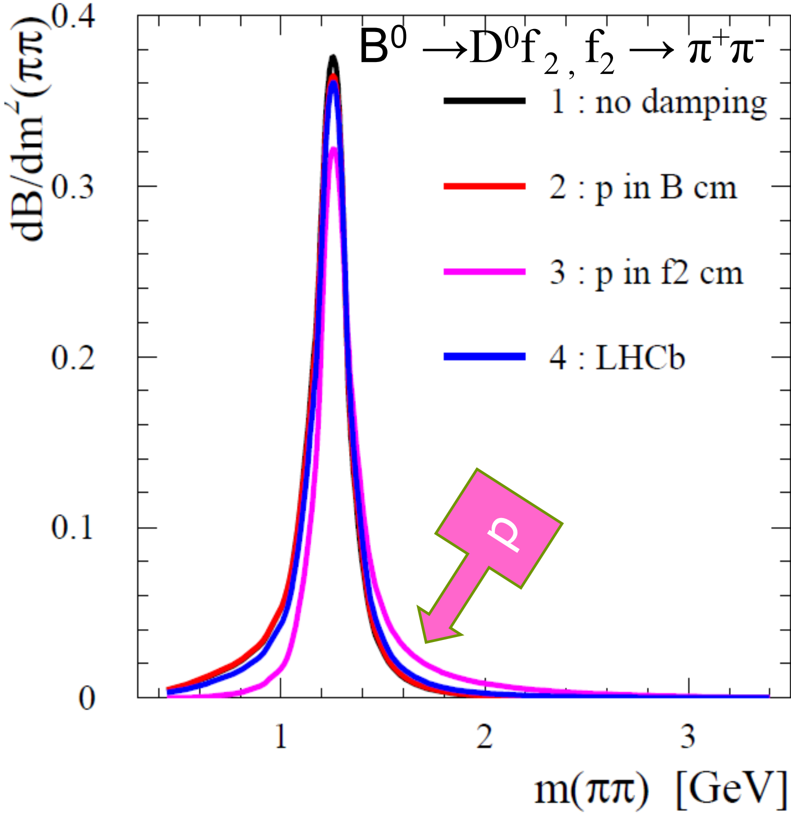
**Theory: none**

- can have a different origin from $F_R$
- why no $F_B$ damping is considered in s;l. decays?
- in what frame is computed the bachelor momentum?

Notation:
« p' » is in B c.m. (B factories)
« p » is in resonance c.m. (LHCb)
$p = p' \times m_B/m$

« p » evaluated in the resonance frame gives large enhancements at high masses

**Use p', evaluated in B frame**



# Conclusions

## D* component

- D* production in B decays is usually not precisely defined and leaves room for additional (few %) uncertainties

- We make a proposal to compare D* meson production with theory, in hadronic and s.l. B decays, which removes these uncertainties

- Measured BR($B \rightarrow D^* \, l \, \nu$, $D^* \rightarrow D\pi$) for light or tau leptons, within $\Delta m$ = 9-10 MeV, are expected to agree with computations done using $\Gamma_{D^*}=0$.

## $D^*_V$ component

- The $D^*_V$ mass variation is usually described by the D* pole modified by damping factors.These factors have no well defined interpretation behind and several mechanisms can contribute at large $D\,\pi$ mass values. Therefore, experimental procedures need to be used to measure directly their effects. S.l. and charged $B^- \rightarrow D^+\pi^-\pi^-$ decays seem promising in this respect.

-We expect that $B \rightarrow [D\,\pi]_{broad}\, l\, \nu$ is dominated by the $D^*_V$ component; LHCb can be in a good position to measure this channel.

- The momentum used in the $F_B(p)$ damping has to be evaluated in the B rest frame; if not, unphysical situations are met.

# STOP

# Physics interpretation

$$R - 1 \approx \frac{1}{16\pi} g^2_{D^* D\pi} m^2_{D^*} \frac{1}{\pi} \frac{1}{p_2(m^2_{D^*})^3} \int ds \frac{\phi(s) - \phi(m^2_{D^*})}{(s - m^2_{D^*})^2 + (m_{D^*}\Gamma_{D^*})^2}$$

$$\phi(s) = \frac{p_2'^3(s)\, p_1^3(s)}{s^{3/2}}$$

forgetting about damping factors

- R -1 is proportional to the strong coupling $g^2$
- $p_2$ and the integral have a smooth variation with $m_{D^*}$
- the limit $m_{D^*} \rightarrow m_D + m_\pi$ is finite (R-1 $\approx$ 0.09) in spite of the fact that $\Gamma \rightarrow 0$ in this case

# *Integral over all phase space*

**PDG**

BR($B^0_d \to D^{*-}\pi^+$; $D^{*-} \to \overline{D}^0\pi^-$) = (1.855 ± 0.089) $10^{-3}$ (**5%** relative uncertainty)

expt. conditions not well specified

**$BR_3$ x $10^3$**

+7.6%

+2%

| $r_{BW}$ or α $(GeV/c)^{-1}$ | 0 | 1.6 | 4.0 |
|---|---|---|---|
| no mass cut | 1.996 | 1.933 | 1.893 |
| | 1.996 | 1.968 | 1.917 |

high mass tails

R varies between 1.08 to 1.02

The D* has a tail at high masses which contains few % of the signal, in spite of its very small width.

Estimates are dependent on damping hypotheses

exponential damping : exp[-α(p-$p_0$)] (used at B-factories)

Blatt-Weisskopf damping

# Damping factor: $F_B(p)$

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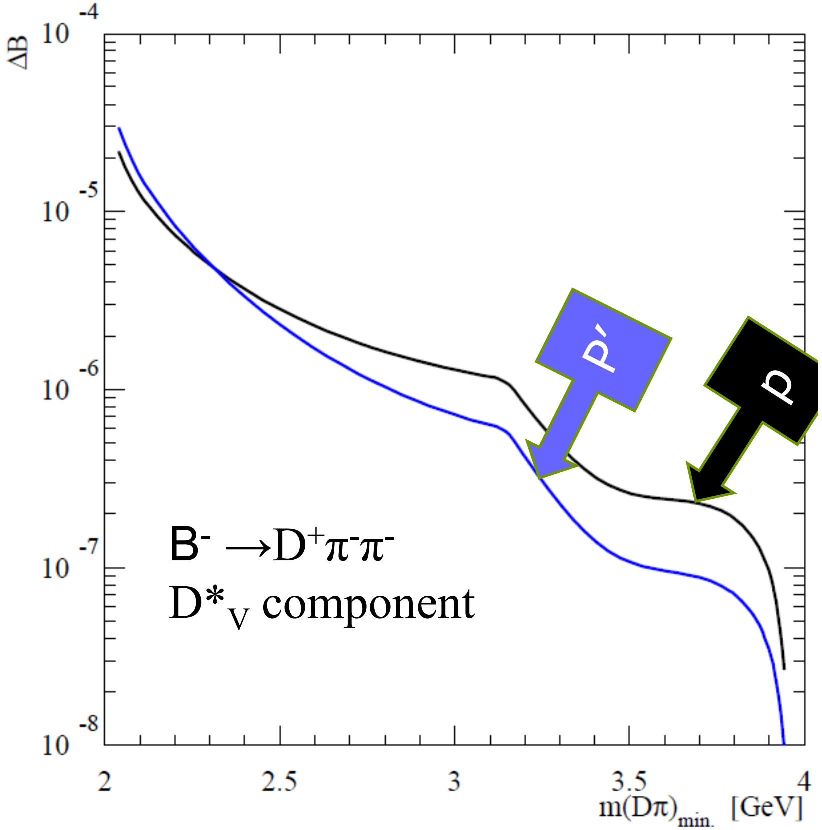
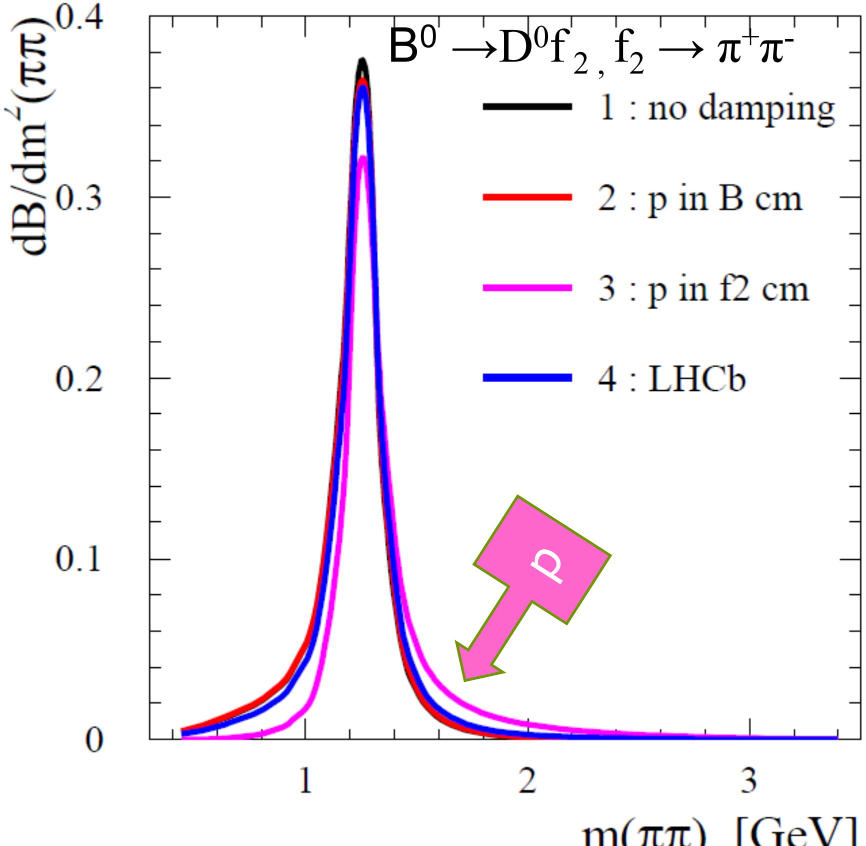



« p » evaluated in the resonance frame gives large enhancements at high masses
Cannot compare damping parameters evaluated using different conventions

# What is a D*? (physics interpretation)

## A paradox?

- $R(\Delta m) = 1$ is verified if $\Delta m \approx 10$ MeV ~ 100 $\Gamma(D^*)$

$$\Gamma_3 = \frac{1}{\pi}\int_{(m_D+m_1)^2}^{(m_B-m_2)^2} ds\, \frac{\Gamma_{B_d^0\to D^{*-}\pi^+}(s) \quad s^{1/2} \quad \Gamma_{D^{*-}\to D^0\pi^-}(s)}{(s-m_{D^*}^2)^2 + s\Gamma_{D^*}^2(s)}$$

total width

$$\lim_{\Gamma_{D^*}\to 0} \Gamma_3 = \Gamma_{B_d^0\to D^{*-}\pi^+}(m_{D^*}^2) \times BR = \Gamma_2 \text{ x BR}$$

$$\Gamma_{D^*}(s) = \frac{g^2}{24\,\pi\, s}\left(p_1^3 + \frac{1}{2}\, p_2^3\right) + \Gamma_{D^*}^{em.}(s) + \Gamma_{D^*}^{others}(s)$$

(forgetting damping factors)

$D^0\pi^+$ | $D^+\pi^0$ | meas. at $m_{D^*}$ | $= 0$ at $m_{D^*}$ | $= 1$ at $m_{D^*}$

g = 16.8 ± 0.2 is obtained from the measurement of $\Gamma_{D^*}(m_{D^*})$

**PDG**

BR($B^0_d \rightarrow D^{*-}\pi^+$; $D^{*-} \rightarrow \overline{D}^0\pi^-$) = (1.855 ± 0.089) $10^{-3}$ (**5%** relative uncertainty)

**BR$_3$ x $10^3$**

+7.6% +2%

| $r_{BW}$ or α $(GeV/c)^{-1}$ | 0 | 1.6 | 4.0 |
|---|---|---|---|
| no mass cut | 1.996 | 1.933 | 1.893 |
| | 1.996 | 1.968 | 1.917 |

high mass tails

not stable versus damping hypothesis

exponential damping : exp[-α(p-$p_0$)] (used at B-factories)

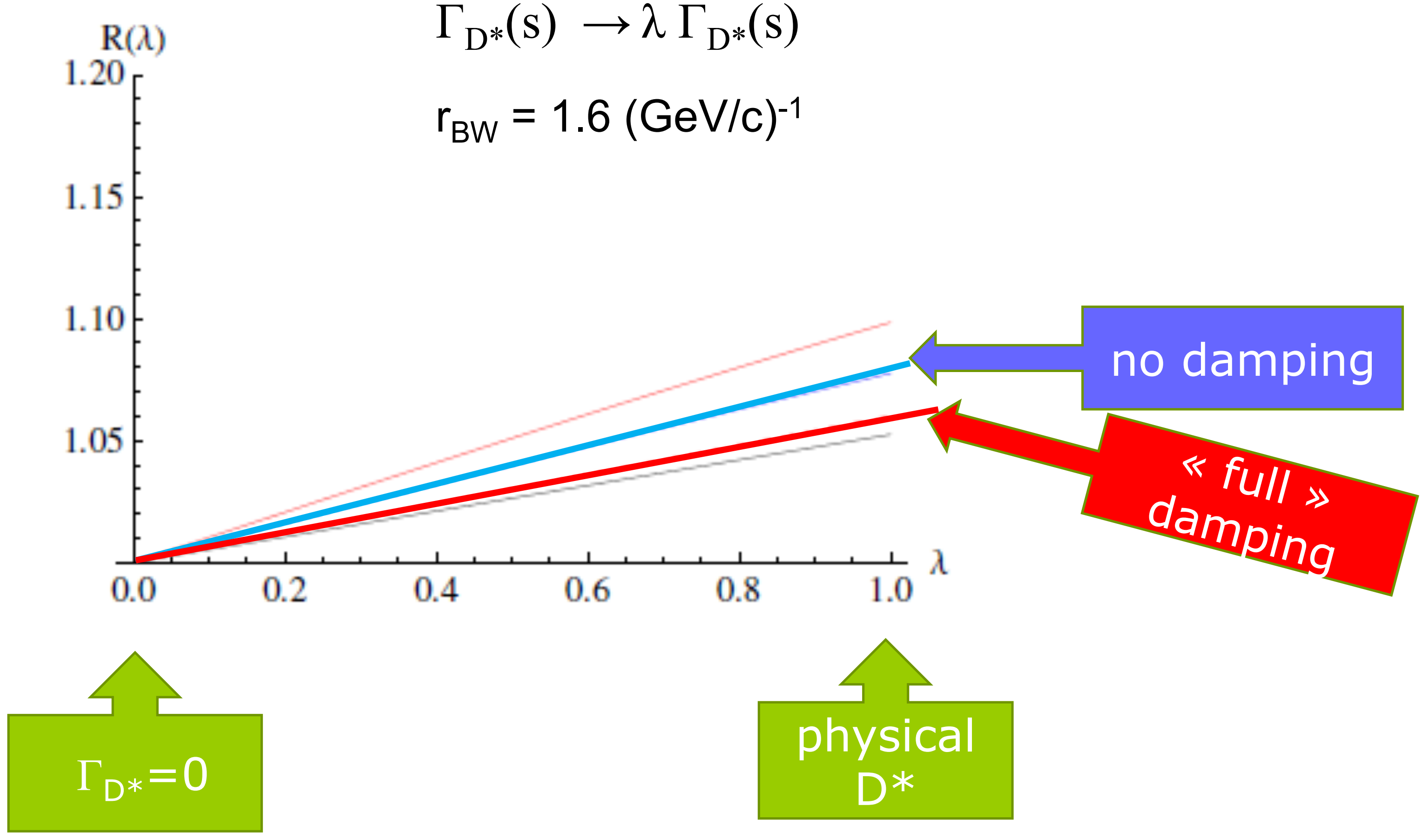
Blatt-Weisskopf damping

# D* tail : limit when g → 0

## Consistent but not physical

$$\Gamma_{D*}(s) \rightarrow \lambda\, \Gamma_{D*}(s)$$

$r_{BW}$ = 1.6 $(GeV/c)^{-1}$



# What is a D*?

The D* is a quite standard hadronic state, except for the fact that it happens to be very close and above threshold, which generates an accidentally very small width.

Therefore there is no theoretical justification

- to apply to it specific forms of damping factors, unlike done at B factories,

….. but, at present, who knows the behavior of these factors?

- to skip the resonance denominator as done at LHCb.

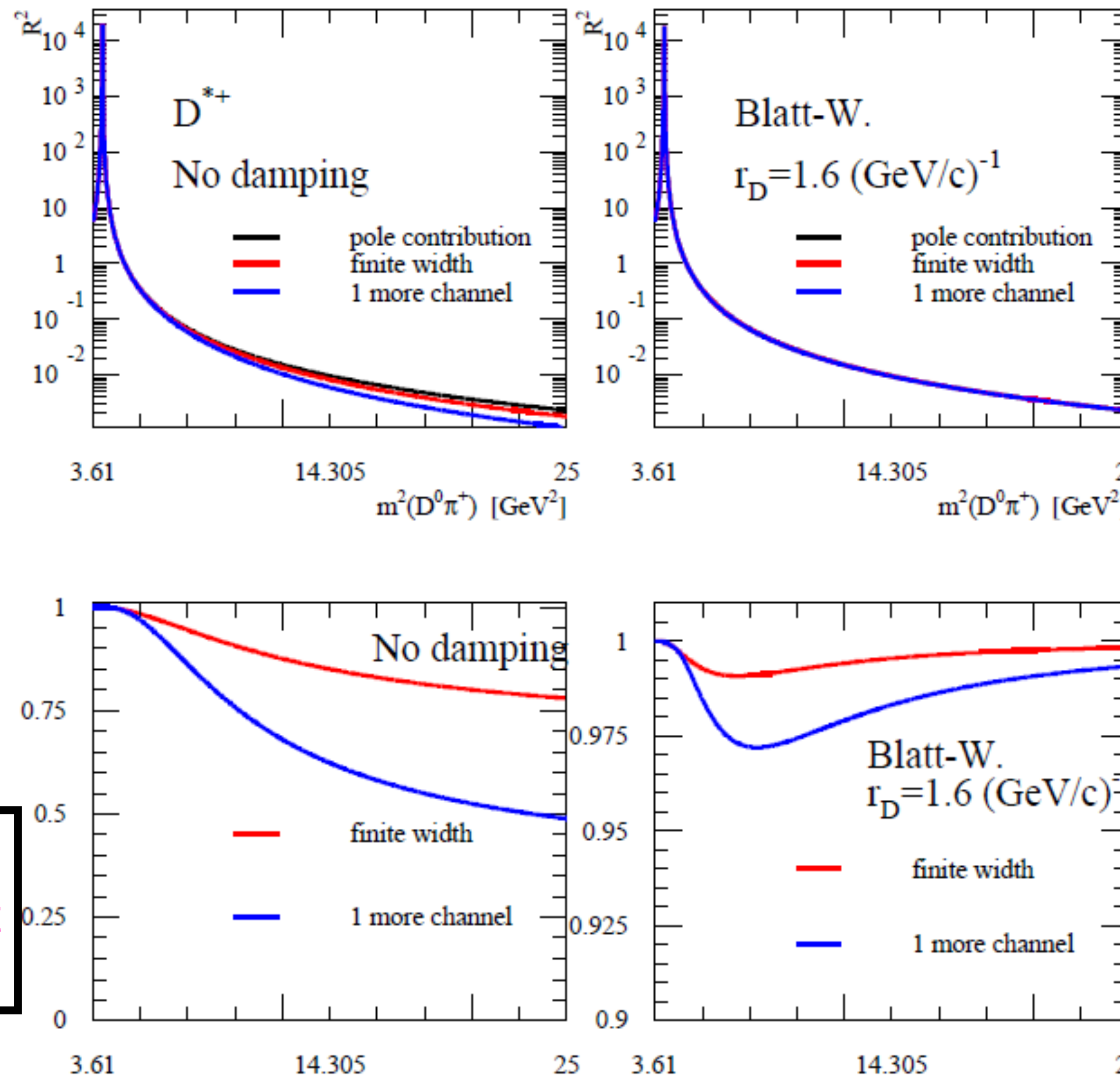
# Damping factor: $F_R(q)$

## Theory: none

- only models, not based on QCD
- a natural damping is provided by the opening of new decay channels when the mass increases
- the two mechanisms are not equivalent
- $F_R(q)$ is evaluated in the resonance rest frame

## Proposal

Analyze $B \to D\pi \, l \, \nu$ events to measure the $D^*_V$ component versus $m(D\pi)$.



# Integral over all phase space

## PDG

BR($B^0_d \to D^{*-}\pi^+$; $D^{*-} \to \bar{D}^0\pi^-$) = (1.855 ± 0.089) $10^{-3}$ (5% relative uncertainty)

## Theory

$$\Gamma_2 \equiv \Gamma_{B^0_d \to D^{*-}\pi^+}({m^*_D}^2) = \frac{g_2^2}{8\pi}\frac{1}{m^2_{D^*}}{p'_2}^3(m^2_{D^*})$$ → $g_2$ using BR(PDG)

$$\Gamma_{D^{*-}\to \bar{D}^0\pi^-}(s) = \frac{g^2}{24\pi}\frac{p_1^3}{s} \times F^2_R(s)$$ ← g using $\Gamma(D^*)$ measurement

$$\Gamma_3 = \frac{1}{\pi}\int_{(m_D+m_1)^2}^{(m_B-m_2)^2} ds \frac{\Gamma_{B^0_d\to D^{*-}\pi^+}(s) \quad s^{1/2} \quad \Gamma_{D^{*-}\to\bar{D}^0\pi^-}(s)}{(s-m^2_{D^*})^2 + s\Gamma^2_{D^*}(s)}$$

$F_B(s)$

$F_R(s)$

$F_R(s)$

It verifies:

$BR \equiv BR_{D^{*-}\to\bar{D}^0\pi^-}(m^2_{D^*})$

$$\lim_{\Gamma_{D^*}\to 0}\Gamma_3 = \Gamma_{B^0_d\to D^{*-}\pi^+}(m^2_{D^*}) \times BR$$

R = $\Gamma_3$ / ($\Gamma_2$ x BR) is independent of the normalisation ($g_2$)