



**HAL**  
open science

# Local Error Estimates of the Finite Element Method for an Elliptic Problem with a Dirac Source Term

Silvia Bertoluzza, Astrid Decoene, Loïc Lacouture, Sébastien Martin

► **To cite this version:**

Silvia Bertoluzza, Astrid Decoene, Loïc Lacouture, Sébastien Martin. Local Error Estimates of the Finite Element Method for an Elliptic Problem with a Dirac Source Term. 2015. hal-01150745v5

**HAL Id: hal-01150745**

**<https://hal.science/hal-01150745v5>**

Preprint submitted on 6 Feb 2016

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Local Error Estimates of the Finite Element Method for an Elliptic Problem with a Dirac Source Term

Silvia BERTOLUZZA, Astrid DECOENE, Loïc LACOUTURE and Sébastien MARTIN

February 3, 2016

**Abstract:** The solutions of elliptic problems with a Dirac measure right-hand side are not  $H^1$  and therefore the convergence of the finite element solutions is suboptimal. The use of graded meshes is standard remedy to recover quasi-optimality, namely optimality up to a log-factor, for low order finite elements in the  $\mathbb{L}^2$ -norm. Optimal (or quasi-optimal for the lowest order case) convergence for Lagrange finite elements has been shown, in the  $\mathbb{L}^2$ -norm, on a subdomain which excludes the singularity. Here, on such subdomains, we show a quasi-optimal convergence in the  $H^s$ -norm, for  $s \geq 1$ , and, in the particular case of Lagrange finite elements, an optimal convergence in  $H^1$ -norm, on a family of quasi-uniform meshes in dimension 2. The study of this problem is motivated by the use of the Dirac measure as a reduced model in physical problems, for which high accuracy of the finite element method at the singularity is not required. Our results are obtained using local Nitsche and Schatz-type error estimates, a weak version of Aubin-Nitsche duality lemma and a discrete inf-sup condition. These theoretical results are confirmed by numerical illustrations.

**Key words:** Dirichlet problem, Dirac measure, Green function, finite element method, local error estimates.

## 1 Introduction.

This paper deals with the accuracy of the finite element method on elliptic problems with a singular right-hand side. More precisely, let us consider the Dirichlet problem

$$(P_\delta) \begin{cases} -\Delta u_\delta &= \delta_{x_0} & \text{in } \Omega, \\ u_\delta &= 0 & \text{on } \partial\Omega, \end{cases}$$

where  $\Omega \subset \mathbb{R}^2$  is a bounded open  $C^\infty$  domain or a square, and  $\delta_{x_0}$  denotes the Dirac measure concentrated at a point  $x_0 \in \Omega$  such that  $\text{dist}(x_0, \partial\Omega) > 0$ .

Problems of this type occur in many applications from different areas, like in the mathematical modeling of electromagnetic fields [17]. Dirac measures can also be found on the right-hand side of adjoint equations in optimal control of elliptic problems with state constraints [8]. As further examples where such measures play an important role, we mention controllability for elliptic and parabolic equations [9, 10, 21] and parameter identification problems with pointwise measurements [23].

Our interest in  $(P_\delta)$  is motivated by the modeling of the movement of a thin structure in a viscous fluid, such as cilia involved in the muco-ciliary transport in the lung [15]. In the asymptotic of a zero diameter cilium with an infinite velocity, the cilium is modelled by a line Dirac of force in the source term. In order to make the computations easier, the line Dirac can be approximated by

a sum of punctual Dirac forces distributed along the cilium [20]. In this paper, we address a scalar version of this problem: problem  $(P_\delta)$ .

In the regular case, namely the Laplace problem with a regular right-hand side, the finite element solution  $u^h$  is well-defined and for  $u \in H^{k+1}(\Omega)$ , we have, for all  $0 \leq s \leq 1$ ,

$$\|u - u^h\|_s \leq Ch^{k+1-s} \|u\|_{k+1}, \quad (1)$$

where  $k$  is the degree of the method [11] and  $h$  the mesh size. In dimension 1, the solution  $u_\delta$  of Problem  $(P_\delta)$  belongs to  $H^1(\Omega)$ , but it is not  $H^2(\Omega)$ . In this case, the numerical solution  $u_\delta^h$  and the exact solution  $u_\delta$  can be computed explicitly. If  $x_0$  coincides with a node of the discretization,  $u_\delta^h = u_\delta$ . Otherwise, this equality holds only on the complementary of the element which contains  $x_0$ , and the convergence orders in  $H^1$ -norm and  $\mathbb{L}^2$ -norm are  $1/2$  and  $3/2$  respectively. In dimension 2, Problem  $(P_\delta)$  has no  $H^1(\Omega)$ -solution, and so, although the finite element solution can be defined, the  $H^1(\Omega)$ -error makes no sense and the  $\mathbb{L}^2(\Omega)$ -error estimates cannot be obtained by a straightforward application of the Aubin-Nitsche method.

Let us review the literature on error estimates for problem  $(P_\delta)$ , starting with discretizations on quasi-uniform meshes. Babuška [4] showed an  $\mathbb{L}^2(\Omega)$ -convergence of order  $h^{1-\varepsilon}$ ,  $\varepsilon > 0$ , for a two-dimensional smooth domain. Scott proved in [25] an a priori error estimate of order  $2 - \frac{d}{2}$ , where the dimension  $d$  is 2 or 3. The same result has been proved by Casas [7] for general Borel measures on the right-hand side.

To the best of our knowledge, in order to improve the convergence order, Eriksson [14] was the first who studied the influence of locally refined meshes near  $x_0$ . Using results from [24], he proved convergence of order  $k$  and  $k + 1$  in the  $W^{1,1}(\Omega)$ -norm and the  $\mathbb{L}^1(\Omega)$ -norm respectively, for approximations with a  $P_k$ -finite element method. Recently, by Apel and co-authors [2], an  $\mathbb{L}^2(\Omega)$ -error estimate of order  $h^2 |\ln h|^{3/2}$  has been proved in dimension 2, using graded meshes. Optimal convergence rates with graded meshes were also recovered by D'Angelo [12] using weighted Sobolev spaces. A posteriori error estimates in weighted spaces have been established by Agnelli and co-authors [1].

These theoretical a priori results are based upon graded meshes, which increase the complexity of the meshing and the computational cost, even if the mesh is refined only locally, especially when the right-hand side includes several Dirac measures, that can be static or moving. Therefore Eriksson [13] developed a numerical method to solve the problem and recovers the optimal convergence rate: the numerical solution is searched in the form  $u_0 + v_h$  where  $u_0$  contains the singularity of the solution and  $v_h$  is the numerical solution of a smooth problem. This method has been developed in the case of the Stokes problem in [20].

However, in applications, the Dirac measure at  $x_0$  is often a model reduction approach, and a high accuracy at  $x_0$  of the finite element method is not necessary. Thus, it is interesting to study the error on a fixed subdomain which excludes the singularity. Recently, Köppl and Wohlmuth have shown in [19] optimal convergence in  $\mathbb{L}^2$ -norm for the Lagrange finite elements (the result is quasi-optimal for the  $P^1$ -element). In this paper, we consider the problem in dimension 2, and we show :

1. Quasi-optimal convergence in  $H^s$ -norm, for  $s \geq 1$ . This result applies to a wide class of finite-element methods and beyond, including Lagrange and Hermite finite elements and wavelets. The  $\mathbb{L}^2$ -error estimates established in [19] are not used and the proof is based on different arguments.
2. Optimal convergence in  $H^1$ -norm for the Lagrange finite elements. This result is obtained by direct use of the optimal  $\mathbb{L}^2$ -norm convergence result in [19].
3. Optimal convergence in  $H^1$ -norm in the particular case of the  $P^1$ -Lagrange finite element using different arguments than those used for the previous results.

These results imply that graded meshes are not required to recover optimality far from the singularity and that there are no pollution effects. In addition, by linearity of Problem  $(P_\delta)$ , the result holds in the case of several Dirac masses. The paper is organized as follows. Our main results are presented in Section 2 after recalling the Nitsche and Schatz Theorem, which is an important tool for the proof presented in Section 3. In Section 4 another argument is presented to obtain an optimal estimate in the particular case of the  $P_1$ -finite elements. We illustrate in Section 5 our theoretical results by numerical simulations and, in Section 6, we discuss the generalization of our approach to the three-dimensional case.

## 2 Main results.

In this section, we define all the notations used in this paper, formulate our main results and recall an important tool for the proof, the Nitsche and Schatz Theorem.

### 2.1 Notations.

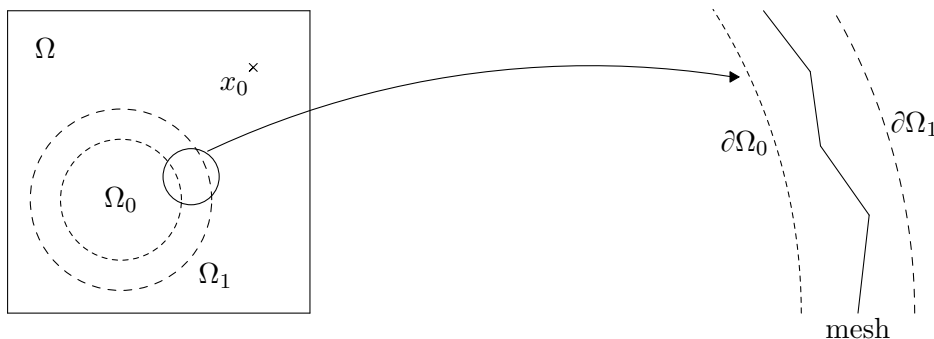


Figure 1: Domains  $\Omega_0$  and  $\Omega_1$ .

For a domain  $D$ , we will denote by  $\|\cdot\|_{s,p,D}$  (respectively  $|\cdot|_{s,p,D}$ ) the norm (respectively the semi-norm) of the Sobolev space  $W^{s,p}(D)$ , while  $\|\cdot\|_{s,D}$  (respectively  $|\cdot|_{s,D}$ ) will stand for the norm (respectively the semi-norm) of the Sobolev space  $H^s(D)$ .

For the numerical solution, let us introduce a family of quasi-uniform simplicial triangulations  $\mathcal{T}_h$  of  $\Omega$  and an order  $k$  finite element space  $V_h^k \subset H_0^1(\Omega)$ . To ensure that the numerical solution is well-defined, the space  $V_h^k$  is assumed to contain only continuous functions. The finite element solution  $u_\delta^h \in V_h^k$  of problem  $(P_\delta)$  is defined by

$$\int_{\Omega} \nabla u_\delta^h \cdot \nabla v_h = v_h(x_0), \quad \forall v_h \in V_h^k. \quad (2)$$

For  $s \geq 2$ , we will also evaluate the  $H^s$ -norm of the error on a subdomain of  $\Omega$  which does not contain the singularity, and, whenever we do so, we will of course assume the finite elements to be  $H^s$ -conforming. We fix two subdomains  $\Omega_0$  and  $\Omega_1$  of  $\Omega$ , such that  $\Omega_0 \subset\subset \Omega_1 \subset\subset \Omega$  and  $x_0 \notin \overline{\Omega_1}$  (see Figure 1). We consider a mesh which satisfies the following condition:

**Assumption 1.** For some  $h_0$ , we have for all  $0 < h \leq h_0$  (see Figure 1),

$$\overline{\Omega}_0^m \cap \Omega_1^c = \emptyset, \text{ where } \overline{\Omega}_0^m = \bigcup_{\substack{T \in \mathcal{T}_h \\ T \cap \Omega_0 \neq \emptyset}} T,$$

and  $\Omega_1^c$  is the complement of  $\Omega_1$  in  $\Omega$ .

## 2.2 Regularity of the solution $u_\delta$ .

In this subsection, we focus on the singularity of the solution, which is the main difficulty in the study of this kind of problems. In dimension 2, problem  $(P_\delta)$  has a unique variational solution  $u_\delta \in W_0^{1,p}(\Omega)$  for all  $p \in [1, 2[$  (see for instance [3]). Indeed, denoting by  $G$  the Green function,  $G$  is defined by

$$G(x) = -\frac{1}{2\pi} \log(|x|).$$

This function  $G$  satisfies  $-\Delta G = \delta_0$ , so that  $G(\cdot - x_0)$  contains the singular part of  $u_\delta$ . As it is done in [3], the solution  $u_\delta$  can be built by adding to  $G(\cdot - x_0)$  a corrector term  $\omega \in H^1(\Omega)$ , solution of the Laplace problem

$$\begin{cases} -\Delta \omega = 0 & \text{in } \Omega, \\ \omega = -G(\cdot - x_0) & \text{on } \partial\Omega. \end{cases} \quad (3)$$

Then, the solution is given by

$$u_\delta(x) = G(x - x_0) + \omega(x) = -\frac{1}{2\pi} \log(|x - x_0|) + \omega(x).$$

It is easy to verify that  $u_\delta \notin H_0^1(\Omega)$ . Actually, we can specify how the quantity  $\|u_\delta\|_{1,p,\Omega}$  goes to infinity when  $p$  goes to 2, with  $p < 2$ . According to the foregoing, if we write  $u_\delta = G + \omega$ , since  $\omega \in H^1(\Omega)$ , estimating the behavior of  $\|u_\delta\|_{1,p,\Omega}$  as  $p$  converges to 2 from below (which will be denoted by  $p \nearrow 2$ ) is reduced to estimating the behavior  $\|G\|_{1,p,B}$ , where  $B = B(0, 1)$  where  $B$  is the ball of center 0 and radius 1.  $G \in \mathbb{L}^p(\Omega)$  for all  $1 \leq p < \infty$ , and using polar coordinates, we get, for  $p < 2$ ,

$$|G|_{1,p,B}^p = \int_B |\nabla G(x)|^p dx = \int_0^1 \int_0^{2\pi} \left( \frac{1}{2\pi} \frac{1}{r} \right)^p r d\theta dr = (2\pi)^{1-p} \int_0^1 r^{1-p} dr = \frac{(2\pi)^{1-p}}{2-p}.$$

Finally, when  $p \nearrow 2$ ,

$$\|u_\delta\|_{1,p,\Omega} \sim \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{2-p}}. \quad (4)$$

## 2.3 The Nitsche and Schatz Theorem.

Before stating the Nitsche and Schatz Theorem, let us introduce some known properties of the finite element spaces  $V_h^k$ .

**Assumption 2.** Given two fixed concentric spheres  $B_0$  and  $B$  with  $B_0 \subset\subset B \subset\subset \Omega$ , there exists an  $h_0$  such that for all  $0 < h \leq h_0$ , we have for some  $R \geq 1$  and  $M > 1$ :

**B1** For any  $0 \leq s \leq R$  and  $s \leq \ell \leq M$ , for each  $u \in H^\ell(B)$ , there exists  $\eta \in V_h^k$  such that

$$\|u - \eta\|_{s,B} \leq Ch^{\ell-s} \|u\|_{\ell,B}.$$

Moreover, if  $u \in H_0^1(B_0)$  then  $\eta$  can be chosen to satisfy  $\eta \in H_0^1(B)$ .

**B2** Let  $\varphi \in \mathcal{C}_0^\infty(B_0)$  and  $u_h \in V_h^k$ , then there exists  $\eta \in V_h^k \cap H_0^1(B)$  such that

$$\|\varphi u_h - \eta\|_{1,B} \leq C(\varphi, B, B_0)h \|u_h\|_{1,B}.$$

**B3** For each  $h \leq h_0$  there exists a domain  $B_h$  with  $B_0 \subset\subset B_h \subset\subset B$  such that if  $0 \leq s \leq \ell \leq R$  then for all  $u_h \in V_h^k$  we have

$$\|u_h\|_{\ell, B_h} \leq Ch^{s-\ell} \|u_h\|_{s, B_h}.$$

We now state the following theorem, a key tool in the forthcoming proof of Theorem 1.

**Theorem** (Nitsche and Schatz [22]). Let  $\Omega_0 \subset\subset \Omega_1 \subset\subset \Omega$  and let  $V_h^k$  satisfy Assumption 2. Let  $u \in H^\ell(\Omega_1)$ , let  $u_h \in V_h^k$  and let  $q$  be a nonnegative integer, arbitrary but fixed. Let us suppose that  $u - u_h$  satisfies

$$\int_{\Omega} \nabla(u - u_h) \cdot \nabla v_h = 0, \quad \forall v_h \in V_h^k \cap H_0^1(\Omega_1).$$

Then there exists  $h_1$  such that if  $h \leq h_1$  we have

(i) for  $s = 0, 1$  and  $1 \leq \ell \leq M$ ,

$$\|u - u_h\|_{s, \Omega_0} \leq C \left( h^{\ell-s} \|u\|_{\ell, \Omega_1} + \|u - u_h\|_{-q, \Omega_1} \right),$$

(ii) for  $2 \leq s \leq \ell \leq M$  and  $s \leq k < R$ ,

$$\|u - u_h\|_{s, \Omega_0} \leq C \left( h^{\ell-s} \|u\|_{\ell, \Omega_1} + h^{1-s} \|u - u_h\|_{-q, \Omega_1} \right).$$

In this paper, we will actually need a more general version of the assumptions on the approximation space  $V_h^k$ :

**Assumption 3.** Given  $B \subset \Omega$ , consider  $p' \geq 2$ , there exists an  $h_0$  such that for all  $0 < h \leq h_0$ , we have for some  $R \geq 1$  and  $M > 1$ :

**$\tilde{\mathbf{B}}1$**  For any  $0 \leq s \leq R$  and  $s \leq \ell \leq M$ , for each  $u \in H^\ell(B)$ , there exists  $\eta \in V_h^k$  such that, for any finite element  $T \subset B$ ,

$$|u - \eta|_{s, p', T} \leq Ch^{d(1/p' - 1/2)} h^{\ell-s} |u|_{\ell, 2, T}.$$

**$\tilde{\mathbf{B}}3$**  For  $0 \leq s \leq \ell \leq R$ , for all  $u_h \in V_h^k$ , for any finite element  $T$  in the family  $\mathcal{T}_h$ , we have

$$\|u_h\|_{\ell, p', T} \leq Ch^{d(1/p' - 1/2)} h^{s-\ell} \|u_h\|_{s, 2, T}.$$

Assumptions  **$\tilde{\mathbf{B}}1$**  and  **$\tilde{\mathbf{B}}3$**  are generalizations of assumptions **B1** and **B3**. They are quite standard and satisfied by a wide variety of approximation spaces, including all finite element spaces defined on quasi-uniform meshes [11]. The parameters  $R$  and  $M$  play respectively the role of the regularity and order of approximation of the approximation space  $V_h^k$ . For example, in the case of  $P_1$ -finite elements, we have  $R = 3/2 - \varepsilon$  and  $M = 2$ . Assumption **B2** is less common but also satisfied by a wide class of approximation spaces. Actually, for Lagrange and Hermite finite elements, a stronger property than assumption **B2** is shown in [5]: let  $0 \leq s \leq \ell \leq k$ ,  $\varphi \in \mathcal{C}_0^\infty(B)$  and  $u_h \in V_h^k$ , then there exists  $\eta \in V_h^k$  such that

$$\|\varphi u_h - \eta\|_{s, B} \leq C(\varphi) h^{\ell-s+1} \|u_h\|_{\ell, B}. \quad (5)$$

Applied for  $s = \ell = 1$ , inequality (5) gives assumption **B2**.

## 2.4 Statement of our main results.

Our main results are Theorems 1, 2 and 3. The rest of the paper is mostly concerned by the proof and the numerical illustration.

**Theorem 1.** *Let  $\Omega_0 \subset\subset \Omega_1 \subset\subset \Omega$  satisfy Assumption 1,  $1 \leq s \leq k$ . Let  $u_\delta$  be the solution of problem  $(P_\delta)$  and  $u_\delta^h$  its Galerkin projection onto  $V_h^k$ , satisfying (2). Under Assumptions 2 and 3, there exists  $h_1$  such that if  $0 < h \leq h_1$ , we have,*

$$\|u_\delta - u_\delta^h\|_{1,\Omega_0} \leq C(\Omega_0, \Omega_1, \Omega) h^k \sqrt{|\ln h|}. \quad (6)$$

*In addition, for  $s \geq 2$ , if the finite elements are supposed  $H^s$ -conforming, we have*

$$\|u_\delta - u_\delta^h\|_{s,\Omega_0} \leq C(\Omega_0, \Omega_1, \Omega) h^{k+1-s} \sqrt{|\ln h|}. \quad (7)$$

**Remark 1.** *The main tool in proving Theorem 1 is the Nitsche and Schatz Theorem, and the result holds for all the spaces verifying Assumptions 2 and 3. The class of such spaces includes spaces beyond finite elements, including, for instance, wavelets.*

Section 3 will be dedicated to the proof of Theorem 1.

In the particular case of Lagrange finite elements, Köppl and Wohlmuth [19] showed, in the  $\mathbb{L}^2$ -norm of a subdomain which does not contain  $x_0$ , quasi-optimality for the lowest order case, and optimal a priori estimates for higher order. The proof is based on Wahlbin-type arguments, which are similar to the Nitsche and Schatz Theorem (see [27, 28]), and different arguments from the ones presented in this paper, like the use of an operator of Scott and Zhang type [26]. Using this result it is possible to prove quite easily optimal convergence in  $H^1$ -norm for Lagrange finite elements. This result reads as follows:

**Theorem 2.** *Consider a domain  $\Omega_2$  such that  $\Omega_0 \subset\subset \Omega_1 \subset\subset \Omega_2 \subset\subset \Omega$ ,  $x_0 \notin \overline{\Omega_2}$ , and satisfying Assumption 1. Let  $u_\delta$  be the solution of problem  $(P_\delta)$  and  $u_\delta^h$  its Galerkin projection onto the space of Lagrange finite elements of order  $k + 1$ . There exists  $h_1$  such that if  $0 < h \leq h_1$ , we have*

$$\|u_\delta - u_\delta^h\|_{1,\Omega_0} \leq C(\Omega_1, \Omega_2, \Omega) h^k. \quad (8)$$

**Remark 2.** *This result is optimal and thus slightly stronger than inequality (6), but it is limited to Lagrange finite elements and to the  $H^1$ -norm, due to the use of an operator of Scott-Zhang type. Theorem 1 is more general: it holds for a wide class of finite elements and it allows to estimate the error in  $H^s$ -norm, for any  $s \geq 1$ .*

**Proof of Theorem 2.** In the particular case of Lagrange finite elements, Köppl and Wohlmuth proved in [19] the following convergence in the  $\mathbb{L}^2$ -norm of a subdomain which does not contain  $x_0$ :

$$\|u_\delta - u_\delta^h\|_{0,\Omega_1} \leq C(\Omega_1, \Omega_2, \Omega) \begin{cases} h^2 |\ln(h)| & \text{if } k = 1, \\ h^{k+1} & \text{if } k > 1. \end{cases} \quad (9)$$

Let us apply the Nitsche and Schatz Theorem on  $\Omega_0$  and  $\Omega_1$  for  $l = k + 1$  and  $q = 0$ ,

$$\|u_\delta - u_\delta^h\|_{1,\Omega_0} \leq C \left( h^k \|u_\delta\|_{2,\Omega_1} + \|u_\delta - u_\delta^h\|_{0,\Omega_1} \right).$$

Using (9), we get

$$\|u_\delta - u_\delta^h\|_{1,\Omega_0} \leq Ch^k.$$

For the particular  $P_1$ -Lagrange finite elements, we prove the optimal convergence in  $H^1$ -norm using completely different arguments. This proof involves a technical assumption on the mesh, namely Assumption 4 in Section 4.2: the distance of the Dirac mass to the edges of the mesh triangles is assumed to be at least of the same order as the mesh size  $h$ . The result reads as follows:

**Theorem 3.** *Let  $\Omega_0 \subset\subset \Omega_1 \subset\subset \Omega$  satisfy Assumption 1 and consider a mesh such that there exists a domain  $B_\varepsilon$  satisfying Assumption 4 with  $\varepsilon$  of the same order as the mesh size. The  $P_1$ -finite element method converges with order 1 for the  $H^1(\Omega_0)$ -norm. More precisely:*

$$\|u_\delta - u_\delta^h\|_{1,\Omega_0} \leq C(\Omega_0, \Omega_1, \Omega)h.$$

The proof of this result is detailed in Section 4.

### 3 Proof of Theorem 1.

This section is devoted to the proof of Theorem 1. We first show a weak version of the Aubin-Nitsche duality lemma (Lemma 1) and establish a discrete inf-sup condition (Lemma 2). Then, we use these results to prove Theorem 1.

#### 3.1 Aubin-Nitsche duality lemma with a singular right-hand side.

The proof of Theorem 1 is based on the Nitsche and Schatz Theorem of Section 2.3. In order to estimate the quantity  $\|u_\delta - u_\delta^h\|_{-q,\Omega_1}$ , we will first show a weak version of Aubin-Nitsche Lemma, for the case of Poisson Problem with a singular right-hand side.

**Lemma 1.** *Let  $f \in W^{-1,p}(\Omega) = (W_0^{1,p'}(\Omega))'$ ,  $1 < p < 2$ , and  $u \in W_0^{1,p}(\Omega)$  be the unique solution of*

$$\begin{cases} -\Delta u = f & \text{in } \Omega, \\ u = 0 & \text{on } \partial\Omega. \end{cases}$$

Let  $u_h \in V_h^k$  be the Galerkin projection of  $u$ . For finite elements of order  $k$ , letting  $e = u - u_h$ , we have for all  $0 \leq q \leq k - 1$ ,

$$\|e\|_{-q,\Omega} \leq Ch^{q+1}h^{2(1/p'-1/2)}|e|_{1,p,\Omega}. \quad (10)$$

*Proof.* We aim at estimating, for  $q \geq 0$ , the  $H^{-q}$ -norm of the error  $e$ :

$$\|e\|_{-q,\Omega} = \sup_{\phi \in \mathcal{C}_0^\infty(\Omega)} \frac{|\int_\Omega e\phi|}{\|\phi\|_{q,\Omega}}. \quad (11)$$

The error  $e \in W_0^{1,p}$  satisfies

$$\int_\Omega \nabla e \cdot \nabla v_h = 0, \quad \forall v_h \in V_h^k.$$

Consider  $\phi \in \mathcal{C}_0^\infty(\Omega)$  and let  $w^\phi \in H^{q+2}$  be the solution of

$$\begin{cases} -\Delta w^\phi = \phi & \text{in } \Omega, \\ w^\phi = 0 & \text{on } \partial\Omega. \end{cases}$$

In dimension 2, by the Sobolev injections established for instance in [6],  $H^{q+2}(\Omega) \subset W^{1,p'}(\Omega)$  for all  $p'$  in  $[2, +\infty[$ . Thus, for any  $w_h \in V_h^k$ ,

$$\left| \int_\Omega e\phi \right| = \left| \int_\Omega e\Delta w^\phi \right| = \left| \int_\Omega \nabla e \cdot \nabla w^\phi \right| = \left| \int_\Omega \nabla e \cdot \nabla (w^\phi - w_h) \right| \leq |w^\phi - w_h|_{1,p',\Omega} |e|_{1,p,\Omega}.$$

We have to estimate  $|w^\phi - w_h|_{1,p',\Omega}$ . It holds

$$|w^\phi - w_h|_{1,p',\Omega}^{p'} = \sum_T |w^\phi - w_h|_{1,p',T}^{p'}.$$



For all  $0 \leq q \leq k - 1$  and for all element  $T$  in  $\mathcal{T}_h$ , thanks to Assumption **B1** applied for  $s = 1$ ,  $\ell = q + 2$ , there exists  $w_h \in V_h^k$  such as

$$|w^\phi - w_h|_{1,p',T} \leq Ch^{2(1/p'-1/2)}h^{q+1}|w^\phi|_{q+2,2,T}. \quad (12)$$

We number the triangles of the mesh  $\{T_i, i = 1, \dots, N\}$  and we set

$$a = (a_i)_i \text{ and } b = (b_i)_i, \text{ where } a_i = |w^\phi - w_h|_{1,p',T_i} \text{ and } b_i = |w^\phi|_{q+2,2,T_i}.$$

By (12), we have, for all  $i$  in  $\llbracket 1, N \rrbracket$ ,

$$a_i \leq Ch^{2(1/p'-1/2)}h^{q+1}b_i.$$

We recall the norm equivalence in  $\mathbb{R}^N$  for  $0 < r < s$ ,

$$\|x\|_{\ell^s} \leq \|x\|_{\ell^r} \leq N^{1/r-1/s}\|x\|_{\ell^s}.$$

Remark that here  $N \sim Ch^{-2}$ . As  $2 < p'$ , we have  $\|b\|_{\ell^{p'}} \leq \|b\|_{\ell^2}$ . Then, we can write

$$\begin{aligned} |w^\phi - w_h|_{1,p',\Omega} &= \|a\|_{\ell^{p'}} \leq Ch^{q+1}h^{2(1/p'-1/2)}\|b\|_{\ell^{p'}} \\ &\leq Ch^{q+1}h^{2(1/p'-1/2)}\|b\|_{\ell^2} \\ &\leq Ch^{q+1}h^{2(1/p'-1/2)}|w^\phi|_{q+2,2,\Omega} \\ &\leq Ch^{q+1}h^{2(1/p'-1/2)}\|\phi\|_{q,\Omega}. \end{aligned}$$

Finally, using this estimate in (11), we obtain, for  $q \leq k - 1$ ,

$$\|e\|_{-q,\Omega} \leq Ch^{q+1}h^{2(1/p'-1/2)}|e|_{1,p,\Omega}.$$

□

**Corollary 1.** For finite elements of order  $k$ , for any  $0 < \varepsilon < 1$ ,

$$\|u_\delta - u_\delta^h\|_{-k+1,\Omega} \leq Ch^k h^{-\varepsilon} |u_\delta - u_\delta^h|_{1,p,\Omega}, \quad (13)$$

where  $p \in ]1, 2[$  is defined by

$$p = \frac{2}{1 + \varepsilon} \left( \text{and so } p' = \frac{2}{1 - \varepsilon} \right). \quad (14)$$

*Proof.* We will apply Lemma 1 to estimate  $\|u_\delta - u_\delta^h\|_{-q,\Omega}$  for  $(p, p')$  defined in (14). In inequality (10):

$$2 \left( \frac{1}{p'} - \frac{1}{2} \right) = 2 \left( \frac{1 - \varepsilon}{2} - \frac{1}{2} \right) = -\varepsilon. \quad (15)$$

Finally, for finite elements of order  $k$ ,

$$\|u_\delta - u_\delta^h\|_{-k+1,\Omega} \leq Ch^k h^{-\varepsilon} |u_\delta - u_\delta^h|_{1,p,\Omega}.$$

□

### 3.2 Estimate of $|u_\delta - u_\delta^h|_{1,p,\Omega}$ .

It remains to estimate the quantity  $|u_\delta - u_\delta^h|_{1,p,\Omega}$  by bounding  $|u_\delta^h|_{1,p,\Omega}$  in terms of  $|u_\delta|_{1,p,\Omega}$  (equality (17)). To achieve this, we will need the following discrete inf-sup condition.

**Lemma 2.** For  $0 < \varepsilon < 1$ ,  $p$  and  $p'$  defined in (14), we have the discrete inf-sup condition

$$\inf_{u_h \in V_h^k} \sup_{v_h \in V_h^k} \frac{\int_\Omega \nabla u_h \cdot \nabla v_h}{\|u_h\|_{1,p,\Omega} \|v_h\|_{1,p',\Omega}} \geq Ch^\varepsilon.$$

*Proof.* The continuous inf-sup condition

$$\inf_{u \in W_0^{1,p}} \sup_{v \in W_0^{1,p'}} \frac{\int_\Omega \nabla u \cdot \nabla v}{\|u\|_{1,p} \|v\|_{1,p'}} \geq \beta > 0$$

holds for  $\beta$  independent of  $p$  and  $p'$  (and thus independent of  $\varepsilon$ ). It is a consequence of the duality of the two spaces  $W_0^{1,p}(\Omega)$  and  $W_0^{1,p'}(\Omega)$ , see [18]. For  $v \in W_0^{1,p'}(\Omega)$ , let  $\Pi_h v$  denote the  $H_0^1$ -Galerkin projection of  $v$  onto  $V_h^k$ . This is well defined since  $W_0^{1,p'}(\Omega) \subset H_0^1(\Omega)$ . We apply Assumption  $\tilde{\mathbf{B3}}$  to  $\Pi_h v$  for  $\ell = s = 1$ , and get

$$\|\Pi_h v\|_{1,p',\Omega} \leq Ch^{-2(1/2-1/p')} \|\Pi_h v\|_{1,2,\Omega} \leq Ch^{-2(1/2-1/p')} \|v\|_{1,2,\Omega} \leq Ch^{-2(1/2-1/p')} \|v\|_{1,p',\Omega}.$$

Moreover, for any  $u_h \in V_h^k \subset W^{1,p}(\Omega)$ ,

$$\begin{aligned} \|u_h\|_{1,p,\Omega} &\leq C \sup_{v \in W_0^{1,p'}} \frac{\int_\Omega \nabla u_h \cdot \nabla v}{\|v\|_{1,p',\Omega}} = C \sup_{v \in W_0^{1,p'}} \frac{\int_\Omega \nabla u_h \cdot \nabla \Pi_h v}{\|v\|_{1,p',\Omega}} \\ &\leq Ch^{-2(1/2-1/p')} \sup_{v \in W_0^{1,p'}} \frac{\int_\Omega \nabla u_h \cdot \nabla \Pi_h v}{\|\Pi_h v\|_{1,p',\Omega}} \\ &\leq Ch^{-2(1/2-1/p')} \sup_{v_h \in V_h^k} \frac{\int_\Omega \nabla u_h \cdot \nabla v_h}{\|v_h\|_{1,p',\Omega}}. \end{aligned}$$

Finally, thanks to Poincaré inequality, and to inequality (15),

$$\inf_{u_h \in V_h^k} \sup_{v_h \in V_h^k} \frac{\int_\Omega \nabla u_h \cdot \nabla v_h}{\|u_h\|_{1,p,\Omega} \|v_h\|_{1,p',\Omega}} \geq Ch^\varepsilon.$$

□

Then, we can estimate  $|u_\delta - u_\delta^h|_{1,p,\Omega}$  :

**Lemma 3.** With  $p$  and  $p'$  defined in (14),

$$|u_\delta - u_\delta^h|_{1,p,\Omega} \leq C \frac{h^{-\varepsilon}}{\sqrt{\varepsilon}}. \quad (16)$$

*Proof.* According to Lemma 2, it exists  $v_h \in V_h^k$ , with  $\|v_h\|_{1,p',\Omega} = 1$ , such that

$$h^{2(1/2-1/p')} \|u_\delta^h\|_{1,p,\Omega} \leq C \int_\Omega \nabla u_\delta^h \cdot \nabla v_h = C \int_\Omega \nabla u_\delta \cdot \nabla v_h \leq C \|u_\delta\|_{1,p,\Omega}.$$

So we have

$$|u_\delta - u_\delta^h|_{1,p,\Omega} \leq |u_\delta|_{1,p,\Omega} + |u_\delta^h|_{1,p,\Omega} \leq Ch^{-2(1/2-1/p')} \|u_\delta\|_{1,p,\Omega}. \quad (17)$$

All that remains is to substitute  $\|u_\delta\|_{1,p,\Omega}$  for the expression established in (4). For  $p$  defined as in (14),

$$\|u_\delta\|_{1,p,\Omega} \leq \frac{C}{\sqrt{2-p}} \leq \frac{C}{\sqrt{\varepsilon}}.$$

Finally, with (15) and (17), we get

$$\|u_\delta - u_\delta^h\|_{1,p,\Omega} \leq C \frac{h^{-\varepsilon}}{\sqrt{\varepsilon}}.$$

□

### 3.3 Proof of Theorem 1.

We can now prove Theorem 1.

*Proof.* The function  $u_\delta$  is analytic on  $\overline{\Omega}_1$ , therefore the quantity  $\|u_\delta\|_{k+1,\Omega_1}$  is bounded. If we suppose  $s = 1$ , Nitsche and Schatz Theorem gives, for  $\ell = k + 1$  and  $q = k - 1$ ,

$$\|u_\delta - u_\delta^h\|_{1,\Omega_0} \leq C \left( h^k + \|u_\delta - u_\delta^h\|_{-k+1,\Omega_1} \right).$$

Thanks to (13) and (16),

$$\|u_\delta - u_\delta^h\|_{-k+1,\Omega} \leq Ch^k \frac{h^{-2\varepsilon}}{\sqrt{\varepsilon}},$$

therefore, taking  $\varepsilon = |\ln h|^{-1}$ ,

$$\|u_\delta - u_\delta^h\|_{-k+1,\Omega} \leq Ch^k \sqrt{|\ln h|}. \quad (18)$$

Finally, we get the result of Theorem 1 for  $s = 1$  (inequality (6)):

$$\|u_\delta - u_\delta^h\|_{1,\Omega_0} \leq Ch^k \sqrt{|\ln h|}.$$

Now, let us fix  $2 \leq s \leq k$ , Nitsche and Schatz Theorem gives, for  $\ell = k + 1$  and  $q = k - 1$ ,

$$\|u_\delta - u_\delta^h\|_{s,\Omega_0} \leq C \left( h^{k+1-s} + h^{1-s} \|u_\delta - u_\delta^h\|_{-k+1,\Omega_1} \right).$$

So, thanks to (18), we get the second result of Theorem 1 (inequality (7)),

$$\|u_\delta - u_\delta^h\|_{s,\Omega_0} \leq Ch^{k+1-s} \sqrt{|\ln h|}.$$

which ends the proof of Theorem 1. □

## 4 Proof of Theorem 3.

To prove this theorem, we first regularize the right-hand side, and prove that in our case the solution  $u_\delta$  of  $(P_\delta)$  and the solution of the regularized problem coincide on the complementary of a neighborhood of the singularity (Theorem 4). The proof of Theorem 3 is based, once again, on the Nitsche and Schatz Theorem and on the observation that the discrete right-hand sides of problem  $(P_\delta)$  and of the regularized problem are exactly the same, so that the numerical solutions are the same too (Lemma 5).

## 4.1 Direct problem and regularized problem.

The results presented in this section are valid in any dimension  $d \geq 1$ . However they will only be applied in dimension 2 in Section 4.3 in order to prove Theorem 2. Let  $\varepsilon > 0$ , and  $f_\varepsilon$  be defined on  $\Omega$  by

$$f_\varepsilon = \frac{d}{\sigma(\mathbb{S}_{d-1})\varepsilon^d} \mathbf{1}_{B_\varepsilon}, \quad (19)$$

where  $B_\varepsilon = B(x_0, \varepsilon)$  and  $\sigma(\mathbb{S}_{d-1})$  is the Lebesgue measure of the unit sphere in dimension  $d$ . The parameter  $\varepsilon$  is supposed to be small enough so that  $\overline{B_\varepsilon} \subset\subset \Omega$ . The function  $f_\varepsilon$  is a regularization of the Dirac distribution  $\delta_{x_0}$ . Let us consider the following problem:

$$(P_\varepsilon) \begin{cases} -\Delta u_\varepsilon &= f_\varepsilon & \text{in } \Omega, \\ u_\varepsilon &= 0 & \text{on } \partial\Omega. \end{cases}$$

Since  $f_\varepsilon \in \mathbb{L}^2(\Omega)$ , it is possible to show that problem  $(P_\varepsilon)$  has a unique variational solution  $u_\varepsilon$  in  $H_0^1(\Omega) \cap H^2(\Omega)$  [16]. We will show the following result:

**Theorem 4.** *The solution  $u_\delta$  of  $(P_\delta)$  and the solution  $u_\varepsilon$  of  $(P_\varepsilon)$  coincide on  $\tilde{\Omega} = \overline{\Omega} \setminus B_\varepsilon$ , ie,*

$$u_\delta|_{\tilde{\Omega}} = u_\varepsilon|_{\tilde{\Omega}}.$$

The proof is based on the following lemma.

**Lemma 4.** *Let  $d \in \mathbb{N} \setminus \{0\}$ ,  $\varepsilon > 0$ ,  $x \in \mathbb{R}^d$ ,  $v$  a function defined on  $\mathbb{R}^d$ , harmonic on  $\overline{B}(x, \varepsilon)$ , and  $f \in L^1(\mathbb{R}^d)$  such that*

- *$f$  is radial and positive,*
- *$\text{supp}(f) \subset B(0, \varepsilon)$ ,  $\varepsilon > 0$ ,*
- $\int_{\mathbb{R}^d} f(x) dx = 1.$

*Then,  $f * v(x) = \int_{\mathbb{R}^d} f(y)v(x-y) dy = v(x).$*

*Proof.* As  $\text{supp}(f) \subset B(0, \varepsilon)$ , using spherical coordinates, we have:

$$f * v(x) = \int_0^\varepsilon \int_{\mathbb{S}^{d-1}} f(r)v(x-r\omega)r^{d-1} d\omega dr = \int_0^\varepsilon r^{d-1}f(r) \left( \int_{\mathbb{S}^{d-1}} v(x-r\omega)d\omega \right) dr.$$

Besides,  $v$  is harmonic on  $\overline{B}(x, \varepsilon)$ , so that the mean value property gives, for  $0 < r \leq \varepsilon$ ,

$$v(x) = \frac{1}{\sigma(\partial B(x, r))} \int_{\partial B(x, r)} v(y) dy = \frac{r^{d-1}}{\sigma(\partial B(x, r))} \int_{\mathbb{S}^{d-1}} v(x-r\omega) d\omega,$$

thus

$$f * v(x) = \int_0^\varepsilon f(r)v(x)\sigma(\partial B(x, r)) dr = v(x) \int_0^\varepsilon \int_{\mathbb{S}^{d-1}} f(r)r^{d-1} d\omega dr = v(x) \int_{B(0, \varepsilon)} f(y) dy = v(x).$$

□

Now, let us prove Theorem 4.

*Proof.* First, let us leave out boundary conditions and consider the following problem

$$-\Delta u = f_\varepsilon \text{ in } \mathcal{D}'(\mathbb{R}^d). \quad (20)$$

As  $-\Delta G = \delta_0$  in  $\mathcal{D}'(\mathbb{R}^d)$ , we can build a function  $u$  satisfying (20) as:

$$u(x) = f_\varepsilon * G(x) = \int_{\mathbb{R}^d} f_\varepsilon(y)G(x-y) dy = \int_{\mathbb{R}^d} f_\varepsilon(x_0+y)G(x-x_0-y) dy = \left( f_\varepsilon(x_0+\cdot) * G \right)(x-x_0).$$

Moreover, for all  $x \in \Omega \setminus \overline{B_\varepsilon}$ ,  $G$  is harmonic on  $\overline{B}(x-x_0, \varepsilon)$ , and  $f_\varepsilon(\cdot+x_0)$  satisfies the assumptions of Lemma 4, so that  $u(x) = \left( f_\varepsilon(x_0+\cdot) * G \right)(x-x_0) = G(x-x_0)$ . We conclude that  $u$  and  $G(\cdot-x_0)$  have the same trace on  $\partial\Omega$ , and so  $u + \omega$ , where  $\omega$  is the solution of the Poisson problem (3), is a solution of the problem  $(P_\varepsilon)$ . By the uniqueness of the solution, we have  $u_\varepsilon = u + \omega$ . Finally, for all  $x \in \Omega \setminus \overline{B_\varepsilon}$ ,  $u_\varepsilon(x) = u_\delta(x)$ . Since these functions are continuous on  $\tilde{\Omega} = \Omega \setminus B_\varepsilon$ , this equality is true on the closure of  $\tilde{\Omega}$ , which ends the proof of Theorem 4.  $\square$

**Remark 3.** Theorem 4 holds for any radial positive function  $f \in \mathbb{L}^1(\mathbb{R}^d) \cap \mathbb{L}^2(\mathbb{R}^d)$  such that

$$\text{supp}(f) \subset B(0, \varepsilon) \text{ and } \int_{\mathbb{R}^d} f(x) dx = 1,$$

taking  $f_\varepsilon = f(\cdot - x_0)$ . It is a direct consequence of Lemma 4.

**Remark 4.** Theorem 4 is true in dimension 1, taking  $f_\varepsilon = \frac{1}{2\varepsilon} \mathbb{1}_{I_\varepsilon}$ , where  $I_\varepsilon = [x_0 - \varepsilon, x_0 + \varepsilon] \subset ]a, b[ = I$ . In this case, we can easily write down the solutions  $u_\delta$  and  $u_\varepsilon$  explicitly,

$$u_\delta(x) = \begin{cases} \frac{b-x_0}{b-a}x - a\frac{b-x_0}{b-a} & \text{if } x \in [a, x_0], \\ -\frac{x_0-a}{b-a}x + b\frac{x_0-a}{b-a} & \text{if } x \in [x_0, b]. \end{cases}$$

$$u_\varepsilon(x) = \begin{cases} \frac{b-x_0}{b-a}x - a\frac{b-x_0}{b-a} & \text{if } x \in [a, x_0 - \varepsilon], \\ -\frac{x^2}{4\varepsilon} + \left( \frac{x_0}{2\varepsilon} + \frac{a+b-2x_0}{2(b-a)} \right) x + \frac{a(x_0-b) + b(x_0-a)}{2(b-a)} - \frac{x_0^2 + \varepsilon^2}{4\varepsilon} & \text{if } x \in [x_0 - \varepsilon, x_0 + \varepsilon], \\ -\frac{x_0-a}{b-a}x + b\frac{x_0-a}{b-a} & \text{if } x \in [x_0 + \varepsilon, b]. \end{cases}$$

and observe, as shown in Figure 2, that  $u_\delta$  and  $u_\varepsilon$  coincide outside  $I_\varepsilon$ .

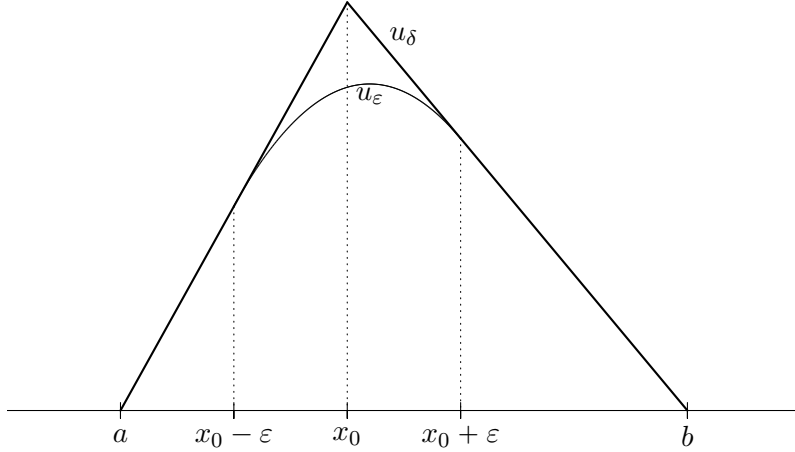


Figure 2: Illustration of Theorem 4 in 1D.

#### 4.2 Discretizations of the right-hand sides.

At this point, we introduce a technical assumption on  $B_\varepsilon$  and the mesh.

**Assumption 4.** *The domain of definition  $B_\varepsilon$  of the function  $f_\varepsilon$  is supposed to satisfy*

$$B_\varepsilon \subset T_0,$$

where  $T_0$  denotes the triangle of the mesh which contains the point  $x_0$  (Figure 3).

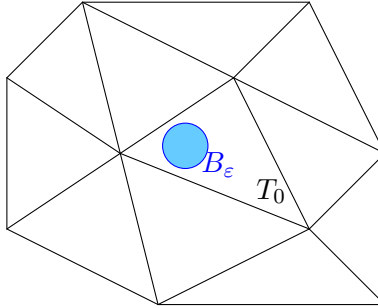


Figure 3: Assumption on  $B_\varepsilon$ .

**Remark 5.** *The parameter  $\varepsilon$  will be chosen to be  $h/10$ , so it remains to fix a “good” triangle  $T_0$  and to build the mesh accordingly, so that Assumption 4 is satisfied. Remark that it is always possible to locally modify any given mesh so that it satisfies this assumption.*

**Lemma 5.** *Under Assumption 4,*

$$u_\varepsilon^h = u_\delta^h,$$

where  $u_\delta^h$  and  $u_\varepsilon^h$  are respectively the  $P_1$ -finite element solutions of problems  $(P_\delta)$  and  $(P_\varepsilon)$ .

*Proof.* Let us write down explicitly the discretized right-hand side  $F_\varepsilon^h$  associated to the function  $f_\varepsilon$ : for all node  $i$  and associated test function  $v_i \in V_h^1$ ,

$$(F_\varepsilon^h)_i = \int_\Omega \frac{1}{\sigma(B_\varepsilon)} \mathbb{1}_{B_\varepsilon}(x) v_i(x) dx = \int_{B_\varepsilon \subset T_0} \frac{1}{\sigma(B_\varepsilon)} v_i(x) dx,$$

and  $v_i$  is affine (and so harmonic) on  $T_0$ , therefore

$$(F_\varepsilon^h)_i = \begin{cases} v_i(x_0) & \text{if } i \text{ is a node of the triangle } T_0, \\ 0 & \text{otherwise.} \end{cases}$$

We note that  $F_\varepsilon^h = D^h$ , where  $D^h$  is the discretized right-hand side vector associated to the Dirac mass. That is why, with  $A_h$  the Laplacian matrix,

$$u_\varepsilon^h - u_\delta^h = \sum_{i \text{ node}} \left[ A_h^{-1} (F_\varepsilon^h - D^h) \right]_i v_i = 0.$$

□

**Remark 6.**  $F_\varepsilon^h = D^h$  holds as long as  $B_\varepsilon \subset T_0$ . Otherwise, we still have  $u_\delta|_{\Omega_0} = u_\varepsilon|_{\Omega_0}$  (Theorem 4), but  $F_\varepsilon^h \neq D^h$ , and so  $u_\delta^h|_\Omega \neq u_\varepsilon^h|_\Omega$ .

### 4.3 Proof of Theorem 3.

Theorem 3 can now be proved.

*Proof.* First, by triangular inequality, we can write, for  $s \in \{0, 1\}$ :

$$\|u_\delta - u_\delta^h\|_{s, \Omega_0} \leq \|u_\delta - u_\varepsilon\|_{s, \Omega_0} + \|u_\varepsilon - u_\varepsilon^h\|_{s, \Omega_0} + \|u_\varepsilon^h - u_\delta^h\|_{s, \Omega_0}.$$

Besides, thanks to Theorem 4, we have

$$\|u_\delta - u_\varepsilon\|_{s, \Omega_0} = 0, \tag{21}$$

and thanks to Lemma 5, we have

$$\|u_\delta^h - u_\varepsilon^h\|_{s, \Omega_0} = 0.$$

Finally we get

$$\|u_\delta - u_\delta^h\|_{s, \Omega_0} \leq \|u_\varepsilon - u_\varepsilon^h\|_{s, \Omega_0}. \tag{22}$$

We will apply the Nitsche and Schatz Theorem to  $e = u_\varepsilon - u_\varepsilon^h$ . With  $\ell = 2$ ,  $s = 1$ , and  $p = 0$ ,

$$\|e\|_{1, \Omega_0} \leq C (h \|u_\varepsilon\|_{2, \Omega_1} + \|e\|_{0, \Omega_1}). \tag{23}$$

The domain  $\Omega$  is smooth and  $f_\varepsilon \in \mathbb{L}^2(\Omega)$ , so  $u_\varepsilon \in H^2(\Omega) \cap H_0^1(\Omega)$ , and then, thanks to inequality (1),

$$\|e\|_{0, \Omega_1} \leq \|e\|_{0, \Omega} \leq Ch^2 \|u_\varepsilon\|_{2, \Omega} \leq Ch^2 \|f_\varepsilon\|_{0, \Omega}.$$

As  $\|f_\varepsilon\|_{0, \Omega}$  can be computed exactly,

$$\|f_\varepsilon\|_{0, \Omega} = \left( \int_\Omega \left( \frac{1}{\pi \varepsilon^2} \mathbb{1}_{B_\varepsilon}(y) \right)^2 dy \right)^{1/2} = \frac{1}{\varepsilon \sqrt{\pi}},$$

for  $\varepsilon \sim h/10$  (in order to satisfy the assumption on  $B_\varepsilon$ ), we get

$$\|e\|_{0, \Omega_1} \leq Ch. \tag{24}$$

Finally, according to Theorem 4,  $u_\delta|_{\Omega_1} = u_\varepsilon|_{\Omega_1}$ , therefore combining (23) and (24), we get

$$\|u_\varepsilon - u_\varepsilon^h\|_{1,\Omega_0} = \|e\|_{1,\Omega_0} \leq Ch. \quad (25)$$

At last, using inequalities (22) and (25) we obtain the expected error estimate, that is

$$\|u_\delta - u_\delta^h\|_{1,\Omega_0} \leq Ch.$$

□

## 5 Numerical illustrations.

In this section, we illustrate our theoretical results by numerical examples.

**Concentration of the error around the singularity.** First, we present one of the computations which drew our attention to the fact that the convergence could be better far from the singularity. For this example, we define  $\Omega$  as the unit disk,

$$\Omega = \{x = (x_1, x_2) \in \mathbb{R}^2 : \|x\|_2 < 1\},$$

$\Omega_0$  as the portion of  $\Omega$

$$\Omega_0 = \{x = (x_1, x_2) \in \mathbb{R}^2 : 0.2 < \|x\|_2 < 1\},$$

and finally  $x_0 = (0, 0)$  the origin. In this case, the exact solution  $u_\delta$  of problem  $(P_\delta)$  is given by

$$u(x) = -\frac{1}{4\pi} \log(x_1^2 + x_2^2).$$

When problem  $(P_\delta)$  is solved by the  $P_1$ -finite element method, the numerical solution  $u_\delta^h$  converges to the exact solution  $u_\delta$  with order 1 in the  $\mathbb{L}^2$ -norm on the entire domain  $\Omega$  (see [25]). This example shows that the convergence far from the singularity is faster, since the order of convergence in this case is 2 (see [19]). The difference between the convergence rates for the  $\mathbb{L}^2$ -norms on  $\Omega$  and  $\Omega_0$ , led us to make the conjecture that the preponderant part of the error is concentrated around the singularity, as can be seen in Figures 4, 5, 6, and 7, which show the distribution of the error for  $1/h \simeq 10, 15, 20$  and 30.

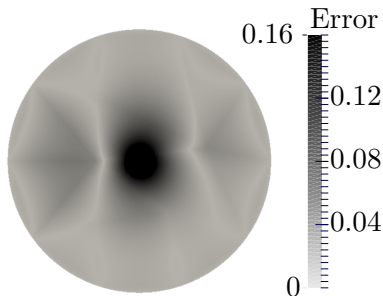


Figure 4: Error for  $1/h \simeq 10$ .

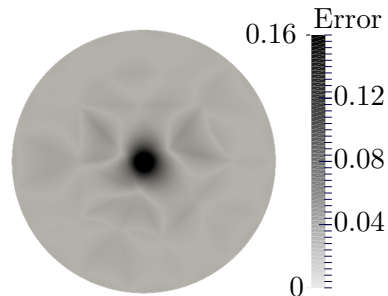


Figure 5: Error for  $1/h \simeq 15$ .



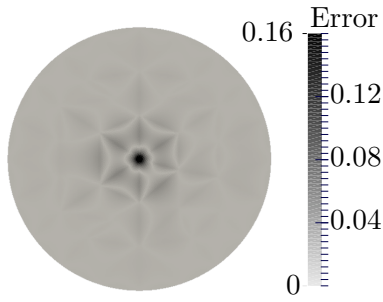


Figure 6: Error for  $1/h \simeq 20$ .

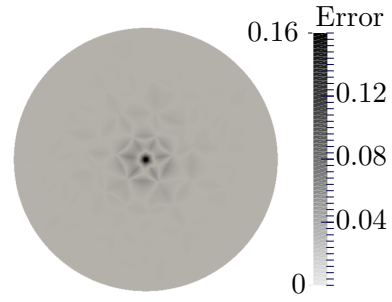


Figure 7: Error for  $1/h \simeq 30$ .

**Estimated orders of convergence.** Figure 8 shows the estimated order of convergence for the  $H^1(\Omega_0)$ -norm for the  $P_k$ -finite element method, where  $k = 1, 2, 3$  and  $4$ , in dimension 2. The convergence far from the singularity (i.e. excluding a neighborhood of the point  $x_0$ ) is the same as in the regular case: the  $P_k$ -finite element method converges at the order  $k$  on  $\Omega_0$  for the  $H^1$ -norm, as proved in this paper with a  $\sqrt{|\ln(h)|}$  multiplier.

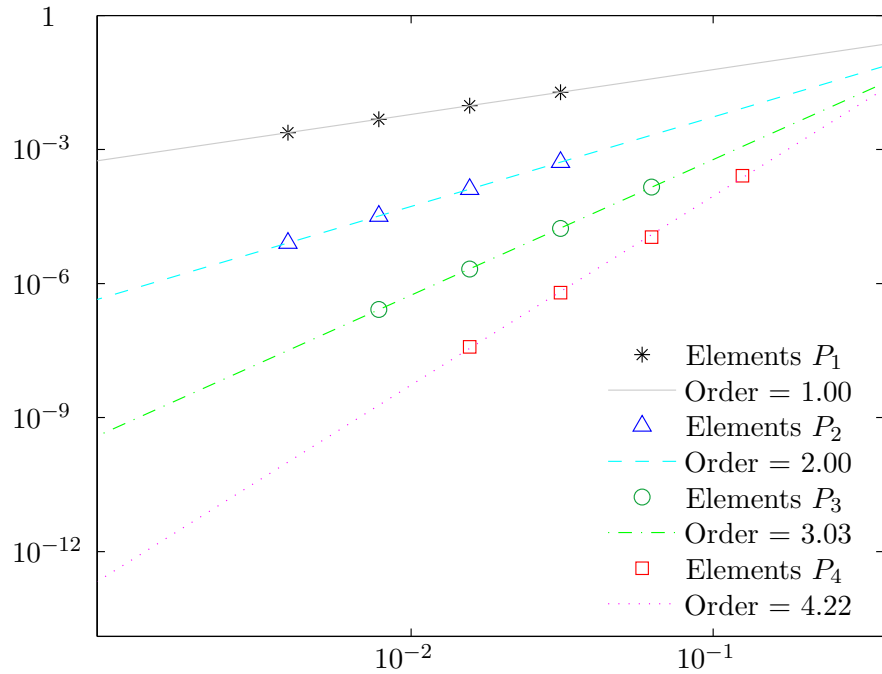


Figure 8: Estimated order of convergence for  $H^1(\Omega_0)$ -norm for the finite element method  $P_k$ ,  $k = 1, 2, 3, 4$ .

## 6 Discussion

### 6.1 The three-dimensional case

**Dirac mass.** The approach presented in this paper can be extended to the three-dimensional case but straightforward adaptations of the proofs lead to a suboptimal result. In the case of Theorem 1, the solution  $u_\delta$  belongs to  $W_0^{1,p}(\Omega)$  for all  $p$  in  $[1, 3/2[$ . As a consequence the couple  $(p, p')$  defined in (14) has to be taken near from  $(3/2, 3)$ . For instance,

$$p = \frac{3}{2 + \varepsilon} \text{ and } p' = \frac{3}{1 - \varepsilon},$$

so that, with the same notations, the result of Corollary 1 becomes

$$\|u_\delta - u_\delta^h\|_{-k+1, \Omega} \leq Ch^k h^{-\varepsilon-1/2} |u_\delta - u_\delta^h|_{1,p, \Omega}.$$

Moreover, the discrete inf-sup condition in dimension 3 is

$$\inf_{u_h \in V_h^k} \sup_{v_h \in V_h^k} \frac{\int_\Omega \nabla u_h \cdot \nabla v_h}{\|u_h\|_{1,p, \Omega} \|v_h\|_{1,p', \Omega}} \geq Ch^{\varepsilon+1/2}.$$

Thus when dealing with the estimate for  $|u_\delta - u_\delta^h|_{1,p, \Omega}$ , we get

$$|u_\delta - u_\delta^h|_{1,p, \Omega} \leq Ch^{-\varepsilon-1/2} |u_\delta|_{1,p, \Omega}.$$

Finally, with the asymptotics in 3d

$$\|u_\delta\|_{1,p, \Omega} \sim \frac{1}{\sqrt[3]{4\pi}} \frac{1}{\sqrt[3]{3-2p^2}},$$

we get the estimate

$$\|u_\delta - u_\delta^h\|_{1, \Omega_0} \leq C(\Omega_0, \Omega_1, \Omega) h^{k-1} \sqrt[3]{|\ln h|^2}.$$

which is clearly suboptimal.

Theorem 3 is also suboptimal in 3d, even if better. Indeed, in 2d or in 3d, the proof readily adapts until the computation of  $\|f_\varepsilon\|_{0, \Omega}$ , which is in 3d

$$\|f_\varepsilon\|_{0, \Omega} = \frac{1}{2} \sqrt{\frac{3}{\pi}} \frac{1}{\varepsilon \sqrt{\varepsilon}},$$

so that we get

$$\|u_\delta - u_\delta^h\|_{1, \Omega_0} \leq C\sqrt{h}.$$

**Line Dirac along a curve.** In 3-dimension, a line Dirac  $\delta_\Gamma$  along a curve  $\Gamma \subset\subset \Omega$  belongs to  $H^{-1-\eta}$  for all  $\eta > 0$ , so that the solution  $u_\Gamma$  of the Poisson Problem with the line Dirac  $\delta_\Gamma$  belongs to  $H^{1-\eta}$ . Actually, we have  $u_\Gamma \in W^{1,p}(\Omega)$  for all  $p \in [1, 2[$ . In this case, with the same notations and assumptions as in Theorem 1, we have the following estimate for  $u_\Gamma$  and its Galerkin projection  $u_\Gamma^h$ ,

$$\|u_\Gamma - u_\Gamma^h\|_{1, \Omega_0} \leq C(\Omega_0, \Omega_1, \Omega) h^k \sqrt{|\ln h|},$$

which is quasi-optimal. This result is shown using the same arguments as the ones presented in Section 3, but cannot be obtained with the tools given in the proof detailed in [19].

## 6.2 Dirac mass near the boundary

Theorem 3 excludes some critical cases: Dirac mass should not be closer and closer to the border of the domain  $\Omega$ . Indeed, for example in the case  $d(x_0, \partial\Omega) \sim h^2$ , Assumption 4 cannot be satisfied with  $\varepsilon \sim h/10$ , but only with  $\varepsilon \sim h^2/10$ . Nevertheless, this small value of  $\varepsilon$  implies

$$\|u - u_h\|_{1,\Omega_0} \leq C,$$

so that our method does not even prove the convergence of the approximate solution in this case. Actually, if the distance  $d(x_0, \partial\Omega)$  tends to 0, the norm  $\|u\|_{1,p,\Omega}$ , for a fixed  $1 \leq p < 2$ , tends to  $+\infty$ , so that the problem becomes more and more singular. But this question is a completely different problem and should be treated in a different way.

## References

- [1] J. P. Agnelli, E. M. Garau, and P. Morin. *A posteriori* error estimates for elliptic problems with Dirac measure terms in weighted spaces. ESAIM Math. Model. Numer. Anal., 48(6):1557–1581, 2014.
- [2] T. Apel, O. Benedix, D. Sirch, and B. Vexler. A priori mesh grading for an elliptic problem with Dirac right-hand side. SIAM J. Numer. Anal., 49(3):992–1005, 2011.
- [3] R. Araya, E. Behrens, and R. Rodríguez. A posteriori error estimates for elliptic problems with Dirac delta source terms. Numer. Math., 105(2):193–216, 2006.
- [4] I. Babuška. Error-bounds for finite element method. Numer. Math., 16:322–333, 1970/1971.
- [5] S. Bertoluzza. The discrete commutator property of approximation spaces. C. R. Acad. Sci. Paris Sér. I Math., 329(12):1097–1102, 1999.
- [6] H. Brezis. Analyse fonctionnelle. Collection Mathématiques Appliquées pour la Maîtrise. [Collection of Applied Mathematics for the Master’s Degree]. Masson, Paris, 1983. Théorie et applications. [Theory and applications].
- [7] E. Casas.  $L^2$  estimates for the finite element method for the Dirichlet problem with singular data. Numer. Math., 47(4):627–632, 1985.
- [8] E. Casas. Control of an elliptic problem with pointwise state constraints. SIAM J. Control Optim., 24(6):1309–1318, 1986.
- [9] E. Casas, C. Clason, and K. Kunisch. Parabolic control problems in measure spaces with sparse solutions. SIAM J. Control Optim., 51(1):28–63, 2013.
- [10] E. Casas and E. Zuazua. Spike controls for elliptic and parabolic PDEs. Systems Control Lett., 62(4):311–318, 2013.
- [11] P. G. Ciarlet. The finite element method for elliptic problems, volume 40 of Classics in Applied Mathematics. Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA, 2002. Reprint of the 1978 original [North-Holland, Amsterdam; MR0520174 (58 #25001)].
- [12] C. D’Angelo. Finite element approximation of elliptic problems with Dirac measure terms in weighted spaces: applications to one- and three-dimensional coupled problems. SIAM J. Numer. Anal., 50(1):194–215, 2012.

- [13] K. Eriksson. Finite element methods of optimal order for problems with singular data. Math. Comp., 44(170):345–360, 1985.
- [14] K. Eriksson. Improved accuracy by adapted mesh-refinements in the finite element method. Math. Comp., 44(170):321–343, 1985.
- [15] G. R. Fulford and J. R. Blake. Muco-ciliary transport in the lung. J. Theor. Biol., 121(4):381–402, 1986.
- [16] P. Grisvard. Elliptic problems in nonsmooth domains, volume 24 of Monographs and Studies in Mathematics. Pitman (Advanced Publishing Program), Boston, MA, 1985.
- [17] J. D. Jackson. Classical electrodynamics. John Wiley & Sons, Inc., New York-London-Sydney, second edition, 1975.
- [18] D. Jerison and C. E. Kenig. The inhomogeneous Dirichlet problem in Lipschitz domains. J. Funct. Anal., 130(1):161–219, 1995.
- [19] T. Köppl and B. Wohlmuth. Optimal a priori error estimates for an elliptic problem with Dirac right-hand side. SIAM J. Numer. Anal., 52(4):1753–1769, 2014.
- [20] L. Lacouture. A numerical method to solve the Stokes problem with a punctual force in source term. C. R. Mecanique, 343(3):187–191, 2015.
- [21] D. Leykekhman, D. Meidner, and B. Vexler. Optimal error estimates for finite element discretization of elliptic optimal control problems with finitely many pointwise state constraints. Comput. Optim. Appl., 55(3):769–802, 2013.
- [22] J. A. Nitsche and A. H. Schatz. Interior estimates for Ritz-Galerkin methods. Math. Comp., 28:937–958, 1974.
- [23] R. Rannacher and B. Vexler. A priori error estimates for the finite element discretization of elliptic parameter identification problems with pointwise measurements. SIAM J. Control Optim., 44(5):1844–1863, 2005.
- [24] A. H. Schatz and L. B. Wahlbin. Maximum norm estimates in the finite element method on plane polygonal domains. II. Refinements. Math. Comp., 33(146):465–492, 1979.
- [25] L. R. Scott. Finite element convergence for singular data. Numer. Math., 21:317–327, 1973/74.
- [26] L. R. Scott and S. Zhang. Finite element interpolation of nonsmooth functions satisfying boundary conditions. Math. Comp., 54(190):483–493, 1990.
- [27] L. B. Wahlbin. Local behavior in finite element methods. In Handbook of numerical analysis, Vol. II, Handb. Numer. Anal., II, pages 353–522. North-Holland, Amsterdam, 1991.
- [28] L. B. Wahlbin. Superconvergence in Galerkin finite element methods, volume 1605 of Lecture Notes in Mathematics. Springer-Verlag, Berlin, 1995.