Note

Ion Pair-Directed Borylation of Aromatic Phosphonium Salts

Bernadette Lee, Madalina T. Mihai, Violeta Stojalnikova, and Robert J Phipps

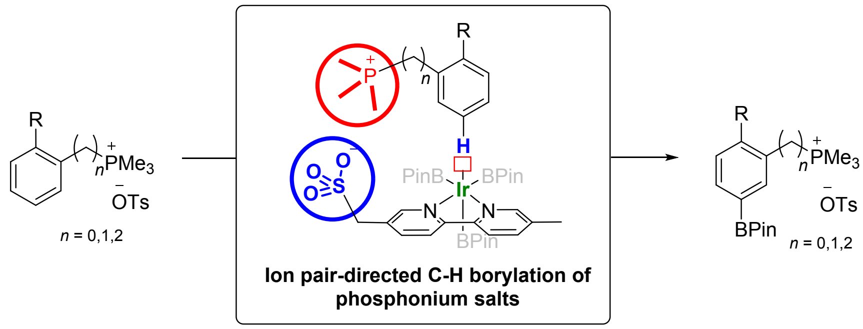
J. Org. Chem., **Just Accepted Manuscript** • Publication Date (Web): 22 May 2019

Ion Pair-Directed Borylation of Aromatic Phosphonium Salts

Bernadette Lee, Madalina T. Mihai, Violeta Stojalnikova and Robert J. Phipps*

Department of Chemistry, University of Cambridge, Lensfield Road, Cambridge, CB2 1EW, UK.

Supporting Information Placeholder



ABSTRACT: Control of positional selectivity in C-H activation reactions remains a challenge for synthetic chemists. Non-covalent catalysis has the potential to be a powerful strategy to address this challenge. As part of our ongoing investigations into the use of ion-pairing interactions in site-selective catalysis, we demonstrate that several classes of aromatic phosphonium salts undergo iridium-catalyzed C-H borylation with high selectivity for the arene *meta* position. This is achieved using a bifunctional bipyridine ligand bearing a pendant sulfonate group which had previously been successful for borylation of aromatic ammonium salts. In this case, the phosphonium salts give higher meta-selectivity than the corresponding ammonium salts. We propose that the high selectivity occurs due to an attractive electrostatic interaction between substrate and ligand in the transition state for borylation.

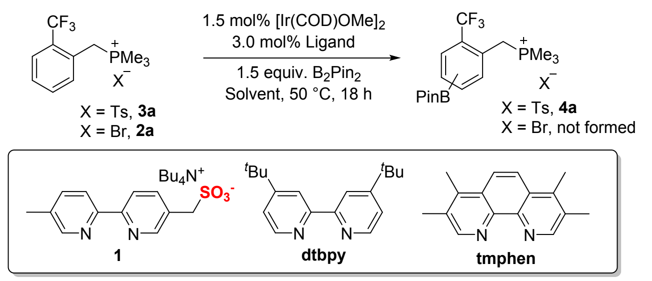
The direct functionalization of arene C-H bonds using transition metal catalysis constitutes a highly effective method for elaboration of aromatic compounds. Numerous advances have been made, particularly over the last two decades. It is notable however that the majority of these advances result in selective reaction at the arene *ortho* position, as a consequence of proximity to a directing group. Strategies that are able to reach further to the more remote *meta* and *para* positions are less common and as a consequence these positions are typically more difficult to access.[1]

We and others have recently been exploring strategies which exploit a temporary non-covalent interaction between substrate and ligand to guide the reactive transition metal to a particular position in the selectivity-determining transition state for C-H bond functionalization.[2,] This approach builds on previous advances for controlling regioselectivity in reactions including aliphatic C-H activation,[3] hydroformylation[4] and others. We have been particularly interested in applying this idea to control regioselectivity in arene C-H functionalization via C-H borylation, which has been investigated by a number of groups.[5,6,7] Specifically, we were curious to explore a scenario in which the catalyst engages in ion-pairing interactions with the substrate, as this is far rarer than using hydrogen bonding and relatively unexplored.[8] In our previous work, we developed an anionic bipyridine ligand (**1**) for application in iridium-catalyzed C-H borylation. [9] This ligand bears a pendant sulfonate group which we hypothesized may engage in attractive electrostatic interactions with a quaternary ammonium moiety in the substrate, directing C-H borylation to occur at the arene *meta* position. Gratifyingly, high *meta*-selectivity was obtained with a variety of chain lengths between the quaternary ammonium group and the arene, despite initial concerns that substantial substrate flexibility may be incompatible with the relatively low directionality of ion-pairing interactions. However, in these studies we only examined quaternary ammonium salts as cationic groups on the substrates.

Phosphonium salts have number of important chemical applications, including as phase transfer catalysts, ionic liquids, and lipophilic cations. They can be transformed into reactive intermediates upon deprotonation to form ylides, as widely used in the Wittig reaction and variants.[10,11] Several recent studies have shown that certain phosphonium salts can also be used in cross coupling reactions.[12] Hence, we were keen to explore whether our ion-pair directed method for controlling regioselectivity in C-H borylation would be compatible with arenes bearing a phosphonium group, in order to demonstrate greater generality of the approach.

We began our studies with trifluoromethyl-substituted benzyl trimethyl phosphonium salt **3a**, possessing a tosylate counterion (Table 1). An initial evaluation with standard borylation ligand **dtbpy** gave no conversion in THF at 50 ^{o}C (entry 1), but we found that switching to a more reactive **tmphen** ligand gave high conversion to a mixture of *meta* and *para* isomers with poor selectivity, as expected (entry 2). We were happy to see that using our sulfonate ligand **1** in place of **tmphen**, good conversion was obtained with 7:1 *meta*:*para* selectivity, in line with our hypothesis (entry 3). Under the same conditions, the same phosphonium cation but bearing bromide as the counteranion (**2a**) gave no conversion, presumably due to the very poor solubility of the starting material (entry 4), hence we continued optimization using **3a**. An evaluation of solvents revealed that in 1,4-dioxane the *meta* selectivity was greatly improved (>20:1) and with full conversion (entry 5). Selectivity was reasonably tolerant to solvent variation (entries 6-8) although non-polar solvents were not suitable, likely due to solubility issues (entry 9). A control borylation of **3a** in dioxane with **tmphen** revealed a slight bias towards *para* selectivity, highlighting the dramatic effect that our anionic ligand **1** has on this substrate's intrinsic selectivity towards C-H borylation (entry 10).

Table 1. Evaluation of ligand 1 on benzylphosphonium salt 3a.

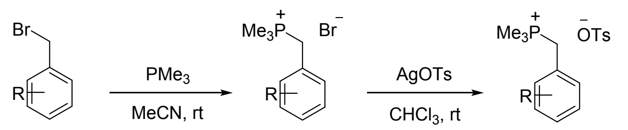


Entry	X	Ligand	Solvent	meta: para[a]	% Conv.[b]
1	OTs	dtbpy	THF	--	0
2	OTs	tmphen	THF	1 : 1.3	91
3	OTs	1	THF	7 : 1	93
4	Br	1	THF	--	0
5	OTs	1	Dioxane	>20 : 1	100
6	OTs	1	CH_2Cl_2	>20 : 1	77
7	OTs	1	CH_3CN	12 : 1	92
8	OTs	1	MTBE	7 : 1	32
9	OTs	1	Cyclohexane	--	0
10	OTs	tmphen	Dioxane	1 : 1.6	100

[a] *Meta*:*para* ratios are taken from analysis of crude ^{1}H NMR spectra. [b] Determined by ^{1}H NMR with reference to 1,2-dimethoxyethane internal standard.

With optimal conditions in hand, we proceeded to evaluate the scope of the transformation. The substrates could be synthesized very readily from substituted benzyl bromides by benzylation of trimethylphosphine, followed by anion exchange with silver tosylate, both steps proceeding with generally high yields (Scheme 1). Whilst the use of silver is not ideal from a cost standpoint, it is also possible to access these tosylate salts from benyl tosylates (see Scheme 3).

Scheme 1. Synthesis of benzyl phosphonium salts 2 and 3



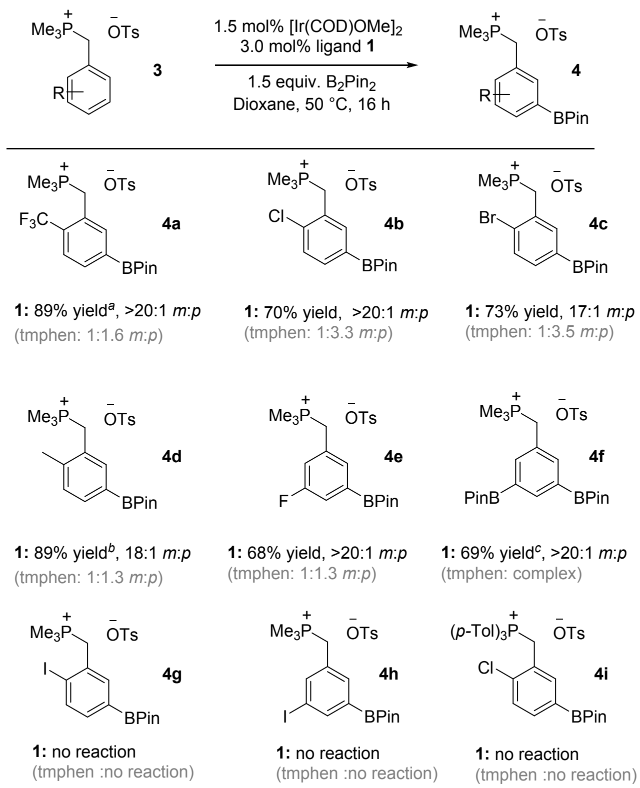
R	% Yield
2-CF_3 (**2a**)	96
2-Cl (**2b**)	84
2-Br (**2c**)	76
2-Me (**2d**)	77
3-F (**2e**)[a]	84
H (**2f**)	96
2-I (**2g**)	58
3-I (**2h**)	97

R	% Yield
2-CF_3 (**3a**)	96
2-Cl (**3b**)	96
2-Br (**3c**)	93
2-Me (**3d**)	81
3-F (**3e**)	73
H (**3f**)	98
2-I (**3g**)	95
3-I (**3h**)	90

[a] Prepared as the chloride rather than bromide salt

We first examined the 2-chloro substituted salt and found that this also gave high *meta* selectivity using ligand **1** (Scheme 2, **4b**). Similarly to the CF_3-substituted substrate, the use of **tmphen** gave some bias towards *para* selectivity, in this case 3.3:1 *para*:*meta* (see values in parenthesis). A bromo-substituted variant also worked very well, giving 17:1 *m*:*p* selectivity (**4c**). In the case of the electron donating methyl substituent, a higher catalyst loading of 6 mol% Ir was required for good conversion, and this substrate too gave high selectivity (**4d**). The small size of fluorine resulted in substrate **4e** giving a mixture of isomers under borylation with **tmphen**, but with ligand **1**, only the *meta*-borylated isomer was observed (>20:1). Finally, an unsubstituted benzylphosphonium salt also performed well (**4f**). In this case, it was not possible to stop at mono borylation and so three equivalents of B_2Pin_2 were used to obtain the di-*meta*borylated product in good yield. The iodo-substituted phosphonium salts **3g** and **3h** unfortunately were found to give no conversion either with **tmphen** or ligand **1**. Interestingly, the triarylbenzylphosphonium salt **3i** was also found to give no reaction with either ligand. It should be mentioned that in many cases small amounts of starting material were still present at the end of the reaction and these were impossible to separate from the borylated products as the salts were not purifiable on silica and had to be precipitated. The yields quoted have been adjusted to reflect this based on the molar mass of starting material (see Experimental section).

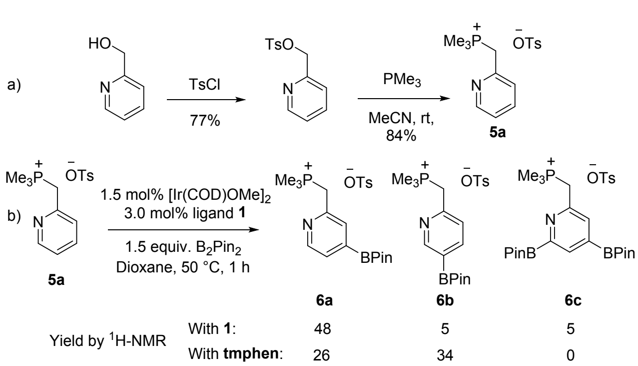
Scheme 2. Scope of substituents on benzylphosphonium salts 3



[a] ^{1}H NMR yield with reference to an internal standard quoted due to decomposition during purification. [b] Double catalyst loadings used, reaction at 70 °C. [c] 3 eq. B$_2$Pin$_2$ used.

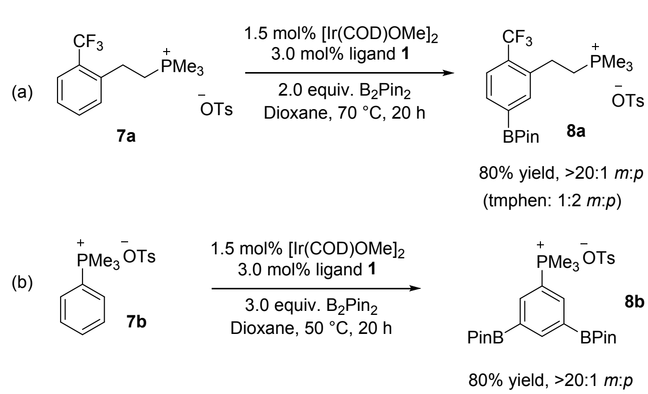
Borylation of a pyridine-derived phosphonium salt was next examined to evaluate whether selectivity between the 4- and 5-positions could be obtained. In this case, the counterion exchange according to the previous substrate synthesis using silver failed in the presence of the basic pyridine. So an alternative approach was taken via the intermediate tosylate, which allows substrates to be accessed from benzyl alcohols. This approach can be advantageous for some substrates as it installs tosylate directly as the counteranion (Scheme 3, a). For the pyridine substrate **5a**, it was quite challenging to prevent over borylation to **6c**, but by stopping the reaction after 1 h, useful amounts of **6a**, the product of borylation at C4, could be obtained and the C4:C5 ratio was 10:1 (corresponding to the *m*:*p* ratio in non-heteroarenes). In contrast, with **tmphen** the C4:C5 ratio was ~1:1 (Scheme 3, b).

Scheme 3. Synthesis and borylation of pyridylphosphonium salt 5a



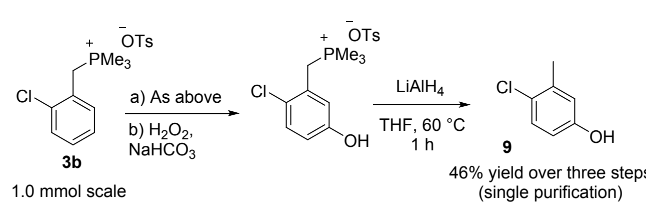
We next sought to vary the carbon chain of the phosphonium salt to evaluate whether selectivity would be maintained if it is either extended or reduced. We were pleased to find that trifluoromethyl-substituted phenethyl phosphonium salt **7a** gave >20:1 m:p selectivity in good yield (Scheme 4a). In contrast, control borylation of this substrate with **tmphen** as ligand gave 1:2 *m*:*p*. Whilst we did explore substituents apart from CF_3 in this class, we found that less electron-withdrawing substituents typically gave only moderate conversions and so these were not further pursued due to the challenges of separating product from unreacted starting material (*vide supra*). Phenyltrimethyl phosphonium tosylate (**7b**) gave excellent *meta*-selectivity, resulting in di*meta* borylated product **8b** (Scheme 4b). These results provide encouragement that phosphonium salts are likely to be tolerant of a range of chain lengths, as we had previously seen with the corresponding ammonium salts which gave meta-selectivity with both 2- and 3- carbon linker lengths.[9]

Scheme 4. Borylation of longer chain phosphonium salt 7a and phenyltrimethyl phosphonium tosylate (7b)



Finally, we demonstrate the *meta*-selective borylation of **3b** on 1.0 mmol scale and telescope this with conversion of the BPin to a hydroxyl group followed be reduction of the phosphonium functionality with lithium aluminium hydride (Scheme 5).[13] This example of further elaboration highlights the potential of our method for the rapid access to complex arene building blocks.

Scheme 5. Larger scale reaction and elaboration of product



In summary, we have demonstrated that aromatic phosphonium salts are compatible with our previously reported sulfonate ligand **1** to enable C-H borylation to be directed to the arene *meta* position. The selectivities are in general very high and we envisage that this study provides further evidence of the utility of ion pairing interactions in the design of new catalyst scaffolds for site-selective functionalization.

EXPERIMENTAL SECTION

Materials and Methods. All reagents, unless otherwise stated, were used as supplied from commercial sources without further purification. CH_2Cl_2, THF and Et_2O were purified by distillation on site under inert atmosphere via the following processes: THF and Et_2O were pre-dried over sodium wire then distilled from calcium hydride and lithium aluminium hydride. CH_2Cl_2 and *n*-hexane were distilled from calcium hydride.

^{1}H NMR spectra were recorded on a 600 MHz Bruker Avance DRX-600 spectrometer, 500 MHz Bruker DCH Cryoprobe or 400 MHz QNP Cryoprobe. Chemical shifts are reported in parts per million (ppm) and the spectra are calibrated to the resonance resulting from incomplete deuteration of the solvent ($CDCl_3$: 7.26 ppm, CD_3OD: 3.31 ppm, $(CD_3)_2SO$: 2.50 ppm). ^{13}C NMR spectra were recorded on the same spectrometers with complete proton decoupling. Chemical shifts are reported in ppm with the solvent resonance as the internal standard ($^{13}CDCl_3$: 77.16 ppm, t; $^{13}CD_3OD$: 49.00 ppm, sept; DMSO-d_6: 39.51 ppm, s). Data are reported as follows: chemical shift δ/ppm, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, br = broad, m = multiplet or combinations thereof; ^{13}C signals are singlets unless otherwise stated), coupling constants *J* in Hz, integration (1H only). ^{1}H-COSY, HSQC, HMBC and NOESY were used where appropriate to facilitate structural determination. The carbon attached to boron was generally not observed by ^{13}C spectroscopy due to quadrupolar relaxation. ^{1}H NMR signals are reported to 2 decimal places and ^{13}C signals to 1 decimal place (2 decimals places if the peaks are not distinguishable with only 1 decimal place). ^{19}F NMR spectra were recorded on a 400 MHz Bruker Avance III HD Spectrometer, and ^{19}F signals are reported to 2 decimal places. ^{31}P NMR spectra were recorded on a 600 MHz Bruker Avance DRX-600 spectrometer or a 400 MHz Bruker Avance III HD Spectrometer, and ^{31}P signals are reported to 2 decimal places.

High Resolution Mass Spectra (HRMS) were recorded on a Waters Micromass LCT Premier TOF spectrometer using a positive electrospray ionization (ESI+). Measured values are reported to 4 decimal places are within ±5 ppm of the calculated value. The calculated values are based on the most abundant isotope.

Infrared (IR) spectroscopy was performed using a Perkin Elmer Spectrum One FT infra-red spectrophotometer sampling accessory, scanning from 4000–600 cm^{-1}. IR absorption maxima (ν_{max}) are reported in wavenumbers (cm^{-1}).

General procedure for the synthesis of phosphonium 4-methylbenzenesulfonates (GP1). The corresponding phosphonium bromide (or chloride) salt and silver *p*-toluenesulfonate (1.1 eq.) were dissolved in $CHCl_3$. The reaction mixture was stirred at room temperature for 30 min, then filtered through $MgSO_4$. The filtrate was collected, and the solvent was removed under reduced pressure to afford the product.

Trimethyl(2-(trifluoromethyl)benzyl)phosphonium bromide (**2a**):

To a solution of 2-(trifluoromethyl)benzyl bromide (1.25 g, 5.2 mmol) in acetonitrile (10 ml) was added a 1.0 M solution of trimethylphosphine in toluene (5.8 ml, 5.8 mmol, 1.1 eq.). The reaction mixture was stirred at room temperature for 1 h under an argon atmosphere. The solvent was then removed under reduced pressure, and the salt precipitated with $CHCl_3$ and Et_2O (approximately 1:10 ratio of $CHCl_3$:Et_2O). The salt was collected by filtration, washed with Et_2O and dried *in vacuo* to yield the title compound as a white powder (1.58 g, 5.0 mmol, 96%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.85 (dd, *J* = 7.7, 2.2 Hz, 1H), 7.72 (d, *J* = 7.9 Hz, 1H), 7.64 (t, *J* = 7.6 Hz, 1H), 7.49 (t, *J* = 7.7 Hz, 1H), 4.37 (d, *J* = 16.7 Hz, 2H), 2.24 (d, *J* = 14.2 Hz, 9H); ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 133.0 (d, $^3J_{C–P}$ = 4.7 Hz), 128.9 (d, $^5J_{C–P}$ = 3.8 Hz), 128.8 (qd, $^2J_{C–F}$ = 29.8 Hz, $^3J_{C–P}$ = 5.7 Hz), 127.3–127.1 (m), 126.9 (dq, $^3J_{C–F}$ = 1.6 Hz, $^2J_{C–P}$ = 9.0 Hz), 123.9 (qd, $^1J_{C–F}$ = 273.8 Hz, $^4J_{C–P}$ = 1.5 Hz), 27.9 (d, $^1J_{C–P}$ = 51.1 Hz), 9.2 (d, $^1J_{C–P}$ = 54.3 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −58.81; ^{31}P NMR (243 MHz, $CDCl_3$) δ 28.29. HRMS *m/z* (ESI+) [M – Br]$^+$ calculated for $[C_{11}H_{15}F_3P]^+$ 235.0858, found 235.0849;

Trimethyl(2-(trifluoromethyl)benzyl)phosphonium 4-methylbenzenesulfonate (**3a**):

Followed **GP1**, used trimethyl(2-(trifluoromethyl)benzyl)phosphonium bromide (0.53 g, 1.7 mmol), silver p-toluenesulfonate (0.53 g, 1.9 mmol, 1.1 eq.) and chloroform (5 ml). The title compound was obtained as a white solid (0.66 g, 1.6 mmol, 96%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.73 (d, J = 8.2 Hz, 2H), 7.69 (d, J = 7.9 Hz, 1H), 7.66 (d, J = 7.7 Hz, 1H), 7.54 (t, J = 7.5 Hz, 1H), 7.44 (t, J = 7.4 Hz, 1H), 7.12 (d, J = 7.9 Hz, 2H), 4.06 (d, J = 16.8 Hz, 2H), 2.31 (s, 3H), 2.08 (d, J = 14.4 Hz, 9H); ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 143.6, 139.4, 133.2 (d, $^3J_{C–P}$ = 4.8 Hz), 133.0 (d, $^4J_{C–P}$ = 2.3 Hz), 128.9 (qd, $^2J_{C–F}$ = 30.2 Hz, $^3J_{C–P}$ = 5.7 Hz), 128.72, 128.65 (d, $^5J_{C–P}$ = 3.5 Hz), 127.3 (qd, $^3J_{C–F}$ = 1.7 Hz, $^2J_{C–P}$ = 8.7 Hz), 127.1 (m), 125.8, 124.0 (qd, $^1J_{C–F}$ = 273.3 Hz, $^4J_{C–P}$ = 1.6 Hz), 27.7 (d, $^1J_{C–P}$ = 50.3 Hz), 21.3, 8.4 (d, $^1J_{C–P}$ = 54.1 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −58.86; ^{31}P NMR (243 MHz, $CDCl_3$) δ 29.07; HRMS m/z (ESI+) [M – OTs]$^+$ calculated for $[C_{11}H_{15}F_3P]^+$ 235.0858, found 235.0853;

(2-Chlorobenzyl)trimethylphosphonium bromide (**2b**):

To a solution of 2-chlorobenzyl bromide (0.65 ml, 5 mmol) in acetonitrile (10 ml) was added a 1.0 M solution of trimethylphosphine in THF (5.5 ml, 5.5 mmol, 1.1 eq.) dropwise. The reaction mixture was stirred at room temperature for 1 h under an argon atmosphere. The solvent was then removed, and the salt precipitated with Et_2O. The salt was collected by filtration, washed with Et_2O and dried in vacuo to yield the title compound as a white powder (1.18 g, 4.2 mmol, 84%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.74–7.72 (m, 1H), 7.40–7.39 (m, 1H), 7.26-7.29 (m, 2H), 4.32 (d, J = 16.2 Hz, 2H), 2.21 (d, J = 14.2 Hz, 9H); ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 133.9 (d, $^3J_{C–P}$ = 6.2 Hz), 132.7 (d, $^3J_{C–P}$ = 5.0 Hz), 130.3 (d, $^5J_{C–P}$ = 3.3 Hz), 130.1 (d, $^4J_{C–P}$ = 3.9 Hz), 128.0 (d, $^4J_{C–P}$ = 3.5 Hz), 126.9 (d, $^2J_{C–P}$ = 9.3 Hz), 28.1 (d, $^1J_{C–P}$ = 50.1 Hz), 9.1 (d, $^1J_{C–P}$ = 54.0 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 28.82. HRMS m/z (ESI+) [M – Br]$^+$ calculated for $[C_{10}H_{15}ClP]^+$ 201.0594, found 201.0587.

(2-Chlorobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3b**):

Followed GP1, used (2-chlorobenzyl)trimethylphosphonium bromide (0.56 g, 2 mmol), silver *p*-toluenesulfonate (0.61 g, 2.2 mmol, 1.1 eq.) and chloroform (5 ml). The title compound was obtained as a white solid (0.72 g, 1.9 mmol, 96%). ^{1}H NMR

(600 MHz, $CDCl_3$) δ 7.75 (d, J = 8.2 Hz, 2H), 7.54–7.52 (m, 1H), 7.39 (d, J = 7.4 Hz, 1H), 7.28–7.22 (m, 2H), 7.14 (d, J = 7.9 Hz, 2H), 4.04 (d, J = 16.4 Hz, 2H), 2.32 (s, 3H), 2.08 (d, J = 14.4 Hz, 9H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 143.6, 139.5, 133.8 (d, $^{3}J_{C-P}$ = 6.1 Hz), 132.8 (d, $^{3}J_{C-P}$ = 4.9 Hz), 130.2 (d, $^{5}J_{C-P}$ = 3.3 Hz), 129.9 (d, $^{4}J_{C-P}$ = 3.9 Hz), 128.8, 128.0 (d, $^{4}J_{C-P}$ = 3.5 Hz), 127.3 (d, $^{2}J_{C-P}$ = 9.3 Hz), 125.8, 27.8 (d, $^{1}J_{C-P}$ = 49.8 Hz), 21.3, 8.2 (d, $^{1}J_{C-P}$ = 53.8 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 29.51; HRMS m/z (ESI+) $[M – OTs]^+$ calculated for $[C_{10}H_{15}ClP]^+$ 201.0594, found 201.0596;

(2-Bromobenzyl)trimethylphosphonium bromide (**2c**):

To a solution of 2-bromobenzyl bromide (1.25 g, 5 mmol) in acetonitrile (10 ml) was added a 1.0 M solution of trimethylphosphine in THF (5.5 ml, 5.5 mmol, 1.1 eq.) dropwise. The reaction mixture was stirred at room temperature for 15 min under an argon atmosphere, with the product being observed to precipitate from solution. The reaction mixture was then filtered, and the solids washed with Et_2O then dried *in vacuo* to yield the title compound as a white powder (1.24 g, 3.8 mmol, 76%). ^1H NMR (600 MHz, $CDCl_3$) δ 7.77–7.75 (m, 1H), 7.61 (d, J = 8.0 Hz, 1H), 7.36 (t, J = 7.5 Hz, 1H), 7.22 (tt, J = 7.7, 2.1 Hz, 1H), 4.37 (d, J = 16.2 Hz, 2H), 2.25 (d, J = 14.2 Hz, 9H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 133.7 (d, $^{4}J_{C-P}$ = 3.2 Hz), 132.7 (d, $^{3}J_{C-P}$ = 4.9 Hz), 130.3 (d, $^{4}J_{C-P}$ = 3.9 Hz), 128.7 (d, $^{2}J_{C-P}$ = 9.2 Hz), 128.6 (d, $^{5}J_{C-P}$ = 3.6 Hz), 124.5 (d, $^{3}J_{C-P}$ = 6.5 Hz), 30.5 (d, $^{1}J_{C-P}$ = 50.0 Hz), 9.1 (d, $^{1}J_{C-P}$ = 54.0 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 28.80. HRMS m/z (ESI+) $[M – Br]^+$ calculated for $[C_{10}H_{15}BrP]^+$ 245.0089, found 245.0082;

(2-bromobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3c**):

Followed GP1, used (2-bromobenzyl)trimethylphosphonium bromide (0.65 g, 2 mmol), silver *p*-toluenesulfonate (0.61 g, 2.2 mmol, 1.1 eq.) and chloroform (5 ml). The title compound was obtained as a white solid (0.78 g, 1.9 mmol, 93%). ^1H NMR (600 MHz, $CDCl_3$) δ 7.76 (d, J = 8.2 Hz, 2H), 7.59–7.56 (m, 1H), 7.30 (t, J = 7.5 Hz, 2H), 7.18 (tt, J = 7.8, 2.1 Hz, 1H), 7.14–7.13 (d, J = 7.9 Hz, 2H), 4.10 (d, J = 16.3 Hz, 2H), 2.33 (s, 3H), 2.12 (d, J = 14.3 Hz, 9H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 143.6, 139.5, 133.6 (d, $^{4}J_{C-P}$ = 3.3 Hz), 132.7 (d, $^{3}J_{C-P}$ = 4.8 Hz), 130.1 (d, $^{4}J_{C-P}$ = 3.9 Hz), 129.1 (d, $^{2}J_{C-P}$ = 9.2 Hz), 128.8, 128.6 (d, $^{5}J_{C-P}$ = 3.5 Hz), 125.8, 124.5 (d, $^{3}J_{C-P}$ = 6.4 Hz), 30.3 (d, $^{1}J_{C-P}$ = 49.7 Hz), 21.3, 8.3 (d, $^{1}J_{C-P}$ = 53.8 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 29.32; HRMS m/z (ESI+) $[M – OTs]^+$ calculated for $[C_{10}H_{15}BrP]^+$ 245.0089, found 245.0086;

Trimethyl(2-methylbenzyl)phosphonium bromide (**2d**):

To a solution of 2-methylbenzyl bromide (0.67 ml, 5 mmol) in acetonitrile (10 ml) was added a 1.0 M solution of trimethylphosphine in THF (5.5 ml, 5.5 mmol, 1.1 eq.) dropwise. The reaction mixture was stirred at room temperature for 1 h under an argon atmosphere, with the product being observed to precipitate from solution. The reaction mixture was then filtered, and the solids washed with Et_2O then dried *in vacuo* to yield the title compound as a white powder (1.01 g, 3.9 mmol, 77%). ^1H NMR (600 MHz, $CDCl_3$) δ 7.37 (dd, J = 7.6, 2.7 Hz, 1H), 7.24 (m, 2H), 7.21–7.19 (m, 1H), 4.20 (d, J = 16.3 Hz, 2H), 2.43 (d, J = 1.4 Hz, 3H), 2.21 (d, J = 14.2 Hz, 9H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 137.0 (d, $^{3}J_{C-P}$ = 5.7 Hz), 131.5 (d, $^{5}J_{C-P}$ = 3.4 Hz), 131.2 (d, $^{3}J_{C-P}$ = 5.0 Hz), 128.5 (d, $^{4}J_{C-P}$ = 4.0 Hz), 126.7 (m), 27.8 (d, $^{1}J_{C-P}$ = 49.4 Hz), 20.7 (d, $^{4}J_{C-P}$ = 1.3 Hz), 8.8 (d, $^{1}J_{C-P}$ = 54.1 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 28.25. HRMS m/z (ESI+) $[M – Br]^+$ calculated for $[C_{11}H_{18}P]^+$ 181.1141, found 181.1137

Trimethyl(2-methylbenzyl)phosphonium 4-methylbenzenesulfonate (**3d**):

Followed GP1, used trimethyl(2-methylbenzyl)phosphonium bromide (0.52 g, 2 mmol), silver *p*-toluenesulfonate (0.61 g, 2.2 mmol, 1.1 eq.) and chloroform (5 ml). The title compound was obtained as a white solid (0.57 g, 1.6 mmol, 81%). ^1H NMR (600 MHz, $CDCl_3$) δ 7.77 (d, J = 8.1 Hz, 2H), 7.22–7.19 (m, 3H), 7.15–7.14 (m, 3H), 3.95 (d, J = 16.4 Hz, 2H), 2.33 (s, 3H), 2.31 (d, J = 1.3 Hz, 3H), 2.06 (d, J = 14.3 Hz, 9H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 143.7, 139.4, 137.0 (d, $^{3}J_{C-P}$ = 5.7 Hz), 131.4 (d, $^{5}J_{C-P}$ = 3.4 Hz), 131.2 (d, $^{3}J_{C-P}$ = 4.9 Hz), 128.7, 128.3 (d, $^{4}J_{C-P}$ = 4.0 Hz), 127.1 (d, $^{2}J_{C-P}$ = 9.0 Hz), 126.7 (d, $^{4}J_{C-P}$ = 3.6 Hz), 125.8, 27.4 (d, $^{1}J_{C-P}$ = 49.1 Hz), 21.3, 20.2 (d, $^{4}J_{C-P}$ = 1.4 Hz), 8.0 (d, $^{1}J_{C-P}$ = 54.0 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 28.85; HRMS m/z (ESI+) $[M – OTs]^+$ calculated for $[C_{11}H_{18}P]^+$ 181.1141, found 181.1134;

(3-fluorobenzyl)trimethylphosphonium chloride (**2e**):

To a solution of 3-fluorobenzyl chloride (0.60 ml, 5 mmol) in acetonitrile (10 ml) was added a 1.0 M solution of trimethylphosphine in THF (5.5 ml, 5.5 mmol, 1.1 eq.) dropwise. The reaction mixture was stirred at 60 °C for 6 h, then at room temperature for 16 h, under an argon atmosphere. The solvent was then removed, and the salt precipitated with Et_2O. The salt was collected by filtration, washed with Et_2O and dried *in vacuo* to yield the title compound as a white powder (0.92 g, 4.2 mmol, 84%). ^1H NMR (400 MHz, DMSO-d_6) δ 7.50–7.44 (m, 1H), 7.24–7.17 (m, 3H), 3.90 (d, J = 17.2 Hz, 2H), 1.83 (d, J = 14.8 Hz, 9H); $^{13}C\{^1H\}$ NMR (101 MHz, DMSO-d_6) δ 162.3 (dd, $^{1}J_{C-F}$ = 244.2 Hz, $^{4}J_{C-P}$ = 3.9 Hz), 132.4 (dd, $^{3}J_{C-F}$ = 8.5 Hz, $^{2}J_{C-P}$ = 8.5 Hz), 131.2 (dd, $^{3}J_{C-F}$ = 8.9 Hz, $^{4}J_{C-P}$ = 3.6 Hz), 126.2 (dd, $^{4}J_{C-F}$ = 3.0 Hz, $^{3}J_{C-P}$ = 5.5 Hz), 116.8 (dd, $^{2}J_{C-F}$ = 22.3 Hz, $^{3}J_{C-P}$ = 5.2 Hz), 114.9 (dd, $^{2}J_{C-F}$ = 21.2 Hz, $^{5}J_{C-P}$ = 3.9 Hz), 29.2 (d, $^{1}J_{C-P}$ = 49.1 Hz), 7.1 (d, $^{1}J_{C-P}$ = 54.0 Hz); ^{19}F NMR (376 MHz, DMSO-d_6) δ −113.08 (d, $^{5}J_{F-P}$ = 2.7 Hz); ^{31}P NMR (243 MHz, DMSO-d_6) δ 28.11. HRMS m/z (ESI+) $[M – Br]^+$ calculated for $[C_{10}H_{15}FP]^+$ 185.0890, found 185.0882

(3-fluorobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3e**):

Followed GP1, used (3-fluorobenzyl)trimethylphosphonium chloride (0.44 g, 2 mmol), silver *p*-toluenesulfonate (0.61 g, 2.2 mmol, 1.1 eq.) and chloroform (10 ml). Stirred at room temperature for 3 h rather than 30 min. The title compound was obtained as an off-white solid (0.52 g, 1.5 mmol, 73%) that turned reddish in colour over time. ^1H NMR (400 MHz, DMSO-d_6) δ 7.51 (d, J = 8.1 Hz, 2H), 7.49–7.43 (m, 1H), 7.24–7.17 (m, 3H), 7.12 (d, J = 8.0 Hz, 2H), 3.81 (d, J = 17.1 Hz, 2H), 2.29 (s, 3H), 1.80 (d, J = 14.8 Hz, 9H); $^{13}C\{^1H\}$ NMR (101 MHz, DMSO-d_6) δ 162.3 (dd, $^{1}J_{C-F}$ = 244.9 Hz, $^{4}J_{C-P}$ = 3.8 Hz), 145.7, 137.8, 132.3 (dd, $^{3}J_{C-F}$ = 8.7 Hz, $^{2}J_{C-P}$ = 8.7 Hz), 131.2 (dd, $^{3}J_{C-F}$ = 8.7 Hz, $^{4}J_{C-P}$ = 3.6 Hz), 128.2, 126.2 (dd, $^{4}J_{C-F}$ = 3.0 Hz, $^{3}J_{C-P}$ = 5.3 Hz), 125.6, 116.8 (dd, $^{2}J_{C-F}$ = 22.2 Hz, $^{3}J_{C-P}$ = 5.4 Hz), 115.0 (dd, $^{2}J_{C-F}$ = 21.1 Hz, $^{5}J_{C-P}$ = 4.0 Hz), 29.1 (d, $^{1}J_{C-P}$ = 48.9 Hz), 20.9, 7.0 (d, $^{1}J_{C-P}$ = 54.0 Hz); ^{19}F NMR (376 MHz, DMSO-d_6) δ −113.02 (d, $^{5}J_{F-P}$ = 2.7 Hz); ^{31}P NMR (243

MHz, DMSO-d$_6$) δ 28.07; HRMS *m/z* (ESI+) [M – OTs]$^+$ calculated for [$C_{10}H_{15}FP$]$^+$ 185.0890, found 185.0887;

Benzyltrimethylphosphonium bromide (**2f**):

To a solution of benzyl bromide (1.2 ml, 10 mmol) in acetonitrile (20 ml) was added a 1.0 M solution of trimethylphosphine in toluene (11 ml, 11 mmol, 1.1 eq.) dropwise. The reaction mixture was stirred at room temperature for 1 h under an argon atmosphere, with the product being observed to precipitate from solution. The reaction mixture was cooled on ice, then filtered, and the solids washed with Et_2O then dried *in vacuo* to yield the title compound as a white powder (2.36 g, 9.6 mmol, 96%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.43–7.41 (m, 2H), 7.38–7.34 (m, 3H), 4.27 (d, J = 16.1 Hz, 2H), 2.16 (d, J = 14.1 Hz, 9H); ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 130.1 (d, $^3J_{C–P}$ = 5.4 Hz), 129.5 (d, $^4J_{C–P}$ = 3.5 Hz), 128.5 (d, $^5J_{C–P}$ = 4.0 Hz), 128.2 (d, $^2J_{C–P}$ = 9.2 Hz), 30.6 (d, $^1J_{C–P}$ = 49.6 Hz), 8.5 (d, $^1J_{C–P}$ = 54.8 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 26.32. HRMS *m/z* (ESI+) [M – Br]$^+$ calculated for [$C_{10}H_{16}P$]$^+$ 167.0984, found 167.0978;

Benzyltrimethylphosphonium 4-methylbenzenesulfonate (**3f**):

Followed GP1, used benzyltrimethylphosphonium bromide (0.99 g, 4 mmol), silver *p*-toluenesulfonate (1.23 g, 4.4 mmol, 1.1 eq.) and chloroform (10 ml). Stirred at room temperature for 1.5 h rather than 30 min. The title compound was obtained as a white solid (1.32 g, 3.9 mmol, 98%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.77 (d, J = 8.1 Hz, 2H), 7.27–7.26 (m, 3H), 7.23–7.21 (m, 2H), 7.14 (d, J = 8.0 Hz, 2H), 3.93 (d, J = 16.4 Hz, 2H), 2.32 (s, 3H), 1.95 (d, J = 14.3 Hz, 9H); ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 143.8, 139.4, 130.2 (d, $^3J_{C–P}$ = 5.3 Hz), 129.2 (d, $^4J_{C–P}$ = 3.5 Hz), 128.81, 128.75 (d, $^2J_{C–P}$ = 9.2 Hz), 128.1 (d, $^5J_{C–P}$ = 3.9 Hz), 125.8, 29.9 (d, $^1J_{C–P}$ = 49.0 Hz), 21.3, 7.4 (d, $^1J_{C–P}$ = 54.5 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 27.16; HRMS *m/z* (ESI+) [M – OTs]$^+$ calculated for [$C_{10}H_{16}P$]$^+$ 167.0984, found 167.0982;

(2-iodobenzyl)trimethylphosphonium bromide (**2g**):

To a solution of 2-iodobenzyl bromide (1.48 g, 5 mmol) in acetonitrile (10 ml) was added a 1.0 M solution of trimethylphosphine in toluene (11 ml, 11 mmol, 2.2 eq.) dropwise. The reaction mixture was stirred at room temperature for 3 h under an argon atmosphere. The solvent was removed, and the salt was precipitated with $CHCl_3$ and Et_2O (approximately 1:5 ratio of $CHCl_3$:Et_2O). The salt was collected by filtration, washed with Et_2O and dried *in vacuo* to yield the title compound as a white powder (1.09 g, 2.9 mmol, 58%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.90 (d, J = 8.0 Hz, 1H), 7.74 (dt, J = 7.8, 2.2 Hz, 1H), 7.42 (t, J = 7.6 Hz, 1H), 7.06 (tt, J = 7.8, 2.0 Hz, 1H), 4.41 (d, J = 16.1 Hz, 2H), 2.28 (d, J = 14.1 Hz, 9H); ^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$) δ 140.6 (d, $^4J_{C–P}$ = 3.2 Hz), 132.4 (d, $^2J_{C–P}$ = 9.2 Hz), 131.8 (d, $^3J_{C–P}$ = 4.9 Hz), 130.4 (d, $^4J_{C–P}$ = 3.9 Hz), 129.5 (d, $^5J_{C–P}$ = 3.6 Hz), 101.0 (d, $^3J_{C–P}$ = 6.9 Hz), 35.0 (d, $^1J_{C–P}$ = 49.9 Hz), 9.4 (d, $^1J_{C–P}$ = 54.0 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 28.90. HRMS *m/z* (ESI+) [M – Br]$^+$ calculated for [$C_{10}H_{15}IP$]$^+$ 292.9951, found 292.9940;

(2-iodobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3g**):

Followed GP1, used (2-iodobenzyl)trimethylphosphonium bromide (0.75 g, 2 mmol), silver p-toluenesulfonate (0.61 g, 2.2 mmol, 1.1 eq.) and chloroform (10 ml). The title compound was obtained as a white solid (0.90 g, 1.9 mmol, 95%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.85 (d, J = 8.0 Hz, 1H), 7.75 (d, J = 8.1 Hz, 2H), 7.53 (dt, J = 7.8, 2.3 Hz, 1H), 7.33 (t, J = 7.5 Hz, 1H), 7.13 (d, J = 7.9 Hz, 2H), 7.00 (tt, J = 8.0, 1.8 Hz, 1H), 4.11 (d, J = 16.2 Hz, 2H), 2.32 (s, 3H), 2.13 (d, J = 14.4 Hz, 9H); ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 143.8, 140.4 (d, $^4J_{C–P}$ = 3.1 Hz), 139.4, 132.9 (d, $^2J_{C–P}$ = 9.1 Hz), 131.7 (d, $^3J_{C–P}$ = 4.8 Hz), 130.1 (d, $^4J_{C–P}$ = 3.8 Hz), 129.4 (d, $^5J_{C–P}$ = 3.6 Hz), 128.7, 125.8, 100.8 (d, $^3J_{C–P}$ = 6.8 Hz), 34.8 (d, $^1J_{C–P}$ = 49.3 Hz), 21.3, 8.5 (d, $^1J_{C–P}$ = 53.7 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 29.76; HRMS m/z (ESI+) [M – OTs]$^+$ calculated for [$C_{10}H_{15}IP$]$^+$ 292.9951, found 292.9943;

(3-iodobenzyl)trimethylphosphonium bromide (**2h**):

To a solution of 3-iodobenzyl bromide (0.30 g, 1 mmol) in acetonitrile (2 ml) was added a 1.0 M solution of trimethylphosphine in toluene (1.1 ml, 1.1 mmol, 1.1 eq.) dropwise. The reaction mixture was stirred at room temperature for 1.5 h under an argon atmosphere, with the product being observed to precipitate from solution. The reaction mixture was then filtered, and the solids washed with Et_2O then dried *in vacuo* to yield the title compound as a white powder (0.36 g, mmol, 0.97 mmol, 97%). ^{1}H NMR (600 MHz, CD_3OD) δ 7.79–7.77 (m, 2H), 7.39–7.37 (m, 1H), 7.24–7.21 (m, 1H), 3.76 (d, J = 16.3 Hz, 2H), 1.87 (d, J = 14.3 Hz, 9H); ^{13}C{^{1}H} NMR (151 MHz, CD_3OD) δ 138.5 (d, $^3J_{C–P}$ = 5.4 Hz), 137.4 (d, $^5J_{C–P}$ = 3.9 Hz), 131.0 (d, $^2J_{C–P}$ = 9.0 Hz), 130.8 (d, $^4J_{C–P}$ = 3.5 Hz), 129.0 (d, $^3J_{C–P}$ = 5.0 Hz), 94.3 (d, $^4J_{C–P}$ = 4.1 Hz), 29.2 (d, $^1J_{C–P}$ = 49.8 Hz), 6.3 (d, $^1J_{C–P}$ = 55.2 Hz); ^{31}P NMR (243 MHz, CD_3OD) δ 27.25. HRMS *m/z* (ESI+) [M – Br]$^+$ calculated for [$C_{10}H_{15}IP$]$^+$ 292.9951, found 292.9938;

(3-iodobenzyl)trimethylphosphonium 4-methylbenzenesulfonate **(3h):**

Followed GP1, used (3-iodobenzyl)trimethylphosphonium bromide (0.25 g, 0.67 mmol), silver *p*-toluenesulfonate (0.22 g, 0.8 mmol, 1.2 eq.) and chloroform (15 ml). The title compound was obtained as a white solid (0.28 g, 0.60 mmol, 90%). ^{1}H NMR (400 MHz, DMSO-d$_6$) δ 7.73–7.69 (m, 2H), 7.47–7.44 (m, 2H), 7.32–7.29 (m, 1H), 7.21 (t, J = 7.7 Hz, 1H), 7.10–7.08 (m, 2H), 3.69 (d, J = 16.9 Hz, 2H), 2.26 (s, 3H), 1.76 (d, J = 14.7 Hz, 9H); ^{13}C{^{1}H} NMR (101 MHz, DMSO-d$_6$) δ 145.9, 138.2 (d, $^3J_{C–P}$ = 5.3 Hz), 137.6, 136.7 (d, $^5J_{C–P}$ = 3.8 Hz), 132.1 (d, $^2J_{C–P}$ = 9.0 Hz), 131.2 (d, $^4J_{C–P}$ = 3.3 Hz), 129.3 (d, $^3J_{C–P}$ = 5.1 Hz), 128.1, 125.5, 95.6 (d, $^4J_{C–P}$ = 4.0 Hz), 28.9 (d, $^1J_{C–P}$ = 48.8 Hz), 20.8, 7.0 (d, $^1J_{C–P}$ = 54.0 Hz); ^{31}P NMR (243 MHz, DMSO-d$_6$) δ 27.86; HRMS *m/z* (ESI+) [M – OTs]$^+$ calculated for [$C_{10}H_{15}IP$]$^+$ 292.9951, found 292.9938;

(2-chlorobenzyl)tri-p-tolylphosphonium 4-methylbenzenesulfonate **(3i):**

A solution of 2-chlorobenzyl bromide (0.25 ml, 2 mmol) and tri(*p*-tolyl)phosphine (0.85 g, 2.8 mmol, 1.4 eq.) in acetonitrile (10 ml) was stirred at 50 °C for 30 h under an argon atmosphere. The solvent was then removed, and the crude product was used directly in the next step. The crude product and silver *p*-toluenesulfonate (0.61 g, 2.2 mmol, 1.1 eq.) were dissolved in chloroform (10 ml), then stirred at room temperature for 2 h.

Filtration through $MgSO_4$ and removal of the solvent under reduced pressure yielded the crude product as a yellow solid, which darkened to a grey solid overnight and was then purified by flash column chromatography on silica gel (5% MeOH in CH_2Cl_2). NMR analysis of the product showed that not all of the product was present as the tosylate, thus the ion exchange reaction was repeated. Filtration through $MgSO_4$ and removal of solvent under reduced pressure yielded the title compound as a yellow solid (0.52 g, 0.87 mmol, 44% over two steps). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.75 (d, J = 8.1 Hz, 2H), 7.48 (dd, J = 12.5, 8.0 Hz, 6H), 7.44 (dt, J = 7.9, 2.3 Hz, 1H), 7.38 (dd, J = 8.1, 3.5 Hz, 6H), 7.20–7.14 (m, 2H), 7.10 (t, J = 7.5 Hz, 1H), 7.01 (d, J = 7.9 Hz, 2H), 5.15 (d, J = 14.4 Hz, 2H), 2.46 (s, 9H), 2.28 (s, 3H); ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 146.1 (d, $^4J_{C-P}$ = 3.0 Hz), 144.6, 138.2, 135.7 (d, $^3J_{C-P}$ = 6.3 Hz), 134.1 (d, $^3J_{C-P}$ = 10.3 Hz), 133.4 (d, $^3J_{C-P}$ = 4.8 Hz), 130.8 (d, $^2J_{C-P}$ = 13.0 Hz), 129.7 (d, $^4J_{C-P}$ = 3.9 Hz), 129.4 (d, $^5J_{C-P}$ = 3.2 Hz), 128.1, 127.7 (d, $^4J_{C-P}$ = 3.6 Hz), 126.5 (d, $^2J_{C-P}$ = 9.1 Hz), 126.2, 114.4 (d, $^1J_{C-P}$ = 88.5 Hz), 27.8 (d, $^1J_{C-P}$ = 50.3 Hz), 21.8 (d, $^5J_{C-P}$ = 1.4 Hz), 21.2; ^{31}P NMR (243 MHz, $CDCl_3$) δ 21.71; HRMS *m/z* (ESI+) [M – OTs]$^+$ calculated for $[C_{28}H_{27}ClP]^+$ 429.1533, found 429.1522;

Trimethyl(pyridin-2-ylmethyl)phosphonium 4-methylbenzenesulfonate **(5a):**

Powdered potassium hydroxide (0.88 g, 15.68 mmol) was added to a vigorously stirred solution of 2-pyridinemethanol (1.0 ml, 10.36 mmol) in THF (50 ml) at 0 °C. The reaction mixture was stirred for 15 min, then *p*-toluenesulfonyl chloride (2.56 g, 13.43 mmol) was added. The reaction mixture was then stirred for a further 18 h at room temperature. The reaction mixture was quenched with $NaHCO_3$ and the THF was removed under reduced pressure. The product was then extracted with ethyl acetate (3 × 40 ml), dried with $MgSO_4$ and concentrated under reduced pressure to give a dark red oil. Purification by flash column chromatography on silica gel (20% EtOAc in pet. ether 40–60) afforded the title compound as an orange solid (2.11 g, 8.01 mmol, 77%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.51 (d, J = 4.6 Hz, 1H), 7.83 (d, J = 8.3 Hz, 2H), 7.70 (td, J = 7.9, 1.8 Hz, 1H), 7.42 (d, J = 7.9 Hz, 1H), 7.34 (d, J = 8.1 Hz, 2H), 7.23 (dd, J = 8.0, 5.2 Hz, 1H), 5.14 (s, 2H), 2.44 (s, 3H); ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 153.7, 149.3, 145.1, 137.0, 132.7, 129.9, 128.1, 123.4, 122.0, 71.7, 21.6. Data are in good agreement with those reported in the literature.[9a] To a solution of pyridin-2-ylmethyl 4-methylbenzenesulfonate (1.32 g, 5.01 mmol) in acetonitrile (10 ml) was added a 1.0 M solution of trimethylphosphine in toluene (5.5 ml, 5.5 mmol, 1.1 eq.) dropwise. The reaction mixture was stirred at room temperature for 16 h under an argon atmosphere. The solvent was removed, and the salt was precipitated with $CHCl_3$ and Et_2O (approximately 1:5 ratio of $CHCl_3$:Et_2O). This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with $CHCl_3$. Removal of solvent under reduced pressure and drying *in vacuo* afforded the crude product as a red oil. This was dissolved in CH_2Cl_2 and filtered through an Agilent SampliQ amino cartridge to remove any acids. The solvent was removed under reduced pressure. The precipitation step (with $CHCl_3$ and Et_2O) was repeated to afford the title compound as an orange powder (1.43 g, 4.21 mmol, 84%). Note that the purification step to remove acid is essential – the borylation reaction does not work in the presence of trace acid. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.48 (d, J = 4.3 Hz, 1H), 7.78 (d, J = 8.2 Hz, 2H), 7.66 (td, J = 8.0, 1.2 Hz, 1H), 7.54 (d, J = 7.8 Hz, 1H), 7.23–7.21 (m, 1H), 7.14 (d, J = 7.9 Hz, 2H), 4.15 (d, J = 15.8 Hz, 2H), 2.33 (s, 3H), 2.13 (d, J = 14.5 Hz, 9H); ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 151.1 (d, $^2J_{C-P}$ = 9.4 Hz), 149.3 (d, $^4J_{C-P}$ = 1.9 Hz), 143.9, 139.2, 137.6, 128.6, 125.9, 125.7 (d, $^3J_{C-P}$ = 7.3 Hz), 122.8 (d, $^5J_{C-P}$ = 2.3 Hz), 32.2 (d, $^1J_{C-P}$ = 53.1 Hz), 21.3, 8.9 (d, $^1J_{C-P}$ = 54.9 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 27.46; HRMS *m/z* (ESI+) [M – OTs]$^+$ calculated for $[C_9H_{15}NP]^+$ 168.0937, found 168.0932;

Trimethyl(2-(trifluoromethyl)phenethyl)phosphonium 4-methylbenzenesulfonate **(7a)**

2-(trifluoromethyl)phenethyl 4-methylbenzenesulfonate was synthesized according to a published procedure as a colourless oil (3.33 g, 7.94 mmol, 53%).[9b] 2-(Trifluoromethyl)phenethyl 4-methylbenzenesulfonate (3.33 g, 7.94 mmol) was added to a microwave vial and the vial was sealed, evacuated and backfilled with argon. Acetonitrile (1 M) was added, followed by trimethylphosphine (9.5 ml, 1.2 equiv., 1 M solution in toluene). The resulting reaction mixture was stirred at 80 °C for 24 hours. The solvent was removed under reduced pressure, then Et_2O was added and the title phosphonium salt was isolated by filtration as a white solid (2.90 g, 6.91 mmol, 87%).

^{1}H NMR (600 MHz, Methanol-d_4) δ 7.68-7.70 (m, 3H), 7.61 (t, J = 7.6 Hz, 1H), 7.56 (d, J = 7.6 Hz, 1H), 7.46 (t, J = 7.6 Hz, 1H), 7.21 (d, J = 8.0 Hz, 2H), 3.04-3.10 (m, 2H), 2.49-2.54 (m, 2H), 2.35 (s, 3H), 1.94 (d, $^2J_{PH}$ = 14.6 Hz, 9H); ^{13}C{^{1}H} NMR (150 MHz, Methanol-d_4) δ 142.3, 140.2, 137.9 (dd, J = 17.4, 1.5 Hz), 132.6, 131.2, 128.4, 127.6 (q, $^2J_{CF}$ = 29.5 Hz), 127.2, 125.8 (q, $^3J_{CF}$ = 5.7 Hz), 125.5, 124.7 (q, $^1J_{CF}$ = 272.9 Hz), 24.8 (d, $^1J_{CP}$ = 50.6 Hz), 23.9 (d, $^2J_{CP}$ = 2.0 Hz), 19.9, 6.2 (d, $^1J_{CP}$ = 54.6 Hz); ^{31}P NMR (243 MHz, MeOD-d_4) δ 27.33; HRMS (ESI+): calculated for $[C_{12}H_{17}PF_3]^+$ 249.1014, found 249.1020.

General procedure for iridium-catalysed borylation (GP2). The reactions were carried out in 4 ml 15 × 45 mm crimp top vials. The substrate (0.25 mmol), ligand **1** (3 mol%), B_2Pin_2 (1.5 equiv.) and $[Ir(COD)OMe]_2$ (1.5 mol%) were weighed and added to the vial, which was then sealed, evacuated and backfilled with argon. 1,4-dioxane was then added for a final substrate concentration of 0.2 M. The reaction mixture was stirred and heated in deep-welled heating blocks (IKA DB 5.2) for a specified amount of time, at a specified temperature, followed by removal of solvent and analysis of the crude reaction mixture by ^{1}H NMR. Purification was generally by precipitation with Et_2O.

Calculation of yield in borylation reactions. In some cases, small amounts of starting material remained in the reactions, which were inseperable from the borylated products. The following procedure was then used to determine the yield of the borylated products.The ratio of borylated products to starting material was determined by NMR analysis, using the NMR of the isolated product. This ratio was used to calculate an average molecular weight in order to determine the mmols of product obtained, such that an overall yield could be obtained. The yield of the borylated products was then obtained by multiplying the overall yield by the fraction of borylated products present.

Assignment of meta and para products. When possible, the coupling patterns in the aromatic region were used to assign the respective isomers. Otherwise, assignments were done using information from 2D NMR experiments (COSY, HSQC, HMBC, NOESY). Data for the *para* product was usually obtained from the tmphen control experiments by subtracting the signals for the *meta* product and starting material from the spectra.

trimethyl(5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(trifluoromethyl)benzyl)phosphonium 4-methylbenzenesulfonate **(4a)**

With sulfonate ligand **1** (0.1 mmol scale):

Followed **GP2**, used trimethyl(2-(trifluoromethyl)benzyl)phosphonium 4-methylbenzenesulfonate (**3a**) (40.8 mg, 0.1 mmol), B_2Pin_2 (38 mg, 0.15 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (1 mg, 0.0015 mmol, 0.015 eq.), **1** (1.5 mg, 0.003 mmol, 0.03 eq.) and 1,4-dioxane (0.5 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of the crude ^{1}H NMR with 1,2-dimethoxyethane as the internal standard showed >20:1 *meta*:*para* borylation, in 89% NMR yield.

With sulfonate ligand **1** (0.25 mmol scale):

Followed **GP2**, used trimethyl(2-(trifluoromethyl)benzyl)phosphonium 4-methylbenzenesulfonate (**3a**) (102 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **1** (3.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of the crude ^{1}H NMR with 1,2-dimethoxyethane as the internal standard showed 6.5:1 *meta*:*para* borylation, in 93% NMR yield. The meta product decomposed upon attempted isolation by precipitation with Et_2O, therefore the crude NMR data was used in order to characterise the meta product.

4a: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82 (d, *J* = 7.6 Hz, 1H), 7.72 (d, *J* = 8.0 Hz, 2H), 7.72 (s, 1H), 7.65 (d, *J* = 7.8 Hz, 1H), 7.06 (d, *J* = 7.9 Hz, 2H), 3.90 (d, *J* = 16.4 Hz, 2H), 2.25 (s, 3H), 2.04 (d, *J* = 14.4 Hz, 9H), 1.31 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 143.6, 139.2, 137.8 (d, $^3J_{C-P}$ = 4.8 Hz), 134.8 (d, $^5J_{C-P}$ = 3.3 Hz), 130.9 (qd, $^2J_{C-F}$ = 29.8 Hz, $^3J_{C-P}$ = 5.9 Hz), 128.6, 126.9 (d, $^2J_{C-P}$ = 8.3 Hz), 126.4 (m), 125.9, 123.8 (q, $^1J_{C-F}$ = 273.8 Hz), 84.7, 28.0 (d, $^1J_{C-P}$ = 49.6 Hz), 24.8, 21.2, 8.4 (d, $^1J_{C-P}$ = 54.1 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −58.43; ^{31}P NMR (162 MHz, $CDCl_3$) δ 29.13; HRMS *m/z* (ESI+) $[M - OTs]^+$ calculated for $[C_{17}H_{26}BF_3O_2P]^+$ 361.1710, found 361.1706;

With **tmphen** (0.25 mmol scale):

Followed **GP2**, used trimethyl(2-(trifluoromethyl)benzyl)phosphonium 4-methylbenzenesulfonate (**3a**) (102 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **tmphen** (1.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of the crude ^{1}H NMR with 1,2-dimethoxyethane as the internal standard showed 1:1.6 *meta*:*para* borylation, in 90% NMR yield. It was observed that it was possible to isolate the para product by precipitation by Et_2O, while the meta product decomposed.

***para* product:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (s, 1H), 7.88 (d, *J* = 7.7 Hz, 1H), 7.70 (d, *J* = 8.2 Hz, 2H), 7.55 (dd, *J* = 7.7, 2.5 Hz, 1H), 7.06 (d, *J* = 7.9 Hz, 2H), 4.01 (d, *J* = 17.0 Hz, 2H), 2.25 (s, 3H), 2.02 (d, *J* = 14.4 Hz, 9H), 1.30 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 143.5, 139.3, 138.9 (br s), 133.0 (m), 132.3 (d, $^3J_{C-P}$ = 4.8 Hz), 130.2 (d, $^2J_{C-P}$ = 9.0 Hz), 128.6, 128.2 (dq, $^2J_{C-F}$ = 29.5 Hz, $^3J_{C-P}$ = 5.6 Hz), 125.8, 124.1 (q, $^1J_{C-F}$ = 273.9 Hz), 84.5, 27.9 (d, $^1J_{C-P}$ = 49.4 Hz), 24.8, 21.2, 8.3 (d, $^1J_{C-P}$ = 54.1 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −57.75; ^{31}P NMR (162 MHz, $CDCl_3$) δ 29.19.

(2-chloro-5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzyl)trimethylphosphonium 4-methylbenzenesulfonate **(4b)**

With sulfonate ligand **1:**

Followed **GP2**, used (2-chlorobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3b**) (93 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **1** (3.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of crude ^{1}H NMR showed >20:1 *meta:para* borylation. The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with CH_2Cl_2. Removal of solvent under reduced pressure and drying *in vacuo* afforded the title compounds (83:3:14 *meta:para:*SM) as a light orange powder (99 mg, 0.18 mmol borylated products, 70%, >20:1 *meta:para*).

4b: ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.79 (d, *J* = 8.1 Hz, 2H), 7.72–7.70 (m, 2H), 7.44 (d, *J* = 7.8 Hz, 1H), 7.14 (d, *J* = 8.0 Hz, 2H), 3.97 (d, *J* = 16.0 Hz, 2H), 2.32 (s, 3H), 2.13 (d, *J* = 14.3 Hz, 9H), 1.34 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 143.7, 139.3, 137.9 (d, $^3J_{C-P}$ = 4.8 Hz), 137.1 (d, $^3J_{C-P}$ = 6.0 Hz), 136.3 (d, $^5J_{C-P}$ = 3.8 Hz), 129.9 (d, $^4J_{C-P}$ = 3.0 Hz), 128.7, 126.5 (d, $^2J_{C-P}$ = 9.1 Hz), 125.9, 84.5, 28.4 (d, $^1J_{C-P}$ = 49.8 Hz), 24.9, 21.3, 8.4 (d, $^1J_{C-P}$ = 54.0 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 29.17; HRMS *m/z* (ESI+) $[M - OTs]^+$ calculated for $[C_{16}H_{26}BClO_2P]^+$ 327.1447, found 327.1443;

With tmphen:

Followed **GP2**, used (2-chlorobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3b**) (93 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **tmphen** (1.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane. The reaction mixture was stirred for 16 h at 50 °C. Analysis of crude ^{1}H NMR showed 1:3.3:1.5 *meta:para*:starting material. The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with CH_2Cl_2. Removal of solvent under reduced pressure and drying *in vacuo* afforded the title compounds (15:50:35 *meta:para:*SM) as a brown solid (108 mg, 0.15 mmol borylated products, 62%, 1:3.3 *meta:para*).

***para* product:** ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.81 (s, 1H), 7.75 (d, *J* = 8.0 Hz, 2H), 7.62 (d, *J* = 7.5 Hz, 1H), 7.48–7.47 (m, 1H), 7.12 (d, *J* = 8.0 Hz, 2H), 4.06 (d, *J* = 16.7 Hz, 2H), 2.32 (s, 3H), 2.07 (d, *J* = 14.5 Hz, 9H), 1.34 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 143.7, 139.4, 136.2 (d, $^4J_{C-P}$ = 3.1 Hz), 133.9 (d, $^3J_{C-P}$ = 6.3 Hz), 133.7 (d, $^3J_{C-P}$ = 6.1 Hz), 132.1 (d, $^4J_{C-P}$ = 4.9 Hz), 130.0 (d, $^2J_{C-P}$ = 9.3 Hz), 128.7, 125.8, 84.4, 28.2 (d, $^1J_{C-P}$ = 49.4 Hz), 24.9, 21.3, 8.3 (d, $^1J_{C-P}$ = 53.8 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 29.54.

(2-bromo-5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzyl)trimethylphosphonium 4-methylbenzenesulfonate **(4c)**

With sulfonate ligand **1:**

Followed **GP2**, used (2-bromobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3c**) (104 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **1** (3.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of crude ^1H NMR showed >20:1 *meta*:*para* borylation. The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with CH_2Cl_2. Removal of solvent under reduced pressure and drying *in vacuo* afforded the title compounds (85:5:10 *meta:para:*SM) as a foamy orange-brown solid (107 mg, 0.18 mmol borylated products, 73%, 17:1 *meta:para*).

4c: ^1H NMR (600 MHz, $CDCl_3$) δ 7.78 (d, J = 8.1 Hz, 2H), 7.69 (d, J = 1.6 Hz, 1H), 7.62–7.57 (m, 2H), 7.13 (d, J = 7.9 Hz, 2H), 3.98 (d, J = 15.9 Hz, 2H), 2.31 (s, 3H), 2.12 (d, J = 14.3 Hz, 9H), 1.34 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 143.7, 139.3, 137.7 (d, $^3J_{C-P}$ = 4.9 Hz), 136.3 (d, $^5J_{C-P}$ = 3.3 Hz), 133.3 (d, $^4J_{C-P}$ = 3.2 Hz), 128.7, 128.6 (d, $^2J_{C-P}$ = 9.0 Hz), 128.2 (d, $^3J_{C-P}$ = 6.3 Hz), 125.9, 84.5, 30.9 (d, $^1J_{C-P}$ = 49.4 Hz), 24.9, 21.3, 8.5 (d, $^1J_{C-P}$ = 53.8 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 29.02; HRMS *m/z* (ESI+) [M – OTs]$^+$ calculated for $[C_{16}H_{26}BBrO_2P]^+$ 371.0941, found 371.0931;

With tmphen:

Followed **GP2**, used (2-bromobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3c**) (104 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **tmphen** (1.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of crude ^1H NMR showed 1:3.5 *meta*:*para* borylation.The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with CH_2Cl_2. Removal of solvent under reduced pressure and drying *in vacuo* afforded the title compounds (19:67:14 *meta:para:*SM) as an orange powder (121 mg, 0.20 mmol borylated products, 79%, 1:3.5 *meta:para*).

***para* product :** ^1H NMR (600 MHz, $CDCl_3$) δ 8.01 (s, 1H), 7.77 (d, J = 8.1 Hz, 2H), 7.69 (d, J = 7.6 Hz, 1H), 7.52–7.51 (m, 1H), 7.14 (d, J = 8.0 Hz, 2H), 4.13 (d, J = 16.5 Hz, 2H), 2.33 (s, 3H), 2.12 (d, J = 14.2 Hz, 9H), 1.34 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 143.7, 139.5 (d, $^4J_{C-P}$ = 3.1 Hz), 139.3, 134.5 (d, $^4J_{C-P}$ = 3.4 Hz), 132.0 (d, $^3J_{C-P}$ = 4.8 Hz), 131.9 (d, $^2J_{C-P}$ = 9.3 Hz), 128.7, 125.8, 124.4 (d, $^3J_{C-P}$ = 6.4 Hz), 84.5, 30.7 (d, $^1J_{C-P}$ = 49.7 Hz), 24.9, 21.3, 8.4 (d, $^1J_{C-P}$ = 53.7 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 29.64.

Trimethyl(2-methyl-5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzyl)phosphonium 4-methylbenzenesulfonate **(4d)**

With sulfonate ligand **1** with 3 mol% $[Ir(COD)OMe]_2$ at 70 °C:

Followed **GP2**, used trimethyl(2-methylbenzyl)phosphonium 4-methylbenzenesulfonate (**3d**) (88 mg, 0.25 mmol), B_2Pin_2 (127 mg, 0.5 mmol, 2 eq.), $[Ir(COD)OMe]_2$ (5.0 mg, 0.0075 mmol, 0.03 eq.), **1** (7.6 mg, 0.015 mmol, 0.06 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 70 °C. Analysis of crude ^1H NMR showed 18:1 *meta*:*para* borylation. The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with CH_2Cl_2. Removal of solvent under reduced pressure and drying *in vacuo* afforded the title compounds (90:5:5 *meta*:*para*:SM) as an orange solid (111 mg, 0.22 mmol borylated products, 89%, 18:1 *meta*:*para*).

4d: ^1H NMR (600 MHz, $CDCl_3$) δ 7.77 (d, J = 8.2 Hz, 2H), 7.64 (d, J = 7.6 Hz, 1H), 7.49 (d, J = 2.0 Hz, 1H), 7.22 (d, J = 7.6 Hz, 1H), 7.13 (d, J = 7.9 Hz, 2H), 3.81 (d, J = 16.0 Hz, 2H), 2.35 (s, 3H), 2.32 (s, 3H), 2.06 (d, J = 14.3 Hz, 9H), 1.33 (s, 12H); $^{13}C\{^1H\}$NMR (101 MHz, $CDCl_3$) δ 143.9, 140.8 (d, $^3J_{C-P}$ = 5.5 Hz), 139.2, 136.8 (d, $^3J_{C-P}$ = 5.0 Hz), 134.8 (d, $^5J_{C-P}$ = 3.7 Hz), 131.1 (d, $^4J_{C-P}$ = 3.1 Hz), 128.7, 126.6 (d, $^2J_{C-P}$ = 8.9 Hz), 125.9, 84.0, 27.8 (d, $^1J_{C-P}$ = 49.1 Hz), 24.9, 21.3, 20.5, 8.1 (d, $^1J_{C-P}$ = 54.0 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 28.79; HRMS *m/z* (ESI+) [M – OTs]$^+$ calculated for $[C_{17}H_{29}BO_2P]^+$ 307.1993, found 307.1988;

With **tmphen** with 3 mol% $[Ir(COD)OMe]_2$ at 70 °C:

Followed **GP2**, used trimethyl(2-methylbenzyl)phosphonium 4-methylbenzenesulfonate (**3d**) (88 mg, 0.25 mmol), B_2Pin_2 (127 mg, 0.5 mmol, 2 eq.), $[Ir(COD)OMe]_2$ (5.0 mg, 0.0075 mmol, 0.03 eq.), **tmphen** (3.6 mg, 0.015 mmol, 0.06 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 70 °C. Analysis of crude ^1H NMR showed 1:1.4 *meta*:*para* borylation.The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with CH_2Cl_2. Removal of solvent under reduced pressure and drying *in vacuo* afforded the title compounds (30:42:28 *meta*:*para*:SM) as a brown solid (104 mg, 0.17 mmol borylated products, 68%, 1:1.3 *meta*:*para*).

***para* product:** ^1H NMR (600 MHz, $CDCl_3$) δ 7.76 (d, J = 8.1 Hz, 2H), 7.63 (s, 1H), 7.55 (d, J = 7.6 Hz, 1H), 7.19–7.17 (m, 1H), 7.13 (d, J = 7.9 Hz, 2H), 3.95 (d, J = 16.7 Hz, 2H), 2.32 (s, 3H), 2.30 (s, 3H), 2.03 (d, J = 14.3 Hz, 9H), 1.34 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 143.9, 139.3, 137.7 (d, $^4J_{C-P}$ = 3.3 Hz), 136.4 (d, $^3J_{C-P}$ = 5.7 Hz), 132.8 (d, $^4J_{C-P}$ = 3.4 Hz), 130.5 (d, $^3J_{C-P}$ = 4.7 Hz), 130.4 (d, $^2J_{C-P}$ = 9.1 Hz), 128.7, 125.8, 84.0, 27.7 (d, $^1J_{C-P}$ = 49.0 Hz), 24.9, 21.3, 19.9, 8.0 (d, $^1J_{C-P}$ = 53.9 Hz); **^{31}P NMR (**243 MHz, $CDCl_3$) δ 29.12.

(3-fluoro-5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzyl)trimethylphosphonium 4-methylbenzenesulfonate **(4e)**

With sulfonate ligand **1:**

Followed **GP2**, used (3-fluorobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3e**) (89 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **1** (3.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of crude ^1H NMR showed >20:1 *meta:para* borylation. The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with $CHCl_3$. Removal of solvent under reduced pressure and drying *in vacuo* afforded the *meta* product and starting material (84:16 *meta*:SM, *para* isomer was not detected) as a light orange solid (93 mg, 0.17 mmol borylated products, 68%, >20:1 *meta*:*para*).

4e: ^1H NMR (600 MHz, $CDCl_3$) δ 7.80 (d, J = 8.1 Hz, 2H), 7.44–7.42 (m, 1H), 7.35 (s, 1H), 7.22–7.20 (m, 1H), 7.17 (d, J = 8.1 Hz, 2H), 3.94 (d, J = 16.3 Hz, 2H), 2.33 (s, 3H), 2.03 (d, J = 14.3 Hz, 9H), 1.34 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 162.7 (dd, $^1J_{C-F}$ = 249.7 Hz, $^4J_{C-P}$ = 3.7 Hz), 143.7, 139.5, 131.3 (dd, $^4J_{C-F}$ = 3.0 Hz, $^3J_{C-P}$ = 5.3 Hz), 130.6 (dd, $^3J_{C-F}$ = 7.6 Hz, $^2J_{C-P}$ = 9.1 Hz), 128.8, 125.8, 121.2 (dd, $^2J_{C-F}$ = 18.5 Hz, $^5J_{C-P}$ = 3.1 Hz), 120.2 (dd, $^2J_{C-F}$ = 23.0 Hz, $^3J_{C-P}$ = 5.4 Hz), 84.4, 30.0 (d, $^1J_{C-P}$ = 48.5 Hz), 24.9, 21.3, 7.8 (d, $^1J_{C-P}$ = 54.5 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −112.56; ^{31}P NMR (243

MHz, $CDCl_3$) δ 27.53; HRMS *m/z* (ESI+) $[M - OTs]^+$ calculated for $[C_{16}H_{26}BFO_2P]^+$ 311.1742, found 311.1736;

With tmphen:

Followed **GP2**, used (3-fluorobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3e**) (89 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **tmphen** (1.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of crude ^1H NMR showed 1:1.3:2.6 *meta:para*:starting material. The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with $CHCl_3$. Removal of solvent under reduced pressure and drying *in vacuo* afforded the title compounds (20:26:54 *meta*:*para*:SM) as a brown solid (84 mg, 0.09 mmol borylated products, 37%, 1:1.3 *meta*:*para*).

***para* product:** ^1H NMR (600 MHz, $CDCl_3$) δ 7.77 (d, *J* = 8.0 Hz, 2H), 7.64 (t, *J* = 6.4 Hz, 1H), 7.15 (d, *J* = 8.0 Hz, 2H), 7.03 (d, *J* = 7.0 Hz, 1H), 6.93 (d, *J* = 9.1 Hz, 1H), 4.02 (d, *J* = 16.9 Hz, 2H), 2.33 (s, 3H), 1.97 (d, *J* = 14.4 Hz, 9H), 1.35 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 167.2 (dd, $^1J_{C-F}$ = 253.0 Hz, $^4J_{C-P}$ = 4.0 Hz), 143.7, 139.6, 137.7 (dd, $^3J_{C-F}$ = 8.6 Hz, $^4J_{C-P}$ = 3.7 Hz), 134.7 (dd, $^3J_{C-F}$ = 9.2 Hz, $^2J_{C-P}$ = 9.2 Hz), 128.9, 125.8, 125.6 (dd, $^4J_{C-F}$ = 4.4 Hz, $^3J_{C-P}$ = 4.4 Hz), 116.9 (dd, $^2J_{C-F}$ = 23.6 Hz, $^3J_{C-P}$ = 5.5 Hz), 84.1, 29.6 (d, $^1J_{C-P}$ = 49.2 Hz), 24.8, 21.3, 7.5 (d, $^1J_{C-P}$ = 54.4 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −101.74 (d, $^5J_{F-P}$ = 2.9 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) δ 27.84.

(3,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzyl)trimethylphosphonium 4-methylbenzenesulfonate **(4f)**

With sulfonate ligand **L1:**

Followed **GP2**, used benzyltrimethylphosphonium 4-methylbenzenesulfonate (**3f**) (85 mg, 0.25 mmol), B_2Pin_2 (190 mg, 0.75 mmol, 3.0 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **1** (3.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of crude ^1H NMR showed >20:1 dimeta:para borylation.The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with $CHCl_3$. Removal of solvent under reduced pressure and drying *in vacuo* afforded the title compound (contaminated with <10% mono *meta* product) as a light orange solid (111 mg, 0.17 mmol diborylated product, 69%, >20:1 *dimeta*+*monometa*:*para*)

4f: ^1H NMR (600 MHz, $CDCl_3$) δ 8.22 (s, 1H), 7.81 (d, *J* = 8.1 Hz, 2H), 7.69 (d, *J* = 1.9 Hz, 2H), 7.15 (d, *J* = 8.0 Hz, 2H), 3.73 (d, *J* = 15.7 Hz, 2H), 2.31 (s, 3H), 2.04 (d, *J* = 14.3 Hz, 9H), 1.33 (s, 24H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 143.7, 141.2 (d, $^5J_{C-P}$ = 3.5 Hz), 139.2, 138.6 (d, $^3J_{C-P}$ = 5.2 Hz), 128.7, 127.2 (d, $^2J_{C-P}$ = 8.9 Hz), 125.9, 84.1, 30.8 (d, $^1J_{C-P}$ = 49.2 Hz), 24.9, 21.3, 7.8 (d, $^1J_{C-P}$ = 54.6 Hz); ^{31}P NMR (243 MHz, $CDCl_3$) 26.98; HRMS *m/z* (ESI+) $[M - OTs]^+$ calculated for $[C_{22}H_{38}B_2O_4P]^+$ 419.2688, found 419.2685;

With tmphen:

Followed **GP2**, used benzyltrimethylphosphonium 4-methylbenzenesulfonate (**3f**) (85 mg, 0.25 mmol), B_2Pin_2 (190 mg, 0.75 mmol, 3.0 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **tmphen** (1.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 16 h at 50 °C. The solvent was removed, and the salts precipitated with Et_2O. This was followed by filtration through a pad of $MgSO_4$ and elution of the salts with $CHCl_3$. Removal of solvent under reduced pressure and drying *in vacuo* afforded a dark brown solid. NMR analysis revealed that this was a complex mixture of products (presumably a mixture of starting material and *meta*, *dimeta* and *para* products).

Trimethyl((4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)pyridin-2-yl)methyl)phosphonium 4-methylbenzenesulfonate **(6a) :**

With sulfonate ligand **1:**

Followed **GP2**, used trimethyl(pyridin-2-ylmethyl)phosphonium 4-methylbenzenesulfonate (**5a**) (85 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **1** (3.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 1 h at 50 °C. Analysis of the crude ^1H NMR with 1,2-dimethoxyethane as the internal standard showed 10:1 C4:C5 borylation, in 53% NMR yield (NMR yield used in this case due to possible contamination by the *dimeta* product). For isolation of the product, the solvent was removed. The resultant brown oil was washed with Et_2O (add Et_2O, decant off the Et_2O, repeat 10–15 times to remove most of the residual B_2Pin_2). Drying *in vacuo* afforded the title compounds as an orange powder initially, which became a brown oil upon standing.

6a: ^1H NMR (400 MHz, $CDCl_3$) δ 8.49 (dd, *J* = 4.8, 1.0 Hz, 1H), 7.77 (d, *J* = 8.1 Hz, 2H), 7.65 (s, 1H), 7.56–7.55 (m, 1H), 7.12 (d, *J* = 7.9 Hz, 2H), 4.01 (d, *J* = 15.4 Hz, 2H), 2.31 (s, 3H), 2.14 (d, *J* = 14.6 Hz, 9H), 1.34 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 150.3 (d, $^2J_{C-P}$ = 8.9 Hz), 148.8 (d, $^4J_{C-P}$ = 1.1 Hz), 143.7, 139.2, 129.9 (d, $^3J_{C-P}$ = 7.6 Hz), 128.7, 127.9 (d, $^5J_{C-P}$ = 1.7 Hz), 125.9, 84.8, 32.4 (d, $^1J_{C-P}$ = 54.2 Hz), 24.9, 21.3, 9.2 (d, $^1J_{C-P}$ = 55.1 Hz); ^{31}P NMR (162 MHz, $CDCl_3$) δ 27.36; HRMS *m/z* (ESI+) $[M - OTs]^+$ calculated for $[C_{15}H_{26}BNO_2P]^+$ 294.1789, found 294.1777;

Note: The peaks partially overlap with the SM in the ^1H NMR spectrum

With tmphen:

Followed **GP2**, used trimethyl(pyridin-2-ylmethyl)phosphonium 4-methylbenzenesulfonate (**5a**) (85 mg, 0.25 mmol), B_2Pin_2 (95 mg, 0.375 mmol, 1.5 eq.), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol, 0.015 eq.), **tmphen** (1.8 mg, 0.0075 mmol, 0.03 eq.) and 1,4-dioxane (1.25 ml). The reaction mixture was stirred for 1 h at 50 °C. Analysis of the crude ^1H NMR with 1,2-dimethoxyethane as the internal standard showed 1:1.3 C4:C5 borylation, in 60% NMR yield. For isolation of the product, the solvent was removed. The resultant brown oil was washed with Et_2O. Drying *in vacuo* afforded the title compounds as an orange powder initially. This powder became a brown oil upon standing.

***C5* product:** ^1H NMR (400 MHz, $CDCl_3$) δ 8.77 (s, 1H), 7.96 (d, *J* = 7.7 Hz, 1H), 7.72 (d, *J* = 8.1 Hz, 2H), 7.38 (d, *J* = 7.7 Hz, 1H), 7.18 (d, *J* = 8.0 Hz, 2H), 4.07 (d, *J* = 16.0 Hz, 2H), 2.29 (s, 3H), 2.05 (d, *J* = 14.6 Hz, 9H), 1.33 (s, 12H); $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$) δ 155.1 (d, $^4J_{C-P}$ = 1.7 Hz), 153.5 (d, $^2J_{C-P}$ = 9.2 Hz), 143.7, 143.6, 139.4, 128.7, 125.8, 124.7 (d, $^3J_{C-P}$ = 7.1 Hz), 84.4, 32.4 (d, $^4J_{C-P}$ = 52.8 Hz), 24.9, 21.3, 8.8 (d, $^4J_{C-P}$ = 54.9 Hz); ^{31}P NMR (162 MHz, $CDCl_3$) δ 27.58.

Trimethyl(5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-trifluoromethyl)phenethyl) phosphonium 4-methylbenzenesulfonate **(8a)**

With sulfonate ligand **1** (0.25 mmol scale):

Following general procedure **GP2** using **7a** (105.1 mg, 0.25 mmol), B_2Pin_2 (127.0 mg, 0.50 mmol), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol) and **1** (3.8 mg, 0.0075 mmol) in dioxane (1.25 mL). Stirred in vial at 70 °C for 20 hours. Analysis of crude ^{1}H NMR showed a 26:1:2 ratio of *meta*:*para*:starting material (26:1 *meta*:*para* borylation). Purification by evaporation of solvent and addition of ether, followed by filtration and drying *in vacuo* gave the title compound as a light brown solid (109.2 mg, 0.200 mmol, 80%), as a mixture of 42:1:2.3 ratio of *meta:para:*starting material.

8a: ^{1}H NMR (600 MHz, Methanol-d_4) δ 7.91 (s, 1H), 7.81 (d, J = 7.9 Hz, 1H), 7.71 (d, J = 8.0 Hz, 1H), 7.69 (d, J = 8.1 Hz, 2H), 7.19 (d, J = 8.1 Hz, 2H), 3.06-3.08 (m, 2H), 2.48-2.51 (m, 2H), 2.34 (s, 3H), 1.95 (d, $^2J_{PH}$ = 14.6 Hz, 9H), 1.36 (s, 12H); ^{13}C{^{1}H} NMR (150 MHz, Methanol-d_4) δ 142.4, 140.1, 137.10, 137.12 (d, J = 17.0 Hz), 133.2, 130.0 (q, $^2J_{CF}$ = 29.9 Hz), 128.4, 125.5, 125.2 (q, $^3J_{CF}$ = 5.6 Hz), 124.5 (q, $^1J_{CF}$ = 273 Hz), 84.3, 24.8 (d, $^1J_{CP}$ = 50.8 Hz), 23.8, 23.7, 19.9, 6.2 (d, $^1J_{CP}$ = 54.7 Hz); ^{31}P NMR (243 MHz, Methanol-d_4) δ 27.31; HRMS (ESI+): calculated for [M-OTs]$^+$ $[C_{18}H_{28}BF_3O_2P]^+$ 375.1872, found 375.1879.

With tmphen ligand (0.25 mmol scale)

Following general procedure **GP2** using **7a** (105.1 mg, 0.25 mmol), B_2Pin_2 (127.0 mg, 0.50 mmol), $[Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol) and tmphen (2.0 mg, 0.0075 mmol) in dioxane (1.25 mL). Stirred in vial at 70 °C for 20 hours. Analysis of crude ^{1}H NMR showed a 1:2:1 ratio of *meta*:*para*:starting material. A small sample was triturated with diethyl ether in order to characterise the para isomer. This contained 4:1:3 *para:meta*:starting material.

Para ^{1}H NMR (600 MHz, Methanol-d_4) δ 8.02 (s, 1H), 7.92 (d, J = 7.9 Hz, 1H), 7.67-7.70 (m, 3H), 7.18 (d, J = 8.0 Hz, 2H), 3.04-3.10 (m, 2H), 2.44-2.54 (m, 2H), 2.33 (s, 3H), 1.93 (d, J = 15.0 Hz, 9H), 1.36 (s, 12H); ^{13}C{^{1}H}NMR (150 MHz, Methanol-d_4) δ 142.4, 141.0 (d, J = 17.2 Hz), 140.2, 138.5, 131.6 (q, $^3J_{CF}$ = 5.5 Hz), 130.7, 128.4, 127.2 (q, J = 29.5 Hz), 124.5 (q, $^1J_{CF}$ = 273 Hz) 125.5, 84.3, 24.4 (d, $^1J_{CP}$ = 50.4 Hz), 23.8, 23.7, 19.9, 6.2 (d, $^1J_{CP}$ = 54.6 Hz).

*Trimethyl(phenyl)phosphonium 4-methylbenzenesulfonate (7**b**)*

Dimethylphenylphosphine (0.71 ml, 5 mmol) was dissolved in methanol (10 ml), then methyl *p*-toluenesulfonate (1.37 ml, 6 mmol) was added and the resulting reaction mixture was stirred at room temperature for 16 hours. The crude was concentrated (to about 1 ml), then diethyl ether (20 ml) was added and the resulting precipitate was collected by filtration and washed with more diethyl ether to afford the title product as a white solid (1.58 g, 4.87 mmol, 97%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84 (dd, J = 13.1, 7.3 Hz, 2H), 7.68 (d, J = 8.0 Hz, 2H), 7.58 (dd, J = 7.3, 1.2 Hz, 1H), 7.45 (dd, J = 7.9, 3.0 Hz, 2H), 7.07 (d, J = 8.0 Hz, 2H), 2.36 (d, J = 14.6 Hz, 9H), 2.30 (s, 3H); ^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$) δ 144.0, 139.1, 133.9 (d, $^4J_{C\text{-}P}$ = 3.0 Hz), 131.0 (d, $^2J_{C\text{-}P}$ = 10.4 Hz), 129.8 (d, $^3J_{C\text{-}P}$ = 12.5 Hz), 128.6, 125.9, 122.3 (d, $^1J_{C\text{-}P}$ = 85.5 Hz), 21.3, 9.6 (d, $^1J_{C\text{-}P}$ = 55.8 Hz); ^{31}P (162 MHz, $CDCl_3$) δ 22.47; HRMS (ESI+): calculated for [M-OTs]$^+$ $[C_9H_{14}P]^+$ 153.0828, found 153.0827.

*3,5-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)trimethylphosphonium 4-methylbenzenesulfonate (**8b**)*

Following general procedure **GP2** using **7b** (81 mg, 0.25 mmol), B_2Pin_2 (190 mg, 0.75 mmol), $Ir(COD)OMe]_2$ (2.5 mg, 0.00375 mmol) and **1** (3.8 mg, 0.0075 mmol) in dioxane (1.25 mL). Stirred in vial at 50 °C for 20 hours. Analysis of crude ^{1}H NMR showed >20:1 dimeta:other borylation products. Purification by evaporation of solvent and addition of ether, followed by filtration and drying *in vacuo* gave the title compound as a light brown solid (115 mg, 0.20 mmol, 80%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.51 (s, 1H), 8.06 (d, J = 12.9 Hz, 2H), 7.73 (d, J = 8.0 Hz, 2H), 7.08 (d, J = 8.0 Hz, 2H), 2.41 (d, J = 14.4 Hz, 9H), 2.30 (s, 3H), 1.34 (s, 24H); ^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$) δ 146.6 (d, $^4J_{C\text{-}P}$ = 2.8 Hz), 143.8, 138.9, 138.3 (d, $^2J_{C\text{-}P}$ = 9.8 Hz), 128.5, 125.9, 121.4 (d, $^1J_{C\text{-}P}$ = 83.3 Hz), 84.7, 24.9, 21.3, 9.8 (d, $^1J_{C\text{-}P}$ = 56.1 Hz); ^{31}P (162 MHz, $CDCl_3$) δ 22.34; HRMS (ESI+): calculated for [M-OTs]$^+$ $[C_{21}H_{36}B_2O_4P]^+$ 405.2532, found 405.2542.

*4-chloro-3-methylphenol (**9**)*

Followed **GP2**, used (2-chlorobenzyl)trimethylphosphonium 4-methylbenzenesulfonate (**3b**) (372.8 mg, 1.0 mmol), B_2Pin_2 (381 mg, 1.5 mmol), $[Ir(COD)OMe]_2$ (10 mg, 0.015 mmol), **1** (15.2 mg, 0.03 mmol) and 1,4-dioxane (5 ml). The reaction mixture was stirred for 16 h at 50 °C. Analysis of crude ^{1}H NMR showed >20:1 *meta:para* borylation. The solvent was removed then the residue was dissolved in THF (8.25 ml) and methanol (8.25 ml). $NaHCO_3$ (1.05 g, 12.5 equiv.) was added and the mixture was cooled to 0 °C before dropwise addition of H_2O_2 (3 ml, 30% in water, ~26 mmol). The resulting reaction mixture was stirred at room temperature for 1 hour, then filtcered through Celite and the filtrate was concentrated under reduced pressure and dried under high vacuum. The residue was dissolved in dry THF (5 ml) under an argon atmosphere and cooled to 0 °C. A solution of lithium aluminium hydride (2 ml, 1M in THF, 2 mmol) was added dropwise, then heated to 60 °C for 1 hour. The reaction was cooled to 0 °C and quenched by addition of water, then acidified using 1M HCl and extracted with CH_2Cl_2. The organic layer was dried over $MgSO_4$ and purified by column chromatography on silica gel (5% EtOAc in pet ether 40-60) to afford **9** as a white solid (65 mg, 0.46 mmol, 46% over 3 steps).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.18 (d, J = 8.5 Hz, 1H), 6.71 (d, J = 2.8 Hz, 1H), 6.61 (dd, J = 8.6, 3.0 Hz, 1H), 5.14 (br, 1H), 2.31 (s, 3H); ^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$) δ 153.9, 137.4, 129.8, 126.0, 117.8, 114.1, 20.1; HRMS (ESI+): calculated for [M-H]$^-$ $[C_7H_6ClO]^-$ 141.0113, found 141.0110.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website. Contains ^{1}H NMR and ^{13}C NMR spectra for all compounds.

AUTHOR INFORMATION

Corresponding Author

* rjp71@cam.ac.uk

ACKNOWLEDGMENT

We are grateful to AstraZeneca for a PhD studentship through the AZ-Cambridge PhD program (M.T.M.), the Royal Society for a University Research Fellowship (R.J.P.), the EPSRC (EP/N005422/1) and the ERC (StG 757381). We are very grateful to Dr. Holly J. Davis for performing initial experiments. We thank the EPSRC UK National Mass Spectrometry Facility at Swansea University as well as Professors Steven V. Ley and Matthew J. Gaunt for support and useful discussions.

REFERENCES

1. (a) Dey, A.; Agasti, S.; Maiti, D., Palladium catalysed meta-C–H functionalization reactions. *Org. Biomol. Chem.* **2016,** *14*, 5440-5453; (b) Li, J.; De Sarkar, S.; Ackermann, L., meta- and para-Selective C–H Functionalization by C–H Activation. In *C-H Bond Activation and Catalytic Functionalization I*, Dixneuf, P. H.; Doucet, H., Eds. Springer International Publishing: Cham, 2016; pp 217-257; (c) Mihai, M. T.; Genov, G. R.; Phipps, R. J., Access to the meta position of arenes through transition metal catalysed C–H bond functionalisation: a focus on metals other than palladium. *Chem. Soc. Rev.* **2018,** *47*, 149-171; (d) Dey, A.; Sinha, S. K.; Achar, T. K.; Maiti, D., Game of Directors: Accessing Remote Meta- and Para-C--H Bonds With Covalently Attached Directing Groups. *Angew Chem Int Ed Engl* **2018,** *0*.

2. (a) Davis, H. J.; Phipps, R. J., Harnessing non-covalent interactions to exert control over regioselectivity and site-selectivity in catalytic reactions. *Chem. Sci.* **2017,** *8*, 864-877; (b) Dydio, P.; Reek, J. N. H., Supramolecular control of selectivity in transition-metal catalysis through substrate preorganization. *Chem. Sci.* **2014,** *5*, 2135-2145; (c) Raynal, M.; Ballester, P.; Vidal-Ferran, A.; van Leeuwen, P. W. N. M., Supramolecular catalysis. Part 1: non-covalent interactions as a tool for building and modifying homogeneous catalysts. *Chem. Soc. Rev.* **2014,** *43*, 1660-1733.

3. (a) Breslow, R.; Zhang, X.; Huang, Y., Selective Catalytic Hydroxylation of a Steroid by an Artificial Cytochrome P-450 Enzyme. *J. Am. Chem. Soc.* **1997,** *119*, 4535-4536; (b) Das, S.; Incarvito, C. D.; Crabtree, R. H.; Brudvig, G. W., Molecular Recognition in the Selective Oxygenation of Saturated C-H Bonds by a Dimanganese Catalyst. *Science* **2006,** *312*, 1941-1943.

4. (a) Šmejkal, T.; Breit, B., A Supramolecular Catalyst for Regioselective Hydroformylation of Unsaturated Carboxylic Acids. *Angew. Chem. Int. Ed.* **2008,** *47*, 311-315; (b) Dydio, P.; Detz, R. J.; Reek, J. N. H., Precise Supramolecular Control of Selectivity in the Rh-Catalyzed Hydroformylation of Terminal and Internal Alkenes. *J. Am. Chem. Soc.* **2013,** *135*, 10817-10828.

5. For seminal reports on Ir-catalyzed borylation, see: (a) Cho, J.-Y.; Tse, M. K.; Holmes, D.; Maleczka, R. E.; Smith, M. R., Remarkably Selective Iridium Catalysts for the Elaboration of Aromatic C-H Bonds. *Science* **2002,** *295*, 305-308; (b) Ishiyama, T.; Takagi, J.; Ishida, K.; Miyaura, N.; Anastasi, N. R.; Hartwig, J. F., Mild Iridium-Catalyzed Borylation of Arenes. High Turnover Numbers, Room Temperature Reactions, and Isolation of a Potential Intermediate. *J. Am. Chem. Soc.* **2002,** *124*, 390-391; (c) Takagi, J.; Sato, K.; Hartwig, J. F.; Ishiyama, T.; Miyaura, N., Iridium-catalyzed C–H coupling reaction of heteroaromatic compounds with bis(pinacolato)diboron: regioselective synthesis of heteroarylboronates. *Tetrahedron Lett.* **2002,** *43*, 5649-5651; (d) Boller, T. M.; Murphy, J. M.; Hapke, M.; Ishiyama, T.; Miyaura, N.; Hartwig, J. F., Mechanism of the Mild Functionalization of Arenes by Diboron Reagents Catalyzed by Iridium Complexes. Intermediacy and Chemistry of Bipyridine-Ligated Iridium Trisboryl Complexes. *J. Am. Chem. Soc.* **2005,** *127*, 14263-14278; For leading reviews on Ir-catalyzed borylation, see: (e) Mkhalid, I. A. I.; Barnard, J. H.; Marder, T. B.; Murphy, J. M.; Hartwig, J. F., C−H Activation for the Construction of C−B Bonds. *Chem. Rev.* **2010,** *110*, 890-931; (f) Hartwig, J. F., Regioselectivity of the borylation of alkanes and arenes. *Chem. Soc. Rev.* **2011,** *40*, 1992-2002; (g) Ros, A.; Fernandez, R.; Lassaletta, J. M., Functional group directed C-H borylation. *Chem. Soc. Rev.* **2014,** *43*, 3229-3243.

6. (a) Roosen, P. C.; Kallepalli, V. A.; Chattopadhyay, B.; Singleton, D. A.; Maleczka, R. E.; Smith, M. R., Outer-Sphere Direction in Iridium C–H Borylation. *J. Am. Chem. Soc.* **2012,** *134*, 11350-11353; (b) Preshlock, S. M.; Plattner, D. L.; Maligres, P. E.; Krska, S. W.; Maleczka, R. E.; Smith, M. R., A Traceless Directing Group for C-H Borylation. *Angew. Chem. Int. Ed.* **2013,** *52*, 12915-12919; (c) Kuninobu, Y.; Ida, H.; Nishi, M.; Kanai, M., A meta-selective C–H borylation directed by a secondary interaction between ligand and substrate. *Nat. Chem.* **2015,** *7*, 712-717; (d) Chattopadhyay, B.; Dannatt, J. E.; Andujar-De Sanctis, I. L.; Gore, K. A.; Maleczka, R. E.; Singleton, D. A.; Smith, M. R., Ir-Catalyzed ortho-Borylation of Phenols Directed by Substrate–Ligand Electrostatic Interactions: A Combined Experimental/in Silico Strategy for Optimizing Weak Interactions. *J. Am. Chem. Soc.* **2017,** *139*, 7864-7871; (e) Hoque, M. E.; Bisht, R.; Haldar, C.; Chattopadhyay, B., Noncovalent Interactions in Ir-Catalyzed C–H Activation: L-Shaped Ligand for Para-Selective Borylation of Aromatic Esters. *J. Am. Chem. Soc.* **2017,** *139*, 7745-7748; (f) Davis, H. J.; Genov, G. R.; Phipps, R. J., meta-Selective C−H Borylation of Benzylamine-, Phenethylamine-, and Phenylpropylamine-Derived Amides Enabled by a Single Anionic Ligand. *Angew. Chem. Int. Ed.* **2017,** *56*, 13351-13355; (g) Bisht, R.; Hoque, M. E.; Chattopadhyay, B., Amide Effects in C−H Activation: Noncovalent Interactions with L-Shaped Ligand for meta Borylation of Aromatic Amides. *Angew. Chem. Int. Ed.* **2018,** *57*, 15762-15766; (h) Wang, J.; Torigoe, T.; Kuninobu, Y., Hydrogen-Bond-Controlled Formal Meta-Selective C–H Transformations and Regioselective Synthesis of Multisubstituted Aromatic Compounds. *Org. Lett.* **2019,** *21*, 1342-1346; (i) Lu, X.; Yoshigoe, Y.; Ida, H.; Nishi, M.; Kanai, M.; Kuninobu, Y., Hydrogen Bond-Accelerated meta-Selective C–H Borylation of Aromatic Compounds and Expression of Functional Group and Substrate Specificities. *ACS Catal.* **2019,** *9*, 1705-1709.

7. For examples of phosphine-directed borylation, see: (a) Crawford, K. M.; Ramseyer, T. R.; Daley, C. J. A.; Clark, T. B., Phosphine-Directed C-H Borylation Reactions: Facile and Selective Access to Ambiphilic Phosphine Boronate Esters. *Angew. Chem. Int. Ed.* **2014,** *53*, 7589-7593; (b) Fukuda, K.; Iwasawa, N.; Takaya, J., Ruthenium-Catalyzed ortho C−H Borylation of Arylphosphines. *Angew. Chem.* **2019,** *131*, 2876-2879; (c) Wen, J.; Wang, D.; Qian, J.; Wang, D.; Zhu, C.; Zhao, Y.; Shi, Z., Rhodium-Catalyzed PIII-Directed ortho-C−H Borylation of Arylphosphines. *Angew. Chem. Int. Ed.* **2019,** *58*, 2078-2082.

8. (a) Breslow, R.; Rajagopalan, R.; Schwarz, J., Selective functionalization of doubly coordinated flexible chains. *J. Am. Chem. Soc.* **1981,** *103*, 2905-2907; (b) Breslow, R.; Heyer, D., Directed steroid chlorination catalyzed by an ion-paired template. *Tetrahedron Lett.* **1983,** *24*, 5039-5042.

9. (a) Davis, H. J.; Mihai, M. T.; Phipps, R. J., Ion Pair-Directed Regiocontrol in Transition-Metal Catalysis: A Meta-Selective C–H Borylation of Aromatic Quaternary Ammonium Salts. *J. Am. Chem. Soc.* **2016,** *138*, 12759-12762; (b) Mihai, M. T.; Davis, H. J.; Genov, G. R.; Phipps, R. J., Ion Pair-Directed C–H Activation on Flexible Ammonium Salts: meta-Selective Borylation of Quaternized Phenethylamines and Phenylpropylamines. *ACS Catal.* **2018,** *8*, 3764-3769.

10. Byrne, P. A.; Gilheany, D. G., The modern interpretation of the Wittig reaction mechanism. *Chem. Soc. Rev.* **2013,** *42*, 6670-6696.

11. (a) McNulty, J.; Das, P., Highly Stereoselective and General Synthesis of (E)-Stilbenes and Alkenes by Means of an Aqueous Wittig Reaction. *Eur. J. Org. Chem.* **2009,** *2009*, 4031-4035; (b) McNulty, J.; Das, P., Aqueous Wittig reactions of semi-stabilized ylides. A straightforward synthesis of 1,3-dienes and 1,3,5-trienes. *Tetrahedron Lett.* **2009,** *50*, 5737-5740; (c) Das, P.; McLeod, D.; McNulty, J., A direct synthesis of functionalized styrenes and terminal 1,3-dienes via aqueous Wittig chemistry with formalin. *Tetrahedron Lett.* **2011,** *52*, 199-201.

12. (a) Hwang, L. K.; Na, Y.; Lee, J.; Do, Y.; Chang, S., Tetraarylphosphonium Halides as Arylating Reagents in Pd-Catalyzed

Heck and Cross-Coupling Reactions. *Angew. Chem. Int. Ed.* **2005,** *44*, 6166-6169; (b) Zhang, X.; McNally, A., Phosphonium Salts as Pseudohalides: Regioselective Nickel-Catalyzed Cross-Coupling of Complex Pyridines and Diazines. *Angew. Chem. Int. Ed.* **2017,** *56*, 9833-9836.

13. Bailey, W. J.; Buckler, S. A., Phosphorus Compounds. I. Reduction of Benzylphosphonium Compounds with Lithium Aluminum Hydride1. *J. Am. Chem. Soc.* **1957,** *79*, 3567-3569.