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How important is the structure of school vaccine requirement opt-out provisions? Evidence from Washington, DC's HPV vaccine requirement

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Recent increases in vaccine-preventable diseases have led policymakers to reconsider the scope of vaccine requirement exemptions. Yet eliminating these provisions is politically difficult. Beginning in 2009, sixth grade girls in Washington, DC were required to receive the HPV vaccine or submit a one-time opt-out form. In 2014, the requirement was expanded to all students grades 6–12, and those not vaccinating were required to opt-out annually. I show that the movement from a one-time opt-out provision to an annual requirement increased the probability that teen girls in Washington, DC initiated HPV vaccination by 11 percentage points. Teen boys were 20 percentage points more likely to be vaccinated. Back-of-the-envelope calculations suggest 7 fewer cases of cervical cancer and 41 fewer cases of oropharyngeal cancer for the 33,000 enrolled during the 2017/2018 year. Using the initial value of cancer care and the value of a statistical life year, my estimates imply nearly $36 million in savings compared to $1.5 million spent on vaccination. In generalizing these results to other states, effect sizes even one-tenth the size of my most conservative estimate would imply meaningful reductions in the nationwide incidence of HPV-related cancers.

> "Research is needed to investigate the extent to which different forms of opt-out provisions may contribute to or detract from vaccination."—Calo et al. (2016)

1. Introduction

Seventy-nine million Americans are infected with human papillomavirus (HPV) making it the most common sexually transmitted infection in the United States (CDC, 2017). Approximately 80 percent of sexually active people will contract HPV during their lives (Cleveland Clinic, 2018). HPV is a group of more than 200 related viruses (National Cancer Institute, 2020a), and HPV types 16 and 18 are responsible for 66 percent of all cervical cancers in the US (CDC, 2018). Over 40,000 people annually are diagnosed with an HPV-related cancer (Van Dyne et al., 2018). Approximately 11 million men are currently thought to have oral HPV (Deshmukh et al., 2017), and the incidence of male oral cancer exceeds the incidence of cervical cancer in women (Mourad et al., 2017).

Unlike most cancers, there is a highly effective vaccine that provides near complete protection against some of the most dangerous strains of HPV (Villa et al., 2005; Villa et al., 2006). Yet in 2018, only 68 percent of teens had initiated HPV vaccination and only 55 percent were fully vaccinated.[1] Over the last decade, more than 40 states have introduced legislation on HPV vaccination, many of which sought to leverage the success of other school-entry vaccine requirements by mandating HPV vaccination (Barraza et al., 2016).

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[1] In November of 2016, the Advisory Committee on Immunization Practice (ACIP) began recommending a 2-dose series for full protection (Meites, Kempe and Markowitz 2016). Prior to that it was a 3-dose series.

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However, these mandates have proven politically difficult. For example, the New York state Parent Teachers Association announced opposition to a recent bill which would require middle school students to receive the HPV vaccine, despite re-expressing its support for other mandated vaccinations (Times Herald-Record, 2020). Only three states and the District of Columbia have successfully adopted HPV vaccine school requirements, and vaccination proponents argue that their broad opt-out provisions limit their efficacy (Reynolds, 2012).[2]

In this paper, I provide the first causal evaluation of how Washington, DC's 2014 HPV vaccine school requirement affected vaccine coverage. I find that the requirement increased the probability that a teen was fully vaccinated against HPV by nearly 20 percentage points—a 71 percent increase over the 2013 vaccination rate. I use an event study specification to show that this increase was not driven by pre-existing trends in vaccination. The use of placebo permutation tests confirms that the increase is larger than would be expected by chance. I also show that the estimate is robust to employing a synthetic control design. Back-of-the-envelope calculations imply that this requirement will directly result in 7 fewer cases of cervical cancer and 41 fewer cases of oropharyngeal cancer for the 33,000 students enrolled in Washington, DC schools during the 2017/2018 academic year. After accounting for the initial costs of cervical and oropharyngeal cancer care, as well as the statistical value of the life years lost, my estimates imply nearly $36 million dollars in reduced cancer savings compared to the $1.5 million it cost to vaccinate these students.

While important for policymakers, generalizing these estimates to the broader US requires caution. For one, the HPV vaccine initiation rate in the US in 2018 was higher than Washington, DC's initiation rate immediately prior to the policy change (68 percent vs. 62 percent). Moreover, vaccine initiation rates between girls and boys have converged. In 2018, 70 percent of girls and 67 percent of boys had received at least one shot of the HPV vaccine. As a result, school requirements may no longer induce larger increases in take-up for teen boys than teen girls. Yet even subject to these caveats, considering how these estimates could generalize is a useful exercise. There are 30 million 6–12th grade students in the US (National Center for Education Statistics, 2018). Applying my most conservative estimated increase in vaccine initiation (10.9 percentage points) still yields approximately 3.27 million more vaccinated students and over 6000 fewer cases of cervical cancer.

In addition to learning about ways to improve HPV vaccination, the Washington, DC policy change offers broader insights into the importance of how vaccine mandates are implemented. While respondents view vaccine school requirements more favorably if they contain opt-out provisions, these provisions likely reduce the mandates' efficacy (Calo et al., 2016). Indeed, there is a positive association between the ease of opting-out of vaccination and the number of exemptions granted in a state (Blank et al., 2013) and repealing non-medical vaccine exemptions is associated with greater vaccine coverage (Nyathi et al., 2019; Richmine, Dor, and Moghtaderi, 2019). Beginning in 2009, sixth grade girls in DC were required to (i) receive the HPV vaccine or (ii) submit a one-time opt-out form. In 2014, the requirement was expanded to 6th grade boys and all students up through 12th grade. Additionally, all those not vaccinated were required to opt-out annually. As such, the treatment for teen girls was not a movement from "no requirement" to an "HPV vaccine requirement," but rather a change from a one-time opt-out in 6th grade to an annual opt-out requirement all the way through 12th grade.

For teen girls, I find a 11-percentage point increase in HPV vaccine initiation and a 20-percentage point increase in vaccine completion. This pattern suggests that the annual reminder induced girls who had previously opted-out of HPV vaccination to receive their first shot, while also encouraging girls who had initiated vaccination to complete the vaccine series. In support of this pathway, I show that DC's 2014 HPV vaccine requirement reduced the probability that a teen girl had initiated but not completed the HPV vaccine. Additionally, I find that the 2014 requirement increased the probability that teen girls completed HPV vaccination within the recommended timeframe conditional on initiation. In contrast to these results for teen girls, I find that the increase in vaccine completion for teen boys is fully explained by an increase in vaccine initiation.

In Section 2, I discuss the history of the HPV vaccine, state HPV vaccine school requirements, and the existing literature on policies promoting HPV vaccination. In Section 3, I provide an overview of the NIS-Teen data and show descriptively that DC experienced a dramatic increase in HPV vaccination in the post-school requirement period. I then discuss my identification strategies, as well as the difficulties of conducting statistical inference with a single treated unit. In Section 4, I show that DC's 2014 HPV vaccine school requirement led to a large statistically significant increase in HPV vaccination, and I explore how the relationship varied by sex, grade level, race/ethnicity, and mother's educational attainment. In Section 5, I use my estimates to project the number of cancers prevented due to the 2014 mandate, and I estimate the cost savings associated with these reductions. Finally, I conclude in Section 6 by discussing the policy implications of my estimates and areas for future research.

2. Policy background & existing literature

In this section, I provide a history of the HPV vaccine within the United States. I discuss when various age and sex groups were eligible to receive the vaccine, as well as state HPV vaccine school requirements. Next, I summarize the literature on vaccine mandates with a focus on the structure of these requirements. Finally, I discuss existing work on ways to improve HPV vaccination.

[2] These states are Hawaii, Rhode Island, and Virginia, though Hawaii's requirement did not take effect until the 2020/2021 school year. In 2007, then-governor Rick Perry issued an executive order requiring that 6th grade girls in Texas be vaccinated against HPV. The order was vacated by the legislature, and the issue was used against Perry during a debate when he ran for the Republican presidential nomination (NPR 2011).

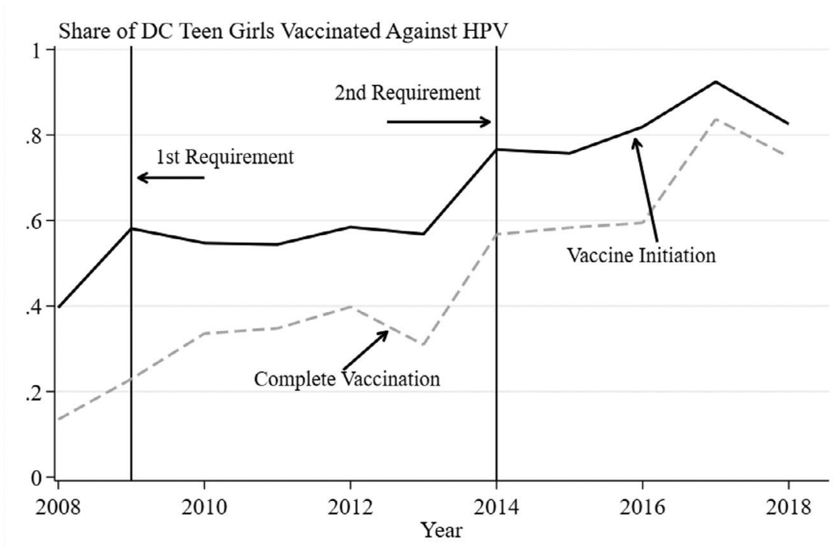

Fig. 1. Share of teen girls in Washington, DC vaccinated against HPV
Note: The figure plots the share of DC teen girls receiving at least one dose of the HPV vaccine (solid black line) and the share fully vaccinated against HPV (dashed gray line). A full dose of the HPV vaccine was 3 shots between 2008 and 2016, while it was changed to only 2 shots beginning in 2017. Beginning with the 2009/2010 academic year, sixth grade girls were required to be vaccinated or submit a one-time opt-out form. Beginning in 2014, the requirement was extended to include all students 6–12th grade and those not vaccinating had to opt-out annually. The statistics were obtained by utilizing the sample weights.
Source: National Immunization Survey—Teen 2008–2018

2.1. Policy background

Gardasil—the trade name of the HPV vaccine—was approved for girls ages 9–26 in June 2006.[3] Initially, the Advisory Committee on Immunization Practices (ACIP) recommended a 3-dose vaccination series for 11- and 12-year-old girls (FDA, 2006), and that unvaccinated 13–26 year old females catch-up on vaccination (Meites et al., 2019). While several states have enacted legislation to educate the public about the HPV vaccine (NCSL, 2020), only three states and DC require HPV vaccination for school attendance.

In April of 2007, Virginia began requiring that girls initiate HPV vaccination prior to entering 6th grade starting in the 2008/2009 academic year.[4] Similarly, DC Law 17–10 included an HPV vaccine school requirement for teen 6th grade girls starting in the 2009/2010 school year. Notably, this order applied to all girls, including those in private and parochial school, and I show in Fig. 1 that the share of teenage girls in DC initiating the HPV vaccine rose by approximately 20-percentage points following the first mandate. However, after viewing an information sheet about HPV shown in Figure A1, parents had broad latitude to opt out of vaccination "for any reason." Since then, only two other states adopted HPV vaccine school requirements. In 2015, Rhode Island began requiring all middle school students, regardless of sex, to receive the HPV vaccine, and Hawaii began requiring HPV vaccination starting in the 2020/2021 academic year (NCSL, 2020).[5]

During the same month that DC's 2009 mandate went into effect, Gardasil was approved for teen boys and young men (FDA, 2009). However, DC's requirement was not expanded to include teen boys until the 2014/15 school year. At this point, the policy was also modified so that parents choosing not to vaccinate their children became required to opt-out annually (American Academy of Pediatrics DC Chapter, 2015; Ko et al., 2020). I summarize these policy changes and the students bound by the requirements in Table 1. [6]

[3] Between 2009 and 2016, a variant of the HPV vaccine was sold in the US under the trade name Cervarix. It left the US market due to low demand (FDA 2009; GSK 2016).

[4] Because the National Immunization Survey-Teen begins in 2008, I am unable to leverage identifying variation from Virginia's requirement. I opt to focus on the DC requirement instead of including Rhode Island for two reasons. First, Rhode Island had the highest HPV vaccination rate in the US prior to its school requirement, while the nationwide HPV vaccination rate in 2018 was similar to Washington, DC's prior to DC's HPV mandate (68 percent vs. 62 percent). Because of this, my results may be more generalizable to other settings. Additionally, because DC had already implemented an HPV vaccine requirement in 2009, the 2014 policy change provides insights into the importance of having annual opt-out form relative to a one-time option that cannot be measured in Rhode Island.

[5] In 2007, then-governor Rick Perry signed an executive order requiring that Texas 6th grade girls receive the vaccine (Tanne 2007). The legislature passed a bill overruling the executive order and it was never implemented (NPR 2011).

[6] The DC Immunization Program received Prevention and Public Health Funding Awards through the CDC in 2013, 2016, and 2017 (American Academy of Pediatrics DC Chapter 2015) totaling $2,251,008 in additional funding to help implement the expanded school vaccine

Table 1
Washington, DC's HPV vaccine school requirement over time.

	(1) 2006–2008	(2) 2009–2013	(3) ≥ 2014
Females			
6th Graders	No Requirement	Vaccine Required or Opt-Out	Vaccine Required or Annual Opt-Out
7th-12th Graders	No Requirement	No Requirement	Vaccine Required or Annual Opt-Out
Males			
6th Graders	No Requirement	No Requirement	Vaccine Required or Annual Opt-Out
7th-12th Graders	No Requirement	No Requirement	Vaccine Required or Annual Opt-Out

Note: Beginning with the 2009/2010 school year, sixth grade girls were required to receive the HPV vaccine or submit a one-time opt-out form. In 2014, the HPV vaccine school requirement was expanded to include teen boys and older students. Additionally, non-vaccinating students became required to opt-out annually.

2.2. Vaccine mandates

In addition to the protection provided to the vaccinated person, immunization offers social benefits by lowering the probability that others contact an infected person. Because these social benefits are not internalized, coverage rates remain below the social optimum. Accordingly, policymakers have explored methods of improving vaccination, including mandating immunization for school attendance (Orenstein and Hinman, 1999). While several papers have studied whether these requirements increase immunization (Abrevaya and Mulligan, 2011; Ward, 2014; Carpenter and Lawler, 2019; Luca, 2020), less attention has been paid to the structure of these mandates. Yet recent outbreaks of vaccine-preventable diseases have increased interest in exemptions allowing individuals to remain unvaccinated (Olive et al., 2018), with authors finding that vaccination falls when it is easier to obtain an exemption (Blank et al., 2013; Nyathi et al., 2019; Richmine, Dor, and Moghtaderi, 2019).

While broad exemptions may undermine the efficacy of vaccine mandates, it is worth noting that these policies may still improve coverage by signaling the importance of vaccination. For example, Lawler (2017) used the 2003–2013 NIS-Child to show that while state hepatitis A mandates increased vaccine take-up by 8 percentage points, ACIP recommendations increased vaccination by 20 percentage points. Similarly, Lawler (2020) found that meningococcal vaccine recommendations increased vaccine take-up among the targeted population by 133 percent relative to the baseline mean.

2.3. HPV vaccination

I am unaware of any economics study which has attempted to determine the causal effect of state HPV vaccine school requirements. Instead, the existing work on these policies in the public health literature is largely based on correlational comparisons. Perhaps most related to this project, Ko et al. (2020) used the 2017 NIS-Teen to compare HPV vaccine initiation rates in areas with HPV vaccine school requirements (DC, Virginia, and Rhode Island) to non-treated areas. The authors then used the 2008–2017 NIS-Teen to perform a difference-in-differences style analysis.

Ko et al. (2020) found a positive association by comparing DC's pre- and post-policy vaccination rates to the change experienced by a composite region generated from Delaware, Maryland, Pennsylvania, and West Virginia. For teen girls, the authors used 2008 as the pre-period and 2009–2017 as the post period, thereby precluding the 2014 policy change from separately affecting girls. They found a 15 percent increase in the likelihood that teen girls were vaccinated, though the result was statistically insignificant. For teen boys, they used 2008–2013 as the pre-period and 2014–2017 as the post-period, and the authors reported a statistically significant 94 percent increase in vaccination. However, they did not probe whether their result could be attributable to a pre-existing trend in vaccination. Nor did they control for time-varying state-level policies—such as DC's grant to promote HPV vaccination— which could bias their estimate upwards. Finally, the authors did not adjust their standard errors to account for the fact that there was only one treated unit in each analysis.

Thompson et al. (2018) examined the relationship between Rhode Island's 2015 HPV vaccine school requirement—which applied to both girls and boys—and parental-reported vaccination using the 2010–2016 NIS-Teen data. Using a triple-difference style specification, the authors documented an 11-percentage point increase in the likelihood that boys were vaccinated; the estimate for girls was statistically insignificant. In a subsequent paper, Thompson et al. (2020) documented a 13-percentage point increase for teen boys using provider-verified data, and they reported finding no meaningful increase when examining DC's mandate. In both cases, the authors failed to control for other vaccine-related policies or adjust their standard errors to account for having only one treated unit.

With so few states requiring HPV vaccination, researchers have examined other policies which may improve coverage. Lipton and Decker (2015) used the 2008–2012 National Health Interview Survey to show that the Affordable Care Act's dependent coverage provision increased the probability that a 19- to 25-year-old woman was vaccinated for HPV by 8 percentage points compared to a control group of 18- and 26-year-olds. Churchill (2020) found that the ACA Medicaid expansions were associated with increased

requirement. In Appendix B, I provide a month-by-month granular breakdown of how this funding was spent, as obtained from the Department of Health and Human Services.

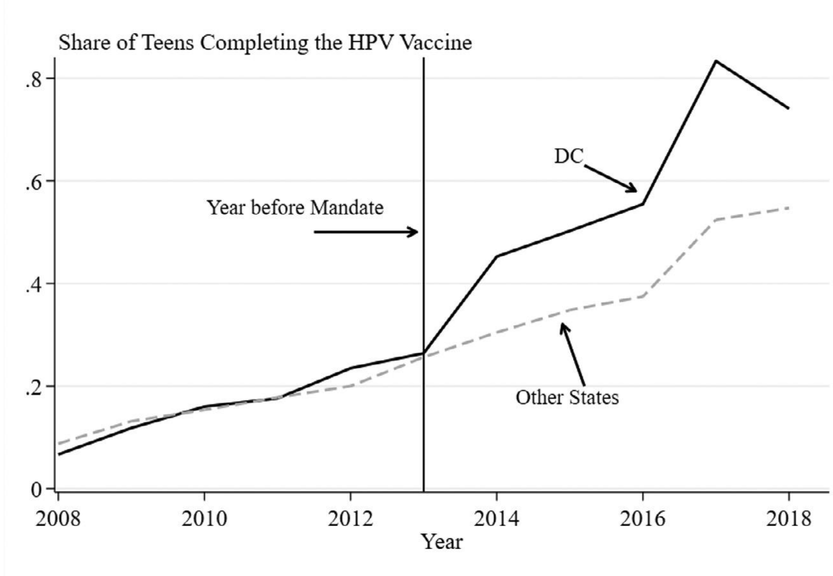

Fig. 2. HPV vaccination rates were trending similarly in Washington, DC and the rest of the country prior to the school vaccine requirement and diverged in the post-period
Note: The figure plots the share of teens fully vaccinated against HPV in Washington, DC (solid black line) and the rest of the country (dashed gray line). A full dose of the HPV vaccine was 3 shots between 2008 and 2016, while it was changed to only 2 shots beginning in 2017. The statistics were obtained by utilizing the sample weights.
Source: National Immunization Survey—Teen 2008–2018

Medicaid coverage and HPV vaccination for both teen boys and teen girls, with the largest effects for poorer teens, non-white teens, and teens whose mothers lacked college degrees.

Other research has demonstrated the important role of physician contact in vaccination. Carpenter and Lawler (2019) found that middle school Tdap booster requirements increased HPV vaccination by 4–5 percentage points. Because the Tdap booster and HPV vaccine are both recommended for 11- to 12-year-olds (CDC, 2020a), the authors argued that the effect was due to the requirements increasing age-appropriate teens' contact with vaccine providers. This pattern is consistent with Moghtaderi and Adams (2016), who found that NIS-Teen respondents who were more likely to encounter physicians for reasons aside from vaccination—such as for mandatory wellness checks or previous asthma diagnoses—were more likely to receive the HPV vaccine.

3. Data & methodology

In this section, I describe the specifics of the NIS-Teen data. I show descriptively that the share of DC teens vaccinated against HPV increased dramatically concurrent with the 2014 HPV vaccine school requirement. The average vaccination rate in all other states was unchanged. I then describe my two empirical strategies intended to test whether this is a causal effect—difference-in-differences and synthetic control.

3.1. Data: national immunization survey-teen

I obtain HPV vaccination data from the 2008–2018 National Immunization Survey (NIS)-Teen which contains individual-level, provider-verified, state-representative vaccination data on teenagers ages 13–17. The NIS-Teen is administered by the Centers for Disease Control and Prevention (CDC) in two parts. First, the CDC uses telephone surveys to collect demographic information about eligible teens and their parents and guardians. Survey interviewers ask parents which vaccines their teen has received, and whether they may contact the vaccine provider(s). As a follow-up, paper questionnaires are mailed to each provider to obtain provider-verified information on each vaccination, including the number of doses and dates of administration. To guard against the possibility that DC's HPV vaccine school requirement changed the probability that parents reported vaccination without affecting vaccine take-up, I utilize the provider-verified immunization data and restrict my sample to teens with adequate provider information.[7]

I show in Fig. 2 that DC and the rest of the United States had similar rates of HPV vaccination prior to 2014. In 2013, 26 percent of DC teens had completed the HPV vaccine (22nd highest in the nation), which was identical to the average vaccination rate throughout

[7] In 2018, 71.9 percent of eligible households completed the phone survey, and 58.2 percent of these respondents granted permission for the surveyors to contact their teen's vaccination providers. Of these questionnaires, 92.5 percent were returned. Overall, 48.3 percent of teens with completed household interviews had adequate provider information.

the rest of the country. By 2018, the share was nearly 20 percentage points higher in DC than the rest of the country (74 percent vs. 55 percent), and DC had the second highest HPV vaccination rate in the US.[8] Similarly, I show in Table 2 that the average HPV vaccine completion rate was 17 percent for both DC and the rest of the country during the 2008–2013 period (columns 2 and 5 row 1), and only around 30 percent of teens had received at least one dose of the vaccine (columns 2 and 5 row 2). Throughout the post-period, DC's average vaccination rate was considerably higher columns 3 and 6 row 1).

It is worth noting that DC experienced a demographic change throughout this period. From 2008–2013, over 70 percent of teens were identified as black (column 2 row 11). In the post-period, 66 percent of DC teens were identified as black (column 3 row 11). At the same time, the share of teens whose mothers lacked a high school degree fell (18 percent vs. 13 percent) and the share living in households earning less than $20,000 a year fell (31 percent vs. 25 percent). To the extent that white teens, teens with more educated mothers, and wealthier teens were more likely to receive the HPV vaccine, it is possible that these composition changes could bias my estimates. However, I show in Figure A2 that these changes were part of a smooth trend and did not occur concurrent with the 2014 school requirement. Additionally, white teens throughout the rest of the US had a lower vaccination rate than non-white teens (27 percent vs. 34 percent), so the direction of any potential bias is unclear.

3.2. Methodology: difference-in-differences with randomization inference

While the descriptive statistics in Fig. 2 indicate an increase in DC's HPV vaccination rate after the school requirement was implemented in 2014, I formally test this relationship using the following linear probability model:

$$\mathrm{VACC}_{\mathrm{ist}} = \alpha + \beta \cdot \mathbf{1}\{s = DC\} \cdot \mathbf{1}\{t \geq 2014\} + \mathbf{X}'_{ist}\gamma + \mathbf{B}'_{st}\delta + \theta_s + \tau_t + \varepsilon_{ist} \quad (1)$$

where VACC is an indicator for whether the teen, i, in state, s, was fully vaccinated against HPV in year t. The coefficient of interest, β, measures how much more likely a teen in DC was to be vaccinated against HPV after the implementation of the 2014 school HPV vaccine requirement.

To account for the fact that DC's demographic composition was changing throughout the sample period in a way that may have been correlated with vaccination, I include a vector of individual-level characteristics, **X**. These includes indicators for the teen's sex (male, with female omitted), the teen's age (13, 14, 15, 16, with 17 omitted), the teen's grade level (6–8th, 9–12th, high school graduate, with "unenrolled" omitted), and the teen's race/ethnicity (white, black, Hispanic, with "other" omitted). The vector also includes indicators for mother's age (≤ 34, 35–44, with 45+ omitted), mother's educational attainment (less than high school, high school graduate, some college, with college omitted), and household income (less than $20 K, $20–30 K, $30–40 K, $40–50 K, with $50K+ omitted).

I account for state-level time-varying characteristics related to HPV vaccination. The vector **B** includes indicators for Washington, DC's 2009 HPV vaccine requirement, whether the vaccine was approved by the FDA and/or recommended by ACIP for the teen. It also includes indicators for other vaccine mandates, including a Tdap booster requirement (Carpenter and Lawler, 2019), a meningococcal booster mandate, post-secondary school meningococcal education mandate, a secondary school meningococcal education mandate, and a post-secondary meningococcal vaccine mandate (Lawler, 2020). It also includes indicators for whether a pharmacist has prescriptive authority for the HPV vaccine, whether a pharmacist has general authority for the HPV vaccine, whether the pharmacist has patient-specific authority for the HPV vaccine, whether some minors can consent to any medical procedure, and whether some minors can consent to receive the HPV vaccine.[9]

To account for access to the vaccine, the vector **B** also includes an indicator for whether the state purchases the HPV vaccine for all children through a universal purchase program, Mulligan et al. 2018), as well as state requirements that the HPV vaccine be covered by private health insurance (Hoss, Meyerson, and Zimet 2019). The vector also controls for whether the state received National Cancer Institute (NCI) or National Association of County and City Health (NACCHO) HPV vaccine grants, as well as the real value of CDC grants issued per person that year for HPV vaccination (American Academy of Pediatrics DC Chapter, 2015). Finally, I include time-invariant state fixed effects, θ, and location-invariant year fixed effects, τ.

To conduct inference, I employ the variant of Fisher's (1935) permutation test used by Buchmueller et al. (2011) and Cunningham and Shah (2018).[10] First, I estimate Eq. (1) an additional 50 times iteratively assuming that each of the control states was treated in 2014. I then compare the $\hat{\beta}$ for the actual 2014 DC treatment to the placebo distribution. To achieve 10 percent statistical significance using a two-tailed test, DC's coefficient must be larger (or smaller) than all but two states. Similarly, 5 percent statistical significance requires the coefficient to be at the top of the placebo distribution. As such, this is a demanding statistical test.

It is possible that DC's HPV mandate had differential effects depending on the teen's grade level, race/ethnicity, and/or maternal education. I test this possibility by interacting an indicator for being a member of the group of interest with the independent variable, every control variable, the state fixed effects, and the year fixed effects using the triple-difference specification in Eq. (2):

$$VACC_{ist} = GROUP_{ist} \times \left(\alpha + \beta \cdot \mathbf{1}\{s = DC\} \cdot \mathbf{1}\{t \geq 2014\} + \mathbf{X}'_{ist}\gamma + \mathbf{B}'_{st}\delta + \theta_s + \tau_t\right) + \varepsilon_{ist} \quad (2)$$

[8] Rhode Island, Delaware, Connecticut, Maine, New York, New Mexico, Vermont, Pennsylvania, California, North Carolina, New Hampshire, Nebraska, Arizona, Louisiana, Massachusetts, Washington, Iowa, Texas, West Virginia, Oklahoma, and Oregon all had higher vaccination rates in 2013. By 2018, only Rhode Island had a higher rate of vaccine completion. As mentioned previously, Rhode Island adopted an HPV vaccine mandate in 2015.

[9] I am grateful to Emily C. Lawler for providing me with these policy variables.

[10] With the traditional "clustering" framework, the underlying assumption necessary for the asymptotic approximations is that the number of individuals within a state grows larger. This assumption is not satisfied with one treated state.

Table 2
Summary statistics.

	(1) Washington, DC	(2)	(3)	(4) Remaining US	(5)	(6)
	Overall	2008–2013	2014–2018	Overall	2008–2013	2014–2018
Vaccination						
Complete Vaccination	0.360	0.165	0.617	0.282	0.168	0.419
	(0.480)	(0.371)	(0.486)	(0.450)	(0.374)	(0.493)
Vaccine Initiation	0.551	0.353	0.813	0.434	0.297	0.600
	(0.497)	(0.478)	(0.390)	(0.496)	(0.457)	(0.490)
Teen Demographics						
Age 14	0.199	0.194	0.207	0.198	0.197	0.199
	(0.400)	(0.395)	(0.405)	(0.398)	(0.398)	(0.399)
Age 15	0.208	0.208	0.207	0.209	0.212	0.205
	(0.406)	(0.406)	(0.406)	(0.407)	(0.409)	(0.404)
Age 16	0.223	0.221	0.225	0.206	0.207	0.204
	(0.416)	(0.415)	(0.418)	(0.404)	(0.405)	(0.403)
Age 17	0.175	0.182	0.167	0.189	0.187	0.191
	(0.381)	(0.386)	(0.373)	(0.392)	(0.390)	(0.393)
6–8th Grade	0.245	0.243	0.249	0.272	0.273	0.272
	(0.430)	(0.429)	(0.432)	(0.445)	(0.445)	(0.445)
9–12th Grade	0.729	0.729	0.729	0.714	0.713	0.715
	(0.445)	(0.445)	(0.445)	(0.452)	(0.452)	(0.451)
HS Graduate	0.016	0.013	0.020	0.010	0.010	0.009
	(0.126)	(0.114)	(0.139)	(0.098)	(0.102)	(0.094)
White	0.157	0.146	0.170	0.560	0.578	0.537
	(0.363)	(0.353)	(0.376)	(0.496)	(0.494)	(0.499)
Black	0.696	0.726	0.656	0.140	0.142	0.136
	(0.460)	(0.446)	(0.475)	(0.347)	(0.350)	(0.343)
Hispanic	0.111	0.096	0.131	0.213	0.201	0.227
	(0.314)	(0.295)	(0.337)	(0.409)	(0.400)	(0.419)
Household Controls						
Mother $\leq$ 34	0.120	0.118	0.123	0.092	0.096	0.087
	(0.325)	(0.323)	(0.329)	(0.289)	(0.295)	(0.282)
Mother 35–44	0.386	0.389	0.383	0.449	0.458	0.439
	(0.487)	(0.488)	(0.486)	(0.497)	(0.498)	(0.496)
Moher < HS	0.155	0.177	0.126	0.129	0.134	0.122
	(0.362)	(0.382)	(0.332)	(0.335)	(0.341)	(0.328)
Mother HS Graduate	0.294	0.306	0.278	0.244	0.260	0.224
	(0.456)	(0.461)	(0.448)	(0.429)	(0.439)	(0.417)
Mother Some College	0.210	0.199	0.225	0.259	0.263	0.253
	(0.408)	(0.4000	(0.417)	(0.438)	(0.440)	(0.435)
Income $\leq$ $20K	0.283	0.310	0.247	0.186	0.187	0.184
	(0.450)	(0.463)	(0.431)	(0.389)	(0.390)	(0.388)
Income $20–30K	0.135	0.114	0.163	0.107	0.107	0.106
	(0.342)	(0.318)	(0.369)	(0.309)	(0.309)	(0.308)
Income $30–40K	0.099	0.099	0.099	0.087	0.092	0.081
	(0.299)	(0.299)	(0.298)	(0.281)	(0.288)	(0.272)
Income $40–50K	0.057	0.058	0.055	0.076	0.080	0.070
	(0.231)	(0.233)	(0.229)	(0.265)	(0.272)	(0.256)
State-Level Controls						
Tdap Requirement	1.000	1.000	1.000	0.793	0.629	0.991
	(0.000)	(0.000)	(0.000)	(0.405)	(0.483)	(0.094)
CDC Grant per Person	2.119	3.730	4.051	0.090	0.062	0.181
	(6.686)	(8.527	(8.812)	(0.403)	(0.309)	(0.599)
ACA Medicaid Expansion	0.789	0.629	1.000	0.325	0.100	0.582
	(0.408)	(0.483)	(0.000)	(0.468)	(0.301)	(0.493)
HPV Vaccine Available	0.896	0.816	1.000	0.907	0.829	1.000
	(0.306)	(0.387)	(0.000)	(0.291)	(0.376)	(0.000)
HPV Vaccine Recommended	0.803	0.654	1.000	0.814	0.661	1.000
	(0.397)	(0.476)	(0.000)	(0.389)	(0.473)	(0.000)
Consent to HPV Vaccine	1.000	1.000	1.000	0.088	0.046	0.139
	(0.000)	(0.000)	(0.000)	(0.284)	(0.210)	(0.346)
Consent to Any Procedure	0.000	0.000	0.000	0.126	0.127	0.125
	(0.000)	(0.000)	(0.000)	(0.332)	(0.333)	(0.331)
Prescriptive Authority	0.000	0.000	0.000	0.071	0.009	0.146
	(0.000)	(0.000)	(0.000)	(0.257)	(0.095)	(0.353)
General Authority	0.892	0.809	1.000	0.369	0.370	0.367
	(0.311)	(0.393)	(0.000)	(0.483)	(0.483)	(0.482)
Patient-Specific Authority	0.000	0.000	0.000	0.050	0.040	0.062
	(0.000)	(0.000)	(0.000)	(0.217)	(0.195)	(0.241)

(*continued on next page*)

Table 2 (*continued*)

	(1) Washington, DC	(2)	(3)	(4) Remaining US	(5)	(6)
	Overall	2008–2013	2014–2018	Overall	2008–2013	2014–2018
NCI Grant	0.000	0.000	0.000	0.081	0.000	0.179
	(0.000)	(0.000)	(0.000)	(0.273)	(0.000)	(0.381)
NACCHO Grant	0.000	0.000	0.000	0.046	0.000	0.102
	(0.000)	(0.000)	(0.000)	(0.210)	(0.000)	(0.303)
Meningococcal Booster Mandate	0.000	0.000	0.000	0.066	0.002	0.143
	(0.000)	(0.000)	(0.000)	(0.248)	(0.043)	(0.350)
Meningococcal Post-Secondary Education Mandate	1.000	1.000	1.000	0.779	0.779	0.780
	(0.000)	(0.000)	(0.000)	(0.414)	(0.415)	(0.414)
Meningococcal Education Mandate	0.000	0.000	0.000	0.570	0.558	0.584
	(0.000)	(0.000)	(0.000)	(0.495)	(0.497)	(0.493)
Meningococcal Post-Secondary Mandate	0.000	0.000	0.000	0.149	0.130	0.172
	(0.000)	(0.000)	(0.000)	(0.356)	(0.337)	(0.377)
Must Cover HPV Vaccine	0.000	0.000	0.000	0.073	0.068	0.079
	(0.000)	(0.000)	(0.000)	(0.260)	(0.251)	(0.270)
Universal Purchase	0.000	0.000	0.000	0.050	0.031	0.072
	(0.000)	(0.000)	(0.000)	(0.217)	(0.172)	(0.259)
Observations	3488	1909	1579	197,406	105,358	92,048

Source: National Immunization Survey-Teen 2008–2018.
Note: Summary statistics utilize the sample weights.

To interpret β as the causal effect of DC's school HPV vaccine requirement on vaccination, I must assume that vaccine coverage would have evolved similarly to the rest of the United States had it not been for the mandate. While this assumption is fundamentally untestable, I explore whether vaccination was trending differently from the rest of the country prior to the requirement using the following event study framework:

$$VACC_{ist} = \alpha + \sum_{j=2008,\ j\neq 2013}^{2018} \beta^{j}\mathbf{1}\{s = DC\}\cdot \mathbf{1}\{t = j\} + \mathbf{X}'_{ist}\gamma + \mathbf{B}\prime_{st}\delta + \theta_s + \tau_t + \varepsilon_{ist} \tag{3}$$

where β^{j} is allowed to vary with each year. For ease of comparison, I use 2013—the year prior to the mandate—as the reference year. Eq. (3) allows me to test for parallel trends in the pre-period and capture whether the relationship between DC's school requirement and immunization varied over time.

As with Eq. (1), traditional methods of inference are invalid. Instead of testing whether the pre- and post-implementation coefficients are different from zero (and each other), I again follow Cunningham and Shah (2018) and construct 95 percent placebo intervals for each β^{j}. As I will show in the results section, the interpretation of this event study specification differs from that typically seen in empirical work. To interpret the school requirement as having a causal effect on immunization, the estimated coefficients should be near zero and bounded within the 95 percent placebo intervals during the pre-period. In the post-period, the estimated coefficients should exceed the placebo-generated intervals.

3.3. Methodology: synthetic control analysis

I also explore the robustness of the estimates to using a synthetic control framework (Abadie and Gardeazabal, 2003; Abadie et al., 2010), which is intended to alleviate concerns that the rest of the US is not necessarily an appropriate control for DC. First, I aggregate the variables of interest to the state-year-level. I then construct a "Synthetic DC" from the subset of the control states that best approximates DC's HPV vaccination rates in the pre-period. This Synthetic DC serves as the counterfactual for how the vaccination rate would have evolved in absence of the school requirement.

The synthetic counterfactual is constructed by assigning non-negative weights to the 50 potential donor states to minimize Eq. (4):

$$\left(\mathrm{VACC_{DC}} - \mathrm{VACC_{SC}W}\right)'\mathrm{V}\left(\mathrm{VACC_{DC}} - \mathrm{VACC_{SC}W}\right) \tag{4}$$

where $\mathrm{VACC_{DC}}$ is a (K x 1) vector of outcome variables from the pre-period, $\mathrm{VACC_{SC}}$ is a (K x J) matrix of the same variables for every other state, W is a (J x 1) vector of weights that sum to 1, and the diagonal matrix V contains the "importance weights" assigned to each variable in VACC. I construct Synthetic DC by matching on three lagged values of the dependent variable (2009, 2011, and 2013), though I show in the appendix that the results are robust to choosing alternative years or simply matching on the average vaccination rate from 2008 to 2013. I conduct inference using the placebo technique proposed by Abadie et al. (2010).

4. Results

In this section, I show that DC's 2014 HPV vaccine school requirement led to a large increase in the probability that teens were vaccinated against HPV. Using an event study specification, I show that this relationship was not driven by a pre-existing trend in

Table 3
Washington, DC's HPV vaccine school requirement increased HPV vaccine completion.

	(1)	(2)	(3)	(4)	(5)
		Groups			
	Overall	Teen Boys	9–12th Graders	Non-White	Mother Lacked a BA
DC's 2014 Mandate	0.221***	0.198***	0.182***	0.180***	0.183***
Placebo 95% Lower Bound	−0.075	−0.140	−0.086	−0.083	−0.085
Placebo 95% Upper Bound	0.073	0.095	0.056	0.099	0.096
DC's 2014 Mandate x Group		0.035	0.056	0.025	0.093*
Placebo 95% Lower Bound		−0.105	−0.083	−0.114	−0.114
Placebo 95% Upper Bound		0.112	0.066	0.087	0.096
R^2	0.184	0.194	0.188	0.188	0.188
Observations	200,894	200,894	200,894	200,894	200,894

Source: National Immunization Survey—Teen 2008–2018.
Note: The dependent variable is an indicator for whether the teen has received the full HPV vaccination (3 doses until 2016 and 2 doses in all subsequent years). The independent variable of interest is an indicator for Washington, DC's 2014 HPV vaccine school requirement. The regression equation also controls for the teen's sex (male, with female omitted), age (14, 15, 16, 17, with 13 omitted), grade level (6–8th grade, 9–12th grade, high school graduate, with "not enrolled" omitted), and race/ethnicity (white, black, Hispanic, with "other" omitted). The specification also controls for mother's education (less than high school, high school diploma, some college, with college degree omitted), mother's age (at most 34, 35–44, with 45+ omitted), household income (less than \$20 K, \$20–30 K, \$30–40 K, \$40–50 K, with \$50K+ omitted), the presence of a school Tdap vaccination requirement, the presence of a school meningococcal vaccine requirement, and the real value of the CDC grants awarded per person for HPV vaccination during that year. Finally, it includes time-invariant state fixed effects and location-invariant year fixed effects. Column (1) considers the full sample. Column (2) interacts an indicator for being male with the treatment indicator, the full set of controls, the state fixed effects, and the year fixed effects. Column (3) repeats this process but uses an indicator for being in grades 9–12, column (4) an indicator for being non-white, and column (5) an indicator for having a non-college educated mother. To perform inference, the 95 percent intervals are obtained by estimating placebo treatments for each of the other 48 states. The estimates utilize the sample weights.
*** $p < 0.01$, ** $p < 0.05$,.
* $p < 0.10$.

immunization. I also document an increase in HPV vaccine initiation, intentions to vaccinate, and the likelihood of having been recommended the vaccine. Finally, I show that this pattern is robust to utilizing a synthetic control framework.

4.1. Vaccine completion

I first show in Table 3 that the 2014 school requirement was associated with a 22-percentage point increase in the likelihood that teens were fully vaccinated against HPV (column 1).[11] As I show in Fig. 3, the estimated increase is well outside of the 95 percent placebo interval (Panel A) and is over twice the size of the largest placebo coefficient (0.22 vs. 0.09). Moreover, this increase is large relative to the pre-period mean; between 2008 and 2013 only 17 percent of students were fully vaccinated against HPV, and only 26 percent were vaccinated as of 2013.[12]

Next, I use the event study specification from Eq. (3) to test whether HPV vaccination was trending differentially in DC prior to the 2014 requirement. In Fig. 3, I show that DC teens were no more likely to be vaccinated against HPV than their counterparts throughout the rest of the US (Panel B). Indeed, the pre-period coefficients are all within the 95 percent placebo interval. However, after the requirement was implemented in 2014, the probability of complete vaccination increased by approximately 20 percentage points. Each of the coefficients from the post-period is outside of the placebo distribution, indicating that the increase was unlikely to have been from chance.

Because teen girls were already bound by the 2009 HPV vaccine school requirement, I next test whether girls and boys were differentially affected by the 2014 policy change. In Fig. 4, I show that the 2014 school requirement was associated with a 20-percentage point increase in complete vaccination for teen girls (Panel A) and similarly a 23-percentage point increase for teen boys (Panel B). While the point estimate for teen boys is larger, these estimates are statistically indistinguishable from each other when I use the triple-difference specification from Eq. (2). In Table 3, I am unable to reject that the additional 3 percentage point increase experienced by teen boys was attributable to chance (column 2).

[11] Coefficients and standard errors for the covariates are reported in Table A1. In Figure A3, I show that my results are robust to including observations from Rhode Island and Virginia.

[12] As mentioned previously, the number of doses required for full coverage changed from 3 shots to 2 shots in late 2016. In Table A2, I show that my estimate is robust to restricting the sample to years 2008-2016 (column 1) and to recoding complete coverage as requiring 3 shots for the full sample period (column 2). Additionally, the NIS-Teen moved from being a landline phone survey to including cellphone respondents in 2011, and the survey underwent a redesign in 2014. I show that my estimate is robust to whether I utilize the sample weights (column 3). I also show that the estimate is robust to dropping 2013 (column 4) when some teens may have begun vaccinating in anticipation of the 2014 requirement, and the estimate is robust to controlling for only state and year fixed effects (column 5).

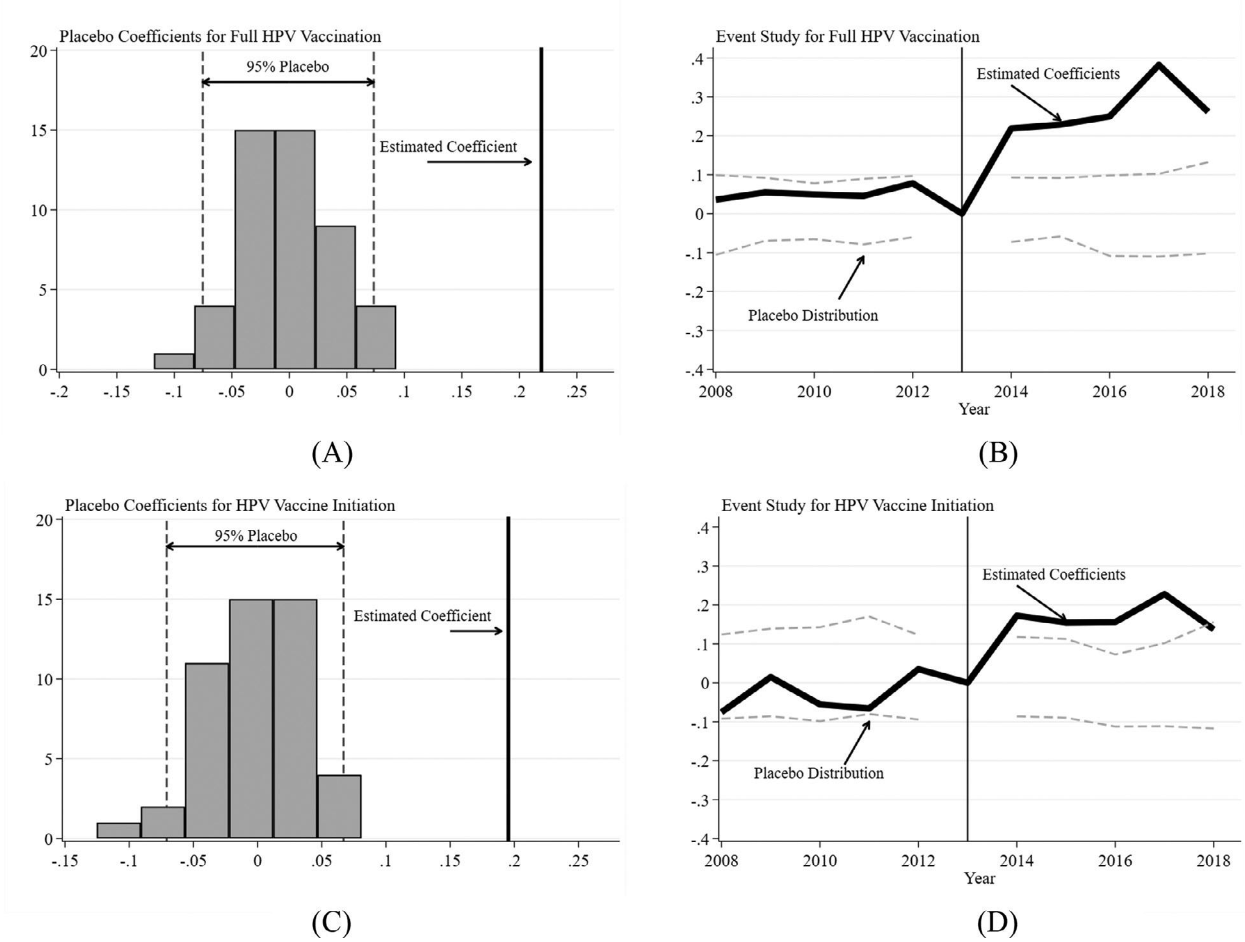

Fig. 3. Washington, DC's 2014 HPV vaccine school requirement increased HPV vaccination
Note: The dependent variable in Panels (A) and (B) an indicator for having been fully vaccinated against HPV (3 doses prior to 2017 and 2 doses thereafter), while the dependent variable in Panels (C) and (D) is an indicator for having received at least 1 dose of the vaccine. In Panels (A) and (C) the independent variable of interest is an indicator for Washington, DC's 2014 HPV vaccine school requirement. Estimates are obtained using Eq. (1). In Panels (B) and (D) the independent variables of interest are indicators for each year—with 2013 omitted—to capture dynamic effects. When the black line is within the placebo interval, the estimate was likely to have been obtained by chance. When the black line is outside the interval, it is unlikely that the estimate was obtained by chance. The estimates utilize the sample weights.
Source: National Immunization Survey—Teen 2008–2018

In the remaining columns of Table 3, I use the triple-difference specification to test for heterogeneity by grade level (column 3), race/ethnicity (column 4), and mother's educational attainment (column 5).[13] While the point estimates suggest larger increases for older and non-white teens, the differences are statistically insignificant.[14] However, I do detect a statistically significant 9-percentage point larger increase for teens whose mothers lacked college degrees. Prior to the 2014 mandate, teens in DC with college educated mothers were 8 percentage points more likely to be fully vaccinated compared to teens whose mothers lacked college degrees (22 percent vs. 14 percent). In the post-period, teens in both groups were similarly likely to be fully vaccinated (56 percent vs. 55 percent), suggesting that the 2014 requirement may have helped close the education gap for HPV vaccination.

[13] Unfortunately, the NIS-Teen does not contain information on urban vs. rural status, so I cannot compare Washington, DC to other metropolitan areas. However, it is worth noting that I find identical estimates for white and non-white teens. In addition to being an interesting heterogeneity exercise, limiting my sample to non-white teens may provide me with a better counterfactual for teens in Washington, DC, given that 80 percent of the city is non-white.

[14] It is worth noting that between 2008-2013 in DC, 52 percent of non-white girls had initiated HPV vaccination compared to 63 percent of white girls. Similarly, only 25 percent of non-white girls were fully vaccinated compared to 47 percent of white girls. So, while I cannot conclude that non-white teens experienced a larger percentage point increase in vaccination, the point estimate represents a larger increase from the pre-period mean for non-white teens. This suggests that the 2014 HPV vaccine school requirement may have been more salient for non-white teens and could possibly help close the racial gap in HPV-related cancer incidence.

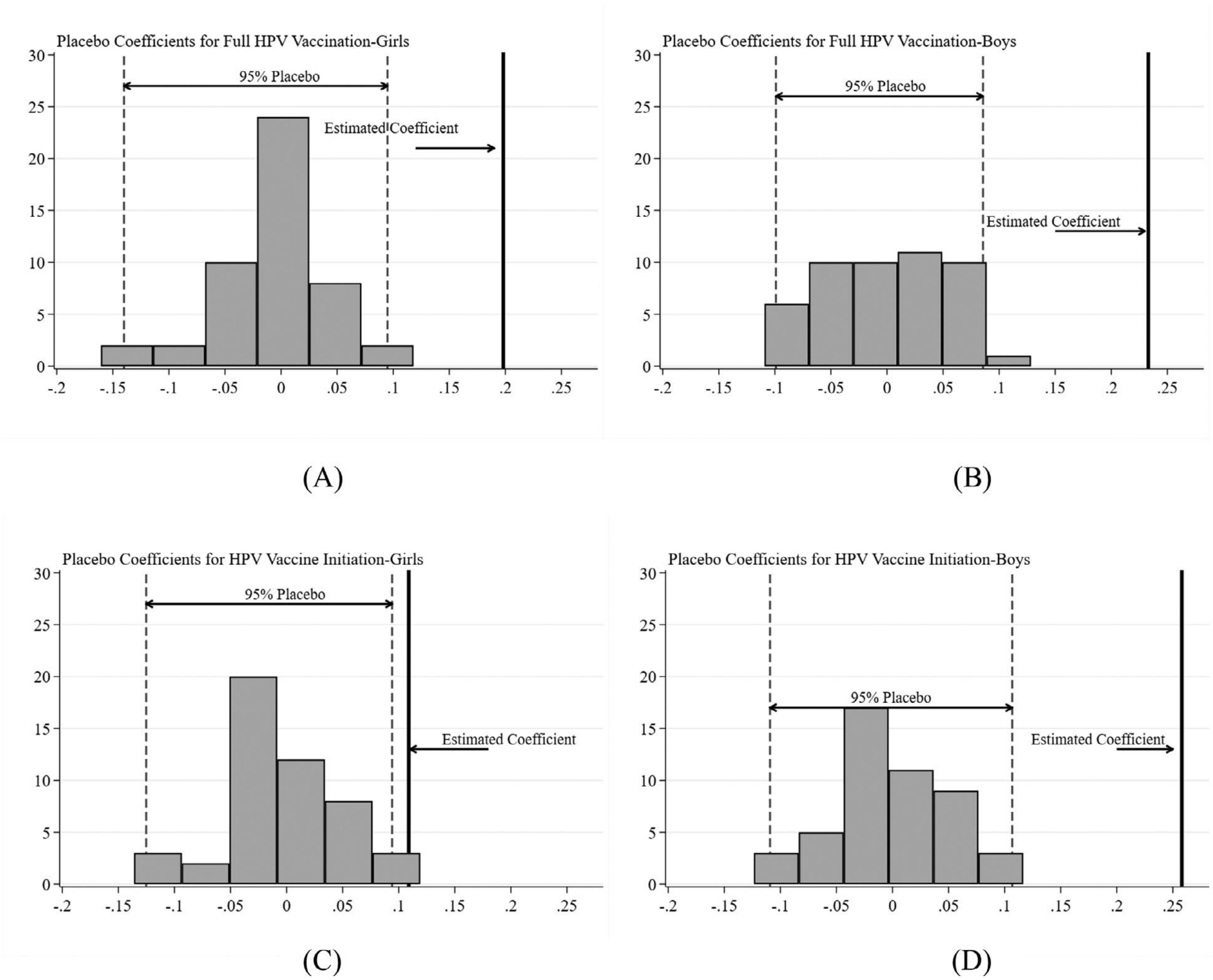

Fig. 4. DC's 2014 HPV vaccine school requirement increased vaccination for both girls and boys
Note: The dependent variable in Panels (A) and (B) an indicator for having been fully vaccinated against HPV (3 doses prior to 2017 and 2 doses thereafter), while the dependent variable in Panels (C) and (D) is an indicator for having received at least 1 dose of the vaccine. The independent variable of interest is an indicator for Washington, DC's 2014 HPV vaccine school requirement. Estimates are obtained using Eq. (1). Panels (A) and (C) restrict the sample to teen girls and Panels (B) and (D) restrict the sample to teen boys. When the black line is within the placebo interval, the estimate was likely to have been obtained by chance. When the black line is outside the interval, it is unlikely that the estimate was obtained by chance. The estimates utilize the sample weights.
Source: National Immunization Survey—Teen 2008–2018

In Fig. 5, I explore whether the increase in HPV vaccination was driven by more general changes in immunization behaviors. First, I show that the 2014 HPV vaccine school requirement was unrelated to the probability that a teen received a Tdap booster. When I use the two-way fixed effects specification from Eq. (1), the point estimate is negative and statistically insignificant (Panel A). Nor is there a noticeable change concurrent with the 2014 policy when examining the descriptive trends (Panel B). Similarly, the point estimate for meningococcal vaccination is negative and within the 95 percent placebo interval, though the estimate is statistically significant at the 10 percent level (Panel C). However, rather than the 2014 policy increasing the share of teens receiving the meningococcal vaccine, the descriptive statistics indicate that the relationship is due to growth in the share of immunized teens in the control states, while DC's rate remained unchanged (Panel D).

Finally, I explore whether DC's 2014 HPV vaccine school requirement affected the likelihood that teens received the influenza vaccine. Unlike the HPV vaccine, Tdap booster, and meningococcal vaccination, the influenza vaccine is administered each flu season, and the 2008–2017 NIS-Teen data contain information on whether the teen received the flu vaccine during the prior three years. For example, the 2017 data reports vaccination for the 2015/16, 2016/17, and 2017/18 flu seasons. Because I do not know the exact date of the survey, individuals in the 2017 data may be interviewed prior to the 2017/18 flu season which stretched from September

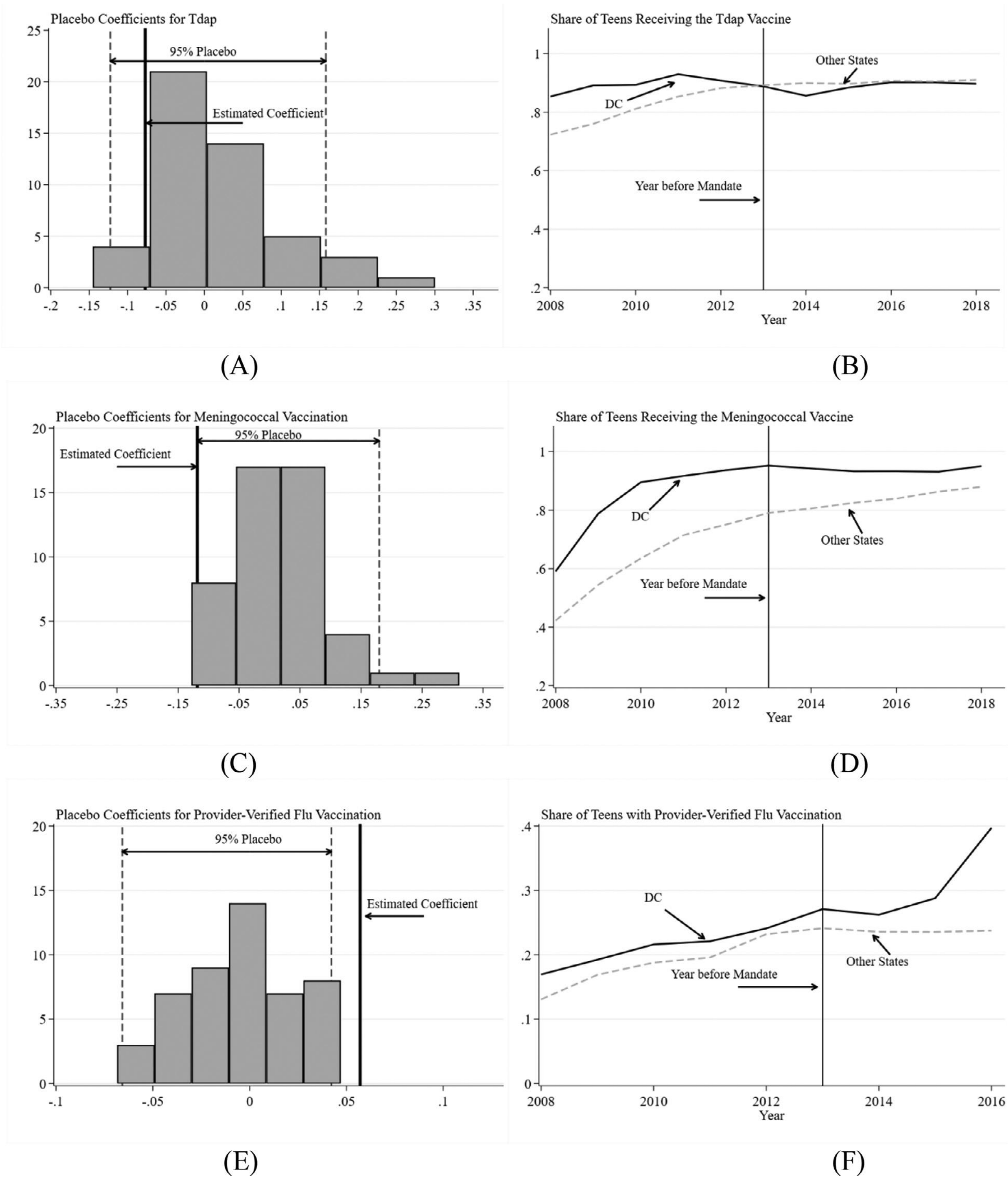

Fig. 5. DC's 2014 HPV vaccine requirement was positively related to influenza vaccination
Note: Panel (A) plots the difference-in-differences estimate of how Washington, DC's 2014 HPV vaccine school requirement affected Tdap vaccination from Eq. (1), as well as the placebo coefficients. Panel (B) plots the shares of teens in DC and the rest of the country receiving the Tdap vaccine after they turned 10. Panel (C) plots the coefficients obtained from Eq. (1) for the meningococcal vaccine, while Panel (D) plots the shares of teens receiving the meningococcal vaccine. Panel (F) shows the estimate from Eq. (1) relating the 2014 policy to the share receiving the influenza vaccine, while Panel (E) plots the share of teens up to date on the flu vaccine. In Panels (A), (C), and (E) when the black line is within the placebo interval, the estimate was likely to have been obtained by chance. When the black line is outside the interval, it is unlikely that the estimate was obtained by chance. The estimates utilize the sample weights.
Source: National Immunization Survey—Teen 2008–2018

Table 4
DC's HPV vaccine school requirement increased HPV vaccine initiation and reduced the likelihood that teen girls initiated but did not complete vaccination.

	(1)	(2)	(3)	(4)	(5)	(6)
	Vaccine Initiation		Vaccine Initiation without Completion		Complete Vaccination within 1 Year of Initiation	
	Girls	Boys	Girls	Boys	Girls	Boys
DC's 2014 Mandate	0.109**	0.258***	−0.089**	0.025	0.195***	0.030
Placebo 95% Lower Bound	−0.125	−0.109	−0.059	−0.050	−0.108	−0.142
Placebo 95% Upper Bound	0.094	0.107	0.055	0.083	0.081	0.209
DC Mean Pre-Period	0.534	0.169	0.248	0.126	0.633	0.984
R^2	0.078	0.309	0.026	0.082	0.068	0.069
Observations	96,051	104,843	96,051	104,843	32,139	19,948

Source: National Immunization Survey—Teen 2008–2018.
Note: The dependent variable in columns (1) and (2) is an indicator for whether the teen has initiated HPV vaccination (at least 1 dose). The dependent variable in columns (3) and (4) is an indicator for whether the teen has initiated vaccination but was not completely vaccinated (1 or 2 doses from 2008 to 2016 and 1 dose from 2017 to 2018). The dependent variable in columns (5) and (6) is an indicator for whether the teen was fully vaccinated within 1 year of vaccine initiation, where the sample is restricted to those initiating vaccination. The odd numbered columns examine teen girls, while the even numbered columns examine teen boys. To perform inference, the 95 percent confidence intervals are obtained by estimating placebo treatments for each of the other 48 states. The estimates utilize the sample weights.
*** $p < 0.01$,.
** $p < 0.05$, * $p < 0.10$.

1st, 2017 through January 31st, 2018.[15] As a result, I utilize data on influenza vaccination for the two flu seasons prior to the survey year. I find suggestive evidence that DC's 2014 HPV vaccine school requirement increased the likelihood that teens received the flu vaccine by almost 6 percentage points (Panel E), though the change appears to have happened over time rather than immediately with the policy change (Panel F).

4.2. Vaccine initiation

In the prior section, I showed that DC's 2014 HPV vaccine school requirement led to a large increase in the probability that teens were fully vaccinated against HPV. I next explore whether the requirement increased the probability that teens received *any* shots of the vaccine. This measure is important because medical research indicates that even a single shot offers considerable protection from HPV (Kreimer et al., 2020). Consistent with the prior estimates, I show in Fig. 3 that the school requirement was associated with a 20-percentage point increase in the probability of vaccine initiation (Panel C). The point estimate is well outside of the placebo interval and over 2.4 times larger than the largest placebo estimate (0.20 vs. 0.08). Furthermore, I show that the probability of vaccine initiation was near zero and within the placebo distribution during the pre-period and that it jumped by nearly 20 percentage points in the post-period (Panel D).

In contrast to the relationship with HPV vaccine completion, I do detect a statistically significant sex-specific difference in vaccine initiation. In Fig. 4, I show that the 2014 policy change increased the likelihood teen girls received the first HPV shot by 11 percentage points (Panel C), while teen boys' vaccine initiation increased by 26 percentage points (Panel D). In Table A4, I use the triple-difference specification from Eq. (2) and confirm that these estimates are statistically different from each other.

These patterns suggest that the 2014 requirement induced teen boys to both initiate and complete the vaccination. Meanwhile, it induced a smaller number of teen girls to initiate the vaccine, while also encouraging girls who had previously initiated vaccination to complete the vaccine series. In support of this possibility, I show in Table 4 that the 2014 school requirement reduced the likelihood that a teen girl had initiated but not yet completed vaccination by 9 percentage points (column 3). In contrast, the point estimate for boys was smaller in magnitude, positive, and statistically insignificant (column 4). Additionally, I show that the 2014 requirement increased the probability that teen girls completed the series on time.[16]

The 2014 policy change expanded the requirement to include all teens grades 6–12 to increase vaccination among older teens. Consistent with this goal, in Table 5 I document a 7-percentage point larger increase in vaccine initiation for students in grades 9–12 (column 1). However, I do not detect a statistically significant difference for non-white teens relative to white teens (column 2). Nor do I detect a statistically significant difference in vaccine initiation by maternal education (column 3), despite having found a maternal education-specific difference in vaccine completion. However, while teens with more educated mothers had higher rates of vaccine completion in the pre-period relative to those with less educated mothers, they were similarly likely to initiate vaccination.

[15] Fewer than 5 percent of respondents are listed as being up to date for the 2017/18 flu season.
[16] I compare the age at which teens received the first shot to the age at which they received the final shot (the third shot prior to 2016 and the second shot thereafter). Because the shots are intended to be given within 6-12 months of each other, I consider a teen as having received the full dose in the appropriate time frame if the final shot was administered at the same age or within one year. Unfortunately, I do not have information on the exact date of administration. As an example, a teen receiving the first shot at 14 would need to have completed the vaccine by 15 to be classified as receiving it on time. Because the number of shots needed for complete vaccination was adjusted from 3 to 2 shots in November of 2016 (Meites, Kempe, and Markowitz 2016), in Table A5 I restrict the sample period to 2008-2016. The results are robust to this restriction.

Table 5
DC's 2014 HPV vaccine school requirement led to larger increases in vaccine initiation for older teens.

	(1) 9–12th Graders	(2) Non-White	(3) Mother Lacked a BA
DC's 2014 Mandate	0.144***	0.172***	0.181***
Placebo 95% Lower Bound	−0.099	−0.091	−0.071
Placebo 95% Upper Bound	0.109	0.092	0.077
DC's 2014 Mandate x Group	0.073**	0.005	0.034
Placebo 95% Lower Bound	−0.084	−0.140	−0.106
Placebo 95% Upper Bound	0.072	0.128	0.078
R2	0.233	0.236	0.234
Observations	200,894	200,894	200,894

Source: National Immunization Survey—Teen 2008–2018.
Note: The dependent variable is an indicator for whether the teen has received at least 1 shot of the HPV vaccine. The independent variables of interest are an indicator for Washington, DC's 2014 HPV vaccine school requirement and the interaction of that indicator with a group-specific characteristic using the triple-difference specification from Eq. (2). Column (1) interacts an indicator for being in grades 9–12 with the treatment indicator, the full set of controls, the state fixed effects, and the year fixed effects. Column (2) repeats this process but uses an indicator for being non-white, and column (3) an indicator for having a non-college educated mother. To perform inference, the 95 percent intervals are obtained by estimating placebo treatments for each of the other 48 states. The estimates utilize the sample weights.
*** $p < 0.01$,.
** $p < 0.05$, * $p < 0.10$.

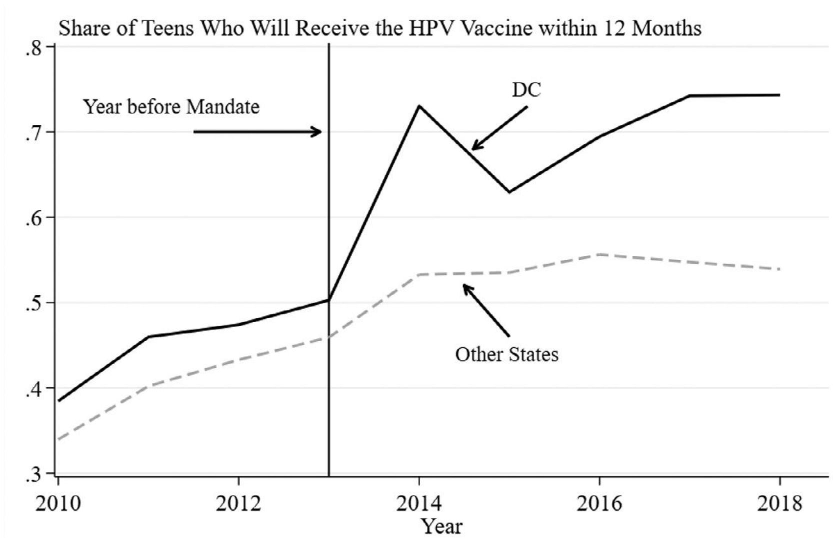

Fig. 6. The share of parents reporting an intent to vaccine their teen against HPV
Note: The figure plots the share of teens whose parents report that they will receive the HPV vaccine during the subsequent 12 months after the interview date in DC (solid black line) and the rest of the country (dashed gray line). The statistics were obtained by utilizing the sample weights.
Source: National Immunization Survey—Teen 2008–2018Source: National Immunization Survey—Teen 2008–2018

In fact, DC teens whose mothers had college degrees were *less* likely to initiate vaccination (34 percent vs. 36 percent), suggesting that the annual requirement may have helped remind less educated mothers that their teen needed to finish the series.

4.3. Vaccination intentions & physician recommendations

I next explore whether the 2014 HPV vaccine school requirement improved awareness about the HPV vaccine. First, I present descriptive statistics in Fig. 6 showing that parents were 23 percentage points more likely to report that they intended to have their child vaccinated within 12 months of the interview date after the policy change.[17] Using Eq. (1), I show in Table 6 that the 2014 requirement increased the probability that parents reported an intent to vaccinate by 17 percentage points (column 1).

Next, I show that the requirement led to a 9.2 percentage point increase in the likelihood that parents reported that their teen had been recommended the HPV vaccine by a health care provider (column 2). This suggests that some physicians would not recommend

[17] This question has only been asked since 2010.

Table 6
DC's HPV vaccine mandate increased physician vaccine recommendations.

	(1) Likely to Vaccinate within 12 Months	(2) HPV Vaccine Recommendation	(3) Parental-Reported HPV Vaccination
DC's 2014 Mandate	0.168***	0.092**	0.147***
Placebo 95% Lower Bound	−0.075	−0.053	−0.090
Placebo 95% Upper Bound	0.087	0.059	0.058
DC Mean Pre-Period	0.445	0.500	0.446
R^2	0.074	0.198	0.158
Observations	104,765	171,596	174,278

Source: National Immunization Survey—Teen 2008–2018.
Note: The dependent variable in column (1) is an indicator for whether the teen's parent reports that the teen is likely to be vaccinated within the next 12 months. The dependent variable in column (2) is an indicator for whether the teen has been recommended the HPV. In column (3), the dependent variable is an indicator for whether the teen's parent reports that s/he has been vaccinated against HPV. The sample period for column (2) is 2010–2018 because the question was not asked in prior years. The independent variable of interest is an indicator for Washington DC's 2014 HPV vaccine school mandate. To perform inference, the 95 percent confidence intervals are obtained by estimating placebo treatments for each of the other 48 states. Observations from Rhode Island and Virginia are excluded because they also implemented HPV vaccine school requirements. The estimates utilize the sample weights.
*** $p < 0.01$,.
** $p < 0.05$, * $p < 0.10$.

vaccination in absence of the school requirement. In a survey of physicians, Gilkey et al. (2015) found that 26 (39) percent of respondents reported that they did not deliver timely recommendations about the HPV vaccine to teen girls (boys), 27 percent did not strongly endorse HPV vaccination, and 32 percent reported that discussing sexually transmitted infections made conversations about the vaccine uncomfortable.[18]

Finally, I examine whether the 2014 requirement increased parental reported HPV vaccination. I show that parents were nearly 15 percentage points more likely to report that their child had received the HPV vaccine (column 3). While a sizable increase, it is smaller in magnitude than the increase using the provider-verified data. One explanation is that some parents have their child immunized for school without knowing what specific vaccines the child receives. Additionally, it is possible that parents are not always aware of what was discussed between the teen and the health care provider.

4.4. Robustness to synthetic control strategy

In this section, I test the robustness of my estimates to the synthetic control identification strategy proposed by Abadie and Gardeazabal (2003) and Abadie et al. (2010). Rather than use the rest of the US as a control group, I select a weighted combination of states which best matches DC's vaccination rate in the pre-period. In this case, every state contributes a positive weight to constructing "Synthetic DC," and I report the exact breakdown in Table A6. As shown in Fig. 7, Synthetic DC matches DC's HPV vaccination rate in the pre-period (Panel A). However, the two series diverge considerably in the post-requirement period. On average, there is a 20-percentage point difference between DC and Synthetic DC in the post-period.[19]

Next, I run the placebo tests proposed by Abadie et al. (2010) and plot the true effect, as well as the 48 placebo effects. Consistent with the results from the prior sections, I find that the estimated increase in HPV vaccination experienced by DC was larger than all the placebo treatment effects (Panel B). The corresponding p-values for each post-period are shown in Figure A4, and I reject the null hypothesis that the post-period estimates are jointly equal to zero ($p<0.01$). As such, both estimation strategies indicate that DC's HPV vaccine school requirement was associated with a large and statistically significant increase in vaccination.

5. Implied reductions in cancer and health care costs

To conceptualize the economic and public health benefits of the HPV vaccine school requirement, it is worth considering how many cases of cancer this policy change may have prevented. The American Cancer Society (2020a) indicates that the lifetime risk

[18] In Table A5, I examine the top 5 reasons given for why parents will not have the child vaccinated against HPV in the subsequent 12 months. The point estimate suggests that parents opting not to vaccinate were 3 percentage points more likely to state that they did not believe that the HPV vaccine was needed (column 1), though the estimate is statistically insignificant. At the same time, these parents were 11 percentage points less likely to cite safety concerns about the vaccine as their reason for not vaccinating (column 3). Similarly, the point estimates indicate reductions in the probabilities of attributing the decision to a lack of knowledge about the vaccine (column 4), as well as a lack of recommendation (column 5). Overall, Table A5 suggests that the HPV vaccine school requirement changed the composition of parents opting to leave the child unvaccinated. These parents were more likely to believe that the vaccine was not needed. This suggests that the parents bound by the school requirement were those who had previously had safety concerns or been unaware of the vaccine.

[19] The pre-period root mean squared prediction error—the metric used to judge the quality of the match—is 0.73. I report the exact post-period coefficients in Table A7. I show in Table A8 that the results are robust to constructing the synthetic control by matching on lagged values from years 2008, 2010, and 2012. In Table A9, I show that the results are robust to matching on the average vaccination rate between 2008 and 2013.

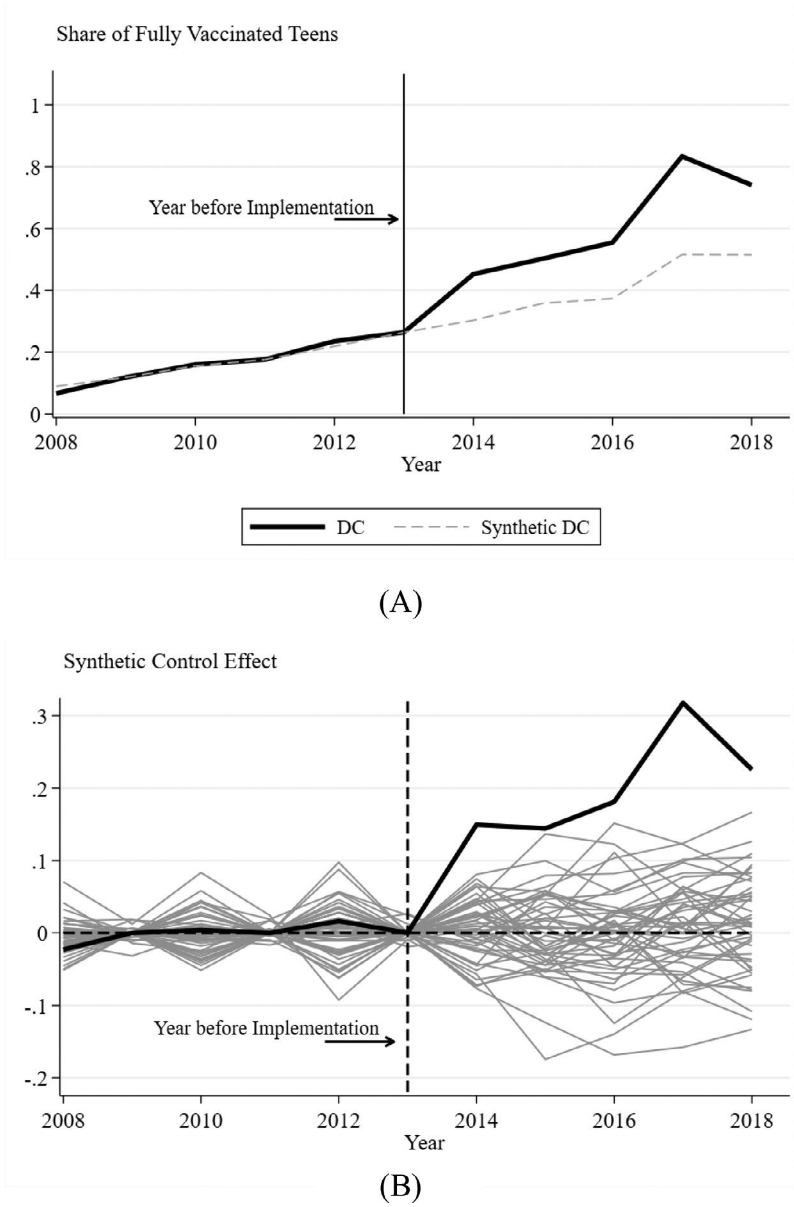

Fig. 7. HPV vaccination increased more in DC than Synthetic DC
Note: The dependent variable is an indicator for having received the full dose of the HPV vaccine (3 shots until 2016 and only 2 shots thereafter). In Panel (A) the thicker dark line indicates the growth in HPV coverage for Washington, DC over the period, while the dashed grey line indicates the counterfactual growth for "synthetic Washington, DC" in absence of the 2014 HPV vaccine school requirement. Synthetic DC is obtained by matching on three lagged values of the dependent variable in the pre-requirement period (2009, 2011, and 2013). The states which contribute to "Synthetic Washington, DC are reported in Table A6, and the exact coefficients for the pre- and post-periods are reported in Table A7. In Panel (B) the thicker dark line is the effect, while the lighter gray lines are placebo effects obtained from repeating this process for the 50 donor states. The shares were obtained utilizing the sample weights.
Source: National Immunization Survey—Teen 2008-2018Source: National Immunization Survey—Teen 2008-2018

of developing cervical cancer is 0.63 percent, and the CDC (2020b) estimates that HPV may be responsible for more than 90 percent of these cancers.[20] The average age of cervical cancer diagnosis is 50 (ACS, 2020b), the initial cost of cervical cancer care is $45,174 (Mariotto et al., 2011), cervical cancer has a 5-year survival rate of 66 percent (ACS, 2020c), and the average cervical cancer death results in 26.1 lost life years (NCI, 2020b).[21] Finally, the Department of Health and Human Services estimates the value of a statistical life year (in 2018 dollars) as falling between $244,000 and $1.3 million depending on the choice of discount rate and the baseline value of a statistical life (Aldy and Viscusi, 2008; US Department of Health and Human Services, 2016; Kniesner and Viscusi, 2019).

The above figures are combined in Eq. (5) to estimate the present value of a prevented cervical cancer. Assuming that girls are vaccinated at 11, the initial cost of cervical cancer care should be discounted by 39 years (50 – 11 = 39). In the second part of the expression, I account for the fact that 44 percent of women die within 5 years after initial diagnosis and that these women lose on average 26 years of life. I use the minimum value of a statistical life year from the DHHS FDA official guidance of $244,000.

$$\text{Prevented Cervical Cancer} = \left(\frac{1}{1+r}\right)^{39} \times \$45,174 + 0.44 \times \$244,000 \times 26 \tag{5}$$

Of course, the HPV vaccine protects against more than just cervical cancer, and approximately 70 percent of oropharyngeal cancers may be linked to HPV. According to the ACS (2020a), the lifetime risk of oropharyngeal cancer is 1.66 percent for men and 0.71 percent for women. The average age of oropharyngeal cancer diagnosis is 62 (ACS, 2021a), the initial cost of care is $39,179 (Mariotto et al., 2011), and the average oropharyngeal death results in 16.9 lost life years (NCI, 2020b). The 5-year survival rate varies from 52 percent (floor of mouth) to 90 percent (lip), and I use the largest survival rate to provide a conservative estimate (ACS, 2021b).

In Eq. (6), I estimate the present value of a prevented oropharyngeal cancer. I discount the initial cost of care by 51 years assuming vaccination at 11 (62–11=51).[22] In the second term, I assume the smallest mortality rate from oropharyngeal cancer (10 percent), again use the minimum value of a statistical life year as recommended by the DHHS official guidance, and account for the 16 lost years.

$$\text{Prevented Oropharyngeal Cancer} = \left(\frac{1}{1+r}\right)^{51} \times \$39,179 + 0.10 \times \$244,000 \times 16 \tag{6}$$

Using a discount rate of 3 percent (Viscusi and Hersch, 2008), I estimate $2.8 million in savings for each cervical cancer prevented and over $400,000 for each oropharyngeal cancer prevented. In 2018, there were 33,614 students enrolled in public or public charter schools in Washington, DC (DC Office of the State Superintendent of Education, 2018). My estimates indicate that the 2014 HPV vaccine school requirement induced 4336 boys ($33,614 \times 0.5 \times 0.258$) and 1831 girls ($33,614 \times 0.5 \times 0.109$) to initiate vaccination. Sonawane et al. (2019) found that the predicted probability of HPV infection was 7.4 percent for unvaccinated women and 2.3 percent for those receiving one dose of the HPV vaccine, implying a vaccine efficacy (CDC, 2012) of 69 percent ((0.074–0.023)/0.074).

Now, I multiply the number of newly vaccinated students by the lifetime risk of acquiring an HPV-related cancer, times the share of those cancers attributable to HPV, times the vaccine efficacy, to obtain the number of cancers prevented. I estimate 7 fewer cases of cervical cancer ($1,831 \times 0.0063 \times 0.90 \times 0.69$) and 41 fewer cases of oropharyngeal cancer ($1,831 \times 0.0071 \times 0.70 \times 0.69 + 4,336 \times 0.0166 \times 0.7 \times 0.69$) for those 33,614 students enrolled during the 2017/18 academic year. Using the discounted values from above, this amounts to approximately $36 million in savings. With the HPV vaccine costing approximately $250 per shot (CVS 2020), my estimates imply it cost slightly more than $1.5 million to vaccinate those 6167 teens. Therefore, the mandate appears cost effective.[23]

While I estimate that DC's 2014 HPV vaccine requirement passes a cost-benefit analysis, there are many reasons to believe that I am *underestimating* the benefits of the mandate. For one, I only account for cervical and oropharyngeal cancer, while the HPV vaccine also protects against cancers of the anus, penis, vulva, and vagina. Additionally, I only account for the initial cost of cancer care and the value of lives lost. I do not account for follow up care for those who do not die. Finally, I only account for the direct benefits to the vaccinated teen, though immunization also helps protect the vaccinated teen's subsequent sexual partners.

While important for policymakers, generalizing these estimates to the US as a whole requires caution. For one, the HPV vaccine initiation rate in the US in 2018 was higher than Washington, DC's initiation rate immediately prior to the policy change (68 percent vs. 62 percent). Moreover, vaccine initiation rates between girls and boys have converged. In 2018, 70 percent of girls and 67 percent

[20] Non-white women experience a higher incidence of cervical cancer relative to white women, and DC is comprised primarily of non-white women. I show in Figure A5 that DC's age-adjusted cervical cancer rate was consistently higher than the US average from 1999-2016, though the gap has been shrinking over time. Indeed, the original 2009 HPV vaccine requirement was implemented as part of the "Human Papillomavirus and Reporting Act of 2007," which also called on the Mayor to "initiate a public information campaign…aimed at educating the public on: (1) The connection between HPV and cervical cancer; (2) The importance of protecting oneself against HPV infection; (3) The value of screening for cervical cancer through regular pap tests; and (4) The effectiveness and risks of the HPV vaccine." By using the nationwide average lifetime risk of developing cervical cancer, instead of the higher DC-specific risk, I will underestimate the number of cancers prevented and the potential cost savings.

[21] The initial cost of care is estimated to be $45,174 for women over 65 and $54,209 for those under 65. Similarly, the estimated cost of oropharyngeal cancer is $41,980 ($39,179) for women (men) over 65 and $50,376 ($47,015) for women (men) under 65 (Mariotto et al. 2011). To be conservative, I always use the smallest number.

[22] By assuming that adolescents are all vaccinated at 11, I am maximizing the length of time between vaccination and what would otherwise be a cancer diagnosis. It is possible that some teens are vaccinated at later years, which would lead to less discounting. Thus, I choose 11 to increase discounting and provide a conservative estimate.

[23] Importantly, if I do not account for the value of lives lost and focus solely on the initial cost of cancer care, I still estimate $455,591 in health care savings.

of boys had received at least one shot of the HPV vaccine. As a result, school requirements may no longer induce larger increases in take-up for teen boys than teen girls. Yet even subject to these caveats, considering how these estimates could generalize is a useful exercise. There are 30 million 6–12th grade students in the US (National Center for Education Statistics, 2018). Applying my most conservative estimated increase in vaccine initiation (10.9 percentage points) still yields 3.27 million more vaccinated students and—failing to account for any form of herd immunity—almost 6400 fewer cases of cervical cancer. Every year, there are 13,800 new diagnosed cases of cervical cancer (American Cancer Society, 2020b), so even an increase in HPV vaccine take-up half the size experienced by Washington, DC would provide dramatic public health benefits.

6. Discussion

Throughout this paper, I have shown that Washington, DC's 2014 HPV vaccine school requirement increased the probability that a teen was vaccinated against HPV by nearly 20 percentage points. Only 28 percent of DC teens had completed the HPV vaccine in 2013, so the estimated effect is large in both absolute magnitude and as a percentage change from the pre-period level. Using an event study specification, I show that this increase was not due to pre-existing trends in the probability of vaccination, and a series of permutation placebo tests show that these increases were far larger than one would expect to obtain by chance. A synthetic control framework also supports these conclusions.

During my 2008–2018 sample period, DC's demographic composition changed considerably. The share of non-white teens fell by 10 percentage points, while the share of teens with college educated mothers rose by 12 percentage points. Critically, though, I show that my estimates do not depend on race and are in fact larger for teens whose mothers lacked college degrees. As such, it does not appear the relationship was driven by an influx of teens who were more likely to be vaccinated. I also show that while teen girls and boys experienced similar increases in the probability of vaccine completion, the point estimate for HPV vaccine initiation was larger for boys than girls. This pattern suggests that the school requirement induced some teen girls who had previously initiated vaccination to finish the vaccine series, and I show that the 2014 requirement increased the likelihood that teen girls initiating vaccination completed the series within the recommended time frame.

Overall, my results indicate that how school vaccine requirements are implemented can be as important as the mandate itself. Except for those girls entering sixth grade in 2014, all of the girls in my sample were already bound by the 2009 HPV vaccine requirement. As such, the 2014 requirement's saliency should have been limited; these girls were already supposed to be vaccinated. However, expanding the requirement to older teen girls and requiring an annual opt-out offered public health officials another chance to encourage vaccination. Because I find that the annual requirement resulted in a 11-percentage point increase in HPV vaccine initiation, it is possible that parents who were uncomfortable vaccinating their middle school daughters against an STI were more comfortable once the girls had entered high school. In estimating the future reduction in cancer incidence, my estimates imply nearly $36 million in benefits compared to the $1.5 million it cost to vaccinate these teens, indicating that the mandate was cost effective.

Of course, this study is not without limitations. For one, conclusions drawn from DC may not easily generalize to the rest of the country. Nearly 80 percent of DC teens are non-white, the entire city spans less than 70 square miles, and DC has a centralized Department of Public Health and State Board of Education. However, it is worth noting that all 50 states require at least some vaccinations for school entry (Schwartz and Easterling, 2015), indicating that the logistical hurdles of an HPV vaccine school requirement are hardly insurmountable.

An additional concern common to all single-state policy evaluations is the possibility that my estimates are driven by an unaccounted-for variable which changed concurrently with the school requirement, though I have controlled for several known policies known to affect vaccine take-up. Moreover, I have not examined potential moral hazard associated with receiving the HPV vaccine, such as changes in risky sexual behaviors or preventative cancer screenings later in life. As more states enact HPV vaccine requirements, it will be important to confirm my estimates in alternative settings and to quantify potential downstream effects. Finally, because the gains from HPV vaccination may not be realized for several decades, I am unable to directly study the relationship between the school vaccine requirement and morbidity. Developing strategies to identify this latter relationship remains an important area for future research.

Declaration of Competing Interest

None.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jhealeco.2021.102480.

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